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What can deep ice, water, sediments, and bedrock at the ice–bed interface tell us?

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We describe the ice, water, bedrock, and sediments found at the ice–bed interface during ice-core drilling and the insights into paleoclimate, ice dynamics, ice-sheet history, and geologic history that they provide.

Ice cores have commonly been collected to develop continuous paleoclimate records and to analyze atmospheric gases in the ice column. Recently, scientists have recognized that materials at the ice–bed interface yield invaluable information about Earth and ice-sheet history on longer timescales. Research is now being devoted to finding million-year-old-plus ice at the bottom of ice sheets, investigating basal thermal regimes, and analyzing sub-ice sediment and bedrock samples collected during drilling campaigns.

Ice at the bottom of ice sheets

Paleoclimate signals preserved in ice cores are revealed, for example, through the analysis of isotopes (Fig. 1), which serve as fingerprints of climate (Wendt et al. p. 102). These signals are captured by yearly surface accumulation, layering younger ice on top of older ice. Under typical conditions, the oldest ice is found at the bottom of ice sheets; however, areas of high ablation can bring this old ice to the surface. While ice has covered parts of East Antarctica for millions of years and central parts of Greenland for ~1 million years, the longest continuous ice-core records extend to only ~800,000 years in Antarctica (Jouzel et al. 2007), and ~128,000 years in Greenland (NEEM community members 2013). Recovering ice-core samples that extend the current climate record to over 1 million years would provide insights into climate change across the Mid-Pleistocene Transition (~1.2 to 0.9 million years ago), a key climate period marked by the changing cyclicity of glacial cycles (Dahl-Jensen 2018). To produce an uninterrupted and coherent record of climate across this transition, continuous stratigraphy is needed; however, discontinuous "snapshots" are also valuable.

Ice flow over rough bed topography and heat from the Earth below can, over thousands of years, disrupt the stratigraphy of the ice column, complicating the age–depth relationship (Martin et al. p. 100). Disturbed chronology is present in long ice cores recovered from Greenland, where ice has folded or overturned near the bed (Chappellaz et al. 1997). In Antarctica, the combination of complex bed topography and ice flow has caused discontinuous layers of old ice to be thrust towards relatively shallow depths, with ~4.3–5.1-million-year-old ice outcropping in the Transantarctic Mountains (Bergelin et al. 2022). Ice cores with disturbed chronologies, while valuable, inhibit the development of continuous paleoclimate records. Efforts are now focused on using ground-penetrating and phase-sensitive radar to examine internal ice-sheet stratigraphy to select ice-core sites that are most likely to have an intact chronology that extends to over 1 million years in Antarctica.

Water at the bed

Preservation of the oldest ice at the bottom of ice sheets depends largely on the thermal state of the ice–bed interface (the basal boundary). Ice sheets act as an insulator between cold air temperatures at the surface and the relatively warm bed, which is heated by geothermal sources from the solid Earth. Thicker ice is a better insulator and thus generally leads to a warmer bed, though the melting point decreases with thicker ice and correspondingly increased pressure. At the West Antarctic Ice Sheet divide, for example, the pressure melting point is estimated to be -2.3°C beneath ~3480 m of ice (Talalay et al. 2020). If the ice is sufficiently warm at the basal boundary, it melts, destroying climate records contained within it, and creating a layer of water at the bed. Water at the bed can also be sourced from ice that melts at the surface and reaches the bed through crevasses and moulins; this and basal meltwater affect ice dynamics, influencing the complexity of ice flow at an ice-core drilling location.

Scientists thus commonly survey prospective ice-core sites using geophysical tools to determine the frozen/thawed state at the basal boundary. Both radar and seismic reflections are stronger over an ice–water interface, so parts of the bed with particularly strong reflections can be specifically

