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# Long Range Science Plan 2026-2036

Prepared by the NSF Ice Drilling Program in collaboration with its Working Groups, Science Advisory Board and with input from the research community

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### NSF Ice Drilling Program (IDP)

Mary R. Albert, Executive Director, Dartmouth  
Louise Huffman, Director of Education and Public Outreach, Dartmouth  
Kristina Slawny, Director of Operations, University of Wisconsin Madison  
Joseph Souney, Director of Digital Communications, University of New Hampshire  
Blaise Stephanus, Program Manager, Dartmouth  
Bill Grosser, Educational Outreach Specialist, Dartmouth

### Science Advisory Board to IDP

Chair: Sarah Shackleton, Woods Hole Oceanographic Institution  
Nathan Chellman, Desert Research Institute  
Joel Harper, University of Montana  
Matthew Siegfried, Colorado School of Mines / Geophysics  
Ryan Venturelli, Colorado School of Mines / Geology  
Trista Vick-Majors, Michigan Technological University

## 1 Introduction

2

3 The progress of national health, prosperity and welfare, and field operations of the national defense may  
4 all be influenced by changes in Earth's linked atmospheric-oceanic-continental systems, especially in times  
5 of rapid change. The Polar Regions have been the harbingers of change and continue to display dramatic  
6 environmental changes. A sophisticated and predictive understanding of the mechanisms of abrupt  
7 changes in Earth's linked systems across a wide range of spatial scales and time is needed to plan for the  
8 future. Glaciers, ice sheets, and subglacial environments contain evidence of the past and present that  
9 provide data that are crucial for predicting the response of the cryosphere and Earth's systems to ongoing  
10 future changes.

11

12 Ice core records have led to many important discoveries; for example, the discovery from the Greenland  
13 Ice Sheet Project 2 ice core showed that dramatic changes can occur abruptly, in less than ten years (NRC,  
14 2002); this revolutionized large-scale environmental science and also has important implications for  
15 policy. The West Antarctic Ice Sheet (WAIS) Divide Core established the benchmark carbon dioxide record  
16 for the most recent glaciation. U.S. and U.K. collaboration on studies of the unstable Thwaites Glacier in  
17 West Antarctica has begun to provide evidence on the possibility of large sea level change in the near  
18 future (e.g., Joughin et al., 2014; Scambos et al., 2017). Recent studies of subglacial sediment and bedrock  
19 below the summit of the Greenland Ice Sheet (Schaefer et al., 2016; Christ et al., 2020; Christ et al., 2023;  
20 Walcott-George et al., 2026) and the West Antarctic Ice Sheet (Venturelli 2020; 2023; Balco et al., 2023;  
21 Small et al., 2026) raise questions about ice sheet resilience to large-scale environmental change. Glacial  
22 ice at the Hercules Dome site in Antarctica archives evidence about the rate of demise of the West  
23 Antarctic Ice Sheet during the last interglacial with its large sea level rise; retrieving the Hercules Dome  
24 ice core remains highest priority for the U.S. ice core science community. Many other basic questions  
25 about Earth's systems remain unresolved, and new scientific plans, in both Antarctica and Greenland, will  
26 address a variety of questions.

27

28 Rapid changes in the speed of fast-flowing outlet glaciers and ice streams observed over the past decade  
29 have created an urgency to understand the dynamics of outlet glaciers and ice sheets. It has long been  
30 recognized that basal conditions exert strong control on the flow of glaciers and ice sheets; and boreholes  
31 drilled to the bed have been used to deploy instruments to measure englacial and basal properties (e.g.,  
32 Engelhardt et al., 1990; Engelhardt and Kamb, 1998; Kamb, 2001; Truffer et al., 1999, 2006; Siegfried et  
33 al., 2023). These fundamental observations have advanced our understanding, and it is clear that spatial  
34 and temporal distribution of sediments and hydraulic conditions at the bed are key to understanding rapid  
35 changes in speed of glacial flow. Furthermore, in cases where the bed of outlet glaciers is slippery,  
36 perturbations at the grounding line propagate inland over short timescales (order of decades), which has  
37 the potential for rapid drawdown of inland ice (Payne et al., 2004; Shepherd et al., 2004; Price et al., 2008;  
38 Joughin et al., 2014; Rignot et al., 2014). Perturbations at grounding lines are triggered by changing ocean  
39 temperature and circulation (Jenkins et al., 2010), and/or subglacial hydrology or sediment dynamics  
40 (Anandakrishnan et al., 2007; Alley et al., 2007; Carter & Fricker, 2012; Christianson et al., 2012; Horgan  
41 et al., 2012; Siegfried et al., 2023; Horgan et al., 2025). Defining the processes that control the dynamic  
42 stability of glaciers and ice sheets is crucial for predicting their response to future possible greenhouse  
43 gas emission scenarios. Great uncertainties in sea level rise projections for the 21<sup>st</sup> century are associated  
44 with the possibility of rapid dynamic responses of the ice sheets to ongoing warming.

45

46 Subglacial environments represent a deep repository of ice history, a resource that remains largely  
47 untapped. Most of our knowledge about subglacial environments comes from geophysical remote sensing

48 and sparse data retrieved from access holes drilled to the bed, or sub-ice-shelf cavities. More detailed  
49 observations are needed to map and understand the variety and complexity of deep ice, subglacial  
50 geology, and the interface between them. The lithosphere under the Antarctic and Greenland ice sheets  
51 remains unknown except by extrapolation from coastal outcrops and remotely-sensed geophysical data.  
52 Subglacial environments also house records of past ice sheet dynamics and longer-term paleoclimatic  
53 histories in their sediment, fossils, microbiology, and stratigraphic basin archives (Scherer et al., 1998;  
54 Christner et al., 2013; Coenan et al., 2019; Schaefer et al., 2023; Christ et al, 2021 and 2023; Venturelli et  
55 al., 2020 and 2023; Siegfried, Venturelli et al., 2023; Davis et al., 2023). Recovering these records for  
56 intervals of past warm periods will contribute to our understanding of future ice sheet behavior under  
57 ongoing warming.

58  
59 New and emerging studies show that subglacial environments harbor unique microbial ecosystems and  
60 that the biogeochemical activities of the microbial communities play a critical role in subglacial weathering  
61 and production/consumption of greenhouse gases (Martinsson et al., 2013; Christner et al., 2014;  
62 Michaud et al., 2016; Davis et al., 2023). Recent studies have illustrated the potential for subglacial water,  
63 and relict carbon from microfossil-bearing sediments, to supply critical carbon and nutrients to sub-ice-  
64 shelf waters (Vick-Majors et al., 2020, Hawkings et al., 2020; Venturelli et al, 2020, 2023), however, the  
65 extent to which microbial activity alters the chemistry of subglacial efflux and the effects of that efflux on  
66 global processes remain outstanding questions. There is considerable scientific and public interest in  
67 subglacial environments, particularly in relation to the discoveries of subglacial lakes beneath the  
68 Antarctic Ice Sheet and the unique life forms they may harbor. Microorganisms that exist under  
69 permanently dark and cold subglacial conditions have broadened our understanding of the phylogenetic  
70 and metabolic diversity of life on Earth (Achberger et al, 2016; Mikucki et al.2016; Davis et al, 2023); this  
71 has opened the door for research on available nutrients and carbon paleoclimatic research, and may help  
72 inform our search for extraterrestrial life. Genomes of microbes trapped under deep ice can provide  
73 indications regarding their period of separation from "contemporary" microbes. Hence, genomic data that  
74 establish timeframes of isolation for populations can contribute to understanding events of the past, for  
75 example the timing of the last WAIS collapse.

76  
77 Technological developments are required to integrate geological drilling technologies with those of ice  
78 drilling, including clean access. The U.S. Antarctic Program complies with the Antarctic Treaty and other  
79 treaties to uphold protection of the environment, including activities that involve drilling through the ice  
80 (NRC 2007). Given the pristine nature of Antarctic subglacial environments in particular, the Scientific  
81 Committee on Antarctic Research (SCAR) has developed a Code of Conduct for access in order to  
82 *"recognize the value of these environments and the need to exercise wise environmental stewardship."*  
83 The US scientific community has taken a lead in advancing international management of the Antarctic  
84 subglacial environment by establishing and documenting methods for achieving microbially clean access  
85 hot water drilling systems (Priscu et al, 2013; Michaud et al, 2020), for use in standardizing drilling and  
86 coring systems in a quantifiable and verifiable approach. In the future, a facility such as the Ice Coring &  
87 Education (ICE) Silo, under conceptual development at the University of Nebraska, could construct custom  
88 columns of ice in a clean system for potential use in testing future development of novel drilling systems.  
89 The NSF Ice Drilling Program has pioneered proven engineering achievements including replicate coring  
90 in ice and the first retrieval of meters of bedrock cores from beneath many meters of glacial ice. It remains  
91 a top priority to engineer new hot-water drilling tools to enable future interdisciplinary scientific  
92 discoveries from within and beneath glaciers and ice sheets.

93 The U.S. ice coring and drilling community has led and participated in fundamental and vital scientific  
94 discoveries for more than sixty years. These discoveries require drilling and coring of glaciers and the polar  
95 ice sheets, a specialized and challenging endeavor that requires extensive planning, technology, and

96 logistics. This IDP Long Range Science Plan identifies U.S.-led science that will require ice drilling in glaciers  
97 and ice sheets. The accompanying IDP Long Range Drilling Technology Plan identifies actions for IDP drill  
98 maintenance and upgrade and development of new drills and technology. These paired plans enable the  
99 community to develop well-coordinated proposals while allowing the NSF to plan for budgets and logistics  
100 to facilitate the science. A draft update of the IDP Long Range Science Plan, including input from the IDP  
101 Science Advisory Board and the IDP Working Groups, is posted to the [icedrill.org](http://icedrill.org) website each spring, with  
102 listserv invitations for comments and suggestions to enable broad community input. The document is then  
103 revised and the final version for the year is sent to the NSF and posted to the [icedrill.org](http://icedrill.org) website in  
104 summer.

105  
106 Science goals articulated in this IDP Long Range Science Plan are all interconnected, but for convenience  
107 in associating scientific endeavors with appropriate ice drilling technology, the science is described in four  
108 themes: 1) past changes; 2) ice dynamics and glacial history; 3) subglacial geology, sediments, and  
109 ecosystems; and 4) ice as a scientific observatory. These four goals and objectives are described below,  
110 together with an outline of their respective needs for drilling technologies. Planning matrices are also  
111 developed to provide a timeline for planning field readiness of ice drilling technologies, so that the  
112 engineering of drilling support for the science will be ready when needed.

113  
114  
115

## 116 **Ice Core Science and Drilling Science Goals**

### 117 **I. Past Changes**

118 Earth is a system that has regional, hemispheric, and global phenomena. It is impossible to understand  
119 large-scale changes without understanding both individual components of the system and the system as  
120 a whole, as evidenced by data from a large number of locations and over a range of time scales.

121  
122 **1. Industrial and Instrumental Period:** Spatially distributed evidence from ice cores spanning the  
123 industrial and instrumental period (last 100-200 years) is still needed to establish human impacts on the  
124 environment, cryosphere and atmosphere. Associated studies of modern surface processes, calibration  
125 of models and correlating remote sensing data with in situ data are needed. Shallow ice cores (generally  
126 <200 m) are relatively easy to recover and consequently more records can be collected to evaluate spatial  
127 patterns of change.

128  
129 Over the past 200 years, human activities have had significant impact on atmospheric composition yet the  
130 impacts in polar and remote high-latitude and high-altitude regions are poorly resolved. Shallow ice coring  
131 programs have been, and will continue to be done through individual or small-group projects at targeted  
132 sites (e.g., ice coring in mid-latitude temperate glaciers, Alaska, and in selected areas of the Arctic and  
133 Antarctic) and through internationally coordinated scientific traverses (e.g., International Trans-Antarctic  
134 Science Expedition, Norwegian-U.S. Scientific Traverse of East Antarctica) or other logistical models (e.g.  
135 RAICA US-South Korea collaboration collecting coastal West  
136 Antarctic ice cores). Some of these shallow coring arrays must also be updated in coming years since many  
137 ice cores, including the International Trans-Antarctic Scientific Expedition cores, were established in the  
138 late 1990s to early 2000s and are thus missing the last 20 years of information. Returning to sites and  
139 taking firn cores to depths of 10-15 m would provide such an update. While shallow coring has been done  
140 in a number of locations, more cores are needed in order to understand whether observed patterns are  
141 regional, hemispheric, or global. Through a combination of over-snow science traverses and coordinated  
142 individual site efforts, an extensive array of relatively easy-to-recover ice core records, driven by individual  
143 and group proposals, is a mainstay of the ice coring community with the following objectives:

- 144
- 145 ● Determine accumulation rate and temperature changes on the Greenland and Antarctic ice sheets  
146 and in alpine regions where instrumental records are rare.
- 147 ● Understand changes in the chemistry and isotopic composition of the atmosphere during the  
148 Industrial Period, including greenhouse gases, acidic species, oxidants, toxic metals, and trace species  
149 such as carbon monoxide and hydrocarbons.
- 150 ● Understand stability and rapid changes along coastal areas of the West Antarctic Ice Sheet. Ice core  
151 records, strategically placed on ice domes along the WAIS coast (e.g., Neff 2020), will provide high-  
152 resolution (annual) records of natural variability in ice, ocean, and atmospheric dynamics in which to  
153 place the recent observations in context, including extreme events and newly appreciated processes  
154 such as atmospheric rivers (e.g., Wille et al., 2022).
- 155 ● Constrain surface mass balance processes including accumulation, surface melt, runoff and refreezing,  
156 and evaluate areas of water retention in perched water tables and aquifers in Greenland and  
157 Antarctica. These data can also be used to ground-truth high-resolution models.
- 158 ● Improve understanding of relevant physical and chemical processes related to snow deposition and  
159 post-depositional changes (including metamorphism, in situ chemical processes, interactions with  
160 cosmic rays, etc.) and their effects on atmospheric chemistry preservation and interpretation of  
161 geochemical signals (including atmospheric) at larger depths.

- 162 ● Calibrate snow/firn/ice properties measured remotely (e.g., borehole, ground, airborne, and satellite-
- 163 based measurements) with in situ data, thereby allowing interpolation based on remote sensing data.
- 164 ● Extract firn air from shallow boreholes to reconstruct the recent evolution of the atmospheric
- 165 composition and study air movement in the porous firn layer.
- 166 ● Produce detailed temporal and spatial (regional-scale) maps of environmental parameters (e.g.,
- 167 temperature, accumulation rate, atmospheric and snow chemistry), and anthropogenic impacts.
- 168 ● Develop an inventory of microbes and available nutrients within ice to improve understanding of the
- 169 role of microbes related to geological, chemical, and climatological changes.
- 170 ● Improve records of global and local volcanism for large-scale forcing and geohazard studies.
- 171 ● Quantify perturbations to atmospheric composition from anthropogenic pollution sources relative to
- 172 the preindustrial atmosphere (e.g., aerosols, metals).
- 173

174 Individuals and small groups conduct studies of these types across glaciological settings ranging from the  
175 Greenland and Antarctic ice sheets, to ice caps and alpine glaciers in low, mid, and high latitudes. Versatile  
176 drills required for 200-year ice coring exist in the current U.S. inventory, and are in high demand; they  
177 need to be upgraded and continuously maintained so that they are functional and can be quickly deployed  
178 to the field. Requirements for drills to achieve these and other ice coring goals are listed in table one. The  
179 IDP Long Range Drilling Technology Plan describes the agile drills in the IDP inventory in detail and  
180 discusses their current condition.

