Subglacial Access Working Group
Access Drilling Priorities in the Ross Ice Shelf Region

1) Summary: The Ross Ice Shelf (RIS) Region, including the ice shelf, associated ocean cavity, and coastal and upstream environments, is a dynamic system resulting from the interactions between ice, ocean, freshwater, and geology. Beneath the ice streams and outlet glaciers that feed the RIS, subglacial hydrological systems redistribute water and nutrients, yet the ultimate impacts of these systems on both ice flux into Ross Ice Shelf and freshwater and nutrient flux into the sub-ice-shelf ocean cavity are poorly understood. Aqueous and sedimentary subglacial environments are inhabited by microorganisms and represent a potentially large planetary reservoir of microbes and (microbially derived) organic carbon transported through the subglacial system and into the sub-ice-shelf cavity, perhaps of the same magnitude as that in the surface oceans.

Glaciological, oceanographic, geological, and biological research in this region benefits from a decades-long history of diverse scientific observations, which provides foundation for the development of focused hypotheses and enables interpretations of new findings in the context of decadal scale ice sheet and ocean evolution, which is difficult to replicate in many other parts of Antarctica. Materials collected from subglacial environments in the region are still rare; to date, only two subglacial lakes (Whillans and Mercer; SLW and SLM) and one grounding zone (Whillans Ice Stream; WGZ) have been cleanly drilled and accessed for sample collection. Current data from these studies indicate widespread microbial activity and potentially novel phylogenetic diversity and evidence for changing environmental conditions on surprisingly rapid timescales. **<u>Understanding the scope and pace of change and quantifying the importance of water and nutrient movement require scientific drilling in this region.</u>** Such campaigns will address questions related to the National Academies of Sciences' 2015 report *Strategic Priority I (How Fast and by How Much Will Sea Level Rise? The Changing Antarctic Ice Sheets Initiative) component i: A multidisciplinary initiative to understand why the Antarctic ice sheets are changing now and how they will change in the future, component ii: Using multiple records of past ice sheet change to understand rates and processes,* and *Strategic Priority II: How do Antarctic biota evolve and adapt to the changing environment? Decoding the genomic and transcriptomic base of biological adaptation and response across Antarctic organisms and ecosystems.*

2) Compelling research questions: The order of these research questions does not indicate priority and notably spans broad themes that are intrinsically linked and require a focused understanding of both modern and paleo processes. All questions are linked by the overarching theme of understanding *the role of water in the advance and retreat of ice sheets and subglacial biogeochemical and sedimentological processes.* These questions are best addressed by interdisciplinary approaches that maximize scientific returns from subglacial drilling projects. The drilling capabilities required to address the science depend on the maintenance of existing drilling technology, as well development of new tools with smaller logistical footprints enabling portable, clean-access approaches.

<u>Q1</u>: What are the linkages between biogeochemical processes and hydrology underneath ice sheets, ice streams, and ice shelves? How do these processes evolve over the course of fill-drain

cycles in dynamic hydrologic systems? What are the consequences for discharge of subglacially derived fluids on biogeochemical processes near grounding zones and in ice-shelf cavities?

Q2: How do subglacial aquatic systems vary spatially and temporally, and what processes control that variability? What are the primary factors (e.g. liquid water flow, ice dynamics including basal melt and accretion, microbial activity) that mediate biological and physicochemical connectivity?

Q3: How does basal ice-shelf meltwater influence nutrient/micronutrient budgets in the HNLC waters of the Southern Ocean? What is the balance between nutrient consumption in the sub-ice-shelf cavity and export to the open ocean? How does nutrient remineralization influence the global carbon budget?

Q4: How do modern and past changes to the circulation and transport of oceanic water masses influence ice-shelf stability? How will the production of Southern Ocean water masses (e.g., Antarctic Bottom Water, Antarctic Intermediate Water, etc.) be influenced by an increase in basal melting, variable freshwater input rates, and shifts in circulation?

Q5: What is the role of subglacial hydrologic connectivity across the grounding line in controlling ice margin advance and retreat? Specifically, what modern glaciological, oceanographic, and geological processes at the bed control the positioning of ice stream grounding lines, ice-shelf melt rates, and past periods of ice-sheet instability? What are the short- and long-term spatial distribution and temporal variability of ice streams and grounding line dynamics as they relate to the stability of Ross Ice Shelf? Constraining these physical parameters will aid in the improvement of numerical models for backcasting and forecasting rates and magnitude of change.