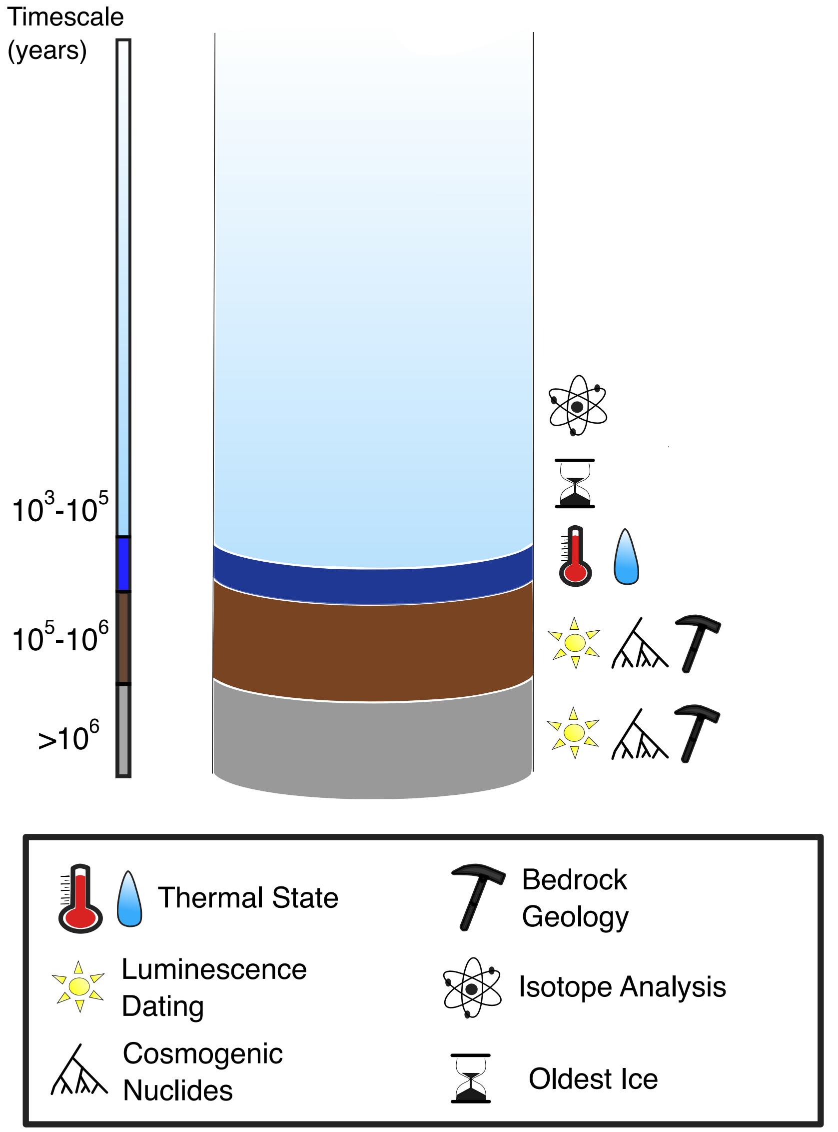

Figure 1: Schematic of a deep ice-core sample, including the subglacial melt (dark blue), sediments (brown), and bedrock (gray). Icons indicate the scientific approaches relevant to deep ice and subglacial materials.

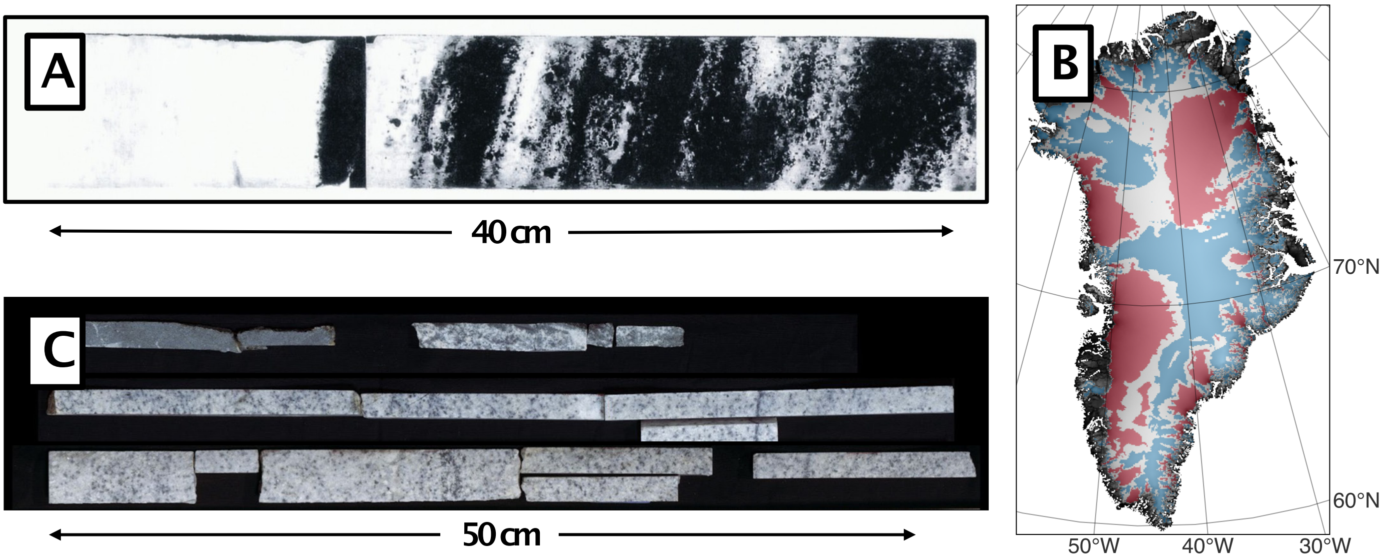

Figure 2: (A) Basal ice from the Byrd ice core, Antarctica (Gow and Meese 1996); **(B)** Bedrock core from GISP2, Greenland (Image credit: Geoffrey Hargreaves); and **(C)** A Greenland-scale product of inferred basal thermal state (blue is frozen, red is melting, gray is not confidently constrained; MacGregor et al. 2022).