181  
182 (photo)  
183 Caption: Part of an ice core retrieved from Mt Hunter Plateau of Denali, Alaska exhibits layering and dust carried to  
184 the area from afar. Photo credit: *Brad Markle, Univ. Washington*

185  
186 **2. Pre-Industrial Baseline:** The Common Era (ca. the last two millennia) is an important temporal focus  
187 because it is long enough to allow investigation of annual to centennial variability, yet short enough that  
188 relevant boundary conditions have not changed appreciably. Thus, this period represents a critical pre-  
189 industrial baseline against which to compare 20<sup>th</sup> century changes in the cryosphere, atmospheric  
190 composition and chemistry. Existing quantitative reconstructions of large-scale environmental changes  
191 spanning the past two millennia continue to be debated, in part due to a lack of annually-resolved records  
192 prior to 1600 B.P. in many areas, and due to the highly regional nature of many processes. A coordinated  
193 international effort to recover a spatial array of annually resolved and calibrated 2,000-year ice core  
194 records has several primary objectives:

- 195 ● Determining regional and high-resolution temporal patterns of temperature, precipitation, sea ice
- 196 extent, and atmospheric composition and chemistry to better understand forcing and particularly
- 197 feedbacks that will also operate in the near future.
- 198 ● Evaluating 20<sup>th</sup> century warming, precipitation, atmospheric circulation, sea ice, and atmospheric
- 199 composition and chemistry changes in the context of the past 2,000 years.
- 200 ● Establishing the extent and regional expression of the so-called Little Ice Age and Medieval Anomaly
- 201 phenomena, and constraining their relationships with regional patterns like the North Atlantic
- 202 Oscillation (NAO), Arctic Oscillation (AO), El Niño Southern Oscillation (ENSO), and Monsoons.
- 203 ● Calibrating local, regional, and global models against a recent but sufficiently long pre-anthropogenic
- 204 period.
- 205 ● Determining the sensitivity of alpine glaciers and ice sheet margins to the relatively warm Medieval
- 206 Anomaly and relatively cold Little Ice Age, with implications for the impact of future warming on water
- 207 resource availability and sea level rise.

- 208 ● Quantifying spatial and temporal patterns of forcing mechanisms that are regionally variable (e.g.,  
209 greenhouse and reactive gases, sulfate, terrestrial dust, biological material, and carbon aerosols [black  
210 and biogenic carbon]), and the record of solar variability.
- 211 ● Assessing the relative roles of anthropogenic and natural forcing on large-scale environmental  
212 evolution prior to and into the industrial period.
- 213 ● Quantifying anthropogenic emission sources and levels prior to the start of the industrial revolution  
214 (1760s), such as from early metal smelting, biomass burning, or other human activities.
- 215 ● Improve understanding of how natural sources of greenhouse gases and aerosols are responding to  
216 high latitude change.

217  
218 New coring associated with these efforts will include Arctic, Antarctic, and mid-latitude sites. Recent and  
219 desired future U.S. or U.S./International efforts include Central Alaska Range and Canada (Eclipse Icefield);  
220 multiple locations in Antarctica including coastal WAIS ice shelves and ice domes; Hercules Dome (the  
221 2,000-year record would be part of a deeper core); Greenland coastal ice caps, and high accumulation  
222 rate sites in Greenland such as the South Dome site (the 2000-year record would be part of a deeper core).  
223 This list is not exclusive, but illustrates the diversity of discussions within the research community.

224  
225 (Photo)  
226 Caption: Scientific drilling on the Mt. Hunter Plateau of Denali, Alaska provides a 2,000-year record of precipitation  
227 and atmospheric circulation in Central Alaska. Drilling at this site was accomplished by wind and solar energy without  
228 the need for gas-fueled generators. Photo credit: Top) *Seth Campbell, CRREL*; Bottom) *Dom Winski,*  
229 *Dartmouth/U.Maine*

230  
231 **3. Large-Scale Global Change:** Large changes driven by external forcing have involved significant  
232 interactions among ice sheets, carbon cycle, vegetation, dust, ocean and atmospheric circulation resulting  
233 in rapid changes in regional conditions. Understanding Earth system dynamics especially in times of rapid  
234 transitions is critical to making improvements in current Earth system models for assessment of future  
235 change. Incomplete evidence about processes and dynamics of abrupt millennial scale change and  
236 regional impacts requires evidence from ice cores to develop more complete knowledge of the underlying  
237 mechanisms. Ice cores are uniquely placed to provide the contrasting polar elements in high resolution  
238 and are the only source of past atmosphere allowing measurements of greenhouse and other trace gases.  
239 Scientific challenges include the following:

- 240 ● Further develop ice core proxies for different aspects of the Earth system, for example to reconstruct  
241 conditions at the ocean surface (e.g., sea ice, marine biological productivity, ocean evaporation  
242 conditions), and in the boreal continental biosphere (e.g., forest fires, land ice extent).
- 243 ● Continue to improve understanding of forcings on millennial and orbital timescales (greenhouse gases,  
244 solar irradiance, aerosols, temperature, snowfall rates).
- 245 ● Improve the absolute and relative chronologies of individual ice cores, in the ice solid and gas phases,  
246 and construct consistent multi-ice-core chronologies.
- 247 ● Develop methods to synchronise ice core records to those from other palaeo archives, in particular for  
248 previous glacial cycles where radiocarbon is unavailable.
- 249 ● Increase the spatial and temporal coverage of the deep ice core network to identify spatial patterns  
250 and regional differences in climatic, environmental, and glaciological conditions.
- 251 ● Apply newer methods to improve the resolution of data from some existing sites. Quantify and  
252 understand the spatial and temporal evolution of rapid changes, and assess how this varies with  
253 background conditions (orbital forcing, greenhouse gas concentration, land ice masses).
- 254 ● Construct, using ice cores carefully synchronized to other records, the sequence of events (including  
255 forcings and responses) through several glacial-interglacial transitions at highest resolution possible.

- 256 ● Use these reconstructions with Earth system modelling to provide a stringent test of mechanisms. This  
257 will require an increase in modeling capability to assess changes at sufficient resolution through  
258 multiple terminations.

259  
260 Under the auspices of IPICS, the international scientific community aspires to a network of ice cores.  
261 Specific U.S. contributions to this network include the completed WAIS Divide core and the South Pole ice  
262 (SPICE) core, and the upcoming core at Hercules Dome. In Greenland, two potential but not yet planned  
263 sites in the Northwest and at South Dome would also contribute to IPICS goals. The projects may vary in  
264 scope and logistical needs, but many are envisioned to be drilling campaigns conducted in two or three  
265 seasons with minimal logistics. Site-specific records of environmental change are the primary objective; it  
266 will not be necessary to undertake the full suite of measurements possible in an ice core, although clearly  
267 such measurements provide data for a variety of future projects. The Foro 1800 drill was used to  
268 successfully drill the South Pole Ice Core to a depth of 1,751 m (age ~ 49,000 years), and the Foro 3000  
269 drill will be used at Hercules Dome. Individual and small group projects targeting specific aspects of  
270 atmospheric variability on millennial to glacial timescales can be conducted at low-accumulation sites such  
271 as Dome C, Antarctica or at ice margin sites with agile drill systems and moderate logistics requirements.  
272

273 **4. High-resolution Records of the Last Interglacial; A Warm-Earth Analog:** The Last Interglacial (LIG)  
274 period (~130k to 110k years ago) was warmer than present due to differences in Earth’s orbital  
275 configuration, and can provide clues about how the Earth will respond as human activities continue to  
276 force global warming. Critical science priorities for ice cores spanning the LIG include:

- 277 ● Determining whether the West Antarctic Ice Sheet experienced partial or total collapse during the LIG,  
278 and determining the extent of the Greenland Ice Sheet during this warmer time. These objectives are  
279 critical for constraining sea level rise estimates in a warmer world.  
280 ● Quantifying the temperature, precipitation, atmospheric circulation, and sea ice extent of Greenland  
281 and Antarctica during the LIG.  
282 ● Establishing whether rapid change events occurred during the warmer world of the LIG.  
283 ● Determining whether the lack of an abrupt change during the deglacial warming (i.e., Bolling Allerod  
284 warming and Antarctic Cold Reversal) contributes to an “overshoot” and a warmer interglacial.  
285 ● Comparing the evolution of the LIG with the recent Holocene.  
286 ● Investigating glacial inception at the end of the LIG.

287 Existing ice core records of the last interglacial are primarily from low accumulation sites in East Antarctica  
288 are insensitive to changes in the marine segments of the ice sheets. The detailed behavior of polar  
289 environmental conditions, greenhouse gases, ice sheet size, and other earth system attributes recorded  
290 by ice cores are not well known for this period, and require high-accumulation conditions. Results from  
291 the North Greenland Eemian (NEEM) ice core in Greenland, and similar results from other Greenland ice  
292 cores, have shown that the Eemian record located there is at least partially recoverable, but not in  
293 stratigraphic order. Large volumes of ice from the last interglacial have been shown to outcrop at the  
294 surface of Taylor Glacier, Antarctica; a record of the MIS6-5 transition has been recovered from folded ice  
295 at the Allen Hills (Yan et al., 2019).

296  
297 (photo)  
298 Caption: The bubbles visible in this piece of ice from an Antarctic ice core contain carbon dioxide and other gases  
299 that were trapped in the ice when formed many thousands of years ago. Ice cores provide the only natural archive  
300 of ancient air. Photo credit: *Oregon State University*.

301  
302 The search for sites with undisturbed ice will continue in both polar regions along with efforts to interpret  
303 folded ice; potential targets are relatively high accumulation sites in Antarctica, such as Hercules Dome,

304 where Last Interglacial ice is likely to be preserved, and possible new sites in Greenland, including near  
305 the Camp Century site in Northwest Greenland. Almost a decade ago and reaffirmed since then, the U.S.  
306 science community, represented by the IDP Ice Core Working Group (ICWG), prioritized Hercules Dome  
307 as the next deep ice core site in Antarctica. The Hercules Dome site has likely preservation of ice from the  
308 last interglacial period (Jacobel et al., 2005) and a sensitivity to a potential collapse of the WAIS (Steig et  
309 al., 2015), as well as the potential to provide bubble-free ice (below the problematic bubble-to-clathrate  
310 transition zone, e.g., Neff 2014) for gas studies during the last glacial-interglacial transition.  
311

312 **5. Evidence from the ice sheet prior to 800,000 years B.P.:** Each time ice core measurements have  
313 extended further back in time, the data reveals new facets of the dynamics. Currently, the oldest record,  
314 from the EPICA core at Dome C, Antarctica, extends back to just over 800,000 years, and shows that  
315 different styles of glacial-interglacial cycles occur even under apparently similar external forcing. Antarctic  
316 ice sheet inception is thought to have occurred 35 million years ago, and although basal processes may  
317 have removed or altered the very oldest ice in many places, ice older than 800,000 years is preserved in  
318 East Antarctica. Recently, the European Beyond-EPICA project announced the recovery of possibly a 1.2  
319 million year old continuous ice at Dome C, although formal dating is needed to confirm this claim.  
320

321 The primary reason to seek ice older than 800,000 years is to further understand one of the major puzzles  
322 of Earth system history: Why did the system change from a dominantly 41k- to a 100k- year glacial cycle  
323 about one million years ago? Numerous research objectives related to this transition, and the earlier time  
324 period, could be addressed with ice core records extending back to ~ 1.5 million years, including:

- 325 ● Evaluating CO<sub>2</sub> relationships prior to 800 ka, to determine whether the change to 100-kyr cycles  
326 and/or the long-term cooling trend from 1.5 – 0.8 Ma was related to changes in greenhouse gas  
327 concentrations.
- 328 ● Clarifying whether 23k-year cycles, linked to orbital precession, are present in ice core records prior  
329 to the transition to 100-kyr cycles around 1 Ma. The 23k-year cycles are not present in marine proxy  
330 records of this age, but are present in both marine records and ice cores after the transition.
- 331 ● Investigating the high-resolution nature of glacial transitions during times of 41k-year cycles.  
332

333 (graph)

334 Caption: 100,000-year 'sawtooth' variability in Antarctic climate over the last 800,000 years is mirrored by generally,  
335 similar variability in atmospheric carbon dioxide (as well as methane and nitrous oxide, not shown) and global ice  
336 volume inferred from deep ocean oxygen isotope records from marine calcium carbonate. Whether Antarctic  
337 climate followed the ice volume record prior to this time, when ice volume records are dominated by a 40,000-year  
338 period, is not known, neither are the mean levels of greenhouse gases and the temporal variability of those levels.  
339 *Figure from Severinghaus et al. (2013).*  
340

341 There are two complementary, but very different, ways of accessing ice older than 800,000 years. The  
342 first is deep ice core drilling at very low accumulation rate sites in interior East Antarctica. This has the  
343 advantage of recovering a continuous record, which, in the younger part, can be compared to other ice  
344 cores (an important consideration for drilling at very low accumulation sites where record integrity may  
345 be an issue). Drilling at such a site requires a large amount of logistics support.  
346

347 The second method is to make use of “blue ice” sites such as at Allan Hills (Spaulding et al., 2013; Higgins  
348 et al., 2015; Shackleton et al., 2026; Marks-Peterson et al 2026) (logistically) less expensive science  
349 projects. A site in the Allan Hills (Kehrl et al., 2018) has been shown by ice penetrating radar to likely have  
350 a continuous record to ~250 ka with several hundred more meters of ice below for the possibility of  
351 continuous records extending to 1 million years. Different drilling requirements are needed for the two

352 approaches. Development of blue ice sampling techniques should continue, given the potential for large  
353 volume sampling, very old ice and the possibility that continuous ice core records will not be discovered.  
354 Consideration of sites where only old ice might be preserved (for example, areas where there is no  
355 accumulation today but has been in the past) should also continue.

356  
357 The IPICS “Oldest Ice” workshop (Fischer et al., 2013) described possible oldest ice sites in East Antarctica  
358 for consideration. The European project “Beyond EPICA” collected a deep core at a site near Dome C. This  
359 “little Dome C” site is shallower than the existing Dome C ice core site to limit the chance of basal melting.  
360 Tentative dating suggests this core is 1.2 million years old. A deep Oldest-Ice core near Dome Fuji is being  
361 drilled by the Japanese program. The Australian “million-year ice core” project is drilling at a site called  
362 “North Patch” near Dome C. Choosing a location with confidence is still difficult; mainly due to poorly-  
363 known geothermal heat flux. Determination of the spatial variability of geothermal heat flux is critical to  
364 the identification of potential drilling sites for oldest ice. Large regions remain unexplored which may  
365 have the optimal site conditions for Oldest Ice. The Rapid Access Ice Drill (RAID, Goodge & Severinghaus,  
366 2016), once deployed on the ice sheet in Antarctica, should be able to create rapid deep access holes for  
367 spatially distributed measurements of geothermal heat flux to facilitate site selection. Field tests in 2019-  
368 20 demonstrated the drill’s ability to cut ice boreholes quickly, take cores of subglacial rock, and deploy  
369 borehole logging tools for ice-age validation (Goodge et al., 2021). There are also additional efforts for  
370 oldest ice site selection programs that involve rapid access with new tools under development such as  
371 ICEDIVER (Winebrenner, 2021). New and ongoing radar, laser altimetry, gravity and magnetic data from  
372 ICECAP and Antarctica’s Gamburtsev Province (AGAP) and COLDEX airborne surveys are helping identify  
373 potential drill sites in East Antarctica. In Greenland, locations on the west side of the east mountain range  
374 where the first ice sheet originated might result in ice more than one million years old. Since the  
375 stratigraphy is likely to be disturbed in that area, methods for dating ice that is not in order  
376 stratigraphically should be further developed before drilling for ice older than 800,000 years in Greenland.

