# SENSITIVITY OF THE WEST ANTARCTIC ICE SHEET TO 2°C – SWAIS 2C

## SCIENTIFIC PROSPECTUS

SWAIS2C


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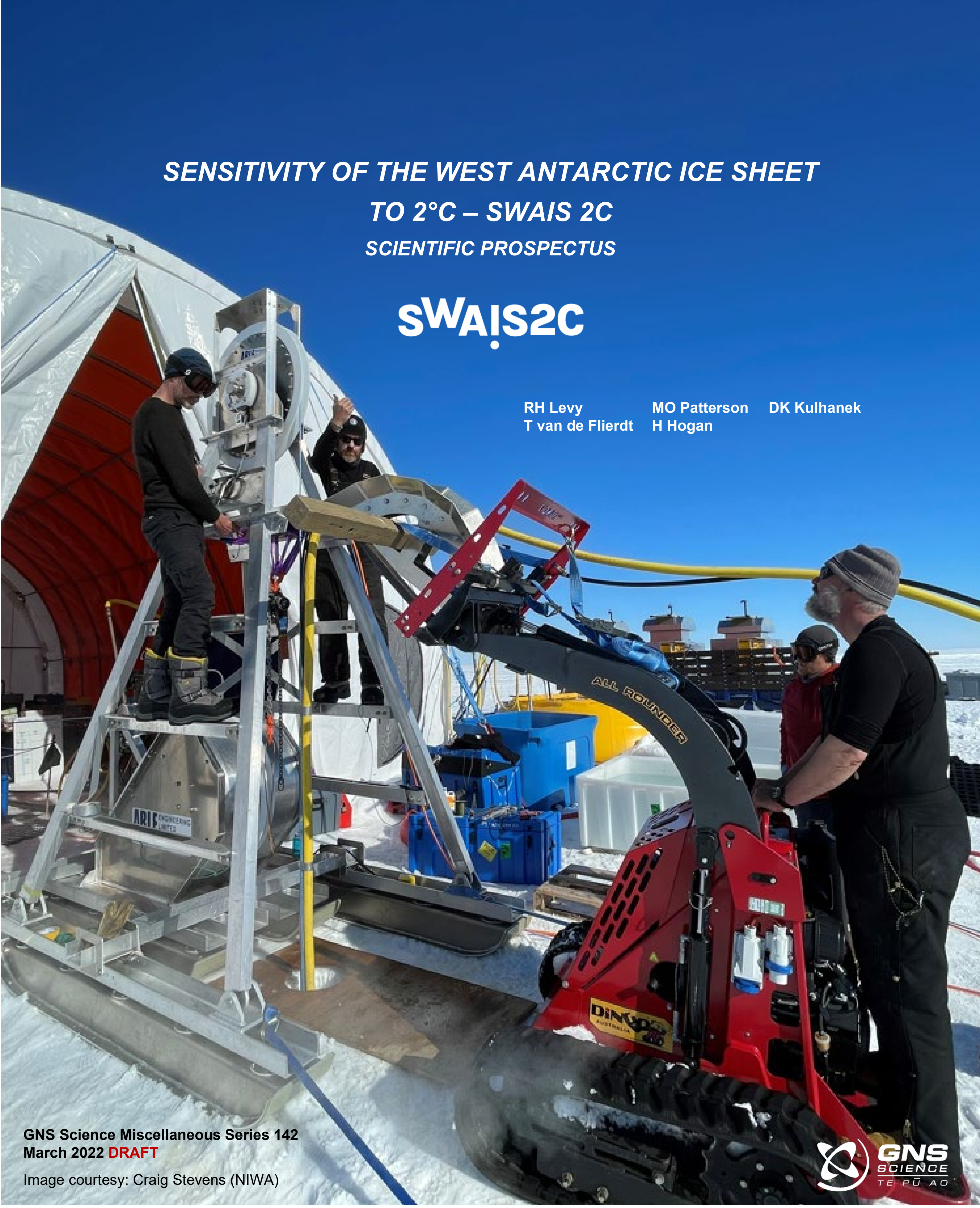



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## ABSTRACT

The West Antarctic Ice Sheet (WAIS) presently holds enough ice to raise global sea level by ~5 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 address this gap, researchers, engineers and logistics providers representing 10 countries have established the SWAIS 2C Project, an international partnership comprised of geologists, glaciologists, oceanographers, geophysicists, microbiologists, climate and ice-sheet modellers and engineers, outlining 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 programme 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).

This document outlines the scientific background rationale, as well as the scientific, drilling operations and logistics implementation plan for the project.

## KEYWORDS

Antarctica, West Antarctic Ice Sheet, Sea-level rise, Quaternary, Neogene, Siple Coast, Kamb Ice Stream, Crary Ice Rise.

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## 1.0 SUMMARY

Antarctic ice-sheet dynamics remain the largest uncertainty in projections of future sea level rise (Bamber et al. 2019; Bulthuis et al. 2019; DeConto and Pollard 2016; Edwards et al. 2019; Golledge et al. 2015; IPCC 2013; Oppenheimer et al. 2019). The West Antarctic Ice Sheet (WAIS), presently losing mass at an accelerating rate (Shepherd et al. 2018; Velicogna et al. 2014), holds enough ice, if melted, to raise global sea level by ~5 m (Fretwell et al. 2013; Morlighem et al. 2020). The 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 and associated average global temperature scenarios to and beyond the +2°C target of the Paris Climate Agreement (UNFCCC 2015). We will examine and quantify the sensitivity of WAIS to external drivers to assess its potential contribution to future sea-level change. Improved understanding of climate, ocean cryosphere and solid Earth interactions will reduce uncertainties in projections for decision-makers so that they can better anticipate and assess hazards and risks associated with sea-level rise under different mitigation pathways and evaluate the efficacy of adaptation strategies.

Previous drilling by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and recent expeditions by the International Ocean Discovery Program (IODP), MeBo, and ANDRILL recovered stratigraphic records of past ice sheet behaviour across the mid to outer continental shelf. Similarly, the response of WAIS to past warmer-than-present climates has been inferred from far-field globally integrated records of sea level and foraminiferal $\delta^{18}O$ (De Vleeschouwer et al. 2017; Westerhold et al. 2020; Zachos et al. 2001). Despite these efforts, unequivocal evidence of major WAIS retreat or collapse and its causes has remained elusive. These critical data are now within reach of our new drilling technology. Through this project, we aim to obtain new geological records of past WAIS behaviour from beneath floating and grounded ice at two sites that we have surveyed in detail: Kamb Ice Stream (KIS-3, Drill Site 1) and Crary Ice Rise (CIR-1, Drill Site 2) (Figure 1.1). These sites offer an opportunity to extend the existing Ross Sea drill-core transect deep into the West Antarctic interior and launch the first Antarctic land-to-sea project.

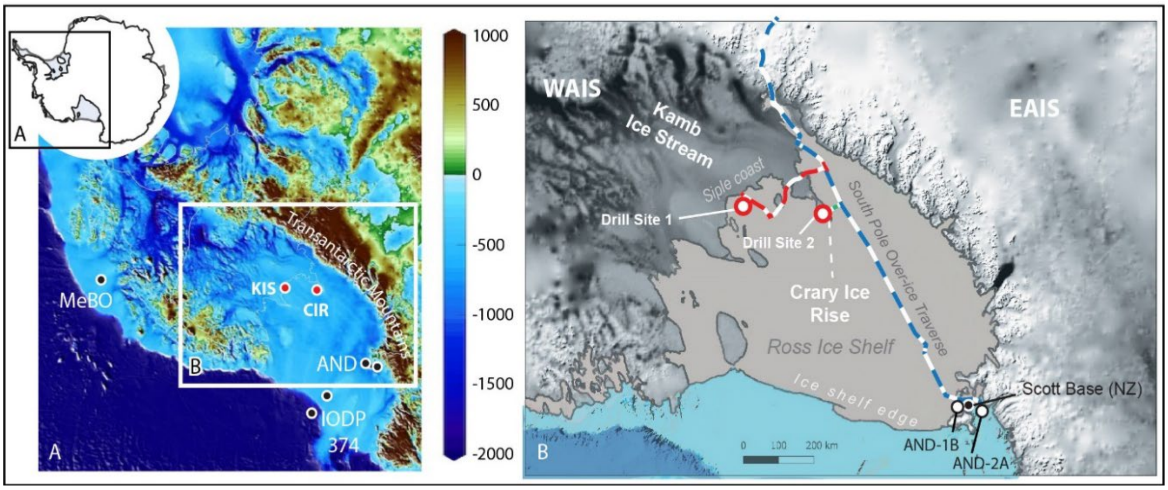


Figure 1.1 Proposed SWAIS 2C drill sites at Kamb Ice Stream (KIS) and Crary Ice Rise (CIR). Inset A: topographic/bathymetric map across West Antarctica (colour scale in metres). Other key drill sites include MeBo, ANDRILL (AND-1B and -2A) and IODP Exp 374 Sites. Inset B: detail of the Ross Ice Shelf to include 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 deep within West Antarctica.

The SWAIS 2C Science Team will use geological data from the new drill cores and associated paleoenvironmental modelling to help improve model-based projections of future ice-sheet-derived sea-level rise on short (decades to centuries) and longer (millennia) time scales. In doing so, we will address the key overarching question: *Under what climatic conditions does the WAIS collapse?* Outcomes of our research will contribute to a robust assessment of short-term, policy-relevant, scenarios of WAIS change, as well as the longer-term changes that will be 'locked-in' by current and forecast emissions trajectories.

# 2.0 THE SWAIS 2C PROJECT: MOTIVATION AND OVERVIEW

## 2.1 Global Context

Satellite observations show that Antarctica is losing mass at an accelerating rate (Bamber et al. 2018; Paolo et al. 2015; Rignot et al. 2019; Shepherd et al. 2018; Velicogna et al. 2014), with WAIS losing mass faster than other regions. WAIS is considered highly sensitive to future climate change, as much of it rests on bedrock -2500 m below sea level and is exposed to warming oceans (Fretwell et al. 2013; Morlighem et al. 2020; Pritchard et al. 2012). Collapse of *marine-based* sectors of WAIS has the potential to drive an increase in global sea level up to 3.6 m.

Glaciologists and geologists have long suggested that WAIS melt contributed to a rise in sea level between 6 and 9 m higher than today ~125,000 years ago (Dutton and Lambeck 2012; Kopp et al. 2009) during the last interglacial (LIG). Importantly, this melt occurred when global temperatures were only ~1°C warmer than pre-industrial values. Under such conditions, Greenland Ice Sheet (GIS) melt likely contributed 1–5 m of sea level (Neem Community Members 2013; Yau et al. 2016), requiring between 1 and 8 m sea-level equivalent from a full or partial collapse of WAIS and/or melt of low-lying areas in East Antarctica. Determining the sequence of future Antarctic sector melting is important, as magnitude, rate and regional pattern of sea-level change around the world is controlled by where and when ice mass is lost (Hay et al. 2014; Mitrovica et al. 2009). Our existing datasets lack direct physical evidence for WAIS disintegration during any of the late Pleistocene interglacials, with temperatures 1–2°C warmer than pre-industrial times. Our two proposed drill sites, Site 1 near the Kamb Ice Stream (KIS-3) grounding zone and Site 2 at Crary Ice Rise (CIR-1) (Figure 1.1), offer a means to obtain this direct evidence.

These unique data archives of Late Cenozoic paleoenvironmental history from extremely difficult to access regions at high southern latitudes will allow us to contribute to scientific objectives of several major global science programmes, including the International Continental Scientific Drilling Programme (ICDP) and IODP. To address fundamental questions regarding Earth system processes under warmer-than-present climates (e.g. ICDP Theme 04 and IODP strategic objective 3), and to identify potential climatic tipping points (e.g. IODP strategic objective 5), requires paleoenvironmental data from key regions that record Earth's history and document sensitivities. Because the magnitude of climate warming projected for the next century has not been experienced by Earth for more than three million years, paleoclimate reconstructions of past Antarctic Ice Sheet (AIS) response during this time interval will provide critical insight into its future behaviour. When integrated with numerical modelling experiments and modern process studies, the new drill-core data will allow us to examine the influence of climate dynamics and solid Earth processes in driving ice sheet variability and resulting sea-level change.

## 2.2 Building on Previous Drilling at the West Antarctic Margin

West Antarctica is 1.97 x $10^6$ $km^2$ in area (the combined size of France, Spain, Sweden and Germany) and is largely ice-covered, which means that its geological archives are hidden. A relatively large number of short (<5 m) sediment cores have been recovered at open marine sites across West Antarctica's continental shelves using gravity and piston coring systems. However, these records generally post-date 20 ka, as it is nearly impossible to penetrate over consolidated till deposited during the Last Glacial Maximum (LGM) using gravity-based coring systems. Scientific drilling offers the only means to access older archives. To date, deep drilling into the West Antarctic continental shelf has only occurred at 13 sites. None are located landwards of the present calving line and thus do not directly sample paleoclimatic records from under the WAIS.

Geological records for the Miocene to Pleistocene in the Ross Sea have been recovered by the ANDRILL programme and at mid and outer continental shelf sites by IODP Expedition 374 (McKay et al. 2019; Figure 1.1). Sedimentary cycles in the AND-2A core revealed a highly dynamic history of ice flowing from East Antarctica throughout the early to middle Miocene and highlighted that marine-based ice advance occurred when $CO_2$ dropped below 400 ppm (Levy et al. 2016). A remarkable sequence of glacial-interglacial cycles comprising diamictite, sandstone, mudstone and diatomite was recovered in the AND-1B core. These data suggested that, while the WAIS advanced and retreated through much of the Plio-Pleistocene (McKay et al. 2012b), it likely completely collapsed during the warmest interglacials and remained absent through much of the early Pliocene (McKay et al. 2012a; Naish et al. 2009). However, these data come from sites approximately 900 km from the modern grounding zone of the WAIS and 1500 km from the ice sheet centre; therefore conclusions about past WAIS behaviour are less conclusive than those that could be drawn from more proximal records (Figure 1.1). The geological ‘smoking gun’ required to identify the timing of WAIS collapse and environmental conditions that caused complete retreat has yet to be obtained. Here we propose to ‘fill the gap’.

## 2.3 The SWAIS 2C Portfolio of Stratigraphic Drilling Objectives

Proxy sea-level records and far-field shoreline reconstructions provide indirect evidence of the timing and magnitude of global ice volume variability (Dutton et al. 2015; Dutton and Lambeck 2012; Grant et al. 2019) and, in some cases, may indicate the relative meltwater contributions from different polar ice sheets when integrated with Glacial Isostatic Adjustment (GIA) modelling (Clark et al. 2002; Hay et al. 2014; Kopp et al. 2015; Mitrovica et al. 2009). However, new geological records next to the AIS are required to identify and quantify the potential contribution from specific sources of meltwater. WAIS is thought to be inherently more susceptible to collapse than the margin of the East Antarctic Ice Sheet (EAIS), but this remains to be demonstrated, as there are no paleoenvironmental records from Antarctica’s interior.

