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A method for successful collection of multicores and gravity cores from Antarctic subglacial lakes

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Abstract

During the 2018–2019 Antarctic field season, the Subglacial Antarctic Lakes Scientific Access project team cleanly accessed Mercer Subglacial Lake, West Antarctica, to sample water and sediments beneath 1087 m of overlying ice. A multicorer was successful in sampling the sediment–water interface, with 4 deployments retrieving 10 cores between 0.3 and 0.4 m in length. Gravity coring was also successful, retrieving cores of 0.97 and 1.78 m in glacial diamict. However, sediment cores retrieved by the gravity cores were shorter than the core barrel penetration (as measured by mud streaks on the outside of the coring system), indicating that the system can likely be improved. This manuscript describes the design, implementation, successes, and lessons learned while coring sediments in a subglacial lake.

Subglacial lakes, 675 in Antarctica and 98 in Greenland, Canada, Iceland, and elsewhere, are one of the most underexplored environments on Earth, despite being important repositories for sedimentary records of ice sheet history (Siegfried et al., 2023) and sites with active microbial ecosystems (Wright and Siegert 2012; Christner et al. 2014; Siegert et al. 2016; Livingstone et al. 2022). Since the first detection of an Antarctic subglacial lake (Robin et al. 1970), the majority of these lakes have been identified with radio echo sounding (Siegert et al. 2016) and more recently satellite altimetry (Fricker et al. 2007; Smith et al. 2009; Fricker et al. 2016). Direct measurement of water and sediment from subglacial lake environments is important for understanding how glaciers will respond to anthropogenic warming, defining subglacial microbial habitats, constraining subglacial carbon cycling, and elucidating ice dynamics (Priscu et al. 2008). Subglacial lakes can form in geologic basins beneath the ice (e.g., Lake Vostok; Robin et al. 1977; Kapitsa et al. 1996) or as a result of water ponding due to the hydraulic gradient governed by overlying ice thickness and basal topography (e.g., Institute

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Author Contribution Statement: Co-lead authors B.E.R. and A.B.M. worked equally in conceptualization, preparation, and editing of the manuscript and figures. J.B. and A.G. devised plans for the gravity corer and tested it in a limited capacity prior to deployment. A.L., B.E.R., D.H., J.E.D., D.D, and M.L.S. sat on a planning subcommittee that interacted with J.B. and A.G. during the design phase. D.D. conceived the prototype deck rigging and described it in this manuscript. R.A.V., T.D.C., M.P., J.E.D., and M.T. served as team members making modifications and decisions regarding coring in the field and provided important edits to the manuscript prior to submission. T.D.C., M.P., M.R.S., A.B.M., D.D., B.C.C. and B.R. drafted key figures for this manuscript. J.E.D., A.B.M., M.L.S., and J.C.P. modified the UWITEC multicorer for deployment in this project. B.C.C. provided photos for the figure depicting multicoring. J.C.P. was the chief scientist of the project and the SALSA Science Team ensured success of deployment through contributions to other crucial aspects of the project.

Brad E. Rosenheim and Alexander B. Michaud are co-lead authors.

E2; Siegert et al. 2014). Sediments deposited in subglacial lakes have the potential to record depositional history, dependent on the mode of sediment transport and deposition as well as any erosional processes, including those driven by changes in overlying ice thickness or by water flow into or out of the water cavity (Bentley et al. 2011). Thus, sampling the sedimentary records from subglacial lakes can provide historical context for these processes.

Accessing subglacial environments is logistically difficult, with additional complexity introduced by implementing environmentally clean access protocols to protect and preserve microbial ecosystems present in the lakes (Priscu et al. 2013; Hodgson et al. 2016; Michaud et al. 2020), as recommended by the Scientific Committee on Antarctic Research Code of Conduct for the Exploration and Research of Subglacial Aquatic Environments (Doran and Vincent 2011; Vincent et al. 2011). Some of the first efforts to directly sample subglacial environments under the Siple coast outlet glaciers (Up-B [Whillans Ice Stream, Fig. 1], Up-A [Mercer Ice Stream, Fig. 1], and Up-C [Kamb Ice Stream], including under interstream ridges and Siple Dome) were successful in collecting sediments from piston cores (Kamb 2001), but did not incorporate clean access technology into their hot water drilling. The Siple Coast campaign collected several sediment cores (up to 3.1 m) for measurement of geophysical (Kamb 2001), sedimentological (Tulaczyk et al. 1998), micropaleontological (Scherer et al. 1998), and biological (Lanoil et al. 2009) properties. More recently, Whillans Subglacial Lake (Priscu et al. 2013; Tulaczyk et al. 2014; Vick-Majors et al. 2016) and the Whillans grounding zone (Michaud et al. 2020; Vick-Majors et al. 2020) were accessed cleanly. Sediment cores were collected from the Whillans Grounding Zone (Coenen et al. 2020; Venturelli et al. 2020) and Whillans Subglacial Lake (Hodson et al. 2016). Hodgson Lake on Alexander Island also has been accessed and sampled including retrieval of a 3.8 m sediment core; this former subglacial lake currently lies below permanent lake ice cover after emerging from a maximum of 465 m of glacial ice cover through Holocene (Hodgson et al. 2016). Ultimately, the tools designed for coring subglacial lakes must overcome a number of challenges to retrieve cored material of more than a few tens of cm in length (Hodgson et al. 2016). These challenges include subfreezing

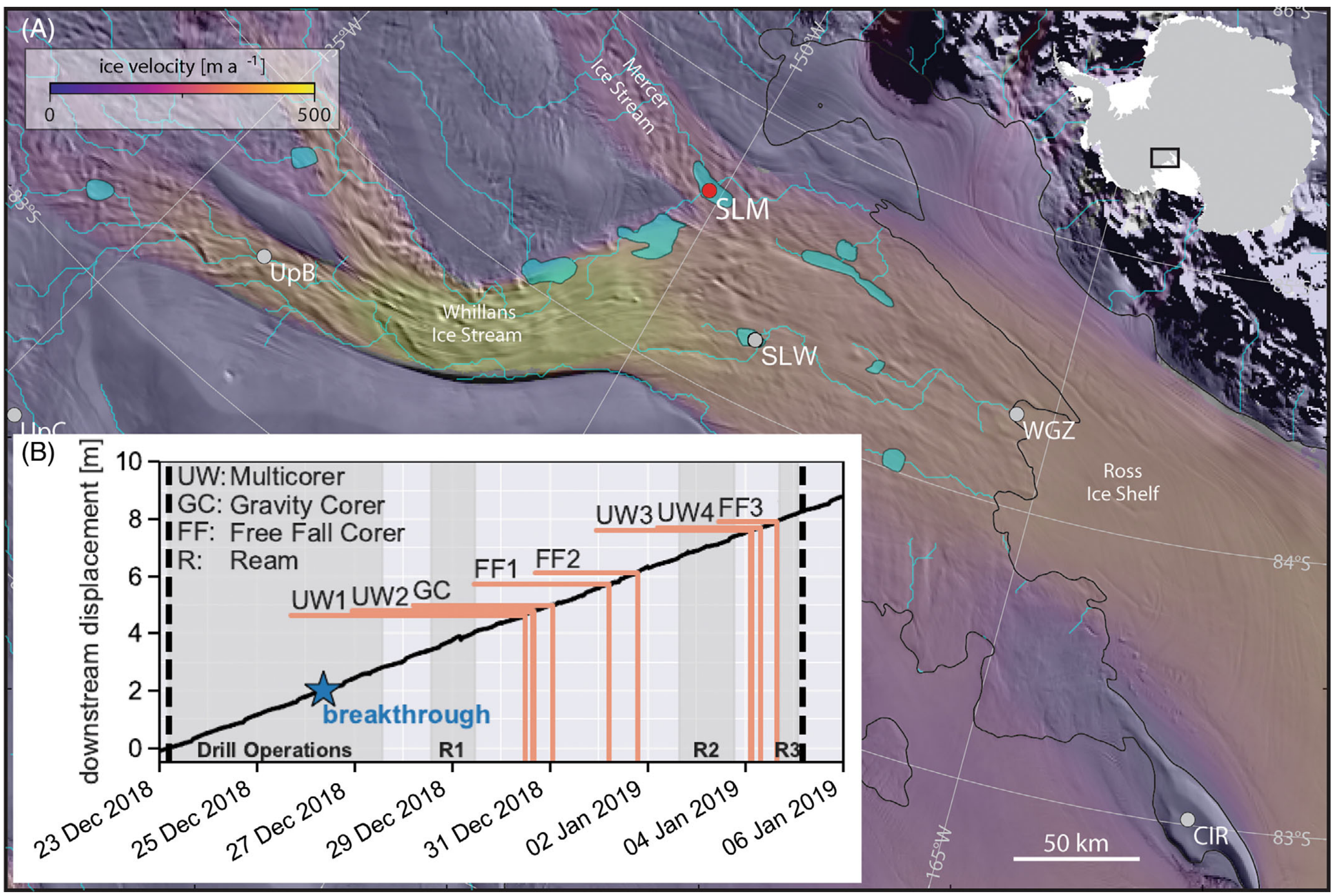

Fig. 1. Location of SLM relative to grounding line of the Ross Ice Shelf and other areas of interest or previous sampling in the Siple Coast region of Antarctica (CIR, Crary Ice Rise; SLW, Whillans Subglacial Lake; UpB, Whillans Icestream; WGZ, Whillans Grounding Zone). Inset shows borehole timeline diagram modified from Priscu et al. (2021).

temperatures through the air-filled borehole, hot water-drilled borehole freeze-back limiting the deployment window, remote locations with limited repair opportunity, the need for clean access to subglacial environments, and dense subglacial sediment that is difficult to core. Furthermore, the limited time to work in boreholes before complete freeze-back has pushed research groups to incorporate multifunctionality into sediment coring devices backed up with simple gravity corers to mitigate against failure (Hodgson et al. 2016).

