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ANTARCTIC SUBGLACIAL SYSTEMS: OBSERVATIONS, MEASUREMENTS AND MODELLING

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ABSTRACTS SUBMITTED TO THE (CANCELLED) SCAR 2020 OSC IN HOBART

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Subglacial precipitates record East Antarctica's response to 1-2 °C warming

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At ~400 thousand years before present, during MIS 11, Earth was 1-2°C warmer and sea level was 6-21m higher than present. Sea level estimates in excess of 10m, however, have been discounted as these require contribution from the East Antarctic Ice Sheet, which has been argued to have remained stable at MIS 11 and for millions of years prior. Here, we show how chemical precipitates that formed beneath the ice sheet record the magnitude of East Antarctic ice loss during MIS 11. Within the Wilkes Basin, precipitates record the accumulation of 234U, the product of rock-water contact within an isolated subglacial reservoir, up to 20 times higher than marine waters. The timescales of 234U enrichment place the reservoir inception to MIS 11. Informed by the observed 234U cycling in the Laurentide ice sheet, where 234U accumulated during periods of ice stability and is purged in response to deglaciation, we interpret our East Antarctic dataset to record ice loss within the Wilkes Basin at MIS 11. The 234U ingrowth within the Wilkes Basin is shared by the McMurdo Dry Valley brines, supporting brine origination from the Wilkes Basin. The requirement that Dry Valley salt and bacteria are marine derived implies that MIS 11 ice loss in the sub-sea level Wilkes Basin was coupled with marine flooding. Collectively these data indicate that the last time Earth warmed 1-2°C, the ice sheet margin at the Wilkes Basin retreated at least 700km inland from the current position, contributing >3-4m to sea level rise.

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Indications for subglacial bathymetric control on ice shelf stability in western Dronning Maud Land, East Antarctica

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The floating ice shelves of Antarctica play a major role in stabilizing the grounded continental ice sheets. Ice shelf thinning due to basal melting with subsequent loss of buttressing at pinning points are prominent contributors to increased ice sheet drainage and subsequent sea level rise. The catchment to the ice shelves of western Dronning Maud Land currently comprises an ice volume equivalent to 0.95 meters of sea level. Since basal melting predominantly depends on ice-ocean interactions, it is vital to attain consistent bathymetric models as boundary conditions for estimating water and heat exchange beneath the ice shelves. We have constructed bathymetric models beneath the Ekström, Atka, Jelbart, Fimbul and Vigrid ice shelves by inverting airborne gravity data, tied to seismically-derived depth reference points. High-resolution magnetic anomaly data across these ice shelves are used to interpret shallow subsurface geological variations whose effects on density variability are accounted for during the inversion. Our bathymetric models reveal deep glacial troughs beneath the ice shelves and sills close to the continental shelf breaks, which currently limit the entry of Warm Deep Water from the Southern Ocean. The average thermocline depth and the average depths of gateways crossing the sills into the sub-ice cavities are similar, leading us to suggest a high sensitivity for these ice shelves to future changes in thermocline depth. Once a significant amount of warm water overtops the sills, the deep troughs will allow for fast access to the grounding line leading to a surge in basal melt rates.

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Trace element dispersal by an Antarctic subglacial sediment plume

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Subglacial environments are distinct cryospheric sources of dissolved nutrients to the euphotic zone, yet their contributions to trace element biogeochemistry remain uncertain. Additionally, the speciation of key bio-limiting micronutrients, such as iron, present within sediment plumes arising from subglacial meltwater discharge is unknown. Enhanced microbial respiration, high weathering rates, and limited diffusion of oxygen, increase the solubility of redox sensitive elements, such as iron (Fe) and manganese (Mn), which enter the ocean as buoyant turbid plumes. Here we characterize the signature, dispersion and physicochemical speciation of bioactive trace metals in a glacial sediment plume and speculate on the geochemical setting beneath west Antarctic Peninsula glaciers. This work reveals sediment plumes arising from subglacial meltwater discharge are important subsurface sources of dissolved and labile particulate Fe (82-100% of total particulate Fe) to resident phytoplankton communities. Our analyses reveal strong co-variation between dissolved and labile particulate pools at plume depths (70-150m), indicating exchange over short length scales. Given that Antarctic glaciers are susceptible to rapid changes in the warming climate, the interface between glaciers and the coastal ocean is poised to be an important control on the quantity and quality of micronutrients transported to downstream nutrient-limited phytoplankton communities.