377  
378 **6. Pre-Quaternary atmosphere:** The possibility that very old ice (>3 million years) is preserved in special  
379 environments (for example, in debris-laden glaciers) in Antarctica (e.g., Yau et al., 2015) is exciting because  
380 it would provide a window into the composition of the atmosphere and environment during times when  
381 global environmental conditions were very different from today. A period of considerable interest is the  
382 mid-Pliocene warm period (3.3-3.0 million years BP), that is well-characterized via global proxy  
383 compilations and model intercomparison studies, and sometimes considered a potential analog for  
384 Earth’s future. The Allan Hills site, where ice as old as 6 million years has been recovered, remains the  
385 most promising location for such work. The extreme strain that the ice has experienced at the Allan Hills  
386 site has resulted in very brittle ice so that dry drilling of ice cores has been a challenge; improving the ice  
387 core quality at this site is a priority for drilling COLDEX ice cores. In other regions, some debris-laden  
388 glaciers contain ancient mixtures of ice and rock, which requires specialized drilling equipment. The IDP  
389 Agile Sub-Ice Geologic Drill (ASIG) has proven to be useful in retrieving rock cores from beneath glacial ice  
390 and also in drilling cores composed of ice/rock mixtures.

391  
392 **7. Large-volume sampling of climatic intervals and tracers of high interest:** Rare isotopes, ultra-trace  
393 species, micro-particles, biological materials, and other measurements that have not yet been fully  
394 exploited in ice core research offer new opportunities for discovery if large volumes of ice (e.g., individual  
395 samples larger than approximately 800 cm<sup>3</sup>) are made available. Examples include <sup>14</sup>C of CH<sub>4</sub> to trace  
396 methane hydrate destabilization during past warming events (Petrenko et al., 2017), nano-diamonds, <sup>3</sup>He,  
397 and micrometeorites as tracers of extraterrestrial impacts, and <sup>14</sup>C of CO as a tracer for atmospheric  
398 oxidizing capacity or past cosmic ray flux (depending on site characteristics). In the case of traditional drill  
399 sites, multiple cores or use of replicate coring technology are needed to obtain larger sample sizes, and in

400 situ melting has been suggested (but not yet successfully used) as a means of sampling large volumes of  
401 air from deep ice core sites. A large-volume ice coring effort has been conducted at the Law Dome DE-08  
402 and Dome C sites in East Antarctica, and promising future sites include Das 2 and South Dome in  
403 Greenland.

404  
405 Blue ice areas such as Allan Hills and Taylor Glacier, Antarctica currently provide the best opportunities  
406 for rapid collection of large samples of ancient ice without a heavy logistics burden (e.g., Buizert et al.,  
407 2014). Ice sections ranging in age from Early Holocene to 6 M-year have already been clearly identified at  
408 these sites (e.g., Korotkikh et al., 2011; Yan, 2019; Shackleton et al, in review) and are ready for  
409 access/sampling at the NSF Ice Core Facility by future projects. Continued studies at these sites would  
410 provide more detailed and complete age maps of the desired outcropping ice areas.

411  
412 Depending on the site and scientific target, a range of ice drilling and sampling tools may be appropriate.  
413 The Blue Ice Drill, Eclipse Drill, Foro 400 drill, 4" drill, hand augers, and chainsaws have all been successfully  
414 used. Continuing efforts to maintain and upgrade the capability to explore and retrieve the ice at these  
415 sites are needed.

416  
417 (photo)  
418 Caption: A large-volume ice core drilled on the Taylor Glacier ablation zone, Antarctica. Bubbles in the ice at the site  
419 contain air with direct evidence of ancient atmospheric composition. The Blue Ice Drill is an easily-transportable  
420 drill capable of retrieving quality firn cores of approximately 9.5 inches in diameter as well as quality solid ice cores  
421 of the same diameter with few cracks up to 70 meters below the firn-ice transition. Photo credit: *Jeff Severinghaus*.

422  
423 **8. Ancient microbial life:** Ice sheets provide chronological reservoirs of microbial cells entombed during  
424 atmospheric deposition and studies have shown that microbial DNA and viable organisms can be  
425 recovered from ice cores collected from both Greenland and the Antarctic as well as temperate glaciers  
426 (e.g., Christner et al., 2001, 2003; Miteva et al., 2004). In addition, the distributions of microbial cells  
427 themselves can serve as climatic records in deep ice (Santibáñez et al., 2018), and the microbes/particles  
428 can provide information on snow crystal nucleation in the atmosphere (Schrod, 2020). Many questions  
429 remain regarding how these organisms survive in deep ice for tens to hundreds of thousands of years, the  
430 origin of these airborne microorganisms, and what their diversity and biogeographic distribution reveals  
431 about conditions during deposition. The ability to obtain larger ice volumes in conjunction with advances  
432 in molecular techniques such as metagenomic analyses (Simon et al., 2009) and methods that can amplify  
433 smaller quantities of nucleic acids will enable more detailed study of the genomic potential of resident  
434 microbes and available preserved organic carbon material (D'Andrilli et al., 2017a,b) and how they  
435 integrate with our understanding of ice core ecology. There is interest in investigating the physiology of  
436 microorganisms recovered from ice cores to elucidate unique physiological properties that enable them  
437 to survive in ice for extended periods of time and that may offer important biotechnological applications  
438 (Cavvicholi et al., 2002). For example, studies have shown novel, ultra small microbial isolates from deep  
439 Greenland glacier ice that may inform on how organisms survive energy deprivation for extended periods  
440 of time (Miteva, 2005). It remains unresolved whether entrapped microorganisms have the potential to  
441 alter gas records, which could offer additional explanation/interpretation for observed gas record  
442 anomaly. There is also interest in investigating the reservoir of ice core carbon, not only as paleo stores  
443 of carbon cycling signatures, but also as reservoirs of reactive carbon that may directly impact surrounding  
444 environments when exposed to the atmosphere with melting, calving, and retreat (D'Andrilli &  
445 McConnell, 2021).

446  
447 Recent studies have characterized organic carbon materials within various Antarctic ice cores and shown

448 changing carbon signals measurable from different conditions (spanning back to 27,000 years ago  
449 (D’Andrilli et al., 2017a, b) and within the Holocene of Arctic and the Antarctic ice cores (Grannas et al.,  
450 2006; Xu et al., 2018; King et al., 2019; Vogel et al., 2019; D’Andrilli & McConnell, 2021). High temporal  
451 resolution organic carbon data from the WAIS Divide ice core emphasized the highly complementary  
452 nature of carbon surveys with routinely surveyed geochemical assays in paleo atmospheric  
453 reconstructions (D’Andrilli et al., 2017a). Notably, the preservation paradigm of geochemicals in ice cores  
454 also extends to biological and other organic materials, therefore it will become increasingly important to  
455 characterize their concentrations and qualitative nature now, in the ice, before it melts to reconstruct our  
456 past, learn about our present, and help better predict their impacts in future warming. The inclusion of  
457 organic material (OM) chemical characterizations in ice coring efforts improves geochemical and biological  
458 paleo atmospheric composition interpretations at broad and fine scales, ice sheet carbon storage  
459 assessments and comparisons with other ecosystem OM, understanding of signatures arising from  
460 preservation mechanisms, and the ability to predict the fate of carbon in ice sheets in the Arctic and  
461 Antarctic.

462  
463 **9. Borehole Array for Spatial Variations:** Although borehole observations cannot directly sample ice to  
464 provide a detailed history, an array of boreholes linked to an ice core can provide information on the  
465 spatial variability for any of the ice cores mentioned above in this report. Notably, the Wide Angle  
466 Topographic Sensor for Operations and Engineering (WATSON) instrument has thus far shown a unique  
467 microscale approach to OM and microbial distribution within the ice sheets and in the future requires a  
468 joining of the microscale, fine scale, and broad scale ice core researchers to best understand small to large  
469 spatial variations of materials in ice. (Eshelman et al., 2019; Malaska et al., 2020). Discoveries from ice  
470 borehole research will continue as additional technology is developed. See also section IV.1 below.

## 471 472 **Summary**

473  
474 Advances in understanding the past require arrays of ice cores with depths ranging from tens of meters  
475 to 3,000 m, and the requirements for the coring or sampling vary. Agile drills currently at IDP-Wisconsin  
476 should be continually maintained in excellent working condition so that they can be used for new projects.  
477 Biologically-clean hand augers and agile drills are needed for biological studies in glaciers. The Foro 3000,  
478 capable of coring up to 3,000 m has been created in the same family of drills as the Foro 1650 (aka  
479 Intermediate Depth Drill for coring up to 1,650 m). The large-diameter Blue Ice Drill for shallow drilling  
480 in blue ice areas has been used successfully on Taylor Glacier, Antarctica, and elsewhere. With continued  
481 science attention to blue ice areas as well as to large-volume sampling in general, a re-designed Blue Ice  
482 Drill that can successfully retrieve samples from 200 m depths would be useful. Estisol-140 is used as  
483 drilling fluid in deep drilling. While Estisol-140 had some issues in the first season of use, changes to the  
484 drill and handling procedures in the second season mitigated many of the issues. Neither Isopar-K nor  
485 Estisol-140 are ideal for biological and OM chemistry measurements in ice cores. For those types of  
486 research, the outer layers of the ice cores must be shaved off manually or within the continuous flow  
487 analysis melting system, since they introduce large contaminants into the measurements (Christner et al.,  
488 2005; D’Andrilli et al., 2017b). Table 1 lists characteristics for drills needed for the areas of the science  
489 outlined in the previous sections that are available through IDP. In addition to the drills in Table 1, several  
490 U.S. universities have university-owned drills that may be available by request directly to the university,  
491 for example, the WISSARD/SALSA clean access drill, Roving Drill, and Shot-hole Drill at the University of  
492 Nebraska-Lincoln, and also the Rapid Access Ice Drill (RAID) at the University of Minnesota.

493

494 **Table 1. Requirements of ice coring drills for scientific studies.**

	Diam (cm)	Depth (m)	Ambient temp(C)	Clean coring ?	Transport type	Site occupancy	Int'l aspects	Drill Name
<200 years	5-7	Horiz.	-20	yes	Backpack	Days	US	-
<200 years	5	15	-30	somet imes	Backpack	Days	US	Hand auger
200 year	7-10	400	-50	no	Twin otter/ Lt traverse	Days/ weeks	US	Eclipse, 4", Foro
200 year	7-10	400	-5 warm ice	no	Twin otter/ Lt traverse	Days/ weeks	US	Thermo-mechanical
200 year	7-10	400	-15	no	Ship/helo	Days/weeks	US or shared	Eclipse, 4", Foro
2k array	7-10	<1,500	-50	somet imes	Twin otter/ Lt traverse	Weeks/ month	US part of IPICS	700 Drill, Foro 1650
40k array	10+	1-3k	-50	no	Twin otter/ Herc	1-2 seasons	US or shared	Foro 1650, Foro 3000
Interglacial	10+	1-3k	-50	no	Herc	Multiple seasons	US only or US-led	Foro 1650, Foro 3000
>800k years	10+	3k	-50	no	Herc & traverse	Multiple seasons	IPICS	Foro 3000
Site selection oldest ice	2-4	<1,000	-50	no	Herc & traverse	2 days	IPICS	RAID
>800k years (blue ice)	25	70-200	-40	no	Twin otter	1-2 seasons	US	Blue Ice Drill
1Ma Allan Hills	10	1200	-40	no	Bassler / Herc	3 seasons	US	FORO 1650
Pre-Quaternary atmosphere	7-25 rock-ice mix	200	-40	no	Helicopter	1-2 seasons	US	ASIG
Tracers; large diameter cores	10-25	200+	-40	no	Helicopter/Bassler/ Traverse	1-2 seasons	US, Australia, France	Blue Ice Drill; 4" Drill
Ancient microbial life/ organic material	25	200+	-40	somet imes	Helicopter twin otter, herc	1-2 seasons	US	SchWD
Borehole Array	8	200 to 3.5k	-40	no	Twin Otter/Lt Traverse	Week	US	RAID

495 Additional information on the drills is given in the IDP Long Range Drilling Technology Plan.

496

497 **II. Ice Dynamics and Glacial History**

498  
499 Rapid changes in speed of fast-flowing tidewater glaciers, outlet glaciers, and ice streams observed over  
500 the past decade create an urgency to understand their dynamics (ref). In West Antarctica, ongoing rapid  
501 loss of ice in the regions of Thwaites Glacier and the Amundsen Sea is occurring, with possible accelerated  
502 loss due to ocean-driven melting at the grounding zone and nearby areas (e.g., Smith et al., 2020). A  
503 complete retreat of the Thwaites Glacier basin and resulting release on surrounding ice in West Antarctica  
504 has the potential to eventually raise global sea level by several meters. It is possible that processes such  
505 as hydrofracture and ice cliff failure could lead to a more rapid collapse of Thwaites Glacier within the  
506 next few decades. To reduce uncertainty in the projected contribution of Thwaites Glacier to sea level  
507 rise, the International Thwaites Glacier Collaboration (ITGC) has undertaken a substantial and coordinated  
508 collaboration over the last decade. The Ross Sea sector of the Antarctic Ice Sheet, with its spatially diverse  
509 and changing natural environment, can facilitate process studies through field sampling and field  
510 measurements which will be used in evaluating the current state of the ice sheet, quantifying the  
511 glaciological and oceanographic processes that may play a role in rapid decay of the ice sheet, and  
512 interpreting past ice sheet changes from subglacial and ice-proximal geologic records to understand ice  
513 sheet sensitivity to forcing on different timescales. In general, predicting responses of glaciers and ice  
514 sheets to future possible environmental change requires models that incorporate realistic ice dynamics  
515 (Alley and Joughin, 2012). Ice loss on the Greenland Ice Sheet is also happening at a dramatic rate, and  
516 contains an additional 7.4 meters of sea level equivalent. Predicting dynamic ice loss of major ice streams  
517 in Greenland and Antarctica are major challenges to the international research community. For both the  
518 Antarctic and Greenland Ice Sheets, understanding the history of past ice sheet change is key for  
519 pinpointing ice sheet sectors most sensitive to change. Understanding the timing and extent of ice sheet  
520 response to the past interglacial, using evidence from within and beneath the ice sheet, will inform  
521 predictions of future changes. Measurements and observations of present-day conditions are needed to  
522 develop and validate such models, as are geological and geochronological observations of past ice sheet  
523 history and ice core evidence of past rates of change. Properties of the ice and the ice-bed interface exert  
524 strong control on the flow of glaciers and ice sheets. Instruments deployed down boreholes drilled to the  
525 bed are needed to collect basic data concerning the spatial and temporal distribution of ice properties,  
526 sediments, and subglacial hydrology.

527  
528 Another approach to aid understanding of future ice-sheet response to local and global conditions is to  
529 reconstruct its history. Histories of ice dynamics (thinning and divide location) and environment  
530 (accumulation and temperature) can be inferred from observations from ice cores, basal ice samples, and  
531 boreholes near ice divides. Ice core and borehole data, including basal ice samples for gas analysis, depth-  
532 profiles of age, layer thickness, temperature, ice fabric, and bubble density all provide constraints for ice  
533 flow models. For example, the depth-age relationship contains information about past accumulation and  
534 past thinning; a thin annual layer at depth could imply either low accumulation in the past or ice sheet  
535 thinning (Waddington et al., 2005; Price et al., 2007). Radar-detected layers can also be used to infer the  
536 flow history of glaciers and ice sheets and the history contained in the layers is more complete if their age  
537 is known (Waddington et al., 2007, Dahl-Jensen et al., 2013); ice cores can be used to date intersecting  
538 radar layers. The high-quality radio echo sounding data from the Center for Remote Sensing of Ice Sheets  
539 (CReSIS) and Operation IceBridge both in Antarctica and Greenland make it possible to detect internal  
540 layers reaching to the bedrock. Disturbances, folding, and larger structures are observed that strongly  
541 influence the local ice dynamics and point towards the need for more complex and anisotropic ice  
542 deformation relations.

