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Scientific history, sampling approach, and physical characterization of the Camp Century sub-glacial sediment core, a rare archive from beneath the Greenland Ice Sheet

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Abstract. Basal materials in ice cores contain information about paleoclimate conditions, glacial processes, and the timing of past ice-free intervals, all of which aid understanding of ice-sheet stability and its contribution to sea-level rise in a warming climate. Only a few ice cores have been drilled through ice sheets to the underlying sediment and bedrock, producing limited material for analysis. The Camp Century ice core, which the US Army drilled in northwest Greenland from 1960-1966 CE, recovered about 3.5 meters of sub-glacial sediment.

Here, we document the scientific history of the Camp Century sub-glacial sediment, and present our recent core-cutting, sub-sampling, and processing methodology and results for what remains of this unique archive. In 1972, curators in the Buffalo Ice Core Laboratory cut the original core segments into 32 segments each about 10-cm long. Since then, two segments are unaccounted for, two were thawed, and two were cut as pilot samples in 2019. With the exception of the two thawed segments, the rest of the extant core remained frozen since collection. In fall 2021, we documented, described, and then cut each of the remaining frozen archived segments (n=26). We saved an archival half and then cut the working half into eight oriented sub-samples under controlled temperature and light conditions for physical, geochemical, isotopic, sedimentological, magnetic, and biological analyses. Our approach maximized sample usage for multi-proxy analysis, minimized contamination, and preserved archive material for future analyses of this legacy sample material.

Grain size, bulk density, sedimentary features, magnetic susceptibility, ice content, as well as pore-ice pH and conductivity, suggest that the basal sediment contains five stratigraphic units We interpret these stratigraphic units as representing different depositional environments in sub-glacial or ice-free conditions: from bottom to top,

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a diamicton with sub-horizontal ice lenses (Unit 1); vertically-fractured ice with dispersed fine-grain sediments (< 20% in mass) (Unit 2); a normally graded bed of pebbles to very fine sand in an icy matrix (Unit 3); bedded very fine to fine sand (Unit 4); and stratified medium to coarse sand (Unit 5). Plant macrofossils are present in all samples and most abundant in Units 3 and 4; insect remains are present in some samples (Units 1, 3, and 5).

Our approach provides a working template for future studies of ice-core basal sediment because it includes intentional planning of core sub-sampling, processing methodologies, and archiving strategies in order to optimize the collection of paleoclimate, glacial process, geochemical, geochronological, and sediment properties from archives of limited size. Our work benefited from a carefully curated and preserved archive, allowing for the application of techniques not available in 1966. Preserving uncontaminated core material for future analytical capabilities is an important consideration for rare archive materials such as these from Camp Century.

1. Introduction

Ice cores serve as paleoclimate archives by offering valuable insights into past atmospheric composition and temperature via the analysis of trapped air and physical and chemical properties of ice. Ice cores typically recover clean glacial ice ('clear ice'), and only a few ice cores have reached the ice-bedrock interface to recover basal materials such as sediment-laden ice (sometimes referred to as 'silty ice' or 'basal ice'), sub-glacial sediment, and sub-glacial bedrock (Talalay, 2013). Isotopic, mineralogic, and geochemical analysis of basal materials from ice cores yields important information about basal ice-sheet processes (Goossens et al., 2016; Gow and Meese, 1996; Herron and Langway, 1982; Souchez et al., 2000; Tison et al., 1994; Verbeke et al., 2002), sub-glacial geology and sediment provenance (Blard et al., 2023; Fountain et al., 1981; Licht and Hemming, 2017; Weis et al., 1997), the timing and duration of ice-free intervals or grounding-line retreat (Schaefer et al., 2016; Venturelli et al., 2020), and the ecosystems that occupied formerly ice-free landscapes now buried beneath the ice (Christ et al., 2021; Souchez et al., 2006; Tison et al., 1998; Willerslev et al., 2007). However, the amount of material retrieved from beneath ice sheets is minimal; sometimes only tens of grams of rock or sediment are available for analysis (Talalay, 2013). Given the specific requirements for sample mass, grain size, and handling needed to enable a wide variety of analyses, strategic sampling and sample distribution protocols are critical to optimize results obtained from such limited quantities of archive material.

Drilled from 1960 to 1966 CE in northwestern Greenland, the ice core from Camp Century was the first to reach the bed of an ice sheet and was the first to recover a core of sub-glacial sediment. This core contains the longest sub-glacial sedimentary sequence recovered from Greenland (Hansen and Langway, 1966) (Figures 1A, 2A). Because the sub-glacial sediment was not sampled at the time of collection and has since been stored frozen, we were able to design a detailed, intentional sub-sampling and analysis plan for multiple geochemical, physical, magnetic, biological, and isotopic proxies.

The purpose of this paper is four-fold. First, we compile and summarize the historical record of the collection, handling, and historical analyses of the Camp Century sub-glacial sediment (Section 2). Second, we detail and explain our approach to documenting, cutting, sub-sampling, and distributing this unique sediment archive to optimize sample usage for multi-proxy analysis, avoid contamination, and preserve material for future studies (Section 3). Third, we present our documentation of the archive and the data collected during the sub-

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sampling and initial processing of the sediment, which allow us to describe the stratigraphy of the Camp Century sub-glacial sediment (Section 4). Fourth, we provide initial interpretations of the depositional history of the sediment and provide lessons learned for handling, sub-sampling, and storing rare archives of ice core basal materials (Section 5).

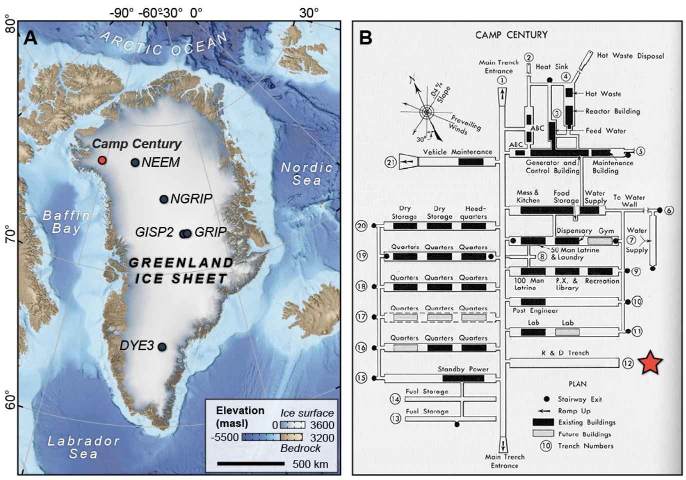

Figure 1: Background images. (A) Overview map of Greenland showing the locations of Camp Century (red circle) and other deep ice cores (dark circles). (B) Schematic layout of the Camp Century installation with the location of the drill trench marked with a red star (Daugherty, 1963; public domain)

2. The scientific history of ice-core drilling at Camp Century and the sub-glacial sediment core

By the 1950s CE, the U.S. military was aware that the Arctic was warming (Thomis, 1955). Such warming had implications for the ongoing militarization of the Arctic during the Cold War, but little was known about past changes in Arctic climate (Doel et al., 2017). To address this knowledge gap, Henri Bader and James Bender, two civilian scientists from the Snow, Ice, and Permafrost Research Establishment (SIPRE) in the U.S. Army Corps of Engineers, lobbied for drilling deep cores into and through the Greenland Ice Sheet (Bader, 1962). Bader had overseen drilling of the first U.S. ice core in Alaska from the Taku Glacier in 1950 CE and Bender had suggested that bubbles trapped in glacial ice preserved ancient atmosphere, the analysis of which could resolve questions about fossil fuel combustion and its relation to climate change (Anon, 1959). Along with Chester Langway, who at the time was a junior researcher at SIPRE, they oversaw drilling of ice cores into the Greenland Ice Sheet at Site II (about 100 km northeast and up ice from Camp Century) in 1956 CE and 1957 CE. Although recovery was poor at Site II and the cores were only a few hundred meters long, they made advances in drilling technology. Analyses on small continuous sections of the ice core demonstrated that the ice preserved records of past climate (Langway, 1958).

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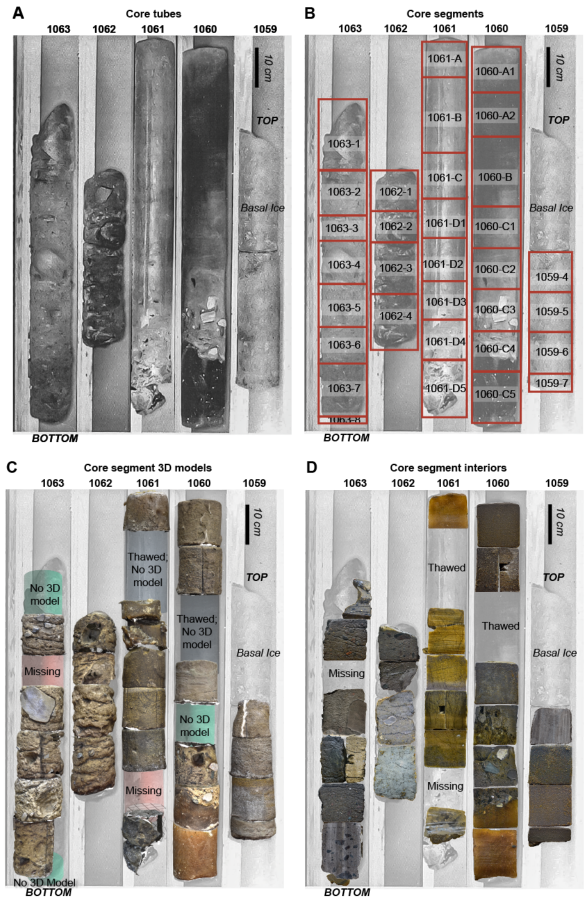

Figure 2: Photographs of the Camp Century sediment core. (A) Historic photograph of the Camp Century sub-glacial sediment core tubes prior to initial cutting in October 1972 (Fountain et al., 1981). (B) Photograph in A with core segments (from cutting in 1972) names overlain. (C) New core photographs (2021) with corresponding sample segment names and 2D rendering of photogrammetric 3D models of the segments rearranged into their original positions. Shaded cylinders: green – no 3D model available, red – missing sample, blue – thawed sample. (D) New core photographs (2021) showing interior cut faces of the archived halves. Note: the photos of interior cut faces are not necessarily oriented along x-y axes in the same manner as the original core. Scale bar in upper right of each panel

Camp Century was a U.S. Army base carved into the surface of the Greenland Ice Sheet. It was built as part of the American militarization of the Arctic (Clark, 1966). The base was ~200 km inland from the ice margin in northwest Greenland at 1890 m asl (Figure 1A). Construction of the camp began in June 1959 CE and was completed in October 1960 CE. Camp Century was constructed in snow and firn using cut-and-cover methods and could house up to 200 people in heated barracks nestled within the snow tunnels. From 1961 to 1963 CE, the base was occupied year-round – powered and heated by a portable nuclear reactor (Corliss, 1968). The U.S.