Sedimentary records from the West Antarctic continental interior are needed to show when the WAIS fully collapsed in the past. Thus, the SWAIS 2C Project will focus its initial efforts along the Siple Coast, adjacent to the grounding zone at KIS and CIR. A new drill developed for the SWAIS 2C Project aims to acquire new Quaternary and Neogene sedimentary drill-core records of ice sheet and environmental variability adjacent to the present-day grounding zone of WAIS. These new records will provide the southern anchor of a drill-core transect in the Ross Sea sector from the continental slope into the heart of West Antarctica. Integration of new drill core data with state-of-the-art climate, ice sheet and GIA modelling will resolve WAIS sensitivity to a warming climate and reconcile its contribution to past global sea-level changes.

We have developed and built new drilling technologies for ice and sediment/rock to enable the international research community to access sedimentary archives beneath ice shelves, sea ice and from ice rises. Our proposed approach is novel, low-cost and opens new opportunities to obtain key records of environmental change and ice-sheet dynamics at remote locations across Antarctica in a manner that is not possible with existing equipment and logistical support.

The two projects at KIS and at CIR have been supported by the ICDP, as well as national science funding agencies and/or Antarctic programmes of Australia, Germany, Italy, New Zealand, South Korea, the United Kingdom and the United States. Several other nations are currently seeking support. The total project, including logistics, has been funded internationally at $4.6 million USD.

## 2.4 Scientific Objectives of the SWAIS 2C Project

The SWAIS-2C Project has five scientific objectives, with associated testable hypotheses and guiding questions outlined below. Our scientific approach and methodologies are described in more detail in Section 2.5.5.

### 2.4.1 Glacial Dynamics since the Last Glacial Maximum to Provide Mechanistic Insights

**Guiding Hypothesis (H1):** Ice-solid-Earth feedbacks influenced ice dynamics along the Siple Coast on a multi-millennial time-scale trajectory during the Holocene.

Here, we seek to understand grounding line dynamics along the Siple Coast margin of WAIS during the LGM-to-Recent. Currently, nearly 40% of WAIS discharges 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; Conway et al. 2002; Hulbe and Fahnestock 2007; Joughin and Tulaczyk 2002; Joughin et al. 2002; Retzlaff et al. 1993). An LGM to present record will provide a wealth of information concerning grounding line dynamics to guide development of better numerical models.

A missing piece in our understanding of ice-sheet dynamics is the role of negative feedbacks in grounding line stabilisation (Bradley et al. 2015; Kingslake et al. 2018; Matsuoka et al. 2015; Siegert et al. 2013). Sub-glacial ice-rise formation along grounding zones may play a fundamental role in LGM to present ice dynamics through negative feedbacks associated with pinning points (Matsuoka et al. 2015). However, evolution of these dynamically relevant topographic features is poorly understood and poorly represented in ice-sheet models. It is hypothesised that shelf ice became grounded at what is now CIR in response to fluctuating discharge from ice streams along the Siple and Gould coasts over the last millennia (Bindschadler et al. 1990; Hulbe and Fahnestock 2007). Conventional reconstructions have long assumed a unidirectional retreat of the grounding line from the continental shelf edge since the LGM (Conway et al. 1999) in response to rising global temperature (Bentley et al. 2014). However, recently uncovered evidence suggests that rapid retreat past the current grounding line during the Holocene was followed by re-advance, although the interplay of topographic and isostatic controls on this behaviour is not well understood (Halberstadt et al. 2016; Kingslake et al. 2018). This ‘re-advance’ hypothesis is supported by isotopically ‘light’ $\delta^{13}C_{org}$ (-31 to -25‰) in Holocene-age sub-glacial lake sediments recovered below the Whillans and Mercer ice streams. These data suggest that marine conditions occurred above the (presently sub-glacial) site during the Holocene (Venturelli et al. 2020). In addition, numerical modelling suggests that post-LGM grounding line retreat was halted (Lowry et al. 2020) and potentially reversed (Kingslake et al. 2018) by crustal uplift due to glacial isostatic adjustment. The timing and magnitude of retreat and re-advance varies significantly between model simulations, leaving large uncertainty in the efficacy of the negative feedback processes involved and in the Holocene history of this important region. A better understanding of the potential for bedrock topography and mantle viscosity to slow or reverse early Holocene grounding line retreat is fundamental to our capability to predict future ice-sheet change and resultant sea-level rise.

**H1 Key Questions:** (1) Has there been significant ice-sheet re-advance in the Siple Coast area since the early Holocene? (2) When did the CIR and KIS unground, and when did CIR re-ground? (3) Was re-advance driven by climatological and/or glaciological processes? (4) Can glacial isostatic adjustment halt ice retreat and cause re-advance?

### 2.4.2 Late Quaternary Sea-Level and Ice-Sheet Contribution in Response to Near-Future Climates

**Guiding Hypothesis (H2):** Ocean temperatures and circulation patterns are the key governing factor in driving WAIS dynamics during warmer-than-present Late Quaternary super-interglacials.

A primary goal of SWAIS-2C is to acquire records of WAIS extent during late Quaternary 'super-interglacials', which were characterised by warmer-than-present conditions both in Antarctica and globally (Brigham-Grette et al. 2013; Melles et al. 2012; Scherer et al. 2008). Proxy environmental data from the LIG (MIS 5e; ca. 129–116 ka) suggest that global mean temperature peaked at 1°C higher than the pre-industrial period (Dutton and Lambeck 2012; Otto-Bliesner et al. 2013). Maximum global mean sea level was 6–9 m above present-day (Austermann et al. 2017; Dutton and Lambeck 2012; Kopp et al. 2009). Global average temperatures during MIS 11 (ca. 425–395 ka) may have been 2°C higher than pre-industrial levels (Dutton et al. 2015; Lang and Wolff 2011) and maximum global mean sea level was 6–13 m higher than today (Dutton et al. 2015; Raymo and Mitrovica 2012). Antarctic margin temperature estimates during MIS 31 (ca. 1.08–1.06 Ma), a super-interglacial with high obliquity and eccentricity alignment, are several degrees warmer than pre-industrial (Beltran et al. 2020), and WAIS collapse has been inferred (Scherer et al. 2008).

Although orbital parameters during these interglacial periods were different from today, their warmer temperatures allow insights into past sensitivity of WAIS to climates that were like those projected under the Paris Agreement target. Sea-level reconstructions imply that WAIS and GIS were significantly smaller during these interglacials and imply a high sensitivity to small temperature increases. However, the ice volume loss and meltwater contribution from each ice sheet is still debated (DeConto and Pollard 2016; Goelzer et al. 2016; IPCC 2013; Neem Community Members 2013; Yau et al. 2016). Ever since the influential paper by John Mercer (Mercer 1978), WAIS collapse is assumed to occur during super-interglacials, but causes of WAIS retreat are equivocal (DeConto and Pollard 2016; Pollard et al. 2015; Sutter et al. 2016), and evidence of full collapse is indirect (McKay et al. 2012b; Neem Community Members 2013; Pollard and DeConto 2009; Scherer et al. 1998).

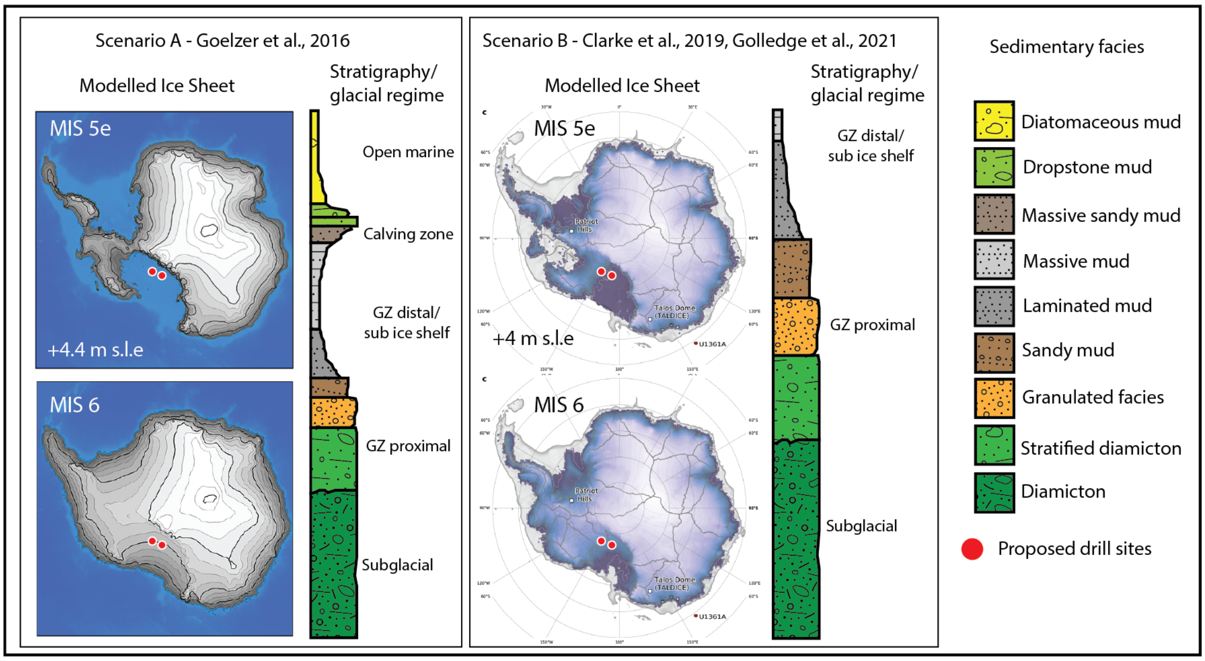


Figure 2.1 Two contrasting published ice-sheet model simulations for the penultimate glaciation (MIS 6) and Last Interglacial (MIS5e) and resulting sedimentary sequences that would accumulate at the KIS and CIR sites for (Scenario A) complete Ross Ice Shelf (RIS) collapse in MIS5e and (Scenario B) a stable RIS in MIS5e. Drilling will identify which sequence (and ice-sheet configuration) is most accurate.

Provenance records from the Amundsen Sea suggest partial WAIS collapse during MIS 5 (van de Flierdt et al. 2019) but a largely unchanged WAIS through other super-interglacials (e.g. there is no retreat signal through MIS 11). This contrasts with observations from the Wilkes Subglacial Basin (East Antarctica), where results imply larger ice loss during MIS 11 compared to MIS 5 (Blackburn et al. 2020; Wilson et al. 2018). These observations suggest that WAIS and EAIS sensitivity varied throughout the Pleistocene. Furthermore, while many ice-sheet modelling studies produce ice volume loss of similar magnitude through these interglacial episodes, they produce significantly different ice-sheet configurations. For example, some models simulate complete collapse of the WAIS during MIS 5 (Goelzer et al. 2016), while others maintain grounded ice in the Ross Sea region (Clark et al. 2020; Golledge et al. 2021) (e.g. Figure 2.1). New geological data from our proposed drill sites near the grounding zone of WAIS in the Ross Sea are required to determine whether WAIS completely or only partially collapsed during Quaternary interglacials (Figure 2.1). Outcomes will provide important targets for ice-sheet modelling and will ultimately improve our ability to simulate sea-level fingerprints, as they are highly dependent on the location of ice mass loss (Hay et al. 2014; Kopp et al. 2015) with important societal implications.

**H2 Key Questions:** (1) Did WAIS contribute to sea-level rise observed during the most recent interglacial (MIS 5)? (2) Did WAIS contribute to sea-level rise during other Late Quaternary ‘super-interglacials’ (e.g. MIS 11 and 31)? (3) What were the environmental conditions in the inner Ross Sea during Late Quaternary interglacials (e.g. ocean temperature, sea ice presence/absence)?

### 2.4.3 Pliocene Ice-Sheet Variability (Current $CO_2$ Forcing and >2°C Warming)

**Guiding Hypothesis (H3):** Marine-based ice sheets were highly dynamic and periodically expanded and retreated across the Siple Coast during the mid-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).

By 2100, projected atmospheric $CO_2$ concentrations will range from 430 to >1000 ppm depending upon future emission scenarios (IPCC 2013; Meinshausen et al. 2020). Proxy-based $pCO_2$ reconstructions suggest that the Pliocene was the last time that atmospheric $CO_2$ levels exceeded 400 ppm and global mean temperatures were a few degrees warmer than pre-industrial (Dowsett et al. 2012; Haywood et al. 2013, 2016). Recent reviews of globally distributed Pliocene sea-surface temperature records indicate that global mean sea-surface temperatures were ~2.3–3.2°C warmer than pre-industrial during Pliocene interglacials when seasonal and regional changes of incoming solar radiation were similar to modern ones (e.g. Marine Isotope Stage KM5) (Haywood et al. 2016; Figure 2.2). This increase in sea-surface temperature was amplified in high latitude regions and coincided with evidence from the AND-1B site of long-lasting periods of open marine conditions prior to 3.3 Ma (Naish et al. 2009; Pollard and DeConto 2009). An extended period of reduced marine-based ice during the early Pliocene was followed by a period of increased WAIS dynamism during the late Pliocene, where marine-based portions of WAIS advanced and retreated across the continental shelves (McKay et al. 2009; Naish et al. 2009). Pliocene WAIS was highly sensitive and responded dynamically when global mean surface temperatures exceeded 2°C, but the extent of glacial retreat and marine incursion into West Antarctica is unknown.

