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PAST GLOBAL CHANGES
MAGAZINE

SEA ICE IN THE POLAR REGIONS

EDITORS
Matthew Chadwick, Karen E. Kohfeld, Amy Leventer, Anna Pieńkowski, Heike Zimmermann and Sarah Eggleston

Early-career perspectives on ice-core science

EDITORS
Jessica Badgeley, T.J. Fudge, Bess Koffman and Summer Rupper

PAGES

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News

Goodbye and welcome to SSC and EXCOM members

PAGES says thank you and bids farewell to four members who will be rotating off the Scientific Steering Committee (SSC) at the end of 2022: Ed Brook, Elena Ivanova, Tamara Trofimova, and Willy Tinner. Willy also served on the Executive Committee (EXCOM) and as co-chair of the SSC for six years. We want to extend our gratitude to all of them for their commitment to PAGES over the years. In January 2023, we welcome Lukas Jonkers and Shiling Yang to the SSC. Martin Grosjean will join the EXCOM, replacing Willy Tinner as co-chair.

PAGES IPO staff update

After almost four years of dedication and commitment as Science Officer, Sarah Eggleston is leaving PAGES in October. We thank her for her valuable contributions, which will shape PAGES' operations for years to come, and wish her much success in her future endeavors!

Open Science Meeting and Young Scientists Meeting: A big thank you!

After a successful Open Science Meeting (OSM) and Young Scientists Meeting (YSM) held online in May 2022, we want to thank the local organizing committee and scientific program committees for making these events possible. Ideas were shared and connections were made helping to grow the community and strengthen paleoscience. Find out about the next OSM: pages-osm.org

Apply to be on our Scientific Steering Committee

Do you wish to guide PAGES' activities and ensure the continuation of a thriving paleoscience network? Then apply to be a part of our SSC; the deadline is 5 April 2023 (term starts January 2024). Details: pastglobalchanges.org/be-involved/ssc/apply

Deadline for funding support and creation of new working groups

The next deadline to propose a new PAGES working group or to apply for financial support for a workshop, as well as to submit a Data Steward Scholarship application (working groups only), is 28 March 2023. Details: pastglobalchanges.org/support

PAGES working group seminar series

PAGES working group Disentangling climate and pre-industrial human impacts on marine ecosystems (Q-MARE; pastglobalchanges.org/q-mare) launched an open seminar series in April. These talks are held on the first Wednesday of each month. Details: pastglobalchanges.org/science/wg/q-mare/seminar-series

The former PAGES working group Ocean Circulation and Carbon Cycling (OC3; pastglobalchanges.org/oc3) has restarted its monthly webinars. Details: pastglobalchanges.org/taxonomy/term/115/meetings

DEEPICE training program

To support early-stage researchers from the DEEPICE project, PAGES, alongside the Oeschger Centre for Climate Change Research, is organizing a training program on science and climate change communication in Meielisalp, Switzerland, in September 2023. Details: deepice.cnrs.fr/training-program

Please help us keep PAGES People Database up to date

Have you changed institutions, or are you about to move? Please check if your details are current: pastglobalchanges.org/people-database

Call for contributions for *Past Global Changes Horizons*

The central theme for the third issue of *Horizons* is how studying past extreme wet and dry phases aids our understanding and informs future action on floods and droughts under current global changes. We welcome illustrated articles, comics, or any other form of illustrated communication (e.g. a photo report of your work in the lab, your collection of specimens, or your adventures and discoveries in the field). First drafts due 31 January 2023. Details: pastglobalchanges.org/news/129518

Past Global Changes Magazine: Changes to distribution

Past Global Changes Magazine is a free magazine published twice annually and delivered in hard copy format free of charge to those interested. We now request that for each issue of the magazine, anyone interested in receiving a hard copy of the magazine logs in to their PAGES database profile, clicks on the box "receive a hard copy of the PAGES magazine", and ensures that their postal address is correct. Check the e-news for deadlines. Details: pastglobalchanges.org/news/129490

Additionally, if you wish to receive hard copies of our earlier magazines, please visit our catalog (pastglobalchanges.org/publications/pages-magazines) and contact us at: pages@pages.unibe.ch

Upcoming issue of *Past Global Changes Magazine*

Our next magazine, guest edited by Xavier Benito, Ignacio Jara, Estelle Razanatsoa, and Giorgia Camperio, focuses on past socio-environmental systems. Although preparations are underway, if you would like to contribute, please contact us: pages@pages.unibe.ch

Calendar

2nd ACME workshop: Numerical ecology and time series analysis of marine proxy data
14-16 November 2022 – Copenhagen, Denmark

PAGES-INQUA joint ECR workshop: Past Socio-Environmental Systems (PASES)
20-24 November 2022 – La Serena y Coquimbo, Chile

DiverseK workshop: Challenges and opportunities for paleo-informed ecosystem conservation in Asia
27-30 November 2022 – Chaoyang Qu, China

International Association of Limnogeology and International Paleolimnology Association joint meeting: Lakes as Memories of the Landscape
27 November - 1 December 2022 – Bariloche, Argentina

