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Sensitivity of the West Antarctic Ice Sheet to +2 °C (SWAIS 2C)

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Abstract. The West Antarctic Ice Sheet (WAIS) presently holds enough ice to raise global sea level by 4.3 m if completely melted. The unknown response of the WAIS to future warming remains a significant challenge for numerical models in quantifying predictions of future sea level rise. Sea level rise is one of the clearest planet-wide signals of human-induced climate change. The Sensitivity of the West Antarctic Ice Sheet to a Warming of 2 °C (SWAIS 2C) Project aims to understand past and current drivers and thresholds of WAIS dynamics to improve projections of the rate and size of ice sheet changes under a range of elevated greenhouse gas levels in the atmosphere as well as the associated average global temperature scenarios to and beyond the +2 °C target of the Paris Climate Agreement.

Despite efforts through previous land and ship-based drilling on and along the Antarctic margin, unequivocal evidence of major WAIS retreat or collapse and its causes has remained elusive. To evaluate and plan for the interdisciplinary scientific opportunities and engineering challenges that an International Continental Drilling Program (ICDP) project along the Siple coast near the grounding zone of the WAIS could offer (Fig. 1), researchers, engineers, and logistics providers representing 10 countries held a virtual workshop in October 2020. This international partnership comprised of geologists, glaciologists, oceanographers, geophysicists, microbiologists, climate and ice sheet modelers, and engineers outlined specific research objectives and logistical challenges associated with the recovery of Neogene and Quaternary geological records from the West Antarctic interior adjacent to the Kamb Ice Stream and at Crary Ice Rise. New geophysical surveys at these locations have identified drilling targets in which new drilling technologies will allow for the recovery of up to 200 m of sediments beneath the ice sheet. Sub-ice-shelf records have so far proven difficult to obtain but are critical to better constrain marine ice sheet sensitivity to past and future increases in global mean surface temperature up to 2 °C above pre-industrial levels. Thus, the scientific and technological advances developed through this program will enable us to test whether WAIS collapsed during past intervals of warmth and determine its sensitivity to a +2 °C global warming threshold (UNFCCC, 2015).

1 Introduction

Human activities are estimated to have caused an increase in average surface temperature of ∼ 1.0 °C above pre-industrial levels (IPCC, 2018, 2021). Global temperature increase is likely to reach +1.5 °C relative to pre-industrial levels between 2030 and 2052 if it continues to rise at the current rate (IPCC, 2018, 2021). Warming of 2 °C could be reached as early as 2039 or as late as the mid-2060s depending on greenhouse gas emissions pathways (Tebaldi et al., 2021). Global mean sea level (GMSL) has already increased by ∼ 22 cm since 1880 (IPCC, 2013). The rate of sea level rise (SLR) has been accelerating over the last several decades due to ocean thermal expansion and increased ice mass loss from Greenland and Antarctica (Velicogna et al., 2014; Nerem et al., 2018; Shepherd et al., 2018; IMBIE team, 2018) and is currently ∼ 3.6 $\mathrm{mm\,yr^{-1}}$ (Oppenheimer and Alley, 2016). The Intergovernmental Panel on Climate Change (IPCC) has forecast a likely range of SLR between 0.29 and 1.1 m by 2100 (Oppenheimer and Alley, 2016). However, uncertainty in these estimates remains, and multiple new lines of scientific evidence indicate a substantially higher GMSL rise is possible due to relatively large contributions from Antarctica's ice sheets (Bamber and Aspinall, 2013; Kopp et al., 2014, 2017; DeConto et al., 2021; Edwards et al., 2021). The range of estimates is partly due to uncertainty regarding glacial processes including marine ice cliff instability (Pollard et al., 2015; DeConto and Pollard, 2016; Edwards et al., 2019; DeConto et al., 2021; Bassis et al., 2021; Golledge and Lowry, 2021; Crawford et al., 2021) and mantle and ice sheet grounding zone dynamics associated with glacial isostatic adjustment (Catania et al., 2012; Gomez et al., 2015; Kingslake et al., 2018; Whitehouse et al., 2019). Efforts to improve our knowledge of glacial processes and dynamics from modern observations and reconstructions of past ice sheet behavior aim to reduce uncertainty in future projections and are a major objective of the Sensitivity of the West Antarctic Ice Sheet to a Warming of 2 °C (SWAIS 2C) Project.

Response of the West Antarctic Ice Sheet (WAIS) to climate warming is the focus of several major national and international science programs including the International Thwaites Glacier Collaboration (https://thwaitesglacier.org/about/itgc, last access: 10 February 2022), the Subglacial Antarctic Lakes Scientific Access (SALSA) Project (Priscu et al., 2021), and SWAIS 2C. This focus on the WAIS is due, in part, to satellite observations that demonstrate the WAIS is losing mass at an accelerating rate (e.g., Bamber et al., 2018; Shepherd et al., 2018; IMBIE team, 2018), with the potential for future melt to contribute 4.3 m to global sea level (Fretwell et al., 2013). WAIS is considered highly sensitive to future warming because much of it is grounded ∼ 2500 m below sea level, and its associated floating ice shelves are exposed to progressively warming ocean waters.