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military operated Camp Century with a strong science program to test technologies that allowed people to live and work in extreme environments. Much of this scientific effort was applied and directed toward better understanding snow auto-compaction and firn deformation, both on the surface of the ice sheet and in the tunnels of Camp Century, which deformed at rates of 0.1 to 1.0 m/yr (Abele, 1964).

A drilling trench was included in the plans for the base (Figure 1B). Personnel from SIPRE, the predecessor of the Cold Regions Research and Engineering Laboratory (CRREL), conducted research on the physical properties of ice and snow and led collection of the Camp Century ice core (Figure 3A). A new thermal ice drill was designed for Camp Century and deployed from 1960 to 1964 CE, but it was plagued with problems related to the removal and collection of meltwater from the borehole (Bader, 1962; Hansen, 1994). The thermal drill extracted three cores: between 1960 and 1961 CE the first hole recovered 186 m, in 1962 CE the second hole recovered 238 m, and in 1963 CE the third hole recovered 264 m. The last hole was then filled with a fluid mixture of 12% trichloroethylene and 88% Arctic diesel fuel when Camp Century closed for the winter and drilling halted (Ragone and Finelli, 1972). In 1964 CE, the fluid-filled third hole was extended to a depth of 535 m. Starting in 1965 CE, an electromechanical drill that used ethylene glycol to melt ice chips in addition to the drilling fluid (Langway and Hansen, 1970; Ueda and Garfield, 1968) advanced more rapidly and extended the third core to 1002 m. In 1966 CE, drilling resumed with the electromechanical drill and near the bottom of the hole encountered silty ice and extended into the ice-sheet bed. It is material recovered then that we consider in this paper.

The ice-sediment interface is in core tube 1059; the base of the Camp Century core is in tube 1063. The original drill log (Table 2 and Figure 4) from July 2nd, 1966 CE, describes the sub-glacial sediment as:

> "[Core tube 1059] 30 cm from top silty ice stops and frozen sand begins. [Core tube 1060] Appears to be a column of frozen sand with some rocks as large as 5 cm in diameter. Permacrete down to 80 cm then a silty ice lens for rest of core. Red, grey, maroon, and green rocks as large as 5 cm in diameter. [Core tube 1061] Silty ice lens down to 0.80 m. Sand and large rocks after 0.80 m. [Core tube 1062] Large rocks and sand, rocks, and sand. [Core tube 1063] Sand and large rocks (17 cm)."

There are discrepancies in the reported drilling depths and thicknesses of clear ice, silty ice, and sub-glacial sediment between the original core log, early literature, and later studies of the Camp Century basal materials (Table 1). The core tube log is confusing and appears to have been amended with multiple, different entries (in differing pencil weights) for depth of core below surface top (Table 2 and Figure 4). While the reported "depth below the surface" of the sub-ice sediment equates to 4.5 m of penetration (Table 2), the sum of the reported length of sediment recovered (on the drilling log) in each core tube is 3.55 m. Thus, it is possible that core recovery was incomplete. However, the original core logs (both tabular and graphical) have notes that read "These depths are in error". Given the rigidity of the frozen material, core compaction is unlikely. Drilling depths were not simple to discern accurately as coring was done by wireline and

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not using rods. Additionally, there is a subtraction error on the hand-written sheet (Figure 4). We conclude it is not possible with the information available in 2023 CE to determine if recovery of the sub-ice sediment was complete or not.

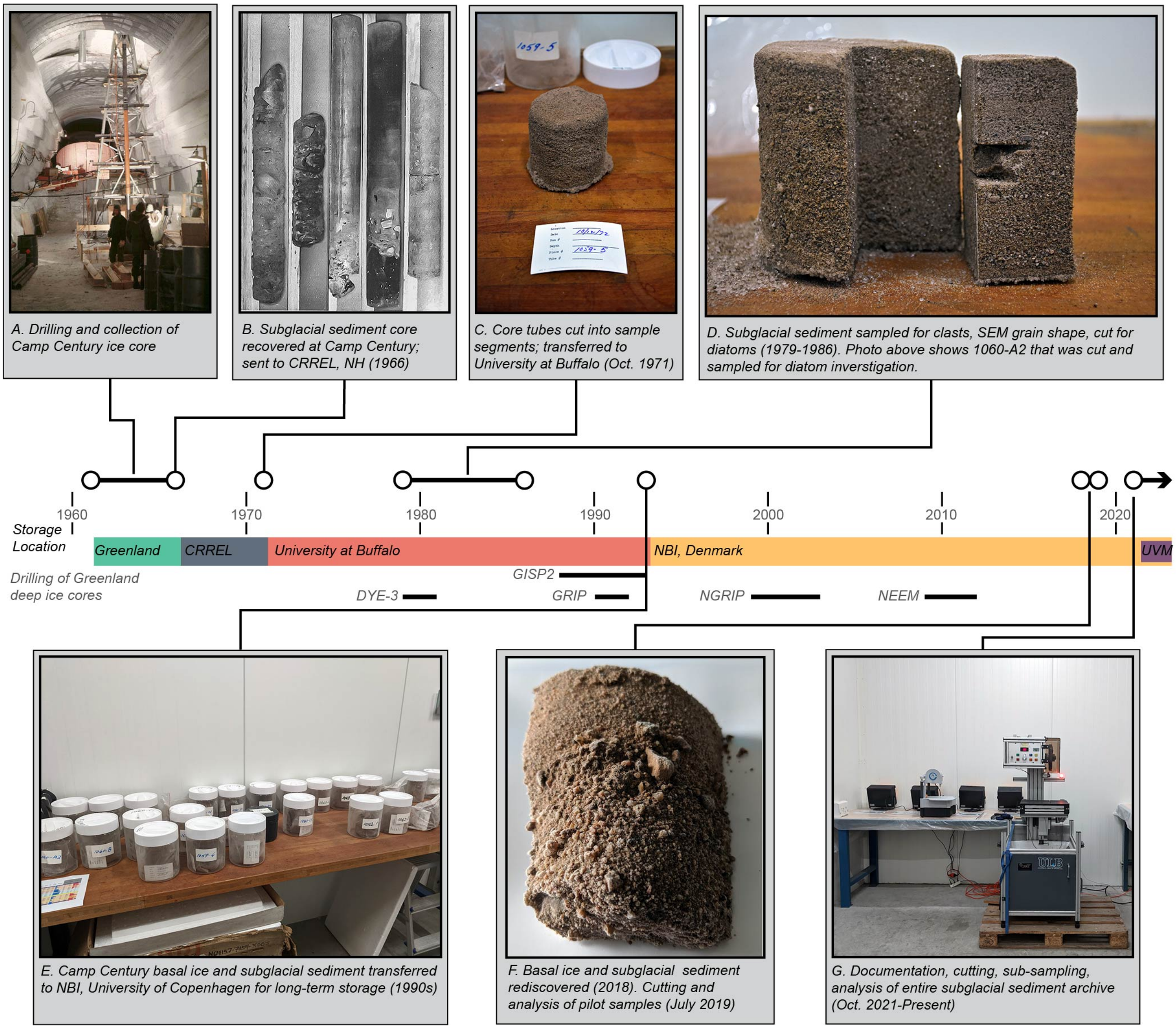

Figure 3: Timeline of the scientific history of the Camp Century sub-glacial sediment including changes in storage location and core cutting and sub-sampling. The duration of drilling campaigns at other Greenland deep ice core sites (Fig 1A) is shown for comparison. Photo credits: (A) Langway (2008) (B) Fountain et al. (1981); (C-G) A. Christ.

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Furthermore, the depths and ice thicknesses documented in the core log are slightly different than those reported by Hansen and Langway (1966):

> "…at a depth of 1,370.5 meters, ice containing silt bands and small pebbles was encountered. On July 4, after drilling through 16.9 meters of this material, the interface at the bottom of the ice cap was reached at a depth of 1,387.4 meters. The bottom material is frozen till; 3.55 meters of this material was recovered. The total depth of the hole is 1,391 meters."

TABLE 1: Discrepancies between reported drilling depths and thicknesses

	Clean glacial ice			Silty ice			Subglacial sediment		
Source	Top depth (masl)	Bottom depth (masl)	Thickness (m)	Top depth (masl)	Bottom depth (masl)	Thickness (m)	Top depth (masl)	Bottom depth (masl)	Thickness (m)
Original core log	0	1354.86	1354.86	1354.86	1373.2	17.34	1373.2	1377.7	3.55
Hansen and Langway, 1966	0	1370.5[a]	1370.5	1370.5[a]	1387.4[a]	16.9	1387.4	1391	3.55
Ueda and Garfield, 1968[b]	0	1356.6	1356.6	NR	NR	NR	1356.6	1360	3.4
Herron and Langway, 1979	0	1359[c]	1359	1359[c]	1375	16	NR	NR	NR
Whalley and Langway, 1982	NR	NR	NR	NR	NR		NR	NR	3.5
Fountain et al. 1981	NR	NR	NR	NR	NR	16	NR	NR	3.5
Recent documentation (2019 - 2021 CE)	NR	NR	1368	NR	NR	17	NR	NR	3.44

NR: not reported; masl: meters above sea level
[a] Calculated based on reported thickness
[b] Reported values in feet were converted to meters. This source did not mention silty ice and included only the depths/thickness of ice and sub-glacial material.
[c] Calculated based on reported drilling depth

Table 2: Transcribed core tube log of sub-ice materials

CORE TUBE LOG

Date 2-Jul-66 **Observer** Donovan **Location** Camp Century

Unexplained notes written on side[a]	Core Tube No.	Length of Core (m)	Depth of Core Below Surface, Top (m)	Condition of Core[b]	Missing or Removed Sections[b]	Reason[b]	Remarks
897	1055	1.48	1369.26	2 pieces silty			1059 to 1063 is sub-ice
	1056	1.45	1370.74	3 pieces silty			
898	1057	0.26	1372.19				
		1.19	1373.5	1 piece silty			These depths are inferred, probably due to the fact that some core was left down the hole
	1058	0.22	1374.69	Silty; a considerable portion of sand on end			
		1.18	1371.92	Silty piece			
899	1059	0.64	1373	30 cm from top silty ice starts and frozen sand begins			Cut into 10 cm pieces - 10/13/72[c]
	1060	0.96	1373.64	Appears to be a column of frozen sand with some rocks as large as 5 cm in diameter. Permacrete down to 80 cm then a silty ice lens for rest of core			" c, d
	1061	0.97	1376.73	Red grey maroon and green rocks as large as 5 cm in *sic* Silty ice lens down to 0.8m Sand and large rocks after 0.80 m			" c, d
900	1062	0.19	1377.7	Large rocks and sand			" c, d
		0.26	1377.89	Rocks and sand			
901	1063	0.83	1377.7	Sand and large rocks (10 cm)			" c, d
			0.83[e]				
			1378.53[e]				
			1377.70[f]				
			1373.20[f]				
			3.50[g]				

[a] Notes written on the side of the log that do not correspond to a table heading that might refer to a box number in which samples were stored.
[b] Condition of core descriptions were written across the two columns to the right.
[c] This note was written in a different ink colour and clearly was added later.
[d] Interpreted to mean 'same as above'.
[e] Purpose of these notes are unclear.
[f] Upper and lower depth range of sub-ice sediment.
[g] Sub-ice sediment thickness.

