Ice Drilling Program Office

Long Range Science Plan 2011-2021

Prepared on behalf of the U.S. ice coring and drilling research community by the Ice Drilling Program Office, in collaboration with its Science Advisory Board and with input from members of the research community

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Table of Contents

Cover photo: *Scientist are drilling a large-volume ice core on the Taylor Glacier ablation zone, Antarctica. Bubblies in the ice at the site contain evidence of ancient atmospheric composition. The Blue Ice Drill is a new, easily-transportable drill capable of retrieving cores of approximately 9.5 inches in diameter up to 15 meters in solid ice.*

Photo Courtesy: Jeff Severinghaus

Executive Summary

Scientific discoveries achieved from, within, and beneath the Arctic and Antarctic ice sheets and temperate glaciers are critical to society today, but they are not achieved without significant advance planning. The Ice Drilling Program Office (IDPO) was established by the National Science Foundation to conduct integrated planning for the ice drilling science and technology communities and provide drilling technology and operational support that enables the community to advance the frontiers of climate and environmental science. The IDPO Science Advisory Board (SAB) are scientists who represent a range of disciplines and who represent the research community to articulate near-term and long range science that will require ice coring or drilling.

This IDPO Long Range Science Plan is updated annually by the IDPO and the SAB in consultation with the broader research community. Its purpose is to articulate the long-range direction for U.S. ice coring and drilling and to identify drills and technology necessary to enable the science. This plan summarizes community recommendations that 1) describe ice core and drilling science goals 2) outline guiding logistical principles for drill and technology development and 3)identify technology investment priorities. A companion plan, the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan, discusses the utility and limitations of currently available drills, and identifies new drills and technology that are needed to move forward on the long-range science goals. A strong recommendation of this report is that funding agencies, including the U.S. National Science Foundation (NSF), plan for the development of new drills and technologies and invest in the training of the next generation of ice coring and drilling scientists and engineers so that the following science goals can be achieved in the coming decade.

Recommended science goals

1. **Climate**

Current climate change can only be fully understood in the context of the past; the goal of this climate science is to develop well-dated histories of climate and atmospheric composition over a wide range of time scales, with a goal of understanding climate forcing and response. This involves recovery of ice cores and arrays of ice cores with time scales of hundreds to hundreds of thousands of years. These efforts represent both U.S.-initiated endeavors as well as US contributions toward the international IPICS science goals. Priority activities include:

- The WAIS Divide ice core will be the highest-resolution climate record from Antarctica. Borehole logging at this site should commence and be completed. If results from borehole logging indicate additional drilling is acceptable, drilling to the maximum depth should be completed. Subsequent replicate coring and borehole logging should be conducted in a way that optimizes the science, while minimizing the logistical costs required for maintaining the infrastructure at WAIS Divide. Such measurements are essential to fully exploit the histories of climate and ice dynamics that are preserved in the core and bore hole at WAIS Divide.
- Ice coring and drilling to support investigations of climate and atmosphere over recent centuries and ice core networks including 200 year investigations and the IPICS 2k year and 40k year array initiatives should continue. The density of 200 to 2,000 year ice core arrays should be increased around the globe to constrain late Holocene regional climate variability and forcing mechanisms. Cores from sites such as South Pole and Hercules Dome have potential to contribute to the 40k

array. Data from these cores are needed to understand spatial and temporal variations of climate over different time scales.
- Understanding glaciological and climate conditions during the last interglacial is key to predicting the response of glaciers and ice sheets to future possible environmental changes. Efforts to extract an undisturbed record of the last interglacial should be supported. In addition to traditional deep ice cores, cores from blue ice regions at the margins of ice sheets have potential for such records.
- Studies of ancient ice are needed to understand the controls on long-term climate change and why the periodicity of glacial cycles has changed. Site selection activities are needed to identify the site for extraction of the oldest possible ice core. In addition, modifications that may be necessary for the DISC drill for oldest ice should be identified and planned. The oldest ice project should be conducted in collaboration with international partners.
- Ecosystems existing within and beneath ice sheets remain largely unexplored. Studies to initiate an inventory of intra-glacial and sub-glacial ecosystems, including investigations of the density, diversity, and physiological state of microbes in the ice and their relationships to past climate are needed. Development of clean technologies for shallow coring efforts and sideways drilling for easily accessible areas should be the near-term steps to foster new science in this arena.

2. **Ice Dynamics, Glacial History, and Geological Evolution**

Current observations of rapid response of glaciers and ice sheets to changing environmental conditions creates urgency to understand the processes of change in glaciers and ice sheets and the prior history embedded in the underlying land. The goal of ice dynamics, glacial history, and geological evolution research is to determine the properties of the ice, the nature of the ice-bed interface, and ice-ocean interactions, and evidence from the geological past entombed under the ice. This research involves drilling access holes through ice that range in depth from meters to kilometers. Priority activities are:

- Drilling through the ice to facilitate recovery of samples of old ice, bedrock and sediment samples should be supported. The last continental frontier, the Antarctic lithosphere, harbors evidence for science questions spanning a wide range of timescales, ranging from supercontinent assembly in the Mesoproterozoic (~ 1 Ga BP) to reconstructing extents of ice sheets during past interglacials, to present day subglacial conditions that affect ice sheet flow. This sub-ice frontier remains largely unsampled due to lack of rapid access drills. Rapid access to deep ice in Antarctica and Greenland will provide the first opportunity to systematically study spatial variability in deep ice, subglacial geology, and the interface between them.
- Priority should be given to developing methods to characterize spatial variations of the geothermal flux, which has strong control on determining whether a bed is melting or frozen. Basal melting/freezing also has implications for selecting sites for extracting old ice.
- Priority should also be given to studying ice-ocean interactions, critical to assessing ice-sheet stability and sea-level rise (Jenkins et al. 2010); the current projects on Whillans Ice Stream and Pine Island Glacier are first steps toward achieving this goal.
- Drilling of coastal ice domes should also be supported. Domes can be used as glaciological "dipsticks" to infer past histories of ice sheets (Conway et al. 1999; Waddington et al. 2005; Price et al. 2008). Information about past histories is needed to develop and validate models, necessary to assess possible responses to future environmental changes.

