U.S. Ice Drilling Program

Long Range Science Plan 2014-2024

June 30, 2014

Sponsor: National Science Foundation

Finalized 29 June 2014

Contents

Cover photo: University of Rochester graduate student Ben Hmiel loading an ice core from the Blue Ice Drill into a melter for measurements in the field. *Photo credit: Vasilii Petrenko.*

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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 may 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 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. The IDPO and its Science Advisory Board (SAB) update this Long Range Science Plan 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 is necessary to achieve the goals articulated here. Specific recommendations for the next decade for a variety of areas including climate change, ice dynamics and glacial history, subglacial geology and ecosystems, and the use of the polar ice sheets as a scientific observatory include:

Recommended science goals

1. 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.

- Emerging 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 in the coming several years.
- Drilling of spatially distributed ice cores and boreholes to support the IPICS goals of investigations of past climate and atmosphere over the past 200 to 40,000 years should continue. Spatially-distributed shallow coring for records ranging from 200 to 2,000 years will include scientific traverses both in Antarctica and in Greenland. An international scientific traverse is being planned from Dome C to South Pole. Multiple scientific traverses in Greenland are urgently needed for study of the ice sheet under the currently changing climate.

Understanding climate signals in remotely-sensed data requires arrays of shallow cores covering a range of accumulation rates both in Greenland and in Antarctica. 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, Antarctica and from Renland and EastGRIP, Greenland.

- 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. The planned South Pole core will not reach Eemian ice, but other sites in Antarctica, including Hercules Dome, should be considered. 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 high 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; current 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 the 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 in Greenland and in other sectors of Antarctica.
- The past extent and volume of the Greenland and West Antarctic Ice Sheets is recorded by cosmogenic nuclides in subglacial bedrock. Samples from beneath these ice sheets will provide information on their thickness and configuration during paleoclimates warmer than the present, and help identify their sensitivity to future possible climate change. Short cores of bedrock from targeted sites are needed to address questions concerning the extent of the ice sheets during past interglacial climates, and the onset of continental glaciations.

3. Subglacial geology, sediments and ecosystems: Bedrock, sediments and ecosystems existing within and beneath ice sheets remain largely unexplored because of the lack of rapid access drills. In particular, the physical conditions at the base of the ice sheets are virtually unknown, but remote sensing of liquid water in subglacial lakes and possibly interconnected hydrologic systems raises concern about thermal conditions and basal slip potential. Likewise, the unknown subglacial geology of Antarctica represents the last continental frontier of geologic exploration, including landscape evolution, past paleoclimates on geological timescales, crustal heat flow, lithospheric stress, ground truth for geophysical imaging, constraints on geodynamical evolution, and relationship with past supercontinents. Rapid access to subglacial environments is needed to address a wide range of science questions. Specifically,

- Direct sampling of the bedrock is needed to validate models of cratonic growth related to supercontinent assembly in the Mesoproterozoic between about 2.0 and 1.1 billion years ago and for constraining the Phanerozoic geological, tectonic and exhumation history of the Antarctic continent. Strategic drill-site selection within mapped drainage basins (using products from the BEDMAP2 project) will also allow greater constraints on provenance studies that utilize onshore moraines and offshore glacial strata.
- There exist virtually no heat flow data for Antarctica. Penetration into bedrock provides the first opportunity to accurately measure the geothermal heat flux, which informs us about geotectonic conditions as well as geothermal contributions to ice-sheet temperature.

- Evidence of Cenozoic ice sheet history preserved in sedimentary rocks of subglacial bedrock basins and in sediment deposits within subglacial lakes will provide further dimensions to the records known only from the margins of the continent and will also help to verify paleo-topographic reconstructions for ice sheet modeling. Likewise, access to subglacial bedrock can provide a unique opportunity to study Cenozoic landscape evolution and long-term ice-sheet stability using a variety of low-temperature thermochronology techniques through to cosmogenic-isotope surface exposure dating.
- 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 present project on Whillans Ice Stream 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, stable, low-background and transparent detection medium for observation of sub-atomic particle interactions. Additional planned projects (e.g. the Askaryan Radio Array) require multiple boreholes at least 150 m deep and 15 cm in diameter.
- 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 must be such that the supporting logistical requirements do not impede the 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 are adaptable 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 considered 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):

- Complete the Intermediate-depth drill and infrastructure, including repair after the first field season. The drill is designed for coring up to 1500 m depth.
- Maintain and upgrade the following existing equipment: hand augers, 4” electromechanical drills, 3” electrothermal drill, 3.25” Badger-Eclipse drills, and logging winches.
- Develop an agile sub-ice rock coring drill capable of retrieving 10 m of rock core beneath ice up to 700 meters thick. The drill should be agile and transportable by helicopter sling-load at least for shallow ice.
- Create an agile shot-hole drill capable of drilling 15 holes per day up to 100 m depth in both East and West Antarctica.
- Develop science requirements, conceptual design and cost estimate of an agile ice coring drill for coring 50 to 700m that has less logistics requirements than the Intermediate Depth Drill and its surface infrastructure.
- Develop science requirements, conceptual design and build an agile, clean hot-water drill for creating 5” holes through up to 6-m of sediment-laden lake ice.
- Complete testing and repair of the Blue Ice drill to enable large-volume sampling of firn and ice up to 200m deep.
- Continue engineering of the Rapid Access Ice Drill (RAID)[1].

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

Priority 2 (needed within the next three years):

- Upgrade the electrothermal drill to improve its performance for coring to 300m through temperate and poly-thermal firn and ice. The drill needs to be agile and lightweight (transportable by helicopter).
- 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.
- Continue to develop drilling technologies, methods and protocols for clean drilling deeper than 200 m into subglacial environments for access and sampling.
- Establish science requirements and cost estimates for minimal upgrades for the DISC drill for use at Hercules Dome, and additional later upgrades for conditions in East Antarctica, with the goal to lessen its logistics requirements while maintaining its replicate coring capability.
- Build or acquire a lightweight backpack drill (e.g. http://www.icedrill.ch/) for shallow coring.

