Ice Drilling Program Office

Long Range Science Plan 2012-2022

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Cover photo: Scientist Emily Longano prepares ice samples at the National Ice Core Laboratory.
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Executive Summary

One of the most pressing environmental issues of our time is the greenhouse gas-induced climate change that will warm 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 and ice sheets contain records of past climate and ice thickness, which provide clues to understanding future climate. They also contain data relating to the physics of ice sheets and processes that control their stability and response to climate change. Furthermore, subglacial environments preserve unique biological and geochemical environments and hold clues to the history of ice cover. 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 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 for U.S. ice coring and drilling science, and 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 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 the oldest ice. 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. Borehole logging and replicate coring are essential to fully exploit the histories of climate and ice dynamics preserved at WAIS Divide.
- Drilling of spatially distributed ice cores to support the IPICS goals of investigations of past climate and atmosphere over the past 2,000 to 40,000 years should continue. The climate record from the core now being extracted from Roosevelt Island is anticipated to extend back 40,000 years; it is likely that cores from South Pole and Hercules Dome will also contain 40,000 year climate records, and these should be extracted in the coming decade.
- 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. There is strong evidence that a core from South Pole would contain Eemian ice; extracting an undisturbed, high-resolution record from the Eemian within the next decade is a high priority. The search for sites to extract undisturbed Eemian ice in Greenland, both by coring and through horizontal sampling of blue ice ablation zones, should continue.

- 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. 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 ought to 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 outlet glaciers and ice streams observed over the past decade create an urgency to understand the dynamics of outlet glaciers and ice sheets. 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), ice-ocean interactions (sub-shelf melting-freezing) 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.
- 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) 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 now being extracted 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 (e.g. Pollard and DeConto, 2009), 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. 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.
- 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 logistical principles

Drills and technologies needed to achieve some of the science goals already exist, however, the drills require regular maintenance and updates. New drills and technologies are needed to achieve additional science goals; the following guiding principles for developing new drills and technologies are recommended:

- Designs should be such that the supporting logistical requirements do not impede the execution of the science.
- Science requirements need to be balanced by consideration of logistical issues including weight, size, costs and time frame for development. All issues need to be clearly defined at the initial stage of planning, and changes during the engineering design and fabrication process must be reassessed by the IDPO.
- Drills and accompanying technology should be developed with consideration of potential use in possible future projects. These drills and the accompanying technology must also be versatile and adaptable.
- Engineering design teams should include individuals with field experience using ice core drills and/or other relevant field experience.

Recommended technology investments

The following high-priority investments in drilling technology are needed to achieve the science goals:

- Maintain and update the existing agile coring/drilling capabilities, including addition of clean, easily portable hand and shallow coring devices.
- Purchase/construct two winches for borehole logging: first priority is a 1.5 km winch; second priority is a 4 km winch. The intermediate winch is underway.
- Develop replicate coring capability. This task is underway for WAIS Divide.
- Purchase/construct a versatile intermediate-depth (1,500 m) drill. This task is underway.
- Modify the Blue Ice Drill for up to 100-m depth large-volume sampling.
- Develop drills that will allow rapid access to the base of ice sheets and ice shelves. Holes of different diameter are needed for specific projects and so modular designs are preferable. The proposed RAID drill is a step in this direction. Existing hot water access drills need to be maintained, and new hot water drills capable of drilling 500 to 2,500 m are urgently needed.
- Design and develop methods and protocols for clean access for sampling of subglacial environments.
- Identify a drilling fluid that is environmentally acceptable and can be used at temperatures down to -55°C.
- Develop methods to sample large quantities (10’s of meters of core) of subglacial bedrock.

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 inform young scientists about the technologies supporting their research and strengthening the community around the ice coring and drilling enterprise.

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 and ice sheets 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 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 speed of fast-flowing outlet glaciers and ice streams observed over the past decade create 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. Further 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). Perturbations at grounding lines are likely caused by changing ocean temperature, circulation, and/or sea level (Jenkins et al., 2010). Definition of 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 dynamical responses of the ice sheets to climate and sea level change.

