U.S. Ice Drilling Program

Long Range Science Plan 2015-2025

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Contents

Cover photo: Ed Brook and Rachael Rhodes cut ice sticks from ice cores drilled with the Blue Ice Drill at Taylor Glacier, Antarctica. The ice will be used for analysis in the field using a continuous melter system. Photo credit: Jacob Ward.

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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 - www.pages-igbp.org/ipics) 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 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.

- Data from the core near the West Antarctic Ice Sheet Divide (WAIS Divide) are providing unprecedented high-resolution climate records for Antarctica for the past 60,000 years. Now that the main core and replicate drilling are complete, the final stage of the project will be to complete the borehole logging studies.
- Drilling of spatially distributed ice cores and boreholes to support both IPICS goals and the 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 requires arrays of shallow cores covering a range of accumulation rates both in Greenland and in Antarctica. Spatially-distributed shallow coring for records ranging from 200 to 2,000 years will include multiple scientific traverses in Greenland for study of the ice sheet under the currently changing climate. In Antarctica, an international French-Italian-U.S. scientific traverse is being proposed from Dome

C to South Pole. Climate records contained in ice cores from Roosevelt Island in the eastern Ross Sea and South Pole are expected to extend back 40,000 years. Additional goals for the coming decade include coring for 40,000-year records from Hercules Dome (as part of a record extending further back at that site) in Antarctica, as well as from Renland and East Greenland Ice Core Project (EGRIP), Greenland. Targeted ice coring to investigate ice, ocean, and atmospheric dynamics along the dynamic Amundsen Sea Coast of Antarctica is in the planning stages.

- Determination of the amount of water retained and frozen in the near surface firn (top ~60 m) on the Greenland Ice Sheet and on the Antarctic Peninsula is needed to better constrain estimates of surface mass balance under current warming conditions.
- An undisturbed climate record from the last interglacial period (the Eemian, ~130,000 to 110,000 years ago) is key to predicting the response of glaciers and ice sheets to future warming. The search for sites to extract Eemian ice in Greenland and Antarctica, both by coring and through horizontal sampling of blue ice ablation zones, should continue. 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. Samples from Antarctica where the climate record may have been impacted by changes in the WAIS during the last interglacial period are important, since WAIS history for this time is poorly known.
- Blue-ice paleoclimate records have potential for providing unlimited samples for atmospheric and ultra-trace component studies and can enable new types of measurements that have previously been impossible, and the Blue Ice Drill may also access ice older than 800,000 years. Blue-ice studies at Mt. Moulton, Taylor Glacier, and Allan Hill exemplify discoveries from this realm so far.
- Ice cores and borehole observations reaching ages between 800,000 years and 1.5M years (or beyond) are a priority. Ice this old provide important evidence about atmospheric composition and climate during times when conditions were very different than today. These data would 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; for extraction of deep cores, these activities should be coordinated with international partners. An undisturbed deep ice core is the primary IPICS goal. "Snapshots" of time periods beyond 800,000 years are potentially available from blue ice regions or areas of discontinuous deposition. Developing further understanding of these regions and sampling them should also be a priority in the search for 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 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 meters) 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 potential basal slip. Likewise, the unknown subglacial geology of Antarctica represents the last continental frontier of geologic exploration, including landscape evolution, paleoclimate 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 remotely sensed products from the British Antarctic Survey 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. Samples of subglacial sediments and ecosystems are needed to establish the diversity, and physiology of microbes and their relationships to past climates and their current ecosystem function below the ice.
- The development of tools, methods and technologies enables clean access to subglacial environments to advance biological and geochemical sampling while maintaining scientific integrity and environmental stewardship. A recent example of an initial effort in this direction was the subglacial Lake Whillans program.

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, experimental astrophysics, and other novel phenomena. Specifically,

- Community winches for 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 preserved in the ice; and sonic logs provide continuous record of ice structure through the ice sheet.
- 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.
- Future planned projects such as the Askaryan Radio Array (ARA) and Generation-2 Ice Cube (G-2IC) require multiple boreholes drilled to at least 150 m deep (ARA) and 2500 m deep (G-2IC) and foresee significant calibration studies of the surrounding ice volume.
- Ice sheets are a quiet platform for seismic monitoring; the South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed in boreholes approximately 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 requiring 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.

Recommended technology investments

The following investments in drilling technologies are needed to accomplish science goals planned for the next decade. Investments prioritized by time include:

Priority 1 (needed this year):

- Maintain and upgrade the following existing agile equipment: hand augers, 2” and 4” electro-mechanical drills, 3” electrothermal drill, 3.25” Badger-Eclipse drills, logging winches, and 30 m hot water shot hole drill.
- Complete fabrication of the Agile Sub-Ice Glacial (ASIG) rock coring drill capable of retrieving 10 m of rock core beneath ice up to 700 meters thick.
- Maintain the DISC Drill, and finish IDPO Science Requirements and IDDO cost estimates for minimal upgrades for the DISC drill for use at Hercules Dome with the goal to lessen its logistics requirements while maintaining its replicate coring capability, keeping in mind upgrades to be added later for future use for Oldest Ice.
- Procure and modify a Winkie drill to also include conditions containing ice.
- Develop IDPO Science Requirements and create a conceptual design and cost estimate for adapting an agile coring drill to minimize logistical requirement for the drill, shelter, and fluid plan for ice coring to approximately 900 m. The system must have significantly smaller logistical requirements than the IDPO Intermediate Depth Drill and associated infrastructure. Published lessons learned (e.g. Sheldon et al, 2014 and Triest et al, 2014) should be considered.
- Develop and build the Lake Ice Drill, a very portable clean access hot-water drill for creating 5” holes through up to 6 m of sediment-laden lake ice.
- Establish IDPO Science Requirements and repair, modify or acquire a very lightweight highly-portable drill for shallow ice coring.
- Prepare for field trials of the Rapid Access Ice Drill (RAID)[1].