Priority 3 (needed within three to five years):

- Construct a jig to support a hand auger to facilitate horizontal coring up to 20 m into ice cliffs.
- Develop the ability to recover ice cores to depths of 300-500 m without use of drilling fluid.
- 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 the science requirements and conduct a feasibility study for a drill capable of coring horizontally (or at low angles) several 100 m.

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 depends on drillers and engineers who have experience in mechanical ice coring and hot water drilling; an ongoing strategy for maintaining this expertise is important.

Introduction

One of the most pressing environmental issues of our time is the greenhouse gas-induced climate 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?

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. 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. 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 these fundamental and vital 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 and 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

1. 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.

- **200-year arrays**: 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. 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.
- 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).
- Calibrate local, regional, and global atmospheric models and 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.

- Determine biogeographical patterns of biological 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, and 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.

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*

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 Warm Period" 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.

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 Amundsen 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.

U.S. driller Lou Albershardt discusses core characteristics and aspects of the N.Z. intermediate depth drill with Darcy Mandeno and Hedley Berge at Roosevelt Island, Antarctica. Credit: *Sepp Kipfstuhl, Alfred Wegener Institute*

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. The specific U.S. contribution to this network (in addition to the WAIS Divide core) will include the new South Pole SPICE core. New sites that have been discussed for future work include Hercules Dome and North Taylor Dome. 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. An intermediate depth coring drill capable of drilling to 1,500 m is currently under construction by IDDO, and will first be used in 2014 on the new South Pole 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 deeper drill in the inventory is the DISC drill, which can reach 4,000 m, but it is logistically heavy and requires more than two seasons for deployment and drilling.

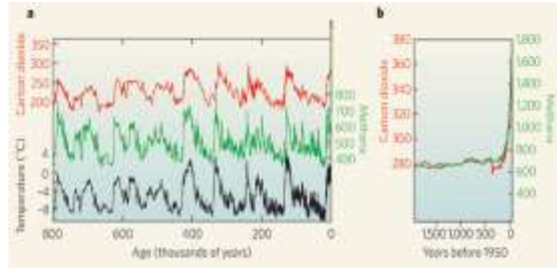
4. High-resolution records of the last interglacial: The last interglacial period (~130,000 to 110,000 years ago) was warmer than present due to differences in Earth's orbital configuration, and can provide clues about how the Earth will behave as human activities continue to force global warming. Critical 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 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.

The bubbles visible in this piece 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*

Recent results from the North Greenland Eemian Ice Drilling (NEEM) ice core in Greenland have shown that the Eemian record 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 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 EDML. U.S. community discussions have been considering South Pole and/or Hercules Dome as possible sites, and both seem to be very viable candidates scientifically. Model results from South Pole suggest that a core there could contain ice from the last interglacial. 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 ~ 1.5M 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 and 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. Technology for quickly creating access holes for spatially distributed measurements of geothermal heat flux in less than 1,000 m of ice with minimal logistics would 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 1M 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 in the U.S. -- 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 (>1.5M 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 for example.

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, micro-particles, 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 collect 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 as 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 4 km, and the requirements for the coring or sampling vary. Agile drills currently at IDDO need to be repaired and maintained in good 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, “backpack drill” for shallow coring is needed for alpine studies. Development of an intermediate depth drill capable of extracting ~1,500 m of core with minimal logistical requirements is in the final stages by IDDO. 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. Development of replicate coring capability for the DISC drill is complete. A large-diameter drill for blue ice areas was used successfully on Taylor Glacier, Antarctica during the 2010-11 and 2011-12 field seasons, and its capability is being expanded for deeper drilling. As the HCFC-141b component of the current drilling fluid is being phased out, there is need to move to a replacement drilling fluid for use in cold conditions, and testing within the international ice core community indicates that ESTISOL-140 shows great promise. A conceptual design for upgrading the DISC drill for cold conditions in East Antarctica should be developed. Table 1 lists characteristics for drills needed for the areas of 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+	3.5-4k	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 4k	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 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 (Conway et al., 1999). 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 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:

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 CC 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 urgently needs refurbishments and enhancements for more portable operation. 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.

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 is believed to be related to the rheological structure of ice. Studies at Siple Dome (Pettit and others 2011, Bay and others 2001) and Dome C (Pettit and others, 2011), for example, have shown that strong vertical gradients in ice effective viscosity 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 and others 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 4 km 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.

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., 2013) 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 combinations 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 (cf. Sugden et al., 2005; Li et al., 2008). 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 as ^{53}Mn ($t_{1/2}$ = 3.7 Myr) and ^{129}I (16.7 Myr) 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 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/oceans 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 the proposed RAID drill), 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 occupancy	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 instrumentation	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 have 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 its 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, which is thought to contain a sedimentary record, as does subglacial Lake Ellsworth and probably others. 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 well contain evidence of the much debated past dynamics and paleoclimate of the East Antarctic Ice Sheet. Recently, Mengel and Levermann (2014) suggested that the portion of the East Antarctic ice sheet overlying the Wilkes Subglacial Basin is held back by only a narrow, low coastal rim, raising cause for concern about ice-sheet stability.

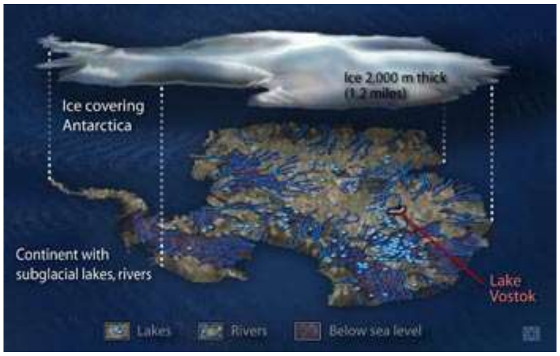


Illustration showing the aquatic system that scientists believe is buried beneath the Antarctic ice sheet. Credit: National Science Foundation, Photo Gallery

Access holes are also needed to recover longer sedimentary cores comparable to those from the continental margins. The rift basins in West Antarctica undoubtedly house stratigraphic records of mid-late Mesozoic and Cenozoic geological, ice sheet evolution and paleoclimate histories. Similarly, 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 well contain evidence of the East Antarctic Ice Sheet's much debated past dynamics and paleoclimate. 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 but is still at an early stage of investigation although the first reports on the microbiology of Subglacial Lake Whillans are forthcoming (Christner et al in review 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.