543

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

546  
547 **1. Basal conditions and geothermal flux:** Direct measurements of bed conditions including frozen/thawed  
548 bed, basal pore water pressure, slip, and sediment properties and deformation are needed to develop  
549 and test realistic models of the controls on the fast flow of ice streams and outlet glaciers. Determination  
550 of whether a bed is frozen or thawed requires coupled thermo-mechanical flow models. A necessary  
551 boundary condition is a realistic realization of the geothermal flux. Geothermal flux has been determined  
552 at a few locations from borehole thermometry, but we expect the geothermal flux to vary significantly  
553 over spatial scales of less than 25 km (Fahnestock et al., 2001). In Greenland, borehole temperature  
554 reconstructions imply low values in south Greenland ( $<40 \text{ mW/m}^2$ , values of  $50 \text{ mW/m}^2$  at Greenland Ice  
555 Core Project (GRIP) and Camp Century and higher values at NEEM ( $80 \text{ mW/m}^2$ ) and North-GRIP ( $130$   
556  $\text{mW/m}^2$ ). Until recently the only measurement in West Antarctica was from Siple Dome ( $69 \text{ mW/m}^2$ ), but  
557 recent borehole temperature measurements from the WAIS Divide borehole indicate a geothermal flux  
558 of at least  $90 \text{ mW m}^{-2}$  and possibly much higher (Cuffey et al., 2016). Measurements of  $\sim 285 \text{ mW m}^{-2}$  at  
559 Subglacial Lake Whillans were made (Fisher et al., 2015). Additional measurements are needed to provide  
560 boundary conditions for ice sheet models. Based on the data to date, geothermal flux values vary  
561 considerably throughout West Antarctica and further investigation is required to provide boundary  
562 conditions for ice sheet modeling.

563  
564 Measurements at the bed of glaciers and ice sheets are hampered because of difficulties accessing the  
565 bed, and keeping boreholes open long enough to deploy sensors. Rapid-access drills that are portable and  
566 capable of drilling to the bed of glaciers and ice sheets multiple times within a several-month field season  
567 are needed to make basic measurements including temperature, heat flux, pressure, deformation, and  
568 slip, and to sample basal sediments and bedrock. The U.S. RAID drill may provide in this capability.  
569 Modular hot-water drills capable of cleanly accessing the bed through 500 m to 2,500 m of ice remain an  
570 urgent need. Logging tools to detect temperature, diameter, inclination, azimuth, and pressure are  
571 needed in connection with the production of ice boreholes.

572  
573 **2. Remote sensing of basal conditions:** Remote sensing such as active and passive seismic arrays and radio  
574 echo sounding complement in situ measurements of bed conditions and englacial properties. Seismic  
575 imaging requires arrays of shallow holes for emplacing sources. The capability for producing large  
576 numbers of shallow holes (25 - 100 m depth, 5 - 10 cm diameter) should be maintained within IDP. The  
577 Rapid Air Movement (RAM) drill needs updates for increased portability, and increased efficiencies  
578 (drilling rate, reduced size, and power consumption) are needed to improve the agility of the RAM drill  
579 for creating shot holes.

580  
581 **3. Sub-ice shelf mass balance:** Ice shelves buttress discharge from ice sheets and ice sheets grounded  
582 below sea level can become unstable after their buttressing ice shelves disintegrate in the Greenland and  
583 Antarctic ice sheets. Ocean temperatures control rates at which the ice shelves melt, and recent  
584 observations (Adusumilli et al. (2020), Schmidt et al (2023), Washam et al. (2023) and Lawrence et al  
585 (2023)) indicate that heterogeneous and small-scale oceanographic processes for sub-shelf melting exert  
586 significant control on the mass balance of ice sheets. Although measurements near the grounding line  
587 have been made and more are being conducted, coverage is still sparse. The melting process is  
588 determined by boundary layer physics that operate on spatial scales of centimeters. Access holes large  
589 enough for deploying instruments on moorings, autonomous underwater vehicles, and remotely operated  
590 vehicles are needed to acquire short-term spatially-distributed data. Additionally, long-term observatories

591 at targeted sites are needed to document temporal variability. All these experiments should be directly  
592 related to grounding-zone studies and linked to oceanographic campaigns beyond the ice shelves.

593  
594 (graphic)  
595 Caption: Heat and mass exchange occurring in sub-ice shelf cavities impact ice flow and ice sheet mass balance.  
596 Image credit: *WISSARD project*.

597  
598 **4. Grounding zone processes:** Improved understanding of processes in grounding zones is needed to  
599 holistically assess the role of ice-ocean interaction on the stability of ice sheets. Conceptual geological  
600 models of grounding-line environments have been inferred from stratigraphic successions, (e.g. Bart et  
601 al., 2017). Remote sensing studies using satellite observations and geophysical surveys have been  
602 conducted at grounding lines of major ice streams (Alley et al., 2007; Anandakrishnan et al., 2007;  
603 Christianson et al., 2013; Horgan et al., 2013), and studies of processes at modern grounding lines are  
604 underway. Records of environmental forcing relevant to grounding zone processes may be provided by  
605 200+ yearlong ice core reconstructions at coastal Antarctic ice rises, and over WAIS since before the  
606 Eemian from an ice core at Hercules Dome. Few direct measurements or materials have been collected  
607 at grounding lines and grounding zones of fast-flowing ice streams and outlet glaciers (Begeman et al.,  
608 2018; Venturelli et al., 2020; Horgan et al., 2025). Small diameter access holes are needed to deploy  
609 instruments to measure spatial and temporal changes in these critical areas. Shallow coring (~300 m) at  
610 Crary Ice Rise, Antarctica could provide a short (1000 year) record while also dating the timing of  
611 grounding at this site and possibly accessing marine ice-filled relic basal crevasses; though ice coring work  
612 was not undertaken, a new 220 m subglacial sediment core was collected in 2025-26 as part of the  
613 international project: Sensitivity of the Antarctic Ice Sheet to 2 Degrees Celsius of Warming (SWAIS2C;  
614 Patterson et al., 2022).

615  
616 **5. Rheological properties of ice:** Rheological properties of ice depend strongly on temperature, impurities,  
617 and texture, including grain size and fabric (Cuffey and Paterson, 2010). Improved understanding of the  
618 controls on the rheology is needed to develop realistic models of deformation of ice sheets. These models  
619 are needed to help develop depth-age relationships in ice cores, understanding flow and shear, and also  
620 to establish past, present, and future responses to possible environmental changes. Folding of deep ice  
621 and large structures forming at the base of the ice are believed to be related to the rheological structure  
622 of ice. Studies at Siple Dome, Antarctica (Bay et al., 2001; Pettit et al., 2011,) and Dome C (Pettit et al.,  
623 2011), for example, have shown that strong vertical gradients in the effective viscosity of ice are likely  
624 present at depth in the ice sheets. These strong variations in ice rheology have the potential to lead to  
625 folding (such as at NEEM, Dahl-Jensen et al., 2013) or the formation of shear bands. Sensors that measure  
626 depth profiles of temperature, fabric, optical stratigraphy, tilt, and borehole diameter in boreholes are  
627 now available and can be calibrated against ice core properties. Rapid-access drills that can drill through  
628 ice up to 3,000 m thick are needed to deploy such sensors. In particular, the ability to drill multiple holes  
629 along a flow line can provide key spatial changes in ice properties. In addition, a system to rapidly access  
630 the ice sheet and then extract ice cores from selected depths would allow analyses of ice properties at  
631 depths of special interest; such a drill does not yet exist but should be planned.

632  
633 **6. Glacial history:** Defining the extent and volume of ice sheets under paleoclimatic conditions warmer  
634 than the present (Mid-Holocene, Eemian, Marine Isotope Stages 11 and 14, and Pliocene warm periods in  
635 Greenland and Antarctica) is an important indicator of future ice sheet vulnerability. A variety of indirect  
636 approaches have been used to constrain the history of ice sheets (glacial geology, paleoceanography,  
637 etc.); dating the basal ice from the ice sheet that has moved across landscapes may help to inform  
638 constraints. Basal ice age can be modeled with age-depth flow models, or more directly by dating trapped

639 air in basal ice. Slow-moving ice in the vicinity of ice divides contains a record of past ice dynamics (thinning  
640 and divide location). Depth profiles of age and temperature from ice cores and boreholes can be used to  
641 extract histories of accumulation and ice dynamics (Waddington et al., 2005; Price et al., 2007). Records  
642 from coastal domes and coastal ice caps are of special interest because they can be used to infer past  
643 extents of ice sheets and the history of deglaciation (Bindschadler et al., 1990; Conway et al., 1999).  
644 Intermediate depth (~1,500 m) cores to measure depth-profiles of age and temperature at targeted  
645 coastal domes are needed to help constrain the deglaciation of ice sheets. Coring on ice domes near the  
646 Amundsen Sea Embayment, Antarctica may be able to provide a context for more recent observed  
647 changes in ice dynamics, particularly accelerated thinning in the most recent several decades.  
648

649 Analysis of bed material (sediment or rock, in grab samples or in cores) is an emerging field in expanding  
650 our knowledge of glacial history and in characterizing past environments that drive ice sheet absence. For  
651 example, cosmogenic nuclides in sediment and bedrock beneath ice sheets can tell us about their former  
652 extent, and the timing and duration of past exposure periods (e.g. Schaefer et al, 2016; Christ et al., 2021,  
653 2023; Balco et al., 2023). Techniques to estimate the size and shape of ice sheets during colder periods  
654 are well established (e.g., Mercer, 1968, Denton et al., 1989, Todd et al., 2010; Bentley et al., 2010; Stone  
655 et al., 2003; Hall et al., 2004; Anderson et al., 2014); determining their extent and thickness under warmer  
656 conditions is more problematic. Much of the evidence is hidden beneath the present ice sheets (Johnson  
657 et al., 2022; Briner et al, 2022). Recovery of basal ice cores for gas analysis is useful when obtained in  
658 conjunction with analysis made in cores of basal material such as sediment and rock. Under shallow ice,  
659 nimble methods for reconnaissance recovery of short rock cores for cosmogenic nuclide techniques to  
660 quantify periods of exposure (ice free) and burial (ice cover) have been developed, for example the Agile  
661 Sub-Ice Geological Drill (ASIG) and ice-enabled Winkie drill for use near the ice margins (Boeckman et al.,  
662 2021; Kuhl et al., 2021; Braddock et al, 2024). Under very deep ice (greater than approximately 1,000 m),  
663 rapid access drilling using the RAID drill may open up new perspectives on ice conditions in a warmer  
664 world.  
665

666 (photo)

667 *Caption: John Goodge and a colleague collecting specimens in the Transantarctic Mountains. Photo credit: John*  
668 *Goodge/University of Minnesota-Duluth.*  
669

670 Depth profile measurements on short (1-5 m) subglacial bedrock cores are used to elucidate glacial history  
671 (Balco et al., 2023), and identify surfaces that constrain subglacial landscape evolution by subglacial  
672 erosion (Balter Kennedy et al., 2021). Erosion reduces and ultimately erases the nuclide profile, so eroded  
673 surfaces must be avoided by targeting surfaces where ice is frozen to the bed. Note, however, that small  
674 amounts of erosion can be identified and the effects constrained using combinations of nuclides with  
675 different production profiles (Liu et al., 1994). With rapid access to subglacial bedrock in which  
676 cosmogenic nuclides can be measured, key problems can be addressed, such as the vulnerability of the  
677 West Antarctic, parts of the East Antarctic, and Greenland Ice Sheets to future warming, Pliocene ice-  
678 sheet collapse, and the onset of continental glaciation in Antarctica. Potential targets to address the  
679 interglacial extent of West Antarctic glaciation include Mt. Resnik, a subglacial peak which rises to within  
680 330 m of the surface near the WAIS divide (e.g., Morse et al., 2002), ice rises particularly along the Siple  
681 Coast such as the Crary and Steershead ice rises (e.g., Scherer et al., 1998), the subglacial roots of nunataks  
682 (rocks emerging above the ice) in the Pine Island and Weddell Sea catchments (Balco et al., 2023; Johnson  
683 et al., 2025). A variety of sites in Greenland including both interior sites (e.g., Schaefer et al., 2016) and  
684 peripheral sites and independent ice cap sites (Briner et al., 2022) would lead to impactful constraints on  
685 past ice sheet and sea level change. For example, targeting certain marine domains and areas bordering  
686 NEGIS would constrain past ice response in Greenland's most vulnerable areas. In addition, ongoing

687 international studies of past ice thickness variations evidenced from multiple cosmogenic nuclides on  
688 nunatak altitude transects in Dronning Maud Land would benefit from future sampling of subglacial  
689 nunatak slopes. Data from beneath high-altitude domes and plateaus in the Transantarctic Mountains,  
690 and also from subglacial debris-rich ice from outlet glaciers that drain marine basin margins (e.g. Wilkes  
691 and Aurora basins), or from subglacial strata directly, could shed new light on the long-running debate  
692 over ice-sheet collapse in the Pliocene (e.g., Webb et al., 1984; Denton et al., 1993).  
693 A variety of isotopes with varying half-lives (half-life:  $t_{1/2}$ ) can be used to constrain long-term ice sheet  
694 stability (e.g.,  $^{37}\text{Cl}$ ,  $^{26}\text{Al}$ ,  $^{10}\text{Be}$ ), and new application of in situ  $^{14}\text{C}$  can constrain Holocene ice sheet changes,  
695 as has been shown in Antarctica (ref). In Greenland for example, in situ  $^{14}\text{C}$  measurements from periphery  
696 ice drilling sites would provide ice sheet models with direct measures of ice sheet presence/absence  
697 during smaller-than-present ice sheet conditions during the Holocene thermal optimum. This Eventually,  
698 measurements of long-lived radionuclides such as  $^{53}\text{Mn}$  ( $t_{1/2} = 3.7$  million years) and  $^{129}\text{I}$  ( $t_{1/2} = 16.7$  million  
699 years) paired with stable  $^3\text{He}$  and  $^{21}\text{Ne}$  may even provide constraints on the early Neogene onset of  
700 Antarctic glaciation, targeting samples from the subglacial Gamburtsev Mountains.

701  
702 **Summary**

703 Understanding present and past behaviors of glaciers and ice sheets is essential for improving predictions  
704 of future behavior of ice sheets and sea level. Improved understanding requires fast-access drilling, such  
705 as those from the IDP Agile Sub-Ice Geological (ASIG) Drill, the IDP ice-enabled Winkie drill, the Rapid  
706 Access Ice Drill (RAID).and Clean-access, hot water drills, though not presently available in the U.S. suite of  
707 tools, are imperative to enable fundamental measurements of: (i) physical conditions, including  
708 geothermal flux, and processes at the beds of glaciers and ice sheets; (ii) physical properties of the ice that  
709 affect ice flow and folding, (iii) physical processes at grounding lines and grounding zones of fast-moving  
710 ice streams and outlet and tidewater glaciers; (iv) ice-ocean interactions at grounding lines, and (v)  
711 analysis of subglacial bed material for records of ice sheet history and microbiology. Past responses of  
712 glaciers and ice sheets and sea level changes also offer clues to future possible responses. Depth profiles  
713 of age and temperature from ice cores can be used to reconstruct past thickness and extent of ice sheets  
714 as well as environmental conditions. Basal ice cores in condition suitable for trapped gas analysis provide  
715 dating of the basal ice. Recovery of subglacial sediments that record paleo conditions and  
716 paleoenvironmental proxy information provide evidence of past conditions in area now covered by ice,  
717 including interglacial conditions that guide model projections of future warmth scenarios. Intermediate  
718 depth (~1,000 m) cores at targeted coastal domes are needed to constrain the extent and timing of  
719 deglaciation. For reconnaissance of sites for bedrock coring under shallow ice, the use of a very agile ice  
720 coring drill (e.g. Foro or Eclipse drill) along with a method of sampling rock at the ice-rock interface using  
721 the same or slightly modified drilling apparatus, would provide a logistically agile way of site selection for  
722 subsequent rock drilling of meters-long rock cores. The collection of basal ice cores for trapped gas  
723 analysis, and subglacial bedrock for cosmogenic nuclides from both strategic periphery sites and also from  
724 the ice sheet interior can provide direct constraints on past ice sheet history.