[1] This development is happening with DOSECC Exploration Services, LLC.

- Prepare WISSARD & UNL Roving drill and recovery of hot water ice cores for projects proposed in 2015[2].

Priority 2 (needed within the next three years):

- Continue development of a scalable, modular hot water access drill for creating access holes in ice from 50 m up to approximately 1,000 m deep with modular potential to be used for clean access.
- Conduct a conceptual design and start construction of an agile shot-hole drill capable of drilling 15 holes per day up to 100 m deep in both East and West Antarctica. This may include consideration of a Rapid Air Movement (RAM) drill upgrade, or other means. A secondary consideration is that a borehole with a 15 cm diameter would make this drill of interest for radio neutrino detectors as well.
- Upgrade the electrothermal drill to allow for coring to 300 m through temperate and polythermal firn and ice. The drill needs to be agile and light weight (transportable by helicopter).
- Build a replicate Blue Ice Drill for wide-diameter drilling to 200 m.

Priority 3 (needed within three to five years):

- Assess the potential of recovering cores to depths of 300-500 m without the use of drilling fluid.
- Develop IDPO Science Requirements for clean access drilling to depths over 3,000 m.
- Conduct a feasibility study to modify the Blue Ice drill to enable large-volume sampling of firn and ice up to 300 m deep.
- Develop IDPO Science Requirements and conduct a feasibility study for a drill capable of coring horizontally (or at low angles) to a depth of several hundred meters.
- Construct a jig to support a hand auger that will facilitate horizontal coring up to 20 m into ice cliffs.

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 continues through the coming decades. The IDPO will continue to work in concert with the scientific community 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.

[2] If funded, this development would happen with an IDPO subaward to the University of Nebraska-Lincoln.

Introduction

One of the most pressing environmental issues of our time is the greenhouse gas-induced climate change that will warm the Earth, and potentially change many other aspects of global climate and environmental systems, including the possibility of abrupt changes in climate and sea level. 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.
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 impacts on 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. Many basic questions about Earth's climate system remain unresolved. For example, what are the climate linkages between the northern and southern hemispheres? What is the human impact on global climate? How do atmosphere-ocean-ice interactions affect the cryosphere? How quickly can sea level rise? How sensitive is climate to greenhouse gases? Emerging results from the WAIS Divide Ice Core are contributing new insights (e.g. WAIS Divide Project Members, 2013, 2015).

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 likely triggered by changing ocean temperature, circulation, sea level (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. Large 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 IDPO, working with its SAB 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 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 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.

Time periods up to 200 years: The broad goal of a 200-year array of ice core records is to establish recent atmospheric records in the upper layers of glaciers and ice sheets.

Over the past 200 years, human activities have had a significant impact on atmospheric composition, 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) 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. With a recent increase in surface melt on ice sheets, particularly in Greenland, shallow cores are used to constrain surface mass balance processes beyond accumulation. Cores and boreholes are needed to access areas of water retention, in perched water tables and aquifers, and areas of refreeze with thick ice lens. In addition, a working group in IPICS is currently preparing a white paper on non-polar ice coring which will address some coordinated international goals related to 200-year arrays. 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 that has started and will continue with the following objectives:

- Determine accumulation rate and temperature changes in the remote dry snow zones of Greenland and Antarctica.
- Elucidate transfer functions between atmospheric chemistry and snow composition.
- Understand changes in the chemistry of the atmosphere during the Industrial Period. Trace species such as hydrocarbons and isotopes of CO (including ^{14}CO) can be used for this purpose.
- Determine relevant physical and chemical processes related to snow deposition and metamorphism, and their effects on atmospheric chemistry and gas preservation in ice cores.
- Relate snow/firn/ice properties to remotely sensed signals (e.g., borehole, ground, and satellite-based measurements), thereby allowing interpolation based on remote sensing data.
- Identify and model post-depositional changes in chemical and physical properties.
- Produce detailed temporal and spatial maps of climate and environmental parameters (e.g., temperature, accumulation rate, chemistry).
- Determine the amount of water retained and refrozen in the near surface firn (top ~ 60 – 90 m) on the perimeter of the Greenland Ice Sheet and on the Antarctic Peninsula to better constrain surface mass balance estimates.
- Calibrate local, regional, and global atmospheric models as well as constrain relationships between regional climate patterns (AO, ENSO, Monsoons) and the "Little Ice Age" and the "Medieval Climate Anomaly".
- Determine the sensitivity of alpine glaciers and ice sheet margins to past warm periods, with implications for the impact of future warming on water resource availability and sea level rise.
- Understand the air-snow exchange of aerosols and gases in alpine regions, and the processes influencing their preservation in ice core records.
- Investigate the spatial patterns of anthropogenic impacts.

- Develop regional records of biomass burning.
- Develop an inventory of microbes within ice to improve understanding of the role of microbes related to geological, chemical and climatological changes.
- Identify biogeographical patterns and understand their role in ice core dynamics. Several of these objectives are critical for interpreting longer timescale records detailed in following sections.
- Understand anthropogenic impacts on greenhouse gases in the atmosphere.
- Improve records of global and local volcanism.