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 and climate change.

Russian drillers accessed Subglacial Lake Vostok during the 2011-12 season, and then during 2012-13 successfully recovered about a 30m-long ice core 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 US 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. Holes may need to be maintained to remain open for days to allow sampling during this time. 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 are needed to fully exploit the histories 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 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.

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 1" Gearhart-Owen cablehead. IDDO has also established a policy of deploying a trained operator to the field along with any IDDO winch.

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 a fully compensated borehole 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.

1.3 Upcoming logging projects

WAIS Divide: Several groups will log the WAIS Divide ice core borehole in the 2014-15 season. Measurements will include 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 will be the first to be done in a borehole with deviation channels.

South Pole intermediate (SPICE) core: After testing in Greenland in Summer 2014, the newly developed intermediate-depth drill will be deployed to the South Pole to retrieve up to

1850 m of core in the 2014-15 and 2015-16 seasons. The SPICE core will take advantage of and supplement the wealth of existing data from shallow cores, snow pits, IceCube hot-water boreholes and meteorological observations. The SPICE Core borehole will be pressure compensated by Estisol 140, providing a new observatory for borehole logging science and test bed for logging in a new drill fluid. 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. Because of 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 experiments.

RAID: The RAID (Rapid Access Ice Drill) is a novel design-stage drill capable of penetrating a 3 km ice sheet and coring samples of ice and subglacial basal rock. RAID is expected to produce 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 3300 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. Logging science will impact design of the drill and qualifying tools, and community involvement in the design and procurement of the winch and qualifying tools is anticipated. 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 under-balanced boreholes could be of interest for deformation studies, although removal of the casing and fluid head will limit the lifetime of the borehole to a few years.
RAID should also select a subset of holes for long-term preservation, to serve as observatories and to allow for future technology developments. Preservation would require leaving a sturdy casing in place, maintaining and periodically extending the casing above the snow surface, 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 and maintenance: 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.

At some level, IDDO should also be tasked with borehole maintenance. This includes extending and maintaining the borehole casing, removing ice plugs, and supplying the sheave wheels and towers needed for borehole access. The Borehole Logging Working Group (BLWG) will need to prioritize borehole preservation and determine the scope of preservation efforts.

1.5 Borehole Allocation Committee: The 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 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 2500 m deep, half-meter diameter boreholes at a rate of about three per week.

Proposed low-energy 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. These experiments 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 (<10 m) spacing. These projects will enable R & D 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, plans to instrument on the order of 100 km^2 of ice with radio antennas to detect radio pulses from so-called GZK-scale neutrinos. ARA requires holes at least 200 m deep and 15 cm diameter, with 100 m spacing. In 2012-13, a hot-water drill was used to make ~7" holes to 200 m depth at a rate of one per day. Thirteen holes were drilled in total, enough for 2 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. For the ARA experiment, for example, an antenna placed at a depth of 1 km, on the end of a low-loss high-bandwidth coaxial cable, could be used for testing the detector with a variety of pulsers at the surface.

3. South Pole deep or intermediate ice core: Momentum is building for the U.S. program to retrieve an intermediate or deep ice core at South Pole station. A South Pole core would take advantage of and supplement the wealth of existing data from shallow cores, snow pits, IceCube hot-water boreholes and meteorological observations. Such a core would also benefit ongoing astrophysics projects, by providing ground truth measurements of ice chemistry, fabric and particulates for characterization of optical, radio and acoustic properties. If drilled near the station, the borehole from the coring mission would serve as an enduring access point to calibrate existing and new instruments.

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 in boreholes. A similar observation network is planned for Greenland.

5. Ice sheet as an archive of recent past atmospheric composition: In 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 in 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 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 boreholes. Identifying which boreholes need maintenance and determining methods of repair are activities that need urgent attention.

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. 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: Climate Change Planning Matrix 2014-2024

	2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				2024			
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			x	x			x	x																									
Greenland scientific traverses										x	x			x	x			x	x																									
Antarctic agile drilling projects	x			x	x			x	x			x	x																															
South Pole - Dome C scientific traverse																x	x			x	x																							
Temperate glaciers										x	x			x	x																													
2k array																																												
Arctic		x	x			x	x																																					
Antarctic	x			x	x			x	x																																			
Siple Coast coastal dome																												x	x															
Amundsen Sea coastal dome																																x	x											
40k Network																																												
40k-WAIS Divide																																												
Borehole logging at WAIS				L	L			L	L																																			
Acquisition planning-intermediate drill																																												
int drill fabrication	x																																											
int drill field test in Greenland		x																																										
int drill prep for deployment			x																																									
40k - South Pole																																												
Intermediate drill coring				I	I			I	I																																			
Borehole logging at South Pole												L	L																															
40k - North Taylor																																												
Intermediate drill coring												I	I			I	I																											
Borehole logging at North Taylor																																												
40k - Qaannaaq NW Greenland																																												
Intermediate drill coring														I	I			I	I																									
Borehole logging at Qaannaaq																			L				L																					
40k - Western Coastal Dome Greenland																																												
Intermediate coring West Greenland																										I	I			I	I													
Borehole logging at West Greenland																															L			L										
40k - South Dome Greenland																																		I	I			I	I					
Intermediate depth coring South Dome																																		I	I			I	I					
Borehole logging at South Dome																																							L			L		
40k - Herc Dome																x	x																											
Site selection																																												
DISC drill coring																				D	D			D	D			D	D															
40k - Renland																																												
Drilling (Danish drill)						x	x																																					
40k - Siple Dome																																												
Borehole logging	L																																											
Large-vol Sampling ClimateTransitions																																												
Taylor Glacier coring	B			B	B			B	B																																			
Summit Greenland coring		B	B			B	B																																					
Allen Hills coring																I	I			B	B																							
Pre-Quaternary Atmosphere																																												
Site selection East Antarctica - 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 upgrades					x	x	x	x	x																																			
Implement DISC upgrades													x	x	x	x	x													x	x	x	x											
Drilling for oldest ice - DISC																																				D	D			D	D		D	D