Quantifying the response of the WAIS to future warming remains a significant challenge. Direct physical evidence of WAIS response in the past, when global mean temperatures were 2 °C warmer than pre-industrial times, offers constraints that will help reduce uncertainty. The international SWAIS 2C Project aims to obtain such records from the West Antarctic interior (Fig. 1) to understand past and current drivers of WAIS dynamics and identify thresholds in the system. Outcomes will improve projections of the rate and size of ice sheet changes under a range of elevated greenhouse gas levels in the atmosphere and associated average global temperature scenarios up to and beyond the 2 °C target of the Paris Climate Agreement (UNFCCC, 2015). The SWAIS 2C Project consists of an interdisciplinary group of engineers, geologists, glaciologist, geophysicists, oceanographers, microbiologists, and climate and ice sheet modelers collaborating to enhance our understanding of (1) WAIS dynamics during past intervals of warm climate and (2) ice, atmosphere, solid Earth, and ocean interactions and feedbacks at the WAIS grounding zone and the margins of the Ross Ice Shelf cavity through the instrumental period. This in-

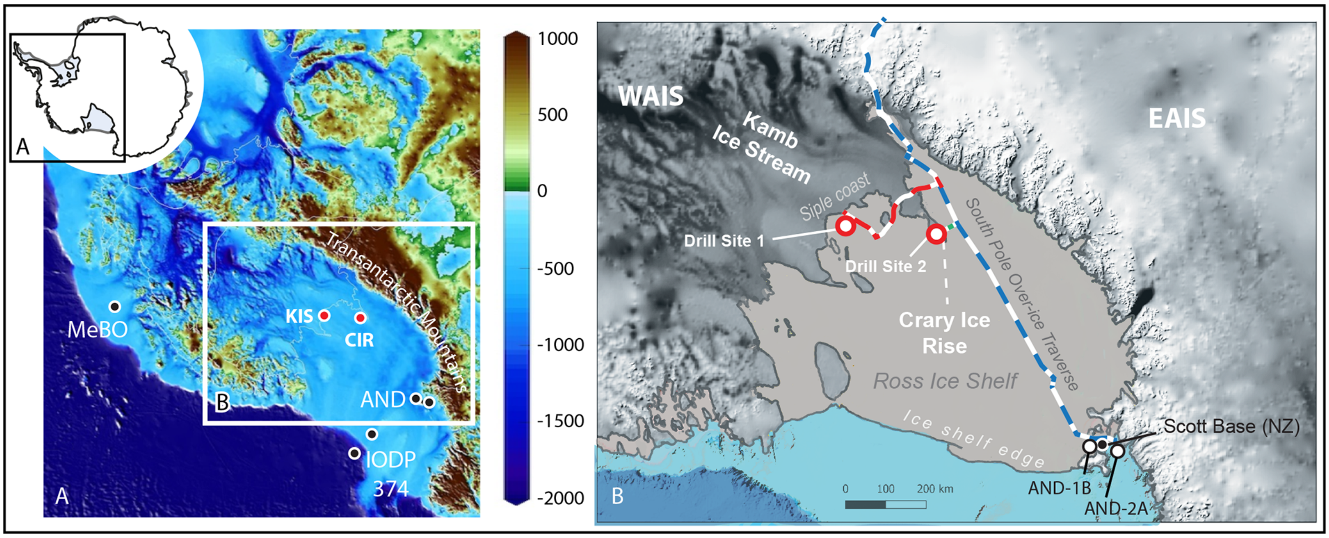

Figure 1. Proposed SWAIS 2C drill sites at Kamb Ice Stream (KIS) and Crary Ice Rise (CIR). **(A)** Topographic/bathymetric map across West Antarctica (color scale in meters). Other key drill sites include MeBO, ANDRILL (AND-1B and -2A), and IODP Exp. 374 sites (Fretwell et al., 2013). **(B)** Detail of the Ross Ice Shelf showing the South Pole Over-Ice Traverse and routes to drill sites 1 (KIS) and 2 (CIR). The new sites would anchor the southern end of a drill site transect deeply within West Antarctica.

formation will help determine the likely future response of the WAIS to projected warming and identify environmental implications for the Ross Sea sector and far-field consequences. The international partnership currently comprises 10 nations (Australia, Germany, Italy, Japan, Netherlands, New Zealand, South Korea, Spain, the United Kingdom, and the United States) but is still developing, with participation contingent on successful outcomes from national and international proposals.

2 SWAIS 2C: testing ice sheet sensitivities to a +2 °C global warming threshold

Integral to the SWAIS 2C Project's overall goal is the recovery of new Neogene and Quaternary sedimentary archives from beneath the Ross Ice Shelf at the grounding zone of the WAIS (Fig. 1). Because the magnitude of climate warming projected for the next century has not been experienced by Earth during the instrumental period, paleoclimate reconstructions of WAIS response during time intervals of analogous warmth to what is projected in the future, such as Pleistocene "super-interglacials" and the warmer-than-present Pliocene and Miocene (e.g., Melles et al., 2012; McKay et al., 2012; Levy et al., 2019), will provide critical insights into its future behavior (Retzlaff et al., 1993; Conway et al., 2002; Joughin and Tulaczyk, 2002; Mitrovica et al., 2009; Joughin et al., 2012; Hay et al., 2014). When integrated with numerical modeling experiments, modern process studies, and biological data, the new drill core data will allow us to examine the influence of climate dynamics and solid Earth processes in driving ice sheet fluctuations. Thus, the SWAIS 2C Project proposes to quantify the Antarctic ice sheet (AIS) contribution to past (with drilling) and future (with modeling) sea level change, through an improved understanding of climate, ocean, cryosphere, biosphere, and solid Earth interactions and feedbacks, so that decision-makers can better anticipate and assess risk associated with SLR and thus make more informed decisions around mitigation pathways. Thus, these unique data archives of late Cenozoic paleoenvironmental history will address the following key question: *what can we learn from past "greenhouse" conditions in Earth's climate to better anticipate future changes in the hydrological and biogeochemical cycle*? This is associated with theme 4, Environmental Change, in the International Continental Scientific Drilling Program (ICDP) 2020–2030 Science Plan.

