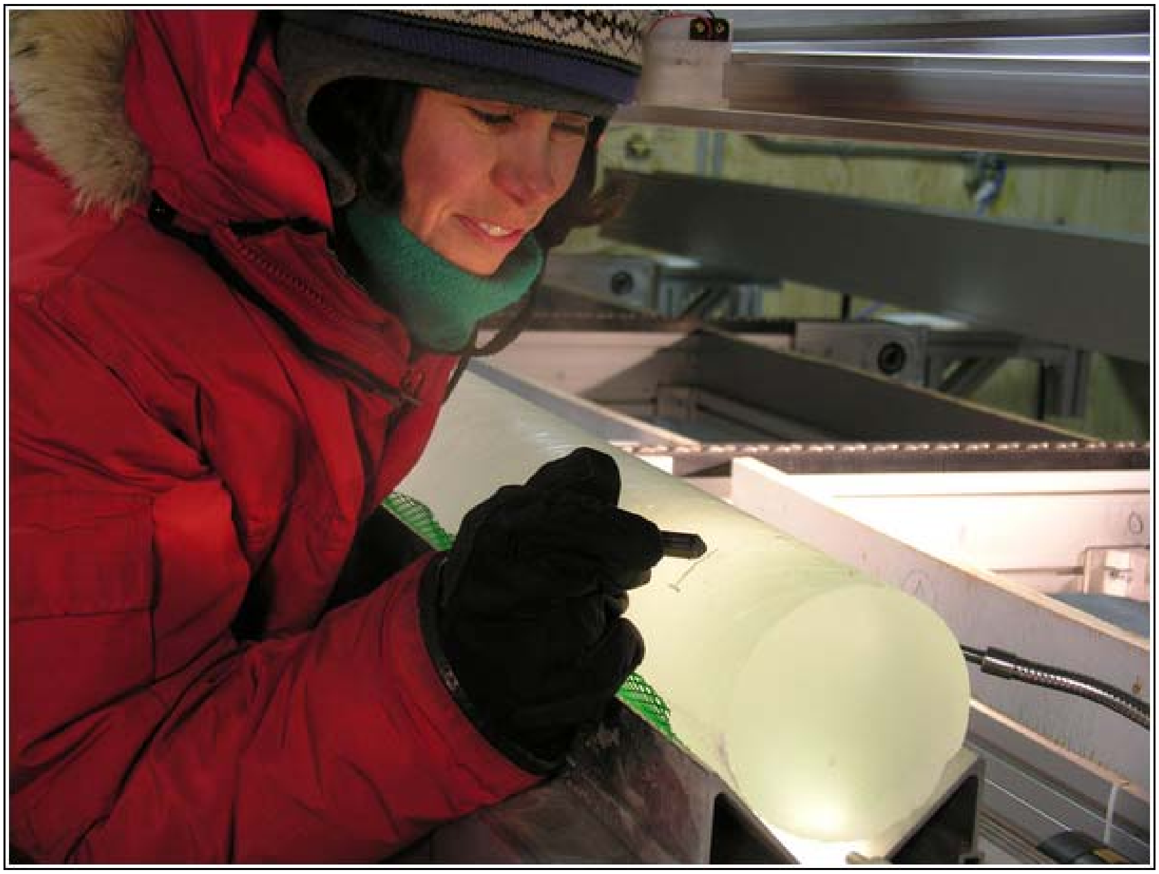
U.S. Ice Coring and Drilling Research Community

# Five-Year Science Plan



Prepared by Ice Drilling Program Office in collaboration with its Senior Advisory Board and with input from members of the research community

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Cover photo: Rebecca Anderson, scientist at the Desert Research Institute, examines an ice core section. Credit: *Photo courtesy of Kendrick Taylor (DRI, 2008)*

## Introduction

One of the most pressing environmental issues of our time is the potential that greenhouse gas warming may trigger abrupt climate change. In order to predict the future with confidence, we need to understand the mechanisms of abrupt climate change and the nonlinear impacts that current warming may have on the cryosphere. Furthermore, the beds of ice sheets and glaciers, and ice-ocean interface under ice shelves, are well recognized as being critical boundaries for ice dynamics, so evaluating conditions there is crucial to being able to predict ice sheet behavior during future warming scenarios. These subglacial environments are also of interest to the biological community in learning more about the ecosystems of these unique and extreme environments.

Past changes are recorded with unparalleled evidence in and under the polar ice sheets and temperate glaciers. Detecting climate change from ice core records is a relatively new science that has evolved over the past fifty years. 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 (e.g. NRC, 2002). This discovery has revolutionized climate science and also has important impacts on policy; it established some of the key groundwork leading to the 2007 award of the Nobel Peace Prize to the IPCC for climate science.