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. New and emerging studies show that subglacial environments harbor unique microbial ecosystems. Many show that 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 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 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 plan well-coordinated proposals while allowing the NSF to plan for budgets and logistics to facilitate the science. SAB-recommended updates to the IDPO Long Range Science Plan are posted to the icedrill.org website each spring, with listserv invitations for comments and suggestions to enable broad community input. The document is then revised, approved by the SAB, and the final version for the year is posted to the icedrill.org website in summer.

Science goals articulated in this document are all interconnected, but for convenience they are described in four categories: climate change; ice dynamics and glacial history; subglacial geology, sediments and ecosystems; and ice as a scientific observatory. These four goals and objectives are described below, together with an outline of their respective needs for drilling technologies. Planning matrices are also developed to provide a timeline for the development of technologies, so that the support for the science will be ready when needed.

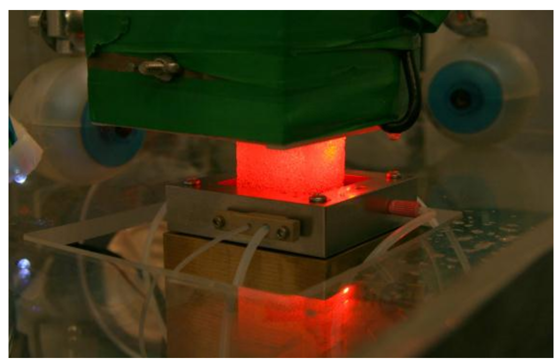
Ice Coring and Drilling Science Goals

I. Climate Change

Earth's climate system involves local, regional, hemispheric, and global phenomena. It is impossible to understand global climate without understanding both individual components of the system and the system as a whole, as evidenced by data from a large number of locations and over a range of time scales. Issues articulated by many U.S. scientists (e.g. ICWG, 2003) were central to the themes in the IPICS white papers (Brook and Wolff, 2006), hence a number of the categories below reflect those themes.

1. 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. 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 will continue with the following objectives:

- 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 spatial maps of climate and environmental parameters (e.g., temperature, accumulation rate, chemistry).
- Validate 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 intra-glacial and subglacial ecosystems to improve understanding of the role of microbes in ice related to geological, chemical and climatological changes.
- Determine biogeographical patterns of biological material deposition and understand their role in ice core dynamics. Several of these objectives are critical for interpreting longer timescale records detailed in following sections.
- Understand anthropogenic impacts on greenhouse gases in the atmosphere.



This image is of an ice core sample sitting on a melter head in an ultra-trace chemistry laboratory. Records taken from a Greenland ice core showed pollution from coal burning in North America and Europe that traveled through the atmosphere and deposited in the Arctic Region were higher 100 years ago, contrary to the expectation that pollution was at a peak in the 1960s and 1970s. Credit: *Joseph McConnell, Desert Research Institute*

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 various states of repair in the current U.S. inventory. They are used often, and need to be maintained in top form 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 needed, include a very lightweight 5 cm diameter "backpack drill" for alpine shallow coring, and a hand auger capable of clean, horizontal, 2m-deep coring from glacier sides with the auger carried on a backpack and operated by a single drill operator.

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 AD 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: (1) establishing the extent and regional expression of the so-called "Little Ice Age" and "Medieval Warm Period" phenomena; (2) evaluating 20th-century warming in the context of the past 2,000 years; (3) establishing spatial and temporal patterns of temperature, precipitation, and sea ice extent; (4) quantifying spatial and temporal patterns of climate-forcing mechanisms that are regionally variable (e.g., sulfate, terrestrial dust and associated biological material, black carbon aerosols), and the record of solar variability; (5) 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 would primarily be in the Arctic and Antarctic, but likely include mid-latitude sites as well; several countries, including the United States, are considering new coring associated with the 2,000-year array theme. New U.S. or U.S./International efforts that have been discussed or will soon start include Roosevelt Island in the Ross Sea (the 2,000-year record would be part of a deeper core), Detroit Plateau on the Amundsen Coast, the Central Alaska Range, and possibly the Aurora Basin in Antarctica or a high accumulation rate site in Greenland. This list is not exclusive, but illustrates the diversity of possibilities.

