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Technologies for retrieving sediment cores in Antarctic subglacial settings

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Accumulations of sediment beneath the Antarctic Ice Sheet contain a range of physical and chemical proxies with the potential to document changes in ice sheet history and to identify and characterize life in subglacial settings. Retrieving subglacial sediment cores presents several unique challenges to existing sediment coring technologies. This paper briefly reviews the history of sediment coring in subglacial environments. It then outlines some of the technological challenges and constraints in developing the corers being used in sub-ice shelf settings (e.g. George VI and Larsen Ice Shelf), under

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ice streams (e.g. Rutford Ice Stream), at or close to the grounding line (Whillans Ice Stream) and in subglacial lakes deep under the ice sheet (e.g. Lake Ellsworth). The key features of the corers designed to operate in each of these subglacial settings are described and illustrated together with comments on their deployment procedures.

1. Introduction

(a) Why retrieve sediment cores from subglacial settings?

Sediments accumulate in many aquatic environments. Where the water column is stable, sediments can retain their stratigraphy and, with their range of incorporated environmental proxies, provide long-term records of environmental change [1]. Seismic profiling has confirmed the presence of layered subglacial sediments in a range of Antarctic locations (figure 1), and in different subglacial settings including subglacial lakes, ice streams, the subglacial grounding zone and beneath ice shelves (figure 2). These profiles have revealed sites with sediment sequences ranging from 150 m to several 100s of metres thick such as South Pole Lake [5] and Lake Vostok [6–8], sites with at least a few metres of sediment such as Lake Ellsworth [6,9], and sites where sediments cannot be clearly resolved from seismic data [10]. So far sediment cores have been retrieved from a range of these subglacial settings including subglacial lakes at the grounding zone [11] and under Antarctic ice streams (e.g. [12,13]) and ice shelves. Well-preserved sequences of layered sediments have also been directly sampled at former subglacial lakes at the retreating margins of the ice sheet (e.g. [3,4]). These sediment cores have been analysed to provide records of glacial history and/or the presence of life. These broad scientific goals are described later.

(i) Ice sheet glacial history

Sedimentary basins within lakes, channels and former seaways under the Antarctic Ice Sheet (AIS) all have the potential to provide records of the overriding ice sheet history and changes in subglacial hydrology [6,12,14]. Under the West Antarctic Ice Sheet (WAIS), these records are particularly valuable as they have the potential to provide records of changes in WAIS stability over glacial–interglacial cycles. The history of the WAIS, and in particular the date when it last decayed is not known; yet is critical to assessing the present-day risk of ice sheet collapse and consequent sea-level rise. Far field records show sea levels were 3–20 m higher than present during previous interglacials suggesting that one or more of the major ice sheets were substantially smaller than today. During the last interglacial (Marine Isotope Stage 5e, 127–118 ka), temperatures in Antarctica were up to 6°C higher [15] and global sea-level peaked at least +6.6 m (95% probability) [16,17]; in Marine isotopic Stage 11 (420–360 ka)—the closest analogue to our present interglacial in terms of orbital configurations and (pre-industrial revolution) atmospheric greenhouse gas concentrations—sea levels have been estimated at +6−13 m [18]. It is not known how much the AIS contributed in total to each of these events, or indeed which parts of WAIS or East Antarctic Ice Sheet (EAIS) saw major volume changes. Specific targets for sediment core records therefore include: (i) the former seaways that were established during the last ice sheet collapses [19,20]; (ii) lake basins in fjord settings such as Lake Ellsworth, which are likely to have accumulated marine sediments during the previous collapse(s) of the WAIS [6] and (iii) sites at or close to the grounding line which will shed light on past and present grounding line dynamics (e.g. [10,21]).

Different locations may record ice sheet behaviour on a range of timescales. For example, the post glacial retreat of the WAIS in the Amundsen Sea and Bellingshausen Sea embayments has been tracked from sediments in continental shelf cores [22]. Field observations of ice thickness change and imaging of the sea floor suggest that the current ice stream margins of the ice sheet in the Amundsen Sea and Bellingshausen Sea are particularly sensitive to future decay on account

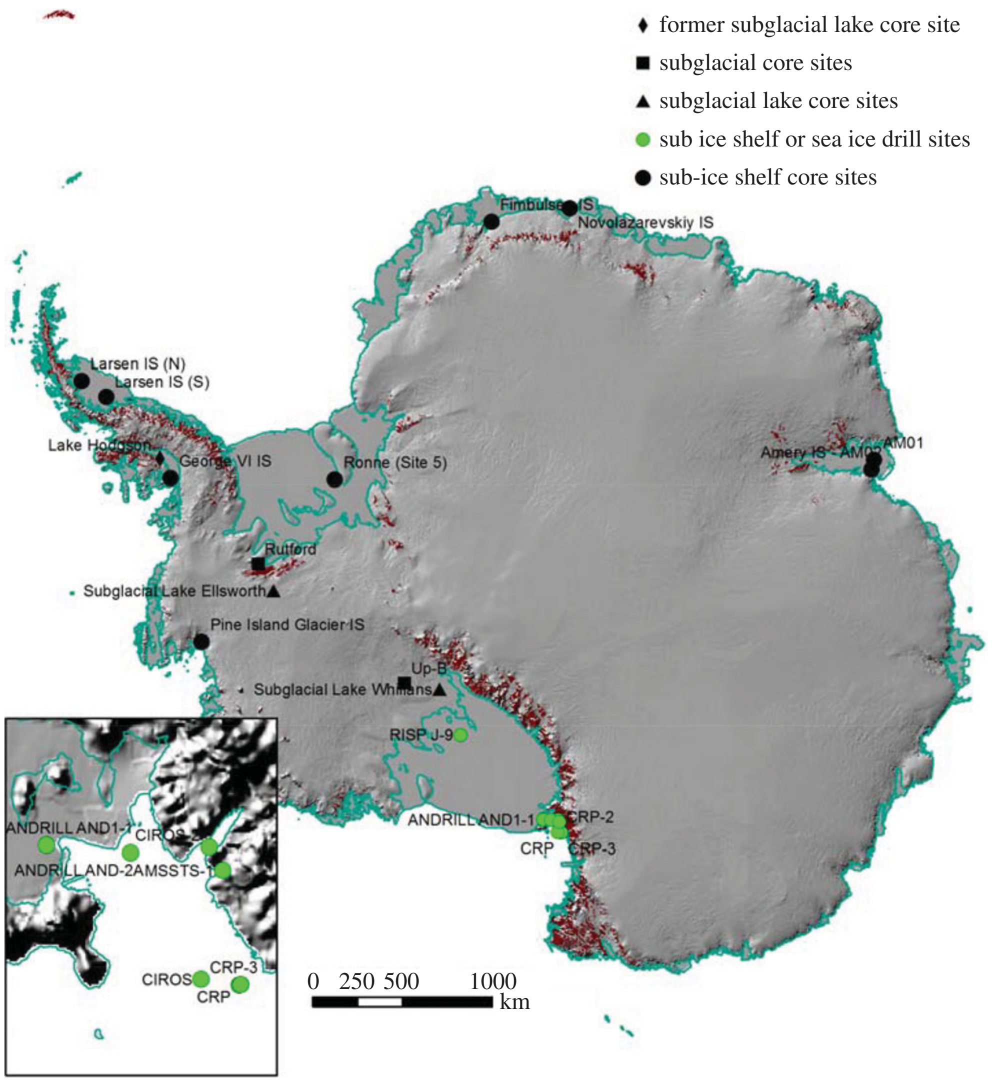

Figure 1. Location of sediment cores retrieved (or planned to be retrieved) from subglacial locations. Inset shows detail of boxed area in McMurdo Sound, Ross Sea. ANDRILL, Antarctic Geological Drilling; CRP, Cape Ross Project; CIROS, Cenozoic Investigation in the Western Ross Sea; IS, Ice Shelf; RISP, Ross Ice Shelf Project; Up-B, Upstream B. Note that Rutford and Subglacial Lake Ellsworth are planned core retrievals. The area around Upstream B and neighbouring ice streams saw up to 50 core retrievals in the 1980s and 1990s, summarized in Kamb *et al.* [2]. Lake Hodgson was a subglacial lake until the Late Holocene [3,4]. (Online version in colour.)