Part of an ice core retrieved from Mt Hunter Plateau of Denali exhibits layering and dust carried to the area from afar. 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, ice caps, 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 a very lightweight 5 cm diameter "backpack drill" for alpine shallow coring; a support for a hand auger capable of clean, horizontal, 2 m-deep coring from glacier sides with the auger carried on a backpack and operated by a single drill operator, and an upgraded thermal drill for collection of cores from temperate ice where water is present.

2. 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 variability of climate, yet short enough that relevant climate boundary conditions have not changed appreciably. Existing quantitative reconstructions of the past two millennia continue to be debated, in part due to a lack of annual data prior to 1600 B.P.in many areas, and 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:

- Establishing the extent and regional expression of the so-called "Little Ice Age" and "Medieval Climate Anomaly" phenomena.
- Evaluating 20th-century warming in the context of the past 2,000 years.
- Establishing spatial and temporal patterns of temperature, precipitation, sea ice extent, and atmospheric gases.
- Quantifying spatial and temporal patterns of climate-forcing mechanisms that are regionally variable (e.g., greenhouse 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.
- Providing the context for recent ice, ocean and atmospheric dynamics observed along the Amundsen Sea Coast.

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, or planned U.S. or U.S./International efforts include Roosevelt Island in the Ross Sea (the 2,000-year record would be part of a deeper core), South Pole (the 2,000-year record would be part of a deeper core); Central Alaska Range (Mt. Hunter plateau), British Columbia; Detroit Plateau on the Antarctic Peninsula; ice domes along the Amundsen Sea Coast; the Aurora Basin in Antarctica; Hercules Dome near South Pole; and high accumulation rate sites in Greenland. This list is not exclusive, but illustrates the diversity of discussions within the research community.

Scientific drilling on the Mt. Hunter Plateau of Denali provides a 1,000-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. Credit: a) *Seth Campbell, CRREL; b) Dom Winski, Dartmouth*

3. 40,000-year network: The past 40,000 years include the glacial-interglacial transition and our present warm period, the Holocene, as well as a sequence of abrupt swings in climate as recorded in Greenland ice cores and other climate archives. The glacial-interglacial transition is the best-documented global response to very large-scale changes in climate boundary conditions, 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 very 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.

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 WAIS Divide core as well as the current South Pole Ice Core (SPICE) project, and the Hercules Dome site is being considered for future work. Drilling by New Zealand with U.S. science collaboration is complete on Roosevelt Island, and is an important contribution to the network. Greenland cores at Renland and EGRIP cores, led by Denmark, will also contribute. 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 capable of coring to 1,500 m is being used on the South Pole (SPICE) project. As discussed in the IDDO Long Range Drilling Technology Plan, current agile drills in the inventory have a maximum depth of several hundred meters. The only other drill in inventory capable of drilling deeper is the DISC drill, which can reach 4,000 m, but it is logistically heavy and requires more than three seasons for deployment and drilling.

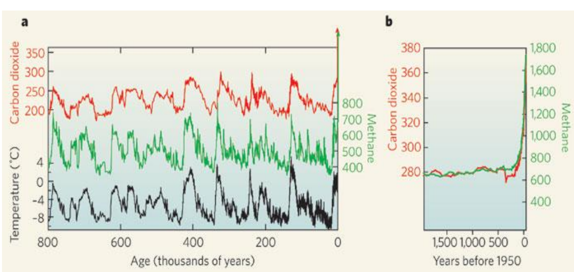
4. High-resolution records of the last interglacial: The last interglacial period (~130,000 to 110,000 years ago) was warmer than present due to differences in Earth's orbital configuration, and can provide clues about how the Earth will behave as human activities continue to force global warming. Critical questions concern the possibility of tipping points of abrupt change during interglacial climates, the evolution of greenhouse gases in warm climates, the possibility of ice sheet collapse, and changes in ocean circulation during warm climates. 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). As a result, 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 from ice cores in both polar regions. Recent results from the North Greenland Eemian Ice Drilling (NEEM) ice core in Greenland have shown that the Eemian record located there is recoverable, but not in stratigraphic order. The search for sites with unfolded ice will continue in both polar regions; likely targets are relatively high accumulation sites in Antarctica where last interglacial ice is likely to be preserved, and possible new sites in Greenland. Drilling sites are likely to be at remote locations in Antarctica


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. Credit: *Oregon State University.*

where accumulation is moderate, on the order of 10-cm/year. A recent European core at Talos Dome in Antarctica includes the last interglacial period, as did the earlier EPICA Dronning Maude Land (EDML). U.S. community discussions are focusing in the near term on Hercules Dome as a possible site. Some coastal domes, such as the Renland Ice Cap in Greenland, are also possibilities. For these studies as well as those in other categories, because particular depths are of interest to a number of investigators, the community needs the capability to do replicate coring at targeted depths. This is particularly important for ice cores covering the last interglacial period and penultimate glacial termination since ice flow will invariably make these climatically important sections thin, creating sample limitation problems. The replicate coring capability now exists in the DISC drill system.

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. Ice is generally thought to have been present continuously in parts of East Antarctica for at least 1.5 million years. 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: the transition about 1,200,000 - 800,000 years ago from a world dominated by glacial-interglacial cycles lasting about 40,000 years to one with 100,000-year cycles. Numerous questions about this transition, and the earlier time period — including the role of greenhouse gases; the relationship between ice sheet behavior and climate; the relationship between long-term, late-Cenozoic cooling and climate cyclicity; and the persistence of abrupt climate change - could be addressed with ice core records extending back ~ 1.5 million years.