725  
726 Table 2 below lists the characteristics required of drills for endeavors in subglacial science. The IDP Long  
727 Range Drilling Technology Plan discusses IDP drills available for retrieving cores or creating access holes  
728 in ice sheets. Note that the Clean Hot Water Drill (CHWD) in Table 2 is owned by the University of  
729 Nebraska-Lincoln (UNL). In addition to the CHWD, the following UNL drills may be available by direct  
730 request to UNL: the WISSARD/SALSA clean access drill, the Roving Drill, and Shot-hole Drill.

731  
732  
733

734 **Table 2. Requirements of drills needed for studies of ice dynamics and glacial history.**

735

	Diam (cm)	Ice Depth (km)	Core or hole	Ambi ent temp (°C)	Clean access?	Transport type	Site occupanc y	Int'l Aspects	Drill Name
Bed conditions	8	1-3	Hole	-50	maybe	Twin otter/ helo/lt traverse/Herc	<4 weeks	US & others	CHWD
Geothermal flux	5-8	1-3	Hole	-50	no	Twin otter/ helo/lt traverse/Herc	<4 weeks	US & others	RAID
Geologic coring for cosmogenic samples and for basal ice samples	6-10	0.1- 2.5	Basal ice core, Rock core	-50	no	Helo sling load/ Baseler/ traverse	4-8 weeks	US	Winkie/ASIG / RAID
Nimble geologic coring and basal ice coring under shallow ice	3-5	<.5	Basal ice core, Rock core	-30	no	Twin otter/helo/ lt traverse	<4 weeks	US	Winkie/ ASIG
Rheological properties	8	<3k	Hole	-40	no	Herc/ traverse	<4 weeks	US & others	RAID/ CHWD
Internal layering	8-10	<3k	Hole	-40	no	Herc/ traverse	<4 weeks	US & others	RAID/ CHWD
Sub-ice shelf/ice stream instrumentation	10- 25	<1k	Hole	-30	shelf- no; stream- yes	Twin otter/ helo/ herc/ traverse	2 weeks	US & others	CHWD/ SchWD
Ice shelf ROV deployment	100	<1k	Hole	-30	no	Twin otter/ helo/Herc/ traverse	2-4 weeks	US & others	CHWD/ SchWD
Grounding zone	8-75	<1k	Hole	-30	no	Helo/Herc/ traverse	2 weeks	US	CHWD/ SchWD
Seismic imaging	5-10	~100 m	Hole	-40	no	Twin otter/ helo	Hours/da ys	US	RAM/ SHWD

736

737

738 **III. Subglacial Geology, Sediments, and Ecosystems**

739

740 Bedrock, sediments, and ecosystems existing within and beneath ice sheets remain largely unexplored  
741 primarily because of a lack of logistical access to work in the deep field, and also because additional drilling  
742 technologies are required. Rapid access to subglacial environments is needed to address a wide range of  
743 science questions. Specifically:

744

745 **1. Bedrock geology:** The Antarctic continent and its lithospheric plate, play important but poorly  
746 understood roles in global tectonic architecture, leading to contradictory hypotheses. Antarctica is  
747 considered aseismic, but if so, it would be unique among all of the continents. Its plate is surrounded by  
748 mid-ocean-ridges, and hence should be under compression, yet there are active extensional regimes. The  
749 West Antarctic Rift System is one of the largest on Earth, and currently known attributes are unique, by  
750 having only one rift shoulder and by being largely below sea level. In Greenland, island-wide geophysical  
751 datasets have recently been synthesized to map the boundaries between first-order geological provinces  
752 beneath the ice sheet (MacGregor et al, 2024). Recovery of bedrock samples is essential to ground-truth  
753 these geophysical inferences, particularly in geological provinces with no known surface outcrop.  
754 Fundamental questions about bedrock beneath both the Greenland and Antarctic Ice Sheets persist. What  
755 is the origin of subglacial mountain ranges and how have they influenced the overlying ice sheet? What  
756 are the composition, geothermal heat flux, and geotectonic histories of Antarctica and Greenland, and  
757 how do they influence ice sheet behavior? What were the dominant factors controlling the spatial extent  
758 and temporal variability of ice sheets during warm periods in the past? What is the role and history of  
759 subglacial sediments in the interior? What are the physical conditions at the base of the ice sheets? The  
760 state of stress in basement rocks is required for evaluating seismicity and extensional regimes. Boreholes  
761 through the ice into crustal rocks are needed to conduct passive and active seismic experiments for  
762 delineating crustal structure. Continental topography is a significant control on glaciation; rising  
763 mountains and higher elevations focus snow accumulation and become nivation centers for ice sheets.  
764 Sampling bedrock to determine its age and constrain its cooling history using thermochronology is  
765 important for supercontinent reconstruction, understanding the tectonic history of the continent as well  
766 as reconstructing paleotopography for glaciological modeling of ice sheet history. Access boreholes to the  
767 ice sheet bed are required to recover short rock and sediment cores for these studies. Locations should  
768 be based on best estimates of bedrock geology, bed paleotopography, and plausible ice sheet extents  
769 based on models. In Greenland, the ice sheet has waxed and waned during the last 2.5 million years.  
770 Erosion of mountains and ice sheet modeling has simulated past changes, but access to old ice and basal  
771 rocks/material is needed for verification and full understanding.

772

773 **2. Subglacial basins and sedimentary records:** The records of glaciation and their variations in Antarctica  
774 are found in scattered terrestrial deposits and sedimentary basins and can be compared with offshore  
775 records that have been collected near the margins. Interior subglacial basins also likely contain proxy  
776 records of paleo conditions and ice sheet history to complement these records from the continental  
777 margins. Four main categories of sedimentary targets are: subglacial lakes, ice rises, West Antarctic  
778 sedimentary basins, and East Antarctic marine and terrestrial basins. Each category may have a variety of  
779 origins and histories because of differing locations relative to the ice sheet margin and magnitudes of past  
780 ice sheet fluctuations. Thus, they may provide valuable archives of paleo-ice sheet and paleoclimatic  
781 changes. Subglacial lakes occur throughout the continent, the largest being subglacial Lake Vostok.  
782 Subglacial lakes contain sedimentary records; sediments have been collected at the Whillans Subglacial  
783 Lake (Hodson et al, 2016), and Mercer Subglacial Lake (Rosenheim et al., 2023; Siegfried et al., 2023).

784

785 (graphic)

786 Caption: Illustration showing the aquatic system that scientists think is buried beneath the Antarctic ice sheet. Photo  
787 credit: *National Science Foundation, Photo Gallery.*

788 Subglacial ice rises can cause locally grounded “pinning points” that play an important role in buttressing  
789 the discharge of streaming ice from the ice sheet. Recovery of these sediments will provide Neogene and  
790 Quaternary paleo-environmental archives, but may also provide insights on till deformation processes  
791 downstream of ice streams. Shallow drilling of ice rises and acquisition of over-snow seismic reflection  
792 profiles radiating away from ice core sites will allow the deeper geometry of the strata to be evaluated  
793 for locating future drill sites for recovery of long, continuous records in adjacent marine basins. In West  
794 Antarctica, the stratigraphic record in various basins and probable rifted grabens may contain a mid-late  
795 Mesozoic and Cenozoic history of West Antarctic evolution and paleo condition history. Recently, Mengel  
796 and Levermann (2014) suggested that only a narrow, low coastal rim holds the portion of the East  
797 Antarctic ice sheet overlaying the Wilkes Subglacial Basin back, raising concern about ice sheet stability.  
798 In Northwest Greenland, airborne geophysical data have been used to infer the presence of subglacial  
799 sediments deposited in a lacustrine environment (Paxman et al, 2021). Accessing these sediments via  
800 subglacial drilling would enable the recovery of valuable archives of past environmental conditions and  
801 ice sheet history, as has been achieved elsewhere in the Arctic (Melles et al, 2012).

802  
803 Access holes are also needed to recover longer sedimentary cores comparable to those from the  
804 continental margins. Also, the basins on the interior of the Transantarctic Mountains may be sites for good  
805 proxy records of past ice sheet dynamics. These are also excellent sites to measure geothermal heat flux  
806 to help constrain ice sheet bed conditions.

807  
808 **3. Sub-ice microbial ecosystems and biogeochemistry:** Aqueous and sedimentary subglacial  
809 environments in Antarctica and Greenland are inhabited by microorganisms (e.g., Christner et al., 2014;  
810 Dubnick et al., 2017; Davis et al., 2023) and are a potentially large planetary reservoir of microbes and  
811 (microbially derived) organic carbon, perhaps of the same magnitude as that in the surface oceans.  
812 Modeling and direct measurements (Wadham et al., 2012; Michaud et al., 2017) suggests these  
813 environments could contain large volumes of the greenhouse gas, methane, which could greatly impact  
814 atmospheric concentrations in response to rapid deglaciation. It has also been hypothesized that the flux  
815 of dissolved elements and sediments in subglacial waters can enhance primary productivity in the marine  
816 environments they drain into (Hawkings et al., 2020; Vick-Majors et al., 2020; Hawkings et al., 2025).  
817 Elucidating the spatial and temporal distribution and dynamics of these aqueous environments, including  
818 their physical and chemical properties (such as temperature, salinity, and pressure) and associated  
819 biogeochemical processes (i.e., microbial communities and organic carbon material fluxes) are key to  
820 understanding ice sheet stability and the role of large continental ice sheets in global biogeochemical  
821 cycles. The rapid changes anticipated in the size of polar ice sheets may trigger significant reorganization  
822 of subglacial hydrologic conditions, which may feed back into acceleration of ice sheet retreat; the  
823 increased influx of subglacial water and microbial products into marine systems would further amplify  
824 these influences (Vick-Majors et al., 2016).

825  
826 The long timescale of microbial entrapment in sub-ice environments relative to the lifetimes of microbial  
827 cells provides an opportunity to explore questions concerning rates of evolution, and constraints on  
828 biodiversity. The timing of microbial isolation from mixing with the ‘surface’ biosphere can inform how  
829 long an ice mass has existed. Microbial cells and their genomic material should also provide valuable  
830 information that can be linked to paleoclimatic change; such life forms may be the only biological survivors  
831 in areas covered by glaciations for millions of years. Icy systems on Earth also may provide crucial  
832 terrestrial analogs for extraterrestrial life surviving and persisting on icy planetary bodies in our solar  
833 system, such as Mars, Europa, or Enceladus. Of particular interest is the distribution and ecological

834 function of the resident microbes, the extent to which biogeochemical weathering occurs, and the genetic  
835 diversity of microbial communities in subglacial lakes and sediments.  
836 Furthermore, the forward motion of thick layers of water-saturated till beneath fast-flowing ice streams  
837 may provide a pathway for transportation of subglacial biological and diagenetic materials and weathering  
838 products to the surrounding ocean, as does the movement of debris-rich basal ice. The deep subglacial  
839 sediments may contain abundant microbial communities. Some subglacial meltwater is also transported  
840 over long distances within basal drainage systems, which again, likely discharge subglacial nutrients,  
841 microbes and their metabolic products into circum-Antarctic seawater. Biologically clean access holes  
842 through the ice and the acquisition of basal ice cores are needed for this science, and, for scientific and  
843 environmental integrity, these studies must be conducted with clean technology both during access and  
844 sample acquisition. This science is progressing and solutions to the logistical and drilling challenges for  
845 working in the deep field in Antarctica need to be addressed.

846  
847 (photo)

848 Caption: Microbial ecosystems have been found under the West Antarctic Ice sheet (Christner et al., 2014).  
849

850 **4. Subglacial lakes and hydrological systems:** Subglacial hydrodynamics are an important yet poorly  
851 understood factor in ice sheet dynamics in both Antarctica and Greenland. The volume and distribution  
852 of water exert strong influences on the resistance of the bed to ice flow and therefore, is an important  
853 control over ice velocities. More than 650 subglacial lakes have been discovered in Antarctica (Livingstone  
854 et al., 2022). Measurements to quantify present-day lakes and subglacial hydrological systems are  
855 important for understanding ice dynamics, weathering and erosion of subglacial rock, sediment transport  
856 and jökulhlaup events (glacier-dammed lake outburst flood) and microbial ecosystems. Of particular  
857 interest is to establish the diversity of life in subglacial lakes, the degree of hydrological interconnectivity  
858 between lakes and the Southern Ocean, and their influence on the rest of the subglacial hydrological  
859 system. The lakes also house sedimentary evidence of ice sheet and geological histories and changes  
860 (Siegfried et al., 2023; Venturelli et al., 2023). Cleanly drilled access holes and the ability to collect samples  
861 of water and sediments are necessary to understand these systems. In addition, data from Subglacial Lake  
862 Whillans suggests that in active hydrological systems, water geochemistry, microbial life, and hydrology  
863 are intimately connected (Vick-Majors et al., 2016), as in many other terrestrial and marine biospheres  
864 around the world. Understanding the temporal dynamics and geochemical ramifications of subglacial  
865 processes requires installation of sensor strings capable of collecting subglacial hydrological data including  
866 dissolved oxygen concentrations, current velocity and direction, and salinity.  
867

868 Russian drillers accessed Subglacial Lake Vostok, Antarctica during the 2011-12 season, and then during  
869 2012-13 successfully recovered an ice core (~30 m) of the frozen lake water that entered the borehole the  
870 year before. Hot water drilling at Lake Whillans, Antarctica included a filtration unit and UV-treatment  
871 system to decrease contaminants in the drilling water and provide clean access to the subglacial  
872 environment (Priscu et al. 2013), and it was used again to access Subglacial Lake Mercer in 2019 (Priscu  
873 et al. 2021). The filtration technology was successful at reducing microbial bioload and other  
874 contaminants in the drilling fluid as per the Antarctic Treaty Code of Conduct (Michaud et al., 2021).  
875

## 876 **Summary**

877  
878 Subglacial environments contain biologic, climatic, geologic, and glaciologic materials and information,  
879 much of which cannot be obtained elsewhere. Drills to create access holes are urgently needed to sample  
880 basal ice, subglacial water and sediments, and bedrock, but are notably missing from our capabilities  
881 within the IDP. Hole diameter requirements vary depending on instrumentation needed; clean technology

882 is required (NRC, 2007), as is strict environmental review where the bed is wet, except for ice shelves and  
883 grounding zones at the end of drainage basins. Successful sampling will require that access holes receive  
884 regular maintenance, allowing the holes to remain open for several days. Differential ice motion may be  
885 a complicating factor, especially if the ice sheet is sliding at the bed. Given the logistical challenges in  
886 working in the deep field, modular hot water drilling technology and also technologies for sampling  
887 through ice boreholes should all strive to minimize the supporting logistical requirements.  
888

889 The desired characteristics of the drills needed to create clean access holes for the science of the sub-ice  
890 environment are provided in Table 3. For accessing sensitive targets such as subglacial lakes, hot water  
891 drills should have temperature and depth sensors and “smart” drill heads; this technology needs to be  
892 developed. For the drills in Table 3, The IDP Long Range Drilling Technology Plan discusses hot water and  
893 mechanical rapid-access drills that could provide clean access holes for the projects described above in  
894 this report. Clean mechanical rapid-access drills do not currently exist; conceptual and engineering  
895 development is needed. Note that CHWD is the Clean Hot Water Drill owned by the University of  
896 Nebraska-Lincoln; in addition, the University of Nebraska-Lincoln owns the following drills that may be  
897 available by request directly to the university (D. Harwood): the WISSARD/SALSA clean access drill, the  
898 Roving Drill, and Shot-hole Drill.