3 Drill sites

The international SWAIS 2C Project plans to drill at two sites: the first adjacent to the grounding zone at Kamb Ice Stream (November 2022) and the second at Crary Ice Rise (November 2023) (Fig. 1). Both sites are to be accessed by overland traverse using the South Pole Over-ice Traverse (SPOT) route and new routes proved by Antarctica New Zealand. Both sites also offer stable drilling platforms as the Kamb Ice Stream has been stagnant for the past ∼ 150 years (e.g., Retzlaff and Bentley, 1993), and Crary Ice Rise stagnated around ∼ 1 kyr BP (Bindschadler et al., 1990; Catania et al., 2012; Hillebrand et al., 2021).

The Kamb Ice Stream site (KIS-3) is located ∼ 15 km seaward of the contemporary grounding line, where sedi-

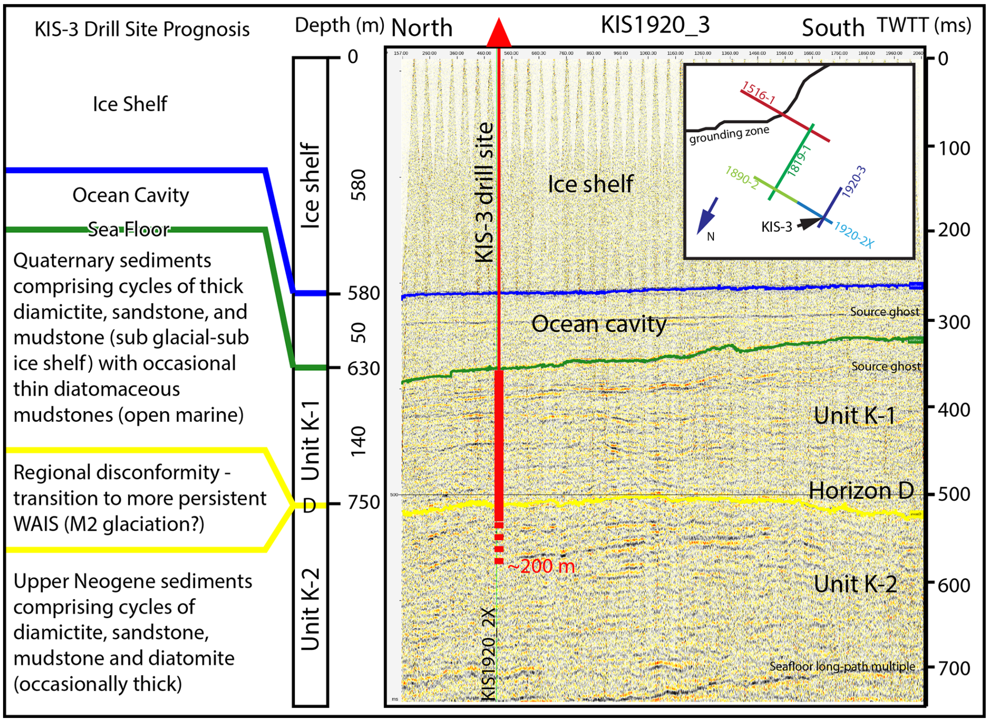

Figure 2. Seismic line KIS 1920_3. The KIS-3 drill site is located on the crossing point with line KIS1920_2X (inset). Drilling prognosis on the left with estimated depths from the surface and a brief description of stratigraphic intervals and horizons. The thick red line shows the 200 m drilling target depth.

ments are overlain by an ocean cavity and the floating Ross Ice Shelf. KIS-3 provides the opportunity to drill a modern ice stream environment from a stable drilling platform as the grounding line is thought to have migrated past the site since stagnation (Horgan et al., 2017). Three seasons of over-snow geophysics and one sub-ice-shelf direct-access program have provided site survey data, including over 70 km of multichannel seismic data. Over-snow seismic data imaged a thin water column (0–60 m) between the ice-shelf base and the seafloor (Fig. 2). Below the seafloor, two units are identified with the upper unit (Unit K-1) characterized by generally homogenous low-amplitude internal reflectivity with occasional high-amplitude horizontal to sub-horizontal internal reflectivity. The unit appears undeformed, and ice sheet modeling experiments suggest negligible glacial erosion at the site. We anticipate that this unit is of Pleistocene age based on the presence of reworked Neogene and Pleistocene diatoms recovered in surface sediments upstream of the drill site. The lower boundary of Unit K-1 is a high-amplitude positive-polarity reflector (Horizon D) at 130–180 m below the seafloor (at 2000 $\mathrm{m\,s^{-1}}$) and is easily recognized throughout the survey region as well as beneath the adjacent Whillans Ice Stream (Fig. 4) (Horgan et al., 2013; Luthra et al., 2016). Reflectivity within the overlying unit is generally disconformable with Horizon D. The polarity and amplitude of Horizon D suggest the upper sedimentary unit is underlain by more lithified sediment (Unit K-2). Horizon D is likely erosional and may reflect initiation of a more extensive and persistent WAIS, potentially coinciding with the marine isotope stage M2 glaciation event (3.312–3.264 Ma) recorded at AND-1B (McKay et al., 2012).