The 100,000-year 'sawtooth' variability in carbon dioxide, methane, and temperature underwent a change about 450,000 years ago, with the amplitude of variation greater after that point than it was before. Concentrations of greenhouse gases in the modern atmosphere are highly anomalous with respect to natural greenhouse-gas variations (present-day concentrations are around 380 p.p.m. for carbon dioxide and 1,800 p.p.b. for methane). Figure from Brook, 2008; see also Luthi et al, 2008.

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 BP if it would save time and money and only recover the older ice. A 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) where old ice may be cropping out at the surface. Continuous records may be difficult to find at such sites, but access is much easier. Different drilling requirements are needed for the two approaches. Strategies were discussed at an IPICS meeting (Corvallis, OR, 2009), with a preference for continuous records, given the potential difficulties of splicing together discontinuous and possibly stratigraphically disturbed blue ice or only deep ice records. Nonetheless, development of blue ice sampling techniques should continue, given the potential for large volume sampling, possible 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; it has a 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 the science. There is a general consensus that given the potential for stratigraphic disturbance and therefore the need for replication, 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. Planning needs to be put in place in order to upgrade the DISC drill, described in detail in the Long Range Drilling Technology Plan, for drilling the main and replicate cores in the very cold conditions found in East Antarctica. In Greenland, locations on the west side of the east mountain range where the first ice sheet originated might result in ice more than 1 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 IPICS group have discussed the possibility of a "hole maker," an access tool that would allow temperature and heat flow measurements and would also be useful for other measurements; such a drill is now under development at the University of Minnesota Duluth - the Rapid Access Ice Drill (RAID) project. In addition, a more agile drill that could create holes as deep as 1,000 m would accelerate discovery.

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 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. A drill for dirty ice (Koci drill) exists but its suitability is limited; the Agile Sub-Ice Geologic drill should be considered for use in areas like Mullins Valley.

Scientists are drilling 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 cores of approximately 9.5 inches in diameter up to 15 meters in solid ice. *Credit: Jeff Severinghaus*.

7. Large-volume sampling for changes across climate transitions: Rare isotopes, gases, microparticles, biological materials, and other measurements that have not yet been fully exploited in ice core research may offer new opportunities for discovery if large volumes of ice can be made available. Examples include ^{14}C of CH_4 to trace methane hydrate destabilization, and 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 adequate sample sizes, and *in situ* melting has been suggested as a means of sampling large volumes of air from deep ice core sites. Blue ice areas have the potential for providing unlimited samples but specialized equipment is needed for sampling. A version of the new large-diameter blue ice drill mentioned above, capable of drilling vertically to ~200 m would greatly improve access to the blue ice archive. Chainsaw-based quarrying tools such as those used at Mt. Moulton and in marble quarries might also be considered. Furthermore, there are good reasons to consider true “horizontal ice coring,” where a long core through a glacier could provide a continuous stratigraphic record.

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 interrogating 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, ultrasmall microbial isolates from deep Greenland glacier ice that may inform 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. Acquisition of a lightweight, highly portable drill for shallow coring is needed for alpine studies. A drill capable of coring up to 3,000 m is needed, and could be developed either by modifying the Intermediate Drill for deeper depths, or modifying the DISC drill for reduced logistical requirements. A conceptual design for upgrading the DISC drill for drilling at Hercules Dome, and then later for cold conditions in East Antarctica should be developed. The large-diameter IDDO Blue Ice Drill for blue ice areas was used successfully on Taylor Glacier, Antarctica, and its capability is being for deeper drilling is being tested. In addition, as the HCFC-141b component of the current drilling fluid is being phased out, there is a need to move to a replacement drilling fluid for use in cold conditions; ESTISOL-140 has been used but some issues still need to be addressed. 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 in formation 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)	Drilling fluid	Ambient temp (C)	Clean coring?	Transport type	Site occupancy	Int'l aspects
<200 years	5-7	horizontal	none	-20	yes	Backpack	Days	US
<200 years	5	15	none	-30	sometimes	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	sometimes	Twin otter/ lt traverse	Weeks/month	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 (oldest ice)	10+	3.5k	TBD	-50	no	Herc & traverse	Multiple seasons	IPICS
>Site selection 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 others
Pre-Quaternary atmosphere	7-25 rock-ice mix	200	none	-40	no	Helicopter	1-2 seasons	US/ maybe others
Novel tracers biogeochem processes	25	200^{+}	none	-40	no	Helicopter	1-2 seasons	US
Ancient microbial life	25	200^{+}	none	-40	sometimes	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. Predicting responses of glaciers and ice sheets to future possible environmental change requires models that incorporate realistic ice dynamics (Alley and Joughin, 2012). 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 Sensins 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.