CVAS and 2k: Centennial climate variability at regional scale in models and reconstructions
6-10 March 2023 – Potsdam, Germany, and online

5th VICS workshop: Moving forward by looking back
22-24 May 2023 – Bern, Switzerland

pastglobalchanges.org/calendar

Featured products

C-SIDE

Highlighted in the special issue "Reconstructing Southern Ocean sea-ice dynamics on glacial to historical time scales", Jones J et al. investigated sea-ice changes in the Southern Ocean during the last 140,000 years; Chadwick M et al. published a paper that covers sea-ice records from 12,000-130,000 years ago; and Crosta X et al. review what proxy records tell us about Antarctic sea ice over the past 130,000 years in the first of two review papers from the C-SIDE working group.
pastglobalchanges.org/publications/129064
pastglobalchanges.org/publications/128985
pastglobalchanges.org/publications/129168

CRIAS and VICS

White S et al. published an article in *Climate of the Past* on persistent cooling in the North Atlantic region after the 1600 CE Huaynaputina volcanic eruption.
pastglobalchanges.org/publications/129100

PALSEA

Yokoyama Y et al. examined plutonium isotopes in the north Western Pacific sediments coupled with radiocarbon in corals, recording the precise timing of the Anthropocene.
pastglobalchanges.org/publications/129285

SISAL

Verniers T et al. used stalagmite thorium concentrations as a new proxy for reconstructing Southeast Asian dust flux, and Bühler JC et al. investigated global relationships between speleothems and five climate models.
pastglobalchanges.org/publications/129445
pastglobalchanges.org/publications/129306

Cover

Collage of images showcasing sea-ice and ice-core research at both poles
Photo credits: Ruediger Stein, Claire Allen, Amy Leventer, Bradley Markle and Erin McClymont.

About this issue

Sea ice in the polar regions is a very relevant topic today, and the focus of multiple PAGES working groups. Two of these groups – Arctic Cryosphere Change and Coastal Marine Ecosystems and Cycles of Sea-Ice Dynamics in the Earth system – combined forces to produce the current collection of 12 science highlights in this *Past Global Changes Magazine* issue. The following section on ice-core science, by early-career researchers, provides another perspective on research at the poles.

Arctic Cryosphere Change and Coastal Marine Ecosystems

The PAGES working group on Arctic Cryosphere Change and Coastal Marine Ecosystems (ACME; pastglobalchanges.org/acme) provides a community platform to critically assess and refine available coastal marine proxies that can be used to reconstruct cryosphere changes and their multifaceted ecosystem impacts. ACME seeks to promote a leap forward in the accuracy of paleo reconstructions that are central for deciphering cryosphere-biosphere interactions in the Arctic region at relevant timescales.

Figure 1: Fresh water and sediment input into the Arctic Ocean are expected to increase with climate change (Photo credit: NASA Earth Observatory/Jesse Allen).

Figure 2: Sea ice in the Southern Ocean (Photo credit: Pearse Buchanan).

Cycles of Sea-Ice Dynamics in the Earth system

Southern Ocean sea ice plays several important roles within the Earth system, affecting nutrient cycling and marine productivity, as well as modulation of air–sea gas exchange and deep water formation in high latitudes. As sea ice changes in the future, it is important for Earth system models to be able to simulate the effects of these changes.

The aim of the Cycles of Sea-Ice Dynamics in the Earth system (C-SIDE; pastglobalchanges.org/c-side) working group is to reconstruct changes in sea-ice extent in the Southern Ocean for the past 130,000 years, reconstruct how sea-ice cover responded to global cooling as the Earth entered a glacial cycle, and to better understand how sea-ice cover may have influenced nutrient cycling, ocean productivity, air–sea gas exchange, and circulation dynamics.

Early-career perspectives on ice-core science

The Ice Core Early Career Researchers Workshop (ICECReW; pastglobalchanges.org/calendar/128625) brought together a diverse group of US-based scientists to discuss past and future ice-core projects, to build community, and to develop 10 articles showcasing the current state and future directions of ice-core science. From million-year-old samples of the atmosphere to microbes living within ice sheets, the ICECReW early-career participants seek to share with you the immense value of ice cores for understanding the Earth system.

For more information and to get involved in ice-core research or to connect with other early-career scientists, go to:

- Ice Core Young Scientists (ICYS; pastglobalchanges.org/icys)
- Polar Science Early Career Community Office (PSECCO; psecco.org)
- Association of Polar Early Career Scientists (APECS; apecs.is)
- Polar Impact (polarimpactnetwork.org)

Figure 3: Ice core (Photo credit: NASA's Goddard Space Flight Center/Ludovic Brucker).

Meet our guest editors

Jessica Badgeley
University of Washington, Seattle, USA

Jessica recently completed her PhD under the supervision of Dr. Eric Steig and Dr. Gregory Hakim. Her research explored the ways in which the network of polar ice cores can be leveraged to learn about climate and ice-sheet changes. Her current focus is on Antarctic Ice Sheet ice-surface elevation change, particularly in West Antarctica. Along with research, Jessica emphasizes outreach and collaboration. For over 10 years, she has been involved in Inspiring Girls Expeditions, a team-oriented organization that seeks to inspire female-identifying high-school-age youth by bringing them into the field with female-identifying professional scientists, mountaineers, and artists.