The Crary Ice Rise site (CIR-1) overlies grounded ice that is frozen at the bed. CIR-1 is downstream of Whillans Ice Stream, adjacent to Kamb Ice Stream, and accounts for over 50 % of the buttressing of the Whillans Ice Stream (Retzlaff et al., 1993). Recent geophysical surveying at CIR collected over 15 km of seismic data that are interpreted to include a Holocene grounding zone wedge (GZW) deposit (Unit C-1) overlying gently dipping strata (Unit C-2) (Fig. 3). The wedge-shaped sequence (Unit C-1) occurs above a regional disconformity (Horizon H) and is characterized by discontinuous (chaotic) reflectors and velocities estimated at 2200 $\mathrm{m\,s^{-1}}$. Several hundred meters of stratified and lithified sediment characterize Unit C-2, and while the age of this unit is unknown, we suggest that the gently dipping layers represent glacial–interglacial cycles comprising glacial till and open marine strata deposited during the Neogene. This hypothesis is based on sediments recovered from Crary Ice Rise during hot-water drilling efforts in the 1980s, where Neogene marine diatoms (Scherer et al., 1988) were recovered, suggesting grounding line retreat and open-water conditions as recent as the Pliocene (∼ 3 Ma) (Scherer, 1991). Venturelli et

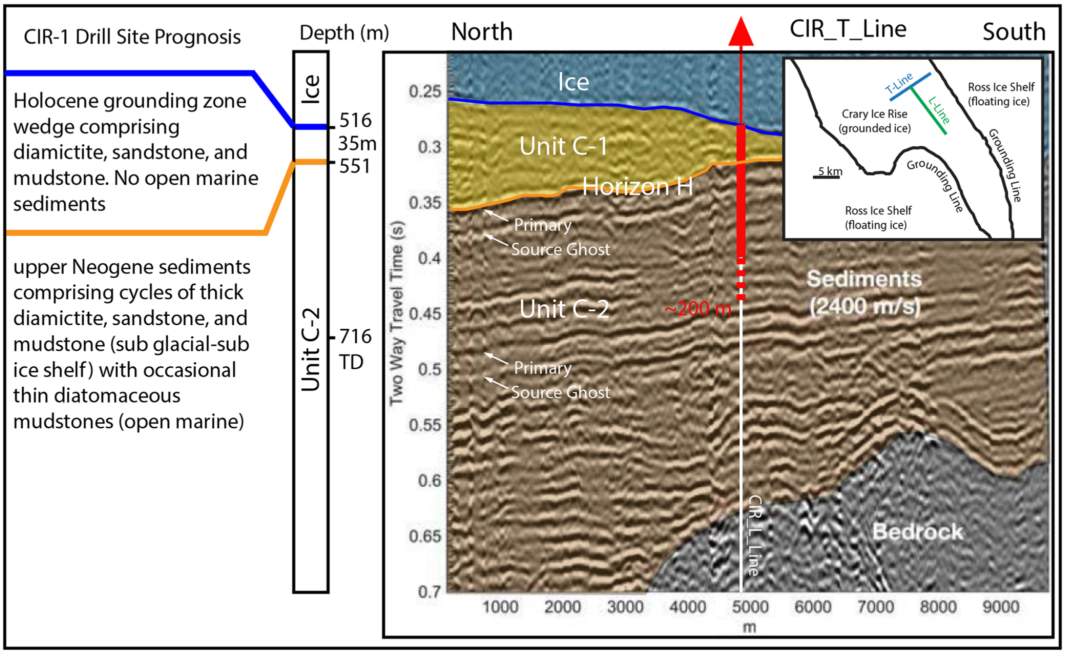

Figure 3. Seismic line CIR_T. The CIR-1 drill site is located on the crossing point with line CIR_L (inset). Drilling prognosis on the left with estimated depths from the surface and a brief description of stratigraphic intervals. The thick red line shows the 200 m drilling target depth.

al. (2020) demonstrated that nearby sediments and upstream deposits reflect periods of sub-ice-shelf deposition as recent as the mid-Holocene.

While there is an extensive network of seismic reflection surveys around the Antarctic margin and across the Ross Sea region, these marine data cannot be directly correlated to our proposed sub-glacial drill sites as over-ice/land-based surveys are logistically challenging, and relevant data do not exist. However, we postulate that sedimentary sequences recovered in the ANDRILL cores (Naish et al., 2009; Levy et al., 2016) and from the central Ross Sea (Hayes et al., 1975a, b; McKay et al., 2019) extend south beneath the Ross Ice Shelf and WAIS (Fig. 4). This hypothesis is based on (1) the character of the seismic sequences we have imaged at the proposed drill sites and, more specifically, the regionally extensive seismic reflector, Horizon D, which likely separates Neogene and Quaternary strata; and (2) reworked late Neogene and Quaternary diatoms recovered in subglacial sediments at CIR, Whillans Ice Stream, and KIS. Recovery of these new interior WAIS stratigraphic records will provide the southern anchor of a drill core transect in the Ross Sea Embayment (McKay et al., 2016), connecting the Ross Sea continental shelf (Naish et al., 2009; Levy et al., 2016; Fielding, 2018; McKay et al., 2019) to the West Antarctic interior, thereby providing a more coherent understanding of the processes regulating WAIS dynamics.