of their reverse bed slopes and the influence of warm circumpolar deep water on melting the ice sheet base. Already, the rapid ice thinning, flow acceleration and grounding line retreat observed in this sector over recent decades are unusual in the context of the past 10 000 years [22]. Over longer timescales (multiple glacial cycles) the sediments from seaways and sites on the flanks of interior highlands might be most appropriate to target for records of major WAIS change during interglacials. These sites may also contain sediments that will reveal the Cenozoic development of the West Antarctic rift basin [23]. By contrast, with the exception of some marine basins, the EAIS is considered more stable than the WAIS and has persisted in some areas for at least 15 Myr, but may have lost all of its marine-based ice as recently as the Pliocene [24]. Here, sediments have accumulated in stable basins (e.g. Lake Vostok) and may provide a long-term record of the EAIS and pre-glacial environments. Geophysical surveys in settings such as Lake Vostok have revealed

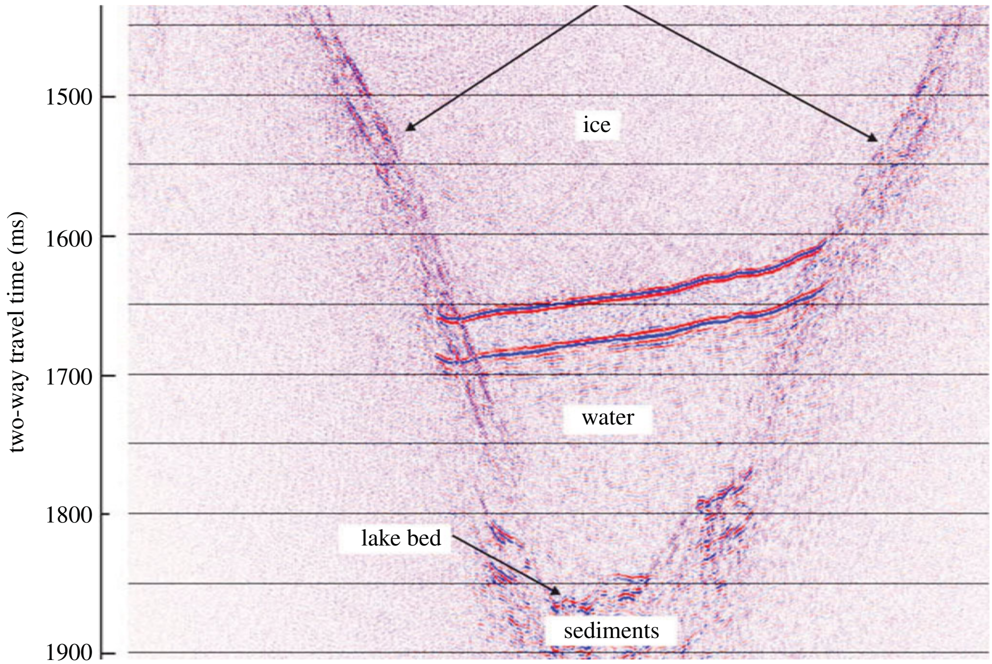

Figure 2. Seismic reflection profile beneath sub-glacial Lake Ellsworth showing the sediments present in the lake. (Online version in colour.)

thick deposits of layered subglacial sediments [7]. These would potentially provide continuous records compared with sedimentary records re-deposited at the margins of the ice sheet, where the records are often discontinuous and where the relative contributions from West and East Antarctica can be less easy to decipher [25].

(ii) Life in subglacial environments

The other area of considerable research involves the identification and characterization of life in subglacial settings. This includes understanding the origin of life found there and the biological processes for survival under extreme pressures, the absence of light and limited nutrients. There is speculation that unique life forms may have evolved to survive in these environments following the formation of the AIS. This is particularly the case for the EAIS where some subglacial environments may have persisted since the Early Cenozoic. Under the WAIS, the repeated deglaciations will have exerted different evolutionary pressures, and studies so far indicate that at least some of the life forms present are derived from marine organisms present during interglacial periods when the ice sheet was absent [26].

Owing to the aggregation of microbial cells around particulate matter in aquatic systems [27] and in biofilms on surfaces [28], the optimal place to search for life in new and unexplored environments is at interfaces, or in regions where there might be higher levels of heterogeneity or gradients in the physical and chemical environments. For this reason, the sediment surface in subglacial lakes is considered the optimal place to search for life, particularly in low biomass ecosystems where the expected cell number is low (for example in Lake Hodgson, subglacial sediment cell counts varied from 4.4 ($\pm$0.6) $\times$ 10^7 cells g^{-1} wet sediment at 240–260 cm, to 1.2 ($\pm$0.7) $\times$ 10^7 at 260–280 cm [26]) or approaching detection limits. They are also places where biomass will tend to accumulate through the natural processes of sedimentation. Sediment surfaces are also particularly good places to search for life as they will be a source of nutrients diffusing from the sediment [29]. A process influenced by turbulence, temperature and nutrient concentration gradients [30]. Sediment surfaces are often associated with a strong oxic/anoxic transition or gradient [31], and this oxic/anoxic gradient in turn influences the local chemistry [32], generating a strong selection pressure for higher microbial biodiversity over relatively small spatial scales. Indeed, the first report of microbes in samples from the sediment environment beneath the AIS showed that cells were abundant, but of low diversity [33].

Because most of the conditions required for life are often met at the sediment–water interface, the focus of life detection experiments has been on collecting intact surface sediments and analysing accumulated sediments for biogeochemical signatures that life persisted there. Particular attention has been paid to collecting these sediments cleanly so that no microbe contaminants are introduced to the pristine environment, and the samples recovered are not contaminated by surficial microbes [34]. Collectively, these studies are contributing to knowledge on how microbial life exists in extreme environments, which is relevant to understanding the evolution of life both on the Earth, during periods of global ice cover (i.e. Snowball Earth, [35]) and potentially on other celestial bodies with hydrospheres, such as the Jovian moon Europa, which has a liquid ocean beneath a crust of ice [36].

In order to address these two major questions on ice sheet history and life in subglacial environments, sediment samples are needed from beneath the ice sheet. This is technologically and logistically challenging. This paper briefly reviews the history of sediment coring in subglacial environments. It then outlines some of the technological challenges and constraints in developing corers for use in sub-ice shelf settings (George VI, Larsen, Ronne, Ross), under ice streams (Siple Coast, Rutford Ice Stream), in lakes at or close to the grounding line (Lake Whillans) and in subglacial lakes deep under the ice sheet (Lake Ellsworth).