899  
900

901 **Table 3. Requirements of drills needed for studies of subglacial geology, sediments, and ecosystems.**  
902

	Diam. (cm)	Depth (km)	Core or hole	Ambient temp (°C)	Transport type	Site occupa ncy	Int'l aspects	Environ restrictions	Drill Name	
Sediments/i ce sheet dynamics (Wet bed)	10-25	0.2-3	Hole, sediment core	-50	Helo/Twin Otter/travers e/Herc	weeks	U.S. & others	Clean access	CHWD/ SchWD	
Biogeochem (Wet bed)	3-25	<3	Hole, sediment/r ock, basal ice core	-50	Helo/Twin Otter/travers e/Herc	weeks	U.S. & others	Clean access	CHWD/ SchWD	
Bedrock geology/ Tectonics (Frozen bed)	5-10	1-3	Icehole, rock core	-50	Herc/travers e	4-8 weeks	U.S.	None (dry bed only)	RAID/ ASIG	
Geology/ ice sheet history (Wet bed)	5-20	<4k	Hole, rock core	-50	Herc/travers e	weeks	U.S. & others	Clean access	-	
Deep Subglacial lake biogeochem (Wet bed)	50-100	3-4k	Hole, sediment, basal ice core	-50	Herc/TwinOt ter /traverse	4-8 weeks	U.S. & others	Clean access	CHWD	

903  
904  
905  
906

907 **IV. Ice as a Scientific Observatory**

908

909 Polar ice sheets and mid-latitude ice caps archive evidence of the past and ice dynamics and also serve a  
910 variety of endeavors that use the ice as a platform for science. Borehole access to the interior of the ice  
911 sheet enables wide-ranging observations, from glaciology, climatology, and planetary science to  
912 experimental astroparticle physics.

913

914 **1. Borehole logging for past conditions and ice dynamics:** Borehole logging of both fast-access holes and  
915 boreholes originally drilled for ice cores greatly enhance evidence of the past and ice dynamics preserved  
916 in the ice. These analyses are difficult or impossible to obtain by other methods, and complement  
917 observations from ice cores and remote sensing platforms. Borehole logging is nondestructive, non-  
918 contaminating, continuous, and immune to core damage or drill depth errors and permits study of a large  
919 volume of ice in situ. Ice sheet boreholes serve as enduring scientific observatories. For example, borehole  
920 paleothermometry probes provide the most direct measurement of temperature histories and can be  
921 used to calibrate other paleoclimatic indicators. Optical borehole probes can rapidly obtain stratigraphic  
922 records, which are more coherent and detailed than can be reconstructed from core measurements.  
923 Borehole sonic loggers can provide continuous records of ice fabric that are difficult or impractical to  
924 obtain using thin sections of core. Repeated measurements of fabric, tilt, and hole deformation improve  
925 modeling of ice sheet behavior and stability over time as an ice sheet flows over uneven terrain. Logging  
926 multiple nearby rapid access holes permits advanced studies of past conditions and ice flow.

927

928 **1.1 Winches:** Winch platforms that can support borehole-logging projects are important community  
929 resources. IDP has three winches in inventory, one for intermediate depth (1.5 km) and two for deep (4  
930 km) applications. IDP has adopted a standard wireline for all community winches, a 3/16" four-conductor  
931 armored oil-patch cable with a 1" Gearhart-Owen cable head. IDP has also established a policy of  
932 deploying a trained operator to the field along with the IDP winches, particularly the deep winches.  
933 Although this cost is not directly reflected in proposal budgets, a cost estimate is included with each  
934 proposal requiring IDP resources, for NSF budgeting purposes, as is the case with ice and rock coring drills.  
935 In certain cases, the PI or members of the PI's team may be trained and certified to operate the winches,  
936 particularly the intermediate depth winch.

937

938 (photo)

939 Caption: Ryan Bay and Elizabeth Morton deploy borehole-logging instruments at Siple Dome, Antarctica. Photo  
940 credit: *Joseph Talghader*.

941

942 Pre-deployment winch telemetry testing of all logging tools is essential for successful fieldwork. Whenever  
943 possible, logging tools should be tested over the winch that will be used in the field. In some cases IDP  
944 leaves winches deployed to save logistical cost and effort, and tools must instead be tested on winch-  
945 cable systems that are electrically similar.

946 Pressure testing of new borehole tools prior to deployment is performed at an IDP facility in Madison,  
947 Wisconsin. IDP maintains a pressure chamber for testing tools up to pressures of 6 kpsi. The chamber is  
948 approximately a 3-meter cylinder with an inside diameter of 25.4 cm. Pressure testing is especially  
949 important with Estisol-140 drill fluid, since it is more aggressive than other drill liquids and even small  
950 leaks may damage internal components.

951

952 **1.2 Borehole preservation:** Where practical, drilling practices and materials should be chosen to produce  
953 and maintain clean uniform boreholes, and to keep the boreholes accessible. Anticipated failure modes  
954 of glacial boreholes include:

- 955 · “Natural” end-of-life borehole collapse: Depending on the strain regime, complete collapse of even a
- 956 borehole fully compensated with fluid occurs over years and is largely unavoidable.
- 957 · Borehole collapse due to removal or failure of borehole casing: Premature collapse can be avoided by
- 958 leaving the casing in place, proper casing design, and maintenance.
- 959 · Borehole burial: Burial of borehole casing by snow accumulation.
- 960 · Ice plug: An ice plug can form at the fluid level when a partial casing failure permits snow and ice to
- 961 accumulate in the well.

962  
963 Over time borehole-drilling fluids can become turbid, degrading optical measurements. Best practices  
964 should include avoiding the introduction of substances such as heavy greases in the borehole, and  
965 materials that can be dissolved by solvents used as drill fluids. IDP also provides towers and sheave wheels  
966 needed for borehole access. The IDP Englacial and Subglacial Access Working Group aims to work with  
967 community scientists to develop a strategy to make best use of available boreholes.

968  
969 **1.3 Recent logging projects: WAIS Divide:** Several groups have logged the WAIS Divide ice core borehole  
970 in the 2014 to 2017 time frame. Measurements included temperature, optical, and seismic profiling, and  
971 an acoustic caliper along with a kHz acoustic fabric logger for the kHz range. WAIS Divide drilling included  
972 five replicate coring deviations and this logging activity was the first to be done in a borehole with  
973 deviation channels. The Replicate Coring System for the DISC drill was designed in order to make all  
974 deviations on the uphill side of the main borehole, so that logging tools naturally follow gravity and remain  
975 within the parent channel. The deviations did affect logging data and some issues were encountered  
976 while passing the deviations, in particular the acoustic logging tool was diverted into the side channel at  
977 the deviation with the most borehole damage near 3,000 m, but accessed the main borehole on a  
978 following attempt. Three other logging tools followed the main borehole and passed all deviations without  
979 incident. The deviation drilling and subsequent borehole logging at WAIS Divide was largely successful.

980  
981 **South Pole Ice (SPICE) core:** The Foro 1650 (aka Intermediate-Depth Drill) was deployed to the South Pole  
982 for the 2014-15 and 2015-16 field seasons, successfully collecting 1,751 m of ice core. The SPICE Core  
983 borehole is pressure compensated by Estisol-140, which has caused convective problems in temperature  
984 logging because of its high viscosity. Estisol-140 has also exhibited a tendency to cloud, which could affect  
985 optical logging. The SPICE core project is a benefit to ongoing South Pole in-ice particle physics projects,  
986 by providing ground truth measurements of ice chemistry, fabric, and particulates for characterization of  
987 optical, radio, and acoustic signal propagation. Due to the proximity of the drill site to the IceCube and  
988 ARA arrays, the borehole continues to serve as an access point for calibration of existing and future South  
989 Pole in-ice physics and astrophysics experiments.

990  
991 **Rapid Access Ice Drill (RAID):** The RAID drill can penetrate deep ice sheets and core small samples of ice  
992 and subglacial basal rock material (Goodge & Severinghaus, 2016), and it recently demonstrated capability  
993 for ice borehole logging (Goodge et al., 2021). RAID can produce 3-5 boreholes every season, and these  
994 boreholes will potentially serve as scientific observatories for the study of ice and records of the past.  
995 RAID will require a dedicated logging winch integrated with the drilling platform, capable of reaching 3,000  
996 m for logging immediately following borehole cutting. Measurement of pressure will ensure that the  
997 borehole is properly compensated and optical dust logging will provide immediate verification of the  
998 depth-age model. Additional measurements could include temperature, diameter, borehole  
999 inclination/trajectory, and a camera. It would be desirable to rapidly log temperature and borehole  
1000 diameter immediately after drilling, possibly at the same time as the optical dating. These preliminary  
1001 readings could form baselines for subsequent measurements and time evolution studies. Infrastructure  
1002 will be needed to manage future borehole logging projects that will make use of RAID boreholes.

1003

1004 **RAID borehole instrumentation and preservation:** RAID has the potential to create many deep boreholes  
1005 over a number of years. Instrumenting and preserving every RAID borehole indefinitely is impractical.  
1006 The RAID project, with englacial and subglacial research community, will need to determine the scope of  
1007 instrumentation and preservation efforts. The science goals and the number of holes to instrument,  
1008 preserve, the priority of holes and the duration of the effort will need to be weighed against cost and  
1009 availability of logistics.

1010

1011 Borehole preservation effort could be separated into short-term (<5 years) and long-term time horizons.  
1012 Preservation of each RAID borehole for 3 - 5 years will allow for repeat measurements, particularly in  
1013 studies of borehole temperature and deformation. Uncased and under-balanced boreholes could be of  
1014 interest for deformation studies, although removal of the casing and fluid head will limit the lifetime of  
1015 the borehole to a few years.

1016

1017 RAID may also select a subset of holes for long-term preservation, to serve as observatories and to allow  
1018 for future technology developments. Preservation would require leaving a sturdy casing in place,  
1019 maintaining, and periodically extending the casing above the snow surface, as well as removal of ice plugs  
1020 when necessary. Holes near ice divides could be kept open for decades in principle. In off-axis zones,  
1021 shearing could severely limit borehole lifetime and closure may occur at discrete depths. In higher  
1022 accumulation areas, it may be possible to use an extended casing supported by a lightweight tower to  
1023 relieve maintenance effort. Qualifying tools (borehole diameter, inclination/trajectory, camera) could be  
1024 useful for assessing borehole condition prior to fielding a more substantial logging mission. Holes selected  
1025 for long-term preservation would likely be chosen to form a geographically diverse set.

1026

1027 **1.4 Borehole qualifying:** IDP does not currently maintain logging tools for verifying borehole parameters  
1028 such as inclination, diameter, depth, roundness, temperature, etc. There is growing consensus in the  
1029 logging community that IDP should develop this capability. A hole qualifying system could be deployed  
1030 each season as a hole is drilled or upon hole completion. The information provided by such a logging  
1031 system could be crucially important for drillers, particularly for drills with little or no down-hole sensing  
1032 capacity, such as the Foro 3000, the Foro 1650, or the RAID. These logging measurements could also  
1033 provide a baseline for longer-term borehole deformation studies.

1034

1035 **1.5 Borehole Allocation Committee:** The IDP Englacial and Subglacial Access Working Group (ESAWG)  
1036 will be exploring formation of a special committee to advise IDP on management of community borehole  
1037 resources as the research community continues to grow. These resources include winch and winch  
1038 operators, logging tools and accessories, and borehole time. Pre-deployment reviews of logging projects,  
1039 with participation by IDP engineers, will ensure that new tools are safe and ready to deploy.

1040

1041 **2. Ice as platform for physics and astrophysics:** Substantial efforts are under way to use glacial ice as a  
1042 platform for study of fundamental physics and astrophysics. These experiments make use of polar ice as  
1043 an abundant, clean, stable, low-background and transparent (to radio and optical waves) detection  
1044 medium for observation of sub-atomic particle interactions.

1045

1046 **The IceCube Neutrino Observatory** ([icecube.wisc.edu](http://icecube.wisc.edu)) uses the glacial ice sheet at the South Pole to  
1047 detect the optical signals generated by high-energy neutrinos traveling to Earth from cosmic sources and  
1048 interacting in the ice. The observatory includes over 5000 photo sensors instrumenting 1km<sup>3</sup> of clear ice  
1049 down to 2.5 km depth. The Enhanced Hot Water Drill (EHWD) was developed for IceCube as a powerful,

1050 fast access drill capable of creating 2,500m deep, half-meter diameter boreholes at a rate of about three  
1051 per week.

1052  
1053 (photo)

1054 *A Digital Optical Module (DOM) is lowered into a hole in the ice at Amundsen-Scott South Pole Station for the IceCube*  
1055 *project. IceCube detects neutrinos from distant astrophysical sources. Photo credit: Ethan Dicks, National Science*  
1056 *Foundation.*

1057  
1058 An upgrade to the IceCube detector, known as “the IceCube Upgrade”, will add seven highly instrumented  
1059 strings at the center of IceCube, and is planned for the South Pole field season 2025-26. The scientific  
1060 objectives of the IceCube Upgrade include the study of fundamental properties of neutrinos (such as  
1061 neutrino flavor changes and mass hierarchy), precision calibration of IceCube sensors, and a refined  
1062 measurement of the optical properties of the ice. The Upgrade geometry will have inter-string spacing of  
1063 ~20 m and three meters of vertical spacing between sensors at the most densely instrumented depths of  
1064 the array. This detector will include a variety of sensors and calibration devices to take advantage of the  
1065 large boreholes reaching a depth of up to 2650 m. Hot-water drill upgrades, aimed at improving the  
1066 optical clarity of the refrozen water column, will include filtration of large-particle impurities and cold  
1067 reaming to avoid bubble formation.

1068  
1069 **IceCube-Gen2** is a proposed very large expansion for future Antarctic neutrino astronomy that includes  
1070 an upgraded optical array, a surface array, and a radio detector array. With 120 additional strings 250 m  
1071 apart, the optical array for IceCube-Gen2 will increase the effective volume of IceCube by an order of  
1072 magnitude, while only doubling the amount of in-ice instrumentation. This expanded array will improve  
1073 the detection capability in the PeV energy range by an order of magnitude and provide high statistics  
1074 samples of extraterrestrial neutrinos, for better characterization of source distribution, spectrum and  
1075 flavor composition. The IceCube-Gen2 radio array will expand the footprint of IceCube to cover 500 square  
1076 kilometers with shallow and near-surface deep antennas. Presently, the ARA experiment at South Pole  
1077 and the RNO-G experiment at Summit Station in Greenland use radio antennas to search for radio signals  
1078 generated by neutrinos at ultra-high energies beyond 10 PeV.

1079  
1080 IceCube-Gen2 will require improvements to the EHWD, including a more mobile and efficient hot water  
1081 plant, and a modular sled-mounted drill system, which is less complex and requires a smaller operations  
1082 crew. The radio array will require rapid drilling of 6-11” diameter holes to near surface depths of 150 m  
1083 and the associated technology and engineering support. Detector stations will be spaced 1.25 km apart in  
1084 a rectangular grid spaced away from the South Pole station along a power and communications backbone.

1085  
1086 **ARA** currently consists of 5 stations with five strings of sensors deployed to 200 m. Due to its proximity to  
1087 the IceCube and ARA detectors, the SPICE core borehole serves as an access point for calibration beacons  
1088 or standard candles, as part of the South Pole facility and infrastructure. Calibration beacons can be  
1089 operated at multiple depths and hence probe different ice temperatures, densities, fabrics and impurity  
1090 levels. Targeted calibration campaigns allow for measurements that have implications for radio and  
1091 optical detection of high-energy neutrinos and provide opportunities for basic glaciology research. In the  
1092 future, radio-illuminating beacons could provide signals in the 100 - 1,000 MHz frequency range out to a  
1093 radius of 20 km, thus permitting studies of neutrino detection over areas up to 1,000 km<sup>2</sup>, and also help  
1094 in understanding anomalous features seen in ice-penetrating radar surveys.