4 New capabilities in drilling subglacial sediment

Engineers from New Zealand's Antarctic Research Centre Science Drilling Office have developed a hot-water/rock drilling system capable of recovering ~ 200 m of sediment in places where the combined depth of the ice shelf (or sea ice) and water column is < 1000 m thick. The Antarctic Intermediate Depth Drilling (AIDD) system is housed in a tent that permits all-weather operation (Fig. 5). The new "light-weight" drilling system is designed for long-distance ice traverse. The sediment/rock drill (Multipower Products Ltd MP1000) is an industry-standard wireline system. Soft sediment coring will use two systems: a hydraulic piston corer (HPC) and a punch corer. Hard rock drilling will require diamond-bit rotary coring technology. Thus, cores will be recovered using three different approaches depending on lithology: (1) a hydraulic piston corer inside an NQ-sized drill rod (bit internal diameter, ID – 57.2 mm, outer tube bit throat ID – 51 mm), the preferred coring tool which will be used until refusal when it will be supplemented with punch coring; (2) rotary coring with NQ2 drill string (bit ID – 50.5 mm); and (3) rotary coring with a BQTK-sized rod (bit ID – 40.7 mm), which may be used in harder lithologies and may be used to cut the NQ drill string if necessary.

The combined rig, drill, and casing package weighs ~ 30 t, making it feasible to deploy within the constraints of existing Antarctic science support programs, with a much smaller logistical footprint than previous Antarctic drilling programs (i.e., ANDRILL; Falconer et al., 2008). This drill system's

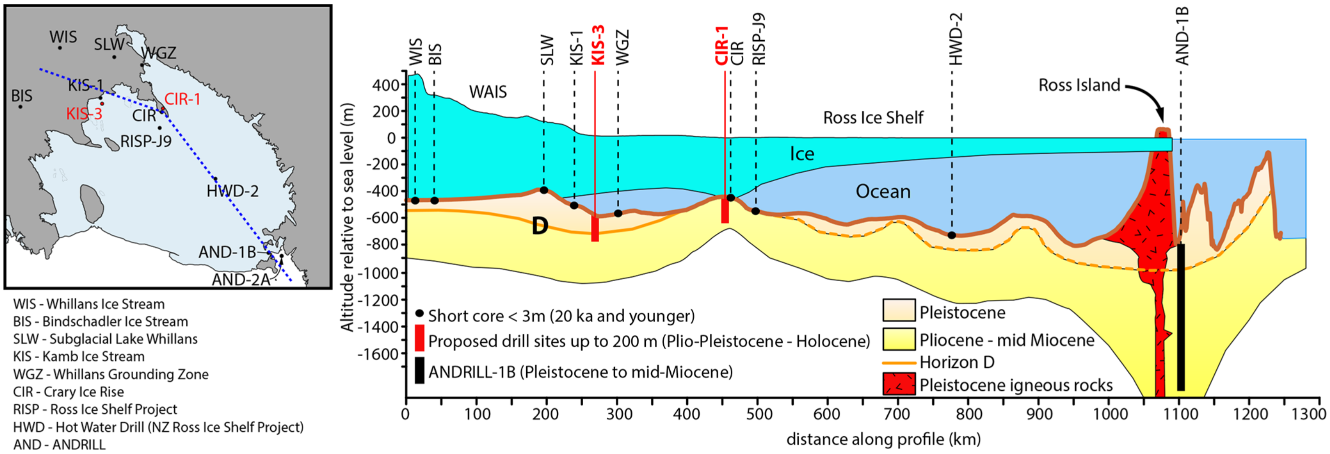

Figure 4. Regional stratigraphic correlation schematic. Dashed blue line is the location of the cross section. D is Horizon D identified at the KIS-3 site.