2. Brief history

(a) Sub-ice shelf sediment sampling

With the exception of major deep drilling efforts (e.g. ANDRILL) in the Ross Sea [25], only a handful of studies have successfully recovered sediment samples from beneath Antarctic ice shelves. Published data are limited to cores recovered from beneath the Amery Ice Shelf [37–40], and one 0.28 m-long core from beneath the Novolazarevskiy Ice Shelf which indicated contemporary ice shelf stagnation [41]. An unpublished study also recovered 0.31–0.6 m long cores from beneath the Fimbulsen Ice Shelf in 1991/1992 [42] using a 2.4 m-long gravity corer (Benthos Model 2171) [43]. Work on Amery Ice Shelf between 2001 and 2010 used a purpose-built slim-line, 12 cm diameter gravity corer, recovering cores up to 1.44 m. The most significant finding of this work was the identification of a strong connection between the sub-shelf and open-water marine environments. Post *et al.* [39,40] documented a diverse and high biomass sessile benthic community up to 100 km inland from the calving front (i.e. core AM01b), sustained by the advection of diatoms and organic material from the open ocean. The benthic assemblage was indistinguishable from habitats typically found in Antarctic coastal locations dominated by annual sea ice. This finding has clear implications for interpreting the ice shelf presence or absence in the geological record, suggesting that the presence of open-ocean indicators, including diatom-bearing sediment, may not always be a robust indicator of the ice shelf absence.

Sediment coring beneath the Ross Ice Shelf began as part of the Ross Ice Shelf Project (RISP) between 1978 and 1979, when 58 short gravity cores were collected from site J-9 over two field seasons [44,45]. The strategy was to deploy one heavy gravity corer once per day as the ice shelf flowed, resulting in a tight transect of cores. The corer had a 3 m barrel, but most cores were 1 m or less in length. The sediments consisted of a diatomaceous diamicton dominated by mixed Miocene sediments, including common Lower Miocene diatomite clasts. The matrix included a mixed assemblage of diatoms spanning Palaeogene to Upper Miocene ages, but none that were unequivocally less than 9 Myr old. The cores were characterized by a distinct colour change at 10–18 cm beneath the surface [45]; the lower unit was greenish grey with relatively high total organic carbon (TOC, 0.43%), whereas the upper unit was lighter in colour with lower TOC (0.28%) [46]. Harwood *et al.* [47] found little significant difference between the two units with regard to diatom assemblages, implying similar sediment provenance, but speculated that the upper unit may represent an active biological layer influenced by exposure of Miocene sediment to sub-ice shelf marine conditions, and may represent debris rain-out from basal ice during grounding line retreat. No Quaternary diatoms were found in RISP sediments, implying little accumulation of materials advected beneath the ice shelf at this site. However, coring may have failed to recover the true sediment–water interface [45,48]. That is perhaps borne out by the fact that modern diatoms were found living in seawater within crevasses at nearby Crary Ice Rise [49], which would then be expected to accumulate on the nearby sub-ice shelf sea floor. In 1987, a sediment sample was recovered (by accident) during hot water drilling at the Crary Ice Rise. This sample contained a Miocene diatom assemblage that is slightly younger than the youngest age at RISP, but also contained no Pliocene or Pleistocene diatoms [48].

Major geological rotary drilling projects from a sea-ice platform, began in 1975 with Dry Valley Drilling Project Site 15 [50] and continued with the McMurdo Sound Sediment and Tectonic Studies (MSSTS) [51], Cenozoic Investigations in the Western Ross Sea (CIROS) [52] and the Cape Roberts Project (CRP) [53]. This body of work together with the new drilling technologies developed during these efforts paved the way for the ANDRILL McMurdo Ice Shelf (MIS) Project in 2006. ANDRILL employed a sea-riser system, similar to that used on the CRP, as well as a combination of soft sediment coring (in upper soft sediments) and continuous wireline diamond-bit coring [54]. The 1285 m long AND-1B core provided a benchmark, but discontinuous, record of Antarctic glaciation stretching back 14 Myr, with evidence for multiple periods of ice-sheet growth and retreat [55]. Three different soft-sediment coring tools were used to recover the sediment–water interface and the upper few metres of strata, whose integrity was compromised by embedding a sea riser for rotary coring [56]. First, a small (approx. 80 kg) gravity corer from Alfred-Wegener-Institute (AWI) fitted with either a 1.0 or a 1.5 m-long plastic core barrel was used to recover the sediment–water interface and up to 0.5 m of sediment below the surface. Second, the sea riser for the rotary drill was lowered to within a few metres of the seafloor, and the PQ drill string with a 1.6 m-long push corer was deployed through the riser and recovered cores up to 1.5 m long. Third, at the start of the main borehole, an extended nose case sampler was used in advance of a rotating PQ-model drill bit to core to a depth where sediment became sufficiently consolidated to cement the sea riser, and collected up to 0.9 m of core.

ANDRILL-MIS was the first to drill through an ice shelf, employing a hot water drill (HWD) system. ANDRILL Southern McMurdo Sound drilling (AND-2A) used a fast-ice platform, similar to earlier McMurdo Sound drilling programmes. Subsequently, between November 2010 and January 2011, the ANDRILL HWD system drilled four additional holes as part of a site survey at Coulman High to the east of Ross Island (figure 1). The gravity corer designed by the AWI was deployed with 0.5–2 m plastic core barrels, free falling between 5 and 20 m above the sea floor. In total, 28 short cores were recovered containing information on the retreat history of the LGM ice sheet [57]. Taken together the drill cores and short sediments recovered from beneath the Ross Ice Shelf have significantly advanced our understanding of sub-shelf depositional processes and facies [58,59] and have also contributed to a more comprehensive understanding of microbial communities and carbon cycling in these unique environments [60].

Most recently, the British Antarctic Survey (BAS) has recovered sub-ice shelf sediment cores from eight sites beneath the Ronne, Larsen and George VI Ice Shelves to investigate sedimentary processes and glacial history [61,62]. Hot water drilling through 350–780 m ice allowed access into sub-ice shelf cavities of between 190 and 640 m water depth. A BAS/UWITEC percussion corer (described below) was deployed which had the capability to penetrate and recover semi-consolidated glacial sediment cores up to 3 m.

(b) Subglacial ice sheet sediment sampling

The first sediment samples from directly beneath the AIS were extracted from a series of approximately 50 holes drilled beneath the Siple Coast ice streams between 1988 and 2000 by a California Institute of Technology (Caltech)-led team (see [2] for a review; figure 1). These recovered cores of deformable clay-rich diamicton from an area of the Ross Sea embayment that would have been inundated with seawater during periods of Pleistocene and earlier WAIS retreat [12]. Most sediments were studied for their engineering properties as part of a wider research effort to understand ice stream basal motion. However, a number of sediment cores less than 3 m long were recovered by the Caltech piston corer from the upstream part of Ice Stream B (Whillans) via 1030 m hot water-drilled ice holes to access sediments deposited about 600 m below sea level [13]. These sediments were studied in detail and showed no significant lithostratigraphic variation, other than minor variance in diatom fragment abundance [12]. The assemblage was dominated by Upper Miocene taxa, but four of the samples contained Quaternary diatoms and high concentrations of beryllium-10 which both provided evidence of a Late Pleistocene or Quaternary retreat of the grounded ice sheet in the Ross Sea sector [12]. A common piston coring design was modified for the narrow borehole deployment. The system consisted of a plastic core liner fitted into a steel core barrel with a cutting head and metal core catcher and piston, topped by a coiled release rope for a wireline messenger-triggered dead drop into the sediment. The system could also be used as a simple gravity corer, which works well with most unconsolidated till.

