Subglacial Access Working Group
Access Drilling Priorities in the Ross Sea Sector of the Antarctic Ice Sheet
Informal proposed title: Ross Ice Shelf and Ice Streams

1) Summary: The Ross Sea Sector of the Antarctic Ice Sheet, with its spatially diverse and changing natural environment, offers the US polar science community outstanding opportunities for drilling supported field research addressing the strategic research priorities identified in the recent NAS 2015 report on *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research.* Scientific drilling is necessary in this region to address the Strategic Priority I (How fast and by how much will sea level rise?) by collecting samples and data which will be used in: (i) evaluating the current state of the ice sheet, (ii) quantifying the glaciological and oceanographic processes that may play a role in rapid decay of the ice sheet, and (iii) interpreting past ice sheet changes from subglacial and ice-proximal geologic records to understand ice sheet sensitivity to climate forcing on different timescales. Recent ice sheet and ice shelf drilling projects completed in this region further highlighted its potential to address the evolution and adaptation of Antarctic marine and subglacial biota (Strategic Priority II in NAS 2015 report). Glaciological, oceanographic, and biological research in this region benefits from a decades-long history of scientific observations in this region, which permit development of focused hypotheses and enable interpretations of new findings in the context of decadal scale ice sheet and ocean evolution to the extent that is difficult to replicate in many other parts of Antarctica.

Beyond its relevance to both of the Strategic Priorities discussed above, drilling-based science in the Ross Sea sector of Antarctica will fulfill the recommendation of the NAS 2015 report for continued support of investigator-driven, 'blue sky' projects in a region which is relatively accessible with airplanes and surfaces traverses and where such projects can take advantage of synergies with other national programs, including the already funded New Zealand Ross Ice Shelf Programme.

2) Compelling research questions (order does not imply ranked importance or priority)**:**

2.1) How will discharge from fast moving ice streams evolve in the near future as a result of changes in ice sheet geometry, grounding line dynamics, evolution of bed properties, subglacial water flow, and shear margin migration?

2.2) What processes at the bed control the observed flow-speed variability of the Ross Ice Streams such as the stick-slip behavior of Whillans Ice Stream and the flow-speed modulation of Bindschadler Ice Stream?

2.3) What oceanic and glaciological processes control the spatially variable ice shelf melt rates and how susceptible are these processes to increases in melt rates under warming climate? Are there dynamic feedbacks between ice shelf mass balance and: calving, grounding line migration, ice discharge rates from the grounded ice sheet, etc.?

2.4) What is the relative role of glaciological, oceanographic, and geologic processes in determining the position and migration of grounding lines?

2.5) How will changing conditions of the CDW, driven by increasing water temperatures and modified sea ice production in the Ross Sea, influence or drive changes in RIS grounding line melt rates?

2.6) How do far-field ocean waves influence ice shelf edge calving? How does the transport of water masses (e.g., modified circumpolar deep water), as well as tidal circulation around the ice shelf cavity influence the stability of the ice shelf, and the circulation of water masses through the cavity? Will the production of Antarctic Bottom Water be influenced by increases in basal melting processes and shifts in circulation?

2.7) What was the configuration of the Antarctic ice sheets, and their contribution to global sea level highstands, during Pleistocene warm periods (interglacials)? Are current ice sheet models capable of reproducing the past ice coverage and volume?

2.8) How do ice-ocean interfaces support biological ecosystems and how to these ecosystems respond to changes in ice shelf conditions due to climate change?

2.9) What is the nature and significance of biological communities discovered at J9, the Whillans Ice Stream grounding zone, and Coulman High (near the front of the Ross Ice Shelf); How are these sustained in the dark waters of the cavity and far from the calving front? What are their adaptive features? How is the food web linked? What are the links between the ice shelf surface and benthos, and polynya productivity?

2.10) How does basal ice shelf melt water influence micronutrient budgets in the HNLC waters of the Southern Ocean? Do micronutrients get exported from the ice shelf cavity to the open ocean, or are they consumed in the cavity itself? How does remineralization in the ice shelf cavity influence the carbon budget?