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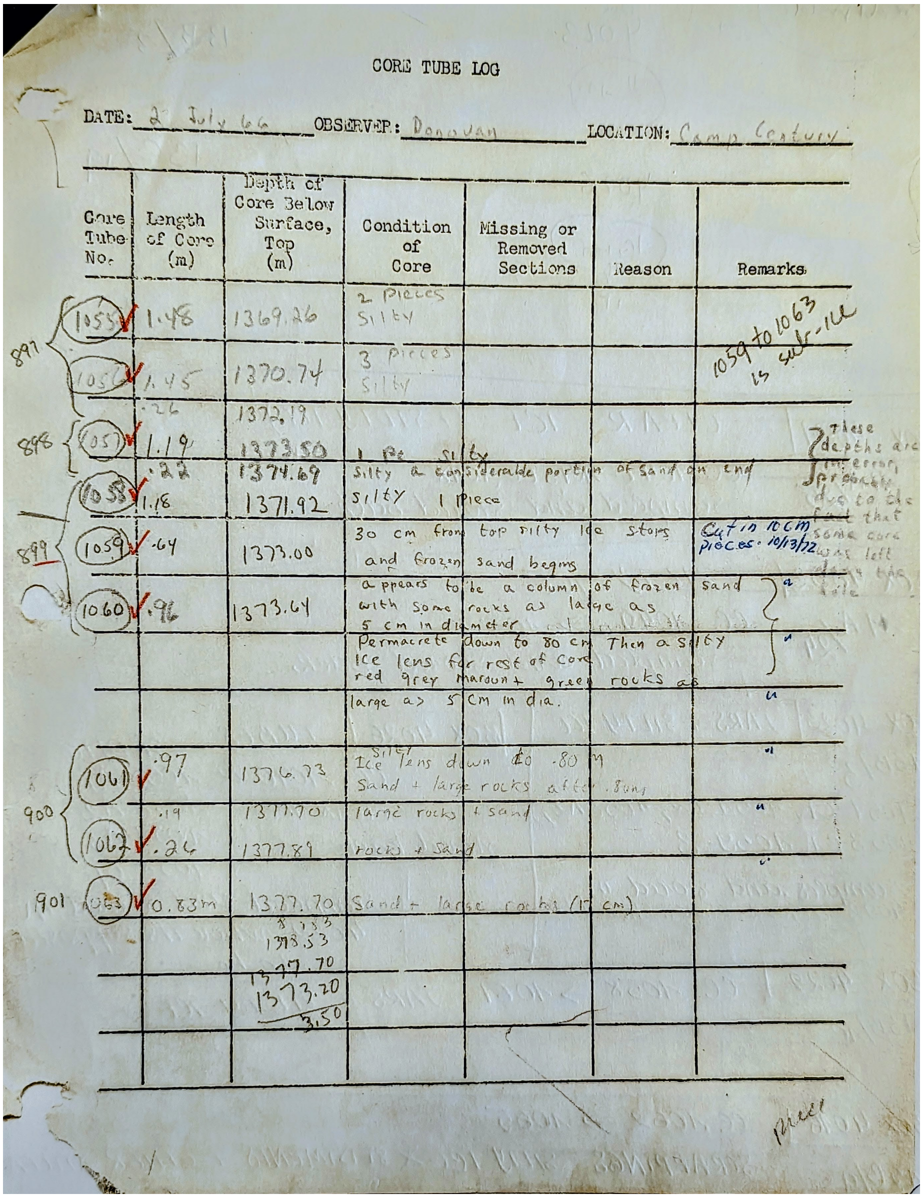

CORE TUBE LOG

DATE: 2 July 66 OBSERVER: Donovan LOCATION: Camp Century

Core Tube No.	Length of Core (m)	Depth of Core Below Surface, Top (m)	Condition of Core	Missing or Removed Sections	Reason	Remarks
1055	1.48	1369.26	2 pieces silty			1059 to 1063 is sub-ice
1056	1.45	1370.74	3 pieces silty			
	.26	1372.19				
1057	1.19	1373.50	1 pc silty			These depths are in error, probably due to the fact that some core was left down the hole
	.22	1374.69	silty a considerable portion of sand on end			
1058	1.18	1371.92	silty 1 piece			
1059	.64	1373.00	30 cm from top silty ice stops and frozen sand begins			Cut in 10 cm pieces. 10/13/72
1060	.96	1373.64	appears to be a column of frozen sand with some rocks as large as 5 cm in diameter			
			Permacrete down to 80 cm Then a silty ice lens for rest of core red grey maroon + green rocks as large as 5 cm in dia.			
1061	.97	1376.73	Ice silty lens down to .80 m Sand + large rocks after .8 m			
	.19	1377.70	large rocks + sand			
1062	.26	1377.89	rocks + sand			
1063	0.83m	1377.70	Sand + large rocks (12 cm)			
		1378.53				
		1377.70				
		1373.20				
		3.50				

Figure 4: Scan of original drilling log from Camp Century courtesy of J.P. Steffensen.

Early reports about drilling activities at Camp Century (Ueda and Garfield, 1968) and investigations of the basal materials (Fountain et al., 1981; Herron and Langway, 1979; Whalley and Langway, 1980) are in closer agreement with Hansen and Langway (1966) and report that the thickness of the silty ice and sub-glacial sediment are 16 m and 3.5 m, respectively (Table 1). Note that while most publications report the sediment core was completed on July 4, 1966, the drilling log has the date of July 2, 1966.

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Later in the summer of 1966 CE, Camp Century was abandoned, and the ice and sediment cores were transported frozen (likely with dry ice as was used for previous cores but with no record of temperature monitoring) from Greenland to the United States and stored at CRREL in Hanover, New Hampshire (Figure 3). At some point between 1966 CE and 1972 CE, the five core tubes containing the sub-glacial sediment were photographed alongside each other; the only known photograph of the intact sedimentary archive is presented in Fountain et al. (1981) (Figures 2A, 3B).

In October 1972 CE, the sub-glacial sediment from each core tube was cut into 32 segments, each about 10 cm long (Figure 3C, Table 2). The cutting of the sub-glacial sediment preceded Chester Langway's move from CRREL to the University at Buffalo in 1974. The date and sample name were recorded on tags kept with each cylindrically-shaped segment in glass jars. Each segment was given a sample name that included the tube number and a sequential number or letter (e.g., 1059-4, 1061-D1). The reasoning behind the sample naming scheme is not explained in any existing records but appears to be related to sedimentological properties observed on the exterior of the core (e.g., sediment and ice content, grain size). The entirety of the Camp Century basal ice and sub-glacial sediment was then transferred to the U.S. National Science Foundation (NSF) Ice Core Storage Facility at University at Buffalo where it remained from 1974 to 1993 CE.

There was renewed interest in the Camp Century ice core basal materials in the late 1970s and early 1980s CE. Susan L. Herron's dissertation research analyzed the ice fabric, debris content, and gas concentrations of the silty ice (Herron and Langway, 1982, 1979). Basic petrological descriptions and some Rb-Sr dating were performed on exterior pebbles and cobbles from core tubes 1062 and 1063 (Fountain et al., 1981). A scanning electron microscope (SEM) analysis of grain shape was conducted on sand from an unspecified portion of the sub-glacial sediment (Whalley and Langway, 1980). Along with five samples of the basal silty ice retained with the Camp Century ice core, segment 1060-A2 was cut during the 1980s CE for investigation for microfossils (Figure 3D) (Harwood, 1986). That sample contained abundant freshwater diatoms and some rare marine diatoms. After Harwood (1986), there is no documented investigation of the Camp Century sub-glacial sediment.

In 1993 CE, the ice cores stored at University at Buffalo, including most of the Camp Century ice core archive, were moved to Denver when the U.S. National Science Foundation contract for ice-core curation and storage was awarded to the University of Colorado for a new, purpose-built ice-core storage facility. At or after that time, the lowermost 131 m of the Camp Century ice core, including the silty ice and sub-glacial sediment, were transferred from University at Buffalo to the ice core facility at the Centre for Ice and Climate at the Niels Bohr Institute (NBI) at the University of Copenhagen, where they have remained in frozen storage in the original boxes from the University at Buffalo (Figure 3E).

The existence of the sub-ice samples was brought to the attention of the ice-core community again in 2017 CE when NBI centralized all ice-core samples to a new single-freezer storage facility. In the summer and fall of 2019 CE, sedimentological properties on the exterior of core segments were described and two pilot samples were cut using a diamond-wire saw from the upper-most (1059-4) and lower-most (1063-7) segments of sub-glacial core sediment (Figure 3F) (Christ et al., 2021). Multiple geochemical and isotopic analyses of these two pilot samples showed that the Camp Century sub-glacial sediment contained a multi-million-year-old record of glacial and vegetation history of northwest Greenland (Christ et al., 2021). In 2021 CE, 55 years after the sub-glacial sediment core was collected and 49 years to the month after it was cut into ~10-cm segments, we documented, cut, and sub-sampled the remaining frozen basal material for multiple analyses (Figure 3G).