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Improved ice sheet bed topography of Antarctica from satellite images: BedImage Antarctica

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The bedrock topography of Antarctica is a critical parameter for ice sheet models and for understanding the geological history of the continent. Recent compilations using radar and gravity data have greatly improved the coverage and resolution of the sub-ice-sheet bedrock surface, but many regions remain poorly mapped. Here we use satellite-image-derived surface ice-sheet morphology and surface ice flow velocity to quantitatively improve the mapping of Antarctica's bedrock topography below the ice sheet through a newly developed technique. The analysis is based upon an inversion of the driving stress equation, with surface velocity used as a parameter to estimate internal and near-basal flow. We calibrate and convolve the approach using gridded BEDMAP2 and BedMachine data and check this against new radar profiles. The result is a detailed 1km resolution comprehensive model of the Antarctic bed. Comparison with BEDMAP2 cells in East Antarctica shows a 0.85 R2 correlation and a standard deviation of 270.6 m. This "BedImage" model provides useful detail in many inland areas that were previously poorly mapped. Additionally, we present sub-kilometre-scale maps of two areas that have ice conditions suitable for higher resolution models.

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Subglacial lake formation in response to thermal conductivity contrasts with or without subglacial topography

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Geothermal heat flux (GHF) is an essential boundary condition for producing accurate numerical models of basal melting, but the magnitude and variation of GHF is poorly characterized beneath polar ice sheets. In this study, we explore small-scale (~1 to 10 km) thermal-refractive effects on GHF at subglacial boundaries resulting from lateral thermal conductivity contrasts associated with subglacial topography and geologic contacts. Heat flux can preferentially flow into or around a subglacial valley depending upon the thermal conductivity contrast with underlying bedrock with magnitudes at the glacial-basement interface ±20 to 40% of regional geothermal heat flux and temperature anomalies on the order of ±10ºC. When bedrock is more conductive than ice, heat flows around valleys and into peaks. Even without topography, subglacial geologic contacts can produce heat flux and temperature anomalies of similar magnitude. Heat flow and temperature are locally increased on the thermally conductive side, adjacent to the geologic contact. To estimate the importance of thermal refractive effects, we analyze the characteristics of 378 subglacial lake localities in East Antarctica. We find 260 lakes occur in regions of thick ice, >2.5 km, which likely reach the melting point as a result of ordinary conduction. However, a significant fraction (~80%) of lakes lies in regions of thin ice with slow velocities. The majority of remaining lakes occur in regions with minimal subglacial topography, indicating thermal refraction due to subglacial contacts may be a significant contributor to subglacial melting. Therefore, models of subglacial geology are required to improve glacial models.

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Grounding zone subglacial properties from calibrated active source seismic methods, Whillans Ice Stream, West Antarctic

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The presence of water, sediment, or bedrock beneath glaciers and ice sheets can control ice flow by promoting sliding at the ice-bed interface and deformation of the bed. These conditions can change rapidly, and the potential for change is not captured by commonly employed inversion techniques used to infer bed friction. Aspects of subglacial conditions can be detected remotely using radar and active source seismic methods. While radar techniques provide extensive spatial coverage, seismic techniques provide direct estimates of elastic properties. Here we present novel calibrated active source seismic estimates of subglacial properties from the grounding zone of Whillans Ice Stream, revealing an abrupt transition to the ocean cavity over less than 500 m. The grounded portion of the ice stream is underlain by a substrate that is relatively stiff when compared with the deformable till found elsewhere beneath the ice stream. We also detect thin layers of subglacial water several kilometres upstream of the ocean cavity. The presence of stiff subglacial sediment and thin water layers upstream of the grounding zone support previous studies that have proposed the dewatering of sediment within the grounding zone and the pumping of ocean water into the subglacial system. We compare our findings with existing radar estimates of the transition and highlight the geophysical and direct access program current being undertaken by the New Zealand Antarctic Research Institute and the Antarctic Science Platform.

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Subglacial sedimentary basin distribution in Antarctica unveiled

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Antarctica preserves the largest ice-sheet on Earth. Understanding subglacial sedimentary basin distribution is essential for studying ice sheet behaviour, as it forms an important basal boundary condition for ice sheet dynamics. However, the subglacial sedimentary basin distribution is poorly known in Antarctica. The thick ice sheet with limited outcrop makes it difficult to directly map sedimentary basins, and until now continental-scale sedimentary basin models only have been derived from interpolation of sparse seismic data and inversion of decompensative gravity anomaly. Here we present a high-resolution subglacial sedimentary basin likelihood map using a supervised machine learning method based on continental compilations of geophysical and remote sensing datasets. Classification uncertainty is simultaneously derived from information entropy. The results confirm the existence of subglacial sedimentary basins in West Antarctica and in general define the margins and extents of sedimentary basins in detail. Specifically, in West Antarctica Rift System, model delimits the boundary between sedimentary basins and volcanic rocks. Further, our model shows more widely distributed subglacial sedimentary basins in East Antarctica than been previously recognized. Properties of geophysical and remote sensing data in Recovery Glaciers suggest a high probability of sedimentary basin preservation.