3. **Subglacial Environment**

Discovering ecological conditions within and under glaciers and ice sheets is a young science with challenging logistical and technological access issues. The priority activity for discoveries in the subglacial environment is:

- Continued support for developing methods and technologies for clean access and sampling of sub-glacial environments is needed to maintain stewardship while investigating these sensitive ecosystems. The current project on Whillans Ice Stream is a step toward achieving this goal.

Recommended Logistical principles

Drills and technologies needed to achieve some of the emerging science goals already exist, but some drills require repairs and updates. New drills and technologies are needed to achieve other science goals; the SAB recommends the following guiding principles for developing new drills and technologies:

- 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 factors need to be clearly defined at the initial stage of planning, and changes during the engineering design and fabrication process should be reassessed by the IDPO;
- Drills and accompanying technology for a specific project should be developed with consideration of potential use in possible future projects. They should be versatile and adaptable.

Recommended technology investments

The SAB identifies the following high-priority investments in drilling technology that are needed to achieve the planned science goals. The following are not prioritized:

- Maintain and extend the existing agile coring/drilling capabilities, including addition of clean, easily portable hand and shallow coring devices;
- Purchase/construct two bore-hole logging winches: first priority is a 1-km winch; second priority is a 4-km winch;
- Develop replicate coring capability; progress on this task is well underway for the WAIS Divide project;
- Purchase/construct a versatile intermediate-depth (1000-1500 m) ice coring drill. This project is now in the initial stages of planning;
- Design and 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 modular designs are preferable;
- Identify upgrades to the DISC drill that would allow it to be used in cold conditions in East Antarctica;
- 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.

Recommended human infrastructure investment

Funding agencies, including the U.S. National Science Foundation (NSF), must plan sustained investment in the education, training, and early career mentoring of the next generation of U.S. ice coring and drilling scientists and engineers in order to grow a capable, diverse, and internationally-engaged workforce who will make scientific discoveries in the coming decade that enables understanding of the earth systems and sustainability.

Introduction

This Long Range Science Plan was developed by the Ice Drilling Program Office (IDPO) and its Science Advisory Board (SAB), in consultation with the greater research community, to provide a blueprint for planning that will enable the National Science Foundation (NSF) and other funding agencies to plan budgets and logistics for science reliant on ice coring and drilling in the coming decade. The companion plan, the Long Range Drilling Technology Plan, developed by the Ice Drilling Design and Operations (IDDO) group in collaboration with the IDPO, provides details of the drills, technology, and drilling expertise that are needed to achieve the goals articulated in this Long Range Science Plan. Updated versions of both plans are produced annually in late spring and released in July.

One of the most pressing environmental issues of our time is that warming due to increasing atmospheric concentrations of greenhouse gases could trigger abrupt changes in climate and global sea level. To reduce the uncertainty of future climate and environmental projections, we need to understand the mechanisms of abrupt change and the nonlinear impacts that present rates of warming have on the cryosphere. Ice cores have provided unique and important paleoclimatic records, but these questions cannot be fully answered with existing ice cores; rather, arrays of cores from selected targeted sites are needed to assess environmental change on local, regional, and global scales.

Furthermore, it is well recognized that the beds of ice sheets and glaciers, and the ice-ocean interface under ice shelves exert strong control on ice dynamics; evaluating the controls from these basal conditions is crucial for predicting ice-sheet 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.

Glaciers and ice sheets are sensitive indicators of climate change. Detecting climate change from ice core records is a relatively new science that has evolved over the past fifty years. Since initial ice coring studies in Greenland, ice-coring science has evolved to include programs by many nations and hundreds of universities around the world (Bentley and Koci, 2007; Langway, 2008). 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). This discovery has revolutionized climate science and also has important impacts on policy; it contributed fundamental understanding that led to the 2007 award of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) for climate science.

Although important discoveries have already been made through ice cores, many basic questions about Earth's climate processes remain unanswered. For example, what are the linkages between the northern and southern hemispheres? What is the impact of humans on global climate? And how do atmosphere-ocean-ice interactions affect the cryosphere? Sites of high accumulation on glaciers and ice sheets contain high-resolution archives of past environmental conditions. An international meeting sponsored by the U.S. National Science Foundation in 2004 led to the formation of an international group to conduct joint science planning for future projects, the International Partnerships in Ice Core Sciences (IPICS - Brook and Wolff, 2006). The IPICS white papers described broad science targets for ice coring: 200-year, 2k-year arrays, 40k-year arrays, the last interglacial, and oldest ice (www.pages-igbp.org/ipics). The U.S. ice coring community was involved in establishing the IPICS goals, and so those goals are outlined below, together with additional endeavors that are primarily U.S. activities.

Most of our knowledge about subglacial environments comes from geophysical remote sensing and sparse data from access holes drilled to the bed, subglacial outflow, or from 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.

Members of the U.S. ice coring and drilling community have led the efforts for these and other important discoveries. U.S. scientific productivity, including both knowledge, and training of the next generation of scientists and engineers, critically depends on availability of funding and also on a mechanism to ensure continuity and international cooperation in ice coring and drilling, along with availability of appropriate drills, drilling expertise, and innovations in drilling technology. This Long Range Science Plan was established by the Ice Drilling Program Office (IDPO), working with its Science Advisory Board (SAB) together with the broader research community, to articulate the direction of U.S. ice coring and drilling science. This science direction provides the foundation and direction for developing the Ice Drilling Design and Operations (IDDO) Long Range Drilling Technology Plan for developing new drills and technology. These paired plans then provide a blueprint for the ice coring and drilling science community, which enables the community to plan well-coordinated proposals while allowing the National Science Foundation (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.

The science goals are interconnected, but for convenience they are described in four categories: 1) climate, 2) ice dynamics, glacial history, and geological evolution, 3) subglacial environment, and 4) ice as a scientific observatory. The four are described in more detail in the following sections. Science objectives within each category are accompanied by an outline of the science requirements for the associated drilling technology. Finally, science planning matrices are presented that show the envisioned timing of the field efforts and associated actions for the development of new drilling technology, so that the technology will be ready when needed by the science.

I. Climate

Earth's climate is a complicated system involving 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 white papers of the International Partnerships in Ice Core Sciences (IPICS) (Brook and Wolff, 2006), hence a number of the categories below reflect those themes.