Simpler designs in past expeditions (Hodgson et al. 2016) guided our approach to sample both the sediment–water interface and the deeper sediments of Mercer Subglacial Lake (SLM; Fig. 1), located beneath Mercer Ice Stream, West Antarctica. Overall, the SLM site was located and established in the 2017–2018 austral summer, after which the first traverse of equipment and laboratory containers were overwintered on snow berms. Fuel and additional materials were traversed to the site in the austral summer of 2018–2019, and laboratory, work, and life support spaces were placed around the site of the borehole (Fig. 2). The drill team arrived at camp Subglacial Antarctic Lakes Scientific Access (SALSA) on 12 December 2018, and the full science team was at the camp by 22 December 2018. However, borehole drilling with the hot water drill system commenced on 23 December 2018, after several drilling mechanical issues were solved. SLM was accessed on 26 December 2018, through a narrow opening at the bottom of the ice sheet which was subsequently reamed several times to allow instrument passage. The borehole timeline was adapted to our later-than-anticipated lake access, but still allowed for two complete cycles of instrument deployment over the course of 10 d (Priscu et al. 2021). Ultimately, 10 cores that recovered the sediment–water interface were collected by multicoring and 2.06 m (composite) of sediment were recovered by gravity coring through the 1087 m borehole (Fig. 1; Priscu et al. 2021). The SLM sediment cores provide an unprecedented archive of sedimentary, lake, ice, and microbial processes under the Mercer Ice Stream. Here, we discuss the design of the corers, the deployment protocol, and challenges that were encountered. This is intended to provide guidance to future expeditions that aim to sample subglacial environments.

Methods: Design principles and necessary modifications

Two main tools were used to sample sediments from SLM: a modified multicore device (UWITEC GmbH) that was intended to recover the sediment–water interface and a newly designed brailer-released, free-fall, Borehole Gravity Corer (BGC) designed by technicians at the Woods Hole Oceanographic Institution to penetrate deeper into the sediment column. We describe here the modification of the multicorer and the fabrication of the BGC.

Modified UWITEC multicorer design and modification

The sediment–water interface is a microbiologically active interface in most aquatic systems as well as subglacial lakes (Michaud et al. 2017). Collecting the sediment–water interface while minimizing disturbance is imperative for characterizing and quantifying the rates and processes of microbial activity within and across this fragile boundary. Multicoring devices are simple, short, gravity-based sediment collectors that are widely used to collect intact the sediment–water interface. They typically consist of multiple core barrels mounted on a wide frame to limit bow wake (a wave preceding an object moving through a fluid, related to the size, shape, speed, and fluid viscosity). However, the limited diameter of hot water-drilled boreholes necessitates the corer to be slim in profile and to have a protected, simple release mechanism that is not

Fig. 2. Aerial photograph of the SALSA field camp with Transantarctic Mountains on the horizon. Berms for equipment and fuel bladder storage as well as most of the length of the aircraft skiway are not shown in this field of view. Photo credit: Billy Collins

prone to freezing. A slim profile was achieved by mounting three UWITEC USC 06000 corers onto a central tube, with three protective fins that allowed the corer to contact the walls of the borehole without triggering the core catcher release mechanism. These fins also aided a straight descent within the 15 m subglacial lake water column and vertical entry into the sediments. The core barrels (no liner) were 63.5 mm outside diameter (OD), 59.5 mm inside diameter (ID), and 60 cm long, based upon the UWITEK multicorer employed in Subglacial Lake Whillans (Tulaczyk et al. 2014). The other modification from the standard corers was the substitution of a smooth ball-catcher release bar (Fig. 3A) rather than a threaded rod, which was prone to ice accumulation and difficult to thaw. Overall, the UWITEC multicorer shipped weight was 150 kg, including all core barrels, stoppers, extra weights, and spare parts. In the configuration used for this project, it could be moved and positioned by 2–3 people, but deployment of the corer required a winch.

BGC design and modification

The goal of the gravity corer design was to penetrate deep into the sediment column, using a heavily weighted bomb (in sediment coring, a heavy hydrodynamic weight assembly designed to maximize momentum and to true the direction of a corer) at the top of the core barrel to allow the corer to descend from several meters above the sediment/water interface. Of primary concern was geometry of the borehole and of the lake cavity. Given the likelihood of stiff subglacial sediment (Kamb 2001), the length of the corer needed to be less than the water column depth so that it could be returned to its vertical position within the subglacial cavity if it fell over due to poor penetration. However, estimates of the lake depth were variable based on satellite estimates of ice surface heave (10–20 m estimated during planning stages of this project), limiting the extent to which we could plan the overall length of the coring system. In addition, the planned 0.6 m diameter borehole (it was 0.4 m at the smallest point; Priscu et al. 2021), placed a primary limitation on the diameter of the bomb. We used Teflon®-coated core barrels (wall thickness 0.01 m, accepting threaded sections of custom extruded polyvinyl chloride (PVC) pipe core liners with inner diameter of 0.11 m and outer diameter of 0.12 m) from the long coring system of the decommissioned R/V Knorr (Curry et al. 2008) and designed a new modular weighted bomb system that also housed the brailer release mechanism (Fig. 4). The brailer release mechanism (item number HMI-BRREL, "Release Gillnet Brailer SS," from Seattle Marine and Fishing Supply Company) was designed to carry the corer and release it when at the end of a series of events (impact to cutter, severance of trigger weight, translation of trigger weight acceleration to upward release of brailer basket mechanism; Fig. 4). Once triggered, the brailer released the corer and unfurled a predefined amount of rope which directly connected the corer to the brailer and indirectly connected the entire corer to the winch line after release. The bomb housing could accommodate up to four 84.1 kg