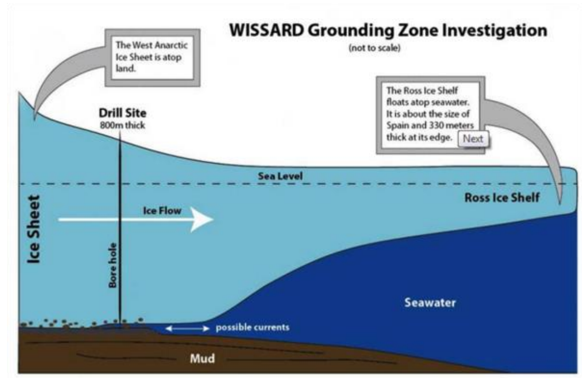
Specific observational data needed to improve and validate models of ice sheet response to environmental change include:

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). 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 proposed 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) needs to be maintained within IDDO. The Rapid Air Movement Drill (RAM) urgently needs refurbishments and enhancements for increased portability. Additionally, increased efficiencies (drilling rate, reduced size and power consumption) are needed to improve the agility of shot hole drills.

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. Exploration of sub-shelf ocean cavities and ice/ocean interactions provide basic data needed to model ice fluxes near the grounding line. Although measurements 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 that 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: 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.

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. 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) 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 exposure age dating should be developed for use near the ice margins. Under deep ice, rapid access drilling is needed 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. Credit: *John Goodge / University of Minnesota-Duluth.*

Cosmic radiation produces a variety of rare long-lived and stable nuclides in the outermost few meters of exposed rock surfaces (e.g. Gosse and Phillips, 2001). When ice sheets are absent these nuclides build up, but even a few meters of ice cover is enough to prevent accumulation

and shield the underlying rock (e.g., Fabel et al., 2002). Hence the presence of cosmogenic nuclides in subglacial bedrock provides unequivocal evidence of ice-free conditions in the past (Nishiizumi et al., 1996). By measuring combi-
Depth profile measurements on short (1-5 m) subglacial bedrock cores will be used to confirm that the nuclides were produced *in situ*, and identify surfaces compromised 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, we can address key problems 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), and 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. 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). Eventually, measurements of long-lived radionuclides such
nations of nuclides with different half-lives, in surfaces at different depths, it should be possible to construct a picture of former ice-sheet extent for comparison with paleoclimate records (e.g. Sugden et al., 2005; Li et al., 2008).
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 could 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, 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. .

Table 2. Requirements of drills needed for studies of ice dynamics and glacial history. The Long Range Drilling Technology Plan discusses existing drills that are capable of coring and drilling ice sheets. The intermediate depth drill is also high priority for this work. In addition, new drills capable of rapid deep access to the dry bed (such as RAID drill currently under construction), nimble drills for reconnaissance rock coring under shallow ice, and hot water drills suitable for access holes through ice shelves and ice streams are essential to advance the ice dynamics and glacial history science goals.

	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	0.5-2.5	Ice hole Rock core	-50	no	Basler/ traverse	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 Ecosystems

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. 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 paleo-topography 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 paleo-topography, 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. Three main categories of sedimentary targets are: subglacial lakes, 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 is thought to contain a sedimentary record as well are other subglacial lakes; sedimentary records have already been collected at Lake Ellsworth. 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.

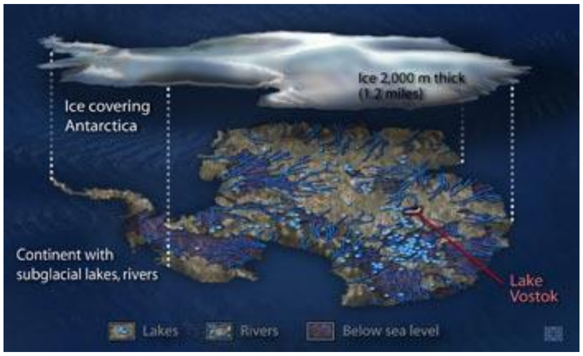
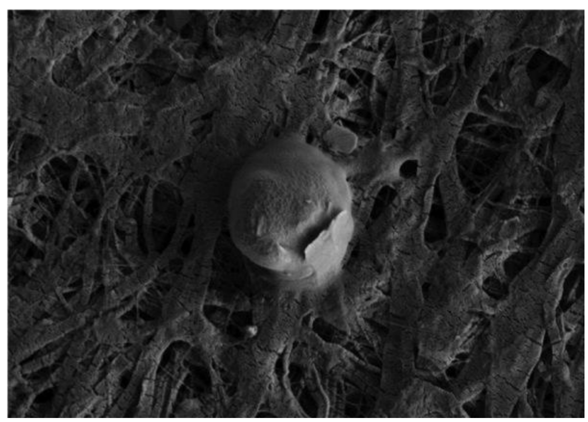


Illustration showing the aquatic system that scientists believe is buried beneath the Antarctic ice sheet. Credit: National Science Foundation, Photo Gallery.

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

3. Sub-ice microbial ecosystems and biogeochemistry: Subglacial and basal zones — where both water and mineral matter come in contact with ice, sediment, or bedrock — provide habitat for microbial life. The long timescale of 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 and/or Enceladus.

The 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: 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.

Table 3 lists desired characteristics of the drills needed to create clean access holes for the science of the sub-ice environment. Other subglacial access requirements are also covered above in Table 2. The Long Range Drilling Technology Plan discusses technical aspects of the drills.