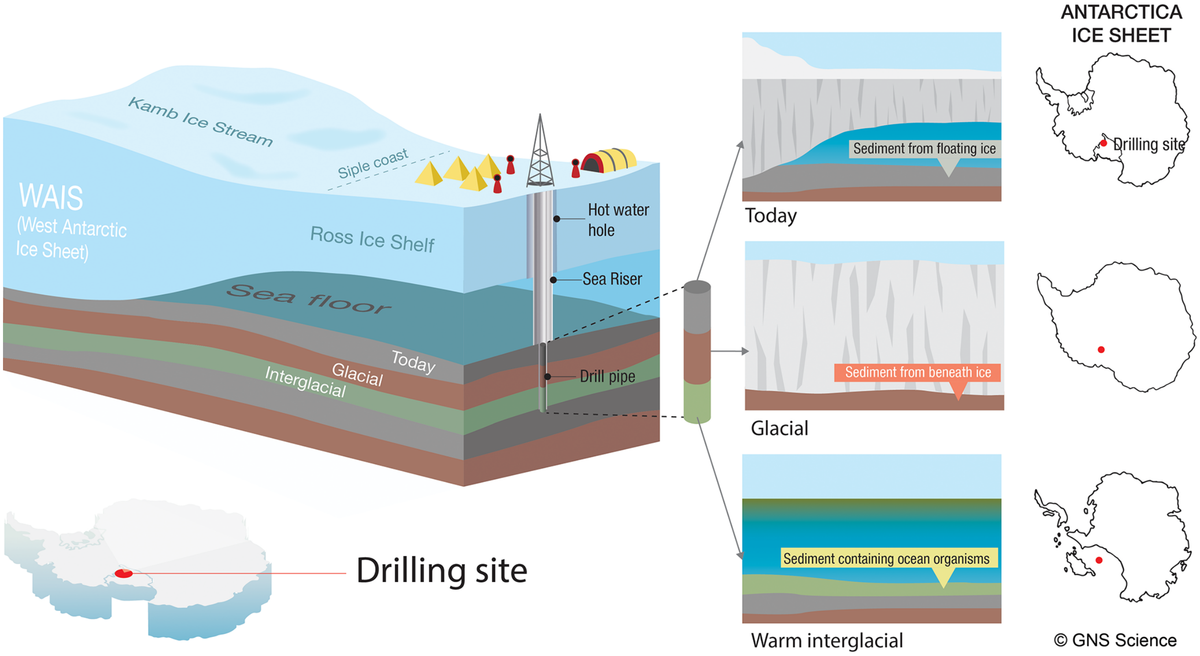

Figure 5. Diagram showing new drilling system sitting on the floating Ross Ice Shelf near the grounding zone at the Kamb Ice Stream site. A drill string up to ∼ 1000 m long will be lowered to the seafloor through a hot-water drilled hole in the ice shelf to core ∼ 200 m into the seafloor to sample sediments deposited in the past.

small logistical footprint will utilize a 24 h drilling operation to maximize core recovered in the short (∼ 14 d) drilling window.

5 The SWAIS 2C Project approach and challenges

Several international workshops have been held to develop the SWAIS 2C Project and to encourage members of the international science community to join. Most recently in October 2020, researchers, engineers, and logistics providers from partner nations attended a 4 h virtual international workshop to further develop the project. Discussions covered project goals, ongoing efforts of site characterization, performance capabilities of the drilling system, logistics, and operational support required to carry out field work, structure and timing of off-ice science workshops, required scientific disciplines for addressing research objectives, potential scheduling and logistical implications due to COVID-19, and numerical modeling experiments. During the workshop, it was acknowledged that areas in which further project development needed to occur centered around downhole logging technologies (e.g., spectral gamma, resistivity, temperature) that are compatible with the new AIDD system and inclusion of research that aims to address outstanding questions in the field of microbiology. In the months following the virtual workshop, science team members carried out detailed discussions with the staff at the ICDP Operational Support Group (OSG) and the Leibniz Institute for Applied Geophysics (LIAG) regarding downhole logging challenges, and additional science team members have been included to address investigations in microbiology. Here we provide an overview of the SWAIS 2C Project goals and approach that were outlined during the virtual workshop but also provide more detail on areas where shortcomings were identified but have since been addressed.

Currently, nearly 40 % of WAIS discharge is through fast-flowing ice streams along the Siple coast, in the region of the KIS and CIR (Price et al., 2001). Over decadal, centennial, and millennial timescales, the velocity of these ice streams has been highly variable (Bindschadler et al., 1990; Retzlaff et al., 1993; Joughin et al., 2002; Conway et al., 2002; Joughin and Tulaczyk, 2002; Hulbe and Fahnestock, 2007; Joughin et al., 2012). Currently there is a major gap in our understanding surrounding the negative feedbacks associated with dynamically relevant topographic features (i.e., pinning points), such as subglacial ice rises and grounding zone deposits, and thus these are poorly represented in ice-sheet models. Therefore, the temporal range of a Last Glacial Maximum (~ 21 ka) to Recent record (i.e., the last 21 000 years) would provide a wealth of information concerning long-term grounding line dynamics. Paleoenvironmental records from the Pleistocene interglacials would provide evidence of WAIS response to climatic conditions when temperatures were 1–2 °C warmer than pre-industrial times. Analysis of Pliocene and Miocene sediment records will reveal the duration of marine ice sheet cover during previous intervals of time when CO_2 levels were like those projected for the coming decades if we fail to meet greenhouse gas emission targets that aim to keep global average temperatures below 2 °C warming. Proxy-based reconstructions of WAIS response during these past warm times will be integrated with numerical modeling experiments and modern process studies to provide critical insight into WAIS behavior (e.g., Hay et al., 2014). These new paleoenvironmental reconstructions from the Neogene and Quaternary will directly address the following four guiding hypotheses: (1) Ice–solid-Earth feedbacks influenced ice dynamics along the Siple coast on a multi-millennial timescale trajectory during the Holocene; (2) ocean temperatures and circulation patterns are the key governing factor in driving WAIS dynamics during the warmer-than-present late Quaternary superinterglacials; (3) marine-based ice sheets were highly dynamic and periodically expanded and retreated across the Siple coast during the mid-Pliocene to late Pliocene (3.3–2.6 Ma) but did not advance across the continental shelf during the early Pliocene (a marine-based WAIS could not grow as climate was too warm prior to the M2 glaciation); and (4) a smaller-than-present terrestrial AIS during the Miocene Climate Optimum (MCO) produced by a combination of high atmospheric CO_2 and tectonic land subsidence resulted in an extensive highly productive shallow marine sea, that subsequently drew down CO_2 and culminated in global cooling and Antarctic Ice Sheet expansion during the middle Miocene Climate Transition (MMCT). These new cores will provide the southern end (most proximal to the ice grounding zone) of a transect of recent drill holes in the Ross Embayment (e.g., ANDRILL program and International Ocean Discovery Program (IODP) Expedition 374). Furthermore, the new SWAIS 2C sites will serve as a connection to drill sites in the Amundsen Sea sector of West Antarctica (PS104 Expedition “ASE-MeBo”, IODP Expedition 379), and the objectives are complementary to the International Thwaites Glacier Project. Ultimately, this land-to-ocean transect across the WAIS will provide a broader understanding of ice sheet history and more accurate predictions of future change.