Sub-ice environments are notoriously difficult to access. At this point, most of our knowledge about subglacial systems derives from geophysical remote sensing with isolated local data from access holes to the bed or sub-ice-shelf cavities. However, rigorous inferences about these systems require broader and more detailed data sets, better coverage of different conditions of the systems, and quantitative analyses especially for testing ice sheet models. These unknowns about ice dynamical responses to warming led the IPCC in their 2007 report, to place lower bounding limits on predictions of future sea level rise rather than being more definitive, and they urged the need for more data collection.

Over the past decade or so, scientists have further recognized the complexity of subglacial environments relative to the microbial ecosystems they host. In this regard, there is intense scientific and public interest in the large subglacial lakes that are being documented, especially below the Antarctic Ice Sheet. Data from such systems broaden our understanding of the phylogenetic and physiological nature of subsurface microorganisms that exist under dark and cold conditions on earth, and also inform predictions used in exploration for extra-terrestrial life.

Members of the U.S. ice coring and drilling community have led the efforts for these and a multitude of other important findings. U.S. scientific productivity, including both knowledge generation and creation of the next generation of scientists, critically depends upon a mechanism for ensuring continuity and international cooperation in ice coring and ice drilling efforts, along with availability of appropriate drills, drilling expertise, and innovations in drilling technology. This five-year science plan was established by the Ice Drilling Program Office (IDPO), working with its Senior Advisory Board and with the broader research community, in order to articulate the direction of U.S. ice coring and drilling science, and to provide the foundation upon which the Ice Drilling Program Office –Ice Drilling Design and Operations (IDPO-IDDO) five-year drilling technology plan can be developed to establish the drills and technology needed to advance the science. This plan, developed in spring of 2009, was posted to the web and list-serve invitations for comments and suggestions were widely distributed. Community input was incorporated. This plan is a living document, and will be updated at least yearly according to input from the science community.

The science can be described in three categories: climate, ice-flow history and response, and subglacial environment and habitat. The three are described in more detail in the following sections. Science objectives within each category are accompanied by an outline of the science requirements of the associated drilling technology.

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# *I. Climate*

**1. ~ 200 yr arrays**

The broad goal of a 200-year array of ice core records is to establish how the recent atmospheric environment is represented 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. Through a combination of over-snow science traverses and coordinated individual site efforts, an extensive array of relatively easy to recover ice core records is planned 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 7) investigate the spatial pattern of anthropogenic impacts. Several of these objectives are critical for interpreting longer timescale records detailed in following sections. Studies of these types are often conducted by individuals and small groups on the Greenland and Antarctic ice sheets as well as on temperate glaciers.

Science requirements for drilling the 200-year array:

- Core/hole diameter: 2-4”
- Depth: up to 400 m
- Drill fluid: none; thermal drilling may be required at some locations
- Site considerations: ambient temperature down to -50 $^{o}$C, minimum time site occupancy
- Transportability: helicopter/Twin Otter, light traverse, human/animal
- International aspects: linked science traverses, coordinated site arrays

**2. 2k arrays**

The time period of the last two millennia is an important focus because it is long enough to allow investigation of climate variability on annual to centennial timescales, yet short enough that relevant climate boundary conditions have not changed appreciably. Existing quantitative reconstructions of the past millennium continue to be debated, in part due to a lack of annual data prior to 1600 AD in many areas and the highly regional nature of many climate processes. A coordinated international effort to recover a spatial array of annually resolved and calibrated 2000 year ice core records has several primary objectives, including: 1) establishing the extent and regional expression of the so-called “Little Ice Age” and “Medieval Warm Period” phenomena; 2) evaluating 20$^{th}$ century warming in the context of the last 2000 years; 3) establishing spatial and temporal patterns of temperature, precipitation, and sea ice extent; 4) quantifying spatial and temporal patterns of important climate forcing mechanisms that are regionally variable (e.g., sulfate, terrestrial dust, black carbon aerosols), and the record of solar variability; and 5) assessing the relative roles of anthropogenic and natural forcing on climate evolution prior to and into the industrial period.

Science requirements for drilling the 2k array:
- Core/hole diameter: 3-4”
- Depth: up to 500-1000 m
- Drill fluid: possibly needed at high accumulation sites; thermal drilling may be required at some locations
- Site considerations: ambient temperature down to -50 $^{o}$C, minimum site time occupancy
- Transportability: Twin Otter, helicopter, light traverse
- International aspects: linked science traverses, coordinated site arrays, possible international standardization on intermediate drill, core diameter, etc.