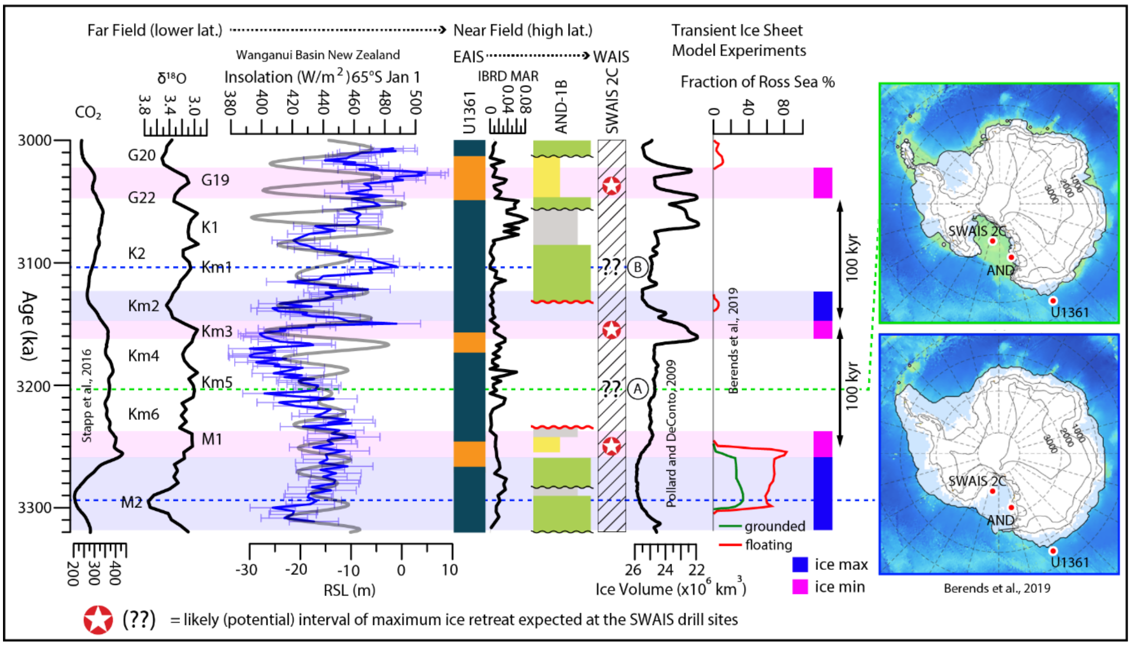


Figure 2.2 Key proxy datasets through the mid-Pliocene (3.3 to 3 Ma). Far left to right: atmospheric $CO_2$, oxygen isotope stack, relative sea-level record from New Zealand and iceberg-rafted debris mass accumulation from Wilkes Land and the Ross Sea (stratigraphy, with yellow indicating ice-free conditions). Two transient ice-sheet model outputs and simulated ice-sheet extent for time slices at M2 (lower) and KM5 (upper). 100 kyr cycles are recorded in the Antarctic records, but high-frequency variability preserved in the relative sea-level records is ambiguous in the near-field records. New records recovered at SWAIS 2C drill sites could 'fill in' stratigraphic gaps (e.g. time slice A), reveal the extent and frequency of WAIS retreat through this interval and help resolve discrepancies between far-field (relative sea level) and near-field (glacial extent or marine incursion) data (e.g. time slice B).

Pliocene sea-level oscillations have been linked to variable orbital influence on the seasonality of climate, captured in $\delta^{18}O$ records of ice volume and temperature (Lisiecki and Raymo 2005) that are commonly used in Pliocene ice-sheet modelling studies (Berends et al. 2019; de Boer et al. 2014; Pollard and DeConto 2009). Pliocene sediments in the Wanganui Basin suggest that the amplitude of sea-level change during the warm mid-Pliocene (3.3–2.7 Ma) was ~7 to 18 m and oscillated in response to astronomically paced 20-kyr changes in local insolation over Antarctica (Grant et al. 2019; Figure 2.2). Although the AND-1B and IODP U1361 records support periodic retreat of the WAIS and EAIS at 40 kyr timescales prior to 3.3 Ma, and 21 and 100 kyr timescales between 3.3 and 2.6 Ma, new records proposed here are required to confirm the frequency of WAIS dynamism and the extent of its retreat during the last time that Earth's climate equilibrated to 400 ppm atmospheric $CO_2$ (Figure 2.2). WAIS variability during Pliocene time could be represented at the SWAIS 2C drill sites by extended periods of open marine conditions or by evidence of astronomically paced local ice advance and retreat. The sediment core record, combined with reconstructions of sea-surface temperatures and sea ice, will help to constrain the sensitivity of WAIS during a 400 ppm atmospheric $CO_2$ world.

**H3 Key Questions:** (1) Was Early Pliocene climate sufficiently warm for open marine conditions to persist along the Siple Coast region throughout glacial and interglacial cycles? (2) Were marine ice sheets able to re-advance across West Antarctica and the Ross Sea during glacial episodes in response to a $CO_2$ decrease and climatic cooling at ~3.3 Ma? (3) How did WAIS respond to astronomical forcing threshold at 3.3 Ma? (4) Did the WAIS collapse during every mid-Pliocene interglacial episode, but, if not, why not?

### 2.4.4 Late Oligocene – Miocene Variability and the Role of Tectonics and Carbon-Cycle Feedbacks

**Guiding Hypothesis (H4):** 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 extensive and highly productive shallow marine seas that subsequently drew down $CO_2$ and culminated in global cooling and ice expansion during the middle Miocene Climate Transition (MMCT).

We anticipate recovering late Neogene and Pleistocene sediments at both the KIS and CIR sites; however, older sediments may also be recovered *in situ* or as re-worked elements. Late Paleogene to Early Neogene strata would allow a number of key science issues, outlined below, to be addressed.

The role of tectonics and vertical crustal movement in WAIS history is an open question. Topographic reconstructions suggest that much of West Antarctica was sub-aerial during the Oligocene and marine basins that transgressed West Antarctica first formed in the Miocene (Paxman et al. 2019; Wilson et al. 2013; Figure 2.3). Analysis of Antarctic drill cores and far-field proxy oxygen isotope data imply that marine ice sheets expanded onto the Antarctic continental shelf in the latest Oligocene as atmospheric $CO_2$ declined, but only because continental shelves remained shallow (Kulhanek et al. 2019; Levy et al. 2019; Naish et al. 2022). These marine ice sheets subsequently retreated as subsidence allowed warm water to transgress across a deepening West Antarctica. Marine ice sheets re-advanced as $CO_2$ dropped below 600 ppm in the early Miocene. However, these hypotheses regarding tectonic / ice sheet / climate feedbacks rely heavily on data from DSDP 270 in the central Ross Sea. Drilling at Siple Coast will provide important paleobathymetric constraints for the paleotopographic models and associated ice sheet histories (Figure 2.3).

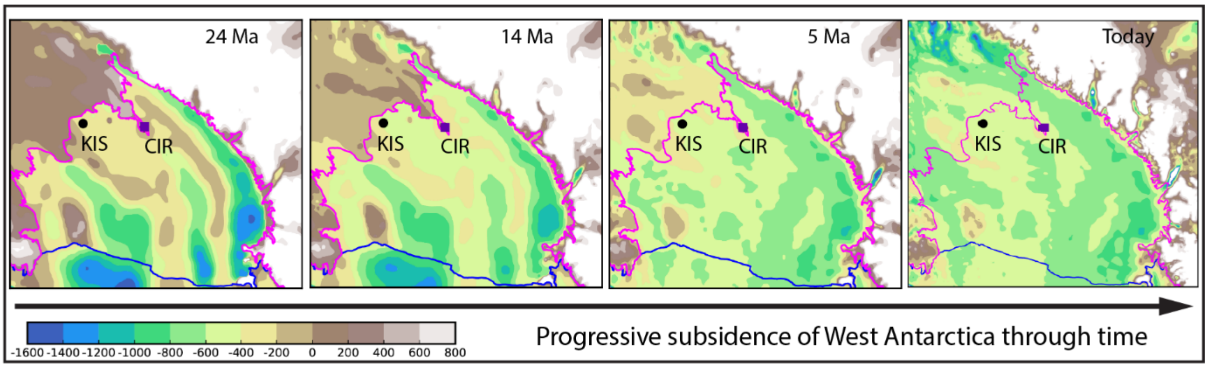


Figure 2.3 Paleotopographic reconstructions for West Antarctica from Paxman et al. (2019) for time slices (left to right) at 24, 14, 5 Ma and today (scale bar in metres). Drilling at KIS and CIR will provide data to test these reconstructions with implications for ice sheet history.

During the MCO (~17 to 15 Ma), atmospheric $CO_2$ levels generally ranged between 300 and 600 ppm (Greenop et al. 2014; Sosdian et al. 2018; Steinthorsdottir et al. 2021) and average global surface temperatures were up to 3–7°C higher than pre-industrial values (You 2010; You et al. 2009; Steinthorsdottir et al. 2021). Such atmospheric $CO_2$ values and climatic conditions could be similar to those expected in the coming decades if emission targets are not reached, making the study of mid-Miocene climate a growing focus of the paleoclimate community (Steinthorsdottir et al. 2020). However, the mechanisms for natural changes in $CO_2$ during the mid-Miocene are unclear (Foster et al. 2012; Pagani et al. 1999; Sosdian et al. 2018, 2020). The MCO coincides with a larger positive $\delta^{13}C$ excursion than any other time in the past 50 million years (Sosdian et al. 2020). The 'Monterey Hypothesis' (Vincent and Berger 1985) implies that long-term cooling and invigorated oceanic upwelling led to enhanced productivity and burial of organic carbon, which caused $CO_2$ draw-down and culminated in the onset of an extensive and persistent AIS by 14 Ma. However, evidence for cooling and AIS expansion lags the $\delta^{13}C$ excursion by several million years (Holbourn et al. 2015; Levy et al. 2016). More recently, it has been suggested that volcanic outgassing caused a $CO_2$ increase to between 500 and 700 ppm at the start of the MCO (Foster et al. 2012). Global warming associated with this increase caused AIS retreat, sea-level rise and associated expansion of 'space' across continental shelves that enhanced organic carbon production and burial (Sosdian et al. 2020). Cooling and ice sheet advance through the Miocene Climate Transition (MCT; ~14 Ma) occurred once volcanic outgassing ended.

Recovery of Miocene sediments from the West Antarctic interior will test these hypotheses. Results from prior drilling (Ross Sea and Wilkes Land margin) showed that Antarctica's ice sheets were highly dynamic during the early to mid-Miocene (Levy et al. 2016; Levy et al. 2019; Pierce et al. 2017; Sangiorgi et al. 2018) and periodically retreated beyond their terrestrial margins during the MCO. New records from IODP Expedition 374 indicate that marine ice sheets retreated from the central Ross Sea through the MCO (McKay et al. 2019; Marschalek et al. 2021). Miocene diatom-bearing marine sediment recovered from sparse mud samples during hot water drilling at CIR in the 1980s (Harwood et al. 1989b) also suggest episodic open marine conditions across much of WAIS during the Miocene. While these data and associated modelling experiments suggest that the AIS retreated landwards of its terrestrial margin during the MCO, we have yet to recover *in situ* records to confirm whether full collapse of the WAIS occurred during peak warmth. Importantly, ice-free shallow marine(?) environments across West Antarctica through the MCO would have been areas where high marine productivity and carbon burial might have contributed to the unique Miocene carbon excursion.

**H4 Key Questions:** (1) Did tectonic subsidence influence marine ice sheet extent in the late Oligocene / early Miocene? (2) Were extensive open marine basins a feature across West Antarctica during the early Miocene? (3) Did marine-based ice sheets develop as more persistent features of the AIS system across the MCT?

### 2.4.5 Life Beneath the Surface – Microbial Communities in Extreme Polar Environments

**Guiding Hypothesis (H5):** 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.

Polar, sub-seafloor microbial communities are among the most under-sampled and poorly understood biomes on Earth, making them a high-interest target for deep biosphere research (Christensen et al. 2017). The deposition of organic matter produced by photosynthetic organisms in surface waters drives the activity and growth of sedimentary microorganisms. Continental shelves provide ample nutrients for primary producers, resulting in the highest abundances of sedimentary microbes in near-shore environments (Kallmeyer et al. 2012). However, sediments deposited in light-deficient sub-glacial waters and beneath grounded ice sheets represent a unique and extreme environment for microbial communities (Achberger et al. 2017). The Siple Coast setting is an ideal location to study microorganisms living in these extreme environments and to determine how their biology and unique adaptations allow them to persist over time. Furthermore, analysis of microbial communities in the different sedimentary facies recovered in the KIS and CIR cores offers a chance to examine how microbial communities evolve as the grounding zone position and thickness of the Ross Ice Shelf change through time (i.e. in response to changing nutrient input under open water versus ice-covered conditions). Whether these environmental changes leave detectable traces in the nucleic acids (i.e. microbial DNA and RNA) that can be extracted from the sediments is a question we aim to answer with potential applications for the reconstruction of Ross Sea ice shelf dynamics. Recovery of sub-glacial material along the Siple Coast region provides an unprecedented opportunity to extend our knowledge of marine benthic microbial communities, the deep biosphere and its biogeochemistry in 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).

**H5 Key Questions:** (1) How does sub-surface metabolic potential contribute to major and trace element cycling and carbon burial? (2) How do microbial communities respond to varying inputs in organic matter (i.e. open versus ice-covered conditions, discharge from sub-glacial lakes) over time? (3) What is the structure of microbial food webs in the extreme sub-glacial and sub-ice-shelf environment? (4) What past environmental conditions are indicated by inactive members of sub-surface communities like cysts and spores?

## 2.5 Strategy and Methods

We have assembled a diverse, international team of scientists, drillers, engineers and Antarctic operations experts that will allow us to achieve our stated goals. The SWAIS 2C Project team has a proven track record in Antarctic research. Specifically, our research methodology is built around an integrated data-model approach that utilises paleoclimatic data from drill cores to improve the ability of Antarctic climate and ice-sheet models to simulate past and future Antarctic environmental conditions and the consequences for global sea level. This approach was implemented in the ANDRILL Program (DeConto and Pollard 2016; Gasson et al. 2016; Golledge et al. 2015; Harwood et al. 2008–2009; Levy et al. 2016;

Naish et al. 2007; Naish et al. 2009; Pollard and DeConto 2009). We will use this proven approach to integrate new data from these locations, previously undrilled, to advance our understanding of the sensitivity of WAIS.

### 2.5.1 Drilling

Our engineers have developed a hot water / rock drilling system capable of recovering up to 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 system is housed in a tent that permits all-weather operation. Hot water is generated by six burners capable of producing 120 L/m of water at 95°C. The melt rate for a pilot hole is 0.2–0.5 m/hr. Reaming the hole to 350 mm diameter (the maximum for our system) in 600-m-thick ice takes 10 hours. A reaming run of five hours every 24 hours is required to maintain the hole at this diameter.

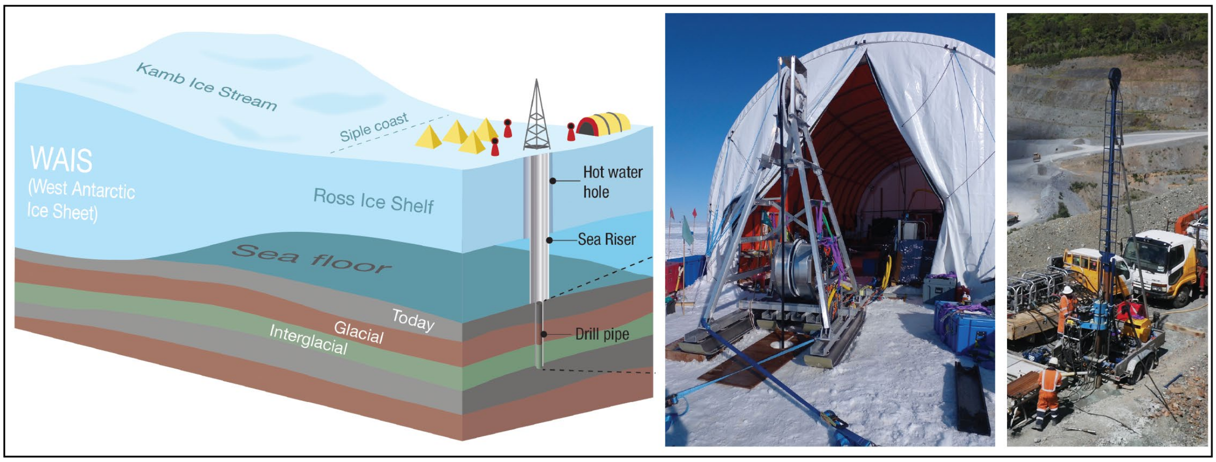


Figure 2.4 Hot water drilling system. Left: 3D concept diagram of the drill system operating through the ice shelf. Centre: Image of hot water drilling (HWD) system outside drill tent. The HWD mast will be moved aside for sediment coring / rock drilling and the drill rig positioned over the HWD ice hole. Right: MP1000 sediment/rock drilling rig being tested in Wellington prior to shipment to Antarctica.