3) Scientific rationale:

Dynamics of ice streams and ocean and their interactions with Ross Ice Shelf (2.1, 2.2, 2.3, 2.4, 2.5, 2.6) - Numerical ice sheet models represent the primary tool for predicting the future contribution of Antarctica to sea level changes but their fidelity still requires fundamental improvements. This is largely because of paucity of quantitative observations that can be used to constrain key processes determining climate sensitivity of polar ice sheets and ice shelves. At present Ross Ice Shelf is experiencing a range of basal melt rates, from nil to nearly 20 m/year, and sometimes high and low rates occur in close proximity to each other. Both spatial variability, and temporal evolution of basal melt rates need to be better understood to build reliable quantitative representation of key controlling processes that can be treated in numerical models. Grounding lines, where ice sheet goes afloat and becomes an ice shelf, represent the most critical but poorly understood glaciological environment that has been accessed through drilling only recently in one location. Yet, most quantitative models predicting rapid collapse of the marine West Antarctic ice sheet rely on runaway grounding line migration as the predominant mechanism driving such collapse. Observationally constrained parameterization of glacial, oceanic, and geologic processes in a range of grounding line environments are needed to evaluate and refine the current models of marine ice sheet instability. Fast ice streaming of grounded ice represents the means by which large volumes of ice can be brought out of the central part of the ice sheet and discharged into the ocean to cause sea level rise. Reliable representation of fast ice motion in ice sheet models demands improved understanding of fast ice motion over different geologic substrata, including weak subglacial tills. Temporal changes in basal resistance, whether mechanical or hydrologic in nature, are also key to understanding future ice sheet evolution. In addition to the bed, there is a need to study ice sheet shear margins, which can migrate and amplify or mute changes in ice discharge from ice streams. These topics and potential projects have a direct link to the "Aquatic" and the "Continental Interior" white papers.

Past ice sheet extent and volume (2.7 above) - Geologic drilling that targets stratigraphic records of Antarctic ice and climate during late Quaternary interglacials can provide the clearest picture of how Antarctic ice has behaved under the most recent periods of higher sea level. The more recent times of relative warmth (warmer than present), Pleistocene interglacials, are accessible at quite shallow burial depths, and have the advantage that boundary conditions including temperature, CO_2 levels, and continental configuration are well known and similar to today. Low-latitude records show that sea level has been higher than today during many of the recent interglacials, but such distal records are unable to show what ice was lost to create that sea-level rise. The only way to determine which drainage basins have contributed to sea-level change in the past is to get the proximal records of ice behavior in individual drainage basins. Stage 5e, the last full interglacial, may be one of the best analogs for the ice sheets' near-term future, and the extent and rate of West Antarctic ice retreat could be addressed at drill sites within deep basins, where the interglacial sediments were not removed during the last glacial maximum. Ideal targets are close to the modern grounding line, where different depositional environments will record shifts of the grounding zone. Documenting the configuration of the Antarctic ice sheet during past warm events is a critical to modeling efforts as doing so provides validation of forecasting models, by testing models ability to match past changes. This topic and potential projects have a direct link to the "Continental Interior" and "Aquatic" white papers.

Ross Ice Shelf and its interactions with biological and ocean processes (2.3, 2.4, 2.5, 2.6, 2.8, 2.9, 2.10) - The National Academy recently reported on strategic vision for Antarctic research. This highlighted the urgent needs for understanding the Southern Ocean and the Antarctic ice sheets and links outside of the Antarctic. This includes better understanding the life through genome-enabled studies in the Southern Ocean, and ice entombed or associated habitats. Improvement in understanding the Ross Ice Shelf, through mapping of the bed (seafloor and basal ice surface), knowledge of the distribution of ice thicknesses and velocities have all been (or will be shortly) significantly improved due to surveys by the Rosetta project, and will continue to be improved with ICESat-2 observations in the next few years. This provides an opportunity to improve the boundary conditions for models of the ice shelf cavity and the outcomes derived from the use of these models. There is a need to link our understanding of Ross Sea processes to the key processes in the ice shelf cavity and impacts on the grounding zone and ice shelf/ice sheet stability. This topic and potential projects have a direct link to the "Aquatic White Paper".

4) Drilling parameters:

- access holes with targeted ice core acquisition over short intervals.
- ice thickness varying from 300-700m on Ross Ice Shelf to 700-1200m on ice streams.
- clean access required over grounded ice but not over seawater
- hole diameter will vary by specific project but can range from 10cm to 70cm
- cleanliness requirements may also be defined by microbiology and geochemistry sample collection needs (rather than environmental stewardship)

5) Sampling requirements:

Targets include geological sampling, ice streams and grounding lines. Tulaczyk et al. (2014; Annals of Glaciology) provides details on sample borehole tools and their deployment timeline.