**3. 40k network**
The past 40,000 years include the glacial/interglacial transition, our present warm period, the Holocene, as well as a sequence of abrupt swings in climate as recorded in Greenland ice cores and other climate archives. The glacial-interglacial transition is the best-documented global response to very large-scale changes in climate boundary conditions, and the earlier abrupt changes are the best examples of this enigmatic process. The Holocene was one of the most stable climatic periods, potentially providing the conditions for an outburst of human societal development. The reason for this apparent constancy in Holocene climate as well as the linkage between pre-industrial climate swings and human development is still a matter of debate. To understand these phenomena we need to understand their spatial and temporal evolution better. Ice cores are uniquely placed to provide the contrasting polar elements of climate in very high resolution and provide a suite of measurements (such as greenhouse gases) only available from ice cores. In addition, we need to understand the response of the Antarctic, Greenland and 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 a matter of debate.

Under the auspices of IPICS (International Partnerships in Ice Core Sciences) the international scientific community is developing plans for a network of ice cores covering the last 40,000 years. The specific U.S. contribution to this network (in addition to the WAIS Divide core) has yet to be determined, but is likely to include one or more new ice cores in Antarctica – sites that have been discussed so far include Taylor Dome, Roosevelt Island, Hercules Dome, and South Pole, with the most discussion to date focused on South Pole. The IPICS 40 ka drilling projects may vary in scope and logistical needs, but many are envisioned to be drilling campaigns conducted in one or two seasons with a minimal logistics burden. 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 cores can provide material for a variety of future projects depending on interest and resources.

Science requirements for drilling 40 ka projects:

- Core/hole diameter: minimum of 4”, which is sufficient for the main objectives. In some cases a larger core may be needed if the project is to be highly comprehensive.
- Flexibility to match drill with logistics constraints and science requirements (for example multiple winch sizes to optimize logistics burden).
- Depth: 1,000 m up to 3,000m.
- Recovery of high-quality core.
- Drill fluid: existing acceptable fluids should work.
- Site considerations: ambient as cold as -50˚C, possible multiple seasons in some cases.
- Transportability and logistics: Ideally deployed without need for Hercules (Twin-Otter, Basler), some projects may be larger. Potential to drill an intermediate depth core in one season.
- International aspects: Some sites may involve core sharing, other sites may be national efforts tied to part of the international spatial array. Standardization of equipment and borehole size may be desired.

**4. High-resolution records of 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. Existing ice core records of the last interglacial are almost all from low accumulation sites in Antarctica. 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. The NEEM ice core in Greenland, one of the original IPICS objectives, is now underway, and will hopefully provide an excellent northern hemisphere record of the last interglacial. Within IPICS, discussions about additional records of the last interglacial are just beginning. Likely targets are relatively high accumulation sites in Antarctica where last interglacial ice is likely to be preserved, and possible new sites in Greenland.

Drilling sites are likely to be deep locations in Antarctica where accumulation is moderate, on order 10 cm/yr. A recent European core at Talus Dome in Antarctica includes the last interglacial period. U.S. community discussions have been considering South Pole as a possible site. Some coastal domes like the Renland Ice Cap in Greenland are also possibilities. For these studies as well as those in other categories, because particular depths in the ice are of great interest to a number of investigators, the community needs the capability to do replicate coring off of the main borehole at depths of interest.

Science requirements for drilling high-resolution records of the last interglacial:

- Core/hole diameter: minimum of 4” but larger may be desired because of intense interest in interglacial section.
- Depth: 1,000 m (e.g. Renland), up to 3,000m.

- Recovery of high-quality core.
- Drill fluid: Existing acceptable fluids should work.
- Site considerations: ambient as cold as -50˚C, multiple seasons.
- Transportability and logistics: depends on site, deep sites will require significant infrastructure for deep drilling (Hercules, etc.).
- International aspects: Not clear at this time. There is interest in the US in re-drilling the Taylor Dome region, which could recover last-interglacial ice. This could be a US-only or US-led project.
- One possible mode of accessing last interglacial is destructive drilling to the depth of interest – possibly with an auger.
- Replicate coring is very desirable for last interglacial sites because the section of interest will be deep.

**4. Evidence from the ice sheet prior to 800k yrs**

Each time ice cores have extended further back in time they have revealed new facets of climate dynamics. The oldest record now, from the European Project for Ice Coring in Antarctica (EPICA) core at Dome C, extends back to just over 800 ka and shows that different styles of glacial-interglacial cycle can occur even under superficially similar external forcing. The Dome C site was selected to recover old ice, but not the oldest available ice. Ice is generally believed to have been present continuously in parts of East Antarctica for at least 1.5 million years. Although basal melting will have removed the very oldest ice in many places, it is reasonable to expect that ice older than 800 ka exists in East Antarctica.