(c) Subglacial lake sediment sampling

The first stratigraphic analyses of sediment cores in an Antarctic subglacial lake setting were from Lake Hodgson, situated at a retreating margin of the WAIS on Alexander Island [3,4]. Here the lake was relatively accessible having emerged from under more than 297–465 m of glacial ice during the last few thousand years. Surface sediments were collected using a UWITEC gravity corer, then three overlapping 2 m-long cores were retrieved with a UWITEC KOL Kolbenlot manually operated percussion piston corer to a total sediment depth of 3.76 m. A multidisciplinary investigation suggested the sediments had been deposited since the last interglacial and that the lake had persisted in a subglacial cavity beneath overriding Last Glacial Maximum ice with a transition from coarse- to fine-grained sediments marking the onset of Holocene deglaciation. Evidence of biological activity was sparse. Organic carbon was present (0.2–0.6%) but the δ13C and C/N values suggested that much of it could have been derived from the incorporation of carbon in catchment soils and gravels and possibly old CO_2 in meteoric ice. The sediment contained a diverse assemblage of microbial forms [26]. The gravity and percussion corers used in Lake Hodgson are commercially available and required no special modifications.

The first clean-access sediment cores from an extant subglacial lake were retrieved from Subglacial Lake Whillans as part of the WISSARD project [63]. A HWD was used to gain access to the lake in January 2013 and three different sediment corers deployed. The recovered sediment cores, which sampled down to 0.8 m below the lake bottom, contained a macroscopically structureless diamicton [11]. This texture is atypical of lacustrine sediment, and certainly does not represent what is anticipated for many different subglacial lake locations in Antarctica. However, it may well be characteristic of dynamic lakes on ice plains that periodically drain and then refill with water. During lake lowstands in such basins, ice streams can periodically ground across much of what would be the lakebed during highstands; massive diamicton being the resulting dominant sediment.

The coring technologies developed for these different subglacial environments are described in further detail below.

3. Coring technologies

A variety of sediment sampling devices have been developed for use in different subglacial environments (table 1). These range from short corers designed to collect an undisturbed sediment–water interface to gravity corers, which penetrate deeper sediments under their own mass. For deeper and stiffer sediments (e.g. glacial tills), corers with manual, hydraulic and electromechanical percussion hammers have been designed to enable more efficient penetration.

Table 1. Summary of corers developed for use in subglacial environments. The table includes details on the aims, logistical constraints, technological challenges and key features of the coring systems.

coring location	aims	logistical constraints	technological challenges	key features of design
former sub-glacial lake at margins of ice sheet: Lake Hodgson [3,4]	4 m sediment core to reconstruct glacial history and the presence of microorganisms	transport via Twin Otter then man-hauling via sledge	4 m overlying ice 90 m water column 25 cm Ø ice auger hole	standard UWITEC piston corer—manual percussion via surface cable
sub ice-shelf: George VI Ice Shelf [61]	multiple 1–3 m sediment cores to reconstruct ice shelf history and sub-ice shelf sedimentation	weight 120–160 kg, transport via Twin Otter	380 m overlying ice, 640 m water column, 20 cm Ø HWD access hole	percussion corer—manually operated via surface rope
sub ice-shelf: Site 5 Ronne Ice Shelf [61]	multiple 1–1.5 m sediment cores to reconstruct ice shelf history and sub-ice shelf sedimentation	weight 120–160 kg, transport via Twin Otter	800 m overlying ice, 400 m water column, 20 cm Ø HWD access hole	percussion corer—manually operated via surface rope with automatic mechanism to release hammer weights, standalone video attached to tether monitors coring procedure
Sub ice-shelf: Larsen Ice Shelf [61]	multiple 1–3 m sediment cores to reconstruct ice shelf history and sub-ice shelf sedimentation	weight 120–160 kg, transport via Twin Otter	370 m overlying ice, 640 m water column, 20 cm Ø HWD access hole	percussion corer—manually operated via surface rope
sub ice-stream: Rutford Ice Stream, planned 2017 [64]	Samples of subglacial till. Multiple cores for ice sheet history and ice dynamics	weight < 500 kg, transport by Twin Otter	2500 m overlying ice, 20 cm Ø HWD access hole, ice temp -25°C	percussion corer—manually operated via surface rope with automatic mechanism to release hammer weights, standalone video attached to tether monitors coring procedure, double core-catcher. Cores 6 cm Ø, up to 3 m long. Maximum corer diameter 11 cm
sub ice-stream: Whillans and Kamb Ice Streams, Ice Stream B [12,13]	multiple 1–3 m sediment cores in subglacial till	light winch, A-frame	1030 m overlying ice, 10 cm Ø HWD access hole	piston or gravity corer—6 m, 5 cm internal Ø

(*Continued.*)

Table 1. (*Continued*.)

coring location	aims	logistical constraints	technological challenges	key features of design
ice plain subglacial lake: Lake Whillans and ice stream grounding zone, WAIS—Whillans [11]	3 intact, up to 50 cm surface sediment cores per deployment. Also recovers bottom water sample. Clean drilling technologies	weight $<$ 150 kg, light winch	750 m overlying ice, 2 m water column, 30 cm Ø HWD access hole	WISSARD modified UWITEC multicorer
ice plain subglacial lake: Lake Whillans and ice stream grounding zone, WAIS—Whillans [11]	1–3 m sediment core with clean drilling technologies	transport via heavy tractor traverse	750 m overlying ice, 2 m water column Sterile corer and handling systems	WISSARD piston/gravity corer
ice plain subglacial lake: Lake Whillans and ice stream grounding zone, WAIS—Whillans [11]	$<$5 m (11 cm diameter) sediment core with clean access technologies	transport via heavy tractor traverse	800 m overlying ice, 2 m water column at the lake and 758 m of ice and 10 m water column at the grounding line. Sterile corer and handling systems	WISSARD hydraulic percussion corer—Designed to recover consolidated sediment, potentially pre-LGM. Stainless steel barrel with plastic liner. Hydraulic piston drives a drop weight that strikes a plate at the top of the barrel. Deployed using crane on a strengthened fibre-optic cable to allow surface communications and monitoring. Special mechanisms for recovery if barrel becomes wedged
deep continental subglacial lake: Lake Ellsworth [65]	intact 30 cm surface sediment core with no contamination	transport in shipping container (5.7 m) Max crane height 8 m	sterile corer and handling systems	Lake Ellsworth surface corer—simple metal core tube on probe with no liner, electromechanical core catcher—remotely activated, downward facing camera to monitor penetration, core frozen before extrusion to maintain sediment–water interface

(*Continued*.)