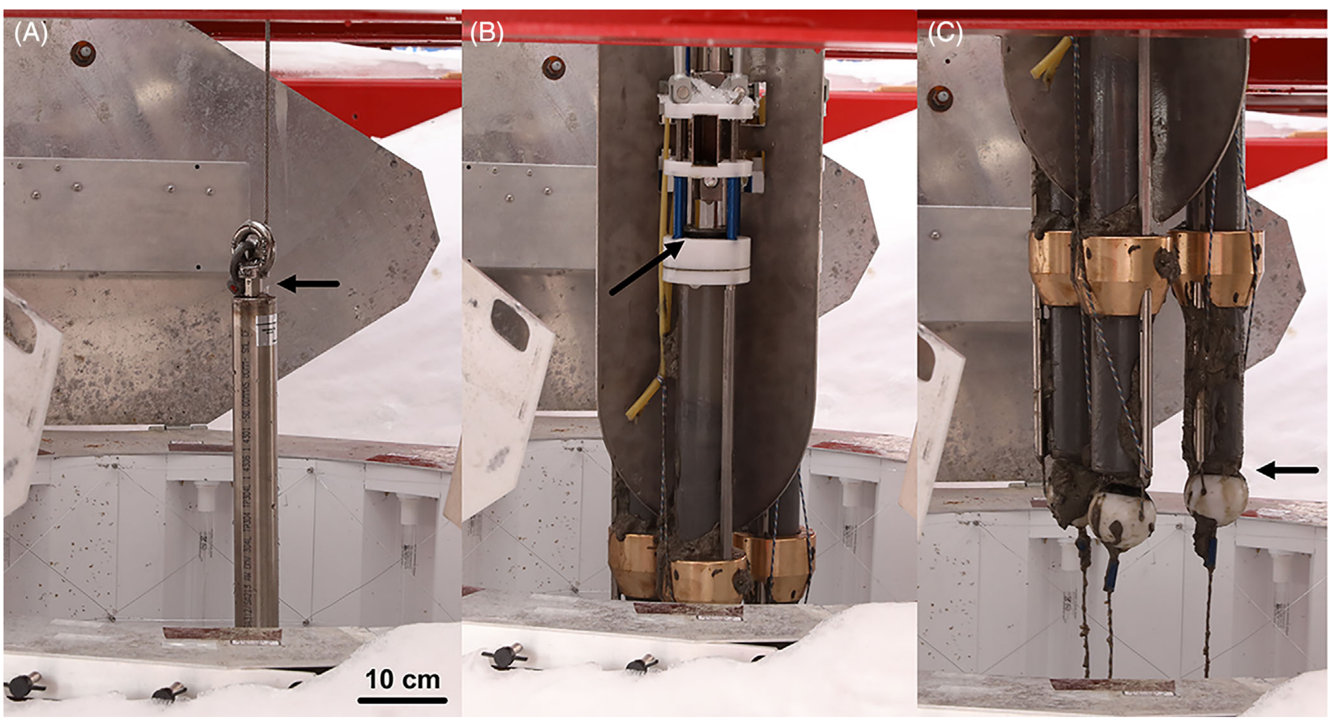

Fig. 3. Multicorer upon retrieval from SLM, showing the top of the multicorer connected to the wire termination with smooth release bar (arrow) (**A**), the middle section of the multicorer with one-way valves (arrow) and mechanism locking in core liners (**B**), and bottom showing core catcher balls (arrow) in place, but not achieving a tight fit with the core liner (**C**). Photos courtesy of Brent Christner.

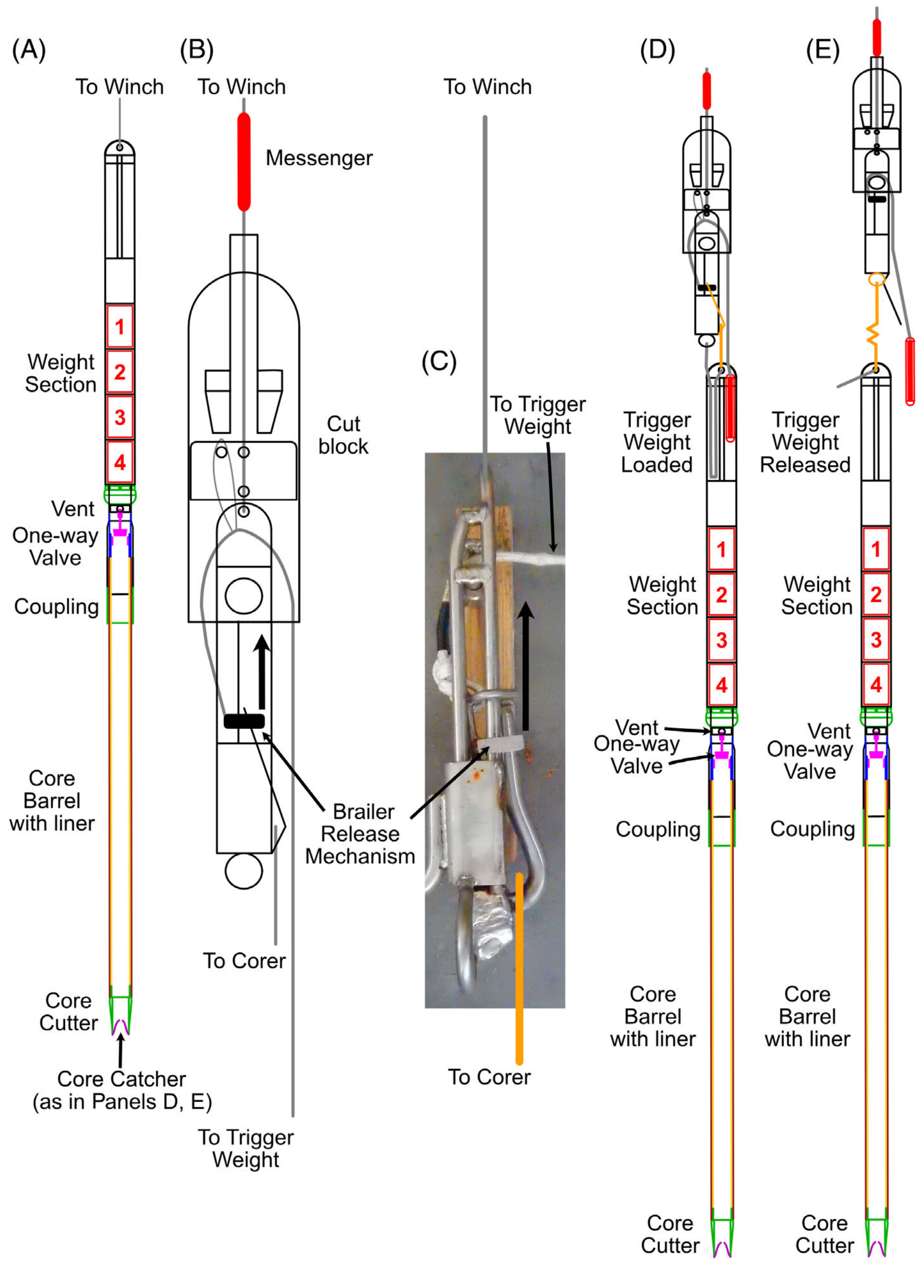

Fig. 4. Schematic drawing of BGC used at SLM during the Subglacial Antarctic Lakes Scientific Access project. (**A**) Full view of the coring assembly. From top to bottom, the drawing displays the core head with four individual, modular weights arranged vertically to allow deployment and retrieval through a nominally 0.6 m borehole. Below the weights there is an axial exit slot and four radial exhaust holes with a one-way plunger valve to release water during corer penetration. Above the weights is space for the brailer release assembly for operation in free fall coring mode. The corehead was joined to the core barrel with a coupling, and the core barrel was lined with a PVC liner and terminated with a core cutter. (**B**) Close up of the brailer release assembly showing cut block and trigger weight rope. (**C**) Staged photo of brailer release with trigger weight rope poised to pull release mechanism up when trigger weight exerts downward force. (**D**) Corer rigged for freefall coring during deployment, prior to messenger-triggered brailer release of entire load. (**E**) Corer in free fall mode after release of the brailer triggered by messenger. In (D) and (E), orange lines between the brailer mechanism housing and the corer depict which ropes are supporting the weight of the corer during transfer of the load in free fall.

modular weights. The BGC system was designed to deploy both as a gravity corer whose maximum deployment speed was regulated by the maximum pay-out speed of the deployment winch, or as a free fall corer obtaining higher velocities depending on the height of the free fall above the sediment/water interface. Free fall capability was made possible by an optional brailer release mechanism, triggered by a 16-kg stainless steel Go-Devil hydrodynamic messenger (a mass, normally cylindrical, that can be secured around a wire or rope suspending aquatic sampling equipment and dropped from the working platform to depth, either to activate a sampling mechanism or initiate a process deep beneath the water surface; Fig. 4). The total weight deployable in either gravity core or free fall core mode was 594 kg (5821 N surface weight), including a full 4.57 m of core barrels (one 1.52 m section and one 3.05 m section) and the associated PVC core liner lengths. The total weight of the short configuration (one 1.52 m section of core barrel and associated core liner) was 402 kg (3940 N surface weight). The equipment was shipped as freight to McMurdo Station in 2018 and traversed over ice to the SALSA field camp. The total mass including the shipping crate, tools, and spare parts was approximately 1180 kg. Thus, both the shipping weight and the deployment weight require heavy machinery, including a suitably powerful winch to pull the corer out of the mud, for deployment and retrieval.

The BGC was designed with standard piston corer cutter noses attached to the core barrel with four set screws (Fig. 4). The screws were lubricated with food-grade antiseize compound (Loctite LB 8014™, Manufacturer's Model Number: 1167237) and covered with residue-free gaffer's tape (Uline, S-21257BL) to prevent contact with the lake or borehole water. The bottom of the core liner could be fitted with an assortment of counter-fingered 316 stainless steel shim stock core catchers with different thicknesses to be matched against the stiffness of the sediment. The system contained a rubber stopper valve allowing exhaust of water through the central cavity of the modular weights in the bomb during corer transit through the water column and sediment penetration. The four radial exhaust holes were drilled at 0.05 m diameter above the 0.105 m exit slot. A plunger valve designed to block both the exit slot and the radial exhaust holes during retrieval had enough clearance to open approximately 0.13 m along the axis of the bomb housing as the corer penetrated sediment.