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 40k years, are still matters of debate.

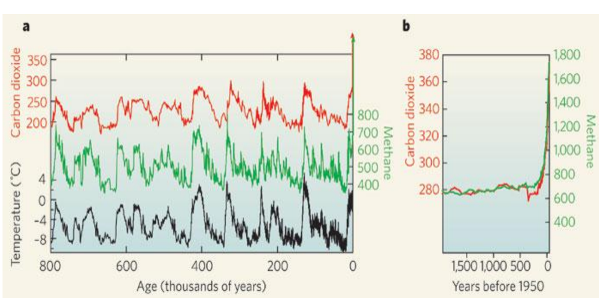
Under the auspices of IPICS, the international scientific community is developing plans for a network of ice cores covering the past 40,000 years. The specific U.S. contribution to this network (in addition to the WAIS Divide core) has yet to be determined, but is likely to include one or more new ice cores in Antarctica — sites that have been discussed so far include South Pole, Hercules Dome, and Taylor Dome, with the most discussion to date focused on South Pole. Drilling by New Zealand with U.S. science collaboration is moving forward for a site on Roosevelt Island, as a contribution to the network. 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 1,000 m or more with minimal logistics is needed for this science. As discussed in the IDDO Long Range Drilling Technology Plan, current agile drills in the inventory have a maximum depth of several hundred meters. The only other drill in the inventory is the DISC drill, which can reach 4,000 m, but it is logistically heavy and requires multiple seasons for deployment and drilling.

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*

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 almost all from low accumulation sites in Antarctica such as Vostok and Dome C. 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. Unfortunately, recent results from the North Greenland Eemian Ice Drilling (NEEM) ice core in Greenland indicate that the Eemian record there is compromised. The search for an undisturbed site is ongoing; 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. 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. A conceptual design for replicate coring has been developed by IDDO, and is currently being implemented with the DISC drill, as discussed in the Long Range Drilling Technology Plan. The NEEM group led by Denmark has made preliminary successful attempts at deviating the NEEM borehole.

5. Evidence from the ice sheet prior to 800,000 years BP: 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 120,000-800,000 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 to 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) and Mt. Moulton (Dunbar et al., 2008) where old ice may be outcropping 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 strong preference for continuous records, given the potential difficulties of splicing together discontinuous and possibly stratigraphically disturbed blue ice or only deep ice records.

Two regions of current attention for sites of oldest ice cores are the Dome A area and the Aurora Subglacial Basin. 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 in the very cold conditions found in East Antarctica.

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; more details of such a drill are discussed below.

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, and a drill for wide-diameter samples from clean blue ice ("blue ice" drill) was used successfully on Taylor Glacier in Antarctica during the 2010-11 field season.

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 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 ~100 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.

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. Acquisition of an intermediate depth drill capable of extracting ~1,000 m of core in one season with minimal logistical requirements is also high priority. Development of replicate coring capability for the DISC drill is now well underway. A large-diameter drill for blue ice areas was used successfully on Taylor Glacier, Antarctica during the 2010-11 and 2011-12 field seasons. A conceptual design for upgrading the DISC drill for cold conditions in East Antarctica should be developed. In addition, because the HCFC-141-b component of the current drilling fluid is being phased out, there is need to identify a replacement drilling fluid that is suitable for use in cold conditions. 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 information on the drills needed to achieve the climate change science as discussed above is given in the IDDO Long Range Drilling Technology Plan.