Table 1. (*Continued*.)

coring location	aims	logistical constraints	technological challenges	key features of design
deep continental subglacial lake: Lake Ellsworth [65]	2–4 m sediment core with clean drilling technologies	transport in shipping container (5.7 m) Max crane height 8 m	>3000 m overlying ice 150 m water column 30 cm Ø HWD access hole, 340 Bar pressure −20°C in bore hole, shared tether with lake probe, sterile handling systems, tether rated for static and shock loads	Lake Ellsworth piston corer with electro-mechanical percussion—20 cm max diameter, piston corer driven by electromechanical percussion hammer, piston with integrated light source and camera, sterile deployment system, tether with electrical power and fibre-optic communication, core barrel, with PVC core liner and pressure release valve to prevent crushing of core liner, double core catchers, up and downward facing cameras to monitor systems and penetration
deep continental subglacial lake: Lake Ellsworth [65]	2–4 m sediment core with clean drilling technologies	transport in shipping container (5.7 m) Max crane height 8 m	shared tether with lake probe, sterile corer and handling systems	Lake Ellsworth gravity corer—750 kg weights, core barrel with PVC liner, core cutter and core catcher, valve to prevent core loss, tether connector (no power or communications)

Pistons are included in some of these corers; designed to limit deformation and loss of the cores during sample recovery.

(a) Sediment corers developed for sub-ice shelf and sub ice-stream settings

Sediment corers have been developed for extracting sediments from hot water-drilled access holes in sub-ice shelf settings to record the history of ice shelf advance and retreat, and from under ice streams to provide an observational basis for understanding fast ice stream flow mechanisms and to interpret ice sheet history.

The ANDRILL programme developed a heavyweight wireline drilling system that is described elsewhere [66] (also see [25]). Briefly, the drilling system is based on a rig commonly used in minerals drilling, with a number of adaptations to allow deployment of a sea riser casing, tide compensation (to permit vertical movement), operation in cold conditions and transport on sledges. Further technological advances were required for drilling beneath fast-moving ice shelves ($0.3\,\mathrm{m\,d^{-1}}$). The next deployment of the ANDRILL drilling system is at Coulman High which involves drilling approximately 800 m of Palaeogene to lowest Miocene strata beneath approximately 260 m of ice shelf moving at $2\,\mathrm{m\,d^{-1}}$.

Elsewhere in sub-ice shelf settings corers have typically been developed as (relatively) lightweight manual percussion corers (figure 3*a*,*b*) that use a common deployment system and tether with other field instruments and are compact enough to be transported by a DeHavilland Twin Otter aircraft.

The corer for sub-ice shelf coring developed by the BAS in collaboration with Austrian engineering company UWITEC consists of a core cutter, core catcher and lined 3 m-long steel barrel (figure 3*a*,*b*). Percussion is driven via a manually operated hammer mounted on a hammer rod with a striking plate (figure 3*a*). In deeper subglacial locations (more than 1 km of tether), the corer has been modified so that the weights are hoisted, then released automatically by a triggered release mechanism (figure 3*c*), resulting in more efficient percussion. In the field, the corer has been deployed via a davit winch or by tethering the corer to a skidoo via an 'A' frame sheave. Up to five 11 kg hammer weights can be added to the corer which has proved effective at recovering sediments, even in relatively hard semi-consolidated glacial material. BAS also use a short gravity corer, consisting of a valve head and liner to collect undisturbed surface samples (figure 3*d*).

Some sub-ice stream sediments are expected to be very soft with high porosity, especially at shallow depths, so core catchers are required to successfully retain this material. Core catchers consisting of steel fingers are commonly used in ocean-floor sediment coring. In subglacial settings, further redundancy has been achieved by deploying double core-catchers (two sets of core catchers assembled one on top of the other). This configuration has been successful in retrieving sediments from beneath ice shelves and has also been incorporated into corer designs for deep continental lakes (Lake Ellsworth).

The HWD used for these sub-ice shelf access experiments had a modified nozzle to aid corer deployment. Specifically, the drill had a brush nozzle, which widens the hole at the ice base, to guarantee recovery of corer into the ice shelf base especially at sites where there are high ocean current velocities.

(b) Sediment corers developed to sample sediments in the grounding zone and shallow subglacial lakes

Sediment cores from the grounding zone can provide important information on ice sheet dynamics and subglacial biology. The WISSARD programme developed three sediment corers to sample sediments from Subglacial Lake Whillans and downstream in the grounding zone of Whillans Ice Stream as it goes afloat into the Ross Sea. This coring was undertaken to assess the future stability of the WAIS in this region and to sample a subglacial lake and microbial ecosystem

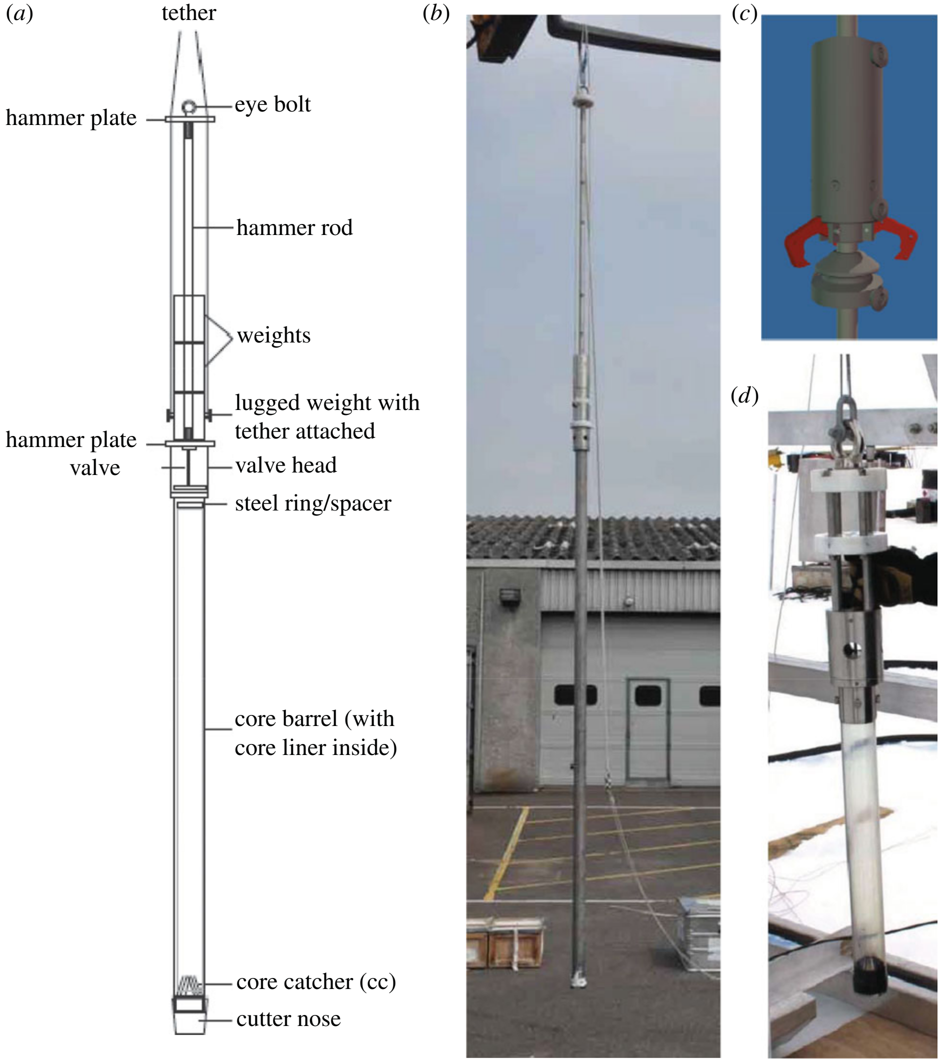

Figure 3. BAS/UWITEC percussion corer designed for use in sub ice shelf settings. (*a*) Simplified schematic of the percussion corer, (*b*) the corer being assembled and tested prior to deployment in Antarctica, (*c*) detail of a prototype auto release mechanism to improve the efficiency of the percussion hammer when operated using long (more than 1 km) cables and (*d*) gravity corer designed to collect surface sediment cores in sub ice shelf settings. (Online version in colour.)

using clean access protocols. The corers included a surface gravity corer, a piston corer and a percussion corer.