Q6: Are current ice sheet models capable of reproducing the past ice coverage, volume and rates of change for both high and low stands of sea-level? How do the processes described in Q5 inform scenarios that are both short-term policy-relevant and relevant to longer-term changes that will be “locked-in” by current and forecast emissions trajectories?

Q7: What were the past configurations of the grounding line in West Antarctica and what subglacial geologic archives can be used to reconstruct past ice shelf and ice sheet geometries in the region? How can investigations of modern subglacial sedimentary processes inform interpretation of past glacial records found today at ice sheet margins?

3) Scientific rationale:

Ross Ice Shelf, subglacial water, and interactions with biogeochemical processes (Q1, Q2 ,Q3)

Multiple lines of evidence presented at the 2019 SAWG Workshop highlighted the importance of the Ross Ice Shelf region in understanding subglacial hydrology as it relates to glaciological, geological, and biogeochemical processes. To date, only two Antarctic subglacial lakes (SLW and SLM) and one grounding zone (WGZ) have been directly accessed using clean-hot water drilling technology. While ground-based and remote sensed geophysical evidence suggest that the subglacial water system in this region is inter-connected, biogeochemical conditions vary among the two lakes and the WGZ from extremely dilute with low-biomass and concentrated dissolved gases to biogeochemical systems with production on the order of some surface aquatic environments. The spatial and temporal variability of hydrologic linkages among these environments and between them and grounding zones are not currently well understood. Temporally and spatially resolved sampling of water, sediments, and ice from both the sub-ice-sheet and sub-ice-shelf environments would build understanding of connectivity across the hydrologic network, and how that connectivity impacts both biology, and past, present, and future grounding line location and stability.

Dynamics of ice streams, grounding lines, and ocean circulation as they relate to the stability of Ross Ice Shelf (Q4, Q5, Q6, Q7)

Development and validation of the next generation of ice sheet models requires a better understanding of key processes and physical parameters relating to ice-sheet sensitivity, particularly as they relate to marine ice sheet instability. Numerical models allow the predictions of equilibrium condition end-member states. Quantitative observations that can be used to constrain fundamental processes determining climate sensitivity of polar ice sheets and ice shelves are currently lacking. Grounding lines represent a critical but poorly observed glaciological environment that has been accessed through drilling only relatively recently in a single location. Observationally constrained parameterization of glacial, oceanic, and geologic processes in a range of grounding line environments are required to evaluate and refine the current models of marine ice sheet instability. Fast ice streaming of the grounded ice sheet represents the means by which large volumes of ice can eventually be discharged into the ocean and contribute to sea level rise. An improved understanding of the spatial and temporal variability, as it relates to geologic substrata and hydrology, along the grounding lines of fast moving ice streams is central to better understanding the mechanisms driving basal melting and grounding line evolution. Furthermore, ice sheet sheer margins, which can potentially migrate and amplify or dampen changes in ice discharge need to be better constrained.

Past ice sheet extent and volume over a range of timescales (Q4, Q5, Q6, Q7)

Ice-sheet simulations focused on assessing Antarctica's contribution to future sea-level rise by the year 2050 predict outcomes ranging from a complete collapse of the interior of the marine-based West Antarctic Ice Sheet (WAIS) to modest changes in grounded ice along the Siple Coast. A better understanding of WAIS history is required to evaluate models used for future predictions. Geological drilling for sediment records, specifically along the Siple Coast, that span a multitude of timescales (e.g., multi-centennial, millennial and millions of years ago) and at different locations along-flow (e.g., downstream of the grounding line, beneath ice rises, WAIS flow divides) can allow for better estimations of ice sheet dynamics.

