Subglacial Access Working Group
Access Drilling Priorities in the Antarctic Continental Interior

1) Summary: Antarctica is the last continental frontier. Due to extensive ice cover many fundamental geologic questions remain unanswered, particularly regarding linkages between the basement geology and the overlying ice sheets. Important research opportunities therefore exist for drilling through the ice sheets to gain access to the subglacial geology. This document summarizes the most compelling science questions and research priorities as defined by the science community that address the geotectonic development of Antarctica, origin of the Gamburtsev Subglacial Mountains, changing extent of the polar ice sheets, and influence on the ice sheets of high-relief subglacial topography and terrestrial heat flow.

2) Compelling research questions:

Here we summarize three high-priority themes for exploration of the subglacial Antarctic interior that can be achieved today with existing technology, listed generally in order relative to Earth's surface but not otherwise in order of importance:

1) *What were the dominant factors controlling the spatial extent and temporal variability of ice sheets during warm climate periods in the past?*
2) *What is the origin of the enigmatic Gamburtsev Subglacial Mountains and how have they influenced the overlying ice sheet?*
3) *What is the composition, geothermal heat flux, and geotectonic history of East Antarctica, and how does it influence ice-sheet behavior?*

Two additional themes should be considered that will require some new technology development:

4) *What is the role and history of subglacial sediments in the interior?*
5) *What are the physical conditions at the base of the East Antarctic ice sheet?*

3) Scientific rationale:

3.1) What were the dominant factors controlling the spatial extent and temporal variability of ice sheets during warm climate periods in the past? Drilling through ice to recover bedrock cores for cosmic ray exposure measurements is a potentially transformative way to study the history and dynamics of ice sheets under climates warmer than the present and during higher atmospheric CO_2 levels in the past. Major questions focus on the following:

a) What was the response of the West Antarctic Ice Sheet (WAIS) during warm and/or prolonged late Pleistocene interglacials such as Marine Isotope Stage 5e (MIS-5e) and MIS-11? More specifically – do WAIS collapses typically start in the Amundsen Sea? Does collapse always lead to the same ice-sheet configuration, or do the Ross, Weddell and Amundsen Sea catchments act independently in response to differences along their ocean margins? In the present-day WAIS, glaciers draining to the Amundsen Sea seem more prone to instability than their Siple Coast counterparts (some have argued that runaway deglaciation of Thwaites and Pine

Island Glaciers has already begun), but is this contrast typical? These questions can be answered by cores obtained from drilling and comparing the exposure history of presently subglacial bedrock surfaces that were exposed by past deglaciation. Because preservation of the cosmogenic nuclide record requires cold-based, non-erosive ice cover, this work is likely to be within the depth range and working capabilities of existing drill systems.

b) How big was the Pliocene Antarctic ice sheet? Many recent reconstructions based on far-field sea-level data and numerical models of the Pliocene Antarctic ice sheet suggest a much-reduced extent during the mid-Pliocene when CO_2 levels were last similar to those at present. The suggested WAIS configuration is similar to that proposed for Pleistocene interglacial collapses, but because higher global sea levels are inferred, additional deglaciation is envisioned to have spread into the marine basins of East Antarctica. Such reconstructions conflict with previous inferences of continuously cold conditions since the Miocene based on the glacial history of the McMurdo Dry Valleys and ancient glacial deposits elsewhere in Antarctica. This can be resolved by strategic subglacial coring to obtain exposure measurements similar to those described above, but additionally focused on East Antarctic drainage systems. Isolated pockets of early glacial sediments preserved in protected subglacial valley walls near bedrock promontories are also desirable targets for short frozen-bed coring.

Careful site selection is critical to projects involving subglacial bedrock exposure drilling. Particular rock types are favorable for the multiple cosmogenic nuclides that must be measured, and it is essential that ice cover at each site be controlled by large-scale ice-sheet dynamics as opposed to local conditions.