We will use a sediment/rock drill (MP1000, Figure 2.4), co-owned by GNS Science an Victoria University of Wellington. The rig is an industry-standard (i.e. proven) wireline system. For soft sediment coring, we will use two systems: a hydraulic piston corer (HPC) and a punch corer designed and built by QD Tech, world leaders in this field. For hard rock drilling, we will use off-the-shelf diamond-bit rotary coring technology. The combined rig, drill pipe and casing package weighs ~30 tonnes, making it feasible to deploy within the constraints of existing Antarctic science support programmes.

Core will be recovered using three different approaches depending on lithology: (1) Hydraulic Piston Corer inside NQ-sized drill rod (bit internal diameter [ID] – 57.2 mm, outer tube bit throat ID – 51 mm) is our preferred coring tool and 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); (3) Rotary coring with BQTK-sized rod (bit ID – 40.7 mm), which will be used in harder lithologies and may be used to cut the NQ drill string if necessary.

This drill system's small logistical footprint (including limited personnel onsite) will utilise a 12-hour drilling operation but will have the option to run a continuous two-shift operation over 24 hours if time (drilling window) becomes a constraint due to ice shelf movement or ice hole re-freeze rate.

### 2.5.2 Downhole Logging

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 mbsf) and likely unconsolidated nature of the surrounding sediment means that 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). These are self-contained, and no logging winch is required for deployment. While a new version of the iMLS depth-measuring device 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 slighly 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) 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 also be possible to deploy four Leibnitz Institute for Applied Geophysics (LIAG) wireline tools: resistivity, magnetic susceptibility, acoustic televiewer and borehole mud temperature and salinity.

### 2.5.3 Initial Core Description, Analysis, Processing and Storage

On-ice core curation will comprise producing a drilling/recovery log and cutting the whole core into 1-m-long sections so that it can be readily transported and stored. On-ice science analysis will be limited to X-ray measurements of each core section using the GNS Science Ecotron EPX-F3200 3.2KW [100kV/60mA] X-ray generator and Carestream Vita Flex digital imager, smear slide analysis of core cutter material and collecting and fixing of samples for microbiology. Fast-track samples from core cutter material may be sent off ice for paleontological assessment as opportunities arise. Where appropriate, microbiology samples will be taken from freshly cut core surfaces using sterile syringes to collect 5–20 $cm^3$ of sediment, which will be fixed and stored for amplicon profiling and metagenomic studies at home institutions. Cores will be flown from the drill site to Scott Base, where they will be stored at ~4°C before transfer to New Zealand for splitting and initial analysis by the scientific team. At the end of an initial characterisation and sampling phase in New Zealand, sediment cores will be transported for permanent storage at the Marine & Geology Repository at Oregon State University.

### 2.5.4 Off-Site Testing, Sampling and Analysis of Samples and Data

Core will be shipped to the University of Otago Repository for Core Analysis (ORCA) facility, where whole core will be processed through a Geotek multi-sensor core logger to collect physical properties data, including gamma attenuation bulk density, compressional p-wave velocity and magnetic susceptibility. Core will also be run through an X-Ray CT scanner at the Invermay campus of AgResearch Ltd. Core will be split once whole-core data have been collected and our team of ~30 scientists from partner countries have convened at the ORCA facility to describe and sample the core. We anticipate that this will occur during the first May following core recovery.

Core will be separated into archive and working halves. High-resolution images and X-ray fluorescence (XRF) analyses will be made on the archive core half. The working half of the core will be examined by the science team, which will include visual core description and preliminary sedimentologic analyses to identify depositional environments (grounded ice, glacial marine and open marine conditions) and provenance. Sub-samples will be taken from the core for initial micropaleontological, geochronological (radiometric dating of appropriate material), organic geochemical analysis and paleomagnetism.

We anticipate involving members of the modelling group at the core processing stage so that we can develop modelling experiments based on preliminary core analyses. This will ensure that modelling and observational/paleoclimatic data are well integrated from the beginning.

Draft Science and Operations reports, as well as an initial report, will be compiled during and immediately following the core workshop and distributed to partner nations upon completion.

### 2.5.5 Primary Scientific Methods

#### *2.5.5.1 Chronostratigraphy and Age Model*

One of the most important datasets to address our hypotheses is development of robust age models for the recovered cores. Chronostratigraphy can be challenging in Antarctic sediments due to high fragmentation and mixing of different ages of glacial sediment. Substantial advances over recent decades have significantly improved the toolboxes available for Antarctic chronostratigraphy, including improved biostratigraphic utility of diatoms, radiolarians and dinoflagellates (Bijl et al. 2013; Clowes et al. 2016; Renaudie and Lazarus 2016; Winter et al. 2012), use of paleomagnetic secular variation (Collins et al. 2012; Hillenbrand et al. 2010; Willmott et al. 2006) and relative paleointensity records (Channell and Lanci 2014; Channell et al. 2009; Ohneiser et al. 2013), in addition to geomagnetic reversal stratigraphy (Florindo et al. 2003, 2013; Kulhanek et al. 2019; Ohneiser and Wilson 2012; Ohneiser et al. 2019; Tauxe et al. 2012; Wilson et al. 2012); tephrostratigraphy (Di Roberto et al. 2019; Hillenbrand et al. 2008; Narcisi et al. 2012) and analysis of radiocarbon in organic material using ramped pyrolysis to reduce the ‘old carbon’ contamination problem (Rosenheim et al. 2008; Subt et al. 2017; Venturelli et al. 2020). Additionally, a statistical technique (constrained optimisation [CONOP]) that integrates biostratigraphic, paleomagnetic and other datasets from the Southern Ocean has allowed development of high-resolution quantitative stratigraphic age models (Cody et al. 2008, 2012; Florindo et al. 2013). Lastly, high-resolution physical properties data (including magnetic susceptibility and gamma ray attenuation bulk density), as well as geochemistry from XRF core scanning, can also be used for cyclicity analysis useful for age model tuning and orbital forcing identification (Patterson et al. 2014).

#### *2.5.5.2 Glacial Regime*

We will identify changes in ice-cover extent and grounding line migrations at KIS and CIR using sedimentary facies analysis and associated proxy data via an approach established during previous Antarctic drill core studies. This approach includes (but is not limited to):

- **Visual core description:** The core description team will follow the visual core description protocol used for ANDRILL (Krissek et al. 2007), which combines a textural classification scheme for gravel-bearing sediment (Moncrieff 1989) and compositional scheme used for marine and volcanoclastic sediments by the ODP (Mazzullo et al. 1988; White and Houghton 2006). Description data will be captured with core logging program PSICAT – ‘Paleontological Stratigraphic Interval Construction and Analysis Tool’, available as freeware.[1]

1 https://github.com/laccore/coretools/releases

- **Sedimentary facies analysis:** Deposition of sediment in glacimarine environments is strongly influenced by the role of ice as a transport medium, as a habitat for diatoms (sea ice) and for its exclusion of light to the upper ocean (shelf ice). Previous sampling of the Antarctic continental shelf seafloor (Alley 1989; Anderson et al. 1984; Domack and Harris 1998; Domack et al. 1999; Dunbar et al. 1985) and deeper drilling by ANDRILL and IODP (Fielding et al. 2011; Krissek et al. 2007; McKay et al. 2009; Naish et al. 2009; Passchier et al. 2011; Patterson et al. 2014) has recovered a range of sediment types and stratigraphic motifs that represent repeated patterns of glacial to interglacial oscillations under different ice-sheet configurations. Sub-ice-shelf sediments provide the most direct evidence of changing ice cover over those sediments as variations from sub-ice-shelf to open marine conditions (i.e. proximity of the grounding and calving lines) are characterised by distinct sedimentary facies that can be distinguished by grain size frequency distributions, water content, shear strength, sediment composition, sedimentary structures, microfossil content/taphonomy, total organic carbon and a range of other environmental proxies (Smith et al. 2019) (summarised in Figure 2.5).

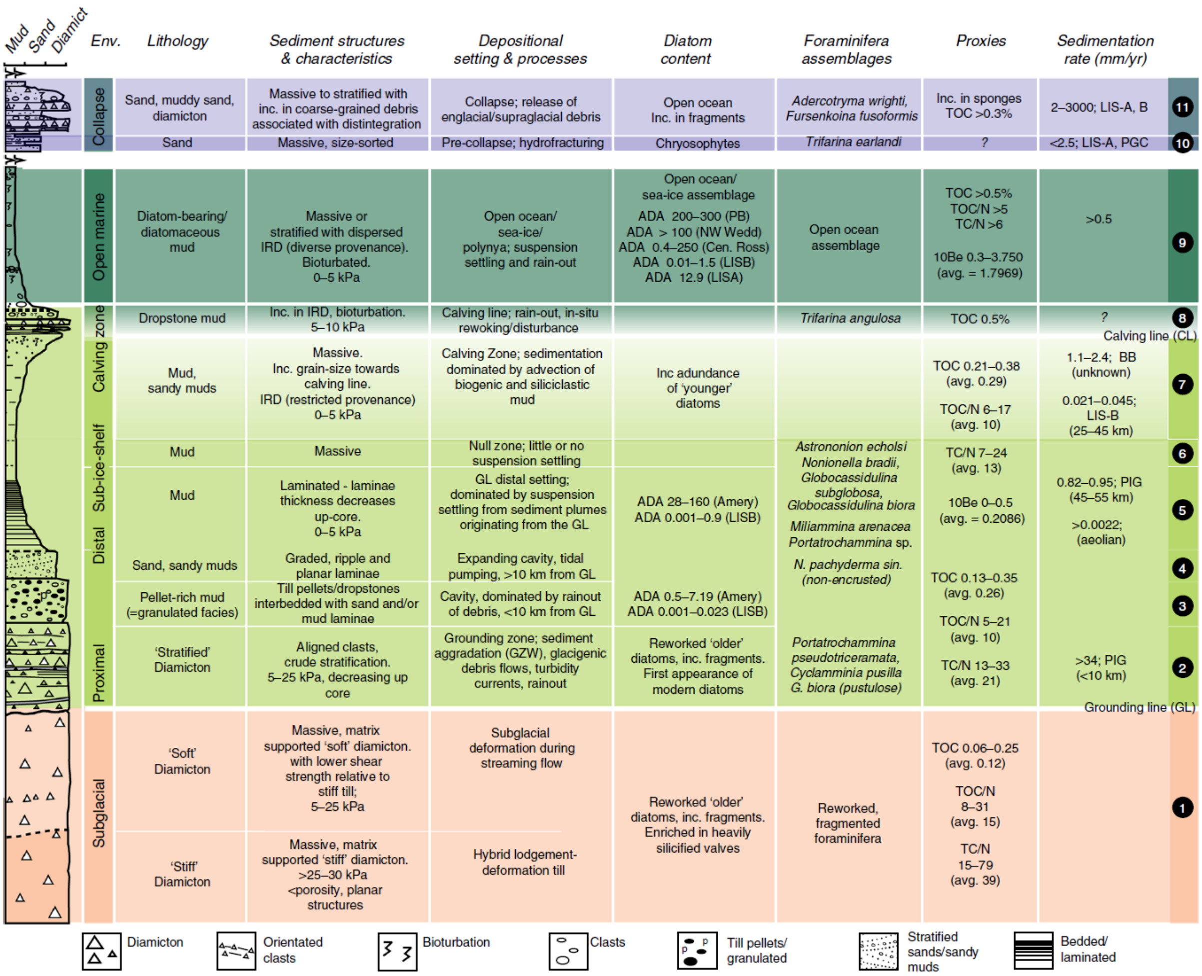


Figure 2.5 Glaciomarine sedimentology and facies model for glacial proximity (from Smith et al. [2019]).

- **Cosmogenic nuclides:** The concentration of *in situ* cosmogenic nuclides in the sand fraction of marine sediment can yield information on the chronology and erosion rate of terrestrial material delivered to the core site. Analysis of $^{10}Be$ and $^{26}Al$ in marine sediment cores will help to distinguish periods of progressive erosion and ice-sheet stability and periods of ice-sheet expansion (Bierman et al. 2016). Analysis of cosmogenic nuclides in sediment recovered from KIS and CIR may allow us to identify variations in ice-sheet stability, including potentially long periods of retreat where erosion of exposed bedrock during interglacials raised isotopic concentrations in the material delivered to the drill core site.

  The concentration of meteoric $^{10}Be$, adsorbed to atmospheric particles and rained out into the marine environment, where it accumulates in marine sediment, can be used as a proxy for ice-shelf presence or absence in the Ross Sea (Yokoyama et al. 2016). Thus, analysis of decay-corrected concentration of $^{10}Be$ through the recovered core material from KIS and CIR can provide a tracer for ice shelf history.

#### *2.5.5.3 Ice Flow Reconstructions (Sediment Provenance)*

The geochemical fingerprint of sediments at a drill site can be traced back to the precursor rocks on the continent, thereby identifying past areas of erosion and associated glacier (and possibly ocean) paleo-flow paths. The varied grain sizes in glacial sediments means a range of provenance tools can be applied, including radiogenic neodymium (Nd) and strontium (Sr) isotope compositions on fine-grained material (Farmer et al. 2006a; Hemming et al. 2007; Roy et al. 2007) and zircon U-Pb dating and hornblende/biotite $^{40}Ar/^{39}Ar$ dating on sand-sized material (Licht et al. 2005, 2014; Simões Pereira et al. 2018). Gravel clast and sand petrography (Giorgetti et al. 2009; Sandroni and Talarico 2011; Talarico et al. 2013; Talarico and Sandroni 2011; Zattin et al. 2012), as well as clay mineralogy, augments the geochemical techniques. Together, these techniques have proven a powerful method for reconstructing past ice-sheet dynamics (Bertram et al. 2018; Cook et al. 2013, 2014; Talarico and Sandroni 2011; Williams et al. 2010; Wilson et al. 2018).