T.J. Fudge
University of Washington, Seattle, USA

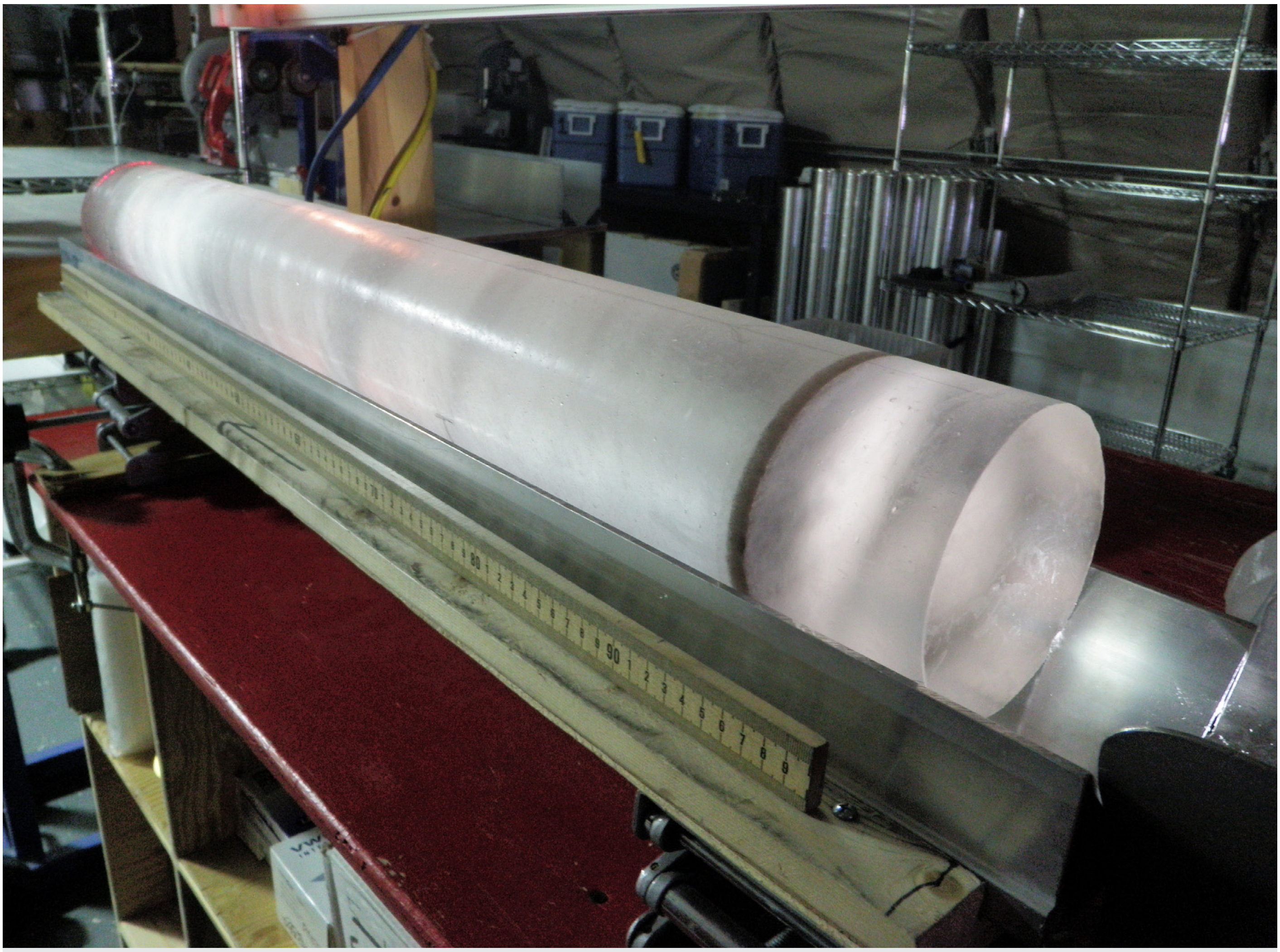
T.J. studies glaciers and past climate, focusing on Antarctic ice cores. He grew up on a small island in California and is drawn to questions about how climate change will impact sea level. T.J. looks at records from the past decades to thousands of years ago that are stored in the ice sheet, to understand how our climate system and ice sheets evolve. He chooses to work at the University of Washington because of great colleagues and students and the amazing natural laboratory that is Washington state.