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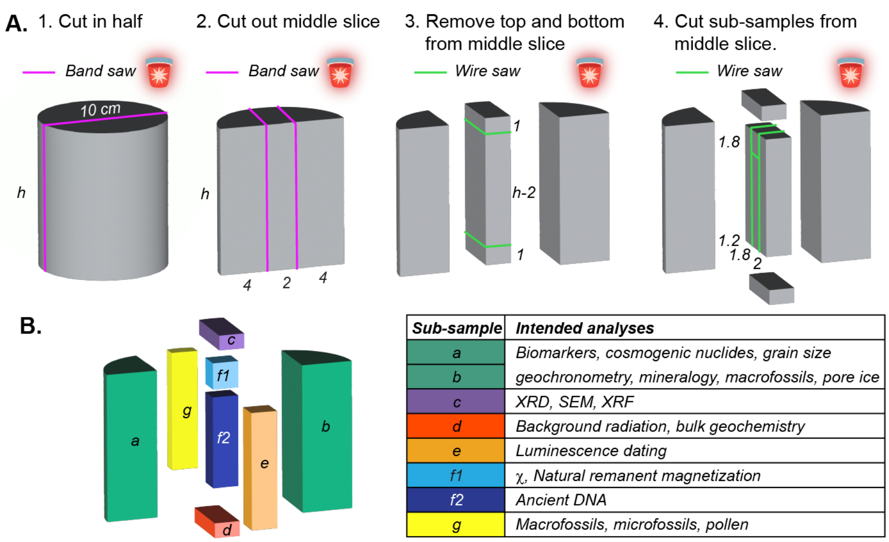
3. Methods

3.1 Sample documentation prior to sub-sample cutting

We documented the archived inventory of core segments of sub-ice material in the freezer laboratory (-20 °C) at the Ice Core Facility of the Centre for Ice and Climate, NBI, at the University of Copenhagen, Denmark. We recorded the label name, mass, and dimensions for each core segment found in the archive (Table S1). We noted ice content, grain size, and visually observable cryo-sedimentary structures for each sample. We tracked the storage orientation (i.e., top direction) of each segment during the entirety of handling and cutting. We then compared the segment name, dimensions, and storage orientation against the original core-tube logs and core photograph (Fountain et al., 1981) to reconstruct the length of sediment recovered in each core tube and to identify samples that were previously sampled, thawed, or missing. From doing this, we estimate that there were 3.44 m of recovered core material based on what is physically present in the inventory and estimating the length of samples that were thawed (n=2) and those now missing (n=2) from the archive.



Sub-sample	Intended analyses
a	Biomarkers, cosmogenic nuclides, grain size
b	geochronometry, mineralogy, macrofossils, pore ice
c	XRD, SEM, XRF
d	Background radiation, bulk geochemistry
e	Luminescence dating
f1	χ, Natural remanent magnetization
f2	Ancient DNA
g	Macrofossils, microfossils, pollen

Figure 5: Sampling cutting. A. Scaled schematic of how samples were cut using the band saw (bright purple lines) and diamond wire saw (bright green lines) in the -20 °C climate-controlled laboratory at NBI. Samples were cut under red light conditions (red light symbol) until sub-sample e was cut and packaged in aluminum foil. All numbers refer to dimension in cm, h = height. B. Sub-samples color-coded according to intended analyses.

For the remaining samples not analyzed in the pilot study (Christ et al., 2021), we took approximately 20 digital photographs of each frozen core segment from all directions. Using these photographs, we constructed three-dimensional photogrammetric models with 3DF ZephyrLite® software using default settings to produce a

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textured mesh for each sample and exported them as 3D objects. We imported the textured meshes for each sample into Adobe Dimension® and compared them against the original core photographs (Fountain et al., 1981) to reconstruct each core tube into its original orientation, determine if samples were stored upside down, and to identify any missing exterior pebbles (images archived at: https://www.morphosource.org/concern/cultural_heritage_objects/000583438). Using Adobe Photoshop® we calculated the color of the frozen sediment by extracting the average RGB value of the exterior and interior cut face of each core segment from digital photographs, converting that RGB value to a HEX color code, and then matching to the best fit Munsell soil color (Table S2).

In the climate-controlled freezer laboratory at NBI, we measured the mass and dimensions (height, radius) of each frozen core segment to calculate the volume and bulk density. Using this data, we derived an estimated % ice content by mass, assuming that this material is a two-component mixture of ice and sediment with densities of 0.9 g/cm^3 and 2.7 g/cm^3, respectively (Table S3). We assumed that core segments had cylindrical geometries for the purpose of calculating the volume. To calculate the volume of oddly-shaped segments, we measured the dimensions of specific individual segments, approximating the segment volume to the volume of "best-fit" simple 3-D geometries.

3.2 Sub-sample cutting design, shipping, and distribution

We designed our core-cutting method to ensure sufficient sample material for varied analyses, retain the orientation of samples during storage, avoid further chemical and/or biological contamination and exposure to light, and save archival material at NBI for future analysis. Using the mass and dimensional measurements, and derived bulk density and ice content for each core segment, we trigonometrically calculated the dimensions of individual frozen sub-samples needed to satisfy sample-size and mass requirements for multiple analyses (Table 3, Figure 5). We cut samples into eight oriented sub-samples (a-g) (Figure 5A) using two different saws in the -20 °C cold-room at NBI: (1) a Gryphon C-40 CR Tall Diamond Band Saw ("AquaSaw XL") with a 1 mm-thick stainless steel diamond blade (Gryphon 301SS-42) using ethylene glycol as a cutting fluid and (2) a Well Diamond-Wire Saw, Model 6234 with a 0.5 mm diameter diamond wire according to the methods of Tison (1994). We cut smaller pieces and those where we needed to avoid glycol contamination with the diamond wire saw.

Table 3: Analytical requirements for intended analyses

Count	Medium	Analysis	Purpose	Allocated sub-sample(s)	Thermal state	Minimum mass of untreated sample material required	Grain size (μm)	Special handling	Designated Laboratory
1	Frozen intact sample	Luminescence dating	Chronology	e	Frozen	40 g		Collected and measured in red light conditions	USU
2	Sediment	Cosmogenic 10Be, 26Al quartz	Chronology, surface weathering and erosion	a,b	Dried	60 g	250-850		UVM, Columbia
3	Sediment	Cosmogenic 21Ne quartz	Chronology, surface weathering and erosion	a,b	Dried	3 g	250-850		Columbia, CNRS
4	Sediment	Cosmogenic 36Cl feldspar	Chronology, surface weathering and erosion	a,b	Dried	20 g	>850		Columbia
5	Sediment	Meteoric 10Be	Chronology, surface weathering and erosion	a,b	Dried	2 g	bulk, 250-500, 500-850		UVM, CNRS
6	Sediment	Background radiation and bulk geochemistry	Luminescence dose rates, 36Cl , physical characterization	d	Dried	10 g	bulk		USU
7	Pore ice meltwater	Water stable isotopees	Paleoclimate	a	Liquid	0.25 mL		Stored in plastic, filtered	UW
8	Frozen intact sample	Ancient DNA	Paleoecology	f2	Frozen	what is available	bulk	Wrapped in plastic wrap	NBI
9	Pore ice meltwater	Dissolved organic geochemistry	Paleoecology, paleoclimate	b	Liquid	5 mL		Stored in glass, filtered	UVM
10	Bulk macrofossils	Bulk organic geochemistry (d13C, d15N)	Paleoecology, paleoclimate	a,b	Wet	0.05 g	bulk organic matieral from 63-125		UW
11	Sediment	Diatom identification	Paleoecology, paleoclimate	a,b,g	Wet	10 g	bulk		UC Boulder
12	Sediment	Foraminifera identification	Paleoecology, paleoclimate	a,b,g	Wet	10 g	bulk		UC Boulder
13	Sediment	Lipid biomarkers	Paleoecology, paleoclimate	a,b	Wet	20 g	<63		Univ at Buffalo
14	Sediment	Macrofossil assemblage	Paleoecology, paleoclimate	a,b,g	Wet	50 g	bulk		UVM, Columbia
15	Sediment	Pollen assemblages	Paleoecology, paleoclimate	a,b,g	Wet	20 g			UVM, Columbia
16	Frozen oriented cube	χ, Natural Remanent Magnetization	Physical properties, magnetostratigraphy	f1	Frozen	6.5 cm^3		Orientation maintained	Montclair State Univ
17	Sediment	Ar/Ar dating of hornblende	Sediment provenance, subglacial geology	a,b	Dried	50 g	125-250		Columbia
18	Sediment	Automated quantitative mineralogy (AQM)	Sediment provenance, subglacial geology	a,b	Dried	5 g	47-63, 63-125, 125-250		GEUS
19	Sediment	U-Pb dating of zircon, apatite, rutile	Sediment provenance, subglacial geology	a,b	Dried	20 g	47-63, 63-125, 125-250		GEUS
20	Sediment	U-Th/He dating of apatite	Sediment provenance, subglacial geology	a,b	Dried	100 g	125-250		Uconn
21	Sediment	Grain size distribution	Sedimentology, stratigraphy, physical characterization	a,b	Dried	not size dependent	bulk		UVM
22	Sediment	Particle size and shape	Sedimentology, stratigraphy, physical characterization	a,b	Dried	5 g	bulk		UVM, CNRS
23	Frozen intact sample	μCT scanning	Sedimentology, stratigraphy, physical characterization	a,b	Frozen	n/a	n/a	Orientation maintained	CRREL
24	Frozen intact sample	3D photogrammetric models	Sedimentology, stratigraphy, physical characterization	Uncut segment	Frozen	n/a	n/a	Orientation maintained	UVM
25	Frozen intact sample	Ice content	Sedimentology, stratigraphy, physical characterization	a,b	Frozen and	not size dependent	n/a		UVM
26	Frozen intact sample	Clay mineralogy SEM, XRD	Surface weathering and erosion	c	Frozen	5 g	<63		UVM
27	Pore ice meltwater	Water cation geochemistry	Surface weathering and erosion	a	Liquid	2 mL		Stored in plastic, filtered	U Arizona, UVM
28	Pore ice meltwater	Water anion chemistry	Surface weathering and erosion	a	Liquid	2 mL		Stored in plastic, filtered	Williams College