Specific to the SWAIS 2C drill sites, a largely intact WAIS during interglacials would see a provenance signal derived from central West Antarctica with predominant 100 Ma zircon U-Pb ages and radiogenic Nd isotopes, similar to the modern day (Farmer et al. 2006b; Licht et al. 2014). In contrast, a partial WAIS collapse would show a larger contribution from northern sources in Marie Byrd Land with older, Palaeozoic U-Pb ages and more radiogenic Nd isotopes (Hart et al. 1997; Pankhurst et al. 1998), while a full WAIS collapse would see additional material input from the southern Transantarctic Mountains and areas as distal as the Ellsworth-Whitmore Mountains (e.g. Jurassic U-Pb ages and non-radiogenic Nd isotope compositions) (Craddock et al. 2017).

#### *2.5.5.4 Paleoenvironmental and Paleoceanographic Reconstructions*

A wide variety of techniques are available to evaluate past marine and terrestrial environments using the recovered core material.

**Micropaleontology:** Microfossil assemblage data provide information regarding changes in depositional environment, water temperature, salinity, nutrients/water fertility, stratification, upwelling, sea-ice occurrence and ages of recycled sediments (Coenen et al. 2020; Harwood et al. 1989a; Leventer et al. 1993, 2002; Scherer 1991a; Scherer et al. 1988; Winter et al. 2012). Diatoms are particularly well suited to trace environmental conditions, as they occupy a broad range of Antarctic environments. Diatom assemblage information can be used as an indicator of sea-ice presence (Armand et al. 2017; Esper and Gersonde 2014; Ferry et al. 2015; Gersonde et al. 2005; Gersonde and Zielinski 2000; Leventer 1998). Additionally, variations in assemblage composition and morphology can be used to estimate sea-surface temperature (Gersonde et al. 2005; Zielinski et al. 1998). Dinoflagellate cysts and marine palynology in general have demonstrated the potential to reconstruct upper water column properties; in particular, sea-ice occurrence, productivity, temperature and meltwater input throughout the Neogene and beyond (Hannah et al. 1998; Hartman et al. 2018; Sangiorgi et al. 2018; Warny et al. 2009). *In situ* terrestrial palynomorphs can provide information on the terrestrial environment and landscape (Sangiorgi et al. 2018; Warny et al. 2009). Even when pollen and spores are re-worked, they offer precious information on the age of the sediments eroded and deposited (for example, from glacial advance) at the drill site.

**Environmental magnetism:** Environmental magnetic fabric studies can reveal subtle changes in terrestrial weathering regime, depositional processes and the strength of ancient ocean currents. Environmental magnetic records have been used to identify changes in terrestrial climate with a magnetic mineral change identified at the Eocene/Oligocene boundary when Antarctica established its first large ice sheet (Sagnotti et al. 1998), identify changes in ice-flow patterns (Brachfeld et al. 2013), terrestrial soil formation and a transition to hyper arid, polar conditions during the Pliocene–Pleistocene (Ohneiser et al. 2020). Magnetic fabric in sediments most commonly relates to depositional or post-depositional processes. In oceanic settings, the strength of the magnetic fabric has been linked to changes in ocean circulation strength (Joseph et al. 1998, 2002; Ohneiser and Wilson 2018), whereas, in glacial environments, fabrics have been linked to shearing or compression of sediments from ice advance (Hooyer et al. 2008). At KIS and CIR, we will use magnetic fabric studies to investigate changes in ocean circulation as the WAIS collapsed and recovered, and how circulation strength varied during interglacials. These data will provide key insights into the oceanic response to ice-volume changes or the oceanic controls on ice volume.

**Geochemistry:** There are numerous geochemical techniques that we can apply to the KIS and CIR cores to address the temperature variability of sub-ice-shelf and ice-proximal environments, biogeochemical cycling of organic matter and Antarctic ice melt history. Paleotemperatures can be reconstructed using clumped isotope paleothermometry ($\Delta47$); organic geochemical proxies, such as isoprenoid GDGT-based paleothermometry (Kim et al. 2012; Shevenell et al. 2011); the long-chain diol index (Beltran et al. 2020; Rampen et al. 2012); and the alkenone unsaturation ratio (Beltran et al. 2020). Organic geochemical temperature proxies usually reflect upper water column temperatures, whereas clumped isotope measurements reflect bottom water temperatures, allowing investigation of water column structure and salinity change through time (Kotthoff et al. 2017; Levy et al. 2016; Petersen and Schrag 2015).

Total organic carbon / total nitrogen values and stable isotope measurements ($\delta^{13}C$ and $\delta^{15}N$) of bulk organic matter are well-established proxies for marine productivity and nutrient cycling. The carbon isotopic signature of specific fatty acids produced by phytoplankton and preserved in sediments are new proxies for open-water productivity, as well as in the marginal sea ice zone, and are useful for understanding carbon-cycle dynamics in the coastal zones around Antarctica (Ashley et al. 2020). In addition, the recently developed nutrient diol index (Gal et al. 2019) has the potential to serve as a quantitative surface nutrient proxy for estimating changes in sea-surface nitrate (or phosphate) concentrations. Furthermore, hydrogen isotope ratios extracted from phytoplankton organic remains reflect a combination of surface-water isotope composition and salinity (Ashley et al. 2020; Feakins et al. 2012; Häggi et al. 2015; Seki et al. 2012), with a high potential to detect meltwater discharge into the ocean.

Lastly, highly branched isoprenoid (HBI) lipids produced by sea ice diatoms and the associated IPSO25 proxy can be used to reconstruct Antarctic sea-ice expansion (Belt et al. 2016; Belt 2019).

#### *2.5.5.5 Ice Sheet and Solid-Earth Feedbacks*

To understand syn-rift tectonism and glacio-isostatic adjustment in sea-level and ice-stability feedback, and ice-sheet evolution in general, data on heat flux, thermochronology, clay mineralogy, clast petrology and geochronology should be partnered with structural investigations on cores. Natural and drilling-induced fractures in cores can constrain the ancient tectonic setting, as well as the contemporary stress field within the West Antarctic Rift System (Paulsen et al. 2014; Wilson et al. 2007). Structural features in glacial sediments, such as deformation bands, micro-shear zones or hydrofractures, provides invaluable information on the state of strain, dewatering mechanisms, ice flow and litho-cryosphere interactions (Menzies et al. 2016). Mineralisation in natural fractures (e.g. vein fillings, fault coatings) can give further indications on syntectonic fluid migration and permeability, diagenetic histories and physical properties of the host rock (Millan 2013). Direct and indirect age constraints may derive from dating of syntectonic mineralisations or volcanic horizons, thermochronology modelling or fossil remains preserved in the core. The data will help define strain regimes and their relation to models of rift evolution and denudation of the Transantarctic Mountains and refine time constraints of tectonic and uplift processes (Lisker and Läufer 2013; Paulsen and Wilson 2009; Rossetti et al. 2003).

Modelling studies aim to better understand the role of solid-Earth feedbacks in stabilising the AIS during grounding line retreat, which are needed to make more accurate predictions of sea-level rise. Existing data from the Siple Coast are insufficient to constrain the existing divergent hypotheses regarding Holocene grounding line instability (Kingslake et al. 2018; Lowry et al. 2020). Here, we aim to test these hypotheses using new sedimentological observations and an improved inversion of the thermal profile, combined with a numerical model ensemble to understand solid-Earth/ice coupling during ice-sheet retreat to better characterise Holocene grounding line history. The thermal profile data will be collected via two methods. Internal ice temperature will be measured using a distributed temperature sensing fibre-optic cable (Fisher et al. 2015; Tyler et al. 2013). Downhole formation temperature measurements will be made using a sediment temperature probe attached to the bottom of the core barrel and isolated from drilling fluid circulation via an inflatable packer. These data will be used to develop a 1D model vertical heat flux through the ice rise and underlying sediment, forced by boundary conditions that emulate divergent grounding scenarios.

#### *2.5.5.6 Microbiology*

Microbiological investigations will determine the abundance, genetic diversity, evolution and metabolic potential of sub-seafloor microbes by using cell counts, community profiling and metagenomics and cutting-edge biosensor techniques (Fulk et al. 2020; Masiello 2020; Shis et al. 2020). Samples will be taken from freshly cut core surfaces using sterile syringes to collect 5–20 $cm^3$ of sediment, which will be fixed and stored for amplicon profiling and metagenomic studies at home institutions, where the taxonomic composition of microbial communities will be determined by DNA extraction (Alawi et al. 2014; Lever et al. 2015), followed by amplification and sequencing of specific fragments of 16S and 18S rRNA genes using PCR primers (Fonseca et al. 2010; Parada et al. 2016; Sinniger et al. 2016), as well as a new primer-free method to obtain full-length 16S and 18S rRNA sequences (Karst et al. 2018) to identify taxa. Quality trimmed amplicon sequences will be clustered into operational taxonomic units (OTUs) with Swarm (Mahé et al. 2014). We will use metagenomics to gain insight into the diversity and functional potential of the microbial communities by sequencing

DNA extracted from the sediment using whole genome shotgun sequencing. These data will be binned into metagenome-assembled genomes (MAGs) using various binning tools (Albertsen et al. 2013) and then improved using iterative techniques (Albertsen et al. 2013; Parks et al. 2015; Sieber et al. 2018) to reconstruct thousands of MAGs representing the archaea and bacteria. Biosensing is a rapidly emerging field that may be transformative for deep biosphere studies. This technique uses bacteria genetically modified to release an indicator gas (Masiello 2020; Shis et al. 2020) in the presence of a designated metabolite. 100–300 µL of interstitial water (sampled and frozen at the drill site) as the analyte will be incubated with the biosensor bacteria and analysed with an in-line gas chromatograph-mass spectrometer to monitor gas concentrations. Taken together, these studies will allow us to: (1) identify potentially active community members, (2) assess the taxonomic and functional diversity of the microbial communities across the collected sediments, (3) determine whether microbial communities reflect past or present conditions and (4) identify key processes prevailing in the Ross Sea sediments.

While data from interstitial waters will constrain microbial reactions (D'Hondt et al. 2004), they can also inform sediment geochemistry (Malone et al. 2002) and sub-glacial sediment-water interaction. To address the dearth of water-rock-microbial interaction data from the Antarctic margin, we will analyse bulk sediments, biogenic opal and interstitial water for major and minor element composition and stable isotope tracers (e.g. $\delta^{18}O$, $\delta^{30}Si$, $\delta^{74}Ge$, $\delta^{56}Fe$, $\Delta 47$).

# 3.0 THE DRILL SITES – REGIONAL CONTEXT AND SITE DETAILS

## 3.1 Regional Setting

### 3.1.1 Modern Setting

The Ross Sea Embayment is bordered by the 3500-km-long Transantarctic Mountain chain to the west and Marie Byrd Land and Siple Coast to the east. The modern WAIS is seated within the lower topographic relief of the West Antarctic Rift System (WARS), one of Earth's major continental extension zones extending across Antarctica from the western Ross Sea Embayment to the Antarctic Peninsula and separating West and East Antarctica (Behrendt et al. 1991). Today, West Antarctica contains an ice sheet with the potential to raise sea level by 5 m if it were to completely melt (Fretwell et al. 2013). Most of the WAIS sits on continental crust that lies well below sea level, in places reaching depths well over 2 km (Fretwell et al. 2013; Morlighem et al. 2020). The bed is retrograde across most of West Antarctica, which makes the WAIS highly vulnerable to ocean warming, and marine ice-sheet instability and the marine-based portions of the ice sheet have the potential to contribute 3.6 m to global sea level (Fretwell et al. 2013).

### 3.1.2 Basement Geology

The best exposed rocks in West Antarctica are in Marie Byrd Land and comprise the Neoproterozoic to Cambrian Swanson Formation, Devonian to mid-Cretaceous magmatic rocks and Cenozoic volcanics (Simões Pereira et al. 2018; Tingey 1991). The Swanson Formation is characterised by zircon U-Pb ages of c. 500–600 Ma and 800–1000 Ma (Pankhurst et al. 1998), with younger intrusion by the Ford Granodiorite (c. 375 Ma) (Korhonen et al. 2010; Pankhurst et al. 1998; Siddoway and Fanning 2009) and the Byrd Coast Granite (95–124 Ma) (Pankhurst et al. 1998; Siddoway 2008). Younger igneous activity in the area is documented along the Ruppert and Hobbs coast (101–110 Ma) (Mukasa and Dalziel 2000) and the Ford Ranges to Edward VII Peninsula (95–120 Ma) (Korhonen et al. 2010; Weaver et al. 1992). During the Cenozoic, starting from ~35 Ma, the region was subjected to intense alkaline volcanism and uplift of the Marie Byrd Land Dome. With an altitude reaching 2700 m today, the Marie Byrd Land Dome is a feature that likely shed sediment southwards into the WARS. Eighteen major volcanoes and many smaller centres are composed of felsic alkaline lavas (Panter et al. 2000). Volcanic centres are suggested to exist under WAIS based on aerogeophyscial surveys (Behrendt et al. 1994, 1996, 2004). Some of the Marie Byrd Land volcanoes have been active during the Pleistocene–Holocene, potentially affecting geothermal heat flow and basal WAIS dynamics (Vries et al. 2017).

Rock exposed along the southern Transarctic Mountains comprise Ross-Orogeny-aged Granite Harbour Intrusives (485–545 Ma) (Goodge et al. 2012; Paulsen et al. 2013). Post-Ross-Orogeny exhumation and erosion of the granitic and metamorphic basement provided Kukri Peneplain, upon which the clastic Beacon Supergroup was deposited. This sequence was intruded by Ferrar Dolerite at c. 180 Ma (Licht et al. 2014). The Whitmore Mountains afford another potential source for sediments into West Antarctica and may have contributed sedimentary rocks, 500–550 Ma (Flowerdew et al. 2007), and granites ~200 Ma (Craddock et al. 2017). Rock sources inland of the southern Transantarctic Mountains are poorly-known, as they are covered by the EAIS (Palmer et al. 2012). Late Cenozoic volcanics in the western Ross Sea region comprise the McMurdo Volcanic Group, part of the Erebus Volcanic Province (Kyle 1990), which range in age from ~19 Ma to present. Drill-core evidence extends the volcanic record in the western Ross Sea back to 26 Ma (Barrett et al. 1987; Di Vincenzo et al. 2009; Gamble et al. 1986; McIntosh 1998, 2000).