Bess Koffman
Colby College, Waterville, ME, USA

Bess is a geochemist and paleoclimate scientist whose research is focused on understanding past climate variability. In particular, she uses ice-core records of atmospheric dust to learn how and why Earth's atmospheric circulation has changed through time. Earth's atmospheric circulation influences large-scale climate variability in several important ways: it affects the transport and delivery of oceanic heat; it exerts a strong influence on the exchange of carbon dioxide (CO_2) between the ocean and atmosphere; and it plays a large role in determining global rainfall distribution. Bess is also interested in the biogeochemical impacts of atmospheric deposition (e.g. mineral dust, volcanic ash, pollutants) on terrestrial and marine environments. Her work on ice, dust, and sediments has taken her to New Zealand, Antarctica, Alaska, and the Republic of Kiribati.

Summer Rupper
University of Utah, Salt Lake City, USA

Summer's research objectives are part of a larger effort to characterize natural climate variability, and to quantify the impacts of climate change on physical and human systems. Her current research projects focus on quantifying glacier contributions to water resources and sea-level rise, assessing glacier sensitivity to climate change, and reconstructing past climate using ice cores and geomorphic evidence of past glacier extents.



Ice core from the West Antarctic Ice Sheet (WAIS) Divide showing a layer of volcanic ash (Photo credit: icecores.org, Heidi Roop, National Science Foundation, USA).

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Early-career perspectives on ice-core science

Jessica Badgeley[1], T.J. Fudge[1], B. Koffman[2] and S. Rupper[3]

Ice cores have changed the way we understand the Earth. Ice cores drilled in the 1990s in Greenland showed definitively for the first time the abrupt nature of climate change events in the past (e.g. Dansgaard et al. 1993; Grootes et al. 1993). Ice cores from Antarctica have yielded a continuous climate history of the past 800,000 years, as well as snapshots of climate older than two million years (Jouzel et al. 2007; Yan et al. 2019, Bergelin et al. 2022), providing important context for climate changes underway today. The global network of ice cores drilled in remote mountainous and polar regions provides insight into topics beyond climate, including the history of wildfires and anthropogenic activities (e.g. Dahe et al. 2002; Grieman et al. 2018). Today, we continue to drill ice cores in Greenland, Antarctica, and mountain glaciers worldwide to better understand the Earth.

It takes a global community of scientists from a variety of disciplines to locate sites, drill cores, conduct analyses, and interpret the data in the broader context of the Earth system (Fig. 1). Like many countries around the world, the United States (US) recognizes both the contributions of ice-core science and the importance of a dedicated and inclusive scientific community. In 2022, the US National Science Foundation, via the Ice Drilling Program, funded a workshop for US early-career researchers to become more deeply involved in the ice-core community. This opportunity came together as the Ice Core Early Career Workshop (ICECReW; icedrill.org/meetings/ice-core-early-career-researchers-workshop-icecrew). Participants shared a collective desire to develop resources to help communicate ice-core science to undergraduate students and ice-core-adjacent researchers, inspiring this contribution to *Past Global Changes Magazine*.

The following 10 articles resulted from collaborations among the early-career scientists who attended the ICECReW workshop. The first article follows an ice core from the field to the lab. The next article addresses how to build an ice-core timescale, which is essential for placing measurements in context. The following eight articles cover key areas of ice-core science and adjacent fields: climate, atmosphere, wildfires, human activity, microbes, snow-to-ice transition, sub-ice materials, and sea-level change.

In reflecting on the important advances of the past decade, one thing is clear. Our community is stronger – and the science is better – when everyone is included. Inclusion has been particularly challenging during the COVID-19 pandemic, and one goal of ICECReW was to connect US early-career researchers of all races, genders, identities, abilities, and disciplines. Inclusion must occur at every level – for instance, the International Partnerships in Ice Core Sciences (IPICS; pastglobalchanges.org/ipics) open science meetings foster international inclusion. Through both individual and institutional actions, we can create a community where all feel welcome.

Figure 1: Photos highlight key elements of ice-core research, from geophysical surveys of potential drilling locations to laboratory analysis and timeseries data: **(A)** Glacier survey on Denali, Alaska (Photo credit: Brad Markle); **(B)** Radar echogram from West Hercules Dome, Antarctica (Image credit: T.J. Fudge); **(C)** Ice-core drilling rig on Mount Logan, Canada (Photo credit: Brad Markle); **(D)** Ice-core barrel at WAIS Divide, Antarctica (Photo credit: Brad Markle); **(E)** Ice core from the Juneau Ice Field, Alaska (Photo credit: Brad Markle); **(F)** Ice-core transport by Basler aircraft at Byrd Station, Antarctica (Photo credit: Lora Koenig); **(G)** US National Science Foundation Ice Core Facility, Colorado (Photo credit: NSF-ICF); **(H)** Processing samples in the Pico-Trace Ultraclean Lab, Lamont-Doherty Earth Observatory of Columbia University, New York, USA (Photo credit: Bess Koffman); **(I)** Ice-core thin section (Photo credit: British Library); **(J)** Ice-core CO_2 and isotope data from the EPICA Dome C ice core, Antarctica (Jouzel et al. 2007; Lüthi et al. 2008; Parkinson 2016).