By designing the BGC with incorporation of a brailer-release free fall mode, we assumed that free fall speeds would be greater than maximum winch speeds. However, the release mechanism was tested extensively in air (never submerged) prior to shipment to Antarctica. The coring operations employed a McArtney MASH 4K winch, spooled with nominal 8 mm (5/16 in.) diameter Plasma™ 12 strand synthetic rope. At full spool, this winch system could pay out 60 m of rope per minute; spooled for our project with 1500 m of Plasma™, it paid out approximately 50 m per minute after 1000 m of rope had been deployed. The velocity obtained in free-fall mode is a function of the length of the freefall, the viscosity of the water in the subglacial lake, the mass of the corer, and the cross-sectional area of the corer (drag), with terminal velocity realized when drag is equal to gravitational acceleration. In assuming that freefall velocity would surpass maximum winch pay-out velocity, we were confronted with the operational question of how much distance we needed to allow the corer to freely fall to surpass maximum winch payout velocity. Conservatively, we can estimate the time and free-fall distance required to surpass the maximum winch payout speed by estimating the balance of gravity (F_g) and drag (F_d) on the falling corer. With the product of mass and acceleration, $ma = m\frac{dv}{dt} = F_g - F_d$, one can write:

$$m\frac{dv}{dt} = mg - 0.5c_d\rho v^2 A \qquad (1)$$

where m is the mass of the corer, v is velocity, t is time, g is gravitational acceleration, c_d is the drag coefficient, ρ is the fluid density, and A is the cross-sectional area. When $v(t=0)=0$, the solution of Eq. 1 is

$$v(t) = \tan h\left(t\frac{q}{2m}\right)\frac{q}{Ac_d\rho} \qquad (2)$$

where

$$q = \sqrt{2Ac_d\rho mg} \qquad (3)$$

Equation 2 provides estimates of the time it takes for the free-falling corer to surpass the velocity of the maximum payout rate of the winch. Using various drag coefficients, ranging from a short cylinder (1.15) to a long cylinder (0.85) and other profiles in between (Hoerner 1965), the maximum time of freefall to overcome the maximum winch pay out rate is approximately 0.06 s after release. Integrating Eq. 3 with respect to time provides the distance above the lakebed to release the corer and to gain enough velocity to surpass the maximum winch payout rate. These distances are practically indistinguishable from one another no matter the drag coefficient used, showing that the freefall needed to only be on the magnitude of centimeters to overcome the winch payout velocity.

Given the eventual measured depth of the lake (15 m; Priscu et al. 2021), calculation of the distance to overcome the winch payout velocity allowed deployment of the free fall corer within the water column, eliminating the risk of allowing the corer to freefall through a tight borehole and the potential for nonvertical orientation during acceleration which would make retrieval difficult, if not impossible. We also had to avoid the potential to shock load the coring system if freefall was initiated too far above the sediment surface. Thus, we decided that a freefall distance of 6–7 m (Table 1), far more than our calculations in the field (which were more rudimentary and conservative than those above) and well within the limits imposed by the depth of the lake, would be more than adequate for producing free-fall velocities higher than winch speeds capable of striking the stiff, dense glacial diamict.

Results: Field operations

Predeployment cleaning

Direct sampling of subglacial lake environments requires drilling and coring equipment to be sanitized before and after deployment to maintain sample integrity and environmental

Table 1. Deployment and retrieval data for the borehole gravity core.

Date	Rigging start time	Rigging and identifier	Core barrel length (m)	Coring start time	Free fall height (m)	Predeployment deck level weight (kg)	Pull-out tension (kg)	Weight at pull-out (kg)	Weight at retrieval (kg)	Exterior mudline (cm – approx.)	Core length (cm)	Core
31 Dec 2018	07:15	GC (01GC)	3	13:32	N/A	499*	998	635	0	200	0	SLM18-01 01GC
01 Jan 2019	15:35	FF (01FF)	3	16:15	7	431	1111	658	549	300	97	SLM18-01 01FF
02 Jan 2019	05:30†	FF (02FF)	3	06:30	7	431	1247	657	549	320	178	SLM18-01 02FF
05 Jan 2019	01:00	FF (03FF)	4.6	03:25	6	522	1215	Not recorded	Not recorded	150	0	N/A

*Weight registered on load cell prior to full speed payout at bottom of borehole; all other weights were measured at deck height.
†No rerigging necessary due to consecutive deployments of the gravity corer.

stewardship (National Research Council 2007; Vincent et al. 2011; Michaud et al. 2020). Sanitization poses challenges because persistent cold temperatures on the working deck can freeze the chemicals used to clean the instruments. A warm laboratory container was therefore required to clean some instruments between deployments. The multicorer was assembled and prepared in a dedicated clean sediment laboratory (Venturelli et al., 2021). The multicorer was cleaned with 3% hydrogen peroxide in two stages. First, the rubber flapper valves and core catcher ropes were cleaned individually while the multicore device was in the warm sediment laboratory, then dried and wrapped in plastic to preserve their cleanliness. Second, the rest of the corer was sprayed with 3% hydrogen peroxide outside on the working deck immediately before deployment and as it was transferred from the sediment laboratory to the borehole by crane. The plastic covers on the critical corer components were removed and checked for proper operation (in particular, any ice formed from spraying with 3% hydrogen peroxide was broken), then the multicore device was deployed.

The BGC was too large to store in the laboratory. To clean it before deployment, it was suspended vertically by a Fassi Model F385 crane within a ~ 10 m deployment preparation hole. It was then decontaminated by spraying with 3% hydrogen peroxide as it was gradually lifted from the deployment preparation hole. The core liners were treated with 3% hydrogen peroxide before insertion in the core barrels to ensure that all surfaces that contacted the lake waters were cleaned. Similarly, modular weights, pendant rope for freefall, the throw bag containing the pendant rope, and the drop weight that pulled the brailer release (Fig. 4) were treated with hydrogen peroxide. Because the BGC was kept outside of the laboratory and on the raised working deck, peroxide treatment resulted in considerable freezing. Proper release of the brailer in free fall mode when testing in the adjacent deployment preparation hole was not hindered by moderate ice formation on its moving parts.

In addition to cleaning equipment, we aimed to prevent any loss of equipment or parts of equipment in the lake. Using a high-mass hydrodynamic messenger designed to impact a cutting block with enough force to shear a line suspending a 6 kg trigger weight for the release of the brailer meant that there were opportunities for line and hardware debris to enter the water column. In the field, with the weighted corehead of the BGC held vertically within the deployment preparation hole, we tested the brailer release several times. Allowing the 17.8 kg Go-Devil messenger to impact the modified hole punch (McMaster Carr 3427A46, 3″ diameter) directly resulted in a bent punch neck. Subsequent attempts to release the brailer incorporated a high-density plastic (Delrin) disk to serve as a dampening surface for the hole punch when contacted by the GoDevil messenger. This Delrin disk was encircled several times with gaffer's tape in case it fractured. In addition, several set screws and the trigger weight rope itself were fastened with gaffer's tape to prevent material shedding into the lake. These modifications allowed successful triggering of the brailer release in the deployment preparation hole without the loss or destruction of any materials.

Deck rigging

The multicorer was deployed and retrieved using a custom-built winch and metering block assembly, all mounted on a prototype load transfer system designed to reduce the turnover time from hot water drilling operations to borehole science operations (Fig. 5). All other equipment deployed into SLM with the exceptions of the BGC and the Deep SCINI ROV (Priscu et al. 2021) used this system. Several deployments were impacted by failure of the braking system to operate when > ~ 700 m of wire had been paid out. For this reason, all multicore deployments required manual operation of a hand brake when the winch began free spooling. The metering block for this system provided consistent estimates of the depth to lake bottom through changing meteorologic conditions and intermittent icing of the sheave and rope, despite intermittent observed slipping of the wire on the sheave. Processing of conductivity-temperature-depth (CTD) data confirmed that the depth to the bottom of SLM was estimated to within several meters by this winch and metering block. Thus, because coring operations happened after initial deployment of water column measurement and sampling devices (Priscu et al. 2021), coring operations were well-informed about the depth of the borehole water column and the lake.

Different deck rigging, including a different sheave normally used on board seagoing research vessels, was required for the BGC due to the mass of the system. We used a marine sheave designed for use with synthetic rope members connected with shackles to an 8″ diameter aluminum I-beam with a 5-ton capacity beam clamp. This arrangement was able to support up to 6000 kg to accommodate potentially high pull-out tensions. The sheave used with the larger corer was designed for shipboard A-frame deployments of equipment, could swing and swivel, and was equipped with its own metering block, counting each turn of the sheave as exactly 1 m. Due to expected pull-out tensions, we used 5-ton capacity beam clamps to secure the sheave to the frame, but we also rigged the platform with come-alongs and cargo straps as safety precautions if the beam clamps failed. This took time to rig before BGC deployments, and that time was increased by slight adjustments to the sheave angle once the corer weight was transferred from the Fassi crane to the sheave. The use of Plasma rope through the sharp cover of the UV iris (Fig. 6) mandated that we position the corer under full load in the precise center of the borehole, and it was a time-intensive (3–6 h, including rigging adjustments) iterative process with several hundreds of kilograms being transferred back and forth between the crane and the winch-sheave assembly over the borehole for each deployment.