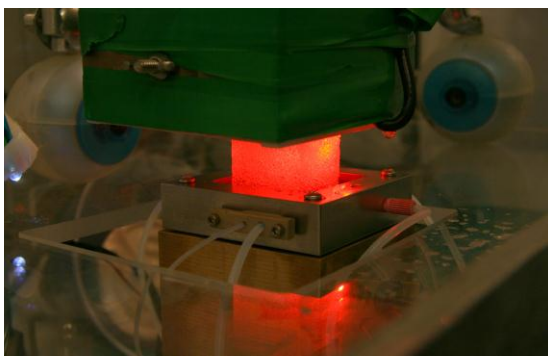
1. 200-year arrays

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:

1. Elucidate transfer functions between atmospheric chemistry and snow composition;
2. Determine relevant physical and chemical processes related to snow deposition and metamorphism, and their effects on atmospheric chemistry and gas preservation in ice cores;
3. 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;
4. Identify and model post-depositional changes in chemical and physical properties;
5. Produce detailed spatial maps of climate and environmental parameters (e.g., temperature, accumulation rate, chemistry);
6. Validate local, regional, and global atmospheric models and constrain the relationship between regional climate patters (AO, ENSO, Monsoons) and the Little Ice Age and Medieval Climate Anomaly;
7. 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;
8. Understand the air-snow exchange of aerosols and gases in alpine regions, and the processes influencing their preservation in ice core records;
9. Investigate the spatial patterns of anthropogenic impacts;
10. Develop regional records of biomass burning;
11. 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; and
12. 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.

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 should 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 to this inventory include a very lightweight 5 cm diameter "backpack drill" for alpine shallow coring, and also 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.



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 was higher 100 years ago, contrary to the expectation that pollution was at a peak in the 1960s and '70s. Credit: *Joseph McConnell, Desert Research Institute*

2. 2k arrays

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 2k-year ice core records (IPICS 2k arrays) 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 last 2k 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 2k-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 2k 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. 40k network

The past 40k 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 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 Holocene climate as well as the linkage between pre-industrial climate swings and human development is still a matter of debate. To understand these phenomena we need to resolve their spatial and temporal evolution. Ice cores are uniquely placed to provide the contrasting polar elements of climate in very high resolution as well as a suite of measurements (such as greenhouse gas concentrations). In addition, we need to understand the response of the Antarctic, Greenland, and other Arctic ice sheets to climate change. In particular, the contribution of the large ice sheets to the glacial/interglacial sea level change, and the temporal evolution over the last 40,000 years, are still matters of debate.

Under the auspices of IPICS, the international scientific community is developing plans for a network of ice cores covering the last 40k 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 40k 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.

response to very large-scale changes in climate conditions for an outburst of human societal development. The reason for this apparent constancy in

For this science it is important that IDPO/IDDO acquire for an intermediate depth coring drill, capable of drilling to 1,000 m or more with minimal logistics. 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. An intermediate depth drill that can reach 1,000 m would facilitate discoveries for the 40k array and also other ice coring goals.

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

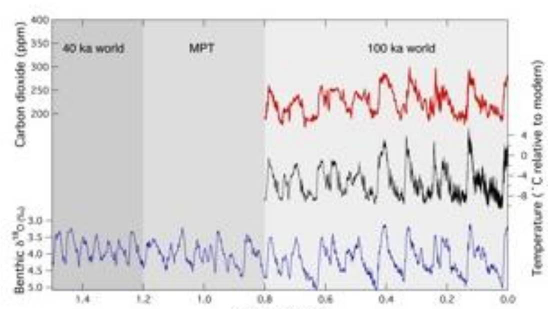
The last interglacial period (~130,000 to 110,000 years ago) was warmer than present due to differences in Earth’s orbital configuration, and can provide clues about how the Earth will behave as human activities continue to force global warming. Critical questions concern the possibility of tipping points of abrupt change in 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 (including possibly WAIS Divide) 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/yr. 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 is also considering replicate coring in Greenland.

5. Evidence from the ice sheet prior to 800k years

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 800k 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 reasonable to expect that ice older than 800k 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 1200-800 years ago from a world dominated by glacial-interglacial cycles lasting about 40k year to one with 100k year cycles. Numerous questions about this transition, and the earlier time period — including the role of greenhouse gases; the relationship between ice sheet behavior and climate; the relationship between long-term, late-Cenozoic cooling and climate cyclicity; and the persistence of abrupt climate change - could be addressed with ice core records extending back ~ 1.5 Ma.



The 100,000-year 'sawtooth' variability in carbon dioxide, methane, and temperature undergoes a change about 1200-800 years ago, with the amplitude of variation greater since 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 Severinghaus et al., 2010.

There are two complementary, but very different, ways of accessing ice older than 800 ka. 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 ka to save time and money and only recover the older ice. A second method is to exploit "blue ice" sites such as Taylor Glacier (Aciego et al., 2009) and Mt Moulton (Dunbar et al., 2008) where old ice may be outcropping at the surface. Continuous records may be difficult at such sites, but access is much easier. Different drilling requirements are needed for the two approaches. At a recent IPICS meeting (Corvallis, OR, 2009) these approaches were discussed, 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 (>1.5 Ma) 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 ice 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 discoveries if large volumes of ice can be made available. Changes in climate and environmental conditions are recorded in ice cores on a variety of time scales; the Dansgaard-Oeschger events of the last ice age are the best-known example. Many questions about the nature and origin of these events require access to very large samples of ice for measurements not possible in traditional ice cores, or to continuous samples to fully understand the dynamics of transitions.

Examples include the use of the ^{14}C concentration of trapped CH_4 to trace methane hydrate destabilization, and nano-diamonds, ^{3}He, and micrometeorites as tracers of extraterrestrial impacts.

Archives for addressing these issues include traditional drilling sites and blue ice sites, but specialized equipment is needed for sampling. 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. For blue ice sites, the new large-diameter blue ice drill mentioned above is required. Chainsaw-based quarrying tools such as those used at Mt Moulton and in marble quarries might also be considered.

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 a 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 2010-2011 field season. 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; more information on each type of drill is given in the IDDO Long Range Drilling Technology Plan.