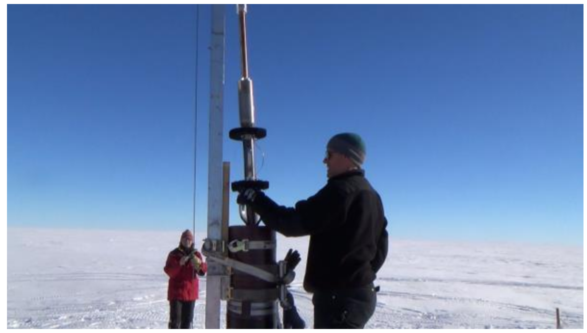
Table 3. Requirements of drills needed for studies of subglacial geology, sediments and ecosystems. The IDDO Long Range Drilling Technology Plan discusses hot water and mechanical rapid-access drills that could provide clean access holes for the projects described above. Clean mechanical rapid-access 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	1-3	Hole, sediment core	-50	Herc/traverse	weeks	U.S. & others	Clean access
Biogeochem (Wet bed)	3-25	<4	Hole, sediment/rock core	-50	Herc/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/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 recently acquired three winches, 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 any IDDO winch. 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 drills.

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. It is recommended that IDDO design and build simulators that mimic the electrical characteristics of winch-cable systems in the program.

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.
- 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 Current and upcoming logging projects

WAIS Divide: Several groups logged the WAIS Divide ice core borehole in the 2014-15 season. Measurements included temperature, optical, and seismic profiling, and an acoustic caliper to be repeated in 2016-17. 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 intermediate (SPICE) core: The newly developed intermediate-depth drill was deployed to the South Pole for the 2014-15 and 2015-16 field seasons, successfully collecting 736 m of core in 2014-15 and up to a total of 1850 m of core in 2015-16. 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 new observatory for borehole logging science and test bed for 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 SPICE project will also 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 novel design-stage drill capable of penetrating a 3,000 m ice sheet, and coring samples of ice and subglacial basal rock. RAID is expected to produce five (5) boreholes every season, and these boreholes will potentially serve as long-term scientific observatories for the study of ice and climate. RAID will require a dedicated logging winch integrated with the drilling platform, capable of reaching 3,300 m for logging immediately following the drill. The system will 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. Infrastructure will be needed to manage future borehole logging projects that will make use of RAID boreholes.

RAID borehole preservation: RAID is expected to produce ~40 boreholes over the course of the project. Preserving every RAID borehole indefinitely is likely to be 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 underbalanced 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, and removal of ice plugs when necessary. Holes near ice divides holes 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.

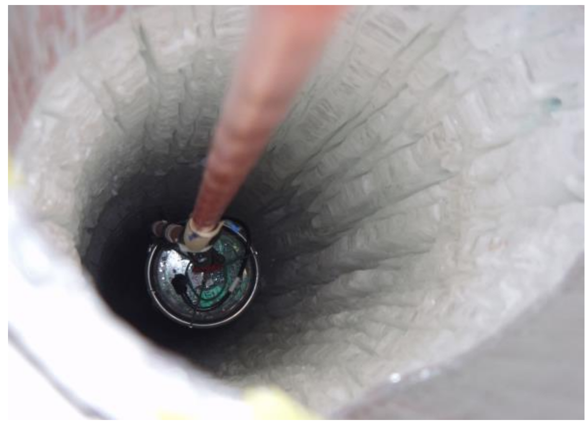
1.4 Borehole qualifying: IDDO does not currently maintain logging tools for verifying borehole parameters such as inclination, diameter, depth, roundness, temperature, etc. There is growing consensus in the logging community that IDDO should develop this capability. A hole qualifying system could be 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.

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 three to five-meter 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.



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. Photograph Credit: Ethan Dicks, National Science Foundation.

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 requires 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, permit studies of neutrino detection over areas up to 1000 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. South Pole deep or intermediate ice core: Currently the U.S. program is drilling an intermediate-depth ice core at South Pole station. The SPICE (South Pole Ice) core will also benefit ongoing astrophysics projects by providing ground truth measurements of ice chemistry, fabric and particulates for characterization of optical, radio and acoustic properties. The borehole from the coring mission will serve as an enduring access point to calibrate existing and new instruments. More information regarding this core is given in the Climate section of this report.

4. 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 approximately 300 m deep within boreholes. A similar observation network is planned for Greenland.

5. 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.

6. 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.

7. 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 Table 4 below, the letters denoting specific drills are: b: badger-eclipse; 4: 4-inch drill; D: DISC drill; N: NZ intermediate drill; H: Hans-Tausen intermediate drill; B: blue ice drill; I: intermediate drill; L: borehole logging; lt: logging tower; R RAID.

Table 4: Past Climate Change Planning Matrix 2015-2025

	2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2025			
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
~ 200 yr investigations																																												
Arctic agile drilling projects		x	x			x	x			x	x																																	
Greenland scientific traverses						x	x			x	x																																	
Antarctic agile drilling projects	x			x	x			x	x			x	x																															
North Taylor												x	x																															
South Pole - Dome C scientific traverse												x	x			x	x																											
Law Dome												x	x																															
Temperate glaciers										x	x																																	
2k array																																												
Arctic		x	x							x	x																																	
Antarctic																																												
Siple Coast coastal dome																								x	x																			
Amundsen Sea coastal dome																												x	x															
South Pole				x	x			x	x																																			
Herc Dome												x	x																															
Dome C (eclipse or IDD)																x	x																											
40k Network																																												
40k-WAIS Divide																																												
Borehole logging at WAIS	L				L																																							
40k - South Pole																																												
Intermediate drill coring	I			I	I																																							
Borehole logging at South Pole								L	L																																			
40k - Qaanaaq NW Greenland																																												
Intermediate drill coring																		I	I			I	I																					
Borehole logging at Qaannaaq																							L			L																		
40k - South Dome Greenland																																												
Intermediate depth coring South Dome																														I	I			I	I									
Borehole logging at South Dome																																			L			L				L		
Last Interglacial - Herc Dome																																												
Site selection												x	x																															
DISC drill at Herc Dome																D	D			D	D			D	D			D	D															
Replicate Coring																																D	D											
Borehole logging at Herc Dome																																				L	L							
Large-vol Sampling ClimateTransitions																																												
Taylor Glacier Blue Ice drill coring	B			B	B																																							
Summit Greenland		B	B					B	B			B	B																															
Pre-Quaternary Atmosphere																																												
Allen Hills												I	I																															
Taylor Glacier																				I	I																							
Site selection for Oldest Ice - RAID												R	R			R	R			R	R			R	R			R	R															
Borehole logging using RAID holes																L	L			L	L			L	L			L	L			L	L											
IPICS oldest ice																																												
Plan DISC upgrade					x	x	x	x	x	x	x																																	
Implement DISC upgrades																								x	x	x	x	x	x															
Drilling for oldest ice - DISC																																D	D			D	D			D	D		D	D
Basal Ice Glaciology																																												
Greenland coring with Int Depth Drill														I	I			I	I			I	I																					