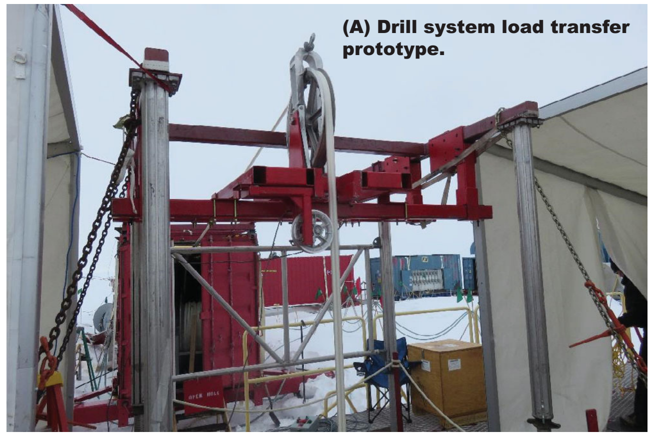

Fig. 5. Deck rigging for hot-water drilling and for scientific operations in the SLM borehole. (**A**) The prototype load transfer system was developed by the University of Nebraska hot water drill team to reduce transfer time between hot-water drilling and science operations. The system allowed the drilling mechanism to remain in place during science operations for ease of reaming (adding energy to the borehole to slow freeze-back). All scientific equipment was deployed and retrieved from this rigging using a custom-built winch and metering block assembly (the smaller sheave oriented perpendicular to the large upper one deploying hot water drilling hose in (**A**)), except the autonomous vehicle and the BGC. (**B**) For the heavier weight of the BGC, an aluminum I-beam (top) was added to the load transfer main frame. The sheave was mounted on this I-beam with a beam clamp and positioned over the center of the borehole with tension (when the sheave is at approximately 45° angle). In the photo, the BGC is at the surface of the borehole and the crane is positioned overhead for load transfer after temporarily supporting the corer on the bracket being emplaced by the two people in the foreground.

Multicore deployment and retrieval

The hazardous part of deployment of coring tools, especially the multicore tool with its sensitive release mechanism, is the transition through the borehole above the piezometric water line (101 m). Cold borehole temperatures above the piezometric water level ranging between −10°C and −25°C, can quickly freeze any cleaning fluid residues, rendering sensitive

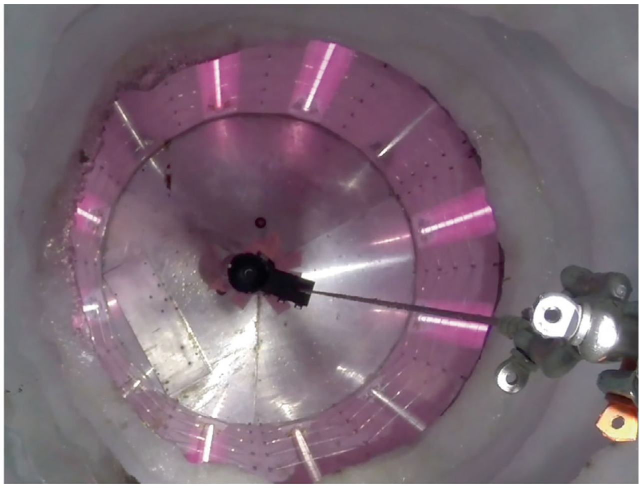

Fig. 6. UV collar and iris viewed from top 3 m of borehole, looking up. The iris was manually operated from the deck above; however, it did contain an interlock preventing the operation of the UV collar when open. The length of each UV light tube is approximately 1 m, distorted by the oblique view. The iris was made of 1.6 mm aluminum which we deemed sharp enough to cut the Plasma rope used to deploy the BGC. Thus, centering the rope in the UV collar of the rope through the iris was critical prior to deployment.

trigger mechanisms nonfunctional. In addition, the multicore tool can hit the sides of the borehole and prematurely trigger if not lowered through the air-filled borehole slowly. During the recovery phase of this tool, sediment cores can also be lost if the multicore tool strikes the borehole walls.

We deployed the multicore tool four times over two deployment windows (Fig. 1B, Table 2) as the ice was moving downstream at approximately 0.66 m day^{-1} (Priscu et al. 2021). The multicore tool did not have any added weights during the deployments. The deployments were conducted by paying out line slowly (10 m min^{-1}) through the air-filled borehole, then easing through the air–water interface, and increasing speed to 25 m min^{-1} in the water-filled borehole. The final 10–15 m before contacting the sediments, the winch payout speed was increased to the maximum speed (50 m min^{-1}). Once the load cell registered an abrupt decrease, the winch was stopped and allowed to rest briefly before slowly reversing to pull out of the sediment. A standard UWITEC ball core catcher mechanism was used at SLM, but the core catcher ropes were prone to sticking before the core catcher ball was in place (Fig. 3C). The failure of the core catcher left the one-way valve at the top of each core tube as the main mechanism keeping the core in place (Fig. 3B). After multicorer pull out, an increase in the free hanging load indicated that the multicore tool was heavier than before penetration and sediment cores were collected. The multicore tool was returned to the surface at 30 m min^{-1} through the water-filled borehole. As in deployment, we significantly reduced the retrieval speed at approximately 105 m depth as the tool approached the air-water interface, slowing to $\sim$ 2 m min^{-1} as the tool moved through the air-water interface and to about 10 m min^{-1} through the air-filled borehole. The entire retrieval process required a smooth velocity transition for successful core recovery.

Once back at the surface, the primary goal was to place rubber stoppers into the bottom of the core barrels without bumping the multicore tool. We performed this step by slowly and steadily raising the multicore tool until the bottom of the core barrels cleared the working deck platform, then quickly secured the rubber stoppers into the bottom of the core barrels. Once stoppers were secure, we cleaned and thawed the multicore components to allow removal of the core barrels from the multicore tool. This cleaning and thawing process required careful use of heat guns taking care not to melt the delicate rubber gaskets at the top of the core barrels. Once the core barrels were removed from the multicorer tool, we performed a load transfer to the crane, which lifted the multicorer tool and transferred it back to the sediment laboratory for complete cleaning and preparation for redeployment (described above).

BGC deployment, coring, and retrieval

Deployment

The BGC was deployed during four separate deployment windows in the SLM borehole. The potential for this type of coring to disturb the upper sediment column and the overlying water mandated that its deployment follow the initial deployments of all other instrumentation, including the multicore (Priscu et al. 2021). Multicoring before gravity coring also provided information about the sediment composition and stiffness, allowing us to adjust our BGC deployment strategy (e.g., corer configuration, core catcher, bomb weight). The first deployment of the BGC was solely as a gravity corer, without rigging the brailer release for freefall coring. We rigged the corer with the lightest of our core catchers, 3.0 mm thickness (Table 1), because of the light, clay-rich sediment we observed in the upper layer of the multicores (Siegfried et al. 2023). The BGC was subsequently deployed three times with the brailer release rigged for freefall coring, and with thicker core catchers (4.0 mm thickness, Table 1).

All four deployments of the gravity coring system used the McArtney MASH4K winch with a marine sheave designed specifically for synthetic rope. The sheave was marked and measured exactly 1 m in circumference, providing a manual method to determine rope payout. There were metering blocks on both the winch and the sheave, however the winch payout meter was not calibrated for 8 mm line and was therefore not used. The marine sheave operated at approximately 45° from vertical when loaded, however it hung at 0° from vertical when no load was attached. This posed challenges for centering the line directly through the UV iris (Rack et al. 2014) and necessitated substantial time to prepare the rigging. For the first deployment when we rigged for gravity coring, we accelerated to maximum winch payout (48 m min^{-1})

Table 2. Deployment and retrieval data for the UWITEC multicorer.