The primary reason to seek this older ice is to further understand one of the major puzzles of climate system history – the transition about 1 million years ago from a world dominated by glacial-interglacial cycles lasting about 40ka to one with 100 ka 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 cyclically, and the persistence of abrupt climate change in earth history, could be addressed with ice core records extending to ~ 1.5 Ma, the current IPICS goal.

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 destructively drill 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 where old ice may be outcropping at the surface. Continuous records may be difficult at such sites but access is much easier. Different requirements are needed for the two approaches.

Science requirements for drilling a 1.5 Ma ice core include:

- Core/hole diameter: minimum of 4”.
- Depth: likely 3500-4000 m.
- Recovery of high-quality core.
- Drill fluid: very cold temperatures probably require new fluids.
- Site considerations: remote, multiple seasons, ambient temperatures as low as -60˚C.
- Transportability and logistics: sites will be remote. Heavy lift aircraft and traverse capabilities likely needed.
- International aspects: US may participate in multinational efforts; US might lead one of several coring efforts.
- One possible mode of accessing old ice is destructive drilling to the depth of interest – this may require an auger.
- Replicate coring is very desirable for oldest ice sites.

Science requirements for drilling at blue ice sites:

- Depths likely 5-20 m, possibly deeper.
- Rapid shallow coring of large number of 3” or 4” diameter cores (hundreds of 5-20 m holes in a season) at different locations.
- Rapid collection of large diameter (10”) cores up to 5 m deep in numerous locations for measurements of rare isotopes and gas species.
- Drill fluid: probably dry drilling.
- Site considerations: blue ice sites will impact aircraft landing possibilities, equipment probably moved in small planes and/or helicopters, transported by snowmobile, sometimes transported from aircraft landing site to blue ice site by snowmobile or other vehicle).
- Transportability and logistics: Will vary, helicopter and small plane transportable. One year or multi-year.
- International aspects: Unclear at this time, but numerous blue ice sites around both polar-regions. Blue ice projects should easily be accomplished by US-only teams.

**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 immediately above, to debris-laden glacier or similar environments, which will require specialized drilling equipment.

Science requirements for the drill:

- Core/hole diameter: 3” to 4”, if multiple cores can be collected. A large diameter coring device may also be desired.

- Drilling in mixed ice-rock matrix.
- Depth: up to 40 m.
- Drill fluid: None.
- Site considerations: Rock-ice mixture; environmental protocol in Dry Valleys and similar regions will be an important consideration.
- Transportability: helicopter transport capability needed.
- International aspects: US only so far, but this is likely to change.

**7. Changes across climate transitions** of rare isotopes, gases, micro-particles and other parameters that have not yet been exploited in ice core research.

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 $^{14}C$ of $CH_4$ 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 large diameter drilling capability discussed above is required. Chain-saw-based quarrying tools like those used in marble quarries might also be considered.

## *II. Ice flow history & response*

**1. Bed conditions**

The characteristics of the bed beneath an ice sheet exert strong control on the flow, along with other factors such as ice thickness and slope. Subglacial waters or water-laden sediments create beds that are more slippery than does a subglacial environment of rock or frozen material; slippery beds contribute to faster glacial flow. Only recently have measurements and analysis begun that relate the impact of rapid drainage of melting surface waters, and purely subglacial drainage of subglacial lakes, to glacier movement. Many more measurements of basal conditions are needed, including sediments and pore pressures, but these have been difficult to obtain, partly because of difficulties accessing the bed and keeping boreholes open long enough to deploy sensors.

Science requirements for the drill for access holes:

- Hole diameter & depth:
  - 3.5” shot hole to firn-ice transition
  - 3” access hole 1 to 4 km depth
- Winches are needed to deploy and control sensors
- Site considerations: ambient temperature as low as -60 $^{o}$C, minimal site occupancy period
- Transportability: Twin Otter to light traverse

**2. Geothermal flux**:

Calculation of frozen/thawed basal conditions requires a coupled thermo-mechanical ice-flow model. One of the inputs for such models is the geothermal flux, which influences the temperature profile in the ice near the bed. Geothermal flux has been estimated from borehole thermometry at several locations, but the spatial pattern of geothermal flux is not well constrained. Rapid access drills that allow installation of heat flux sensors at the base of the ice are needed to make these basic measurements that are critical for realistic modeling of thermal conditions at the base of ice sheets.