(i) Modified UWITEC multicorer

To retrieve intact surface sediments and an undisturbed sediment–water interface, a slightly modified off-the-shelf system was deployed (figure 4). This consisted of three standard UWITEC corers mounted on a frame with self-triggering core catchers. This was deployed from a light winch. Stainless steel 'fins' were mounted on the central rod between coring units as guiding blades for 'skating' on the borehole wall during contact, thus avoiding early triggering of the release mechanism, as well as providing needed weight. Additional stainless steel weight was added to enhance penetration. This system was also an effective bottom water sampler. A standard sediment extruder and slicer was used to slice the core at discrete intervals, allowing

Figure 4. UWITEC multicorer deployed at subglacial Lake Whillans. The corer takes three replicate cores at once preserving the top-most sediment, the sediment–water interface and the water column. (Online version in colour.)

for sequential sampling of the top-most lake sediments. For sediments stiff enough to maintain stratigraphic integrity, water was siphoned off, leaving a few centimetres above the sediment. Zorbitrol^{TM}, a powder that forms a stiff gel when exposed to water was poured into the core tube until the sediment surface was stabilized for shipment.

The UWITEC system generally worked well, but it did experience freezing problems on the core-catcher release mechanism. The sediments were generally stiff enough that in some cases cores were successfully recovered without the ball catchers. A more significant problem was freezing of the suction plates at the tops of the cores. If frozen in place on the way down, then backpressure in the tubes permits no core recovery at all. If they freeze in place after deployment, then pressure will build up in the barrel as cores warm and de-gas, forcing uncontrolled extrusion from the bottom of the cores. These problems resulted in a coring success of under 40%. The mechanisms are made of rubber and Plexiglas, which are susceptible to damage by heat guns. These parts will be replaced with alternate materials to minimize these problems prior to future deployments.

(ii) WISSARD piston corer

A piston corer designed and built by University of California Santa Cruz, based on the Caltech design, was developed to collect a non-deformed sediment core. The piston corer is an update on a 2.5″ version manufactured at Caltech which in turn was adapted from much larger ocean-going corers (figure 5). The corer is manufactured from stainless steel and has a 3 m core barrel. It has its own lightweight winch and cable and can be stacked with different weights to achieve maximum penetration. The corer includes an upper stage with piston and a kevlar release cord coiled in a

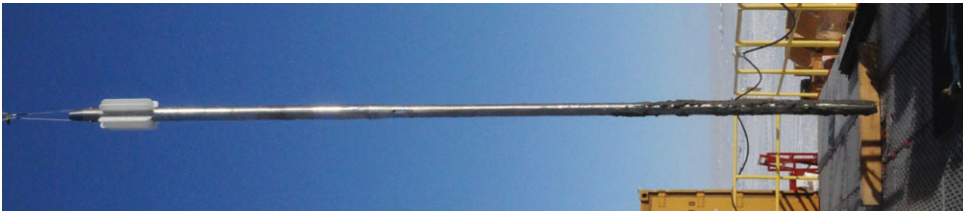

Figure 5. WISSARD/Caltec piston corer. (Online version in colour.)

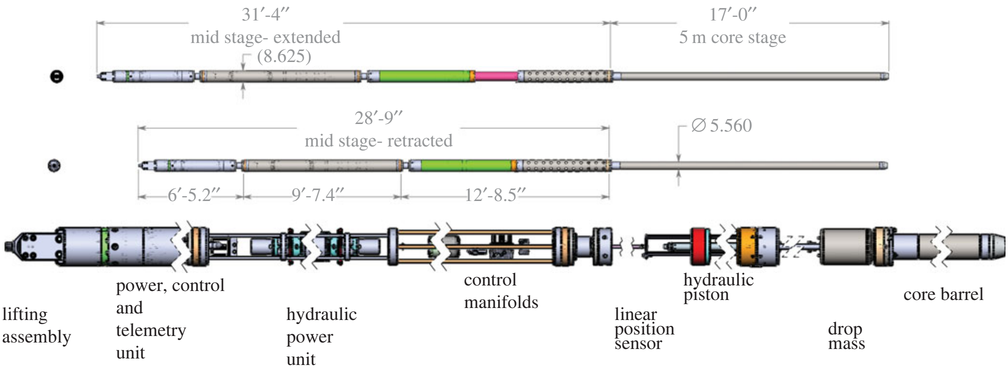

Figure 6. Schematic diagram of the WISSARD hydraulic percussion corer (Designed by DOER-Marine and S. Vogel and built by DOER-Marine). (Online version in colour.)

tube. A dead drop a few metres above the bed (the depth of which needs to be precisely measured) is triggered by a wireline messenger. As the corer penetrates the sediment, the piston inside stops and the sediment is captured without significant compression or disturbance. Retrieving it requires a tall crane because it has to lift the entire deployed assembly. The corer can also be deployed as a gravity corer, acting as a simple open tube with core catcher dropped as fast as the winch will allow with penetration determined by sediment strength weight and speed of drop. The experience at WISSARD shows that subglacial sediments there were sufficiently cohesive that the lack of a piston did not result in loss of core out the bottom of the core barrel.

(iii) WISSARD hydraulic percussion corer

To retrieve deeper consolidated sediments, a hydraulic percussion corer was used. The percussion corer (figures 6–8) was designed to be lowered to Subglacial Lake Whillans and the grounding zone on a strengthened fibre-optic cable of a multipurpose winch. The hydraulic percussion system was specified to hammer a core barrel up to 5 m-long into sediments such as subglacial tills that can potentially be stiff and over-consolidated with depth, and also potentially recover records older than the Last Glacial Maximum. This technology bridges the gap between sediment depths accessible using gravity and piston corers and that achievable using large-scale rotary drilling technologies. As the percussion corer is deployed, a 900 kg mass is released within its casing by unbolting an extension section from inside the casing (between the linear position sensor section and hydraulic piston section in figure 6). Once on the sediment surface, the hydraulic motor is commanded to drive a piston that raises the mass to its maximum height within its casing, and then is tripped to be released in a free-fall, to then strike a plate on the top of the core barrel. This process is automatically repeated every 20–30 s until commanded to stop. A linear position sensor is used to measure the penetration distance with each strike. Coring is stopped when there is either a lack of further penetration or the 5 m-barrel is fully buried in the bottom

Figure 7. WISSARD hydraulic percussion corer. The corer is assembled in the field by bolting together each of the labelled sections. For WISSARD, it was deployed using a knuckle-boom crane from a sledge-mounted deck with an equivalent of a shipboard moon-pool over the borehole. A strengthened fibre-optic cable hanging down beside the corer is attached at its top and used for deployment and recovery as well as communication. (Online version in colour.)