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Geostatistical Simulations of Subglacial Topography and Implications for Water Routing

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Subglacial topography is an important driver of ice sheet movement and subglacial water flow. Bed topography is primarily measured with ice-penetrating radar, but large gaps in data must be interpolated. Topographic interpolations are frequently made with kriging or mass conservation, where ice flow dynamics are used to constrain bed geometry. However, these techniques generate bed topography that is unrealistically smooth, which biases subglacial water routing models and makes it difficult to rigorously quantify uncertainty in subglacial drainage behavior. To address this challenge, we generate geostatistical simulations of bed topography so that the interpolated topography reproduces the spatial statistics of the radar data. We demonstrate a protocol for performing geostatistical simulations of bed topography that uses mass conservation topography as a soft constraint. We then apply a water routing model to these simulations and show that some flowpaths change significantly with each topographic realization. We discuss the implications of our findings for quantifying uncertainty in bed conditions, topographic controls on subglacial water routing, and making hydrological interpretations using interpolated bed topography.

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Provenance of gravel- and sand-sized sediment from both the ice shelf and shallowest seafloor at the HWD-2b site, mid Ross Ice Shelf, Antarctica

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In 2017, the Aotearoa New Zealand Ross Ice Shelf Programme drilled through the Ross Ice Shelf at site HWD-2b [Latitude -80.658, Longitude 174.463]. Presently, HWD-2b lies under the ice flow path from the Liv Glacier in the Transantarctic Mountains. Sediment was recovered from both the ice shelf and by gravity core from the seafloor. Petrographic study of this material aimed to determine whether the ice shelf and seafloor sediment had a shared source. Two size fractions were examined for both the ice shelf and seafloor samples. The pebble-sized fraction was petrographically described in hand specimen and thin section. The plutonic pebbles have a mineralogy consistent with quartz diorite and tonalite. The sandstone pebbles are quartziferous and are typically undeformed and unmetamorphosed. Limestone and volcanic lithologies are not identified. The sand-sized fraction thin sections were stained for potassium and alkali feldspar and point counted (n:310 grains) by the Gazzi-Dickinson method. The ice shelf and seafloor samples are quartz- and plagioclase feldspar-rich, with only a minor lithic/alkali feldspar component. Both samples are likely from similar source rocks, equivalent to a quartz diorite, quartz gabbro or tonalite. This suggests the source of both samples in both size fractions is rich in Ferrar Dolerite and a quartziferous sandstone source, perhaps like Byrd Group or Beacon Supergroup lithologies. These lithologies are consistent with a Central Transantarctic Mountain source, such as is seen around the Liv Glacier or Beardmore Glacier. A shared provenance has implications for ice sheet retreat models since the last glacial maximum.

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Bed diagnosis in the Dome Fuji region, East Antarctica, using airborne radar data and englacial attenuation estimates

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Radar reflectivity of the ice-sheet bed has been used as a diagnostic measure of the basal conditions. Such bed diagnosis could lead to constrain magnitude and spatial pattern of geothermal flux which remains poorly known under the Antarctic Ice Sheet. Radar reflectivity can be estimated from the radar-observed bed returned power by extracting englacial attenuation. Attenuation exponentially depends on ice temperature, and can vary larger than the difference in the bed reflectivity for thawed and dry beds. In the 2016-17 austral summer, Alfred Wegener Institute carried out 150-MHz airborne radar survey for ~19,000 line kilometers in a 400-km by 400-km area including Dome Fuji, East Antarctica, where the Oldest Ice is predicted to present. Bed topography, roughness, and subglacial hydraulic potential were analyzed and subglacial lakes were preliminary mapped already. We extend that study by rigorous analysis of bed returned power. We hypothesize that model-predicted thawed area is consistent with high bed reflectivity area derived from the radar data, when englacial attenuation/temperature is derived for the correct geothermal flux. We carried out attenuation and radar reflectivity estimates for a range of geothermal flux and mapped spatial variations in the attenuation and bed reflectivity.