3.2) What is the origin of the enigmatic Gamburtsev Subglacial Mountains and how have they influenced the overlying ice sheet? The Gamburstev Subglacial Mountains (GSM) represent one of the most enigmatic features of Antarctica. This intracontinental mountain massif is a prominent feature of Antarctica with a large geographic area of about 4.60×10^5 km^2 (compared to the Alps with an area of 2.98×10^5 km^2), and they have total relief greater than 3 km. Their composition, geotectonic origin, development as a high-relief mountain range, apparent old tectonic age, apparent low rates of pre-glacial erosion, hypothesized site of ice-sheet nucleation, and potential site of preserved old ice make it one of the least well understood features of the continental interior. Because they have never been sampled directly, many questions persist about the GSM, including:

- What is the age and composition of their underlying geology?
- What role did these rocks play in craton assembly?
- What is the origin of their high topography?
- How long have they stood and what is their uplift/denudation history?
- How did the East Antarctic ice sheet form, and how have the mountains affected its stability?
- How long have they been encased in ice?
- Are there preserved pockets of pre- or syn-glacial sediment?

- What is the origin of complex basal ice structures observed with geophysical imaging?
- Is there old (>1 Ma) ice?

3.3) What is the composition, geothermal heat flux, and geotectonic history of East Antarctica, and how does it influence ice-sheet behavior? The East Antarctic craton is a Precambrian shield terrain as large as either the continental U.S. or Australia, yet very little is known about its geology due to ice cover. Geophysical data and extrapolation of the outcrop geology fringing East Antarctica suggest it is a composite but stable, thick Precambrian craton. Its geology varies widely (from 3.8 to 0.5 billion years old) and its assembly took place over a period of time between at least 1.7 and 0.5 billion years ago. The limited potential-field geophysical data across East Antarctica and extrapolation of coastal geology leave vast holes in our understanding of its composition, age and geotectonic history. Likewise, correlation with similar geology in southern Australia indicates that there are discrete blocks of differing age and composition, each with its own properties. Key among these properties in Antarctica are the crustal heat production and geothermal heat flux from beneath the East Antarctic ice sheet. All models of ice-sheet stability require an implicit input of geothermal heat flux, yet there are no *in situ* measurements of this key parameter in East Antarctica. Important motivations for subglacial access to the geology of East Antarctica thus include:

- What is the composition and age of crust in East Antarctica?
- What geologic provinces can be identified and how do they relate to the limited exposures elsewhere or to geology of Australia?
- Are there identifiable crustal sutures between provinces and what is their age?
- What is the distribution and variability of geothermal heat flux?
- Can we validate englacial heat flow estimates with in situ measurements?
- How do measured physical properties of recovered rock core samples inform geophysical models (gravity, magnetics, seismology, geotherm)?
- How do the geologic substrate and heat flux influence behavior of the overlying ice sheet?

3.4) What is the role and history of subglacial sediments in the interior? Subglacial sediments can help to address three classes of problems pertaining to different ages of materials and different subglacial processes, summarized below.

a) Subglacial sediments are thought to play a fundamental role in basal sliding, however this has not been well captured in ice-sheet models. Key parameters such as grain size, porosity, permeability, induration and composition are poorly known. Observation and sampling at the base of the Antarctic ice sheets can provide real constraints on these parameters. Sampling sediments of a 'wet' glacial bed will require clean access technology, mixed media tools, and the ability to take deeper cores in moving ice.

b) The presence of subglacial sedimentary basins in the interior of East Antarctica is inferred from aerogeophysical data, but lacks ground truth. These basins might contain records of sedimentary provenance, evidence of glacial deformation, markers for marine inundation, and stratigraphic records of pre-glacial paleoclimate variation. They might also harbor deep life, and significant biogenic gas production is hypothesized where microbial extremophiles may exist. In West Antarctica, sedimentary basins are thought to play a critical role in ice stream onset; they likely have a history of interactions with both subglacial and subaqueous volcanism, which can also provide radiometric age information on timescales relevant to WAIS evolution. Paleoclimate records from ice-covered sedimentary basins will require development of subglacial stratigraphic drilling technologies. Potential targets include the basins of the West Antarctic Rift System (including volcanic centers), the Wilkes Subglacial Basin, and the Aurora Subglacial Basin (with international collaboration)

c) Pockets of early glacial sediments/sedimentary rocks can be preserved in protected 'windows' on subglacial valley walls, such as paleo-fjords and inland glacial valleys (e.g., the "Sirius Group"). In these types of locations, such as in the lee of bedrock/basement highs, sediments or sedimentary rocks may be preserved in frozen-bed conditions and can therefore be targets for subglacial drilling using existing technologies to recover geological cores. The scientific questions and motivations are similar to those described and explained in 3.1 and should be considered in conjunction with exposure age drilling targets. They may also occur in areas that are the targets for 3.2. Where geophysical and site surveys identify pockets of 'young sediment' preserved above bedrock, those sediments are compelling scientific targets for sampling in addition to bedrock.