The small diameter of our new drilling system presents a technical challenge to traditional downhole logging as there are few “off-the-shelf” logging tools slim enough to be deployed through the drill bit into the open borehole. The short drilling/logging window means duration is also an important factor in our logging strategy. Furthermore, the shallow holes (< 200 m b.s.f.) and the likely unconsolidated nature of the surrounding sediment mean logging in an open hole heightens the risk of losing logging tools in the hole. Our approach to downhole logging is therefore to use the ICDP Operational Support Group (OSG) “slimhole” Memory Logging tools (sondes) (iMLS) (https://www.icdp-online.org/fileadmin/icdp/services/img/Logging/OSG_Slimhole_Sondes_Specs_pics_2019-05.pdf, last access: 10 February 2022). These are self-contained, and no logging winch is required for deployment. While a new version of the iMLS depth measuring device (DMD) needs to be built, the existing spectral gamma (mSGR) and resistivity (mDIL) tools can be used without modification with an NQ-sized rotary bit. Other memory tools (sonic (mBCS) and magnetic susceptibility (mMS)) are too big to pass through the NQ rotary bit, although the mBCS can be used with the slightly wider NQ-hydraulic piston corer bit in place. Logging occurs as the NQ pipe is pulled from the hole upon a bit change or upon completion of drilling, with the MEMBAT module and mSGR (possibly mBCS) and mDIL tools assembled as a string. This approach saves critical time and will allow us to log the hole without casing. If time and hole conditions permit, it may be also possible to deploy four Leibniz Institute for Applied Geophysics (LIAG) wireline tools: resistivity, magnetic susceptibility, acoustic televiewer, and borehole mud temperature and salinity.

Temperature gradients will be measured in the seafloor at both KIS-3 and CIR-1. These measurements will allow for important geothermal flux and thermal transients to be determined. Heat flow is presently only determined by one shallow (< 3 m) probe measurement at Whillans Ice Stream and one at KIS, yet it is an important variable for calculating sub-ice shelf conditions for sliding (or "freeze-on"). At CIR we will also utilize recent advances in fiber optic distributed temperature sensor technology to instrument the borehole throughout the ice thickness and into the sediment after drilling. This technology has been used successfully in the region and is an inexpensive alternative to thermistor strings (Tyler et al., 2013; Fisher et al., 2015). Vertical temperature profiles through the ice will allow the numerical modeling team to validate and refine previous estimates of geothermal heat flux and CIR stagnation time.

Given the desire for a small on-ice project footprint, on-ice science analysis will be limited to X-ray imaging, smear slide analysis, porewater geochemistry, and microbiology sampling. Fast-track samples from core cutter material will be sent off-ice for paleontological assessment prior to off-ice science workshops. Researchers from partner countries will meet in Dunedin, New Zealand, at the Otago Repository for Core Analysis (ORCA) facility, housed at the University of Otago, for initial core characterization and sampling following each drilling season and operate in a similar fashion to a typical IODP expedition and post-cruise sampling workshop. At the end of initial characterization and sampling, sediment cores will be transported to the Oregon State University Marine and Geology Repository (OSU-MGR) for long-term storage and made available to the scientific community after a 2-year moratorium period. Our research methodology is built around an integrated data–model approach that utilizes paleoclimate data to improve the skill of Antarctic climate and ice sheet models by simulating past Antarctic environmental conditions and the consequences for global sea level (e.g., Naish et al., 2007; Harwood et al., 2008–2009; Pollard and DeConto, 2009; Naish et al., 2009; Golledge et al., 2015; DeConto and Pollard, 2016; Gasson et al., 2016; Levy et al., 2016). This integrated data–model approach will improve understanding of climate, ocean, cryosphere, and solid Earth interactions. This knowledge can reduce uncertainty in sea level projections, thereby allowing coastal communities to anticipate and assess hazards and risks associated with sea level rise under different emissions pathways and to evaluate the efficacy of adaption strategies.

There are very few studies on the deep biosphere from beneath Antarctica's ice shelves and at grounded ice rises (e.g., Carr et al., 2013). Recovery of subglacial material along the Siple coast region provides an unprecedented opportunity to extend our knowledge of the deep biosphere and its biogeochemistry across the Ross Sea and will build upon earlier work from ANDRILL (Carr et al., 2013), WISSARD (Christner et al., 2014; Vick-Majors et al., 2020), and ongoing work from IODP Expedition 374 (Ash et al., 2019) and the United States-based SALSA (Subglacial Antarctic Lakes Scientific Access) projects (Hawkings et al., 2020; Priscu et al., 2021). Specifically, determining the taxonomy and activity of both living and inactive microbial populations in sediments will provide insights to modern element cycling and past environmental conditions. Key questions surrounding the discipline of microbiology that could be addressed from the SWAIS 2C Project and extend beyond the geological studies include the following: (1) which organisms characterize the microbial communities and the structure of microbial food webs in the extreme subglacial and sub-ice-shelf environment? (2) What is the functional potential of the microorganisms in these environments, which metabolic pathways do they encode, and how do they contribute to major and trace element cycling and carbon burial? (3) How do microbial communities respond to varying environmental conditions (e.g., temperature) and inputs in organic matter (i.e., open vs. ice-covered conditions, discharge from subglacial lakes) over time? (4) What do inactive members of subsurface communities like cysts, spores, and other inactive cells, as well as extracellular DNA, tell us about past environmental conditions?