	Diam. (cm)	Depth (m)	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	5-7	15	none	-30	sometimes	Manual	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	100-1,000	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
>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	100^+	none	-40	no	Helicopter	1-2 seasons	US

II. Ice Dynamics and Glacial History

Rapid changes in speed of fast-flowing outlet glaciers and ice streams observed over the past decade create urgency to understand the dynamics of outlet glaciers and ice sheets. Predicting responses of glaciers and ice sheets to future possible environmental change requires models that incorporate realistic ice dynamics. Measurements and observations of present-day conditions are needed to develop and validate such models. Properties of the ice, and in particular 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 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). Measurements at the bed of glaciers and ice sheets are hampered by problems associated with accessing the bed, and problems 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 500 m to 2,500 m are urgently needed.

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); ice cores can be used to date intersecting radar layers.

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

1. Basal conditions and geothermal flux: Direct measurements of bed conditions including frozen/thawed bed, basal pore pressure, slip, and sediments are needed to develop and test realistic models of the controls on the fast flow of ice streams and outlet glaciers. Determination of whether a bed is frozen or thawed requires a coupled thermo-mechanical flow model. A critical necessary input is a realistic measure of the geothermal flux. Geothermal flux has been estimated 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). Until recently the only measurement in West Antarctica was from Siple Dome (69 mW m^{-2}), but recent borehole temperature measurements in the West Antarctic Ice Sheet (WAIS) Divide drill site indicate a geothermal flux of ~230 mW m^{-2} (Clow, 2012). Based on the data to date, geothermal flux values vary considerably throughout West Antarctica and further investigation is required to aid in modeling.

2. Remote sensing of basal conditions: Remote sensing such as active and passive seismic arrays and radio echo sounding can 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) is present within IDDO with the Rapid Air Movement Drill, and that capability should be maintained and improved. Increasing the speed of drilling while continuing to reduce the size and power consumption of the shot hole drills will be important. Details of the Rapid Air Movement Drill are in the Long Range Drilling Technology Plan.

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) and model results (Pollard and DeConto, 2009) suggest 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). Currently there are no direct measurements 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, which are needed to help develop depth-age relationships in ice cores, and also to establish past, present and future responses to possible environmental changes. Sensors that measure depth profiles of temperature, fabric, optical stratigraphy and tilt in boreholes are now available. Rapid-access drills that can drill through ice up to 4 km thick are needed to deploy these sensors. 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 contain 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. We have many ways to examine the size and shape of ice sheets during colder periods (e.g. Mercer, 1968, Denton et al, 1989, Todd et al., 2010; Bentley et al., 2010; Stone et al., 2003; Hall et al, 2004) but few to determine their extent and thickness under warmer climates. Much of the critical evidence is hidden beneath the present ice sheets. Under shallow ice, nimble methods for reconnaissance recovery of small rock cores 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.

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).

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

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 and Phillips, 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. 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 predictions of future changes in sea level. Improving reliability of risk assessments of future behavior of ice sheets and their components requires access holes to enable basic measurements of: (i) physical conditions, including geothermal flux, and processes at the beds of glaciers and ice sheets; (ii) physical

processes at grounding lines and grounding zones of fast-moving ice streams and outlet glaciers; (iii) 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 help constrain the extent and timing of deglaciati
on.

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. An 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	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	2 weeks	US & others
Ice shelf ROV deployment	100	<1k	Hole	-30	no	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, with only one rift shoulder and 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 is important for 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.

2. Subglacial basins: 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 now being collected near the margins (ANDRILL and SHALDRIL). 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 Antarctica and East Antarctica geological 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.

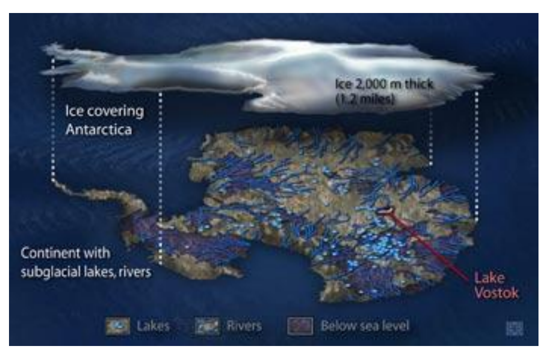


Illustration showing the aquatic system that scientists believe is buried beneath the Antarctic ice sheet. Credit: National Science Foundation, Photo Gallery)

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.