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Subglacial fluid compositions linked to East Antarctic ice sheet's response to Pleistocene climate cycles

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Remote sensing of the East Antarctic ice sheet (EAIS) has revealed a dynamic hydrologic system at its base that plays a major role in regulating ice sheet flow, provides a vast habitat for microbial life, facilitates chemical weathering that fuels oceanic ecosystems, and can lead to basal freezing and growth from the ice sheet base. Despite progress in detecting active subglacial hydrologic systems today, they remain virtually unconstrained over long time scales, such as the response to Pleistocene glacial-interglacial cycles. Here we explore a new record of EAIS basal fluid history in subglacial chemical precipitates from the Wilkes basin using U-series geochronology and geochemical proxies for fluid conditions and source. These samples exhibit mineralogic transitions between opal and calcite, requiring cyclic variation in basal fluid composition. We constrain the timing of these transition using 234U-230Th ages and establish a depositional timeline, which indicates rapid carbonate deposition during interglacials and slow opal growth during glacial periods. We compare mineralogic cyclicity to climate records and find statistically significant correlation between opal-calcite transitions and the benthic δ18O record on both 100kyr and shorter cycles. Collectively, these data provide direct evidence for cyclic variations in EAIS basal water that correspond with glacial-interglacial climatic cycles during MIS 8a-6d and allow us to further explore the interplay between the overlying ice sheet and subglacial aqueous systems.

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3D GPR imaging of subglacial lineations under the Rutford Ice Stream, West Antarctica

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Understanding of present-day glacier dynamics of the West Antarctic Ice Sheet is essential for the reconstruction of its past dynamics. Subglacial lineations, such as mega-scale glacial lineations and drumlins, are known to be indicative of fast ice flow. Numerous theoretical concepts based e.g. on water availability, subglacial geology and flow dynamics, attempt to explain their formation. Nevertheless, a uniform formation theory consistent with observations is still missing.

The Rutford Ice Stream (more than 2km thick, of which 1.4km is below sea level) is one such fast-flowing glacier in West Antarctica: the ice surface speed at the grounding line is >1m/day, stable over the past 30 years. The ice-bed interface is assumed to be at the pressure-melting point. Excising ground-penetrating radar (GPR) and seismic 2D profiles revealed highly elongated lineations, up to ~14 km long, up to 150 m high, and 50-500 m wide, aligned in the ice-flow direction. In one location, the deposition of sediment, arranged as a drumlin, was observed over a period of <10 years.

To study the detailed architecture of three different areas of the lineations 3D grids of GPR data with dimension 3x3km, with cross-line spacing of 20m and an inline spacing ~1.5m, were acquired in 2017/18, enabling 3D-processing and imaging of lineations. Using this unique dataset, to supplement previous findings and with data from the paleo record, we hope to better constrain the formation mechanisms for subglacial lineations and the subglacial physical conditions at the Rutford Ice Stream.

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A bed elevation model for Princess Elizabeth Land in East Antarctica

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We present a new topographic digital elevation model (DEM) for Princess Elizabeth Land (PEL) – the last remaining region in Antarctica to be surveyed. The DEM covers an area of ~900,000 km2 and was established from new airborne radio-echo sounding (RES) data collected by the ICECAP-2 consortium, led by the Polar Research Institute of China, from four different surveys since 2015. Previously, the region was characterised by an inversion using low resolution satellite gravity data across a large (>200 km wide) data-free zone to generate the Bedmap2 topographic product. We use the mass conservation (MC) method to infer bed topography across faster-flowing (>30 m yr-1) regions of the ice sheet and streamline diffusion at slower-flowing areas. Two datasets are available resolution of 1 km (to compare directly with Bedmap2) and 500 m. From the revised bed surface, we are able to better model the flow of subglacial water and assess where the hydraulic pressure is most sensitive to small ice surface gradient changes. Together with BedMachine Antarctica, and Bedmap2, this new PEL bed DEM completes the first order measurement of subglacial Antarctica – an international mission that began 70 years ago.

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The life cycle of an Antarctic active subglacial lake: A process to paleo perspective

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Research over the past decade transformed our view of the dynamic hydrological environment beneath the Antarctic ice sheet, with the ability to influence regional ice velocity, grounding-line stability, and the role of subglacial biogeochemical cycling on coastal ecosystems. Hidden beneath 10s to 1000s of meters of ice, these enigmatic hydrological systems of interconnected lakes and streams are poorly understood, largely due to the short temporal window of the ice-surface observational record from which we infer hydrological dynamics and the lack of in situ instrumentation to directly sample lake properties. We present new airborne and satellite observations that extend the current temporal record of active subglacial hydrology and explore the variability of Antarctic subglacial hydrological systems driven by the filling and draining of subglacial lakes. We then focus on Mercer Subglacial Lake beneath Mercer Ice Stream, West Antarctica, a 15 m deep lake directly accessed while in a draining phase by the Subglacial Antarctic Lakes Scientific Access (SALSA) Project in January 2019. By leveraging in situ observations of the physical and sedimentary setting of a modern active lake system, we can connect the modern observational record to the geologic past and build a conceptual understanding of how subglacial hydrological systems beneath Antarctic ice streams evolve over timescales of days to centuries while interacting with the overlying ice.