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

	2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				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
Ice Dynamics & Glacial History																																												
Acquisition planning - scalable hot water drill																																												
Establish science requirements	x																																											
Engineering design & construction		x			x	x	x	x																																				
Acquisition planning - agile sub-ice geologic drill																																												
Establish science requirements	x																																											
Conceptual & engineering designs		x	x	x	x																																							
Construction & testing						x	x	x	x	x																																		
Acquisition planning-Rapid Access Ice Drill																																												
Detailed design RAID	x																																											
Drill fabrication RAID			x	x	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
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
Sub-ice shelf mass balance																																												
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x			x	x																																			
Ice dynamics																																												
Downhole logging & measurement - RAID																				x	x			x	x			x	x			x	x			x	x			x	x		x	x
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
Siple Coast Intermediate Depth ice coring																												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	x
WAIS Siple Coast Grounding Zone - WISSARD	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	x
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							

The ice dynamics and glacial history community has identified numerous research directions, but progress is hampered by the lack of rapid-access drills that are technically and logistically suitable. The development of the Agile Sub-Ice Geologic drill and RAID will enable more scientific investigations of subglacial ice dynamics and glacial history, and the development of new drills in years 2014 and beyond will help to foster discoveries.

Table 6: Subglacial Geology, Sediments and Ecosystems Planning Matrix 2014-2024

	2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				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
Subglacial Geology, Sediments, & Ecosystems																																												
Acquisition planning - scalable hot water drill																																												
Establish science requirements	x																																											
Engineering design & construction		x			x	x	x	x																																				
Acquisition planning - agile sub-ice geologic drill																																												
Establish science requirements	x																																											
Conceptual & engineering designs		x	x	x	x																																							
Construction & testing						x	x	x	x	x																																		
Acquisition planning-Rapid Access Ice Drill																																												
Detailed design RAID	x																																											
Drill fabrication RAID			x	x	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
In-situ stress measurements - RAID																x	x			x	x			x	x			x	x			x	x			x	x			x	x		x	x
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
Subglacial hydrology & sediment dynamics																																												
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
Microbial ecosystems & biogeochem																																												
WISSARD	x			x	x																																							
Hydrothermal systems West Antarctica				x	x			x	x																																			
WAIS Siple Coast Grounding Zone - WISSARD	x			x	x																																							
Grounding line - GLIDE				x	x																																							

Acquisition of the Rapid Access Ice Drill (RAID) and the Agile Sub-Ice Geologic drill will enable discovery of the nature of the unexplored lithosphere underlying the Greenland and Antarctic Ice Sheets. Bedrock, sediments and ecosystems existing within and beneath ice sheets have remained largely unexplored because of the lack of rapid access drills. Until the RAID is developed, investigation of the geology beneath thin ice will be possible when the Agile Sub-Ice Geologic drill is complete.

Table 7: Ice as a Scientific Observatory Planning Matrix

	2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				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
Ice as a Scientific Observatory																																												
Borehole logging - paleoclimate/ice dynamics																																												
WAIS Divide borehole logging - paleoclimate	x																																											
Siple Dome borehole logging - paleoclimate				x	x																																							
Siple Dome borehole logging - ice dynamics				x	x																																							
Englehardt Ridge borehole logging - ice dynamics				x	x																																							
Exploration of basal ice near Dome A												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

The borehole logging community is a strong proponent for repairing the GISP2 and other deep boreholes to enable continued observation of the interior of the ice sheet for a variety of science goals, as discussed in the Observatory section of the report. Identification of methods to repair borehole casing and identifying which boreholes need maintenance are activities that will need attention, but to date there are no plans for doing so.

A number of low-energy physics experiments are being constructed or proposed to be embedded within the IceCube instrumented volume; these experiments will deploy a relatively large density of photocathodes in a small ice volume, requiring hot-water drills capable of making deep access holes at small (5 m) spacing. In addition, the ARA experiment (Askaryan Radio Array), in early development at South Pole, will require holes at least 150 meters deep and 15 cm diameter, with approximately 100 m spacing over 5 km^2. Tests during 2010-11 indicated that the existing RAM (Rapid Air Movement) drill is not adequate for ARA because of air losses in the firn; instead a mini-hot-water drill has been used for ARA pilot studies.

Radar studies indicating the possibility of novel basal ice formation processes warrant investigation by coring into one of the features, using the Intermediate Depth Drill, at a site near Dome A in Antarctic summer seasons 2016-17 and 2017-18.

Associated logistical challenges

In addition to planning the science and associated drilling technology, logistical challenges impact the timing of the field science. Potential limitations on the field science needed to address urgent issues of climate and environmental change include:

(1) 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. One of the current mixture components, HCFC-141b, is being phased out as a result of the Montreal Protocol, and will not be available for future drill sites. A potential new replacement fluid, Estisol 140, has been identified by international partners with a reasonably low viscosity for the very cold temperatures of East Antarctica. It needs to be tested and evaluated to determine whether it is appropriate for the analytical methods used in the scientific analysis of ice core chemistry and biology. Ongoing discussions of this issue are underway.

(2) 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 good planning and ongoing vigilance. IDPO will continue to work with the research community, NSF, and the support contractors for possible changes in 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.

(3) The National Ice Core Laboratory (NICL), funded by NSF, is the key location for processing and archive 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; the refrigerant used is no longer compliant and must be replaced.

(4) 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 needs to be repaired and maintained for current and future science, as do the casings of boreholes at Siple Dome and Taylor Dome. Evaluation and maintenance of key boreholes needs to be planned.