Table 1. Requirements of drills for ice coring: Climate Research

	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	Manual	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	<40	none	-40	no	Helicopter	1-2 seasons	US/ maybe others
Rare isotopes, etc.	25	<40	none	-40	no	Helicopter	1-2 seasons	US

The IDDO Long Range Drilling Technology Plan discusses in detail a variety of drill systems, many of which exist and several that need to be developed in order to fulfill the science requirements articulated above. Appendix 1 of the Long Range Drilling Technology Plan matches specific drill systems with the respective science endeavors, while Appendix 2 gives the timing of development and field projects.

II. Ice Dynamics, Glacial History, and Geological Evolution

The observed rapid response of glaciers and ice sheets to changing environments depends not only on the nature of the forcing, but also on the properties of the ice, and in particular, the ice-bed interface. For example, fast-flowing ice streams and outlet glaciers have slippery beds; in cases where the bed is weak, 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 can be caused by changing ocean temperature, circulation, and/or sea level (Jenkins et al., 2010). Improved understanding of basal conditions, and ice/ocean interactions is critical to assessing responses of alpine glaciers, outlet glaciers and ice streams, and ice sheets to on-going environmental change.

Histories of ice dynamics (thinning and divide location) and climate (accumulation and temperature) can be extracted from observations from ice cores and boreholes near ice divides. Ice core and bore hole data — including depth-profiles of age, layer thickness, temperature, ice fabric, and bubble density all provide constraints for ice flow models. For example, the depth-age relationship contains information about past accumulation and past thinning; a thin annual layer at depth could imply either low accumulation in the past or ice sheet thinning (Waddington et al., 2005; Price et al, 2007). Radar-detected layers can also be used to infer the flow history of glaciers and ice sheets (Conway et al. 1999; Fahnestock et al. 2001), but the history contained in the layers is much richer if their age is known (Waddington et al, 2007). Radar-layers can be dated by tracking them to dated ice cores. Geologic evidence such as glacial trimlines and moraine limits also provide constraints on past thickness and extent of glaciers and ice sheets (Mercer, 1968, Denton et al, 1989). The constraints are much improved if methods such as radiocarbon dating or exposure-age dating can be used to date outcrops (Todd et al., 2010; Bentley et al., 2010; Stone et al., 2003; Hall et al, 2004). Determining ice thickness during past interglacials is more problematic, but extracting and dating samples from targeted locations beneath glaciers and ice sheets would provide information about the global distribution of ice during interglacial periods. The Antarctic lithosphere remains virtually unsampled except for rock outcroppings along the edges; developing rapid access capability for geologic coring under thick ice would enable discoveries from this last continental frontier.

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 and past conditions are needed to develop and validate such models. Remote sensing methods such as InSAR, seismic and radar sounding yield fundamental information, but these data need to be supplemented with observations from ice cores and boreholes. Specific observational data that are needed 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 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, 2001). In addition, measurements of spatial and temporal variations of basal pore pressure, slip, and sediments are needed for input into models.

Such measurements at the bed of glaciers and ice sheets are difficult, partly because of problems associated with accessing the bed, and also keeping boreholes open 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.

2. Remote sensing of basal conditions

Remote sensing techniques such as seismic imaging and radio echo sounding can complement the in-situ measurements of bed conditions and englacial properties. Such remote sensing techniques (in particular seismic imaging) require shallow holes for emplacing sources. The capability for producing large numbers of shallow holes (25-100m depth, 5-10cm 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. The Rapid Air Movement Drill is discussed in more detail 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-ice-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 is 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 (Anandankrishnan 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 for analyses of ice properties at depths of special interest; such a drill does not yet exist but should be considered.

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 (~1000m) cores to measure depth-profiles of age and temperature at targeted coastal domes are needed to help constrain the deglaciation of ice sheets.

Dated glacial trimlines and moraine limits also provide constraints on past thickness and extent of glaciers and ice sheets. Determining ice thickness during past interglacials is more problematic, but extracting and dating rock samples from targeted locations beneath glaciers and ice sheets would provide much needed data on the global distribution of ice during interglacial periods. Access boreholes to the ice sheet bed are required to recover short rock and sediment cores for these studies. Locations for such studies should be based on best estimates of bedrock geology, and plausible ice sheet extents.

7. Geological and tectonic history

The massive Antarctic ice sheet makes subsurface access difficult, hence the geological and tectonic history of Antarctica is far from fully known. The continent and its lithospheric plate play important but poorly understood roles in global tectonic architecture, leading to contradictory current impressions. 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. Drill holes through the ice into crustal rocks will allow 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.

Summary

Understanding present and past behaviors of glaciers and ice sheets is essential for predictions of changing sea level; improved understanding of ice dynamics require drills that create access holes of varying diameters into and through glaciers and ice sheets. If we are to improve the reliability of risk assessments of future behavior of ice sheets and their components, access holes are needed for measurements to increase understanding of: (i) physical conditions 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. Grounding zones may also be sites where discharge of microbial and geochemical weathering products that originated in upstream subglacial and englacial environments occurs. These systems are discussed in section III.2.

Studies of past responses of glaciers and ice sheets to climate and sea-level change offer clues to future possible responses. Specifically, depth profiles of age and temperature provide information about past extents of ice sheets and histories of deglaciation. Intermediate depth (~1000m) cores at targeted coastal domes are needed to help constrain the extent and timing of deglaciation. Determining ice thickness during past interglacials is more problematic. Extracting and dating rock samples from targeted locations beneath glaciers and ice sheets would provide much needed information about the global distribution of ice during interglacial periods; access boreholes to the bed are required to recover short rock and sediment cores for these studies.

Table 2 lists characteristics for drills needed for studies of ice dynamics, glacial history, and geological evolution. The IDDO Long Range Drilling Technology Plan discusses some of the existing drills capable of making holes in ice sheets. However new drills capable of rapid deep access to the dry bed, and hot water drills suitable for access holes through ice shelves and ice streams are essential to advance the ice dynamics science goals.