Time intervals of specific interest for deep sediment cores should be those depths that span warmer than present conditions (2°C and warmer) with a focus on interglacial episodes through the late Quaternary (past 1 million years). These geologically recent periods of warmth are integral to providing constraints for modeling experiments to help inform policy. Marine Isotope Stage (MIS) 5e, which was the last full interglacial, may represent one of the best analogs for ice sheet extent in the "near future," yet no direct record of this period has been constructed from direct sampling of sediment cores. Ice rises along grounding zones play an important role in the buttressing of ice shelves yet are poorly resolvable in whole-ice-sheet models. Thus, integrated studies of ice stream dynamics and the evolution of ice rises provide ideal data sets for ice-sheet sensitivity studies.

The ice streams that drain West Antarctica through the Siple Coast have internal dynamics that drive large-magnitude space and time variability in ice flux. Thus, individual drainage basins may respond differently to climatic variability. Adjacent sub-ice-shelf basins downstream from Siple Coast grounding lines have been identified from the ROSETTA-Ice airborne survey, and may provide ideal targets to recover long stratigraphic sediment core records that reveal changes in depositional environment along grounding line zones, beneath the WAIS divide dome, and into Late Neogene marine basins.

International interest in the Siple Coast region is anticipated to make these research objectives possible through the strategic sharing of logistics and funding. These subglacial basin records near the modern grounding line, and within marine basins of the Ross Embayment and Siple Coast, will directly complement the offshore records recently recovered by the International Ocean Discovery Program (IODP) Expedition 374, thus allowing for constraints on the extent of both ice advance/retreat across the shelf, while also tying in changes relating to paleocirculation of both outflowing Antarctic Bottom Waters and the advection of Circumpolar Deep Waters onto the continental shelf. These subglacial access holes can also be utilized for the examination of water column properties (current, salinity, temperature, velocity) and sub-ice-shelf biology using oceanographic casts and moorings, and cameras/ROV, for oceanographic monitoring.

4) Sampling Requirements: In this region, the collection of materials, including water and sediments, has focused on subglacial lakes and grounding zones. There are both overlapping and unique sampling and access requirements within each target type. New direct sampling of the subglacial environment should be guided by remote sensing and ground-based geophysical surveys.

- Long-term variability of subglacial aquatic physicochemical conditions
    - Deployment of fiber-optic cable with sensors capable of collecting oxygen, temperature, conductivity, lake level, and current data over periods of months to years in the subglacial environment. Ideally, monitoring deployments would be coordinated in order to achieve datasets that are directly comparable among sites.
    - Target sites include lakes and proximate grounding zone environments.
- Lake access and grounding line - Direct Sampling
    - Clean access hot-water systems at a range of depths (medium-scale [~500 m] and deep-scale [>2000 m] systems).
    - Collection of water samples (ca. 1-10L at a time; at discrete depths where applicable, pumping samples to the surface in some cases for specific analyses).
    - Collection of subglacial sediment cores (1-3 m minimum, 10+ m would lead to transformative science). Deeper coring potential could be developed with wire-line core retrieval, and use of water pressure for local generation of electricity to power drills and coring samplers for basal ice and sediment.
    - Deployment of sub-ice *in-situ* water filtration systems.
    - Deployment of custom-made PI instrumentation of varying weight (typically <100-1000 lbs, but could be several thousands of lbs).

    - Inspection of subglacial environments with cameras and/or AUV/ROV vehicles.
    - Collection of basal ice including sediment-laden basal materials.
    - Borehole measurements and continuous monitoring sensors detecting geophysical, hydrological, and sedimentological properties.
    - Collect complementary ice core records for a collection of a spectrum of time series data (i.e., ice rises)
    - Ice cavity oceanography through deployment of moorings and exploration with AUVs/ROVs in keeping with the SOOS long-term measurement plan

- Subglacial basins
    - Geophysics site survey with vibroseis
    - Hot water drilling, clean access
    - Stratigraphic development utilizing shallow and intermediate drilling of strata in adjacent basins to ice rises and grounding lines.
    - Borehole measurements and continuous monitoring with sensors capable of detecting geophysical, hydrological, and sedimentological properties.
    - Drilling for stratigraphic records using new ANDRILL-style drilling/coring, and development of with wire-line core retreival capability, and use of water pressure for local generation of electricity to power drills and coring samplers for basal ice and sediment core recovery 50 to 200 m sections.
    - Water sample collections