Science requirements for the drill for access holes:

- Hole diameter & depth:
  - 3.5” shot hole to firn-ice transition
  - 3” access hole 1 to 4 km depth
- Winches are needed to deploy and control sensors
- Site considerations: ambient temperature as low as -60 $^{o}$C, minimal site occupancy period
- Transportability: helicopter or Twin Otter to light traverse

**3. Properties of the ice that affect flow**

Even in the coldest places on Earth, ice is always closer to its melting point than any other naturally-deposited material; the material properties of glacial ice can change dramatically under varying conditions of temperature, age, compression, and flow.

Initially deposited as snow with accumulation over many thousands of years, the processes of firnification, transition to ice, and densification create a complicated, layered system with variable density, porosity, and mechanical and thermal properties. Bubbles in the ice impact glacial properties on the small scale, while moulins and cracks evidence complicated internal and basal plumbing on larger scales. All of these aspects impact ice flow. A variety of new technology and new sensors are becoming available that can facilitate study of the behavior of the ice, which will lead to improvements in that ability to model glacial flow under changing climates. Rapid access holes are needed to deploy sensors for making observations from the surface to the bed.

Science requirements for the drill for access holes:

- Drill needed for making lots of access holes, e.g.12 per season
- Hole diameter: ~ 3”
- Depth: up to 4 km
- Site considerations: ambient temperature as low as -40 $^{o}$C , minimal time site occupancy
- Transportability: LC-130 Hercules or light traverse

- Science requirement for community logging winches:
- winch for 3-4 km holes (heavy transport)
- winch for 1-km holes (easy transport)

**4. Internal layering (tracers of flow history)**

Profiling of the ice sheet using radar and seismic methods often reveals internal layering of the ice. The pattern of the layers (generally assumed to be isochrones) can be used to interpret the flow history of ice sheets. The history that can be extracted from these layer patterns is much improved if the layers can be dated by tracking them to a dated ice core. Further, the properties of ice that causes various radar-detected and seismic-detected layers can vary. Collection of ice samples in areas of interest is needed to calibrate radar and seismic data and to get an age-depth relationship for the layer tracing. The goal of this coring would be to get quickly down to the ice of interest, without spending the time to carefully collect the overlying core, and could be useful in locations where the layers can be traced over to a well-dated ice core.

Science requirements for drilling internal layering:

- Core from targeted depths only
- Hole diameter: 3-4”
- Depth: up to 4 km
- Site considerations: ambient temperatures as low as -40 $^{o}$C
- Transportability: LC-130 Hercules or light traverse
- International aspects: single nation or international collaboration

**5. Ice surface paleo-elevations & land surface paleo-topography**

Ice surface elevations around continental mountains and nunataks during past ice sheet maxima and minima constrain the size of ice sheets, and through modeling, can constrain their past extents and volumes. Ice paleo-elevations during interglacials may be estimated by exposure dating of subglacial bedrock where the ice sheet is frozen to its bed. All models that reconstruct ice sheet history rely on bed topography because ice sheets nucleate on highlands. Present models use existing topography because paleo-topography data are lacking. By dating rocks and understanding tectonic and igneous events establishing highlands and basins through Antarctica's history, these models may reproduce more realistic paleo-ice-sheet behavior.

Tectonic processes such as uplift and subsidence significantly influence ice sheet dynamics because elevation influences ice thickness, surface temperature, and accumulation rates and hence whether ice sheets are frozen to, or sliding at their bed. Regional structural basins may be locally forced below sea level or be formed as narrow troughs by rifting processes, and pre-existing faults weaken local rocks to allow easier erosion. Changes in continental elevations with time significantly change bed conditions on tectonic time-scales.

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.

Science requirements for the drilling for paleo-elevation, topography:

- Core/hole diameter: 2.5-3"/3-4", rock & sediment coring at bottom of borehole
- Core length: 1 m for rock, 10 m for sediment
- Depth; Targets are shallow areas up to 1 km ice thickness.
- Site considerations: ambient temperatures as low as -60$^{o}$C, at bed 0 to -10$^{o}$C
- Transportability: LC-130 Hercules, traverse
- International aspects: Some countries aiming to get samples in near future (e.g., China at Dome A).

**6. Processes that control the sub-ice-shelf mass balance**

Exploration of sub-ice-shelf ocean cavities and interactions between ice shelves and ocean waters are important for providing data on rates of ice flux, crevassing, especially bottom crevasses, physical properties of the ocean and ocean circulation within ice-shelf cavities. Isolated measurements have and are being gathered from different ice shelves but coverage is very sparse and some, including the Ross Ice Shelf, have almost no data available.