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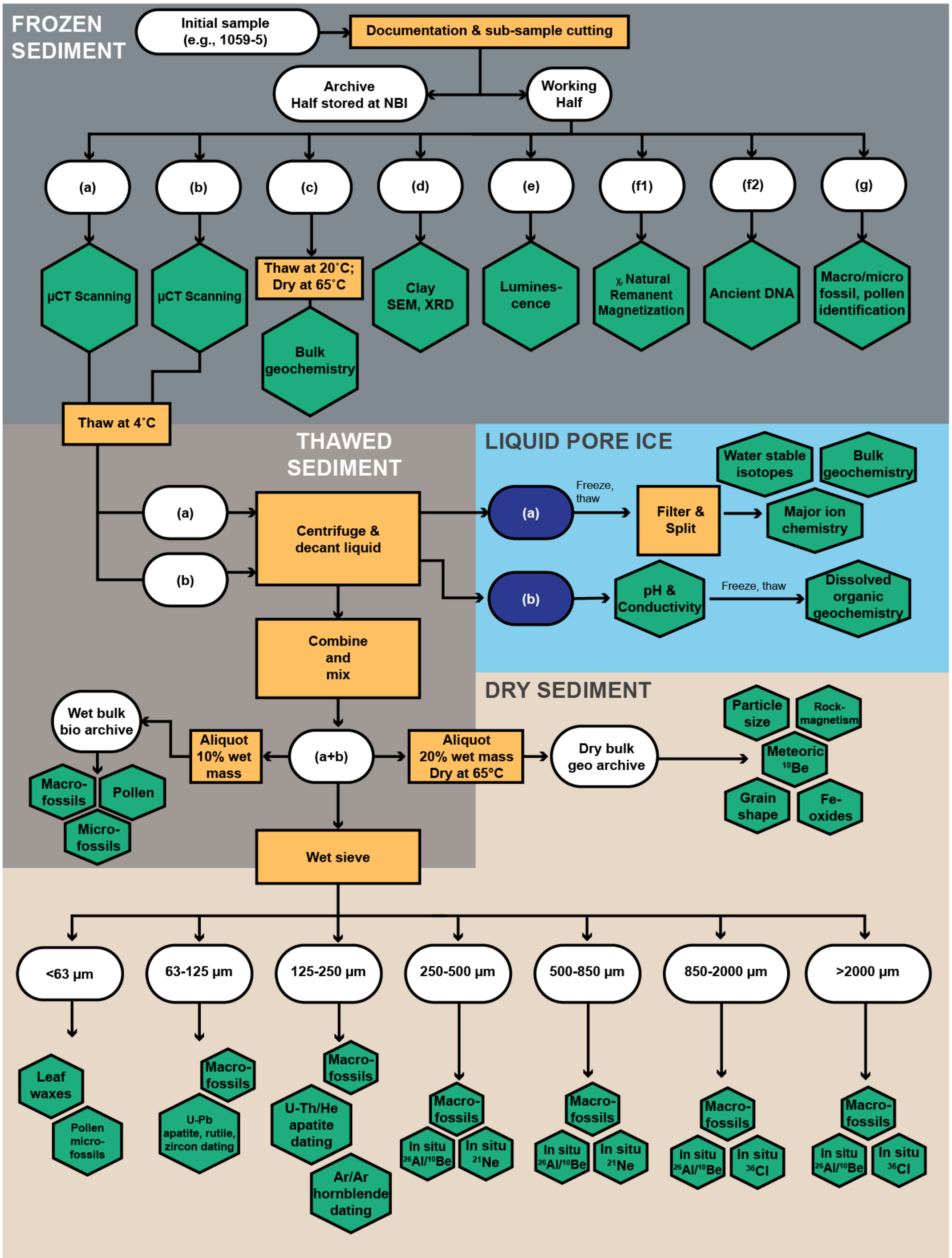

Figure 6: Sample cutting, sub-sampling, and processing flow diagram. White boxes indicate sample materials, orange boxes indicate major processing steps, and green hexagons indicate analyses.

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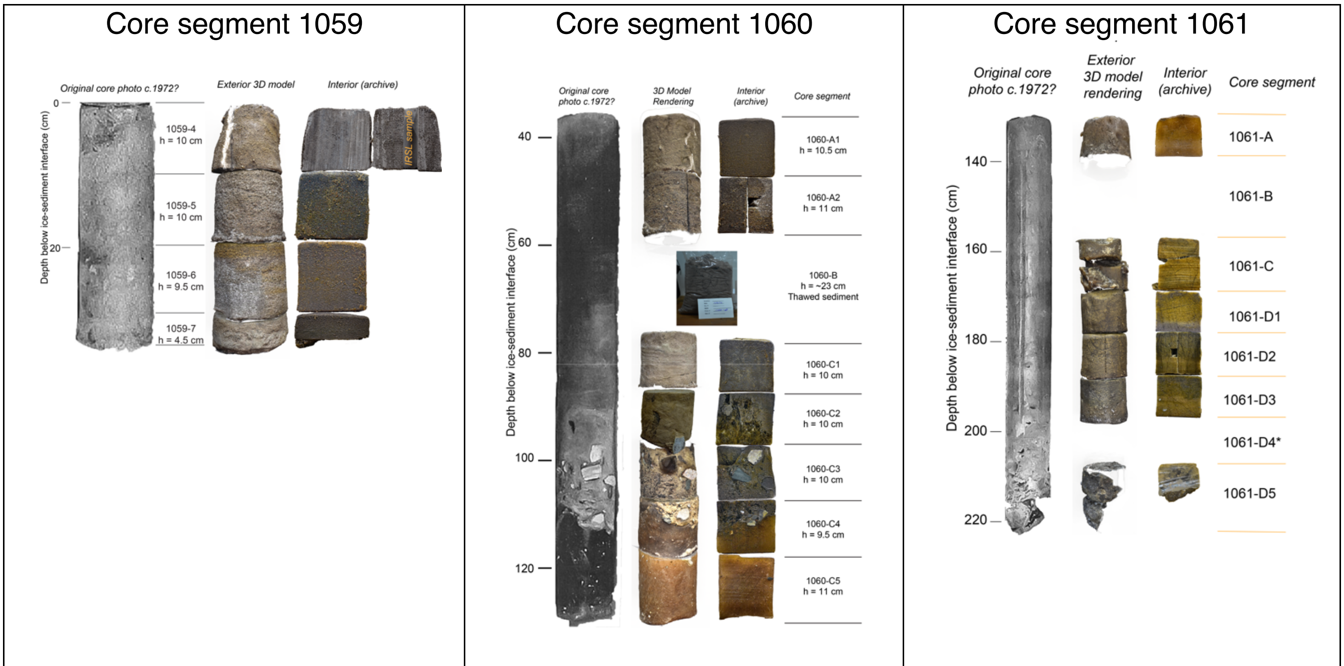

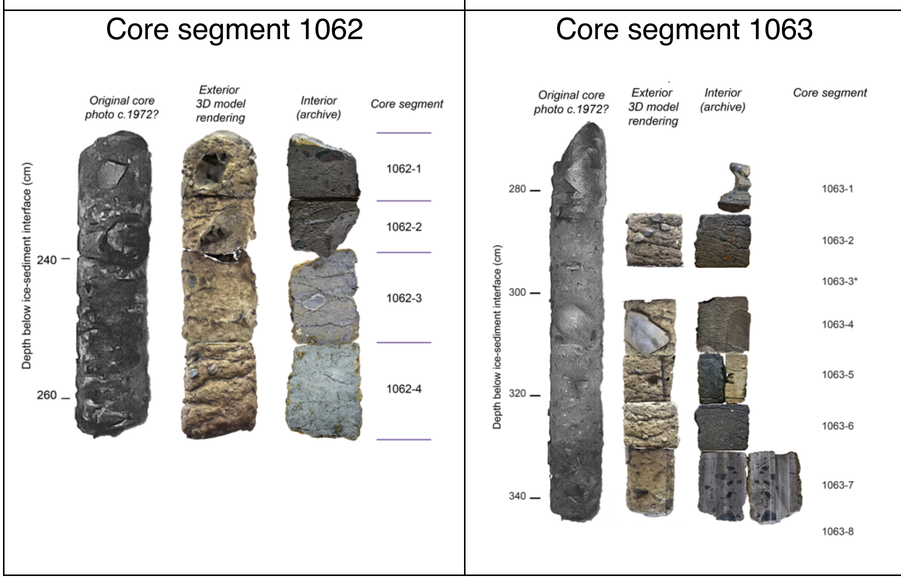

Figure 7: Each tube of the sub-ice sediment core. Comparison of the photographs taken between 1966-1972 (black and white, US Army image, public domain), the 3D photogrammetry model, and the pieces cut for this study in 2021 for this study.

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We cut core segments from the entire sub-glacial sediment core (e.g., segments 1059-5 through 1063-8). After cutting each sample, we removed the bandsaw from the freezer and cleaned it by wiping down and washing working surfaces with tap water and a clean sponge, and then allowed to air dry. We drained and replaced the glycol cutting fluid after every other sample. We saved two aliquots of the ethylene glycol cutting fluid for chemical analysis to identify any potential contamination to pore-ice and biological analyses. We replaced the bandsaw blade when it became dull, typically every 2 to 3 samples. We replaced the diamond wire when necessary, typically after a total cutting length of ~30 cm for the sediment-rich samples, or if the wire snapped during cutting. To prevent light exposure of the interior prism for luminescence measurements, we cut sub-samples (a) through (e) in red-light conditions using photography darkroom lamps and red LED bicycle lights. We handled all sub-samples with nitrile gloves and wrapped sub-sample (f2), which is devoted to biological analyses, in plastic wrap.

Using the bandsaw, we cut each core segment in half along the z-axis to produce an archival half and a working half (Figures 3D, 5A). From the working half, we cut the outer quadrants (sub-samples [a] and [b]) to isolate an interior prism of the core segment. We recorded the dimensions (width, length, height [h]) of sub-samples (a), (b), and the interior rectangular prism. Then, to isolate pristine surfaces, we cut the top and bottom ~1 cm of the interior prism using the diamond-wire saw and saved as sub-samples (c) and (d). Then, we cut the interior prism using the diamond-wire saw to remove a 2 x 2 x (h-2) cm sub-sample (e) for luminescence measurements. We wrapped sub-sample (e) in two layers of aluminum foil to secure the sediment from light exposure and placed in a separate plastic sample bag with the sample orientation kept intact. Then, in normal light conditions using the diamond-wire saw, we cut a ~1.8 x 2 x (h-2) cm slice and from that slice cut a 1.8 x 2 x 2 cm cube of sediment (sub-sample [f1]) for paleomagnetic measurements. We placed sub-sample (f1) into a labeled plastic paleomagnetic cube with the core orientations maintained. The remaining outer piece, sub-sample (g) was kept for macro- and microfossil identification and stored in a separate bag. While most samples were ~10 cm-tall cylinders, we applied slightly different procedures for segments that were previously cut or thawed for sampling, had odd or small geometries, or were too delicate to cut according to the cutting design (Table 4). For all samples, we saved any loose material from the storage container as a separate 'residual' sub-sample for method testing and replicate measurements. We recorded the masses of each sub-sample (a-g), residual material, and archive half (Table S1). The cut interior face of the archived half and sub-samples (a) and (b) were photographed and then briefly described to note ice content, sedimentological properties, and sedimentary features.