Recommendations

Globally-important environmental issues of our time, including the greenhouse gas-induced climate change, and the physics of ice sheets controlling their stability and response to climate change, requires drilling and coring of the polar ice sheets, a specialized and challenging endeavor that requires extensive planning, technology and logistics. Specific recommendations for the next decade include:

Recommended science goals

1. Climate change: Present-day climate change can only be fully understood in context of the past; well-dated histories of climate and atmospheric composition 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 cores that target the past 200, 2,000, and 40,000 years, recovery of ice from last interglacial, and extracting an ice core that reaches 1.5 M. 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:

- Emerging data from the core near the West Antarctic 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 in the coming several years.
- Drilling of spatially distributed ice cores and boreholes to support the IPICS goals of investigations of past climate and atmosphere over the past 200 to 40,000 years should continue. Spatially-distributed shallow coring for records ranging from 200 to 2,000 years will include scientific traverses both in Antarctica and in Greenland. An international scientific traverse is being planned from Dome C to South Pole. Multiple scientific traverses in Greenland are urgently needed for study of the ice sheet under the currently changing climate. Understanding climate signals in remotely-sensed data requires arrays of shallow cores covering a range of accumulation rates both in Greenland and in Antarctica. The climate record from the core now being extracted from Roosevelt Island is anticipated to extend back 40,000 years, and it is likely that the retrieval of the SPICE core from South Pole will also contain 40,000-year climate records. Additional goals for the coming decade include coring for 40,000-year records from Hercules Dome, Antarctica and from Renland, Greenland.
- 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. The planned South Pole drilling of the SPICE core will not reach Eemian ice, but other sites in Antarctica, Hercules Dome for example, should continue to be considered. One key consideration is to sample the Eemian in Antarctica where the climate record may have been impacted by changes in the WAIS during the last interglacial period, since WAIS history for this time is poorly known.
- Blue ice paleoclimate records have the 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. Mt. Moulton, Taylor Glacier, and Allan Hill exemplify the discoveries from this realm so far.

- Ice cores reaching ages between 800,000 years and 1.5M years (or beyond) are a high priority for IPICS. 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; and these activities should be coordinated with international partners. Such sites may be traditional deep ice core sites, or blue ice regions, though an undisturbed deep ice core is the primary IPICS goal.

2. 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 urgency to understand their dynamics. Predicting responses of glaciers and ice sheets to future possible change requires models that incorporate realistic physics and dynamics. Measurements of present-day conditions are needed to develop and validate such models. These measurements are key to improving the understanding 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). Another approach to understanding future possible response of ice sheets is to examine their behavior in the past. Histories of ice dynamics (thinning and divide location) and climate (accumulation and temperature) can be inferred from ice core and borehole measurements. For example, the depth-age relationship from an ice core contains information about past accumulation and past thinning; a thin annual layer implies either low accumulation in the past or ice sheet thinning.

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; the current project on Pine Island Glacier is a step 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 interpret the 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. Borehole logging of ice rheology, temperature, inclination and azimuth is needed to provide data for modeling ice sheets 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 glacial record from the core from Roosevelt Island will help constrain Holocene deglaciation of the Ross Sea. Depth-age profiles from other targeted locations are essential for understanding the timing and extent in Greenland and in other sectors of Antarctica.

- 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 to indicate their sensitivity to potential climate change. Short bedrock cores 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. Rapid access to subglacial environments is needed to address a wide range of science questions. As technologies mature, deep-penetration drills can be eventually adapted for clean access. Specifically,

- Direct sampling of the bedrock is needed to validate models of cratonic growth related to supercontinent assembly in the Mesoproterozoic about 1M years ago and for constraining the Phanerozoic geological and tectonic history of the continent. Any information from in-situ sub-glacial sampling will proof that inferred from geophysical imaging and analysis of onland glacial sediments (moraines) and offshore sedimentary basins.
- Cenozoic ice sheet history preserved in sedimentary rocks of subglacial bedrock basins and in sediment fills of subglacial lakes will provide further dimensions to the records known only from the margins of the continent and also help verify paleo-topographic reconstructions for ice sheet modeling.
- 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; more than 387 subglacial lakes have been identified in Antarctica. 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 and sampling is needed to maintain stewardship while investigating these subglacial systems. The present project on Whillans Ice Stream 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. 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. The acquisition of community winches to support borehole logging is a very high priority.
- Studies of physics and astrophysics (e.g. the now complete IceCube project) make use of polar ice as a clean, stable, low-background and transparent detection medium for observation of sub-atomic particle interactions. Additional planned projects (e.g. the Askaryan Radio Array) require multiple boreholes at least 150 m deep and 15 cm diameter.
- 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.

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 guiding principles for developing new drills and technologies are recommended:

- Designs must be such that the supporting logistical requirements do not impede the 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 are adaptable 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 considered 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):

- Complete the Intermediate-depth drill and infrastructure, including repair after the first field season. The drill is designed for coring up to 1500 m depth.
- Maintain and upgrade the following existing agile equipment: hand augers, 2” and 4” electromechanical drills, 3”

electrothermal drill, 3.25” Badger-Eclipse drills, and logging winches.
- Develop an agile sub-ice rock coring drill capable of retrieving 10 m of rock core beneath ice up to 700 meters thick. The drill should be agile and transportable by helicopter sling-load.
- Conduct a conceptual design and start construction of an agile shot-hole drill capable of drilling 15 holes per day up to 100 m depth in both East and West Antarctica.
- Develop science requirements, conceptual design and cost estimate of an agile ice coring drill for coring 50 to 700m with smaller logistical requirements than the Intermediate Depth Drill and its surface infrastructure.
- Develop and build an agile, clean hot-water drill for creating 5” holes through up to 6-m of sediment-laden lake ice.
- Complete testing and repair of the Blue Ice drill for large-volume sampling of firn and ice up to 200m depth.
- Continue engineering of the Rapid Access Ice Drill (RAID)[2].