### 3.1.3 Sedimentary Basins

Sedimentary basins on the mid- to outer continental shelf have been sampled previously and contain sedimentary rocks dating to the late Eocene (Barrett et al. 1989; Davey et al. 2001; Kulhanek et al. 2019; Levy et al. 2000a, 2000b; McKay et al. 2019; Naish et al. 2001). Re-worked palynomorphs in surface samples collected across the Ross Sea indicate terrestrial sedimentary rocks dating to the Cretaceous were deposited in West Antarctica (Truswell and Drewry 1984). However, as yet, no *in situ* samples have been collected from the West Antarctic interior. The only direct evidence for the age and character of Cenozoic sedimentary sequences in sub-glacial basins beneath the WAIS is provided by the presence of marine and terrestrial microfossils in samples of eroded and re-deposited mixed sub-glacial sediments collected by sediment cores in the Siple Coast region (Coenen et al. 2020; Harwood et al. 1989a; Scherer 1991b; Scherer et al. 1988). Microfossil occurrences are of three types: (1) within pebble-size sedimentary clasts of coherent marine sediment, (2) within small micro-clast aggregates of microfossils and (3) as dispersed microfossils within the sedimentary matrix of diamicton. The small size, high abundance and rapid evolution of marine diatoms make them ideal to identify times of past WAIS retreat and marine sedimentation across West Antarctica. For example, microfossil biostratigraphy, especially the record of marine diatoms, is sufficiently well advanced to date discrete events when marine seas covered parts of West Antarctica and marine sediments were deposited. The source material for these mixed and displaced microfossil assemblages point to extensive marine deposits in West Antarctica. The lateral extent of the marine sediment basin fill would have been controlled initially by local rifted basin geography and followed by regional subsidence, both associated with evolution of the WARS (Behrendt et al. 1991; Paxman et al. 2019).

## 3.2 Drill Sites

### 3.2.1 Regional Correlation

Whereas a relatively extensive seismic reflection network exists 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 (Levy et al. 2016; Naish et al. 2009) and from the central Ross Sea (Hayes et al. 1975a, 1975b; McKay et al. 2019) extend south beneath the Ross Ice Shelf and WAIS (Figure 3.1). This hypothesis is based on the character of the seismic sequences we have imaged at the proposed drill sites, including a regionally extensive seismic reflector – Horizon D, which likely separates Neogene and Quaternary strata – and on re-worked late Neogene and Quaternary diatoms recovered in sub-glacial sediments at CIR, Upstream B, Whillans Ice Stream and KIS.

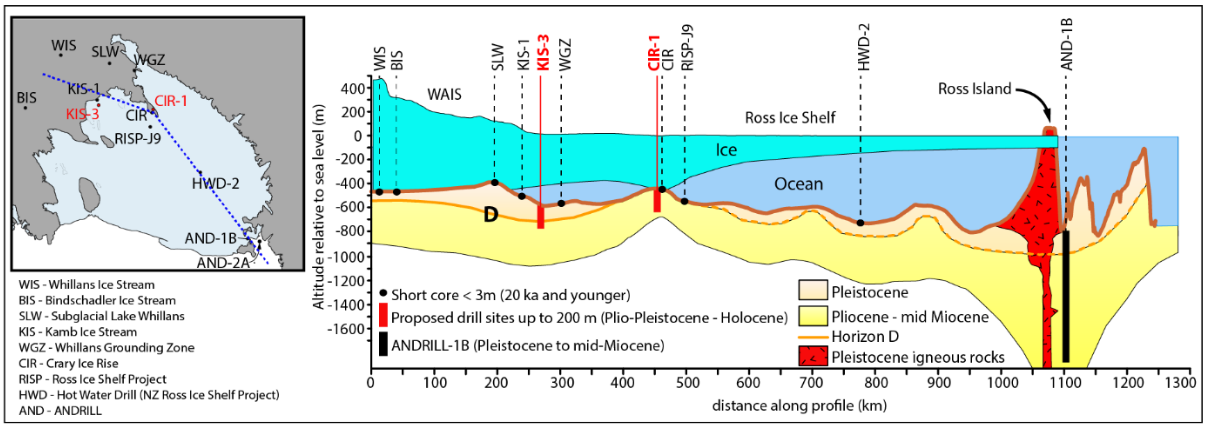


Figure 3.1 Regional stratigraphic correlation schematic. Blue dashed line = approximate location of cross-section. D = Horizon D.

We expect that Quaternary sediments will be intersected at the KIS site but that this package is missing at the CIR site and only a Holocene sediment package is preserved there. This interpretation is based on the absence of Horizon D at CIR, the occurrence of an acoustic package at CIR with clear polarity reversals and dipping reflectors and the absence of re-worked Quaternary diatoms in surface sediments at CIR and RISP-J9 near the CIR-1 site. We expect that these dipping strata are late Neogene or older. We suggest that drilling at KIS-1 and CIR-1 will provide a composite stratigraphy spanning the Miocene to Quaternary. Drilling is required to test/confirm this regional correlation model.

### 3.2.2 Kamb Ice Stream

The KIS drill site is located ~16 km seawards of the grounding zone and more than 600 km along-flow south of the ice-shelf front and Ross Sea. KIS has been stagnant for the past ~150 years (Catania et al. 2006; Retzlaff and Bentley 2017) and offers a rare opportunity to drill a modern ice stream environment from a stable drilling platform, allowing the time needed to reach a 200 mbsf drilling target. Three seasons of over-snow geophysics and one sub-ice-shelf direct-access programme have been used to characterise the KIS site. Geophysical surveying included over 70 km of multichannel seismic, more than 400 km of radio echo sounding, a regional gravity survey and continuous Global Navigation Satellite Surveying observations (Figure 3.2). Hot water drilling through 587 m of ice shelf into a 30-m-thick sub-ice cavity was completed in December 2019 at a location 15 km from the KIS drill site. This proved the capability of the hot water drilling system. A gravity corer was deployed through the hot water drill hole and recovered several short sediment cores up to 0.6 m in length of a sequence comprised of an unconsolidated diamict (Figure 3.3). A geothermal probe was deployed and penetrated 1.7 m below the seafloor, indicating that the upper several metres of sediment (at least) are unconsolidated. The NASA Icefin ROV was deployed and collected imagery from the sea floor and base of the ice shelf (Figure 3.4). Telemetered oceanographic data from a mooring left in the ocean cavity upon completion of the field programme show that ocean currents are tidally driven (biomodal in direction), with flow in the upper and low parts of the water column moving in opposite directions (‘estuarine flow’). Importantly, current speeds rarely exceed 15 cm/s and are typically <10 cm/s.

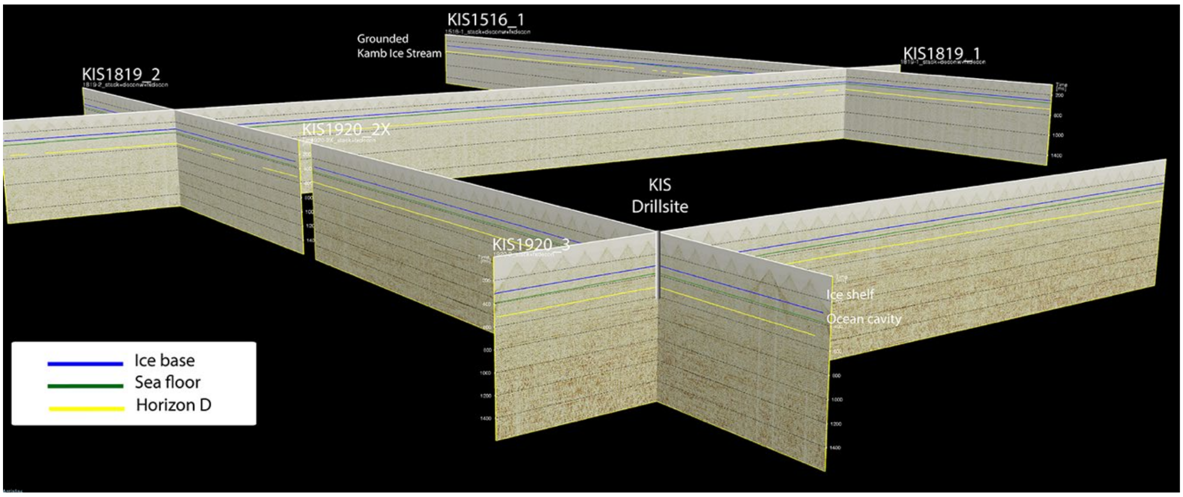


Figure 3.2 Fence diagram of available seismic data across the region around the KIS Drill Site. Correlation lines highlight the base of the ice shelf (blue line), sea floor (green line) and regional extent of Horizon Unit K-1 sits above Horizon D and Unit K-2 sits below.

Over snow seismic data imaged a shallow water column (0—60 m) overlying a generally smooth sea floor throughout the survey area. Beneath the sea floor the upper unit (Unit K-1) (Figure 3.5) is characterised by generally homogenous low amplitude internal-reflectivity with occasional higher amplitude horizontal to sub-horizontal internal reflectivity. The unit appears undeformed by tectonics and ice sheet modelling experiments suggest negligible glacial erosion at the site.

Seismic amplitude analysis supports a sedimentary interpretation with estimated bulk densities of ≤ 2000 kg $m^{-3}$ and compressional wave ($V_p$) velocities ≤ 2000 m $s^{-1}$ within the top 20 m (one seismic wavelength at 100 Hz) beneath the seafloor (van Haastrecht 2020). Internal reflectivity, which is most easily identified in the portion of the survey beneath grounded ice (due to the low impedance contrast at the sub-glacial interface) (Figure 3.5) suggests that the unit comprises layered sediments. Where similar units have been imaged in the Ross Sea, drilling has recovered interbedded diatom ooze, muds and sandy muds, diamictite, diatom-bearing/rich mudstone, and diatomite. These deposits, which are interpreted as cycles of sub-glacial, glaciomarine and open-marine sedimentation (McKay et al. 2019) are seismically imaged as a relatively homogenous unit due to the low impedance contrast between lithofacies. Elsewhere on the Siple Coast, active source seismic data from Whillans Ice Stream (Horgan et al. 2013; Luthra et al. 2016) demonstrate a pattern of sedimentation like that imaged in the KIS surveys. Deposition of Unit K-1 is likely to have occurred in accommodation space within the ocean cavity at the grounding zone or beneath the ice shelf. We anticipate that Unit K-1 is Pleistocene, based on the presence of re-worked Neogene and Pleistocene diatoms recovered in surface sediments upstream of the drill site (Figure 3.6). The lower boundary of Unit K-1 is a high-amplitude positive-polarity reflector (Horizon D) at 130–180 m below sea floor (at 2000 m $s^{-1}$) that is best imaged beneath grounded ice (Figure 3.5) but is easily identified throughout the survey region (Figure 3.2). Reflectivity within the overlying unit is generally disconformable with Horizon D, and a reflection event with similar characteristics is also imaged beneath the adjacent Whillans Ice Stream (Horgan et al. 2013; Luthra et al. 2016). The polarity and amplitude of Horizon D suggests that the upper sedimentary unit is underlain by more lithified sediment. Horizon D is further characterised by a package of underlying reflectors (Unit K-2), which supports our interpretation that Horizon D is erosional and may reflect initiation of a more extensive and persistent WAIS, potentially coinciding with the M2 glaciation event recorded at AND-2A (McKay et al. 2012a).

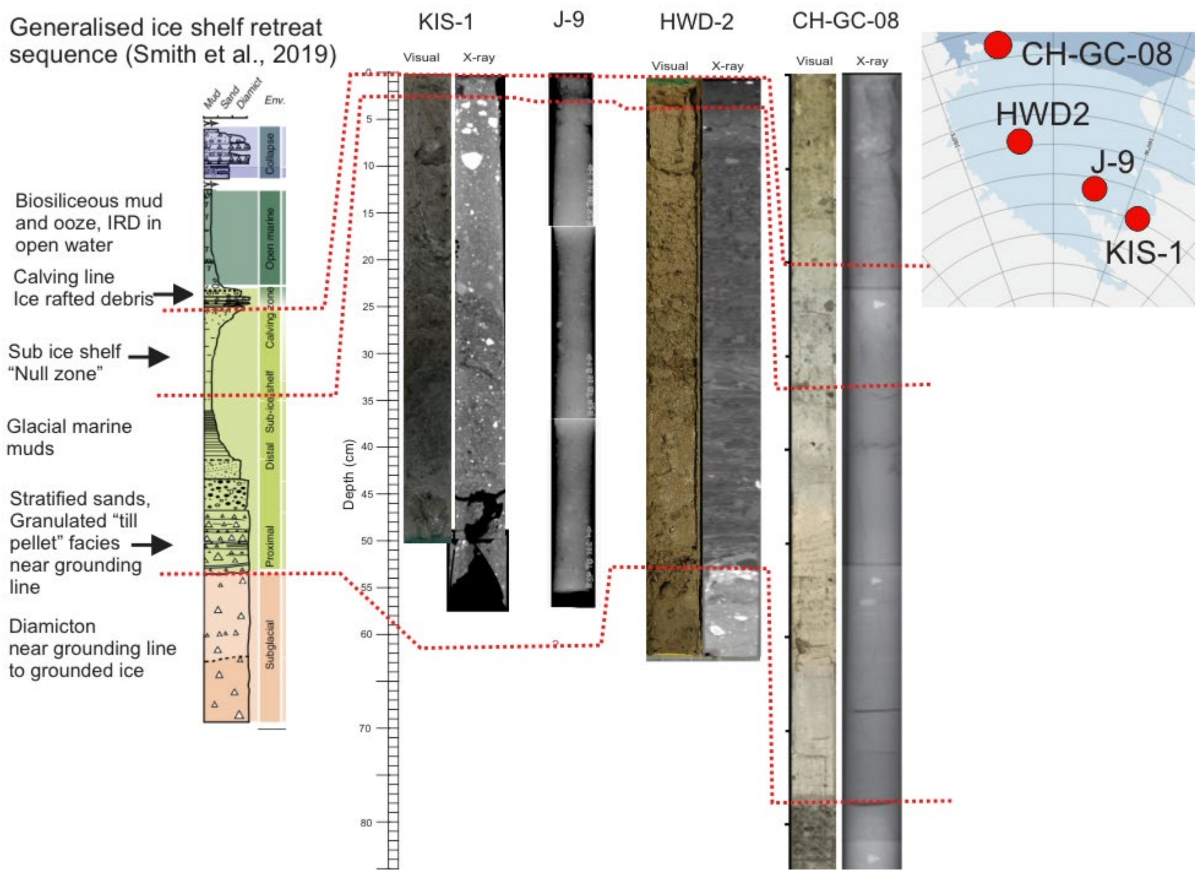


Figure 3.3 Stratigraphic comparison for four sediment cores collected from beneath the Ross Ice shelf, compared to the generic ice shelf retreat model of Smith et al. (2019). Based on the lithology, stratigraphy, degree of compaction and microfossil content, we are confident that all cores contain a post-LGM ice-shelf retreat facies sequence.