1095  
1096 (photo)

1097 *Caption: The Big Rapid Access Isotope Drill (British Antarctic Survey) is set up for drilling for the Radio Neutrino*  
1098 *Observatory in Greenland (tent cover not shown). Photo courtesy of Delia Tosi.*  
1099

1100 **RNO-G** is currently in construction in Greenland with plans to instrument 40 km<sup>2</sup> using 35 stations. Seven  
1101 stations have been deployed over the 2021 and 2022 summer field seasons. Each station includes three  
1102 holes, drilled down to a nominal depth of 100 m, with the possibility of up to 200 m holes used for  
1103 instrumentation in-situ calibration. In addition, three slots, three meters deep, are required for antennas  
1104 deployed just below the surface. By using multiple probes in the same boreholes, it will be possible to link  
1105 the firn density profile with its electromagnetic properties, improving our understanding of the ice  
1106 properties. Drilling is conducted with the BigRAID (Big Rapid Access Isotope Drill) setup on a sled along  
1107 with integrated weather sheltering. This drill is designed for fast access by removing ice chips from the  
1108 hole, with no core extracted. The 11-inch holes are used for radio antennas to detect the radio pulses  
1109 from high energy neutrinos. Field work over three to four Arctic summer seasons has been proposed and  
1110 funding has been secured for the instrumentation.

1111  
1112 **3. Seismic studies:** The Global Seismographic Network includes seismic monitoring stations for  
1113 earthquakes and other events such as emissions from calving and sliding glaciers and ice sheets. The South  
1114 Pole Remote Earth Science and Seismological Observatory has seismic equipment installed ~300 m deep  
1115 within boreholes. Two additional low noise seismometers, developed by USGS, will be installed at 2400 m  
1116 depth as part of the IceCube Upgrade and that will augment South Pole long period seismological  
1117 observations. A similar remote observation network is planned for Greenland.

1118  
1119 **4. Ice sheet as an archive of recent past atmospheric composition:** In the very cold areas of ice sheets  
1120 where snow rarely melts, many decades of snowfall create a porous network of firn in the top many tens  
1121 of meters of the ice sheet. The firn serves as an archive of atmospheric composition, with the oldest air  
1122 existing at depth. Sampling firn air from various depths within boreholes drilled in the ice sheet enables,  
1123 for example, observation of the patterns and extent of anthropogenic emissions

1124  
1125 **5. Exploration of basal ice formation processes:** Radar imaging of basal conditions under the Antarctic  
1126 and Greenland ice sheets reveals structures that have been proposed to result from accretion ice grown  
1127 onto the base of the ice sheet. In order to acquire the ice to test this hypothesis, drilling at sites in  
1128 Greenland, or near Dome A in East Antarctica, could access these ice features with the 1,500 m  
1129 Intermediate Depth Drill.

1130  
1131 **6. Meteorite collection:** Glaciers and ice sheets are sites for efficient collection of meteorites and  
1132 micrometeorites. Micrometeorites yield clues to the origin and evolution of the solar system. Some are  
1133 visible to the human eye on the surface of some blue ice areas, while others may be swept up inside  
1134 melted water wells created in the ice at established field stations.

1135  
1136 **Summary**

1137  
1138 Ice sheets serve as a platform for a wide range of observations spanning many areas of science. In some  
1139 areas, for example, firn-air studies and seismic monitoring proven-drills already exist for making the  
1140 necessary access holes. Dedicated hot water drills have proven to be effective in creating deep boreholes  
1141 in rapid succession. Other areas are at an early stage and will require further development of RAM drills  
1142 or reverse circulation drills. A rapid access drill, with the capability to bore through several kilometers of  
1143 ice to retrieve rock cores is nearly ready for deployment. The borehole logging community is a strong  
1144 proponent for repairing and maintaining boreholes at Greenland Ice Sheet Project 2 (GISP2) site at the

1145 Summit site, at Siple Dome, Antarctica, and other sites. Identifying which boreholes need maintenance,  
1146 prioritizing those with highest scientific value for future logging, and determining methods of repair are  
1147 activities that need urgent attention. The IDP Englacial and Subglacial Working Group will prepare a list of  
1148 boreholes in the U.S. program and will work with the community to create a prioritized list to be preserved  
1149 for science.

1150

1151

## 1152 **Science Planning Matrices**

1153

1154 Goals to advance the frontiers of the science in ways that enable evidence-based decision making and  
1155 that inspire the next generation of scientists are described in the previous sections of this report.  
1156 Community planning for the execution of the science is important for providing coordinated scientific  
1157 investigations, and also for planning the associated logistical and funding requirements. For each area  
1158 described above, Tables 4 through 7 identify the current plans for timing of the field research. In cases  
1159 where new technologies are needed, a timeline for the development of technologies is provided. Black  
1160 font in a matrix indicates projects that are currently funded, and blue font indicates those in the scientific  
1161 planning phase.

1162

1163 In Tables 4 to 7 below, the notation denoting specific drills to be used are: A: Agile sub-ice geological drill;  
1164 b: Badger-eclipse; B: Blue ice drill; f: Foro 400 drill; F: Foro 3000 drill; I: Intermediate depth drill (Foro1850);  
1165 L: Borehole logging; Lt: Logging tower; R: RAID drill; r RAM drill; Sc: Clean Scalable hot water drill; S:  
1166 Stamphli drill; SW: Shallow Wet Drill; T: Thermomechanical drill; U: UNL CHWD drill; W: Winkie drill; 4: 4"  
1167 drill; 7: 700 m coring drill, x: hand auger, sidewinder, or prairie dog.

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**Table 7: Ice as a Scientific Observatory Planning Matrix 2026 – 2036**

*(Note the chart is an image. Please type the needed corrections/additions here)*

	2026				2027				2028				2029				2030				2031				2032				2033				2034				2035				2036							
	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				
<b>Ice as a Scientific Observatory</b>																																																
<b>RNO-G<sup>2</sup></b> (Greenland)		x	x			x	x																																									
<b>ICECube Gen2<sup>1</sup></b> (optical, radio, & slots; South Pole)													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				

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1210  
1211  
1212

Points of Contact for projects in Table 7: <sup>1</sup>Karle; <sup>2</sup>Wissel

## 1213 **Associated logistical challenges**

1214  
1215 In addition to planning the science and associated drilling technology, logistical challenges impact the  
1216 timing and possibilities of the science field work. Challenges to conducting the field activities include:

- 1217  
1218 ● There remains an urgent need for reliable over-snow vehicles and sleds for scientific traverses in  
1219 both Greenland and Antarctica in order to address the priority science goals identified in science  
1220 community consensus documents, including the IDP Long Range Science Plan 2025-2035 (this  
1221 document). In addition, the 2015 National Academies report “A Strategic Vision for NSF  
1222 Investments in Antarctic and Southern Ocean Research” articulated the need for improved ground-  
1223 based access to the deep field in Antarctica. Access to sites on the Antarctic and Greenland Ice  
1224 Sheets has become very restricted due to the limited, aging fleet of LC-130 air support and few  
1225 scientific traverse vehicles. With multiple science communities requesting flights or traverses to  
1226 support their science on the ice sheets, access to the deep field remains a limiting factor in  
1227 executing new scientific endeavors.
- 1228  
1229 ● The U.S. research community has been advocated modular clean, hot water drills with the capability  
1230 to be deployed both at grounding zones and subglacial lakes for over a decade in order to enable  
1231 clean access to the subglacial environment. That need remains unmet despite its potential to enable  
1232 new scientific discoveries.
- 1233  
1234 ● The U.S. National Science Foundation Ice Core Facility (NSF-ICF) in Denver is the main location for  
1235 processing and archiving of U.S. ice cores for science. The NSF-ICF, which is fully funded by the NSF  
1236 Office of Polar Programs and managed by the USGS, was originally built in 1993. A new facility has  
1237 been constructed in a location adjacent to the existing facility. Moving the ice core archive into the  
1238 new facility is planned to occur in early 2026, with the expected reopening of the facility on March  
1239 of 2026. The NSF-ICF will remain open to the scientific community during construction with facility  
1240 updates to be provided on our website when construction starts. The NSF-ICF is preparing for the  
1241 move by actively inventorying samples that are not in our database. The updated inventory in the  
1242 NSF-ICF will be available for use and advertised through a variety of venues to enable broader  
1243 participation across the science community, increase potential collaboration among researchers,  
1244 and to provide an entry point for researchers new to the ice core community. Please reach out with  
1245 any questions to [nicl@usgs.gov](mailto:nicl@usgs.gov).
- 1246  
1247 ● The community wishes to instrument and maintain key boreholes as long-term observatories for  
1248 conducting measurements with existing and new instruments. GISP2 at Greenland summit is one  
1249 of the most influential and widely cited records in paleoclimatology, but measurements have shown  
1250 that the borehole casing is collapsing and already not navigable by most logging instruments. There  
1251 are also boreholes in Antarctica. The IDP Englacial and Subglacial Working Group will lead  
1252 community discussions to discuss an approach and selection method for prioritizing boreholes for  
1253 instrumentation and preservation.
- 1254  
1255 ● Drilling ice cores deeper than ~300 m generally requires a drilling fluid mixture that has a density  
1256 similar to ice to maintain core quality and prevent borehole closure. The fluid must also have a  
1257 viscosity that is low enough to permit passage of the drill sonde through the fluid many times during  
1258 the drilling process. Estisol-140 was used for the South Pole SPICE core and will likely be used for  
1259 future drilling projects until an improved fluid is identified.

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- An ice drill testing and calibration facility would be useful to engineers for testing during drill development and to scientists for englacial ice sensor development. The Ice Coring & Education (ICE) Silo, under conceptual development at the University of Nebraska-Lincoln, would be such a facility. UNL is investigating the repurposing of an abandoned Cold War Atlas-F missile silo. The UNL concept envisions a 150 foot ice column chamber, 10 foot diameter, within which a column of ice could be custom-built to replicate predicted ice, englacial, and subglacial conditions, all within a series of stacked 10 foot tall, individually refrigerated collars. An ice drilling/coring testing, calibration, and design facility in the continental U.S. would enable access for the science and engineering community to experiment with novel drilling instrumentation designs. Testing, modifying, and calibrating ice drilling tools in a controlled setting will reduce risk and enhance success of drilling in remote environments, and avoids the logistical limitations of testing on the Greenland or Antarctic ice sheets. The ice drilling test facility would also allow for the training of new drillers before deployment into the deep-field, contributing to the development of the next generation of polar engineers and scientists.

1277 **Recommendations**

1278

1279 **Recommended science goals**

1280

1281 **1. Past Changes:** Present-day change can only be fully understood in context of the past; well-dated  
1282 histories of past conditions and the atmosphere over a wide range of time scales are needed to  
1283 understand forcings and responses. Drilling of spatially-distributed ice cores and boreholes at many  
1284 locations to investigate past conditions and atmosphere over the past 200 to 40,000 years should  
1285 continue. Understanding signals in remotely-sensed data, understanding impacts on the transition from  
1286 snow to firn to ice on ice sheets, and calibrating high-resolution models, all require arrays of shallow cores  
1287 covering a range of accumulation and melt rates both in Greenland and in Antarctica; these efforts should  
1288 continue. Spatially-distributed shallow coring for records ranging from the recent past to 2,000 years in  
1289 Greenland may investigate the ice sheet under the currently changes.

1290 Specific goals include the following:

- 1291 ● Determining patterns of hydroconditions variability, feedbacks, and past extent of high-altitude  
1292 glaciers and aerosol deposition requires ice coring in the North Pacific coastal mountain ranges.
- 1293 ● Determining the amount of meltwater retained and refrozen in the near surface firn (top ~60 m) on  
1294 the Greenland Ice Sheet and on the Antarctic Peninsula is critical for improving estimates of surface  
1295 mass balance under current warming conditions.
- 1296 ● Targeted ice coring to investigate ice, ocean, and atmospheric dynamics in WAIS coastal domes and  
1297 coastal ice caps and along the dynamic Amundsen Sea Coast of Antarctica, and near Camp Century  
1298 along the northwest coast of Greenland, are active and engaged on ongoing planning.
- 1299 ● A record from the last interglacial period (the Eemian, ~130k to 110k years ago) is key to predicting the  
1300 response of glaciers and ice sheets to future warming. Eemian ice was recovered from the Camp  
1301 Century, Greenland core in the 1960's, and an effort to retrieve an intermediate depth ice core from  
1302 this region is in the planning stages. In Antarctica, extracting a record from Eemian ice is especially  
1303 important for helping constrain environmental and glacial histories of the WAIS during the last  
1304 interglacial, and is the primary motivation for the upcoming deep drilling at Hercules Dome, where  
1305 replicate coring will retrieve deep ice with the compressed interglacial record. A deep ice core from  
1306 Hercules Dome, *the highest-priority next deep ice core for the U.S. ice core science community* as  
1307 determined by the IDP Ice Core Working Group and the proposal has been funded by NSF, will lead to  
1308 understanding whether the WAIS collapsed during the last interglacial period (MIS5e), and if it did not  
1309 collapse, then under what conditions was it stable? WAIS history during the Eemian is poorly known;  
1310 because large sea level rise due to current warming may occur if the WAIS becomes destabilized, an  
1311 understanding of the WAIS during the last interglacial is urgent.
- 1312 ● Blue ice areas are providing samples for atmospheric and ultra-trace component studies and can  
1313 enable further new types of measurements that have previously been impossible, including analysis of  
1314 ice up to 6M years old. Blue-ice studies at Allan Hills, Mt. Moulton, and Taylor Glacier have been fruitful  
1315 from this realm so far; such studies at blue ice sites should continue, with other sites of interest  
1316 including Elephant Moraine and Reckling Moraine
- 1317 ● Ice cores and borehole observations reaching ages between 800,000 years and 6 M years (and beyond)  
1318 are significant, for these data may provide new insight into the effects of greenhouse gases and the  
1319 observed change in periodicity of glacial cycles during the mid-Pleistocene. The search to identify sites  
1320 suitable for extracting ancient ice should continue. Through COLDEX, U.S. scientists will continue to  
1321 retrieve samples of ancient ice from blue ice regions that provide snapshots of conditions that existed  
1322 over several million years ago.

- 1323 ● An intermediate-depth (1200 m) core in the Allan Hills accumulation zone may give continuous ice as  
1324 old as 1Ma and aid interpretation of discontinuous Allan Hills Blue Ice records; drilling such a core has  
1325 been proposed by COLDEX.  
1326

1327 **2. Ice dynamics and glacial history:** Rapid changes in the speed of fast-flowing outlet glaciers and ice  
1328 streams observed over the past decade create an urgency to understand the dynamics of outlet glaciers  
1329 and ice sheets. Ice sheet models that incorporate realistic physics and dynamics at appropriate spatial and  
1330 temporal scales are needed to predict the "tipping point" when ice-loss becomes irreversible, resulting in  
1331 ice-sheet collapse and rapid sea level rise. Observational data are needed to develop and validate the  
1332 models. Measurements of the ice-bed interface (frozen-thawed, hard-soft bed conditions, sliding, shear),  
1333 ice-ocean interactions (sub-shelf and basal melting-freezing rates), temperatures and ice deformation  
1334 properties through the ice, geothermal bedrock conditions and ice-atmosphere interactions (surface mass  
1335 balance) are key. Another approach to understanding future possible response of ice sheets is to examine  
1336 their behavior in the past. Dated marine and terrestrial glacial deposits provide information about past  
1337 ice volume. In regions where such data are not available, histories of ice-sheet thickness can be inferred  
1338 from radar-detected layers combined with ice core and borehole measurements.