Priority 2 (needed within the next three years):
- Upgrade the electrothermal drill to allow for coring to 300m through temperate and poly-thermal firn and ice. The drill needs to be agile and light weight (transportable by helicopter).
- 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.
- Continue to develop drilling technologies, methods and protocols for clean drilling deeper than 200 m into subglacial environments for access and sampling.
- Establish science requirements and cost estimates for minimal upgrades for the DISC drill for use at Hercules Dome, and additional later upgrades for conditions in East Antarctica, with the goal to lessen its logistics requirements while maintaining replicate coring capability.
- Build or acquire a lightweight backpack drill (e.g. http://www.icedrill.ch/) for shallow coring.

Priority 3 (needed within three to five years):
- Construct a jig to support a hand auger to facilitate horizontal coring up to 20 m into ice cliffs.
- Conduct a feasibility study and conceptual design for recovering cores to depths of 300-500 m without use of drilling fluid.
- 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 the science requirements and conduct a feasibility study for a drill capable of coring horizontally (or at low angles) several 100 m.

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

References

Aciego, S.M., K.M. Cuffey, J.L. Kavanaugh, D.L. Morse and J.P. Severinghaus (2007) "Pleistocene ice and paleo-strain rates at Taylor Glacier", Antarctica. *Quat. Res.*, **68**, 303-313.

Alley, R.B. and I. Joughin, (2012) Modeling Ice-Sheet Flow. *Science*, **336**(6081): 551-552.

Alley, R.B., S. Anandakrishnan, T.K. Dupont, B.R. Patizek, D. Pollard (2007) "Effect of sedimentation on Ice-sheet grounding-line stability", *Science*, **315**(5820), 1838-1841.

Anandakrishnan, S., G. Catania, R.B. Alley, H.J. Hogan (2007) "Discovery of till deposition at the grounding line of Whillans Ice Stream", *Science*, **315**(5820), 2835-2838.

Anderson, J.B., H. Conway, P.J. Bart, A.E. Kirshner, S.L. Greenwood, R.M. McKay, B.L. Hall, R.P. Ackert, K. Licht, M. Jakobsson and J.O. Stone. (2013) Ross Sea paleodrainage and deglacial history during and since the LGM. *Quat. Sci. Rev.* http://dx.doi.org/10.1016/j.quascirev.2013.08.020

Bay, R.C., B.F. Price, G.D. Clow, and A.J. Gow. Climate logging with a new rapid optical technique at Siple Dome (2001) *Geophysical Research Letters*, **28**(24), 4635-4638.

Bentley, M.J., C.J. Fogwill, A.M. Le Brocq, A.L. Hubbard, D.E. Sugden, T.J. Dunai and S.P.H.T. Freeman (2010) "Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea embayment: Constraints on past ice volume change", *Geology*, **38**(5), 411-414.

Brook, E. (2008) "Paleoclimate: Windows on the Greenhouse", *Nature*, **453**, 291-292.

Brook, E. and E. Wolff (2006) "The future of ice coring science", *EOS Trans. AGU* **87**(4), 39.

Cavicchioli, R., Siddiqui, K. S., Andrews, D., & Sowers, K. R. (2002) "Low-temperature extremophiles and their applications", *Current Opinion in Biotechnology*, *13*(3), 253-261.

Carter, S.P. and H.A. Fricker (2012) "The supply of subglacial meltwater to the grounding line of the Siple Coast", Annals of Glaciology, 53 (60) 267-280, doi, 10.3189/2012AoG60A119.

Christianson, K., R. W. Jacobel, H. J. Horgan, S. Anandakrishnan and Alley R. B. (2012) "Subglacial Lake Whillans - Ice-penetrating radar and GPS observations of a shallow active reservoir beneath a West Antarctic ice stream", Earth and Planetary Science Letters 331-332(0): 237-245.

Christianson, Knut, B.R. Parizek, R.B. Alley, H.J. Horgan, R.W. Jacobel, S. Anandakrishnan, B.A. Keisling, B.D. Craig, and A. Muto (2013) Ice sheet grounding zone stabilization due to till compaction. Geophysical Research Letters, 40, 5406–5411, doi:10.1002/2013GL057447.

Christner, B. C., Mosley-Thompson, E., Thompson, L. G., & Reeve, J. N. (2001) "Isolation of bacteria and 16S rDNAs from Lake Vostok accretion ice", *Environmental Microbiology*, *3*(9), 570-577.

Christner, B. C., Mosley-Thompson, E., Thompson, L. G., & Reeve, J. N. (2003) "Bacterial recovery from ancient glacial ice", *Environmental Microbiology*, *5*(5), 433-436.

Christner, B.C. et al in review 2014: Personal Communication 2014.

Clow, G., (2012) Personal Communication, 2012.

Conway, H., B.L. Hall, G.H. Denton, A.M. Gades and E.D. Waddington (1999) "Past and future grounding-line retreat of the West Antarctic Ice Sheet", *Science*, **286**(5438), 280-283.

Cuffey, K.M. and W.S.B. Paterson (2010) "*The Physics of Glaciers"* (4th Ed). Elsevier, ISBN: 978-0-12-369461, 704pp.

Dahl-Jensen et al (2013) "Eemian interglacial reconstructed from a Greenland folded ice core". Nature 493(7433). p.489-494

Denton, G.H., J.C. Bockheim, S.C. Wilson and M. Stuiver (1989) "Late Wisconsin and Early Holocene glacial history, inner Ross Embayment, Antarctica", *Quat. Res.* **31**, 151-182.

Denton, G.H., D.E. Sugden, D.R. Marchant, B.L. Hall and T.I. Wilch (1993) "East Antarctic Ice Sheet sensitivity to Pliocene climatic change from a Dry Valleys perspective", *Geografiska Annaler,* **75**, 155-204.

Dunbar, N.W., W.C. McIntosh and R.P. Esser (2008) "Physical setting and tephrochronology of the summit caldera ice record at Mount Moulton, West Antarctica", *Geol. Soc. of Amer. Bull.*, **120**(7-8), 796-812.

Engelhardt, H., N. Humphrey, B. Kamb, M. Fahnestock (1990) "Physical conditions at the base of a fast moving ice stream", *Science*, **248**(4951), 57-59.