In addition to building a more inclusive ice-core community, continued advances in ice-core science will be enabled through measurements of ice from new sites. Some current and future projects include multiple searches for a continuous climate record spanning 1.5 million years in East Antarctica, and projects targeting previous warm periods—such as the Last Interglacial (~130,000 years ago)—to determine the amount and rate of sea-level rise at that time. New cores from mountain regions are filling in the global network and providing important regional perspectives. In the coming decades, ice coring will not only expand on Earth but will also likely extend to the Moon and Mars. These are all significant undertakings that require international partnership and cooperation.

Analytical improvements and integration of ice-core data with other proxy records and with models will be just as important for the field as drilling new cores. Clumped isotope analysis enables insight into past atmospheric conditions, while micrometer-scale measurements push the spatial and temporal resolution of the old, highly-thinned portions of ice cores. Advances in timescale development already permit synchronization of ice cores with many paleoclimate proxy records, allowing for global assimilation with climate models. Such efforts provide benchmarks for model performance, aiding in our projections of future climate change.

As we look to the future of ice-core science, we see great promise among the current generation of early-career scientists. We are excited to showcase their perspectives on some of the important ice-core science developments in the articles that follow.

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From drilling to data: Retrieval, transportation, analysis, and long-term storage of ice-core samples

Lindsey Davidge[1], H.L. Brooks[2] and M.L. Mah[3]

Polar and alpine glacial ice is scientifically valuable, but it is logistically challenging to drill, transport, and store. We summarize the process of retrieving and analyzing a new core and identify archived samples that might be available for new research.

Ice cores collected from polar ice sheets and alpine glaciers provide a frozen archive of past atmospheric gases and precipitation that are important to glaciological and climate sciences. Ice-core analyses produce exceptionally well-resolved observations of local, regional, or global changes in the atmosphere over time. This is because as snow falls, a variety of physical processes affect its material properties and composition, and these signals get preserved through time. For example, ice flow direction affects the mineral orientation of frozen water, atmospheric composition determines the particle load and aqueous chemistry of an ice layer, and global and regional temperatures change the isotopic composition of the precipitation falling at an ice-core site; further, atmospheric gases trapped in the pore spaces between ice crystals are preserved and can be measured directly from ice-core samples (Banerjee et al. p. 104). Consequently, there are dozens of analyses that may be desirable to perform on a single ice-core sample. Drilling and preserving ice-core samples is challenging because cores are retrieved from frozen, often remote, and sometimes very deep (i.e. thousands of meters) sites. Despite this, cores are routinely recovered from scientifically advantageous locations, and ice samples are typically archived in storage facilities, where they may be available to support future research.

Drilling an ice core

Though the ice drilling process is similar at most sites, scientific objectives dictate the desired ice volume and depth, and cargo restrictions and site temperature may constrain equipment choices. Most core segments are about 10 cm in diameter and 1 m long, though the exact dimensions are determined by the size of the drill. Most core samples are retrieved by electromechanical drills; these drills contain a hollow cylinder, called the core barrel, that is equipped with rotational cutting teeth at the bottom (see Johnsen et al. 2007). Above the core barrel, an anti-torque device stabilizes the drill within the borehole while the cutters are spinning, and the entire drill assembly is suspended from a tripod or tower by an armored electrical cable (Fig. 1a). The rotating cutters pulverize a ring of ice, leaving a cylindrical pillar intact to enter the core barrel, while the remnant ice chips are removed from the cutting interface by circulating fluid and/or by helical flights (Fig. 1b). Each time the drill has progressed far enough to fill the core barrel, the ice pillar is broken off at its base, and the entire assembly is winched up to the surface. For electromechanical drills, the cutting force is supplied by electric motors, and the rate of penetration can be controlled by changing the weight above the bit. When drilling in ice warmer than -10°C, mechanical cutters tend to stick, and ice chip transport becomes difficult; at such sites, a ring-shaped heater is typically used to incise the ice instead in a process called thermal drilling (see Zagorodnov and Thompson 2014).

Glaciers and ice sheets are particularly inhospitable drilling environments. At the surface, heavy winds scour and redistribute recent snowfall, often burying scientific equipment or causing large snow drifts. Deeper in the ice sheet, ice flows under its own weight, causing deep boreholes to deform and close over time. Choices about infrastructure and equipment typically balance labor and cargo requirements with drilling efficiency and core quality. For example, drilling within covered trenches is the best way to avoid the impacts of drifting snow and bad weather, but a windscreen or tent might be a preferred alternative at sites where cargo capacity is limited or where the planned drilling season is short. Small drills or hand augers are used in alpine environments, where transporting personnel, equipment, and cores is often done by small aircrafts or even by foot or pack animal (Matoba et al. 2014; Schwikowski et al. 2014). However, deep ice-drilling projects in Greenland and Antarctica—which must penetrate multiple kilometers into the ice sheet—can utilize longer drill barrels, longer and stronger winch cables, and taller towers to minimize the number of trips up the borehole and accelerate the field campaign (Bentley and Koci 2007; Zhang et al. 2014). Boreholes deeper than about 300 m need to be backfilled with drilling fluid to prevent the borehole from collapsing (Talalay et al. 2014), though drilling fluid can also contaminate fractures within the core, which limits possible analyses.