Table 5: Ice Dynamics and Glacial History Planning Matrix 2014-2024

	2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2025			
	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																																												
Acquisition planning - scalable hot water drill																																												
Engineering design & construction								x	x	x	x																																	
Acquisition planning - agile sub-ice geologic drill																																												
Construction & testing	x	x	x	x	x	x																																						
Acquisition planning-Rapid Access Ice Drill																																												
Detailed design RAID																																												
Drill fabrication RAID	x																																											
North American test RAID	x	x																																										
Final changes & shipment to Antarctica		x	x	x	x	x	x																																					
Field test of RAID								x	x																																			
Basal conditions & geothermal flux																																												
Coring & heat flow East Antarctica - RAID																x	x			x	x			x	x			x	x			x	x			x	x			x	x			x
Sub-ice shelf mass balance																																												
	x			x	x																																							
Ice dynamics																																												
Downhole logging & measurement - RAID																x	x			x	x			x	x			x	x			x	x			x	x			x				
Glacial history																																												
Bedrock coring & cosmogenic dating Pirrit Hills								x	x																																			
Bedrock coring for cosmogenic dating - RAID												x	x			x	x			x	x			x	x			x	x			x	x			x	x			x				
Conditions at the ice sheet bed																																												
Glacial bed sampling - RAID												x	x			x	x			x	x			x	x			x	x			x	x			x	x			x				
Seismic sounding																																												
Antarctica								x	x			x	x			x	x																											
Greenland						x	x			x	x			x	x																													

Table 6: Subglacial Geology, Sediments and Ecosystems Planning Matrix 2015-2025

	2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2025			
	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																																												
Acquisition planning - scalable hot water drill																																												
Engineering design & construction								x	x	x	x																																	
Acquisition planning - agile sub-ice geologic drill																																												
Construction & testing	x	x	x	x	x	x	x																																					
Acquisition planning-Rapid Access Ice Drill																																												
Drill fabrication RAID	x																																											
North American test RAID	x	x																																										
Final changes & shipment to Antarctica		x	x	x	x	x	x																																					
Field test of RAID								x	x																																			
Bedrock geology																																												
Bedrock coring & cosmogenic dating Pirrit Hills								x	x																																			
Bedrock & sediment coring - RAID												x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x			x
In-situ stress measurements - RAID												x	x			x	x			x	x			x	x			x	x			x	x			x	x			x	x			x
Subglacial hydrology & sediment dynamics																																												
WAIS-GL								x	x			x	x			x	x																											
RISB				x	x																																							
Microbial ecosystems & biogeochem																																												
SALSA				x	x			x	x																																			
KISSME				x	x			x	x																																			
Grounding line - GLIDE																																												

Table 7: Ice as a Scientific Observatory Planning Matrix

	2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2024			
	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 - paleoclimate/ice dynamics																																												
Englehardt Ridge borehole logging - ice dynamic	x																																											
Exploration of basal ice near Dome A																																												
basal ice near Dome A								I	I																																			
basal ice in Greenland														I	I			I	I			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 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 project. However IDDO experienced adverse impacts and has indicated that they will most likely not use ESTISOL 140 for future drilling projects. Ongoing discussions about drilling fluids will continue with the goal of identifing 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 and/or traverses, time at field sites must be carefully planned to optimize scientific productivity. Conducting field science and ice core drilling while also minimizing logistical requirements requires planning and ongoing vigilance. IDPO will continue to work with the research community, NSF, and the support contractors for possible changes in the schedule to enable the science to be achieved in a responsible way. We also anticipate the need to plan for expanded traversing capabilities based on projected science interests and planned activities.
- 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 wants 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 - www.pages-igbp.org/ipics) 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 last interglacial, and extracting an ice core that reaches 1.5M years. The U.S. ice coring community was intimately involved in 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.