Engelhardt, H., and B. Kamb (1998) "Basal sliding of Ice Stream B, West Antarctica", *J. Glaciol*. 44(147), 223-230.

Fabel, D., A.P. Stroeven, J. Harbor, J. Kleman, D. Elmore, D. Fink (2002) "Landscape preservation under Fennoscandian ice sheets determined from in situ produced 10Be and 26Al", *Earth Plan Sci Lett.* **201**(2), 397-406.

Fahnestock, M., W. Abdalati, I. Joughin, J. Brozena and P. Goginini (2001) "High geothermal heat flow, basal melt and the origin of rapid ice flow in central Greenland" *Science*, **294**(2338), doi:101126/science.1065370.

Favier, L., G. Durand, S.L. Cornford, G.H. Gudmundsson, O. Gagliardini, F. Giller-Chaulet, T. Zwinger, A.J. Payne and A.M. Le Brocq, (2014) Retreat of Pine Island Glacier controlled by marine ice-sheet instability**,** *Nature Climate Change*, doi:10.1038/nclimate2094

Fischer,H., J. Severinghaus, E. Brook, E. Wolff, M. Albert, O. Alemany, R. Arthern, C. Bentley, D. Blankenship, J. Chappellaz, T. Creyts, D. Dahl-Jensen, M. Dinn, M. Frezzotti, S. Fujita, H. Gallee, R. Hindmarsh, D. Hudspeth, G. Jugie, K. Kawamura, V. Lipenkov, H. Miller, R. Mulvaney, F. Pattyn, C. Ritz, J. Schwander, D. Steinhage, T. van Ommen, and F. Wilhelms (in review 2013) "Where to find 1.5 million yr old ice for the IPICS "Oldest Ice" ice core", Clim. Past Discuss., 9, 2771-2815.

Gagliardini, O., G. Durand, T. Zwinger, R.C.A. Hindmarsh and E. Le Meur. (2010) Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics. *Geophys. Res. Lett.* **37**, doi:10.1029/2010GL043334.

Gosse, J.C. and F.M. Phillips (2001) "Terrestrial in situ cosmogenic nuclides: theory and application", *Quat. Sci. Rev.* **20**, 1475-1560.

Hall, B., C. Baroni and G. Denton (2004) "Holocene relative sea-level history of the southern Victoria Land coast", Antarctica: *Glob. Plan. Change,* **42**, 241-263.

Horgan, H. J., S. Anandakrishnan, R. W. Jacobel, K. Christianson, R. B. Alley, D. S. Heeszel, S. Picotti and Walter J. I. (2012) "Subglacial Lake Whillans - Seismic observations of a shallow active reservoir beneath a West Antarctic ice stream. Earth and Planetary Science Letters 331-332(0): 201-209.

Horgan, H.J., K. Christianson, R.W. Jacobel, S. Anandakrishnan and R.B. Alley (2013) Sediment deposition at the modern grounding zone of Whillans Ice Stream, West Antarctica. Geophysical Research Letters, 40, 1–6, doi:10.1002/grl.50712.

Ice Core Working Group (2003) “United States Ice Core Science: Recommendations for the future, Univ. of New Hampshire”, 48pp. http://nicl-smo.unh.edu/icwg/ICWG2003.pdf

Iken, N.R. (1981) ”Potential effects of subglacial water pressure fluctuations on quarrying”, *J. Glaciol.* **37**(125), 27-36.

Jenkins, A., P. Dutrieux, S.S. Jacobs, S.D. McPhail, J.R. Porrett, A.T. Webb and D. White (2010) “Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat”, *Nature Geoscience*, doi:10.1038/NGE0890.

Joughin, I., B.E. Smith & B. Medley (2014). Marine ice sheet collapse potentially underway for the Thwaites Glacier basin, West Antarctica. *Science*, **344**(6185), 735-738 DOI: 10.1126/science.1249055

Kamb, B. (2001) “Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion” *In* Alley, R.B. and R.A. Bindschadler, *eds. The West Antarctic ice sheet: behavior and environment*. Washington, DC, American Geophysical Union, 157–199. (Antarctic Research Series 77).

Li, Y.K., D. Fabel, A.P. Stroeven and J. Harbor (2008) “Unraveling complex exposure-burial histories of bedrock surfaces under ice sheets by integrating cosmogenic nuclide concentrations with climate proxy records”, *Geomorphology,* **99**, 139-149.

Liu, B., F.M. Phillips, J.T. Fabryka-Martin, M.M. Fowler and W.D. Stone (1994) “Cosmogenic ^{36}Cl accumulation in unstable landforms 1. Effects of the thermal neutron distribution”, *Water Res. Res.,* **30**, 3115-3125.

Luthi, D., M.LeFLoch, B. Bereiter, T. Blunier, J-M Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, T.F. Stocker (2008) “High-resolutions carbon dioxide concentration record 650,000-800,000 years before present”, *Nature,* **453**(15), 379-381.

Mercer, J.H. (1968) “Glacial geology of the Reedy Glacier area, Antarctica”, *Geol. Soc. Amer. Bull.* **79**, 471-486.

Mengel, M. and Levermann, A., (2014) Ice plug prevents irreversible discharge from East Antarctica, , Nature Climate Change, **4**, doi 10.1038/nclimate2226.

Miteva, V. I., Sheridan, P. P., & Brenchley, J. E. (2004) “Phylogenetic and physiological diversity of microorganisms isolated from a deep Greenland glacier ice core”, *Applied and Environmental Microbiology*, *70*(1), 202-213.

Miteva, V. I., & Brenchley, J. E. (2005) “Detection and isolation of ultrasmall microorganisms from a 120,000-year-old Greenland glacier ice core”, *Applied and Environmental Microbiology*, *71*(12), 7806-7818.

Morse, D.L., Blankenship, D.D., Waddington, E.D., Neumann, T.A. (2002) “A site for deep ice coring in West Antarctica: results from aerogeophysical surveys and thermo-kinematic modeling”, *Annals Glaciol.* **35**, 36-44.