Five of the SWAIS 2C partner nations have secured national funding to participate in the project, and the SWAIS 2C Project Team was recently awarded funds to support drilling through the ICDP. Furthermore, several national-level proposals are currently under review. We plan to begin drilling at the KIS site in December 2022. For more information regarding the SWAIS 2C Project, contact the authors of this article.

Data availability. Seismic data presented in this paper can be accessed through the DMC at IRIS and at http://ds.iris.edu/mda/19-016/ (IRIS consortium, 2022) or by directly contacting coauthors Huw Horgan and Paul Winberry for access to our information regarding seismic data.

Team list. A list of science team members for these projects was assembled following an open call for participation at a PAIS (Past Antarctic Ice Sheet) workshop at the XIII International Symposium on Antarctic Earth Sciences in Incheon, Republic of Korea, in July 2019. We note that this list may not be comprehensive, and additional scientists may join the science team during planning and later stages of each project and as funding from international partners is determined. The current SWAIS 2C science team is as follows (last name alphabetical order): Leanne Armand (Australia National University), Jeanine Ash (Rice University), Jacqueline Austermann (Lamont Doherty Earth Observatory), Catherine Beltran (University of Otago), Mike Bentley (Durham University), Craig Cary (University of Waikato), Jason Coenen (Northern Illinois University), Ester Colizza (University of Trieste), Florence Colleoni (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), Giuseppe Cortese (GNS Science), Laura Crispini (Università di Genova), Rob DeConto (University of Massachusetts, Amherst), Paola Del Carlo (Istituto Nazional di Geofisica e Vulcanologia), Alessio Di Roberto (Istituto Nazional di Geofisica e Vulcanologia), Justin Dodd (Northern Illinois University), Bella Duncan (Antarctic Research Centre, VUW), Gavin B. Dunbar (Antarctic Research Centre, VUW), Olaf Eisen (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), José-Abel Flores (Universidad de Salamanca), Fabio Florindo (Istituto Nazional di Geofisica e Vulcanologia), Ed Gasson (University of Exeter), Karsten Gohl (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Nick Golledge (Antarctic Research Centre, VUW), David M. Harwood (University of Nebraska – Lincoln), Huw Horgan (Antarctic Research Centre, VUW), Angelika Humbert (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Francisco J. Jimenez-Espejo (Instituto Andaluz de Ciencias de la Tierra), Liz Keller (GNS Science), Jung-Hyun Kim (Korean Polar Research Institute), Sunghan Kim (Korean Polar Research Institute), Jonathan Kingslake (Lamont Doherty Earth Observatory), Johann P. Klages (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Nikola Koglin (BGR), Jochem Kück (GFZ Potsdam German Research Center for Geosciences), Denise K. Kulhanek (Binghamton University, SUNY; Christian-Albrecht University of Kiel), Andreas Läufer (BGR), Jae Il Lee (Korean Polar Research Institute), Amy Leventer (Colgate University), Richard H. Levy (GNS Science/Victoria University of Wellington), Frank Lisker (Universität Bremen), Gerrit Lohmann (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Dan Lowry (GNS Science), Rob McKay (Antarctic Research Centre, VUW), Gesine Mollenhauer (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Juliane Müller (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Tim Naish (Antarctic Research Centre, VUW), Pierre Offre (Royal Netherlands Institute for Sea Research), Christian Ohneiser (University of Otago), Molly O. Patterson (Binghamton University), Joe Prebble (GNS Science), Sonia Sandroni (Museo Nazionale dell'Antartide, Università di Siena), Francesca Sangiorgi (Utrecht University), Osamu Seki (Hokkaidō University), Louise Sime (British Antarctic Survey), James Smith (British Antarctic Survey), Anja Spang (Royal Netherlands Institute for Sea Research), Paolo Stocchi (Royal Netherlands Institute for Sea Research), Yusuke Suganuma (National Institute of Polar Research), Tina van de Flierdt (Imperial College London), Ryan Venturelli (Tulane University), Paul Winberry (Central Washington University), Thomas Wonik (Leibniz Institute for Applied Geophysics), Kiho Yang (Pusan National University), and Kyu-Cheul Yoo (Korean Polar Research Institute).

Author contributions. MOP, RHL, DKK, DT, and RK organized and facilitated the workshop. MOP, RHL, DKK, TvdF, HH, GBD, TRN, PW, DMH, FF, FJJE, AL, KCY, OS, PS, JPK, JIL, FC, YS, EG CO, JAF, and SWAIS 2C Science Team members contributed to developing the scientific objectives of the SWAIS 2C Project presented in the manuscript. GBD and AL contributed to downhole logging. JA contributed to the microbiology project objectives. AP and DM provided the information presented on the drilling system. PW and HH contributed to site survey information. DT, RK, and DK have managed the project and helped facilitate manuscript development.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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