1339 Specific recommendations include:

- 1340 ● Ice-ocean interactions are not fully understood. Boreholes to deploy instruments to measure  
1341 conditions at ice-ocean interfaces are high priority for investigating ice sheet stability.  
1342 ● Hydraulic conditions in glaciers and ice sheets exert strong controls on basal motion. Much has been  
1343 learned through remote sensing methods, but direct measurements through boreholes to the bed are  
1344 still needed to validate and interpret remote sensing data. Boreholes to the bed at targeted locations  
1345 are urgently needed to measure geothermal fluxes and basal properties.  
1346 ● Ice deformation in ice sheets, glaciers, and ice streams depend on temperature and ice rheology.  
1347 Measurements of ice rheology from ice cores, and borehole logging measurements of temperature,  
1348 diameter, inclination, and azimuth are needed to provide boundary conditions and constraints for  
1349 modeling flow of ice sheets and fast-flowing outlet glaciers and ice streams.  
1350 ● Knowledge of spatial and temporal variations of surface accumulation is critical for quantifying the  
1351 mass balance of glaciers and ice sheets. Accumulation rate histories derived from short (~200 m) firn  
1352 and ice cores can be extrapolated spatially to the catchment scale using radar-detected layers.  
1353 Additional short cores at targeted locations are needed to provide a realistic assessment of surface  
1354 accumulation over ice-sheet scales.  
1355 ● Dated ice cores can be used to infer histories of thickness and configuration of ice sheets. Glacial  
1356 histories contained in coastal ice domes are of particular interest because thickness change near the  
1357 margins is large. The depth-age relationship from Siple Dome, Antarctica provided key information  
1358 about the Holocene deglaciation of the central Ross Embayment, and the depth-age relationship from  
1359 Roosevelt Island will help constrain the deglaciation of the eastern Ross Embayment. Depth-age  
1360 profiles from Hercules Dome and other targeted locations are essential for understanding the timing  
1361 and extent of deglaciation, for example, at ice domes near the outflow of the Amundsen Sea  
1362 Embayment Antarctica, as well as in coastal domes of Greenland.  
1363 ● The past extent and volume of the Greenland and Antarctic Ice Sheets are recorded by analysis of  
1364 subglacial bed materials such as cosmogenic nuclide and luminescence signals in subglacial bedrock.  
1365 Samples from beneath these ice sheets will provide information on their configuration during past  
1366 interglacials to help constrain ice-sheet sensitivity to future possible change. Cores of basal ice and  
1367 bedrock from strategically targeted sites around ice sheet peripheries are needed to pinpoint which  
1368 ice-sheet sectors would add the first decimeters of sea level rise beyond present.  
1369

1370 **3. Subglacial geology, sediments, and ecosystems:** Bedrock, sediments, and ecosystems existing within  
1371 and beneath ice sheets remain largely unexplored because of the lack of rapid access drills. In particular,  
1372 the physical conditions at the base of the ice sheets are virtually unknown, but remote sensing of liquid  
1373 water in subglacial lakes and possibly interconnected hydrologic systems raises concern about thermal  
1374 conditions and basal slip potential. Likewise, the unknown subglacial geology of Antarctica represents the  
1375 last continental frontier of geologic exploration, including landscape evolution, past paleo conditions on  
1376 geological timescales, crustal heat flow, lithospheric stress, ground truth for geophysical imaging,  
1377 constraints on geodynamical evolution, and relationship with past supercontinents. Information on  
1378 subglacial biodiversity and biogeochemistry is limited to the Siple Coast, with nothing known about other  
1379 areas of the Antarctic continent. Subglacial sediments also contain information related to past ice sheet  
1380 history. Rapid access to subglacial environments is needed to address a wide range of science questions.

1381 Specifically:

- 1382 ● Direct sampling of the bedrock is needed to validate models of cratonic growth related to  
1383 supercontinent assembly in the Mesoproterozoic between about 2.0 and 1.1 billion years ago and for  
1384 constraining the Phanerozoic geological, tectonic, and exhumation history of the Antarctic continent.  
1385 Strategic drill-site selection within mapped drainage basins (using products from the BEDMAP2 project)  
1386 will also allow greater constraints on provenance studies that utilize onshore moraines and offshore  
1387 glacial strata.
- 1388 ● There exist virtually no heat flow data for Antarctica. Penetration into bedrock provides the first  
1389 opportunity to accurately measure the geothermal heat flux, which informs us about geotectonic  
1390 conditions as well as geothermal contributions to ice sheet temperature.
- 1391 ● Evidence of Cenozoic ice sheet history preserved in sedimentary rocks of subglacial bedrock basins and  
1392 in sediment deposits within subglacial lakes will provide further dimensions to the records known only  
1393 from the margins of the continent and will also help to verify paleo-topographic reconstructions for ice  
1394 sheet modeling. Likewise, access to subglacial bedrock can provide a unique opportunity to study  
1395 Cenozoic landscape evolution and long-term ice sheet stability using low-temperature  
1396 thermochronology and cosmogenic-isotope techniques.
- 1397 ● Direct measurements at grounding zones of fast-flowing ice streams and outlet glaciers are badly  
1398 needed, as are data from sub-ice-shelf ocean cavities in order to provide basic information needed to  
1399 model ice fluxes near grounding lines and into ice shelves – a critical interface for predicting future ice  
1400 sheet dynamics.
- 1401 ● Direct measurements of bed conditions including frozen/thawed bed, basal pore pressure, slip, and  
1402 sediments are needed to develop and test realistic models of the controls on the fast flow of ice streams  
1403 and outlet glaciers.
- 1404 ● Significant wet environments exist below ice sheets and glaciers; sampling of subglacial habitats  
1405 including sediments, water, and basal ice is needed to establish the diversity and physiology of microbes,  
1406 available nutrients and organic materials, microbial relationships to the past, and ecosystem function  
1407 below the ice. Continued support for developing methods and technologies for clean access to subglacial  
1408 environments and tools for biological and geochemical sampling are needed to investigate these  
1409 subglacial systems in a clean manner that maintains scientific integrity and environmental stewardship.  
1410 The recent studies of Whillans and Mercer Subglacial Lakes are initial steps toward achieving this goal,  
1411 yet with over 650 subglacial lakes in Antarctica much remains to be discovered.

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1413 **4. Ice as a scientific observatory:** Polar ice sheets and mid-latitude ice caps archive evidence of the past,  
1414 and ice dynamics and also serve as a unique platform to conduct observations and experiments  
1415 concerning seismic activity, planetary sciences and experimental astrophysics, and other novel  
1416 phenomena. Specifically:

- 1417 ● Borehole logging of both fast-access holes and boreholes originally drilled for ice cores are needed to  
1418 fully exploit the histories of the past and ice dynamics preserved within the ice. For example,  
1419 temperature logs are used to infer past temperatures and also the geothermal flux; optical logs yield  
1420 detailed records of dust and volcanic events and will be important in searches for million year old ice;  
1421 and sonic logs provide a continuous record of ice fabric and borehole deformation. Community winches  
1422 to support borehole logging are important assets.
- 1423 ● In-ice physics and astrophysics experiments make use of polar ice as a clean, highly stable, low-  
1424 background, and transparent (both optically and in the radio frequencies) detection medium for  
1425 observation of sub-atomic particle interactions. New drilling techniques are under investigation,  
1426 including cleaner drilling and removal of bubbles from the refrozen water.
- 1427 ● Future planned projects (e.g., the RNO-G and Generation-2 Ice Cube) require many boreholes drilled to  
1428 at least 150 m deep (ARA, Gen2-Radio) and 2,600 m deep (Gen2-Optical) and significant calibration  
1429 studies of the surrounding ice volume.
- 1430 ● Ice sheets are a quiet platform for seismic monitoring; the South Pole Remote Earth Science and  
1431 Seismological Observatory has seismic equipment installed in boreholes about 300 m below the surface.  
1432 A similar seismic observation network is planned for the Greenland Ice Sheet. The IceCube Upgrade will  
1433 include 2 seismometer instruments at 2400 m depth sponsored by the USGS.
- 1434 ● Novel basal ice structures that have been remotely sensed but whose existence is not well understood  
1435 should be investigated.
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1438 **Recommended Drill Life Cycle Cost and Logistical Principles**

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Although drills already exist that can achieve some science goals, new drilling technologies are needed to accomplish science goals planned for the next decade. The following principles guiding development of new drills and associated technologies are recommended:

- Drill designs require that the supporting logistical needs are available and do not impede the planned execution of the field science. Current limitations with Antarctic logistics reinforce the desirability of having modular equipment that can be transported by small aircraft and that require few operators on site.
- While developing the science requirements, logistical issues such as weight, size, costs, and time for development, must be clearly defined and transparent at the initial stage of planning. Scientists and engineers working together through IDP must assess the impact of changes as they arise during the engineering design and fabrication process.
- Drills, major drilling subsystems, and accompanying technology must be developed with consideration of potential use in future projects. The drills and technology must be versatile and well documented so that they can be used, maintained, and repaired by other engineers.
- Major drilling systems (e.g., sondes, winches, control and other major electronics systems) should be fungible to the maximum extent possible. Major component interchangeability and logistical agility should be essential deliverables for all new drilling technology projects.
- Engineering design teams must include individuals with field experience using appropriate ice drilling technology and/or other relevant field experience.
- Heavy traversing capability is urgently needed to improve access to many scientifically important regions of the Antarctic and Greenland Ice Sheets, including heavy traverse capability that will enable larger drilling systems in both rotary and hot-water formats, heavy tractor capacity, and berthing facility for personnel.

## 1468 **Recommended Technology Investments**

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1470 The following investments in drilling technologies are needed to accomplish science goals of the U.S.  
1471 science community for the next decade. Many, but not all of the following could be achieved by IDP,  
1472 subject to availability of funding and trained personnel. Investments are prioritized by time (but are not  
1473 prioritized within each Priority level) through consensus of members of the IDP Ice Core Working Group  
1474 and the IDP Englacial and Subglacial Access Working include:

### 1475 1476 **Priority 1** (needed before August 2027)

1477 • Maintain and upgrade agile equipment in inventory, including: Hand Augers, Sidewinders, the 700 Drill,  
1478 the Foro 400 Drill, the FORO 1650 Drill, the 4" Electromechanical Drills, the 3" Electrothermal Drill, the  
1479 3.25" Eclipse Drills, the Stampfli Drill, Logging Winches, the Small Hot Water Drills (SHWD), the Blue Ice  
1480 Drill, the Prairie Dog, the Agile Sub-Ice Geological Drill (ASIG), the Rapid Air Movement Drill (RAM) Drill,  
1481 the Winkie Drill, the Chipmunk Drill, the existing 900 m Hot Water Drill, and the existing stand-alone  
1482 components for use in shallow wet drilling.

1483 • Investigate lighter weight sources of power and/or renewable energy technology to (partially) replace  
1484 or offset generators for drilling systems and ease demand on logistics, with an emphasis on lightweight  
1485 systems, and/or where practical.

1486 • Develop detailed engineering design and cost estimate for the BOLD Drill.

1487 • If COLDEX Phase II is funded, initiate fabrication of the drill NSF approved for COLDEX.

1488 • Complete the Conceptual Design for Foro 1650/3000 replicate coring capability.

### 1489 1490 **Priority 2** (needed before August 2029):

1491 • As the next steps to building a hot water drill for clean subglacial access (for drilling up to 3,000 m  
1492 depth) that minimizes its logistical footprint including fuel supply (e.g. replica of the BAS/NZ deep hot  
1493 water drill), develop the Conceptual Design and Detailed Engineering Design for a clean hot water drilling  
1494 system.

1495 • Develop the Detailed Design for a clean hot water basal ice coring sonde for a hot water drill that has  
1496 the ability to integrate with other hot water drills or deep ice coring drills.

1497 • Develop a multi-optional Conceptual Design and cost estimate for a 4" stand-alone shallow wet drill  
1498 (SWD). Options should include building a brand new SWD, complete the existing conceptual SWD  
1499 configuration to a stand-alone drill, create a stand-alone fluid-capable version of the Foro 400 m drill, and  
1500 others as IDP sees fit.

1501 \* Identify procurement source and cost for potential purchase of a rapid hole qualifier (temperature and  
1502 caliper) to meet the scientific need in borehole access applications.

1503 • Complete the Detailed Design for replicate coring capability for the Foro 1650/3000 Drills.

1504 • Finish adapting a commercial drill rig for retrieving rock core from beneath 200 m of ice (BASE Drill).

1505 • Implement modifications needed for the 700 Drill to increase core quality, length, and production rate.

1506 • Develop the Conceptual Design for collecting a small amount (chips to several cm) of sub-ice rock/mixed  
1507 media/mud in a frozen regime using an intermediate or deep ice core drill in a fluid filled hole, for example  
1508 with the Foro 3000 Drill.

- 1509 • Establish Science Requirements for new drilling fluids for future ice and rock drilling projects, including  
1510 clean ice core drilling (for biological and gas sampling) for future collaboration with international partners.  
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1512 **Priority 3** (needed before August 2031):

- 1513 • Build a hot water drill for clean subglacial access drilling up to 3,000 m depth that minimizes its logistical  
1514 footprint including fuel supply (e.g. replica of the BAS/NZ deep hot water drill).

- 1515 • Establish the IDP Science Requirements for identification and planning of borehole maintenance and  
1516 fluid maintenance over time, including removing (or lowering) drilling fluid from a borehole (for example  
1517 for freezing in a sensor).

- 1518 • Continue investigation and modifications of the RAM 2 Drill to achieve the 100 m depth goal reflected  
1519 in the system Science Requirements.

- 1520 • Establish the Science Requirements for retrieving sidewall ice samples at specific depths in an existing  
1521 borehole without using an ice coring drill.

- 1522 • Write a summary paper outlining the results from past attempts and the prognosis for future use of  
1523 shallow drill fluid columns for ice coring.

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1886 **Acronyms**

AGAP: Antarctica's Gamburtsev Province  
ANDRILL: Antarctic Drilling Project  
AO: Arctic Oscillation  
ARA: Askaryan Radio Array  
ARIANNA: Antarctic Ross Ice shelf Antenna Neutrino Array  
ASIG: Agile Sub-Ice Geological (drill)  
AUV: Autonomous Underwater Vehicle  
BLWG: Borehole Logging Working Group  
CRISIS: Center for Remote Sensing of Ice Sheets  
DISC: Deep Ice Sheet Coring  
DOSECC: Drilling, Observation, Sampling of the Earths Continental Crust (drilling service)  
EDC: EPICA Dome C  
EGRIP: East Greenland Ice core Project  
EHWD: Enhanced Hot Water Drill  
ENSO: El Niño Southern Oscillation  
EPICA: European Project for Ice Coring in Antarctica  
G-2IC: Generation-2 Ice Cube  
GISP2: Greenland Ice Sheet Program II  
GRIP: Greenland Ice Core Project  
GZK: Greisen-Zatsepin-Kuzmin  
HCFC: Hydrochlorofluorocarbon  
ICECAP: A project name, not an acronym  
ICWG: Ice Core Working Group  
IDP: Ice Drilling Program  
IPCC: Intergovernmental Panel on Climate Change  
IPICS: International Partnerships in Ice Core Sciences  
LIG: Last Interglacial  
LRSP: Long Range Science Plan  
NEEM: North Greenland Eemian Ice Drilling  
NEGIS: Northeast Greenland Ice Stream  
NGRIP: North Greenland Ice Core Project  
NRC: National Research Council  
NSF: National Science Foundation  
PINGU: Precision IceCube Next Generation Upgrade  
RAID: Rapid Access Ice Drill  
RAM: Rapid Air Movement (drill)  
ROV: Remotely Operated Vehicle  
SAB: Science Advisory Board  
SALE: Subglacial Antarctic Lake Environment  
SCAR: Scientific Committee on Antarctic Research  
SHALDRIL: Shallow Drilling on the Antarctic Continental Margin  
SleGE: Sub-Ice Geological Exploration  
SPICE: South Pole Ice  
WAIS: West Antarctic Ice Sheet  
WISSARD: Whillans Ice Stream Subglacial Access Research Drilling Project

Sheet  
Subglacial Access Research Drilling