Table 2. Requirements of drills for Ice Dynamics, Glacial History, and Geological Evolution Research

	Diam. (cm)	Ice Depth (m)	Core or hole	Ambient temp (C)	Clean access?	Transport type	Site occupancy	Int'l Aspects
Bed conditions	8	1-4k	Hole	-50	maybe	twin otter/ lt traverse/ Herc*/trav*	<4 weeks	US & others
Geothermal flux	5-8	1-4k	Hole	-50	no	Twin otter/ lt traverse/ Herc*/trav*	<4 weeks	US & others
Geologic coring	8-10	1-4k	Ice hole Rock core	-50	no	Herc/ traverse	4-8 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
Paleo-topography	6-10	1k	Hole + rock core	-40	no	Herc/ traverse	<4 weeks	US
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

* Depending on depth of hole

III. Sub-ice Environment

Subglacial environments are the interfaces between ice, subglacial water, basal sediments, and bedrock. This complex system provides habitat for life, records historical environmental conditions in subglacial sediments, and may contain an unaccounted reservoir of carbon and nutrients. Liquid water is known to exist below the Greenland and Antarctic ice sheets as well as temperate glaciers. Important questions remain about the role of subglacial hydrology in ice sheet stability and microbial dynamics. To understand these pristine systems, environmentally acceptable ways of accessing the sub-ice environment must be developed (NRC, 2007).

1. Subglacial basins: sedimentary record

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. New deep geological cores are being collected near the ice sheet margin by the Antarctic Drilling Project (ANDRILL) and Shallow Drilling on the Antarctic Continental Margin (SHALDRIL) programs. Interior subglacial basins also likely contain proxy records of paleoclimate and ice sheet history to complement these records from the continental margins. Three main categories of sedimentary targets are: subglacial lakes, West Antarctic rift basins, and East Antarctica epeirogenic basins. Each category may have a variety of origins and histories because of differing locations relative to the ice sheet margin and magnitudes of ice sheet fluctuations. Thus, they may provide valuable archives of past ice sheet and climatic 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 epeirogenic 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.

Access holes are required to recover longer sedimentary rock cores comparable to those from the continental margins. 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 guidelines are an important consideration when accessing any subglacial systems.

2. 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 of thermodynamics and substrate availability, rates of evolution, and constraints on biodiversity. Microbial cells and their genomic material should also provide valuable information that can be linked to paleoclimatic change; such life forms may be the only biological survivors in areas covered by glaciations for millions of years. Icy systems on Earth also may provide crucial terrestrial analogs for extraterrestrial life surviving and persisting on icy planetary bodies in our solar system, such as Mars, Europa, or Ganymede.

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, or 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 melt water 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 wise to conduct studies first at sites where the ice is not thick and logistics issues can be readily addressed. Subglacial access through ice two or more miles thick presents tremendous logistical and environmental challenges. The subglacial lake beneath South Pole is a potential target that may be enabled by use of the existing camp at South Pole and possible adaptation of the hot water drill used for the former IceCube project. The cost of such a venture and solution of logistical and environmental issues are well beyond the scope of drilling projects identified in the accompanying Ice Drilling Design and Operations Long Range Drilling Technology Plan, and so is not included in future planning in that document. However, the possible South Pole target was identified by U.S. scientists at the 2011 IDPO Ice Drilling Science Community Workshop.

3. Subglacial lakes and hydrological systems

Subglacial hydrology has been of interest to glacial geologists and glaciologists ever since eskers were recognized as being sediment accumulations from subglacial fluvial conduits. Measurements to quantify current subglacial hydrological systems are important for understanding ice dynamics, weathering and erosion of subglacial rock, sediment transport and jokulhlaup events, microbial ecosystems, and maintaining systems of subglacial lakes. Transfer of significant volumes of water and sediment occurs through these systems. Due to the difficulties of access, subglacial hydrological systems have not been well characterized, and the lack of quantitative data hampers the development of realistic models of ice dynamics.

About 150 subglacial lakes have already been discovered in Antarctica. Of particular importance are studies focusing on spatial variability of life in subglacial lakes, the degree of hydrological interconnectivity between individual lakes, and their influence on the rest of the subglacial hydrological system, as well as the links between lakes and the Southern Ocean. These lakes also appear to house important sediment libraries of ice sheet and geological histories and climate change.

Summary

Evidence now exists for significant wet environments below ice sheets and glaciers. Accessing these wet environments requires clean access, especially if microbes and their habitats are of interest. Subglacial environments contain biologic, climatic, geologic, and glaciologic materials and information, muc of which cannot be obtained anywhere else. Drills to create access holes are needed to sample basal ice, subglacial water, and sediments at selected sites over deep subglacial lakes and other areas of hydrological interest. Hole diameter requirements vary depending on instrumentation needed; clean technology is required, with strict environmental review, and the hole may need to be maintained open for days. Differential ice motion may also be a factor. A conceptual design is needed for a drill that can provide clean access holes that are large enough to deploy subglacial rovers; this design should strive to keep supporting logistical requirements to a reasonably low level.

Access to the complex subglacial environment requires not only a variety of coring and drilling technologies, but in addition the restriction that the drilling must be conducted in a clean, environmentally responsible manner (NRC, 2007). Table 3 below 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 in more detail.

Table 3. Requirements of drills for Sub-Ice Environment Research

	Diam. (cm)	Depth (m)	Core or hole	Ambient temp (C)	Transport type	Site occupancy	Int'l aspects	Environ restrictions
Sediments	10-15	1-3k	Hole	-50	Herc/ traverse	weeks	SIeGE/SCAR	Clean access
Biogeochem	3-25	<4k	Hole	-50	Herc/ traverse	weeks	SALE	Clean access
Geology/ Tectonics wet condtns	15	<4k	Hole	-50	Herc/ traverse	weeks	SIeGE/ ANDRILL	Clean access
Subglacial lake biogeochem	50-100	3-4k	Hole	-50	Herc/ traverse	4-8 weeks	SALE	Clean access

The IDDO Long Range Drilling Technology Plan shows (Appendix 1) the 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, and would need conceptual and engineering development.

IV. Ice as a Scientific Observatory

The polar ice sheets and mid-latitude ice caps archive evidence of past climate 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 paleoclimate and glaciology

Unique geophysical studies employ sensors lowered into boreholes, either fast-access holes or well-maintained boreholes originally drilled for retrieval of ice cores. These analyses are difficult or impossible to obtain by other methods, and complement studies of ice cores and remote sensing data. Unlike core sampling, 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, and methods for repairing several key deep boreholes need to be developed.