Date	Down borehole start time	Retrieval end time	Prepenetration lake surface weight (kg)	Pull-out tension (kg)	Postpenetration lake surface weight (kg)	Core ID and length (cm)
30 Dec 2018	23:29	01:35	454	571	534	SLM18-01 01UWA (49)
						SLM18-01 01UWB (43)
						SLM18-01 01UWC (46)
31 Dec 2018	03:34	05:48	498	572	539	SLM18-01 02UWA (41)
						SLM18-01 02UWB (40.5)
						SLM18-01 02UWC (43.5)
04 Jan 2019	14:27	16:40	373	412	402	SLM18-01 03UWB (34)
						SLM18-01 03UWC (32.2)
04 Jan 2019	19:16	21:20	367	436	399	SLM18-01 04UWB (32.3)
						SLM18-01 04UWC (37.3)

approximately 10 m above the lakebed. For free fall coring, we took a more cautious approach to avoid triggering the brailer release prematurely through unexpected interaction with the lakebed. All instrumentation deployed before the gravity corer had occasionally slipped owing to ice on respective sheaves. We were confident that we knew the depth to the lakebed from previous CTD and camera deployments; however, we anticipated some uncertainty in rope payout. Releasing the brailer for free fall coring incurs two main risks:

1. not enough freefall to overcome the maximum speed of winch payout if we are too close to the lakebed; and
2. shock-loading the pendant with the full weight of the corehead and barrel assembly if we release the brailer too high above the lakebed.

Thus, we deployed the corer relatively slowly (30 m min^{-1} for the first 1000 m, then 10 m min^{-1} until the metering block registered 1050 m, and finally 5 m min^{-1} until a decrease was observed on the load cell). At this point, we knew from slow contact that we had located the lakebed, and we raised the corer up by the number of meters we planned to free fall (Table 1). There is risk assumed by allowing the corer to touch the bottom if the core catcher and cutter nose core into the sediment–water interface. However, we had already sampled this interface prior to free-fall coring, and we interacted with the lakebed very slowly to minimize disturbance of the sediment.

Although the iris for the ultraviolet light source needed to be opened to allow the messenger to pass through during each of the freefall deployments, pay-out of line and equipment was exposed to germicidal UV light and all tools and materials entering the borehole had been decontaminated with 3% hydrogen peroxide solution—only the messenger did not receive disinfection from the UV light collar (Fig. 6). Instead, the messenger was treated with 3% hydrogen peroxide and only handled with newly changed sterile gloves before release.

During the first and second deployment as a freefall corer, we used a 7 m freefall and rigged a 11.9 m long pendant with 363 kg of weight and 3 m of core barrel and liner. Our final deployment used the same amount of modular weight (363 kg); however, we fitted the system with 4.6 m of core barrel and liners. This necessitated a shorter freefall with the same pendant length (Table 1).

Deployment of the gravity corer, rigged for freefall coring and with the full length of core barrel attached, on 05 January 2019, proceeded differently. At this point, no other sampling deployments were planned, and the borehole was beginning to freeze in. During a meeting of all scientists and drill staff, it was decided that this deployment would proceed as borehole maintenance operations were discontinued. The first action was to stop the pumping of warm water to the air-water interface in the borehole, which had been done continuously to keep that interface from freezing. In addition, due to increasingly cold weather and ice buildup during the deployment and retrieval of 02FF, we heated the rope spool with a 480 V blower fan for 1.5 h before launch. Initially, we paid out 25 m min^{-1} of line through the borehole during this deployment. There was an unloading event between 99 and 102 m depth in the borehole as the load cell decreased to 0 kg and the sheave straightened. We determined that the line was still centered in the borehole, and it was thus unlikely we had contacted the sides of the borehole. By raising the corer 3 m and relowered it, we observed that less mass unloaded during than the first descent and proceeded to lower the corer down the borehole at 25 m min^{-1}. We slowed the descent rate to 5 m min^{-1} at 1050 m in the borehole and proceeded until gentle contact with the lakebed, as with previous deployments.

Coring

In gravity core configuration, penetration into the lakebed sediment was determined by a step-like decrease in tension on the load cell, from 499 to 0 kg. In freefall release configuration, we anticipated a potentially violent interaction between corer and lakebed, with the immediate unloading of the corehead and core barrel assembly resulting in a swinging sheave. For the first core configured in freefall release mode, we cleared the operations deck of non-essential personnel and prepared a 4.5-kg brass messenger with a rubber hose insert to protect the Plasma rope. After opening the iris, we dropped the messenger. Ten minutes passed without witnessing the slack on the sheave expected if the coring package detached from the brailer release to contact the lake bottom sediment. We inferred that the 4.5-kg brass messenger had not impacted with enough force to cut the trigger weight rope under the cutting block. We subsequently attached an 18 kg, 41-cm-long stainless-steel hydrodynamic messenger (Go-Devil) to the Plasma rope, opened the UV light iris, and dropped the heavier messenger. After approximately 90 s, we observed slack on the sheave, but the release of the coring package was not as forceful as anticipated—there was ultimately little reason to clear the deck of nonessential personnel. Subsequent cores in free fall release configuration employed only the Go-Devil messenger, and we quickly released approximately 5 m of rope from the winch spool upon slackening of the sheave to minimize any shock loading on the pendant (in the case that penetration plus freefall combined to a greater length then our pendant rope).

Retrieval

Pull-out tensions ranged between 998 kg (gravity core, no freefall) and 1247 kg (core 02FF, Table 1). During retrieval of the gravity core, load decreased to 0 kg on the load cell at 200 m, which had been zeroed for this deployment while suspended over the borehole. Load cell readings also decreased during retrieval of the freefall cores but registered more than the original load in all cases indicating extra material in the core barrel. In all corer deployments, the MASH2K winch was suitable for retrieval of cores in this setting. Retrieval of the coring package after freefall coring was more complicated than in gravity core configuration due to the added length of rope between the brailer release and the core package. Load transfers had to be performed with the crane extended farther than with the gravity core without brailer release, and an additional load transfer was carried out at the end of the brailer pendant.

Upon retrieval of all cores, we observed pebbly mud frozen onto the lower parts of the core barrel and mud streaks on the exterior (Table 1). For the gravity core 01GC, there was no mud in the core tube and the core catcher was inverted. By the weight measured after the pull-out spike in the load cell, we estimated approximately 2.4 m of sediment core assuming all mass was inside the core tubes. The mud streaks on the exterior of the core barrel extended up approximately 2 m, consistent with our estimate. But all sediment was lost through the inverted core catcher fingers. For the first freefall core configuration deployment (01FF), we measured mud streaks to the coupling between the core barrel and the core head (approximately 3 m). However, we observed only muddy, frozen water rather than firm sediment in the top of the core liner once the corer was decoupled from the bomb on deck. Probing with a measuring stick demonstrated that at least 1.5 m of core liner was filled with water and not sediment, less than the total barrel penetration indicated by exterior mud streaks. Retrieval of the second deployment in freefall configuration (02FF) showed mud streaks up to the exhaust valve at the top of the core head. We interpreted this to mean that corer had either penetrated more deeply into the lake sediments or that it had laid down horizontally after coring. The fact that the streaking was present on every face of the core head suggested the first scenario (overpenetration) was more likely than the second (laying the corer down). Retrieval of the third freefall core was challenging and disappointing. The sheave had to be continuously heated due to borehole water and/or ice fog constantly freezing on its surfaces. Upon visual recognition of the top of the corer in the borehole, it was apparent that the core head was full of ice and the rope of the drop weight that releases the brailer had been severed. Once the corer was pulled all the way from the borehole, it was obvious that we had cored ice that had built up at the borehole water–air interface and not mud. We noted $\sim$ 1.5 m of mud-streaking on the outside of the corer, but the core cutter nose was full of densely packed, sutured crystals of ice. The mass of ice penetrated approximately 0.6 m into the core liner, and the rest of the core liner was dry with no mud and no water. Interaction with the frozen surface of the borehole water had filled the core catcher with ice, and the ice impeded the penetration of any sediment into the corer.

To prevent disturbance to the sediment in 01FF and 02FF, an inflatable 0.1-m diameter rubber plumber's plug (a device that can be inserted into a pipe and then expanded by inflation or compression to plug the pipe temporarily) was inserted at the suspected sediment surface while vertical, and the core was laid horizontal. The core liner was removed from the barrel, and then magnetic susceptibility was measured along the core liner to locate the sediment water interface. Excess surface water was drained and two plastic-covered foam plugs (plastic-covered due to the potential of radiocarbon contamination from prior use as a foam tray in the A.P. Crary Science and Engineering Center at McMurdo Station) were inserted at the core tops. The ends of the cores were capped and taped, and the core was stored in the refrigerator. After approximately 36 h of storage, core 01FF was removed for cutting and sampling two whole rounds. Overall, 01FF was measured in the field at 0.97 m in length. The core was split into five sections, with sections 2 and 4 (0.40–0.45 and 0.80–0.85 m) used as communal sampling pucks for various field measurements without splitting the core and potentially contaminating it with ^{14}C radiolabel (Fig. 7). Core 02FF was cut into two sections, capped, taped, and stored for air transportation to McMurdo Station and the continental United States for analysis.