Field storage and transportation

Once at the surface, cores are labeled with orientation and depth information and packaged carefully for transportation. Ice-core samples are susceptible to breakage, alteration, and melt, which means that preserving cores in the field and during transportation requires significant preparation; deep ice cores can be particularly fragile as they are removed from the ice sheet and rapidly decompress at the surface (Neff 2014). To inhibit physical, chemical, and biological alteration, it is desirable to store core samples at temperatures that are comparable to the in-situ temperature of the ice or at a maximum

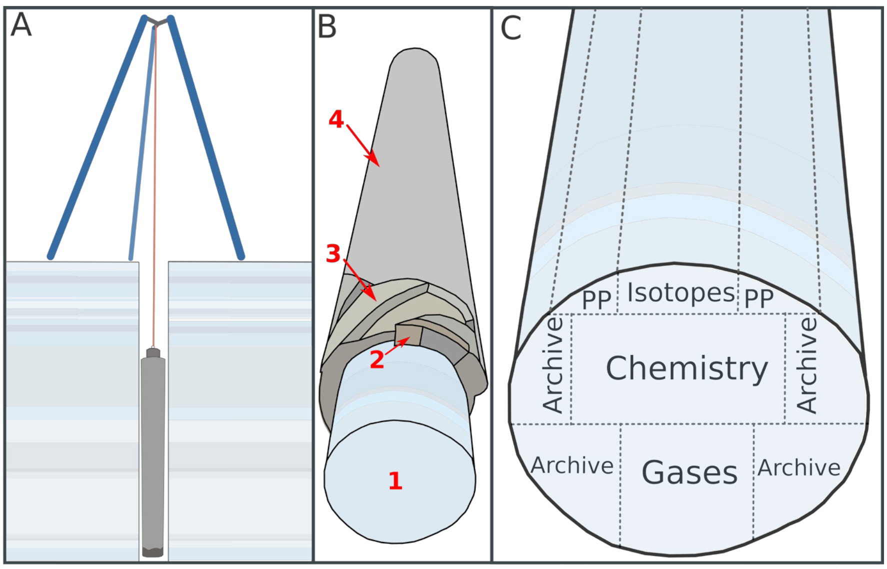

Figure 1: (A) Simplified cross section of an ice-drilling operation (not to scale). **(B)** Stylized drawing of an electromechanical drill, showing the retrieved core (1), cutters (2), helical flights (3), and core barrel (4). **(C)** An example of a cut diagram used to specify the target analyses for each portion of the core (PP = physical properties).