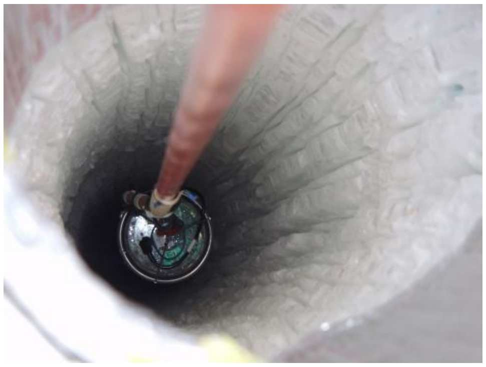
Borehole paleothermometry probes provide the most direct measurement of ancient temperatures and can be used to calibrate other paleoclimatic indicators. Optical borehole probes achieve stratigraphic records, which are far more detailed than can be reconstructed from core measurements. Borehole sonic loggers can provide continuous records of ice fabric that is 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.

In the next few years, IDPO should seek to acquire winches for community use to enable future borehole logging. The logging community envisions having at least two winches available for both intermediate (1 km) and deep (4 km) applications, or a winch system that can be configured as needed for a particular project. After the 2011-12 season, IDPO anticipates acquiring the IceCube logging winch, which has approximately 2700 meters of 4-conductor logging cable. While some probes require 4-conductor telemetry, other digital tools can make do with lighter coaxial logging cable.

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.

The recently completed Ice Cube telescope uses the ice at South Pole for detection of 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, developed for the IceCube project, is an extremely powerful 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 are being constructed or proposed which would be installed within IceCube, in order to use the detector as a veto or shield. Experiments embedded within the IceCube instrumented volume could compete with those situated in underground mines that look for dark matter, neutrino oscillations, supernovae, proton decay and neutrino beams from accelerators. 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 (5m) spacing.

Experiments to detect extremely high-energy neutrinos will make use of very large volumes of polar ice. The ARA experiment (Askaryan Radio Array), in early development at South Pole, plans to instrument of order 100 km3 of ice with radio antennas to detect radio pulses from so-called GZK-scale neutrinos. ARA will require holes at least 150 meters deep and 15 cm in diameter, with approximately 100 m spacing over 5 km2. Preliminary tests in the 2010-11 season indicate that, due to air loss in the firn, existing RAM (Rapid Air Movement) drilling may not be sufficient for ARA. A mini-hot-water drill will be used 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 the world-class research station located at the site, along with a wealth of existing data from shallow cores, snow pits, IceCube hot-water boreholes and meteorological observations. Such a core would also greatly 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 for calibration devices for various experiments.

4. Seismic studies

The Global Seismographic Network includes seismic monitoring stations for earthquakes and other events around the world, including on ice sheets. The ice sheets serve as extremely quiet platforms for seismic monitoring. The South Pole Remote Earth Science and Seismological Observatory has seismic equipment installed approximately 300 m deep in boreholes. Similar observations will occur in boreholes on the Greenland Ice Sheet.

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 old snow, called 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 platforms 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. Versatile winches for intermediate (1 km) and deep (4 km) applications will need to be acquired in order to enable future borehole logging. 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. 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 forecasting the accompanying logistical and funding requirements. For each area described above, the associated matrices shown below identify the current plans for the timing of the field research. In cases where new drilling technology is needed, the steps are identified for development that is needed leading up to deployment of the drills.

In the Climate matrix (Table 4) below, it is possible that drilling at the WAIS Divide site may encounter delays should the shelter over the DISC drill require major maintenance. It is not possible to accurately forecast this situation; updated planning will occur over time as the situation evolves.

Planning for U.S. drilling as part of the Climate 40k networks is a topic of current ice coring community discussion. Strong cases are being made to drill both at South Pole and Hercules Dome, and members of the research community have proposed that the drilling will occur first at South Pole.

In the Planning Matrices below, black lettering in the matrix indicates projects that are funded, and blue lettering indicates projects that are in the planning phase. The letters denoting specific drills are: b: badger-eclipse; 4: 4-inch drill; D: DISC drill; N: NZ drill; H: Hans-Tausen drill; B: blue ice drill; L: borehole logging; I: intermediate drill.

Table 4: Climate Planning Matrix

	2011				2012				2013				2014				2015				2016				2017				2018				2019				2020				2021			
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			x	x			x	x																									
Antarctic	x	x	x	x	x			x	x			x	x																															
Temperate glaciers						x	x			x	x			x	x				x	x																								
2k array																																												
Arctic		x	x			x	x																																					
Antarctic																																												
Temperate glaciers		x	x			x	x																																					
40k Network																																												
40k-WAIS Divide																																												
Drill main core at WAIS-D	D																																											
Borehole logging at WAIS				L				L				L				L	L																											
Replicate coring (RC) at WAIS-D																																												
RC engineering	x	x																																										
RC prototype & lab tests	x	x																																										
RC fabrication	x	x	x																																									
RC field test at WAIS					D																																							
Drill replicate cores at WAIS-D								D	D																																			
Acquisition planning -intermediate drill																																												
establish science requirements	x	x																																										
int drill feasibility & cost estimate	x	x	x	x																																								
int drill detailed design					x	x	x																																					
int drill fabrication							x	x	x	x	x	x	x																															
int drill field test														x																														
int drill prep for deployment															x																													
Acquisition planning -new drilling fluid																																												
Establish science requirements				x	x																																							
Identify new drilling fluid					x	x	x	x	x																																			
40k - South Pole																																												
Intermediate drill coring																I	I																											
40k - Herc Dome																																												
Intermediate drill coring																				I	I																							
High-res records of last interglacial																																												
NEEM																																												
Danish H-T drill																																												
borehole logging		L				L																																						
Evidence from ice prior to 800k years																																												
Blue ice - Taylor glacier																																												
Blue Ice drill design & fabrication		B	B																																									
Blue Ice drill coring	B			B	B																																							
IPICS oldest ice																																												
Plan DISC mods for cold conditions						x	x																																					
Modify DISC for cold conditions												x	x																															
Acquisition planning-Rapid Access Ice Drill																																												
Establish science requirements RAID		x	x	x	x																																							
Conceptual design RAID						x	x																																					
Seek funding for RAID						x	x	x	x	x	x																																	
Detailed design RAID								x	x	x	x	x																																
Drill fabrication RAID											x	x	x	x	x	x	x																											
Field test RAID																		x	x																									
Final changes & shipment to Antarctica																				x	x	x																						
Borehole studies for site selection																								x	x			x	x			x	x											
Drilling for oldest ice																																				D	D			D	D			