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. Ice sheets provide reservoirs of microbial cells entombed during atmospheric deposition. The long timescale of entrapment in 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 (e.g., the Subglacial Antarctic Lake Environment - SALE program). 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 387 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, but it is as yet too early to discuss any scientific results from that operation. In the 2012-13 season the British plan to access subglacial Lake Ellsworth in the interior of West Antarctica, and the US plans to drill into subglacial Lake Whillans upstream from the Siple Coast grounding line. The new drill built for drilling Lake Whillans includes a filtration unit and UV- light system to clean the drilling water to provide for clean access to the subglacial environment. The subglacial lake beneath South Pole is another potential target identified by participants of the 2011 IDPO Ice Drilling Science Community Workshop in

Washington DC. The cost, environmental and logistical issues for this project are beyond the scope of projects currently identified in the Long Range Drilling Technology Plan.

Summary

Subglacial environments contain biologic, climatic, geologic, and glaciologic materials and information, much of which cannot be obtained anywhere else. Drills to create access holes are urgently needed to sample basal ice, subglacial water and sediments, and bedrock cores. Hole diameter requirements vary depending on instrumentation needed; clean technology is required (NRC, 2007), as is strict environmental review. 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. 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	10-15	1-3	Hole	-50	Herc/ traverse	weeks		Clean access
Biogeochem	3-25	<4	Hole	-50	Herc/ traverse	weeks		Clean access
Bedrock geology	8-10	1-4	Icehole, rock core	-50	Herc/traverse	4-8 weeks	U.S.	No
Geology/ Tectonics wet condtns	15	<4k	Hole	-50	Herc/ traverse	weeks	ANDRILL	Clean access
Subglacial lake biogeochem	50-100	3-4k	Hole	-50	Herc/ traverse	4-8 weeks		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 achieve stratigraphic records, which are far more 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.

The acquisition of community winches to support borehole logging is very high. At least two winches are needed for intermediate (1.5 km) and deep (4 km) applications, or a winch system that can be configured as needed for a particular project. IDDO plans to acquire the IceCube logging winch, which consists of approximately 2,700 m of 4-conductor logging cable. In addition, existing boreholes such as those at Greenland Summit (GISP2), and Siple Dome should be repaired and maintained to allow future borehole logging.

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. IceCube may reveal new physical processes associated with the enigmatic origin of the highest energy particles in nature. 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.

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.

A number of low-energy physics experiments under consideration would be constructed within the IceCube array in order to use the detector as an electronic veto or shield. Experiments embedded within the IceCube instrumented volume would supplement those situated in underground mines that search for dark matter, neutrino oscillations, supernovae, proton decay and neutrino beams from accelerators. These experiments will deploy a relatively high density of photocathode 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

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 will require holes at least 200 m deep and 15 cm diameter, with 100 m spacing. Preliminary tests in 2010-11 indicate that the existing Rapid Air Movement (RAM) drill may not be adequate for the ARA experiment. A mini-hot-water drill is currently under development for ARA pilot studies. Other high energy neutrino experiments will use large quantities of ice for particle detection but do not involve significant drilling: the ANITA experiment uses balloon-borne instruments to detect neutrinos interacting with the bulk Antarctic ice sheet; the ARIANNA experiment will detect radio emissions within the Ross Ice Shelf but will only deploy sensors in surface snow. Boreholes situated within or near particle detectors could serve as access points for calibration beacons or standard candles. For the ARA experiment, for example, an antenna permanently emplaced near the array at a depth of 1 km, on the end of a low-loss high-bandwidth coaxial cable, could provide many years of service for 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. 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 with minimum logistical requirements, needs to be designed. At least two versatile winches are needed for intermediate (1.5 km) and deep (4 km) applications in the near future borehole. 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.