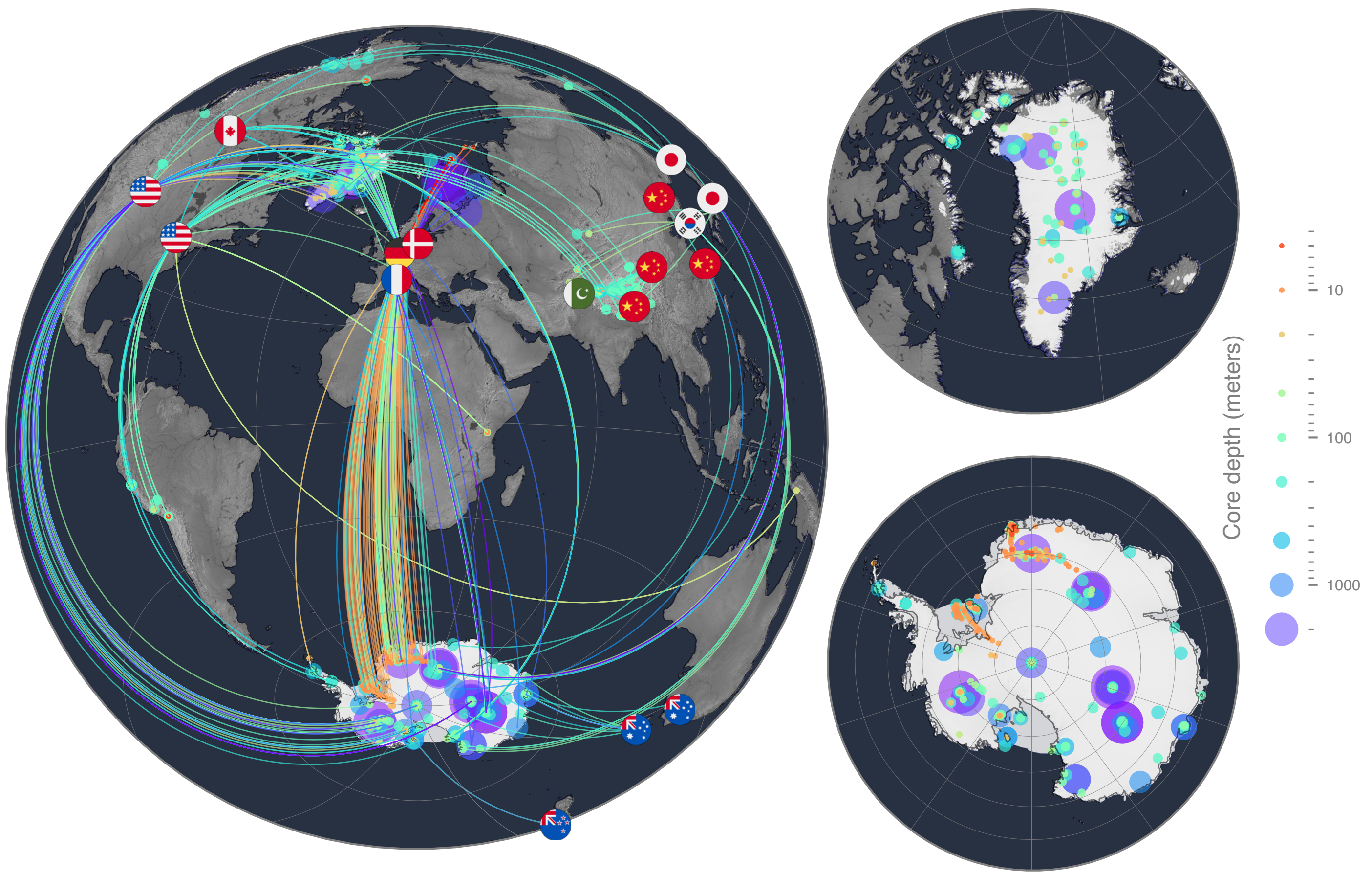

Figure 2: Map of selected ice drilling sites and storage locations, including details of Greenland (top right) and Antarctica (bottom right). Lines link the drill site and ice-storage location for each core (left). Many other archived samples exist in repository facilities around the world. Complete details are available in a corresponding database (Davidge et al. 2022).

of about -20°C. Cores are typically placed in insulated shipping boxes for protection during field storage and transportation. At polar drilling sites that remain frozen at the surface year-round, a shallow, covered trench dug into the snow is often enough to insulate the boxed cores for months or years. Storage at alpine glacier sites can be more complicated because these sites tend to be warmer and wetter than polar locations (e.g. Tsushima et al. 2021). Because of this, drilling at alpine sites is often seasonally constrained, and it is important to remove cores from these temperate sites as quickly as possible and place them in freezer storage.

The availability of onsite storage and field access limitations determine the method and frequency of transportation. Because ice cores from many polar sites can be safely stored at the drilling location–and because polar sites are often accessed by fixed-wing aircraft with substantial capacity for cargo–there is typically less urgency around transporting these cores, and their transportation can be scheduled similarly to other field-site cargo (e.g. Slawny et al. 2014). These cores are sometimes moved into temporary freezer storage at permanent research stations before being shipped to their destination country in refrigerated shipping containers aboard cargo ships or in smaller refrigerators aboard large aircrafts. For ground transport, temperature-controlled containers are transported by truck to national archive facilities or university laboratories for analysis.

Distribution and analysis of ice-core samples

Obtaining diverse measurements on an ice core typically requires that core samples be partitioned and distributed to multiple laboratories (Fig. 1c; as in Souney et al. 2014). Core samples are processed in one of two ways: discretely, by cutting the ice into small pieces and measuring the average properties of each subsample; or continuously, by melting one-meter "sticks" of the core from top to bottom and analyzing the resulting melt stream. It is desirable to make continuous measurements from ice-core samples when possible, because this method produces high-resolution timeseries while also minimizing sample handling and the potential for contamination (e.g. Osterberg et al. 2006; Röthlisberger et al. 2000). The volume of ice that is sent to each collaborating laboratory depends on analytical method requirements and project objectives.

Long-term ice-core storage

Notably, a portion of many cores has been archived in long-term storage facilities for use by future investigators. Ice from hundreds of field sites is stored in ice-core repositories within national research centers or universities (Hinkley 2003). Many of these samples are available for future research – and, indeed, many ice-core studies were conceptualized long after the ice core was originally retrieved. We provide a map of selected ice archives in Figure 2. Many core samples can be accessed by contacting the repository and proposing new strategies to leverage existing core samples to answer outstanding research questions.

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Putting the time in time machine: Methods to date ice cores

Kaden C. Martin[1], S. Barnett[2], T.J. Fudge[3] and M.E. Helmick[4,5]

The depth–age relationship of an ice core is critical to its interpretation; it constrains rates of change and allows for comparisons among records. Chronology advancements will be critical to the investigation of new ice cores over the coming decades.

Ice cores provide remarkable insight into past environmental change. As snow falls on glaciers and ice sheets, it traps things like past air, dust, volcanic ash, and soot from fires (Wendt et al. p. 102; Banerjee et al. p. 104; Brugger et al. p. 106). These environmental indicators are preserved in the ice sheet as fresh snow falls on the surface. By drilling down into an ice sheet or glacier (Davidge et al. p. 98), researchers can travel back in time to determine what the climate was like when the snow fell. However, placing these environmental indicators into a global climate context critically relies on our ability to date these ancient layers.