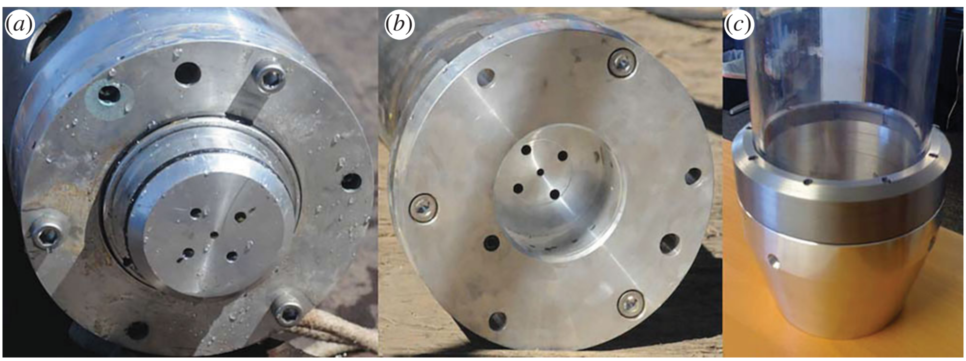

Figure 8. Close-up views of the small water jet conduits at the base of the drop-weight section (*a*), the top of the core barrel (*b*) and the collar of the core cutter (*c*), to be used if the barrel binds in the sediment. This design allows water to be hydraulically pumped down between the steel core barrel and the plastic core liner, then out around the core cutter, and finally is forced up between the outside of the barrel and the binding sediment. (Online version in colour.)

sediment as determined from the linear position sensor. To avoid large pullout strains beyond the capacity of the cable (4500 kg), the hydraulic system was designed to help extract the core barrel (figure 8). The hydraulics can be commanded to force pressurized-water down between the core liner and core barrel with the water exiting via jets through holes in the core cutter head. The water is then forced up the outside of the core barrel to decrease friction between it and the *in situ* sediment wall.

Because the corer is deliberately aimed at consolidated sediments, it contains a further safety feature in case the hydraulic flushing process fails to extract the barrel. Specifically, there are weak-link bolts at the top of the barrel that fail in tension and these will break away so that the rest of the corer assembly can be recovered and only the barrel is lost.

(c) Sediment corers developed for deep continental subglacial lakes

Deep continental subglacial lakes present an additional range of technological challenges (table 1), not least of which is the depth required of the HWD, but also the low temperatures and high pressures experienced there. We describe below three corers developed for the Subglacial Lake Ellsworth (SLE) programme: a shallow, narrow diameter surface corer; a percussion corer and a gravity corer.

(i) Subglacial Lake Ellsworth surface corer

For the Subglacial Lake Ellsworth programme [65], a short corer [67,68] was designed to sample the top few centimetres of sediment from the lake floor, including an intact sediment–water interface which was considered the most likely location to find evidence of life (figure 9). The corer was a lead screw-driven piston corer, mounted on the tip of the lake sampling probe and consisted of a mechanically activated (extended versus a piston) corer barrel (25 mm diameter) with an internal piston and ball valve based core catcher activated at the end of the barrel extension (figure 9). A downward-facing camera and light source, and visual depth gauge on the face of the probe enables the corer to be lowered precisely onto the sediment before the corer barrel extension and ball valve is activated electronically from the surface. On retrieval, when the probe reaches the approximate 300 m air-filled portion of the access hole with an expected minimum temperature of −18°C, the narrow diameter sediment core was expected to freeze. The corer was designed to be detached from the probe to extrude the (frozen) core sample with an intact sediment–water interface.

(ii) Subglacial Lake Ellsworth percussion corer

The percussion corer for Lake Ellsworth (figure 10) is designed to retrieve sediment cores up to 3.8 m long. This corer uses the same communications tether as the lake sampling probe (described above) and the gravity corer (described below), and is designed to be deployed ‘cleanly’ being assembled under clean conditions and stored within a sterile deployment system.

The percussion corer is a mechanically driven percussion piston corer. It is effectively two assemblies: (i) the control interface (CI) housing with Piston-Rod and fixed piston (figure 10; red font) and (ii) the Hammer Unit (HU) attached to the Core-Barrel (figure 10; blue font). A coiled umbilical cable connects the HU and the CI, providing power and communications between the two units and uncoiling on activation of the corer. Prior to deployment the CI and the HU are ‘tied’ together with shear pins to prevent the HU from sliding down the piston-rod.

At the sediment surface, the core barrel is designed to be driven down past the fixed piston by a percussion hammer actuated by a pair of linear motors in the HU coupled to a steel weight (figure 10*a*). On actuation, the linear motors lift and drop the hammer weight (figure 10*c*), repeating this action until deactivated. When the barrel is full, or when there is no more sediment penetration a corer clutch is deployed to prevent further movement of the piston in the core barrel and consequent deformation or loss of the sediment core. The CI houses the power converters, control electronics and communication modems (figure 10). Cameras and light sources provide

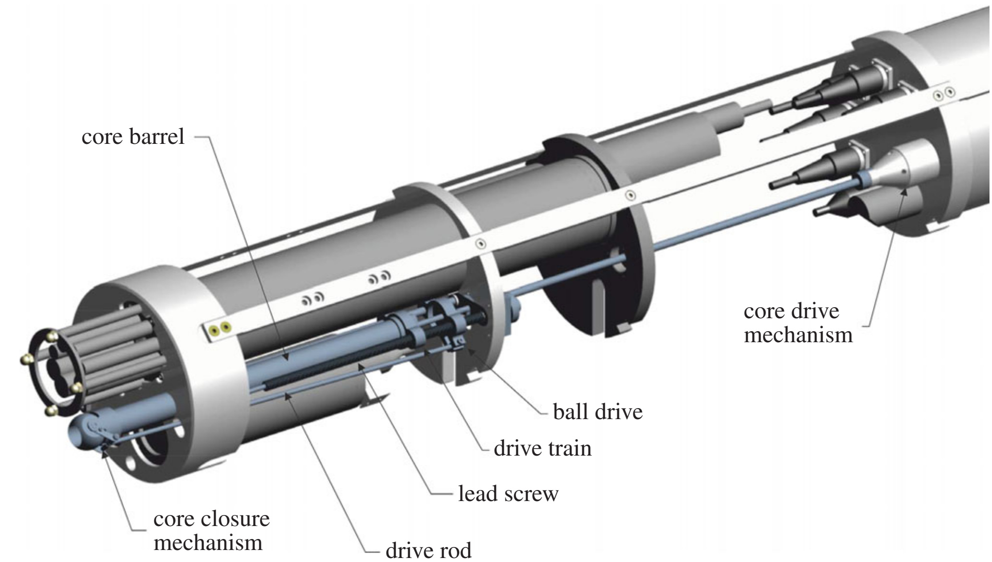

Figure 9. Subglacial Lake Ellsworth short corer at the base of the lake probe. (Online version in colour.)