6) Target locations (where): This group favors targeting locations with the potential to demonstrate hydrologic connectivity between the ice sheet, subglacial lakes, bed sediments, and ocean while providing information in the form of both observational evidence as well as over a range of time scales as it relates to the fundamental processes governing changes in the biosphere, grounding line dynamics, and ice sheet (in)stability. While the Ross Ice Shelf region provides many targets, we focus here on the Siple, Gould, and Scott coasts both for reasons of accessibility and in an effort to maximize current knowledge and share financial responsibility with international partners. Targets should be adjusted based on knowledge availability from remote sensing and ground-based geophysical surveys. Targets are suggested to: 1) take advantage of and build off of existing datasets; and 2) coordinate the glaciological and biogeochemical interests in order to achieve integrated results with broad reach.

Lake targets for sensor deployments should include subglacial lakes Mercer and Whillans, as the combination of time-resolved observations with the existing in-depth biogeochemical datasets for these lakes would greatly expand current knowledge. We also propose to implement long-term observation in additional West Antarctic lake systems both in the vicinity of Mercer and Whillans and focus on those in unexplored territories for in-depth sampling. The choice of location should be informed by remote sensing and ground-based geophysical surveys, but targets thought to be hydrologically connected to Mercer or Whillans will contribute to a more robust understanding of the connectivity between biogeochemical processes and subglacial physical environments.

Grounding zones along the Siple, Gould, and Scott coastlines allow for the opportunity to observe a range of grounding line processes. Specifically, comparisons between Kamb, Whillans, and Mercer ice streams' grounding zones would provide quantitative observational data of system dynamics, while focusing on Bindschadler or Macayeal ice streams may provide the opportunity to examine a system closer to open Southern Ocean dynamics. Drilling upstream and downstream of grounding zones, as well as in lakes with predicted outflows to targeted grounding zones, will provide an opportunity for sensor deployment and paired sampling (e.g., including AUV/ROV surveys, discrete water/sediment sampling), providing further spatial and temporal resolution to our understanding of physical and biogeochemical processes in the region.

Ice rises and subglacial basins along the Siple, Gould, and Scott coastlines provide ideal targets for assessing the ice sheet history along grounding lines in regions that are of integral interest for guiding and validating modeling forecast studies. Recent geophysical studies from Crary Ice Rise should be included in targeting drilling sites that can both illuminate glaciology conditions since ice-grounding events, but also provide insight on geological drilling efforts that aim to age-date the underlying sediments. The glaciological and geological history of Steershead Ice Rise may be less well known at the present time but would spatially complement studies focused on Crary Ice Rise, given that these features buttress streaming ice from both Kamb and Whillans ice streams. Deep subglacial basins between and to the north of these ice rises could potentially yield sedimentary records that provide insight on longer-term variability in the region, which is integral to improve ice-sheet model skill. While ice rises can provide insight on ice dynamics of multi-centennial and millennial scale, adjacent subglacial marine basins have the opportunity to provide insight on long-term "locked in" states (e.g., warmer worlds) that are based on forecasted model trajectories. Connecting these geological records to a subglacial sediment core upstream (e.g., WAIS Divide, Byrd Camp) would allow for large-scale reconstructions of WAIS from the sediment record that test WAIS collapse hypotheses. Ice coring capabilities could be developed within existing clean-access hot water drilling systems to have the potential to recover the ice core records below the present WAIS Divide ice core, and continue into the marine strata below for combined glaciological and geological studies.

Geophysical surveys in the region are integral to identifying suitable drilling targets, and can most efficiently be done with vibrosis, whereas the drilling of ice and sediment can utilize existing technologies through U.S. and international partnerships, and with the engineering and development of new technology utilizing existing infrastructure. A long-term investment in this region will only compliment the decades of work carried out in the McMurdo Sound region and from offshore efforts. International collaboration in this region is feasible for sharing financial and logistical burdens.

4) Drilling parameters: Clean access is required to preserve the scientific integrity of the samples and for environmental stewardship based on the Antarctic Conservation Act Code of Conduct recommendations and SCAR protocol. Ice thickness for near-term targets in the RIS region can vary from 200 m (smaller outlet glaciers) up to 1500 m on ice streams. The present WISSARD drill system is upgradable to a maximum of 2500 m depth, and can achieve wider borehole diameters (i.e. up to 70 cm); the utility of which may be appropriate for long-term targets which were not discussed in RIS working group. Full capabilities of the WISSARD drill are detailed on the IDP website.