Nishiizumi, K., R.C. Finkel, K.V. Ponganis, T. Graf, C.P. Kohl, and K. Marti (1996) ”In situ produced cosmogenic nuclides in GISP2 rock core From Greenland Summit (abstract)”, *AGU Fall Meeting*, San Francisco.

NRC (2002) “Abrupt climate change: inevitable surprises”, *National Academies Press*, Washington, D.C.

NRC (2007) “Exploration of Antarctic Subglacial Aquatic Environments: Environmental and Scientific Stewardship”, *National Academies Press*, Washington, D.C.

Pattyn, F. and 27 others (2013) Grounding-line migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison*, J. Glaciol.*, **59**, doi:10.3189/2013JoG12J129.

Payne, A.J., A. Vieli, A.P. Shepherd, D.J. Wingham, and E. Rignot (2004) "Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans", *Geophys. Res. Lett*. **31**, L23401, doi:10.1029/ 2004GL021284.

Pettit, E.C., E. Waddington, T. Thorsteinsson, A. Gusmeroli, J. Kennedy, C. Ritz, and R. Carns. (2011) Using Borehole Sonic Logging to Infer Ice Microstructure and Climate History. EGU General Assembly. Abstract EGU2011-14160.

Pollard, D. and R.M. DeConto (2009) "Modeling West Antarctic ice sheet growth and collapse through the past five million years", *Nature*, **458**, doi:10.1038/nature07809.

Price, S.F., H. Conway, E.D. Waddington and R.A. Bindschadler (2008) "Model investigations of inland migration of fast-flowing outlet glaciers and ice streams", *J. Glaciol.* **54**(184), 49-60.

Price, S.F., H. Conway and E.D. Waddington (2007) "Evidence for late Pleistocene thinning of Siple Dome, West Antarctica", *J. Geophys. Res.* **112**, doi:10.1029/2006JF000725.

Priscu, J. C., Achberger, A. M., Cahoon, J. E., Christner, B. C., Edwards, R. L., Jones, W. L., Michaud, A.B., Siegfried, M.R. Skidmore, M.L., Spigel, R.H., Switzer, G.W. Tulaczyk, S. & Vick-Majors, T. J. (2013) A microbiologically clean strategy for access to the Whillans Ice Stream subglacial environment. *Antarctic Science*, *25*(05), 637-647.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi & B. Scheuchl, (2014) Widespread, rapid grounding-line retreat of Pine Island, Thwaites, Smith and Kohler Glaciers, West Antarctica, from 1992-2011, *Geophys. Res. Lett.,* **41**, doi:10.1002/2014GL060140.

Shepherd, A., D. Wingham and E. Rignot (2004) "Warm ocean is eroding West Antarctic Ice Sheet", *Geophys. Res. Lett.* **31**, L23402, doi:10.1029/2004GL021106.

Simon, C., Wiezer, A., Strittmatter, A. W., & Daniel, R. (2009) "Phylogenetic diversity and metabolic potential revealed in a glacier ice metagenome", *Applied and environmental microbiology*, *75*(23), 7519-7526.

Spaulding, N.E., J.A. Higgins, A.V. Kurbatov, M.L. Bender, S.A. Arcone, S.Campbell, N.W. Dunbar, L.M. Chimiak, D.S. Introne & P.A. Mayewski. (2013) "Climate Archives From 90 to 250 Ka in Horizontal and Vertical Ice Cores From the Allan Hills Blue Ice Area, Antarctica." *Quaternary Research* 80 (3): 562–74.

Stanton, T.P., W. J. Shaw, M. Truffer, H.F.J. Corr, L.E. Peters, K.L. Riverman, R. Bindschadler, D.M. Holland & S. Anandakrishnan, (2013) Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica. *Science*, **341**, 1236-1239.

Stone, J.O., G.A. Balco, D.E. Sugden, M.W. Caffee, L.C. Sass III, S.G. Cowdery and C. Siddoway (2003) Holocene deglaciation of Marie Byrd Land, West Antarctica. *Science*, **299**(5603), 99-102.

Sugden, D.E., G. Balco, S.G. Cowdery, J.O. Stone and L.C. Sass (2005) "Selective glacial erosion and weathering zones in the coastal mountains of Marie Byrd Land, Antarctica", *Geomorphology,* **67**, 317-334.

Todd, C., J. Stone, H. Conway, B. Hall and G. Bromley (2010) "Late Quaternary evolution of Reedy Glacier, Antarctica", *Quat. Sci, Rev.,* **29**(11-12), 1328-1341.

Truffer, M. W. Harrison, K. Echelmeyer (1999) "Glacier motion dominated by processes deep in underlying till", *J. Glaciol*. **46**(153), 213-221.

Truffer, M. W. Harrison (2006) "In situ measurements of till deformation and water pressure", *J. Glaciol.* **52**(177), 175-182.

Waddington, E.D., T.A. Neumann, M.R. Koutnik, H-P Marshall and D.L. Morse (2007) "Inference of accumulation-rate patterns from deep layers in glaciers and ice sheets", *J. Glaciol.* **53**(183), 694-712.

Waddington, E.D., H. Conway, E.J. Steig, R.B. Alley, E.J. Brook, K.C. Taylor and J.W.C. White (2005) "Decoding the dipstick: thickness of Siple Dome, West Antarctica at the Last Glacial Maximum", *Geology* **33**(4), 281-284.

Webb, P.N., D.M. Harwood, B.C. McKelvey, J.H. Mercer and L.D Stott (1984) "Cenozoic marine sedimentation and ice-volume variation on the East Antarctic Craton", *Geology,* **12**, 287-291.

Acronyms

AGAP: Antarctica's Gamburtsev Province

ANDRILL: Antarctic Drilling Project

AUV: Autonomous Underwater Vehicle

DISC: Deep Ice Sheet Coring

EPICA: European Project for Ice Coring in Antarctica

GISP2: Greenland Ice Sheet Program II

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

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

WAIS: West Antarctic Ice Sheet

WISSARD; Whillans Ice Sheet Subglacial Access Research Drilling