Table 4: Climate Change Planning Matrix

	2012				2013				2014				2015				2016				2017				2018				2019				2020				2021				2022			
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	x	x	x			x	x			x	x			x	x																													
Antarctic	x			x	x			x	x																																			
Temperate glaciers		x	x			x	x																																					
2k array																																												
Arctic		x	x			x	x			x	x																																	
Antarctic								x	x			x	x																															
Temperate glaciers		x	x																																									
40k Network																																												
40k-WAIS Divide																																												
Drill main core at WAIS-D																																												
Borehole logging at WAIS								L	L			L	L			L	L																											
Replicate coring (RC) at WAIS-D																																												
RC field test at WAIS	D																																											
Drill replicate cores at WAIS-D				D	D																																							
Acquisition planning -intermediate drill																																												
int drill engineering design	x	x	x																																									
int drill fabrication			x	x	x	x	x	x	x																																			
int drill field test in Greenland										x																																		
int drill prep for deployment											x																																	
Acquisition planning -new drilling fluid																																												
Establish science requirements		x																																										
Identify new drilling fluid		x	x	x	x	x																																						
40k - South Pole																																												
Intermediate drill coring												I	I			I	I																											
40k - Herc Dome																																												
Intermediate drill coring																				I	I																							
40k - Roosevelt Island																																												
Borehole logging				It	It																																							
40k - Siple Dome																																												
Borehole logging								L	L			L	L																															
Previous Interglacial																																												
NEEM																																												
borehole logging		L																																										
Large-volume paleoclimate records																																												
wide-diameter coring																																												
Blue Ice drill coring	B			B	B	B	B	B	B	B	B	B	B	B	B	B	B																											
IPICS oldest ice																																												
Modify DISC for cold conditions						x	x	x	x	x	x	x	x	x	x																													
Acquisition planning-Rapid Access Ice Drill																																												
Establish science requirements RAID	x																																											
Conceptual design RAID		x	x																																									
Seek funding for RAID		x	x	x	x	x	x	x																																				
Engineering design RAID								x	x	x	x	x																																
Drill fabrication RAID												x	x	x	x	x																												
Test RAID																	x	x																										
Modifications																		x	x	x	x																							
Pack & ship drill to Antarctica																						x	x	x																				
Field test of RAID																									x			x	x															
Borehole studies for site selection																																x	x			x	x							
Drilling for oldest ice																																								D	D			D

Table 5: Ice Dynamics and Glacial History Planning Matrix

	2012				2013				2014				2015				2016				2017				2018				2019				2020				2021				2022			
Ice Dynamics & Glacial History	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
Acquisition planning - logging winches																																												
1500 m depth winch acquisition		x	x	x																																								
4000 m depth winch acquisition				x	x	x																																						
Acquisition planning : 500-2500m hot water drills																																												
Establish science requirements for hot water drills					x	x	x	x																																				
Seek funding for hot water drills									x	x	x																																	
Engineering design & construction hot water drills									x	x	x	x	x																															
Acquisition planning-Rapid Access Ice Drill																																												
Establish science requirements RAID	x																																											
Conceptual design RAID		x	x																																									
Seek funding for RAID		x	x	x	x	x	x	x																																				
Engineering design RAID								x	x	x	x	x																																
Drill fabrication RAID												x	x	x	x	x																												
Test RAID																	x	x																										
Modifications																		x	x	x	x																							
Pack & ship drill to Antarctica																						x	x	x																				
Field test of RAID																									x			x	x															
Borehole studies for oldest ice site selection																																x	x			x	x							
Borehole studies for ice dynamics																																								x	x			
Basal conditions & geothermal flux																																												
WISSARD				x	x			x	x																																			
Seismic-acoustic basal condition	x			x	x			x	x																																			
Sub-ice shelf mass balance												x	x			x	x																											
Ice dynamics																																												
Borehole logging: Siple Dome/Englehardt Ridge								x	x																																			
Glacial history																																												
WISSARD				x	x			x	x																																			
Conditions at the ice sheet bed																																												
WISSARD				x	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 RAID will enable more scientific investigations of subglacial ice dynamics and glacial history, and the development of new drills in years 2014 and beyond (Table 5) will help resolve the problems now facing the ice dynamics and glacial history community.