Ice shelves are thought to be the sentries of ice sheets; ice sheets at or below sea level may become critically unstable after the ice shelves have disintegrated. Recent work suggests that ocean temperatures control rates at which the ice shelves melt. However, temperatures and ocean-cavity circulation under modern ice shelves are poorly known or understood. Short-term spatially distributed measurements such as those from moorings, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) are needed. Additionally, locally placed long-term observatories are needed to document temporal variability. These projects should be directly related to grounding-zone studies and linked with oceanographic campaigns beyond the ice shelves.

Science requirements for the drilling sub-ice-shelf ocean:

- Hole diameter: 3-30”
- Depth (ice): Up to 1,000 m
- Site considerations: Keep hole open for 5-10 days, environmental restrictions may be possible, drill capable of operating with seawater
- Transportability: LC-130 Hercules, traverse
- International aspects: Australia, United Kingdom, European collaborations are active in such studies.

**7. Grounding zone processes**

The grounding zone is a critical area for ice streams and ice sheet stability, yet grounding zone processes are not well understood. 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. Currently there are no direct observations or measurements of grounding lines and grounding zones associated with the sensitive areas of fast-flowing ice streams.

If we are to increase the reliability of risk assessments of future behavior of ice sheets and their components, measurements are needed to understand: (i) physical and chemical grounding line processes relevant to evaluating ice sheet/ice shelf stability; and (ii) the role of subglacial water and till in areas just up-stream from grounding lines to assess the efficiency and continuity of subglacial drainage and deforming bed systems. Grounding zones may also be sites where discharge occurs of microbial and geochemical weathering products that originated in subglacial, basal, and englacial environments upstream. Discussion of these systems is included in III.2.

Short-term measurements are needed, such as by using moorings, AUVs and ROVs. Transects across grounding lines would be ideal to increase spatial coverage for assessing areal variability. Additionally, locally placed long-term observatories are needed to document temporal variability. These projects should be directly related to ice shelf studies and linked with glacial dynamic campaigns on ice sheets.

## *III. Sub-ice environment & habitat*

**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 long geological cores are being collected near the ice sheet margin by the ANDRILL and 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 their location relative to the ice sheet margin and magnitude of ice sheet fluctuations. Thus they are probably valuable libraries 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 is 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. Challenges with this drilling include keeping access holes open for long periods and operating under conditions of differential ice flow movement.

Science requirements for the drilling subglacial basins:
- Access hole diameter: 4-6” + reamer; hole kept open for specified number of days
- Depth: through ice sheet 1-3 km
- Site considerations: Sea level to 3 km, ambient surface temperatures 0 to -50$^{o}$C, clean access technology
- Transportability: Traverse or LC-130 Hercules
- International aspects: International partnering possibilities exist through SCAR’s Expert Group on Sub-Ice Geological Exploration (SIeGE).

**2. Sub-ice microbial ecosystem and biogeochemistry**
Subglacial and basal zones, where both water and mineral matter come in contact with ice, sediment or bedrock, represent environments for microbial life under otherwise frozen conditions. Ice sheets provide one of the best matrices for studies on microbial longevity, genome recycling and environmental control on biotic diversity. Microbial

cells and DNA 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, and 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 US polar biology community is very interested in determining the form, distribution, and activity of life within subglacial lakes and their sediment. Of particular interest are the characteristics of biological niches, biogeochemical cycling, and evolutionary histories of microbial communities in subglacial lakes. 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 to the surrounding ocean. Some subglacial meltwater is also transported over long-distances within basal drainage systems, which again likely discharge subglacial microbes into circum-Antarctic seawater. These studies can be conducted associated with all access and ice coring holes that use clean technology.

Science requirements for the drilling sub-ice ecosystems:

- Access hole diameter: 3-10”, sampling for ice, water and sediment
- Depth: Up to 4 km
- Site considerations: ambient temperatures as low as -60 $^{o}$C, 0 to -10 $^{o}$C at bed, differential movement of ice over the bed, maintain open hole for days, possible environmental contamination issues
- Transportability: LC-130 Hercules or traverse
- International aspects: International partners are available through SCAR’s research program on Subglacial Antarctic Lake Environments (SALE).

**3. Geological and tectonic history**

Due mainly to the continent being almost entirely covered by ice the geological and tectonic history of Antarctica is far from fully known, yet the continent and its lithospheric plate play important but poorly understood roles in global tectonic architecture. Significant features include: Antarctica is considered aseismic, making it anomalous in comparison with other 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 has unique attributes, 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 into crustal rocks will allow passive and active seismic experiments for delineating crustal structure.

A significant control on glaciation is continental topography; 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.