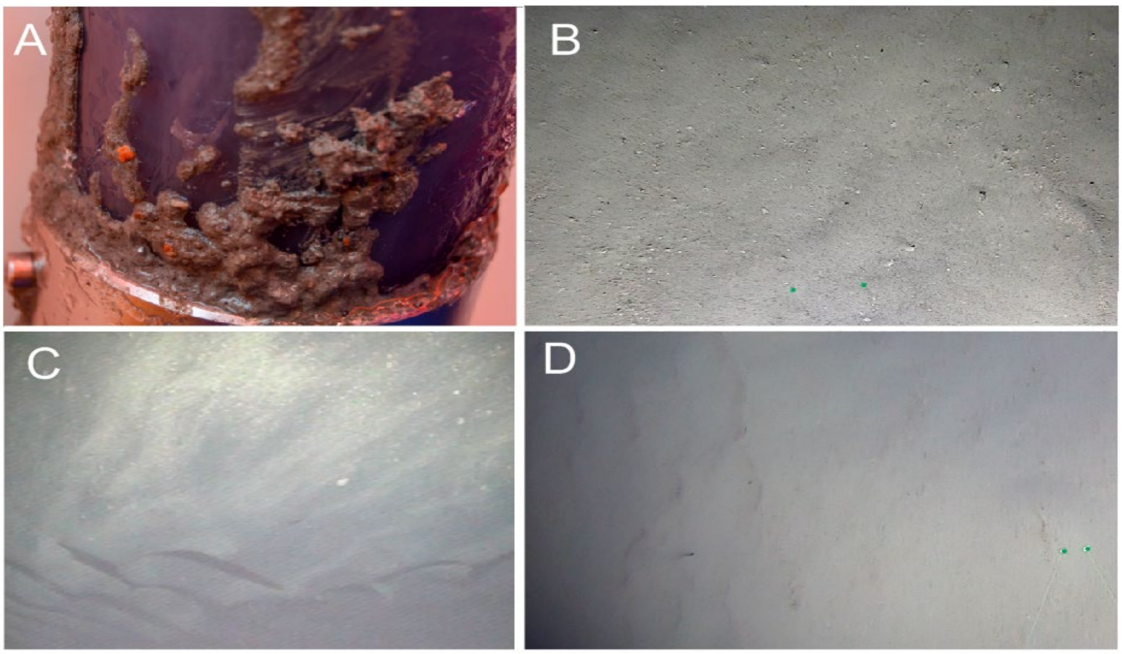


Figure 3.4 Sediment sample and seafloor images at Kamb Ice Stream grounding zone. (A) Sediment recovered from the outside of the gravity corer barrel at KIS-1. Core tube is 6.3 cm in diameter. Screen capture from Icefin ROV videos of: (B) unconsolidated diamict sediment near the KIS-1 site. The green 'dots' at the bottom of the image are points from a laser scale and are 5 cm apart; (C) sediment in the base of the ice shelf near the KIS site; and (D) rippled, unconsolidated sandy-mud with rare dropstones near the KIS site.

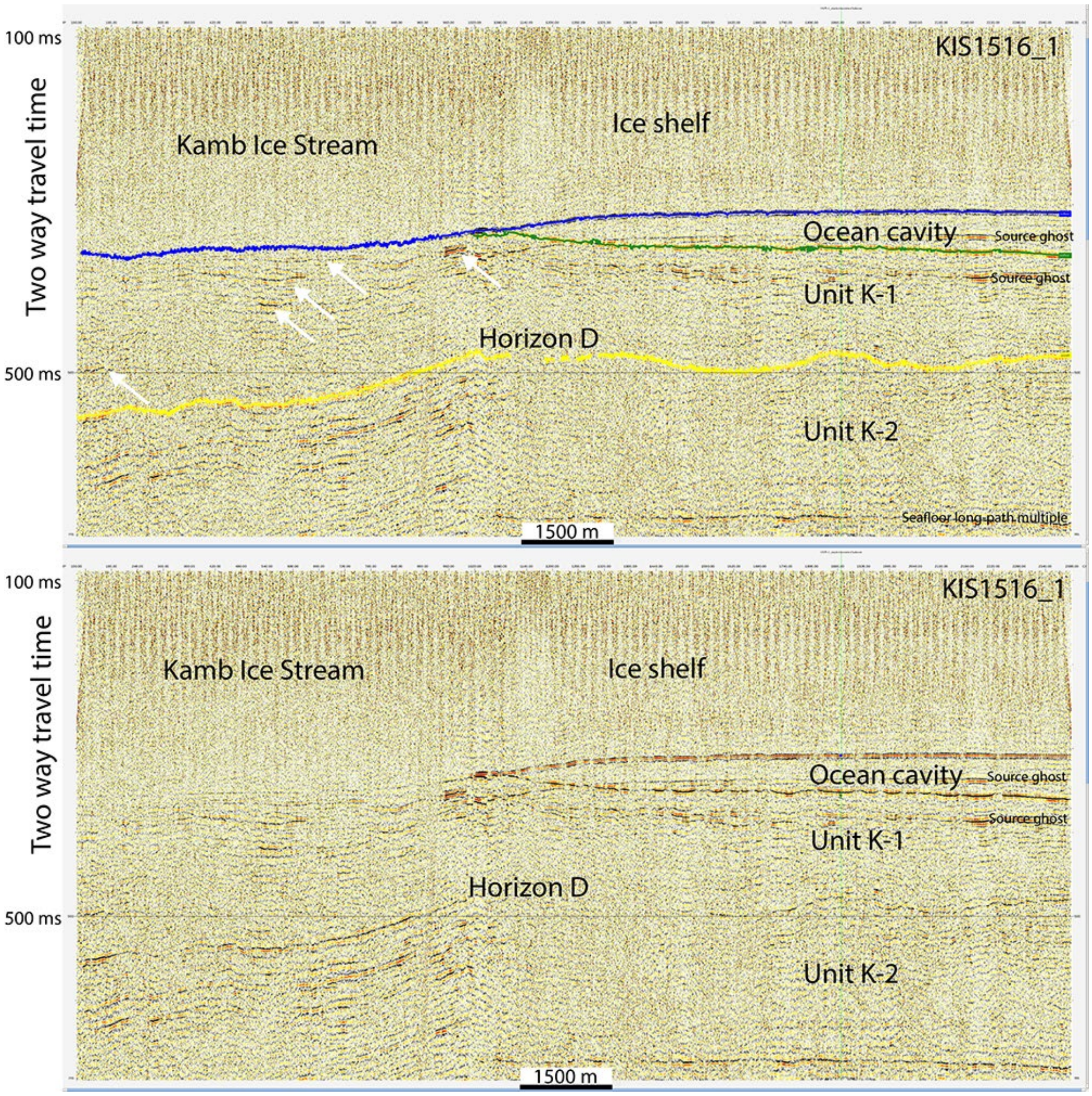


Figure 3.5 Seismic line KIS 1516_1, un-interpreted (top) and interpreted (bottom). Arrows indicate areas of higher-amplitude horizontal to sub-horizontal internal reflectivity, which are best imaged below grounded ice. We expect that these layers extend throughout Unit K-1 but are not imaged as well below floating ice. Horizon D is a regional reflector that separates the upper Unit K-1 (Quaternary) from older sediments in Unit K-2 (Late Neogene).

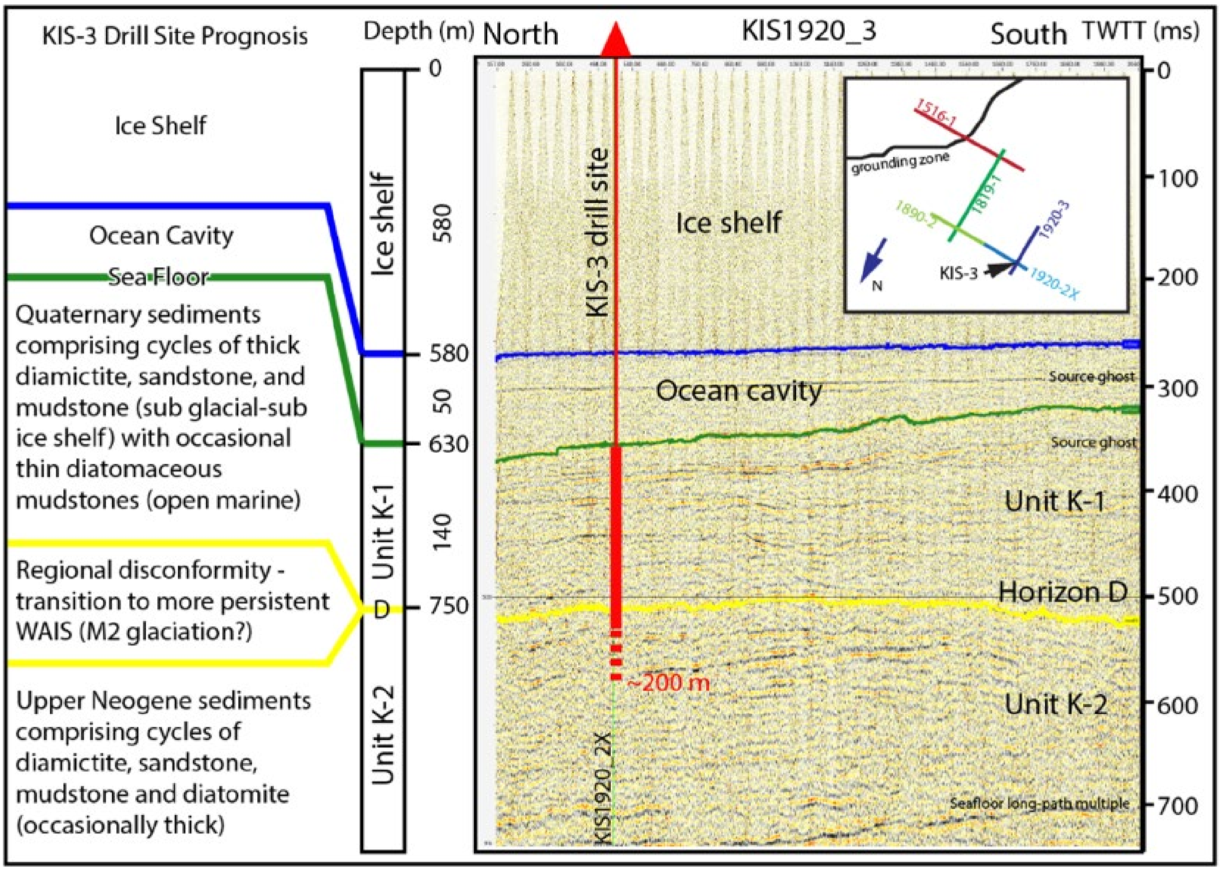


Figure 3.6 Seismic line KIS1920_3 (see inset for location). KIS drill site is located on the crossing point with line KIS1920_2X. Drilling prognosis at left with estimated depths from surface and stratigraphic intervals. Thick red line = 200 m drilling target depth.

### 3.2.3 Crary Ice Rise

CIR is an area of grounded ice frozen at the bed within the Ross Ice Shelf. Borehole temperature measurements estimate that this ice rise stabilised ~1400 AD (Bindschadler et al. 1990; Catania et al. 2012). This site also offers a stable drilling platform due to the slow flowing over-riding ice. Our CIR site also has the advantage of being close to the South Pole Over-ice Traverse (SPOT) route.

Hot water drilling in the 1980s at CIR recovered Miocene diatom-bearing marine sediment from the base of the ice (Scherer and Tulaczyk 1998; Scherer et al. 1988), consistent with gravity core sediment recovered during the Ross Ice Shelf Project (RISP) at Site J-9 (Harwood et al. 1989a) and implying episodic open water conditions. Pliocene taxa, also identified at CIR, were inferred to have been deposited in interior West Antarctic basins during warm periods but transported to the ice rise during subsequent WAIS expansion (Scherer 1991b).

Geophysical surveying at CIR collected over 15 km of seismic data that are interpreted to include a Holocene grounding zone wedge deposit overlying gently dipping strata (Figure 3.7). Acoustic basement is unconformably overlain by several hundred metres of stratified and lithified sediment (Unit C-2) characterised by velocities ≤2400 m $s^{-1}$. A wedge-shaped sequence (Unit C-1) occurs above regional disconformity (Horizon H) and is characterised by discontinuous (chaotic) reflectors and velocities ≤2200 m $s^{-1}$. We interpret this unit as a Holocene Grounding Zone Wedge. Although the age of Unit C-2 is unknown, we suggest that the gently dipping layers represent glacial to interglacial cycles comprising glacial till and open marine strata deposited during the mid- to late Neogene (Figure 3.8).

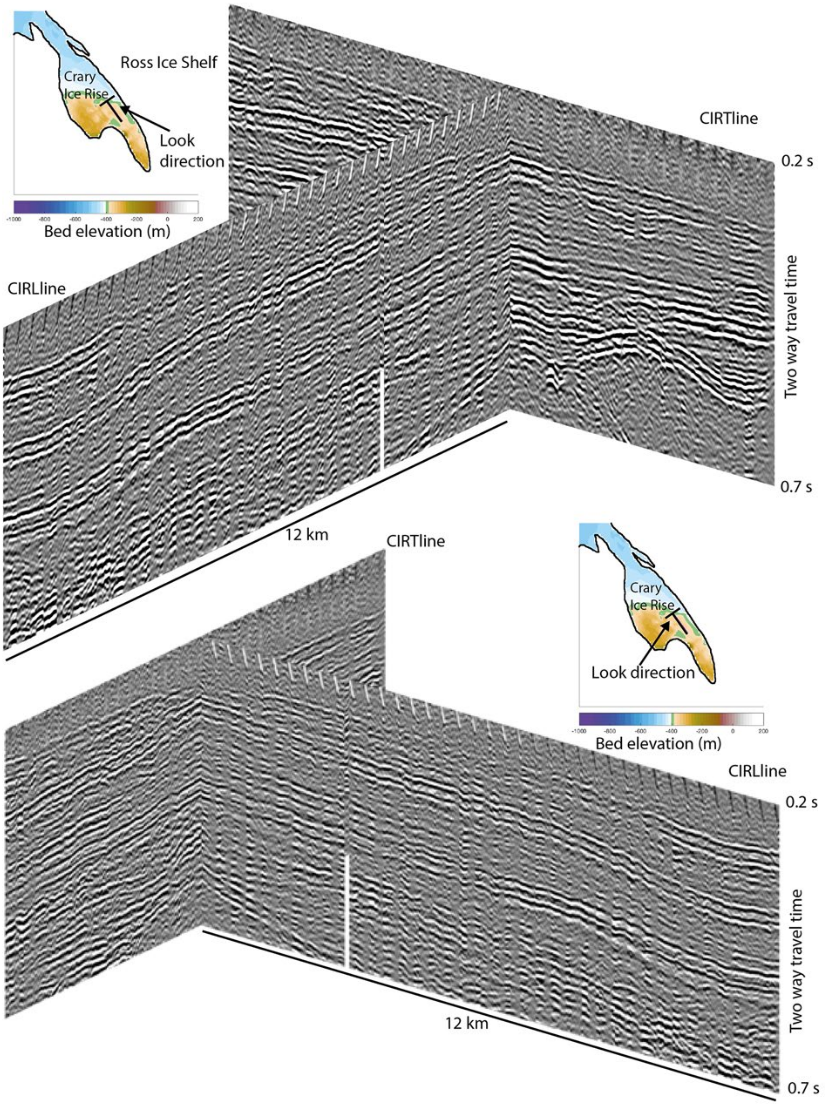


Figure 3.7 Fence diagram of available seismic data across the region around the Crary Ice Rise (CIR) drill site.