- Data from the core near the West Antarctic Ice Sheet Divide (WAIS Divide) are providing unprecedented high-resolution climate records for Antarctica for the past 60k years. Now that the main core and replicate drilling are complete, the final stage of the project will be to complete the borehole logging studies.
- 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 requires arrays of shallow cores covering a range of accumulation rates both in Greenland and in Antarctica. Spatially-distributed shallow coring for records ranging from 200 to 2,000 years will include multiple scientific traverses in Greenland for study of the ice sheet under the currently changing climate. In Antarctica, an international French-Italian-U.S. scientific traverse is being proposed from Dome C to South Pole. Climate records contained in ice cores from Roosevelt Island in the eastern Ross Sea and South Pole are expected to extend back 40,000 years. Additional goals for the coming decade include coring for 40,000-year records from Hercules Dome (as part of a record extending further back at that site) in Antarctica, as well as from Renland and EastGRIP, Greenland. Targeted ice coring to investigate ice, ocean, and atmospheric dynamics along the dynamic Amundsen Sea Cost of Antarctica is in the planning stages,
- Determination of the amount of water retained and frozen in the near surface firn (top ~60 m) on the Greenland Ice Sheet and on the Antarctic Peninsula is needed to better constrain estimates of surface mass balance under current warming conditions.
- An undisturbed 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 to extract Eemian ice in Greenland, both by coring and through horizontal sampling of blue ice ablation zones, should continue. 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. Samples from Antarctica where the climate record may have been impacted by changes in the WAIS during the last interglacial period are

important, since WAIS history for this time is poorly known.

- Blue-ice paleoclimate records have potential for providing unlimited samples for atmospheric and ultra-trace component studies and can enable 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 Hill exemplify discoveries from this realm so far.
- Ice cores and borehole observations reaching ages between 800,000 years and 1.5M years (or beyond) are a priority. Ice this old would tell us about atmospheric composition and climate during times when conditions were very different than today. These data would 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; for extraction of deep cores, these activities should be coordinated with international partners. An undisturbed deep ice core is the primary IPICS goal. “Snapshots” of time periods beyond 800,000 years are potentially available from blue ice regions or areas of discontinuous deposition. Developing further understanding of these regions and sampling them should also be a priority in the search for 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 geotecton-

ic 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 preserved in the ice; and sonic logs provide continuous record of ice structure through the ice sheet. 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 subatomic particle interactions.
- 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 forsee significant calibration studies of the surrounding ice volume.
- Ice sheets are a quiet platform for seismic monitoring; the South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed in boreholes about 300 m below the surface. A similar seismic observation

network is planned for the Greenland Ice Sheet.

- 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.

Recommended technology investments

The following investments in drilling technologies are needed to accomplish science goals planned for the next decade. Investments prioritized by time include:

Priority 1 (needed this year):

- Maintain and upgrade the following existing agile equipment: hand augers, 2” and 4” electromechanical drills, 3” electrothermal drill, 3.25” Badger-Eclipse drills, logging winches, and 30 m hot water shot hole drill.
- Complete fabrication of the agile sub-ice rock coring drill (ASIG) capable of retrieving 10 m of rock core beneath ice up to 700-meters thick.
- Maintain the DISC Drill, and finish IDPO Science Requirements and IDDO cost estimates for minimal upgrades for the DISC drill for use at Hercules Dome with the goal to lessen its logistics requirements while maintaining its replicate coring capability, keeping in mind upgrades to be added later for future use for Oldest Ice.
- Procure and modify a Winkie drill to also include conditions containing ice.
- Develop IDPO Science Requirements and create a conceptual design and cost estimate for adapting an agile coring drill to minimize logistical requirement for the drill, shelter and fluid plan for ice coring to approximately 900 m. The system must have significantly smaller logistical requirements than the IDPO Intermediate Depth Drill and associated

infrastructure. Published lessons learned (e.g. Sheldon et al, 2014 and Triest et al, 2014) should be considered.

- Develop and build the Lake Ice Drill, a very portable clean hot-water drill for creating 5” holes through up to 6-m of sediment-laden lake ice.
- Establish IDPO Science Requirements and repair, modify or acquire a very lightweight highly-portable drill for shallow ice coring.
- Prepare for field trials of the Rapid Access Ice Drill (RAID)[1] .
- Prepare WISSARD & UNL Roving drill & recovery of hot water ice cores for projects proposed in 2015[2].

Priority 2 (needed within the next three years):

- Continue development of a scalable, modular hot water access drill for creating access holes in ice from 50 m up to approximately 1,000 m depth with modular potential to be used for clean access.
- Conduct a conceptual design and start construction of an agile shot-hole drill capable of drilling 15 holes per day up to 100 m deep in both East and West Antarctica. This may include consideration of a RAM drill upgrade, or other means. A secondary consideration is that a 15 cm diameter borehole would make this drill of interest for radio neutrino detectors as well.
- 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 a replicate Blue Ice Drill for wide-diameter drilling to 200 m.

Priority 3 (needed within three to five years):

- Assess the potential of recovering cores to depths of 300-500 m without use of drilling fluid.
- Develop IDPO Science Requirements for clean access drill for depths over 3,000 m.
- Conduct a feasibility study to modify the Blue Ice drill to enable large-volume sampling of firn and ice up to 300 m depth.
- Develop IDPO Science Requirements and conduct a feasibility study for a drill capable of coring horizontally (or at low angles) several 100 m.
- Construct a jig to support a hand auger to facilitate horizontal coring up to 20 m into ice cliffs.

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 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.

[1] This development is happening with DOSECC Exploration Services, LLC.

[2] If funded, this development would happen with an IDPO subaward to the University of Nebraska-Lincoln.

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Acronyms

AGAP: Antarctica's Gamburtsev Province

ANDRILL: Antarctic Drilling Project

ASIG: Agile Sub-Ice Geological (drill)

AUV: Autonomous Underwater Vehicle

DISC: Deep Ice Sheet Coring

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

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

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

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