Science requirements for the drilling geological and tectonic history:
- Access hole diameter: 6" diameter to accommodate coring, to recover geological records 2-3" diameter, 10 m long cores
- Depth: Up to 4 km
- Site considerations: ambient temperatures as low as -60 $^{o}$C, 0 to -10 $^{o}$C at bed, differential movement of ice over the bed, maintain open hole for days, possible environmental contamination issues
- Transportability: LC-130 Hercules or traverse
- International aspects: International partners may be available through the ANDRILL community and SCAR's Expert Group on Sub-Ice Geological Exploration (SIeGE).

**4. Subglacial lakes and hydrological system**

Subglacial hydrology has been of interest to glacial geologists and glaciologists ever since eskers were recognized as being sediment accumulations from subglacial fluvial conduits. More recently subglacial hydrological systems piqued scientific interest as being important forces in ice dynamics, fast ice flow and surges; subglacial weathering and erosion; sediment transport and jokulhlaup events; hosting microbial ecosystems; and maintaining subglacial lake systems. Transfer of significant volumes of water and sediment occurs through these systems. Due to the difficulties of access, subglacial hydrological systems are difficult to characterize and quantify. Although they are recognized as being critical in terms of ice sheet stability they are difficult to model, one reason being our lack of data on their nature and degree and rates of change that occur.

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

Access holes to sample basal ice and subglacial water and sediments are required at selected sites over subglacial lakes and other areas of hydrological interest. Hole diameter requirements vary depending on instrumentation required; clean technology is required and the hole may need to be maintained open for days. Differential ice motion may also be a factor.

Science requirements for the drilling subglacial hydrology:
- Access hole diameter: 3-24", keep hole open for up to 10 days, sampling for ice, water, & sediment

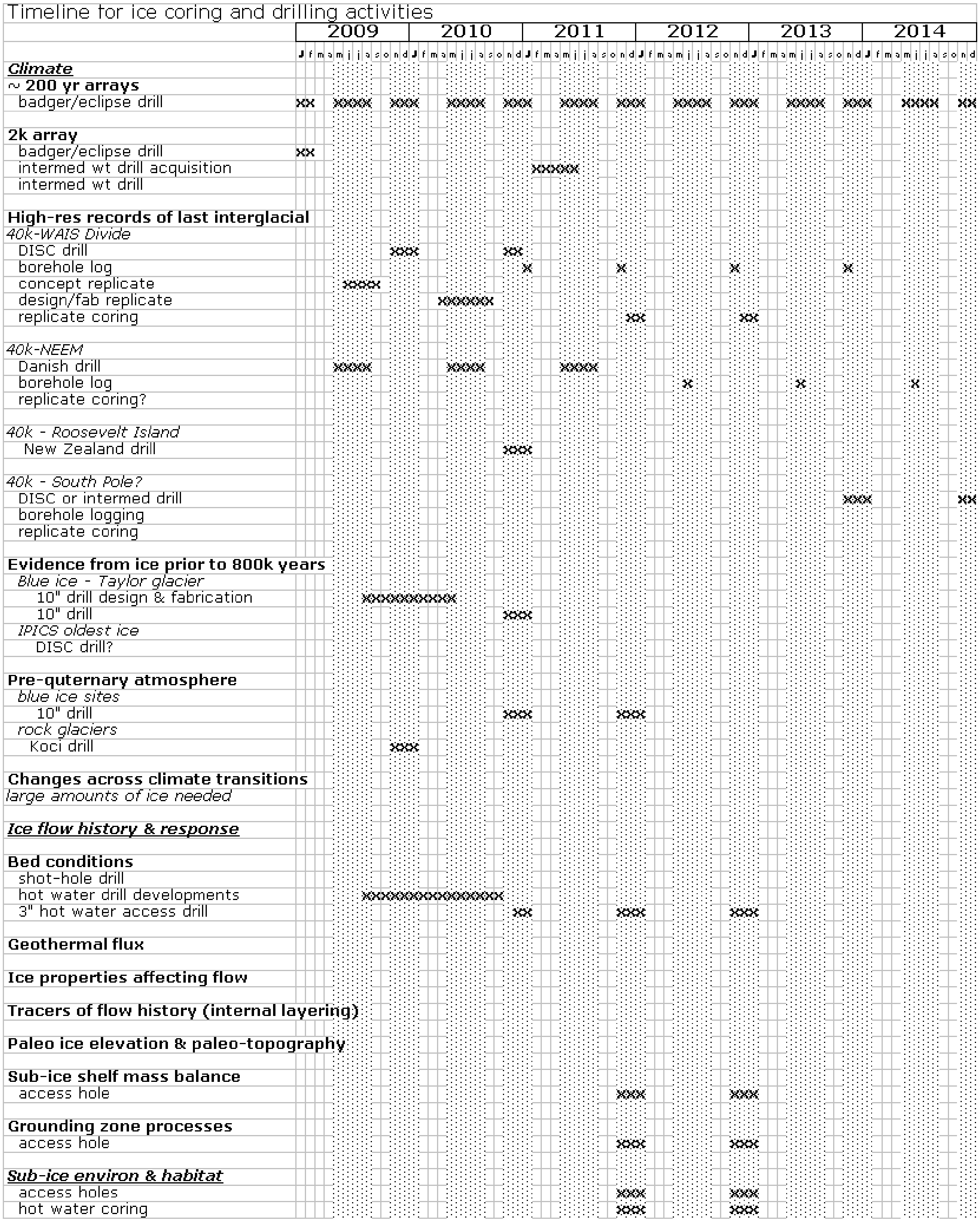
- Depth: Up to 4 km
- Site considerations: ambient temperatures as low as -60 $^{o}$C, 0 to -10 $^{o}$C at bed, differential movement of ice over the bed, maintain open hole for days, environmental contamination issues
- Transportability: LC-130 Hercules or traverse
- International aspects: International partners are available through SCAR's research program on Subglacial Antarctic Lake Environments (SALE).