- Collect water samples (ca. 1-10L at a time).
- Collect subglacial sediment cores (1-3m in general, 10m in the case of investigations of past ice sheet configuration and volume).
- Deploy sub-ice in-situ water filtration systems.
- Establish ice cavity oceanography through deployment of moorings and exploration with AUVs/ROVs in keeping with the SOOS long-term measurement plan.
- Inspect subglacial environments with cameras and/or AUV/ROV vehicles.
- Install a range of sensors beneath and within ice for collection of a spectrum of time-series data.
- Collect short ice cores at target depths and collect basal ice core samples.
- Deploy custom-made PI instrumentation with varying weight (typically <100-1000 lbs but occasionally several thousands of lbs).
- Provide safe working platform around the borehole.

Ross Ice Shelf:

- Connect information from the seaward side of the Ross Ice shelf (e.g., Coulman High – to the inshore part of the ice shelf cavity and grounding zone to the south, as well as across the basin from east to west), to the mid-shelf and to the grounding zone (e.g., being studied by New Zealand in the next few years, with priority on areas on the Siple Coast).
- Interdisciplinary oceanographic studies are needed to better understand carbon cycling between the ice-ocean interface, mesopelagic processes and the benthos in the ice shelf cavity from the ice-edge to the back of the cavity at the grounding line.
- Though access to the ice shelf cavity requires ice shelf penetration in all cases (using some drilling technology that provides access holes that permit sample collections and instrument deployment (30-40 cm diameter holes), specific technologies (e.g., sensors and sampling tools) that are perhaps unique are required to work in these different zones to best study the life and interactions in these different ecosystems. Further – integrative concepts are needed to then understand if the processes at the ice-ocean interface influence the benthos, or whether advective processes are dominant.

- With ROVs, AUVs, discrete seawater samples and biological collections are required. Long term oceanographic measurements and time series data are incredibly valuable to understanding the ice shelf cavity. The New Zealand Antarctic Programme will deploy a mooring at their mid-ice shelf site and a mooring has been deployed near the Coulman High site for the past six years, but additional moorings are needed to be able to inform a better understanding of under-ice circulation, heat budget and tidal modeling efforts.

6) Target locations (where):
Priority on the Ross Ice Shelf and Siple and Gould Coasts is advocated. There is a strong international collaboration that can be leveraged in the proposed focus areas with the New Zealand Antarctic Programme, as they are already planning to support a study to access the cavity under the RIS, and linking processes between the Kamb Ice Stream over the next few years. Paleo-shear margins on Kamb Ice Stream can be investigated at the same time. The nearby Whillans and Mercer Ice Streams offers the opportunity to explore issues related to the dynamics of fast flowing ice, stability of grounding lines, subglacial water discharge and ice stream – ice shelf – ocean interactions.

For geological sampling focused on ice sheet history - Operational goals include recovering long sediment cores into undisturbed strata to allow assessment of how the ice responded in past warm periods. Intervals to be targeted include Pleistocene interglacials, notably Marine Isotope Stages 5e, 11, 31 and Pliocene warm intervals. Targets in the Ross Sea include Granite Harbor, the Mackay Sea Valley, and other deep basins immediately adjacent to the Transantarctic Mountains. Initial seismic profiling, both marine and from floating ice, suggest that significant sediment has survived in subsequent glacial advances. Final site selection will depend on denser seismic data to document the thickest sediment packages that are under a stable floating ice platform.

7) Target timeline (when):
Much of this is doable and currently, or recently, proposed. The New Zealand Antarctic Programme effort on and through the Ross Ice Shelf will happen in the 2017-2018 and 2018-2019 field seasons, as currently planned. The technology is not limited, but rapid access and roving drilling access can be improved, and opportunities for synergies may be available. Linking projects across the continental to seawater side of the Ross Ice Shelf is a priority but does not need to be synchronized in the same season.

For geological sampling for ice sheet history investigations the timeline for site selection is within three years; a timeline for drilling is five years.

A tentative timeline under consideration for the USAP science is:

2018-19 and 2019-20 = mouth of Whillans Ice Stream and the southernmost seawater cavity (to complement NZAP efforts at KIS)
2020-21 and 2021-22 = mid-RIS locations
2022-23 and 2023-24 = RIS front

8) Support requirements (how):

- Drills - existing drills (e.g. WISSARD main drill and roving drill can be used for these projects or the scalable hot-water drill planned by IDDO.)
- Additional drilling technology is required to obtain samples of basal ice.
- Sediment coring capabilities need to be developed to obtain 10m long subglacial cores
- Drills and fuels can be traversed and science personnel and their equipment flown into the drill site.
- Depending on complementary projects that are funded at the same time, traversing capabilities and support need to be investigated for future science needs
- Onsite/camp support - needed when science and tech personnel is in dozens of people.

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National Academies of Sciences, Engineering, and Medicine. 2015. A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research. Washington, DC: National Academies Press.