targeted (Christianson et al. 2012) or avoided (Fudge et al. 2022) depending on the drilling objective. Determining whether the bed is completely frozen, however, can be difficult using geophysical tools because basal melting can occur even where water is not observed. Instead, frozen beds can be determined by interpreting internal stratigraphy or repeat radar measurement to infer whether the ice is moving only by deformation or also by sliding, the latter of which suggests water may be present at the bed (Martin et al. 2009). Comprehensive studies of the Greenland Ice Sheet show that the basal thermal state is mostly thawed in highly dynamic areas, such as the Northeast Greenland Ice Stream drainage, and mostly frozen in the slower-flowing regions (Fig 2c; MacGregor et al. 2022). The basal thermal state of the Antarctic Ice Sheet is less well constrained at the continental scale, but hundreds of subglacial lakes have been identified, indicating areas of thawed bed (Wright and Siegert 2012).

Sub-glacial bedrock and sediments

Bedrock and sediments beneath ice sheets contain valuable information on subglacial geology and ice-sheet history. Ice sheets cover most of Greenland and Antarctica, and thus, little is known about the types of rock that make up these landmasses (e.g. Dawes 2009). Some ice-core drilling campaigns have collected bedrock from beneath the ice sheets, giving geologists the rare opportunity to study the rocks underneath the ice (e.g. Gow and Meese 1996). Sediment is transported by flowing ice, like a conveyor belt, bringing material from the interior of ice sheets to the outer fringes. Analysis of these sediments and ice-flow patterns provides information on the bedrock geology from more central–and hard to access–sections of ice sheets (Fountain et al. 1981).

Sub-ice bedrock and sediments can also reveal information about ice-sheet history, including when areas were ice-free and the duration of ice cover. These ice-sheet histories are valuable for paleoclimate modeling and for predicting how the Greenland and Antarctic ice sheets will respond to future warming and contribute to sea-level rise (Christ et al. p. 116). To determine histories of past ice-sheet change, glacial geologists use two different methods: cosmogenic nuclide dating and luminescence dating (Fig. 1). Combined, these tools can be used to elucidate both how long areas beneath an ice core have been ice-free or ice-covered in the past, and potentially when these ice-free/ice-cover events occurred, thus allowing for assessments of ice-sheet stability over the Quaternary. While previous studies investigating ice-sheet history relied on legacy materials collected during previous ice-core campaigns (Christ et al. 2021; Schaefer et al. 2016), new projects, such as the EXPROBE-WAIS and Thwaites campaigns in Antarctica and GreenDrill in Greenland, specifically target areas for drilling to assess ice-sheet stability rather than develop direct paleoclimate records (i.e. prioritizing bedrock and sediments over a simple ice stratigraphy; Briner et al. 2022). In the United States, these projects are aided by the development of new US Ice Core Drilling Program drills that can quickly drill through the thin parts of ice sheets and collect basal ice and sub-ice materials. This new work is paving the way to investigate ice-sheet histories via bed samples from multiple key locations across the Antarctic and Greenland ice sheets.

Conclusions

Scientists now are increasingly able to investigate the ice–bed interface and the valuable information contained therein. Basal ice that is older than the current records in Greenland and Antarctica would extend terrestrial records of past climate. Knowledge of the basal thermal state is valuable for selecting ice-core sites. Investigating sub-ice sediment and bedrock yields insights into the bedrock geology and ice-sheet history. Several new projects are now focusing on collecting samples from the ice–bed interface to provide more information on this key transition zone. For example, the COLDEX (coldex.org) program is trying to locate the oldest ice on Earth today in Antarctica, while the Pirritt Hills, Thwaites, and GreenDrill projects are focusing on collecting subglacial bedrock and/or sediment to constrain ice-sheet histories in Antarctica and Greenland. These new advances in accessing, processing, and understanding data from the ice–bed interface allow for synergistic science capable of using everything collected in an ice-core campaign, from the surface firn (McCrimmon et al. p. 112) to the bedrock below the ice.

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