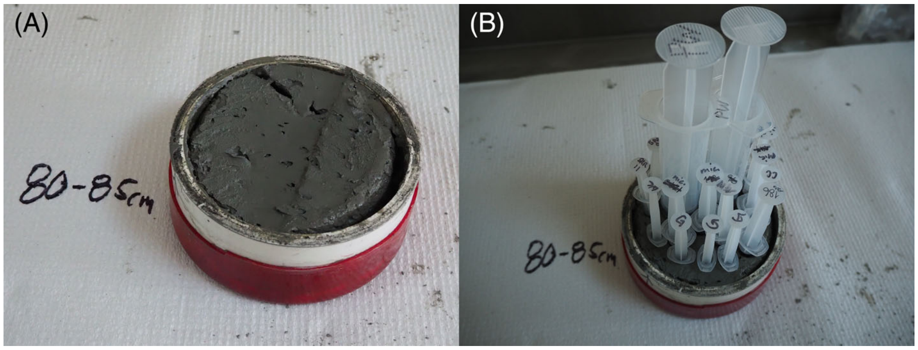

Fig. 7. Field photographs of whole round samples (pucks) cut from core SLM-18-01FF for sampling by all relevant disciplines. (**A**) Whole round samples were cut at 5 cm thicknesses from two locations in the core determined by magnetic susceptibility. (**B**) Whole rounds were capped and only placed on protective laboratory sheets prior to sampling with syringes for various analyses. All syringes were labeled for corresponding analysis (cc, cell counts; G, dissolved gases; mic, microbiology; PW, porewater; SRR, sulfate reduction rates). This sampling method allowed the science team to avoid splitting and opening the cores in the field where elevated ^{14}C radiolabels were being used for biological uptake experiments (Priscu et al. 2021; Venturelli et al. 2021).

Sampling, field analysis, and curation of sediment cores

Overall, the SALSA Science Team succeeded in collecting 10 multicores (Table 2) and 2 freefall cores from a unique and difficult-to-access environment. Of these cores, the longest freefall core collected (1.78 m measured in the field) constitutes the longest sediment core retrieved during clean access of a subglacial lake (Hodson et al. 2016), and is of comparable length to previous gravity and piston cores from the Siple Coast (Kamb 2001) and from beneath the Ross Ice Shelf (Clough and Hansen 1979; Webb 1979). In the field, a subset of pre-drilled multicores was used for porewater extraction and subsampled, whereas others were prepared for shipment directly to the Antarctic Core Collection of the Oregon State University Marine and Geology Repository (OSU-MGR) due to our protocol to avoid radiocarbon contamination of the sediment cores in a remote field camp where some experiments involved elevated levels of ^{14}C (Venturelli et al. 2021). In the field, magnetic susceptibility was measured on all multicores using a Bartington MS3 magnetic susceptibility meter and an 80-mm diameter loop situated to introduce the cores vertically. Magnetic susceptibility was measured on all gravity core sections using a Bartington MS3 magnetic susceptibility meter and a 162-mm diameter loop prior to any discrete core sampling. As described previously, for the benefit of the transdisciplinary goals of the SALSA project, the first gravity core (SLM18-01 01FF, 0.97 m) was cut into five sections, two of which were 5 cm whole rounds ("pucks") that were subsequently subsampled in full while in the field (Fig. 7). These remaining core sections (1, 3, and 5) were capped and sealed for transport to the OSU-MGR Antarctic Core Collection. Puck locations were determined based on the magnetic susceptibility profiles, avoiding depths with distinct changes in susceptibility. We avoided splitting any of the archived cores due to the presence of ^{14}C radiolabel in camp SALSA (chemistry laboratory) and the small chance that sediment could be contaminated (Venturelli et al. 2021). The second gravity core (SLM18-01 02FF, 1.78 m) was capped and wrapped for shipment to the OSU-MGR Antarctic Core Collection without any whole rounds sampled in the field.

The multicores contained fine sediment with a downcore change in density of the sediment that was observed primarily through the insertion of Rhizon samplers (Seeberg-Everfeldt et al. 2005); the tops of these cores were substantially softer and more manageable than the bottoms. However, this contact was only visible in the field measurements of magnetic susceptibility (Fig. 8). The sediment properties of gravity cores from the more consolidated Siple Coast diamict have been interpreted as an atypical deformational till (Kamb 2001; Tulaczyk et al. 1998). This till is known to be without visible structure and includes the large pebble-sized grains up to, and probably beyond, the diameter of the corers that have sampled it (Kamb 2001). Beneath Mercer Subglacial Lake, we corroborated these earlier observations of the diamict based primarily on the material caught in and damaging the gravity cores cutter noses (Fig. 9). Our two successful free fall BGCs, as well as our unsuccessful BGC and our ice-filled free fall BGC, showed extensive damage to the cutter noses. In the field, magnetic susceptibility data appeared noisy most likely due to clasts which we observed on the lakebed with borehole video.

Discussion

Opportunities to access subglacial environments are rare. It is therefore imperative to describe both successes and challenges we encountered during our coring operations at SLM. Ultimately, the most concise summary of our coring operations success is the retrieval of 2.06 m (composite) of core including 10 cores capturing the sediment–water interface in SLM. Our success depended on the proper function of equipment that had not been field-tested in a borehole

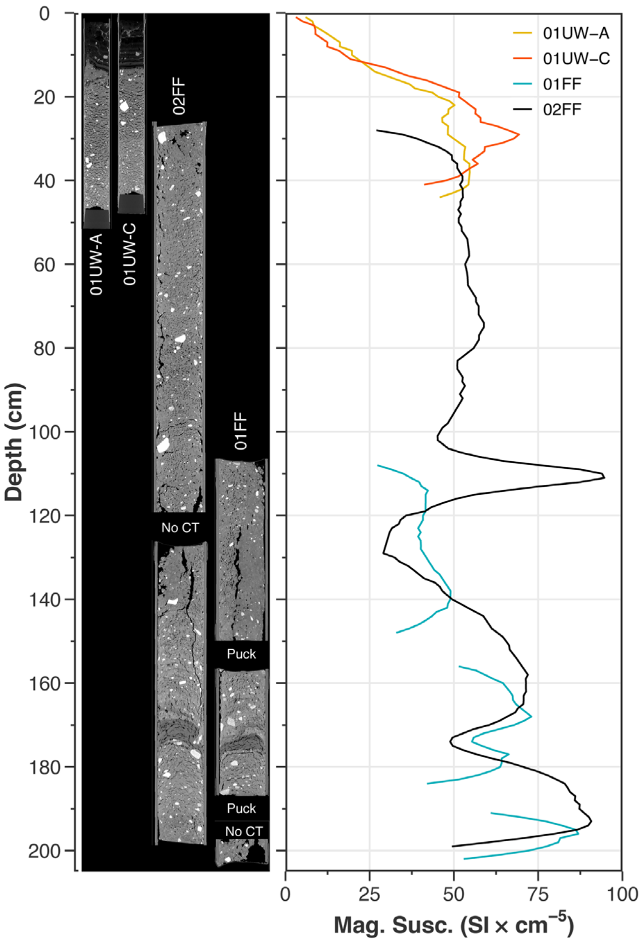

Fig. 8. Computer tomography (CT) scans (left) and magnetic susceptibility trends (right) for all cores taken from SLM using the modified UWITEC multicorer and the BGC. Magnetic susceptibility as well as core properties observed were used to provisionally correlate the cores, resulting in 2.06 m of composite core length (continuous) sampled from SLM.

environment, as well as the presence and maintenance of the borehole by our drill team. The roots of our success obviously precede deployment in relatively benign field conditions for Antarctica; published information available about previous expeditions (Hodgson et al. 2016; Hodson et al. 2016) was invaluable. We took advantage of previous observations that pistons were not needed to minimize sediment deformation of subglacial tills along the Siple Coast (Tulaczyk et al. 1998), and we were budget-limited enough to avoid costly, complex, but sometimes disadvantageous, multifunctionality in the design of the gravity corer. As such, it is important to summarize our challenges more completely for future expeditions.