- Drilling needs for projects focused on in-depth lake sampling would be similar to the WISSARD drill, while sensor deployment could utilize a smaller footprint, scalable system. However, both goals require clean access capabilities and solutions for the recovery of borehole sensor equipment as needed.
- 10-70 cm boreholes are needed to enable sampling activities and/or monitoring on either side of grounding zones.
- Shallower drilling in the mid shelf and the front of the shelf are needed to establish oceanographic controls on grounding zones enabling the deployment of oceanographic moorings (i.e. 35 cm boreholes through ~200-400 m of ice).
- Addressing connectivity requires recovery of basal ice cores, with variable debris concentrations, with a hot water ice core drill, or alternatively with a wire-line system to recover sediment-laden ice cores recovered by electrical drills powered by locally-produced electricity from hot-water pressure-driven generators deep in the ice-borehole.
- Hole diameter will vary by specific project but can range from 10 cm to 70 cm. Larger holes employed by extended sampling campaigns can maximize sample collection and limit borehole time by allowing the collection of larger volume water samples or multiple sediment samples simultaneously. Freeze-back rates, instrument diameter, and time needed to collect different sample types (e.g. water and sediments) versus time to deploy equipment should be considered.

7) Target timeline:

The time frame varies by project, however, the overarching goals described here should be achievable on a 5-10 year timeframe, perhaps sooner for projects utilizing existing equipment, collaborating with international partners and with preliminary proposals already submitted to additional funding agencies such as ICDP (< 5 years). Planning, new system development and upgrades of existing drilling facilities, and drilling implementation would be coordinated and supported by the Ice Drilling Program (IDP) office.

8) Support requirements (how):

- Drilling capabilities vary depending on targets: for larger borehole projects needing a single or few large boreholes, the UNL WISSARD clean access drill (present limit of 1,500 m, upgradable to >2,500 m) has demonstrated success. This drill currently requires significant logistical mobilization support by the ASC, which is appropriate for some targets and project strategies. However, there is a strong need to diversify and provide capabilities that are more flexible and can address a range of project strategies. The UNL Roving Hot Water Drill (1,000 m depth limit, scalable and upgradable to clean-access) is more portable and capable of transport via smaller fixed-wing aircraft (i.e., Twin Otter). In all iterations of hot-water drilling support, the logistical footprint will be large due to fuel requirements.
- Projects with potentially smaller logistical footprints include thinner outlet glaciers, and some areas of ice shelves. Projects that require spatial sampling (2-3 holes or more) would require a smaller footprint (drill and camp) that could be transported site-to-site. More agile

capabilities are desperately needed, and we recommend a focus on technologies comparable to the proposed Scalable Hot Water Drill (ScHWD), and the existing Roving Drill (upgraded to clean access). Fuel need is a limitation that will require any remote hot-water drilling system to have a modest to heavy logistical footprint.
- PI-driven instrumentation and clean-access requirements for tools such as long-term borehole observatory capabilities, such as fiber-optic cables, borehole deployable AUVs, and instrumented water cavities. To address environmental stewardship concerns, these tools should be constructed out of materials that do not pose environmental harm.
- The diameter of instruments/samplers should be minimized to the maximum extent possible to decrease the need for larger boreholes. These instruments should be designed with clean-access approaches in mind.
- Transport depends on project size: larger projects using the full UNL-WISSARD drill requires traverse capabilities, while smaller projects using an agile drill, Roving Drill or proposed (SchHWD) could be supported with Twin Otter or Basler transport capabilities. Known existing thermal melting drills can be supported by helicopter. Drills and support staff also scale with project.
- Depending on complementary projects that are funded at the same time, traversing capabilities and support need to be invested for future science needs.

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Report contributors:
Trista Vick-Majors, Molly Patterson, Britney Schmidt, Keith Makinson, Tilak Hewagama, Jill Mikucki, David Harwood, Dale Winebrenner, Matt Siegfried, Alexander Michaud, Slawek Tulaczyk