Table 6: Subglacial Geology, Sediments and Ecosystems Planning Matrix

	2012				2013				2014				2015				2016				2017				2018				2019				2020				2021				2022			
Subglacial Geology, Sediments, & Ecosystems	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Acquisition planning - hot water access drills					x	x	x	x																																				
Acquisition planning: agile rock coring under shallow ice																																												
Establish science requirements: agile rock coring					x	x																																						
Conceptual design: agile rock coring									x	x	x	x																																
Seek funding for agile rock coring under shallow ice									x	x	x	x																																
Acquisition planning-Rapid Access Ice Drill																																												
Establish science requirements RAID	x																																											
Conceptual design RAID		x	x																																									
Seek funding for RAID		x	x	x	x	x	x	x																																				
Engineering design RAID								x	x	x	x	x																																
Drill fabrication RAID												x	x	x	x	x																												
Test RAID																	x	x																										
Modifications																		x	x	x	x																							
Pack & ship drill to Antarctica																						x	x	x																				
Field test of RAID																									x			x	x															
Borehole studies for oldest ice site selection																																x	x			x	x							
Bedrock geology								x	x			x	x			x	x																							x	x			x
WISSARD				x	x			x	x																																			
Microbial ecosystems & biogeochem																																												
WISSARD				x	x			x	x																																			
Grounding line - GLIDE								x	x			x	x																															
Subglacial lakes & hydrology																																												
South Pole Subglacial Lake Exploration																																												
Site reconnaissance & prep								x	x																																			
Drilling & measurements at S Pole												x	x																															

Acquisition of the Rapid Access Ice Drill (RAID) 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 is possible using the Koci drill. In addition, U.S. science community members are interested in exploration of South Pole Lake, possibly using the IceCube drill (see Section III.2). Community discussions and planning are in very early stages, but this project would not be within the scope or budget of existing IDDO drilling activities.

Table 7: Ice as a Scientific Observatory Planning Matrix

	2012				2013				2014				2015				2016				2017				2018				2019				2020				2021				2022			
	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/glaciology																																												
WAIS Divide borehole logging - paleoclimate	x			x	x			x	x																																			
Siple Dome borehole logging - paleoclimate												x	x																															
Siple Dome borehole logging - ice dynamics								x	x																																			
Englehardt Ridge borehole logging - ice dynamics								x	x																																			
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
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 photocathode 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 will be used for ARA pilot studies.

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 need 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 new replacement must be identified with a reasonably low viscosity for the very cold temperatures of East Antarctica, and the fluid must be appropriate for the analytical methods used in the scientific analysis of ice core chemistry. A fluid used by Danish colleagues at NEEM, and New Zealand colleagues at Roosevelt Island satisfies the criteria for sites of moderate temperature, but its properties are not favorable for drilling in very cold conditions. Further discussions of this issue are planned.

(2) Air support to sites in Greenland and Antarctica is limited. With multiple science communities requesting flights, time at the field site must be carefully planned to optimize scientific productivity. Currently the infrastructure supporting the DISC drill at the WAIS Divide site is nearing the end of its lifetime and is in need of extensive maintenance in the future. 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.

(3) The National Ice Core Laboratory (NICL), funded by NSF, is the key location for processing and archival 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.

(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 may begin in 2013.