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Subglacial lake exploration: Joint UK-Chile preparations for accessing Subglacial Lake CECs, Antarctica

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The subglacial environment remains one of the least-explored places on Earth. Over recent decades more than 400 subglacial lakes have been discovered beneath the Antarctic Ice Sheet, many hidden under kilometres of ice and possibly isolated for up to millions of years. They represent one of the most inaccessible and intriguing environments on the planet and potentially hold unique records of life and of changes in the Earth system.

Subglacial Lake CECs (SLCECs) lies on the ice divide between Institute Ice Stream and Rutford Ice Stream, to the West of the Ellsworth Mountains. It was discovered in 2014 and since then, ground radar and seismic surveys have mapped its surface, bed and subglacial surroundings. The overlying ice is ~2,700 m thick, the lake surface area is ~21 km² and the maximum water depth is at least 310 m.

A joint UK-Chile collaboration is preparing to drill cleanly into SLCECs in the 2021-22 Antarctic summer, to recover water samples from the lake and sediment samples from the bed. Engineers at the British Antarctic Survey (Cambridge, UK) and Centro de Estudios Científicos (Valdivia, Chile) are in the process of upgrading the deep hot-water drill used successfully on the recent BEAMISH Project. This work involves increasing its depth capability and upgrading the cleanliness and sterility of both the drilling and the subsequent sampling. We will present the design of the drill, the proposed sampling activities and a summary of the overall lake exploration programme.

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RECAS autonomous thermal sonde for subglacial lakes exploration: current status and future development

Recas Autonomous Thermal Sonde For Subglacial Lakes Exploration: Current Status And Future Development
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To date, more than 400 relatively small subglacial reservoirs and several large lakes were discovered in Antarctica. Certainly subglacial lakes exist in Greenland. In recent years, different approaches were taken to access and directly sample subglacial water environments. RECoverable Autonomous Sonde (RECAS) allows to access subglacial lake when water remains isolated from the modern ice sheet surface during sampling. The thermal drill can melt a hole to ice sheet bottom and is able to move upwards. It includes two electrically powered thermal drill bits located at both ends of the sonde, heated body, control system, sampling chamber and coiling system. All downhole RECAS components will be sterilized prior to deployment. The melted water is not recovered from the hole and refreezes behind the sonde. The power and signal line is released from the coil inside the sonde. When sampling and monitoring are complete, the coil motor is activated and the top drill bit is powered. It is proposed that the research personnel leave the site after RECAS deployment and the sonde operates as a fully autonomous system. The power is provided by no-live-operator diesel engine generators. The first laboratory tests of the sonde subsystems were carried out during 2018-2019. The test results for the RECAS thermal heads show that the rate of penetration can be as high as 1.80–1.95 m/h. Prototype tests of the whole sonde are scheduled on the spring-summer of 2020. Field tests are planned in season 2020-2021, in the vicinity of the Chinese Antarctic research Zhongshan Station.

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Observations of a deep, narrow channel incised by subglacial water at the grounding line of Kamb Ice Stream

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Large changes in Antarctica's ice flow and discharge can be attributed to dynamics in subglacial water systems. Kamb Ice Stream is a notable example, having slowed from 500m/a to less than 10 m/a due to changes in basal water. The thickening of this ice stream now contributes significantly to the mass balance of West Antarctica. While subglacial water and basal friction are important boundary conditions for ice flow modelling, models describing the Kamb Ice stream rely on poorly constrained estimates of subglacial water. To better estimate subglacial water flux at the foot of the Kamb Ice Stream, in December 2019, we used ground based low frequency radar, phase sensitive radar (ApRES) and satelite positioning to survey a subglacial channel. The channel is likely carved by a buoyant plume of fresh water, which melts into the base of the Ross ice shelf. The narrow channel starts abruptly at the grounding zone where it incises as deep as one third of ice thickness. Results from the survey will be used to model a meltwater channel to better estimate subglacial water flux. This location is scheduled for direct access: in the 2020/21 season a borehole drilled through the ice shelf will allow a suite of observations and the installation of a permanent mooring.

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