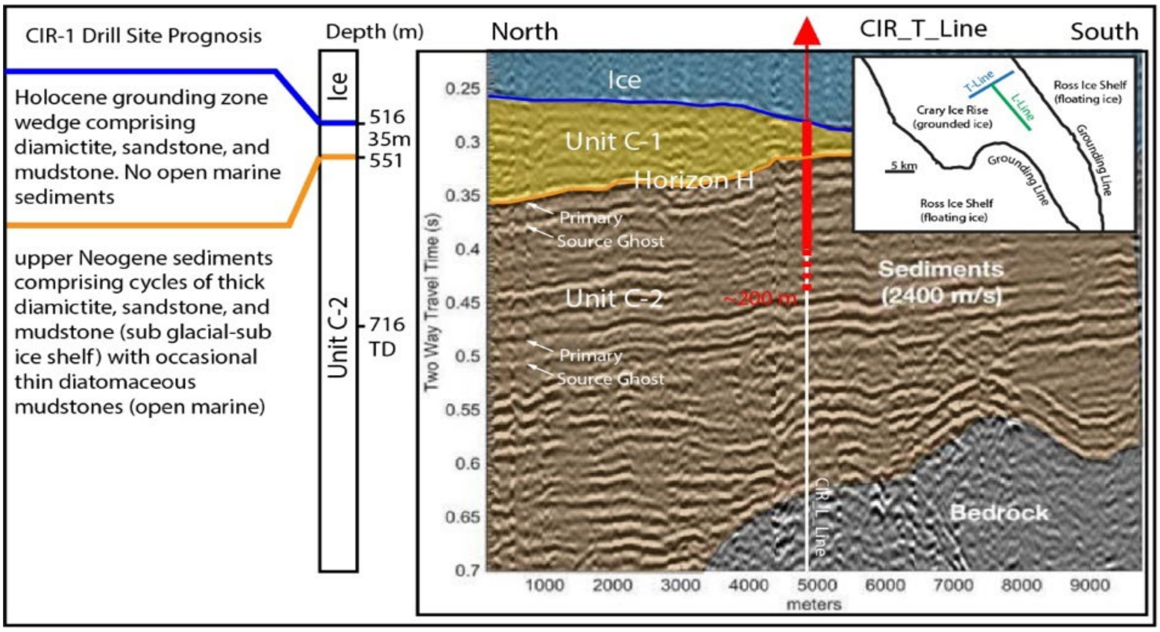


Figure 3.8 Seismic line CIR_T (see inset for location). CIR drill site is located on the crossing point with line CIR-L. Drilling prognosis at left, with estimated depths from surface and stratigraphic intervals. Thick red line = 200 m drilling target depth.

## 4.0 SCIENCE TEAM

An open call for interest and participation in the SWAIS 2C Project was made at a Past Antarctic Ice Sheet Dynamics workshop at the XIII International Symposium on Antarctic Earth Sciences in Incheon, Korea, in July 2019. Following an introduction to the proposed drilling, interested individuals were invited to participate in planning sessions during the workshop. From this, we identified lead science team members from partner nations, who subsequently helped to develop proposals for drilling at the international and national levels. Science team participation is approximately based on the percentage contribution from each partner nation to the total drilling and logistics costs. Most nations have run an internal process to identify science team members. Table 4.1 shows the current the list of people from which we will draw for each field season. We note that some nations partner nations, e.g. the United Kingdom, are still completing their selection process, and staffing will not be finalised until these selection processes are complete. We also note that this list is not comprehensive, and additional scientists may join the science teams during planning and later stages of each project.

Table 4.1 SWAIS 2C Science Team members by country and scientific discipline.

| NATION<br>*lead PI* | CONTRIBUTION to Operations<br>**bold = committed**<br>plain = pending<br>c = cash<br>ik = in kind | SCIENTIFIC DISCIPLINES* | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | CORE DESCRIPTION | CHRONOSTRATIGRAPHY<br>CHEMOSTRATIGRAPHY** | CHRONOSTRATIGRAPHY<br>BIOSTRATIGRAPHY | CHRONOSTRATIGRAPHY<br>PALEOMAGNETISM | GEOCHEMISTRY & MICROBIOLOGY | CORE & DOWNHOLE LOGGING | GEOPHYSICS & MODELING |
| | | cp = clast petrology<br>cm = clay minerals<br>f = fractures<br>ss = sed/strat<br>v = volcaniclastics | C14 = radiocarbon<br>cn = cosmogenic nuclides<br>is = isotopes<br>t = tephrochronology | C = CONOP<br>d = diatom<br>p = palynology<br>r = radiolaria | | in = inorganic<br>m = microbiology<br>o = organic<br>pr = provenance<br>T = thermochronology | pp = physical properties<br>x = XRF scanning<br>l = downhole logging | gp = geophysics<br>gl = glaciology<br>g = GIA<br>c = climate<br>i = ice sheet |
| **UNITED STATES***<br>*Molly Patterson* | **20%<br>c + ik** | *Molly Patterson* [1,ss] | *Ryan Venturelli* [(PDR)C14] | *Jason Coenen* [(PDR)d]<br>**David Harwood**[†,d]<br>**Amy Leventer**[†,d] | | ***Jeanine Ash*** [†,m,in]<br>***Justin Dodd*** [in] | Denise Kulhanek[2,x,in] | *Jacky Austermann* [g]<br>Rob DeConto[c,i]<br>***Jonny Kingslake*** [gl]<br>Paul Winberry[gp] |
| **NEW ZEALAND**<br>*Richard Levy* | **20-30%<br>c + ik** | **Tim Naish**[†,ss]<br>Rob McKay[ss] | | Richard Levy[1,C]<br>*Joe Prebble* [p]<br>Giuseppe Cortese[r] | ***Christian Ohneiser*** | **Catherine Beltran**[o]<br>Craig Cary[m]<br>*Bella Duncan* [(PDR)o] | **Gavin Dunbar**[†,pp,ss] | Nick Golledge[i]<br>**Huw Horgan**[†,gp]<br>Liz Keller[c]<br>*Dan Lowry* [(PDR)i] |
| **GERMANY**<br>*Andreas Läufer* | **10%<br>c** | *Johann Klages* [ss]<br>Nikola Koglin[cp]<br>**Andreas Läufer**[†,f] | | | | Frank Lisker[T]<br>*Juliane Müller* [o] | **Thomas Wonik**[l] | Olaf Eisen[gl]<br>Karsten Gohl[gp]<br>Gerrit Lohmann[c] |
| **KOREA**<br>*Kyu-Cheul Yoo* | **10%<br>c** | **Kyu-Cheul Yoo**[†,ss]<br>*Kiho Yang* [cm] | | | | *Sunghan Kim* [in]<br>Jung-Hyun Kim[o]<br>Jae Il Lee[pr] | | |
| **JAPAN**<br>*Yoshifumi Nogi* | 5-10%<br>c | | Yusuke Suganuma[cn] | | | **Osamu Seki**[†,o] | | |
| **ITALY**<br>*Fabio Florindo* | **10%<br>c** | Ester Colizza[ss]<br>Laura Crispini[f]<br>Paola Del Carlo [v]<br>**Sonia Sandroni**[†,cp] | Alessio Di Roberto[t] | | **Fabio Florindo**[†] | | | **Florence Colleoni**[c,i] |
| **NETHERLANDS**<br>*Paolo Stocchi* | 5%<br>c | | | Francesca Sangiorgi[p] | | Pierre Offre[m]<br>***Anja Sprang*** [†, m] | | Paolo Stocchi[g] |
| **SPAIN**<br>*Francis Jimenez-Espejo* | 5%<br>c | | Jose-Abel Flores[is] | | | | **Francis Jimenez-Espejo**[†,x,in] | |
| **UNITED KINGDOM**<br>*Tina van der Flierdt* | **10-15%<br>c** | | | | | **Tina van der Flierdt**[†,in,pr] | | ***Ed Gasson*** [i] |
| **AUSTRALIA**<br>*Sarah Kachovich* | **5%<br>c** | | | Linda Armbrecht[d]<br>Rebecca Parker[d] | | | | |

1 = Co-Chief 2 = Staff Scientist † = Theme Leader PDR = Post-Doctoral Researcher **bold = Discipline Leader** *italics = early career researcher*
*Some scientists will participate both seasons; others will participate one season to fulfill national quotas.
**Chemostratigraphy scientists will be assigned to other lab groups (e.g. core description, core logging) for the core description workshop.

# 5.0 PROJECT MANAGEMENT AND IMPLEMENTATION PLAN

## 5.1 Overview

We will draw on the project management approach and experience that our team members have gained through involvement in previous international drilling projects (Figure 5.1). We will also implement the formal project management operating model that is used at GNS Science. Our project structure includes a Governance Group, Operations Group and Science Group. The Governance Group will include representatives from project funders (including ICDP), the Director of the Antarctic Research Centre at Victoria University of Wellington (who employs the drilling team) and the General Manager Antarctic Operations, Antarctica New Zealand (ANZ; New Zealand's national programme responsible for Antarctic field logistics and operations). The Project Leads (Chief Scientists) will manage and lead both the Drilling/Field Operations and the Science Operations Groups, reporting regularly to the Governance Group on progress and raising any issues that may impact the project. The Project Leads will be supported by the GNS Science Project Management Office. The Drilling/Field Operations Group is led by the ANZ Field Support Project Manager, ANZ Traverse Manager and Drill Operations Manager, who will work together to ensure that all aspects of the drilling and field operations are planned and implemented. The Drill Operations Manager leads the Hot Water and sediment coring team. The ANZ Field Support Project Manager leads the camp operations team and coordinates air logistics. The ANZ Traverse Manager leads the traverse team. The Science Operations Group is led by the Chief Scientists with support from the Staff Scientist, Core/Data Manager and Science Theme Leaders, who comprise the SWAIS 2C Science Leadership Team (SSLT), which is ultimately responsible for delivering the scientific components and outcomes of the project. A Science Advisory Group and Technical Advisory Group will be available to the SSLT to provide advice and recommendations when needed.

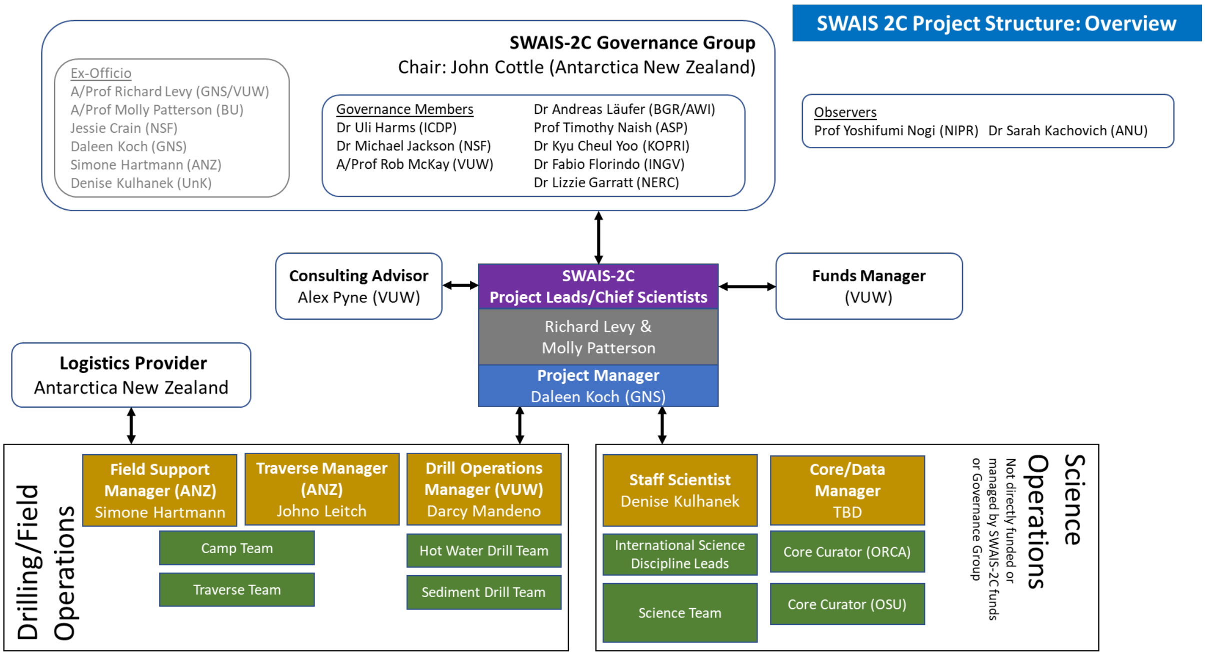


Figure 5.1 Project Management structure.

## 5.2 Sample and Data Management and Publication

The SWAIS 2C Science Leadership Team will work together with the ANZ Data Manager to ensure that sound data management practices are in place. Appropriate team members will attend the ICDP data and sample management workshop prior to the start of the first drilling season. We will use the ICDP mobile Drilling Information System (mDIS), which provides a database for recording data collected and samples taken, during the drilling operations and core description phases of the drilling projects. This mDIS also facilitates depth matching to synchronise data collected on different depth regimes and integrate downhole measurement data. Primary project data are initially archived on the ICDP server and accessed via password by science team members. These data will ultimately be published via an online data repository. New data collected by individual scientists will initially be stored on their own computers and/or institutional servers and backed up regularly. We will establish a project Google drive for sharing of these data during the home institution research phase of the drilling project prior to publication.

All project metadata will be archived in the ANZ data repository, the Antarctica Master Directory and the United States Antarctic Program Data Center. Final datasets will be published via an online data repository (ICDP, Pangaea or Zenodo). The latter allows storage of individual file sizes up to 50 GB, which will be required for CT and hyperspectral data.

Project data will be under moratorium for two years following completion of the core description workshop. Those data will be stored on the ICDP server, where they will remain password-protected until the end of the moratorium. Science Team members will also be required to deposit their data in the repository upon acceptance of their work in a journal or book. Data deposited in the repository will be assigned a digital object identifier (DOI) that can be linked to published manuscripts. Data will be made available for open access via a Creative Commons license.

All Science Team members must submit a research plan and sample request to access samples. During the moratorium, only approved Science Team members will have access to samples. At the end of moratorium, sample access will be co-ordinated by the curator at the Oregon State University Marine and Geology Repository, where the cores will be archived. All Science Team members also incur an obligation to conduct research using samples or data received based on their research plan. To fulfil this obligation, they must submit manuscripts to a peer-reviewed English language journal or book within 24 months after the end of the moratorium.

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