We placed sub-samples (a-d) in the same plastic bag with sample orientations maintained (e.g., up and down direction). All sub-samples (a-g) were kept in the storage freezer at NBI (-30 °C) prior to transfer from NBI to the University of Vermont. The archive halves of all samples remain in the NBI ice core facility in plastic bags inside of glass jars in closed foam boxes shielded from light. We packed sub-samples into insulated shipping containers lined with brine freeze packs that constituted 50% of the interior container volume and allowed to equilibrate at -30 °C for two days before being sealed for transport. We transported all sub-samples from NBI via commercial air travel on a direct flight from Copenhagen, Denmark to Newark, NJ. Within 1 hour of arrival, we transferred samples into a -20 °C chest freezer at Montclair State University and allowed them to cool for two days. We repacked the samples into insulated shipping containers and transported them by car from Montclair, NJ

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to Burlington, VT, where samples were promptly transferred into a -20 °C chest freezer with back-up power and high limit alarms for storage. At all times, samples have remained frozen.

We distributed sub-samples (e) and (d) for the luminescence and bulk chemistry measurements. We placed sub-sample (e) into labeled, opaque resealable bags and then shipped them frozen to Utah State University for luminescence measurements. We thawed each sub-sample (d) overnight in a 65 °C oven, massed each again, and then the dried sediment was shipped to Utah State University for bulk geochemistry and background radiation analyses that will be used for luminescence dose-rate calculations, and interpretation of cosmogenic ^{36}Cl concentrations, and as a comparator for pore water chemistry.

Table 4: Samples with altered cutting or sub-sampling

Sample	Alteration	Reason
1059-7	Thickness of sub-samples (c) and (d) reduced to 0.5 cm	Thin segment; optimized amount of frozen material for (e,f, and g)
1060-A2	Swapped the positions of sub-samples (e) and (f) in the inner prism	Previous cutting exposed inner portion of core to light. Re-arranged to avoid light contamination for (e)
1060-B	All sub-samples collected as grab samples	Sample was thawed and preserved as bulk sediment
1061-C	Sub-samples (e) and (f2) contained two fragments	Sample had fractured during storage
1061-D2	Swapped the positions of sub-samples (e) and (f) in the inner prism	Previous cutting exposed inner portion of core to light. Re-arranged to avoid light contamination for (e)
1061-D4	Not sub-sampled	Sample was missing from archive
1061-D5	Lower ice/rock fragment kept as sub-sample (x)	Sample had odd geometry
1062-4	Sub-samples (e) and (f2) contained two fragments	Sample fractured during wire cutting
1063-1	Sub-samples (a), (b), and (g) taken from fragments on outer part of core	Odd geometry, samples fragmented along ice lens planes
1063-3	Not sub-sampled	Sample was missing from archive
1063-4	Sub-sample (f1) collected from lower slice of inner prism b not kept	Large cobble in sample
1063-5	Swapped the positions of sub-samples (e) and (f) in the inner prism	Previous cutting exposed inner portion of core to light
1063-8	Sub-sample (b) not kept, sub-samples (f1) and (f2) cut from outside of inner prism	small sample

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3.3 Analysis of frozen sediment

Using frozen sub-samples, we measured magnetic properties (f1) and collected micro-computed tomography (µCT) scans (a, b). We measured the magnetic susceptibility of the frozen (f1) sub-samples from each core segment at Montclair State University. Susceptibility measurements were collected in an applied field of 200 A/m and at two frequencies (976 Hz and 3904 Hz) using an AGICO MFK2A Kappabridge (Table S4). Here we report the measurements made at 976 Hz (χ_{976Hz}) as the low-field susceptibility.

Samples were then measured for paleomagnetic inclination, declination, and intensity of remanence at alternating field demagnetization (AFD) levels of 0 mT (natural remnant magnetization [NRM]), 10 mT, and 20 mT using an AGICO JR-6 Spinner Magnetometer (Table S5) and D-tech alternating field demagnetization unit. Samples were kept frozen between AFD treatments. However, by the 20 mT step many of the frozen blocks had partially deformed inside their plastic cubes, and we therefore discontinued AFD treatments. We corrected the orientations of samples that were later noted to have been stored upside down at NBI by rotating the NRM vector 180˚ around the x-axis in the sample coordinate system.

We collected µCT scans from the (a) and (b) sub-samples to create a digital, three-dimensional record and to non-destructively observe and measure sedimentological properties (e.g., porosity, grain size and grain shape) and stratigraphic features at sub-mm-scale resolution. We scanned sub-samples (a) and (b) from each segment using a Bruker SkyScan1173 µCT scanner fit for use in a -10 °C cold room at CRREL in Hanover, NH. Full-sized, ~10 cm-tall samples were scanned at 71 µm/pixel resolution in two overlapping 7.9 cm-tall scans for the bottom and the top of each sub-sample to ensure that the entire sample was scanned.

3.4 Processing and analysis of thawed sediment

Following full documentation and µCT scanning of sub-samples (a) and (b), we thawed these sub-samples from each segment to extract pore ice meltwater, save aliquots of bulk material, and isolate specific grain-size fractions used for varied analyses. For each core segment, we placed sub-samples (a) and (b) in separate sealed plastic and glass containers, respectively, to avoid contamination for pore-ice measurements designated for each sub-sample. Plastic was used for sub-sample (a) because pore ice in this sub-sample was analyzed for stable water isotopes, bulk geochemistry, and major ion chemistry. Glass was used for (b) because pore ice in this sub-sample was analyzed for dissolved organic geochemistry. We measured the frozen mass of each sub-sample, thawed the sub-samples overnight in a 4°C refrigerator, and then re-measured the thawed mass to ensure that no water was lost due to evaporation. After thawing, we transferred the sediment into two 250 mL Nalgene bottles that were centrifuged for 20 minutes to isolate porewater from the solids. The liquid supernatant from sub-sample (a) was transferred into a 50 mL plastic vial, and the supernatant from sub-sample (b) was transferred into a glass test tube. We recorded the mass of the melted pore ice for both sub-samples. Melted pore ice from sub-sample (a) was then stored frozen at -15 °C immediately after it was recovered. We measured pH and conductivity in melted pore ice from sub-sample (b) using calibrated hand-held Myron L conductivity and pH meters (Table S6). Melted pore ice from sub-sample (b) was transferred to a glass jar and stored frozen at -15 °C.

We recombined, gently mixed, and homogenized the wet thawed sediment from sub-samples (a) and (b) and recorded the recombined mass. We saved two bulk aliquots of the recombined sediment. First, ~10% by mass

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of the wet sediment was stored in a plastic bag at 4°C as wet bulk archive for additional biological analyses (e.g., pollen, microfossil, macrofossil characterization). Second, 20% by mass of the wet sediment was oven-dried at 65°C and saved as a dried bulk archive for geological and sedimentological analyses (grain shape, particle size, meteoric ^{10}Be); the mass was recorded before and after drying to calculate the water lost (Table S7). We calculated the % ice content by mass for each sample by subtracting the total mass of water removed for pore ice meltwater samples and the estimated loss of water from drying from the total thawed sediment mass (using the % water lost from the bulk geological aliquot) (Table S7). Then we wet sieved the remaining thawed sediment and stored in plastic bins the >2000, 850-2000, 500-850, 250-500, 125-250, and 63-125 µm grain size fractions. The <63 µm fraction was stored in an acid-washed 5-gallon bucket and allowed to settle for at least 72 hours before decanting water via suction. We transferred the settled wet <63 µm fraction into plastic bags and stored it frozen at -15 °C and then shipped the frozen samples to the University at Buffalo for lipid biomarker analyses. For grain sizes >63 µm, we visually inspected each grain-size fraction for macrofossils and transferred macrofossil specimens floating in water using disposable pipettes into petri dishes for observation and photographic documentation under a dissecting microscope. We transferred macrofossils from each grain size fraction to glass vials filled with distilled (DI) water for storage at 4°C. After removing macrofossils, we dried each grain-size fraction in plastic bins at 60°C overnight, and then measured its dry mass. The dried sediment was stored in plastic bags at room temperature. We calculated the grain-size distribution of each sample using the estimated total dry mass of each sample, the dried masses of each grain size fraction >63 µm, and the estimated the <63 µm mass (Table S7).

For samples composed primarily of ice rather than sediment, we adapted this processing flow. Using a handsaw, we cut sub-samples from 1060-C4 to separate frozen sediment (1060-C4sediment) from underlying sediment-laden ice (1060-C4ice). For the ice-rich samples (1060-C4ice through 1061-D5) only one quadrant (a or b), whichever was smaller by mass, was processed according to the procedure above. The remaining quadrant remains frozen and in storage for future high-resolution sampling and analysis.

4. Results

Below we detail our documentation efforts and results from processing the different sub-samples for an array of analyses (Table 3). We report data for physical properties directly measured on the core as it was processed. Additional data from geochemical, isotopic, and geochronologic analyses will be reported elsewhere. This paper reports fundamental observations that we made during core processing and develops a core stratigraphy to provide context for research performed on sub-samples allocated from the core.

4.1 Sample preservation

Based on our measurements of cut core segments and our reconstruction based on a photograph taken before the core was cut, the Camp Century sub-glacial sediment core is 3.44 m long, which is slightly less than what was originally reported (3.55 m). Our work reveals that most of the core (28 of 32 segments) is intact. Two segments (1061-D4, 1063-3) are missing without documentation of their current location or use for previous analysis. Two segments were previously thawed and have been refrozen: 1060-B is loose, dry sediment and 1061-B is loosely compacted ice particles.