Table 5: Ice Dynamics and History Planning Matrix

	2011				2012				2013				2014				2015				2016				2017				2018				2019				2020				2021			
Ice Dynamics, Glacial History, & Geological E volution	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 winch			x	x		x	x	x	x																																			
Acquisition planning - hot water drills	x	x	x	x	x	x	x	x	x	x	x	x	x																															
Basal conditions & geothermal flux																								x	x			x	x			x	x											
Seismic-acoustic basal condtn detection	x			x	x			x	x			x	x																															
Sub-ice shelf mass balance								x	x			x	x																															
WISSARD																																												
Grounding zone processes																																												
WISSARD								x	x			x	x																															
Rheological properties of ice																								x	x			x	x			x	x											
Glacial history																								x	x			x	x			x	x											
Conditions at the ice sheet bed																								x	x			x	x			x	x											
Subglacial rock coring																								x	x																			

While the ice dynamics community has identified a number of important science topics to pursue, progress in planning field endeavors in many areas is held back by the lack of a rapid-access drill that is logistically acceptable for work in the deep field. The possible development of a rapid access drill identified in the Climate planning matrix will enable many more scientific investigations in Ice Dynamics, Glacial History, and Geological Evolution, and the blue crosses in years 216 and beyond of Table 5 indicate science that may be pursued in the resulting boreholes.

Table 6: Sub-ice Environment Planning Matrix

	2011				2012				2013				2014				2015				2016				2017				2018				2019				2020				2021			
	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
Sub-Ice Environment																																												
Acquisition planning - hot water access drills	x	x	x	x	x	x	x	x	x	x	x																																	
Sedimentary record																																												
Microbial ecosystems & biogeochem																																												
WISSARD								x	x			x	x																															
Geologic& tectonic history																																												
Subglacial lakes & hydrology																																												
Ross Ice shelf acoustic tomography												x	x																															
South Pole Subglacial Lake Exploration																																												
Site reconnaissance & prep												x	x																															
Drilling & measurements at S Pole																x	x																											

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 IDDO drilling activities.

Table 7: Ice as a Scientific Observatory Planning Matrix

	2011				2012				2013				2014				2015				2016				2017				2018				2019				2020				2021			
	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				x	x			x	x			x	x																															
Siple Dome borehole logging												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																								
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
Firn archive of past atmospheric composition																																												

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 (5m) 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 in diameter, with approximately 100 m spacing over 5 km2. Tests in the 2010-11 season indicate that, due to air loss in the firn, existing RAM (Rapid Air Movement) drilling will likely not be sufficient for ARA, and a mini-hot-water drill will be used for ARA pilot studies.

Associated Logistical Challenges

In addition to planning the science and the associated drilling technology, there are non-scientific challenges that may impact the timing of the field endeavors. The following paragraphs present potential limitations on the amount of field science that can be done to address urgent issues of climate and environment. Challenges associated with ice coring and drilling science include:

(1) Drilling ice cores deeper than approximately 300 m necessitates use of a drilling fluid mixture that has a density similar to ice to prevent borehole closure. In addition, the fluid mixture must 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 at the NEEM coring site in Greenland satisfies the criteria for sites of moderate temperature, but its properties are not favorable for drilling in the very cold conditions encountered in East Antarctica. IDPO/IDDO investigations may begin in FY2012, as discussed further in the Long Range Drilling Technology Plan.

(2) There is limited air logistics access to sites on the Greenland and Antarctic ice sheets. With multiple science communities requesting flights, time at the field site must be carefully planned and established to optimize scientific productivity. Currently the surface infrastructure supporting the DISC drill at the WAIS Divide site is nearing the end of its lifetime and may need extensive repair in the coming several years. The process of conducting field science and ice core drilling while also attempting to minimize logistical requirements requires constant vigilance and planning. IDPO and will continue to work with the research community, NSF, and the support contractors for possible changes in schedule, should the need arise, to enable the science to be achieved in a fiscally 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. Recently some infrastructure upgrades were performed and replacement of a critical failure point is scheduled for this year. While these infrastructure improvements are helpful, NICL is an aging facility that will soon reach its full capacity. Expanding the ice core storage facility will require a major NSF investment in infrastructure.

(4) The community desires to maintain key boreholes as long-term observatories, to facilitate discoveries by both existing and new logging applications. GISP2 remains one of the most influential and widely cited records in paleoclimatology. Recently, differential GPS indicated 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 the boreholes at Siple Dome and Taylor Dome. Planning and evaluation will need to occur in order to identify a strategy for repair and maintenance of all major (deep core) boreholes. Action on this item is urgent yet there is not funding to address this issue. As discussed in the IDDO Long Range Drilling Technology Plan, pending availability of funding, borehole repair could begin in 2012.

Conclusion and Recommendations

Glaciers and ice sheets are sensitive indicators of climate, and they contain an important archive of past environmental change. In addition, they are central to the determination of future sea-level. Ice coring and geophysical probing of glaciers and ice sheets are technically and logistically challenging endeavors requiring significant advance planning. In the development of this Long Range Science Plan, the members of IDPO and the IDPO Science Advisory Board (SAB) have interacted with the broader research community to articulate science targets and associated ice drilling technologies (which are further detailed in the companion Ice Drilling Design and Operations Long Range Drilling Technology Plan) that are needed to enable discoveries. This community-based Long Range Science Plan facilitates discussion between the research community and funding agencies, and establishes the need for specific drills and technologies to achieve the proposed science goals. The IDPO Science Advisory Board recommends the following science targets, logistical principles, drilling technologies, and human infrastructure investments for the coming years, and urges funding agencies to plan accordingly.