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 the oldest ice. 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. Borehole logging and replicate coring is essential to fully exploit the histories of climate and ice dynamics preserved at WAIS Divide.
- Drilling of spatially distributed ice cores to support the IPICS goals of investigations of past climate and atmosphere over the past 2,000 to 40,000 years should continue. The climate record from the core now being extracted from Roosevelt Island should extend back 40,000 years; it is likely that cores from South Pole and Hercules Dome also contain 40,000 year climate records, and these should be extracted in the coming decade.
- An undisturbed climate record from the last interglacial period (the Eemian, ~130,000 to 110,000 years ago) is key to predicting the response of glaciers and ice sheets to future warming. There is good evidence that a core from South Pole would contain Eemian ice; extracting an undisturbed, high-resolution record from the Eemian within the next decade is high priority. The search for sites to extract undisturbed Eemian ice in Greenland, both by coring and through horizontal sampling of blue ice ablation zones, should continue.
- Blue ice areas have potential for providing large amounts of ice, needed to extract adequate samples of atmospheric gases and trace components. A version of the new large-diameter blue ice drill capable of drilling vertically to ~100 m would greatly improve access to archives contained in blue ice regions.
- 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 ought to continue; 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 outlet glaciers and ice streams observed over the past decade create urgency to understand the dynamics of outlet glaciers and ice sheets. 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. The key is to improve understanding of the ice-bed interface (frozen-thawed, hard-soft bed conditions), ice-ocean interactions (sub-shelf melting-freezing) and ice-atmosphere interactions (surface mass balance). Another approach to understanding future, possible, responses 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 beneath 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.
- The spatial pattern of the geothermal flux beneath ice sheets is poorly constrained. Boreholes to the bed at targeted locations are urgently needed to measure borehole temperature gradients needed to infer the geothermal flux.
- 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) 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 now being extracted 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.
- Cosmic radiation produces a variety of rare long-lived and stable nuclides in the outermost few meters of exposed rocks. When ice sheets are absent these nuclides build up, but even a few meters of ice cover is enough to shield the underlying rock. Hence the presence of cosmogenic nuclides in subglacial bedrock provides unequivocal evidence of ice-free conditions in the past. 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. 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.

- 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 fast flow of ice streams and outlet glaciers.
- Large areas beneath ice sheets and glaciers are wet; for example, 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 in 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; sonic logs provide continuous record of ice structure through the ice sheet. The acquisition of community winches to support borehole logging is 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 logistical principles

Drills and technologies needed to achieve some of the science goals already exist, however, the drills require regular maintenance and updates. New drills and technologies are needed to achieve other science goals; the following guiding principles for developing new drills and technologies are recommended:

- Designs should be such that the supporting logistical requirements do not impede the execution of the science.
- Science requirements need to be balanced by consideration of logistical issues including weight, size, costs and time frame for development. All issues

need to be clearly defined at the initial stage of planning and changes during the engineering design and fabrication process must be reassessed by the IDPO.

- Drills and accompanying technology should be developed with consideration of potential use in possible future projects. They must be versatile and adaptable.
- Engineering design teams should include individuals with field experience using ice core drills and/or other relevant field experience.

Recommended technology investments

The following high-priority investments in drilling technology are needed to achieve the science goals:

- Maintain and update the existing agile coring/drilling capabilities, including addition of clean, easily portable hand and shallow coring devices.
- Purchase/construct two winches for borehole logging: first priority is a 1.5 km winch; second priority is a 4 km winch.
- Develop replicate coring capability. This task is underway for WAIS Divide.
- Purchase/construct a versatile intermediate-depth (1,500 m) drill. This task is underway.
- Modify the Blue Ice Drill for up to 100 m depth large-volume sampling
- Develop drills that will allow rapid access to the base of ice sheets and ice shelves. Holes of different diameter are needed for specific projects and so modular designs are preferable. The proposed RAID drill is a step in this direction. Existing hot water access drills need to be maintained, and new hot water drills capable of drilling 500 to 2,500 m are urgently needed.
- Design and develop methods and protocols for clean access for sampling of subglacial environments.
- Identify a drilling fluid that is environmentally acceptable and can be used at temperatures down to -55°C.
- Develop methods to sample large quantities (10's of meters of core) of subglacial bedrock.

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 inform young scientists about the technologies supporting their research and strengthening the community around the ice coring and drilling enterprise.

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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

NRC: National Research Council

NSF: National Science Foundation

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