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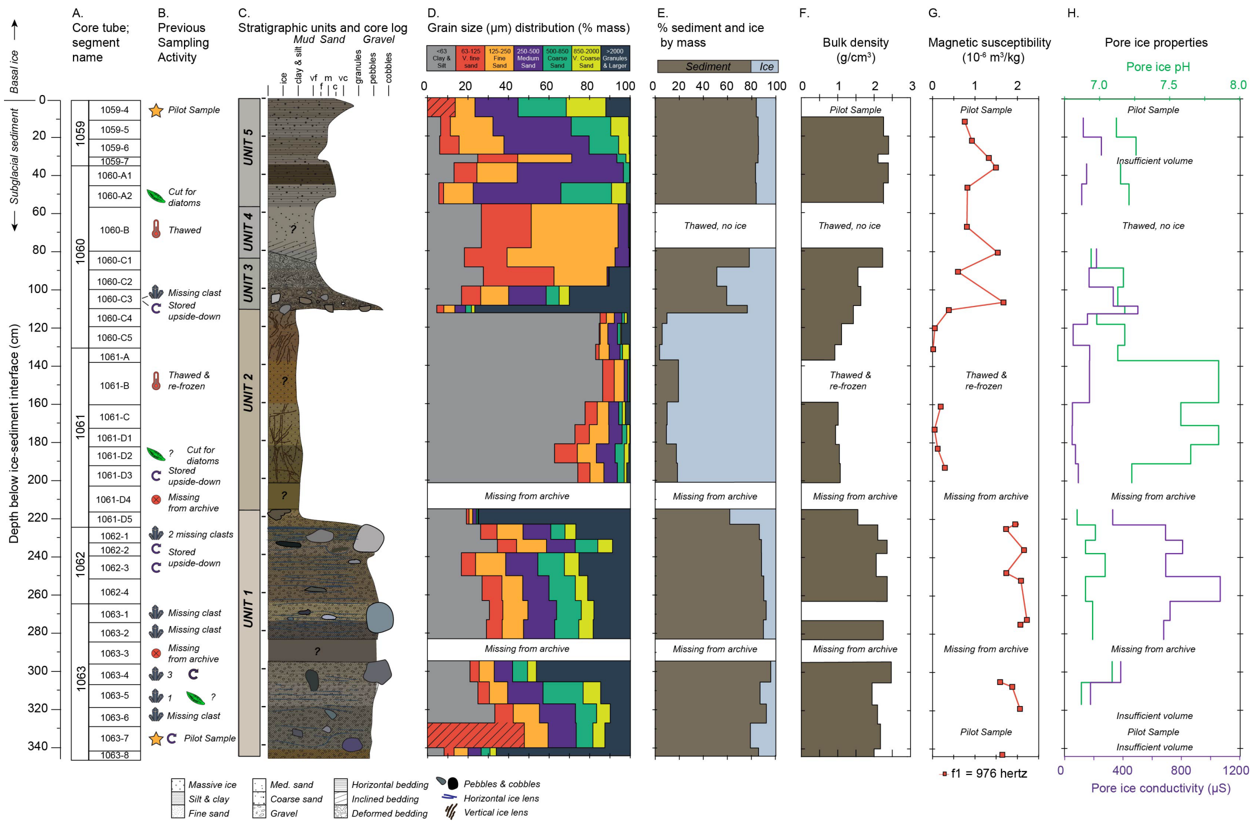

Figure 8: Results compiled from sample documentation and processing (from left to right). A) core tube numbers and sample names created when the core was cut in 1972; B) evidence of altered, previously investigated, or missing samples based on literature, photographs, and recent documentation; C) stratigraphic units and core log; color corresponds to the average soil color of each sample segment; vf – very fine sand, f – fine sand, m – medium sand, c – coarse sand, vc – very coarse sand; D) grain size distribution (by mass) measured from wet sieving; dashed pattern in 63-125 µm for segments 1059-4 and 1063-7 denote <125 µm fraction; E) percent sediment and ice content (by mass); F) frozen bulk density; G) magnetic susceptibility (□) measured at 976Hz; and H) pore ice pH and conductivity. Gaps in datasets due to thawed or missing segments, insufficient pore water, non-cylindrical geometries, or analyses not made on pilot samples.

We confirmed past sampling and investigation of some core segments. A quadrant from segments 1060-A2, 1061-D2, and 1063-5 was previously cut and ~1 cm^3 samples were collected from the interior of the cut quadrant of the core (Figure 3D). These samples were presumably collected for diatom analysis as Harwood (1986) reported abundant freshwater diatoms in segment 1060-A2; however, there is no documented record of diatom analysis in the other two segments. The outer ~3 cm of two 10-cm long segments (1059-4, 1063-7) were

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cut, thawed, and analyzed separately in 2019 CE for a pilot study (Christ et al., 2021). We identified cavities on the exterior of several core segments, some of which correspond to pebbles that were analyzed in Fountain et al. (1981): 1062-1 (2 pebbles), 1063-1 (1 pebble), 1063-2 (1 pebble), 1063-4 (3 pebbles), 1063-5 (1 pebble), 1063-6 (1 pebble). One pebble from the exterior of segment 1060-C3 is missing but there is no documentation of previous sampling activity for this segment. It is possible that this is the clast Herb Ueda mentions in his oral history as having sent to a colleague in Japan (Shoemaker, 2002). Based on the comparison of the original core photograph (Fountain et al., 1981, Figure 2) with recent photographs, 3D photogrammetric models, and visual inspection of the core interior, we identified six core segments that were stratigraphically inverted during storage: 1060-C3, 1061-D3, 1062-2, 1062-3, 1063-4, and 1063-7. Additionally, one side of several segments had a flat icy surface, which may have formed due to partial thawing and refreezing of these segments when they were removed for sampling or photography in the past (e.g., Fig. 3C; Table S). All other segments were cylindrical and therefore had not melted.

4.2 Sedimentology and stratigraphy

Based on the grain-size distribution, the pore-ice content, and sedimentary structures observed on the core cut faces, we identified five stratigraphic units in the Camp Century sub-glacial sediment core (Figure 8). At the base of the core, Unit 1 (215 to 344 cm depth below the ice-sediment interface; segments 1063-8 through 1061-D5) is an olive gray (5Y 4/2) homogeneous, poorly-sorted, clay-rich dimictic (all colors are Munsell designations). Pebbles and cobbles are sub-angular to sub-rounded. Pebbles are composed of a variety of lithologies (e.g. granite, gabbro, tonalite, sandstone); several cobbles in this unit were previously sampled and petrologically analyzed (Fountain et al., 1981). Unit 1 is 11 ± 4% ice by mass and contains sub-horizontal, mm-scale ice lenses with thicknesses ranging from 1 to 2 mm and spacing ranging from 1 to 5 cm. Ice lenses generally do not intersect pebbles and some ice lenses intersect each other. The contact between Unit 1 and 2 is not readily observable due to the fractured and non-cylindrical geometry of core segment 1061-D5 but is suggested by a shift from clay-rich dimictic to sediment-laden ice at 215 cm depth.

Unit 2 (112 to 215 cm depth; segments 1061-D5 through 1060-C4ice) is composed of olive (5Y 4/4) sediment-laden ice, containing sub-vertical inclusions of ice that are longer than they are wide and without sediment. Unit 2 is clearly distinct from sub-glacial sediment (Herron and Langway, 1979). Inclusions commonly cross-cut each other and show tight folded structures based on visual observations. The lower half of Unit 2 (158 to 215 cm depth) displays horizontal color banding between light olive brown (2.5Y 5/6) ice and brown (10 YR 3/2) ice that likely corresponds to greater sediment content that is mostly silt and clay (72 to 78%) with minor amounts of fine to medium sand and rare pebbles. Segment 1061-B (140 to 158 cm depth) was previously thawed and refrozen so there is no observable stratigraphy or structure. The upper part of Unit 2 (112 to 140 cm depth) is moderate orange (10Y 3/2) silty ice with brown (7.5YR 2/4) sub-vertical ice-filled lenses. Sediment content is low (4 to 10% by mass) and is dominated by silt and clay (84%) with minor amounts of fine sand and rare pebbles in ice matrix. Sediment content and grain size decreases in the upper 70 cm of Unit 2. The contact between Unit 2 and Unit 3 (112 cm depth, segment 1060-C4) is unconformable, with pebbly gravel resting over an irregular ice surface.

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Unit 3 (85 to 112 cm depth) is dark olivish gray sediment (2.5 GY 4/2) that fines upward from a pebble gravel to sands and mud in a dark amber (7.5Y 3/4) ice-supported matrix (22 to 49% ice by mass); sediment is concentrated in deformed bands separated by ice. This unit contains abundant macrofossils. Unit 4 (55 to 85 cm depth) is dark greenish gray (10Y 4/2) very fine and fine sand with slightly inclined bedding. Due to prior melting of segment 1060-B we cannot evaluate the ice content within much of this unit. There is a gradational contact between Unit 4 and Unit 5 at ~55 cm. Unit 5 (0 to 55 cm depth) is olive gray (5Y 4/2) bedded medium and coarse sand that is 15% ice by mass.

4.3 Physical characteristics

Bulk density and χ_{976Hz} measurements (Figure 8F, G) both correspond to the stratigraphy and sediment content with generally higher values in the sediment-rich units and lower values in ice-rich units. Bulk density is 2.2 ± 0.2 g/cm^3 (mean ± 1σ) in Unit 1, decreases to 1.1 ± 0.2 g/cm^3 in Unit 2, increases to 1.7 ± 0.3 g/cm^3 in Unit 3, and then increases to 2.3 ± 0.1 g/cm^3 in Units 4 and 5. χ_{976Hz} values are greatest in Unit 1 (1.93 ± 0.22 x10^{-6} m^3/kg), lowest in Unit 2 (0.16 ± 0.14 x10^{-6} m^3/kg) where sediment is substantially diluted by ice, variable in Unit 3 (1.27 ± 0.59 x10^{-6} m^3/kg), and similar through Units 4 and 5 (1.03 ± 0.31 x10^{-6} m^3/kg).

4.4 Paleomagnetic measurements

Paleomagnetic inclinations in Units 1, 3, 4 and 5 are highly variable (Table S5). We do not consider the silty-ice of Unit 2, > 80% ice, to be a reliable geomagnetic field recorder. The steepest inclinations were observed at the 0 mT (NRM) AFD level, which may reflect the acquisition of a viscous remanence in the downward direction (+Z in the sample coordinate system) while in storage at NBI (Figure 3E). Inclinations at the 10 mT and 20 mT AFD levels are shallower than the expected geocentric axial dipole value of 84° at the site latitude, which could result from compaction of subglacial diamict, post-depositional slumping, disturbance from permafrost, or partial thawing of the sample during the AFD treatments and measurements. Identification of normal or reversed polarity is possible from subglacial and grounding line sediment (Hodson et al., 2016; Wilson et al., 2012), though challenging in the Camp Century core due to our limited number of AFD levels. The majority of our samples display positive inclinations, consistent with normal polarity, with the possibility of 3 reversed polarity or excursion intervals in Units 1 and 2.