***IV. Other science***

The polar ice sheets and mid-latitude ice caps can provide both an archive and a natural laboratory for a variety of scientific purposes unrelated to the environmental and climate-related studies described above. Examples include the collection of meteorites and micrometeorites, sensing of extraterrestrial subatomic particles, and seismic monitoring. The drilling requirements for such applications would be developed on a case by case basis and may vary widely. It is likely that most such applications will require access-type drilling, perhaps with filtration of particulates in the extracted material, rather than recovery of intact ice cores.

## Time line

The headings for each of the above endeavors and five-year timeline for those known to be at least in the planning stages as of June 2009 are listed below.



## Associated challenges

Associated challenges to ice coring and drilling include:
(1) The need for an environmentally-acceptable drilling fluid to replace the Isopar K-HCFC 141b mixture that is currently used for drilling at the WAIS Divide site. Drilling fluid is necessary for intermediate and deep coring projects. Community discussion of this issue will be facilitated by IDPO, and studies will be done by IDDO or a contractor to identify a suitable replacement fluid in the coming year or two.
(2) Limited air logistics access to sites on the Greenland and Antarctic ice sheets, and the approach of the end of the lifetime of the infrastructure supporting the drill at the WAIS Divide site. Science, drilling, infrastructure, and access are all issues that must be continually balanced and assessed through the course of a deep drilling project. IDPO and IDDO will work with the research community, NSF, and the support contractors in planning that will enable the science to be achieved.
(3) The continuing need for ice core storage and archive. Currently cores drilled by the U.S. ice coring program are stored at the USGS National Ice Core Laboratory (NICL), an aging facility that will soon reach its full capacity. Upgrading and expanding an ice core storage facility will require a major investment in infrastructure.

## Conclusions and Recommendations

The ice coring and drilling community is clearly well posed to make important discoveries that may impact policy decisions regarding environment and climate. Both new discoveries enabled by existing technologies, and new technologies to enable new science visions are needed to achieve the science goals outlined above.

*Recommendations for enabling drilling technology*

Some of the drills and associated technology needed to achieve the science already exist. However, some existing equipment is in poor repair or is in need of update, while others exist only as elements on a research community wish list. The Senior Advisory Board of the Ice Drilling Program Office echoes the sentiment of many in the research community with the following guiding principles for development of drilling technology:

- Planning for drilling technology needs to include consideration of the cost and availability of logistics beginning with the earliest stages of planning and continuing through the process as decisions are made throughout the engineering design and fabrication process.
- Drills and accompanying technology should be developed with an eye for use in a variety of projects in different remote locations.
- Designs should be developed so that the necessary supporting logistics do not impede the execution of the science.

The Senior Advisory Board also identifies the following as high-priority investments needed during the coming five years for the drilling technology to enable scientific discovery (the following are not prioritized):

1. Maintaining agile coring/drilling capability
2. Two logging winches: 1 km, 4 km (4 km highest priority)
3. Replicate coring capability
4. Purchase or design/construction of an agile intermediate drill
5. Conceptual design for access to the ice sheet bed with a fast, narrow hole
6. Conceptual design for upgrades to the DISC drill to enable use in East Antarctica
7. Conceptual design for access through the ice sheet with a hole large enough to deploy subglacial rovers

**Reference**

NRC, 2002. Abrupt climate change: inevitable surprises. National Academies Press, Washington, D.C., United States.