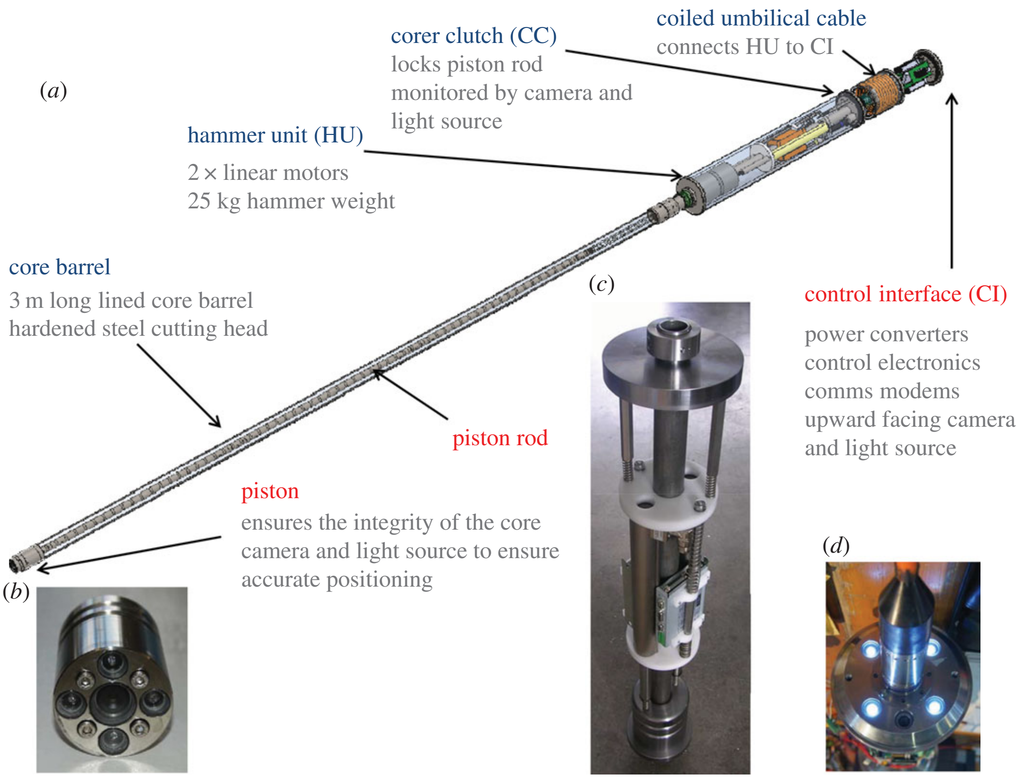

Figure 10. (*a*) Subglacial Lake Ellsworth electromechanical percussion corer engineering schematic. The corer consists of two assemblies: (i) the control interface (CI) housing with Piston-Rod and fixed piston (parts labelled in red) and (ii) the Hammer Unit (HU) attached to the core-barrel (parts labelled in blue). (*b*) The piston with downward facing camera and light sources, (*c*) the hammer mechanism and (*d*) the upper end of the CI showing upward facing camera, light sources and tether connector. (Online version in colour.) Q12

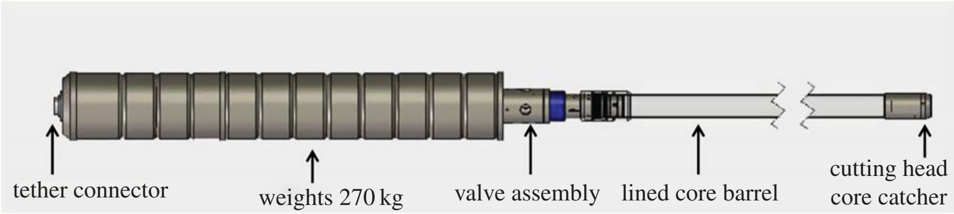

Figure 11. Subglacial Lake Ellsworth gravity corer. (Online version in colour.)

information on the operation and progress of the corer. One camera is located inside the Piston (figure 10*b*) aiding descent and to position the piston precisely at the sediment–water interface. It uses halogen lamps to prevent the piston freezing into the core barrel (there is also a heat-trace cable within the piston rod to prevent it freezing to the HU. Another camera with LED lamps monitors the Piston-Rod-Clutch and Clutch-Camshaft. A third camera with LED lamps is located at the top of the CI; looking upward to identify any changes in inclination angle (i.e. if corer starts to topple) and to aid ascent back into the drill hole at the ice sheet base (figure 10*d*). Communication is via a tether which is connected to a Deck Unit housing the communication and video interfaces, linked to a 0–600VDC 2.4 kW DC Surface-Supply that delivers power to the entire system, and a Guardian K-DVR-4G, 4-channel composite Digital Video Recorder. The CI provides the bi-directional communication to the deck unit, as well as control for the HU and local instrumentation.

Control is via a Deck Unit, consisting of a PC running Windows OS, control software (National Instruments® *LabView*) and the communication and video interfaces. The system is controlled using a Graphical User Interface (GUI) which is a *LabView* virtual instrument.

(iii) Subglacial Lake Ellsworth gravity corer

In the case of a communication failure in the tether and to provide redundancy for the precision piston corer, a simple mechanical gravity corer was constructed with minimal moving parts (figure 11). Gravity corers typically have a high sampling success rate (in ship-based deployments) but have the disadvantages that they can over-penetrate, compress or otherwise deform the sediment. A 6 cm internal diameter core barrel (3.7 m long) was used with 270 kg of head weights to achieve a reasonable balance between corer diameter (a narrow corer penetrates further into (older) sediment) and corer weight (greater weight gives greater penetration but requires a stronger cable to retrieve). This corer can be operated by lowering on the tether and is driven by gravity into the sediment. As with the percussion corer, it is retrieved by the electrical winch at the surface.

4. Future technological developments

It is clear that the demand for subglacial sediment retrieval will continue to grow and as part of this there is likely to be a requirement to retrieve multiple cores—perhaps from multiple holes—in rapid succession, and for deeper penetration of sediment. The former typically requires interchangeable barrels, which is standard in marine sediment coring but if clean subglacial access protocols [34] are being followed then it raises the challenge of ensuring that core barrel (or liner) swaps in the field can be done under clean conditions. For deeper penetration, the coring technology will be limited by the practical length of corers that can be handled at the drillhead. Beyond this limit, wireline rotary drilling will be the most likely way forward but the logistics for this can be very significantly greater in demands and overall cost. Additional challenges include HWD systems capable of maintaining access holes for longer periods, and technologies to meet clean protocols for repeated insertion and retrieval of drill strings into deep ice drill holes. For this reason, it is likely that deep sediment retrieval is likely to remain confined to the margin of the ice sheet (e.g. ANDRILL) for at least the medium term.

For any future sediment corer designs reducing the maximum diameter of weight stacks or percussion systems should be a key aim. In many designs, the corers have slim barrels but with much larger diameter weight stacks or percussion systems behind. These weight stacks create the need for wide diameter drill or core holes in the ice and thus increases fuel demands, drill demands, leading to greater logistics and cost. However, reducing the diameter will likely increase corer length, which may be a problem for handling with the need for a taller tower or crane at the wellhead. There is a balance to be struck between these two factors but it is also worth noting that for a given hole diameter then a slimmer corer means more time in the hole and less likelihood of 'snagging'. Related to this problem, one future development that would be useful would be a device to measure in real-time the diameter of a drill hole such that a clear indication of re-freeze rate and time available for work in the hole is more clearly known. Various borehole monitoring designs, including optical, laser, acoustic and mechanical (calipers) are already under discussion.

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