4.5 Pore ice pH and conductivity

Melted pore ice pH and conductivity are generally inversely related throughout the core (Figure 8H). Conductivity is the lowest in Unit 2, with the highest percentage of ice by mass, and higher in the other units, with maximum values where the percentage of fine grains is the highest. Conversely, pH is the "mirror image" of the bulk density profile, with lower values in sediment-rich units (i.e., Units 1-3, 5) and higher values in ice-rich units (i.e., Unit 2). Unit 1 generally has the lowest pH (mean ± 1σ: 6.96 ± 0.07) and highest conductivity values (653 ± 250 µS, maximum: 1066 µS), while Unit 2 has the highest and most variable pH (7.37 ± 0.35) and lowest conductivity values (129 ± 85 µS; minimum: 52.1 µS). In Unit 3, conductivity increases up-core from 168 to 502 µS but displays stable pH values (7.11 ± 0.10). Units 4 and 5 have similar pH (7.14 ± 0.11) and generally low conductivity (174 ± 53 µS).

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4.6 Macrofossils

Macrofossil remains are present in all of the sub-samples we examined (Figure 9). Initial observation and photographic documentation of isolated macrofossils in sub-samples (a) and (b) indicates that plant macrofossil remains are most abundant in Units 3 and 4, and insect remains are present in Units 1, 3, and 5. Macrofossils are least abundant in Unit 2. The quality of macrofossil preservation is consistently better in the largest size fractions, 850-2000 µm and >2000 µm. In Unit 1, samples contain primarily woody debris, and bryophyte leaves or stem fragments. At the interface between Unit 1 and 2, sample 1062-1 contains insect remains, including chironomid larval head capsules. Unit 2 contains sparse plant remains, mostly fragments of bryophyte leaves. Within Unit 3, a partial chironomid pupa was recovered from sample 1060-C1. Macrofossils in Unit 4, sample 1060-B, are abundant and distinct from those of samples below, including fungal sclerotia. Within Unit 5, samples 1060-A1 and 1059-5 contain chironomid larval head capsules.

5. Implications

5.1 Acquisition and sampling of basal ice core materials

The Camp Century sub-glacial sediment core is a unique archive. It was the first sub-glacial archive recovered from beneath any ice sheet and remains the longest sub-glacial sedimentary archive recovered from Greenland. This sediment archive is also unique because it was carefully curated since 1966; with the exception of two missing samples and two previously thawed samples, the remainder of the archive was still frozen and intact. While the historic documentation of previous cutting, sampling, and core handling activities is incomplete, the excellent preservation of this archive allowed us to reconstruct the original orientation of the sub-glacial sediment core and then design and execute this detailed and comprehensive sampling and analysis plan. We archived, handled, and processed this sediment to ensure that future studies are not compromised either due to contamination or inadvertent loss of key grain-size fractions and minerals for varied analyses that have yet to be developed.

The framework that we devised in this study draws upon the sub-sampling approaches commonly used for ice cores, lake, and marine sediment cores, which save archival material and allocate samples for a variety of analyses (e.g., Hodson et al., 2016; Mckay et al., 2019; Priscu and SALSA Science Team, 2021; Souney et al., 2014). These large community efforts today devise sampling plans that consider current and future, as yet unknown, analytical techniques prior to core collection. In contrast, we devised our plan 55 years after core collection. We share this historical documentation, intentional core cutting and sub-sampling design, and results as a guide for the many on-going and future analyses of the Camp Century sub-sediment archive that will shed light on the paleoclimate conditions, ice-free ecosystems, surface and sub-glacial processes, and chronology of sediment deposition.

This analytical framework could also be useful as a baseline for the study of other sub-glacial sediments, since our preliminary results (Christ et al., 2021) demonstrate that small amounts of rare, archival sub-ice sample material can be used to answer pressing questions in paleoclimate, such as the long-term history of ice sheets. The approach we outline here is currently being used not only for the US National Science Foundation funded project to understand the sub-ice sediment from Camp Century but also by a European Research Council Project

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focused on basal ice core materials from several ice cores including historical ones from Camp Century and Byrd Station.

5.2 Initial interpretation of sediment core stratigraphy and paleo-environments

The Camp Century sub-glacial sediment preserves evidence for different surface and depositional processes in both glaciated and ice-free environments. The absence of stratification, variable grain size, shape, and poor sorting suggest that the diamicton at the base of the core (Unit 1) was sub-glacially deposited, likely as a basal till. The fragmented macrofossil remains in Unit 1 are likely derived from an older non-glaciated landscape and were later incorporated into the till by overriding ice. The presence of mm-scale ice lenses throughout Unit 1 are consistent with permafrost activity; we have little constraint on the age of these ice lenses except that they must have formed after sediment deposition (< 3 My; Christ et al., 2021).

The contact between Units 1 and 2 marks a shift from glaciated to deglacial conditions. The formation of the silty ice in Unit 2 could be explained by different surface processes including permafrost ice wedges, shallow seasonally-thawed thermokarst ponds, or segregation ice. Given the depositional environment and the relatively even distribution of silt throughout the unit, Unit 2 could also represent remnants of basal silty ice buried under the upper units at the time of glacial retreat. Further analysis, including new chronological and stable water isotope data, may better indicate how this unit formed. The unconformable contact between Units 2 and 3, along with upward fining in grain size and abundant vegetation macrofossils, suggests the sediment in Unit 3 might have been deposited by slumping. The very fine to fine-grained bedded sand with abundant macrofossils in Unit 4 suggest subsequent subaerial sediment deposition by low-energy flowing water. The coarsening in grain size up-core from Unit 4 to 5 suggests sediment deposition by higher-energy water. The abundance of well preserved and delicate macrofossil fragments demonstrates the presence of a subaerial ecosystem during the deposition of Units 3, 4, and 5.

The preservation of delicate frozen macrofossils and bedding structures suggests that the internal structures of the Camp Century sub-glacial sediment in units 3, 4 and 5 have not been internally deformed. Basal borehole temperatures at Camp Century (-13.0 °C at time of drilling, -11.8 °C corrected for pressure-melting using local ice thickness) are far below the pressure melting point (MacGregor et al., 2016), indicating that the northwestern Greenland Ice Sheet is presently cold-based and therefore non-erosive. The basal thermal state, and thus erosional character, of this sector of the ice sheet likely varied in the time since the sediment was deposited and over-ridden by ice; however, we have no way to determine if or how much overlying sediment was initially present and then eroded after deposition.

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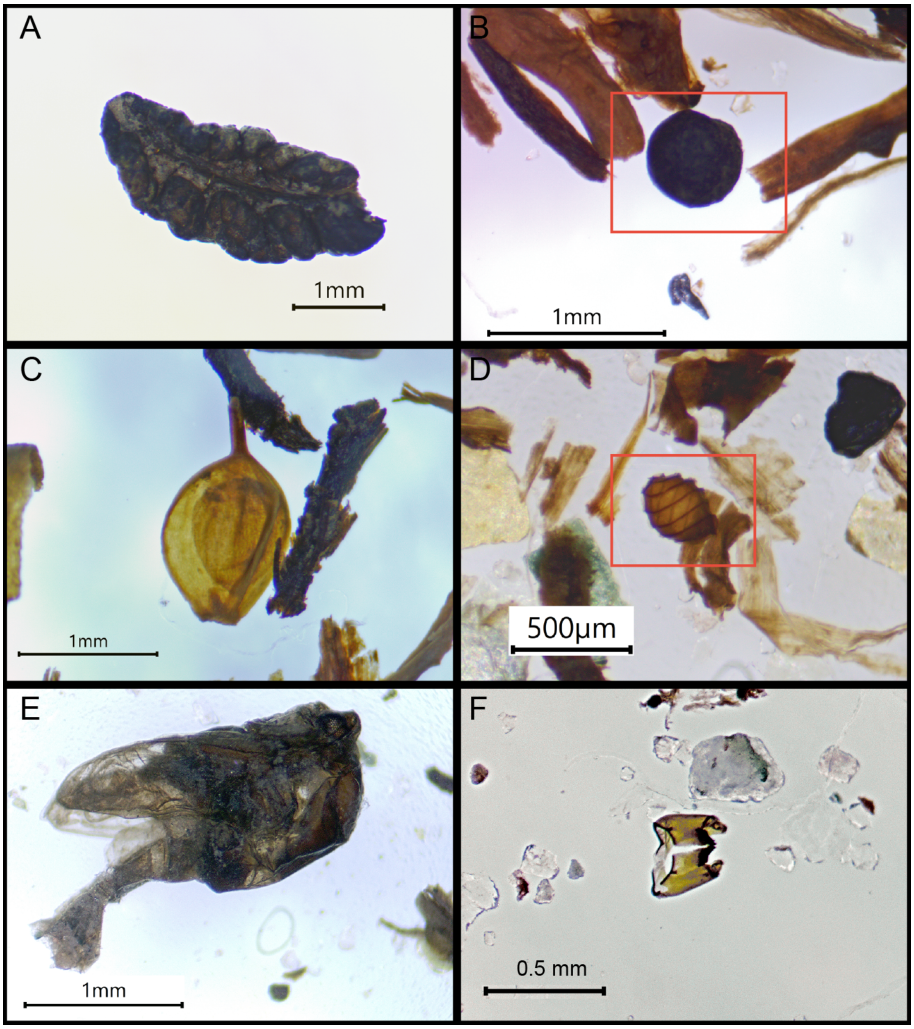

Figure 9: Examples of macrofossils recovered during wet sieving: A) *Dryas octopetala* leaf (1060-A2); B)
560 ***Cenococcum geophilum* sclerotium [red rectangle] (1060-C2); C) *Cyperaceae* seed (1060-C1); D) *Characeae* oospore [red rectangle] (1060-C1); E) partial chironomid pupa (1060-C1); F) chironomid larval head capsule (1062-1).**

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Code/Data availability

We provide data in the manuscript and supplemental tables. Photogrammetric models of most core segments are available for viewing and download at this on-line, public repository: https://www.morphosource.org/concern/cultural_heritage_objects/000583438

Author contributions

AC and PB designed the sample processing methodology with input from TR and ET. JLT, PHB, FF, AC did core logging and cut the core. AC wrote the initial draft of the manuscript and drafted the initial figures with input and data from PB, HM, JS, and CC. All authors read and edited several drafts of the manuscript. PB did several rounds of revision of text and figures with the authors and submitted the manuscript.

Competing interests

The contact author has declares that at least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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Supplementary materials

Table S1: Sample depths and frozen sub-sample masses

Table S2: Soil color

Table S3: Bulk density

Table S4: Magnetic susceptibility

Table S5: Natural Remanent Magnetization

Table S6: Pore ice pH and conductivity

Table S7: Sediment and ice content

Table S8: Grain size distribution

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Table S9: Samples altered during storage

Figure S1: Comparison of estimated and measured ice content