3.5) What are the physical conditions at the base of the East Antarctic ice sheet? Despite a significant effort in study of the ice sheets in West Antarctica and Greenland, much less is known about the physical conditions at the base of the East Antarctic ice sheet, properties of the bed, and slipping ability of the interface. Subglacial coring across the ice sheet-bedrock interface will provide critical observations and sampling of the glacial bed. Key processes or parameters we would like to know include:

- Characterize the materials of the glacial interface
- Constrain the physical conditions at the glacial bed
- Provide observations that can inform a basal slip parameter used in ice-sheet modeling
- Determine the state of glacial erosion
- Determine basal ice properties
- Sample complex basal ice structures

Potential synergies for subglacial drilling within the realm of continental interiors include:

- Hercules Dome ice coring
- Heat flow (target of opportunity)
- Borehole logging

4) Drilling parameters:

- Most of the inland projects require the ability to cut quickly through the ice sheets, both shallow and deep, and then penetrate the bedrock interface in order to take rock cores.
- Most projects will drill in dry, cold-based, frozen-bed conditions and will not require clean access technologies.
- Deep holes through ice and into bedrock will provide an opportunity for *in situ* geophysical and glaciological measurements, perhaps including technologies yet to be developed.
- Long-term goal to provide for stratigraphic drilling in interior sedimentary basins and other areas with wet bed conditions that will require clean access technologies.

5) Sampling requirements

- Rock cores
- Sediment cores
- *In situ* observation and instrumentation

6) Target locations:

Widespread geographic coverage is desired to address most problems, and deeper boreholes can be used as a legacy observatory. Potential sites require lithologies suitable for cosmogenic nuclide measurements and frozen-bed conditions such that glacial erosion has been minimal. Sites near existing bedrock outcrops provide an important reference for larger-than-present ice sheet history. Potential high priority sites include:

- Dronning Maud Land (international support)
- Northern Victoria Land (Wilkes Basin)
- Southern TAM through Ellsworth Mountains
- Subglacial highlands bordering the interior basins of the WAIS
- Flanks and central GSM T
- raverse from Pole to Dome A. Range to grid N and S, targeting bedrock highs and geophysical anomalies

7) Target timeline:

- Projects are currently underway in 2016-18. New projects are expected to develop within the next 2-4 years. Some will be based on reconnaissance projects proposed or underway, while others are likely to draw on results of current proof-of-concept work, and yet others will be targets of opportunity depending on other logistically intensive projects

- 2018-19 and 2019-20; 2 years for coverage of GSM and nearby surroundings. Site recon prerequisites (airborne, ground). Planned SPICECAP project being considered for 2017-18 and 2018-19.

- 2019-20, 2020-21, 2021-22; 3 years; site recon prerequisites (airborne).

8) Support requirements:
General support requirements for scientific drilling in the continental interior include:

- Heavy traverse capability is a key requirement for some drilling platforms (e.g., RAID)
- Air support and light traverse capability is required for some drilling platforms (e.g., ASIG, Winkie)
- Airborne- and ground-based geophysical imaging are critical for site selection, precise drill targeting, providing geophysical context, and evaluating site safety.

Existing technology (ASIG, Winkie, RAID), generally medium logistics (interior traverse, no long-term field camp). Reconnaissance for site selection is likely to require high-resolution ground-based or airborne radar surveys, potentially coupled with other geophysical survey methods to determine lithology.

- Existing technology (RAID), heavy-medium logistics (multi-year interior traverse, no field camp). Reconnaissance for site selection is likely to require high-resolution ground-based or airborne radar surveys, potentially coupled with other geophysical survey methods to determine lithology.

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