Coupled with the UWITEC multicore apparatus that succeeded in previous applications in similar environments, we feel that brailer-released freefall gravity coring is a valuable, relatively simple method that can be used to acquire longer sediment cores. Although our longest core was 1.78 m (Table 1), we anticipate that this coring rig can penetrate up to 3 m in similar substrates. Our observations of mud streaks on the exterior of the core barrel were always longer than the amount of sediment cored (Table 1). This meant that the denser sediments revealed in the magnetic susceptibility data (Fig. 7) formed a plug in the core cutter that was pushed through the underlying diamict. Such a plugging effect may be a result of the density and stiffness of the sediment. However, another variable which may have contributed to this (and that we can control) is the amount of water exhaust from the top of the corer. Exhaust of water during coring with our BGC was accomplished by a spring-loaded plunger and four 0.0254 m diameter holes at the junction between the core head and the core barrel. Before our 4th deployment (Table 1), we decided to test this hypothesis hoping to obtain a longer core. We removed material from the exhaust valve plug to increase the volume through which water could exhaust from the system. We optimistically added 1.5 m to the core barrel, for 4.6 m total length and more total weight. However, that deployment failed due to ice formation at the air–water interface in the borehole and we were ultimately unable to test the hypothesis directly. The presence of ice in the core catcher certainly prevented sediment from entering the core barrel despite the extra weight. To achieve longer cores in conjunction with recovering the sediment water interface, a larger and more efficient water exhaust system with a diameter equal to the internal diameter of the core liner will need to be incorporated to rule out venting limitations as a cause of coring less than the penetration depth as indicated by the observed mudlines (Table 1). Of course, given the large clasts riddling the subglacial till, some serendipity would be in order, as well, to core to 3 m or deeper using this technology in this setting.

As in most Antarctic field science operations, cold temperatures, and ice formation present challenges. On two occasions during our coring operations, we were challenged by ice, one of which ended in success and the other in failure. During our second freefall core deployment (02FF), much colder conditions (−10°C) prevailed. The corer was lowered through the borehole at 25 m min^{-1} and it was noted that the winch was shaking rhythmically and noisily during payout. We noticed that the metering block registered 0 m min^{-1} of payout on several occasions, even when the rope was visibly paying out. Finally, we noticed that, at a reading of 800 m of payout from the metering block, the sheave had developed an asymmetric casing of ice. The rope had been intermittently slipping over the sheave without turning it, and we determined that there was likely more rope paid out than what the metering block measured. Both the slippage and the increased radius of the sheave (from ice coverage) contributed uncertainty to our corer's depth in the borehole and lake. The challenge of this deployment was overcome by our cautious approach with winch speed approaching the lakebed and our effort to lightly touch the lakebed.

Our static frame that supported the sheave posed several problems for both the multicorer and BGC. The multicorer

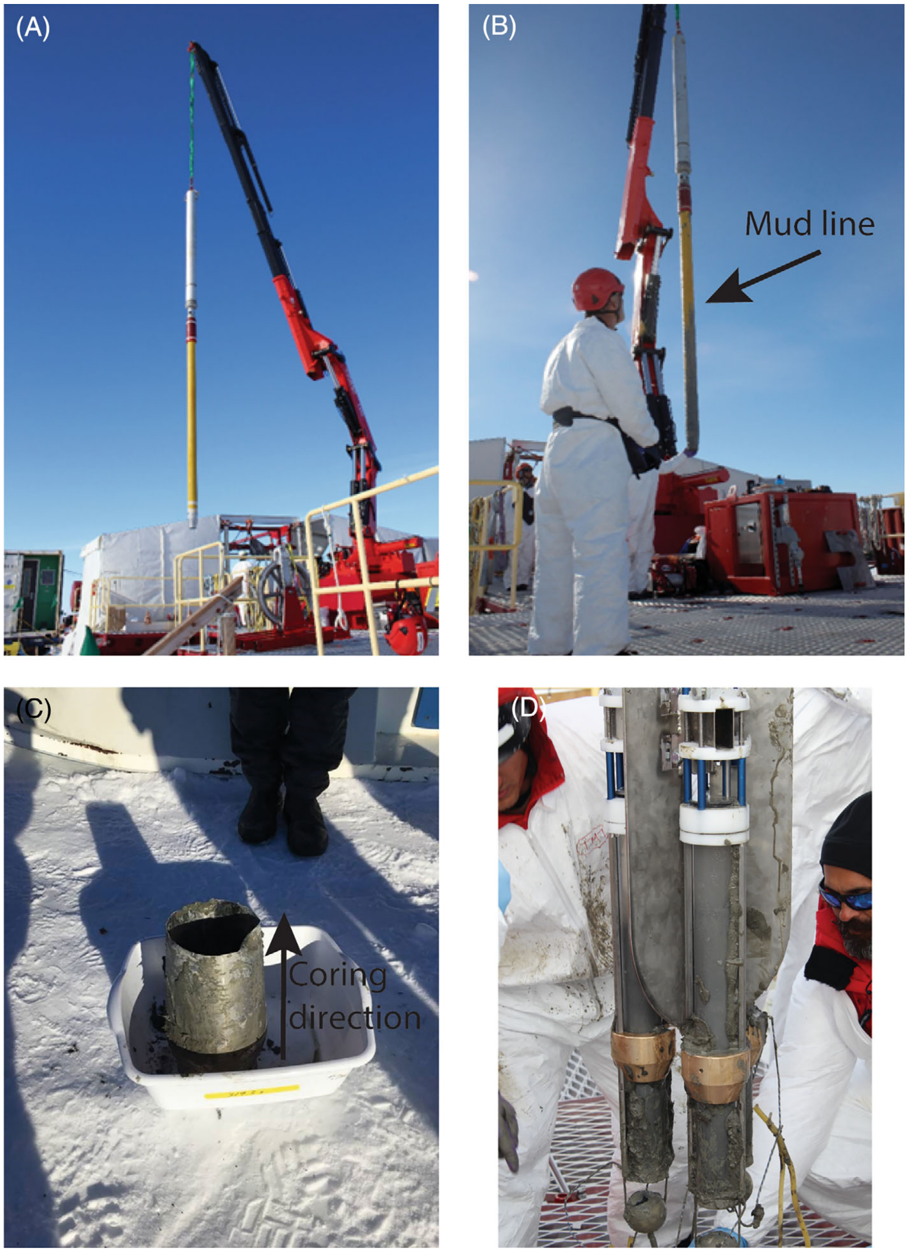

Fig. 9. Deployment (**A**) and retrieval (**B**) of the 01 and 02 January free-fall corers, respectively. We observed mudlines that were higher on the outside of the core barrel than the sediment filling the coring barrel. Damage to the core cutter (**C**) during the 31 December gravity core suggested large cobbles and stiff fabric of the sediment underlying the less dense surficial sediment sampled with the multicorer (**D**).

barely cleared the working deck level, making it difficult to place rubber stoppers in the bottom of the core liners to save cores from falling out of the bottom. Second, the long rigging times for the larger BGC was due to the tight spaces created by the static frame. We suggest that deck operations incorporate a tall, A-frame supported sheave, like on the aft deck of research vessels. This would allow corers to be pulled out of the borehole before load transfer occurs. A sheave on a larger A-frame can be used for drilling as well as wire and rope deployments to center equipment on the borehole every time. This would save time between deployments and result in more samples being collected. During our fourth deployment of the BGC, we were near the end of borehole operations. Given that this was the final SALSA borehole sampling operation, the SALSA science and drill teams decided to start retrieval of drilling equipment from the borehole. First, the drill team stopped the hot water drip into the surface of the hydrostatically balanced borehole water. This constant source of energy into the borehole is designed to prevent freezing at the air-water interface, as the temperatures in the borehole (−30°C to

−20°C) were much colder than the austral summer air temperatures (−10°C to 2°C). The rationale was that the only equipment left to deploy, the BGC, was the largest and heaviest, so some surface ice at the borehole air–water interface would not be an issue for the large BGC. This consideration did not factor in the sensitivity of the brailer release to interactions with the sides of the borehole or any solid surface in the borehole. As discussed above, this decision resulted in the failure to obtain a sediment core due to the packing of the cutter nose and core catcher with large-crystal ice. More importantly, ice formation at the borehole water–air interface was faster than we had predicted and prevented our test of the water exhaust hypothesis. Our experience emphasizes the importance of borehole maintenance; any horizontal ice surfaces can plug the cutter nose as it did in our final attempt to core deeper in Mercer Subglacial Lake.

Overall, our design and implementation efforts resulted in 10 retrieved multicores and 2 gravity cores. Field observations showed intact water-sediment interfaces in our multicores, including evidence of less dense sediment never before observed beneath the glaciers of the Whillans Ice Plain (Kamb 2001). Preliminary data from the gravity cores indicate that over 2 m of core section is present in our cores once correlated. Careful planning, ability to overcome challenges in the field, and serendipity with good weather all contributed to a unique sediment record (Davis et al., 2023; Siegfried et al., 2023; Venturelli et al., 2023) that will potentially elucidate many subglacial geophysical processes, biogeochemical cycles from an unexplored environment, and regional and global climate phenomena. We anticipate that our success can be replicated and exceeded in future endeavors.

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