Recommended science goals

1. Climate

Current climate change can only be fully understood in the context of the past; the goal of this climate science is to develop well-dated histories of climate and atmospheric composition over a wide range of time scales, with a goal of understanding climate forcing and response. This involves recovery of ice cores and arrays of ice cores with time scales of hundreds to hundreds of thousands of years. These efforts represent both U.S.-initiated endeavors as well as US contributions toward the international IPICS science goals. Priority activities include:

- The WAIS Divide ice core will be the highest-resolution climate record from Antarctica. Borehole logging at this site should commence and be completed. If results from borehole logging indicate additional drilling is acceptable, drilling to the maximum depth should be completed. Subsequent replicate coring and borehole logging should be conducted in a way that optimizes the science, while minimizing the logistical costs required for maintaining the infrastructure at WAIS Divide. Such measurements are essential to fully exploit the histories of climate and ice dynamics that are preserved in the core and bore hole at WAIS Divide.
- Ice coring and drilling to support investigations of climate and atmosphere over recent centuries and ice core networks including 200 year investigations and the IPICS 2k year and 40k year array initiatives should continue. The density of 200 to 2,000 year ice core arrays should be increased around the globe to constrain late Holocene regional climate variability and forcing mechanisms. Cores from sites such as South Pole and Hercules Dome have potential to contribute to the 40k array. Data from these cores are needed to understand spatial and temporal variations of climate over different time scales.
- Understanding glaciological and climate conditions during the last interglacial is key to predicting the response of glaciers and ice sheets to future possible environmental changes. Efforts to extract an undisturbed record of the last interglacial should be supported. In addition to traditional deep ice cores, cores from blue ice regions at the margins of ice sheets have potential for such records.
- Studies of ancient ice are needed to understand the controls on long-term climate change and why the periodicity of glacial cycles has changed. Site selection activities are needed to identify the site for extraction of the oldest possible ice core. In addition, modifications that may be

necessary for the DISC drill for oldest ice should be identified and planned. The oldest ice project should be conducted in collaboration with international partners.

- Ecosystems existing within and beneath ice sheets remain largely unexplored. Studies to initiate an inventory of intra-glacial and sub-glacial ecosystems, including investigations of the density, diversity, and physiological state of microbes in the ice and their relationships to past climate are needed. Development of clean technologies for shallow coring efforts and sideways drilling for easily accessible areas should be the near-term steps to foster new science in this arena.

2. Ice Dynamics, Glacial History, and Geological Evolution

Current observations of rapid response of glaciers and ice sheets to changing environmental conditions creates urgency to understand the processes of change in glaciers and ice sheets and the prior history embedded in the underlying land. The goal of ice dynamics, glacial history, and geological evolution research is to determine the properties of the ice, the nature of the ice-bed interface, and ice-ocean interactions, and evidence from the geological past entombed under the ice. This research involves drilling access holes through ice that range in depth from meters to kilometers. Priority activities are:

- Drilling through the ice to facilitate recovery of samples of old ice, bedrock and sediment samples should be supported. The last continental frontier, the Antarctic lithosphere, harbors evidence for science questions spanning a wide range of timescales, ranging from supercontinent assembly in the Mesoproterozoic (~ 1 Ga BP) to reconstructing extents of ice sheets during past interglacials, to present day subglacial conditions that affect ice sheet flow. This sub-ice frontier remains largely unsampled due to lack of rapid access drills. Rapid access to deep ice in Antarctica and Greenland will provide the first opportunity to systematically study spatial variability in deep ice, subglacial geology, and the interface between them.
- Priority should be given to developing methods to characterize spatial variations of the geothermal flux, which has strong control on determining whether a bed is melting or frozen. Basal melting/freezing also has implications for selecting sites for extracting old ice.
- Priority should also be given to studying ice-ocean interactions, critical to assessing ice-sheet stability and sea-level rise (Jenkins et al. 2010); the current projects on Whillans Ice Stream and Pine Island Glacier are first steps toward achieving this goal.
- Drilling of coastal ice domes should also be supported. Domes can be used as glaciological "dipsticks" to infer past histories of ice sheets (Conway et al. 1999; Waddington et al. 2005; Price et al. 2008). Information about past histories is needed to develop and validate models, necessary to assess possible responses to future environmental changes.

3. Subglacial Environment

Discovering ecological conditions within and under glaciers and ice sheets is a young science with challenging logistical and technological access issues. The priority activity for discoveries in the subglacial environment is:

- Continued support for developing methods and technologies for clean access and sampling of sub-glacial environments is needed to maintain stewardship while investigating these sensitive ecosystems. The current project on Whillans Ice Stream is a step toward achieving this goal.

Recommended Logistical principles

Drills and technologies needed to achieve some of the emerging science goals already exist, but some drills require repairs and updates. New drills and technologies are needed to achieve other science goals; the SAB recommends the following guiding principles for developing new drills and technologies:

- 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 factors need to be clearly defined at the initial stage of planning, and changes during the engineering design and fabrication process should be reassessed by the IDPO;
- Drills and accompanying technology for a specific project should be developed with consideration of potential use in possible future projects. They should be versatile and adaptable.

Recommended technology investments

The SAB identifies the following high-priority investments in drilling technology that are needed to achieve the planned science goals. The following are not prioritized:

- Maintain and extend the existing agile coring/drilling capabilities, including addition of clean, easily portable hand and shallow coring devices;
- Purchase/construct two bore-hole logging winches: first priority is a 1-km winch; second priority is a 4-km winch;
- Develop replicate coring capability; progress on this task is well underway for the WAIS Divide project;
- Purchase/construct a versatile intermediate-depth (1000-1500 m) ice coring drill. This project is now in the initial stages of planning;
- Design and 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 modular designs are preferable;
- Identify upgrades to the DISC drill that would allow it to be used in cold conditions in East Antarctica;
- 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.

Recommended human infrastructure investment

Funding agencies, including the U.S. National Science Foundation (NSF), must plan sustained investment in the education, training, and early career mentoring of the next generation of U.S. ice coring and drilling scientists and engineers in order to grow a capable, diverse, and internationally-engaged workforce who will make scientific discoveries in the coming decade that enables understanding of the earth systems and sustainability.

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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