To better understand the time held within ice, ice-core scientists create chronologies. A chronology defines the relationship between time and depth in ice. Like counting tree rings, physically distinct layers and chemical impurities in ice correlate to seasons. These layers are well preserved as an ice sheet grows, aiding in the production of highly-resolved and well-constrained chronologies. To create the time–depth relationship, ice-core scientists rely on a range of techniques including measurements of distinct layers, comparisons with other well-dated records, physics models of snow compression and ice flow, and radiometric dating.

Chronology fundamentals

An intuitive method to develop an ice chronology is via annual-layer counting, where seasonally varying compounds or properties of ice can be used to identify yearly cycles (Fig. 1). Water isotopes, dust, and conductivity are commonly used to achieve this (Andersen et al. 2006; Sigl et al. 2016). Physical properties of ice also aid in this stratigraphy, such as visually distinct winter and summer layers due to extreme polar seasons. Annual layers become thinner with depth due to large-scale ice flow, reducing temporal resolution. Deep within an ice sheet, just a few meters can contain thousands of years of snowfall. Here, other techniques must be used as annual layers become indiscernible and dating becomes challenging.

Chronological information can be shared between cores by matching evidence of abrupt geological events. During volcanic eruptions, ash and sulfate can be deposited onto the ice sheets. These distinct layers are then preserved in the ice. If the same layer is found in different ice cores, the age of that layer can be transferred between them (Fig. 1a, b). This technique has been used to synchronize the ice chronologies of cores from Greenland and Antarctica at these discrete tie-points (Seierstad et al. 2014; Svensson et al. 2020).

A unique challenge of ice-core chronologies is that the ice crystals and the air bubbles trapped between them have different ages. Near the surface, air can move through spaces between grains of snow. This movement of air stops at the snow–ice transition, at ~40–120 m depth (McCrimmon et al. p. 112). At this point, pathways for air have closed and bubbles are sealed in ice, becoming isolated from the atmosphere. Therefore, the ice is older than the gases trapped within. This means that two chronologies are needed—one to study the ice, and one to study the gases.

The age difference between ice and gas at the same depth is Δage ("delta age"). This

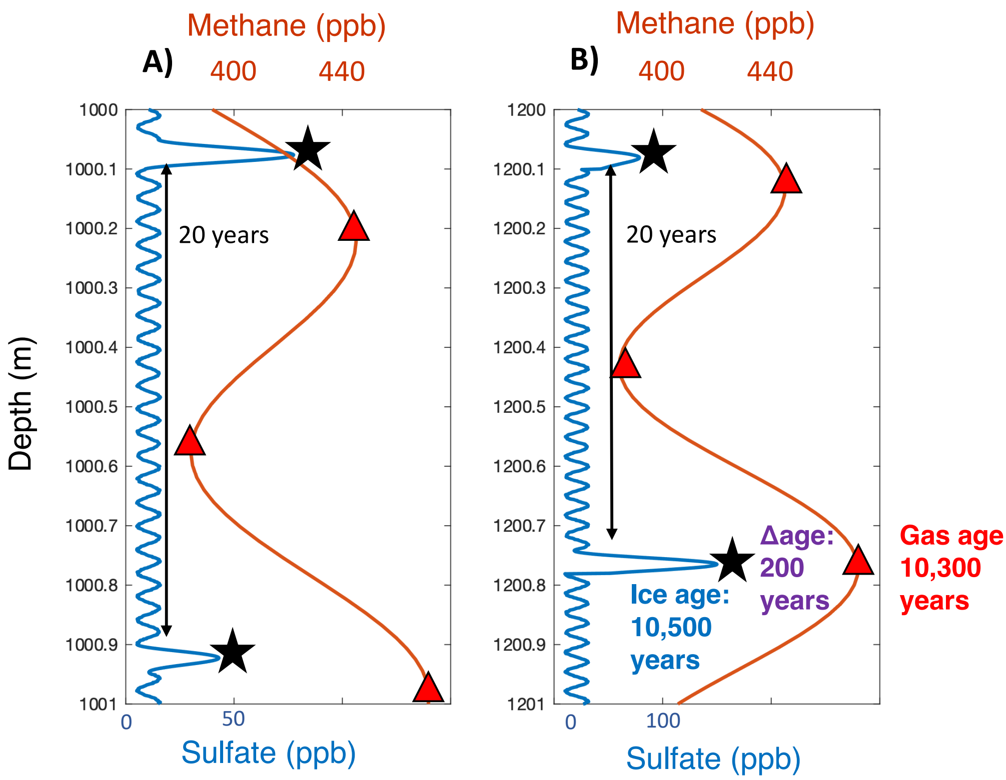

Figure 1: (A, B) Two idealized ice-core records, showing annual layers and volcanic events of sulfate in ice (blue) and methane concentrations in gas (orange). Annual cycles of sulfate can be counted to produce an ice chronology, while methane features can be dated using a firn model reconstruction of Δage or by examining abrupt events. The ages of cores A and B are synchronized by volcanic signals (black stars) and methane features (red triangles). Δage can be calculated between distinct features, and is 200 years in (B).

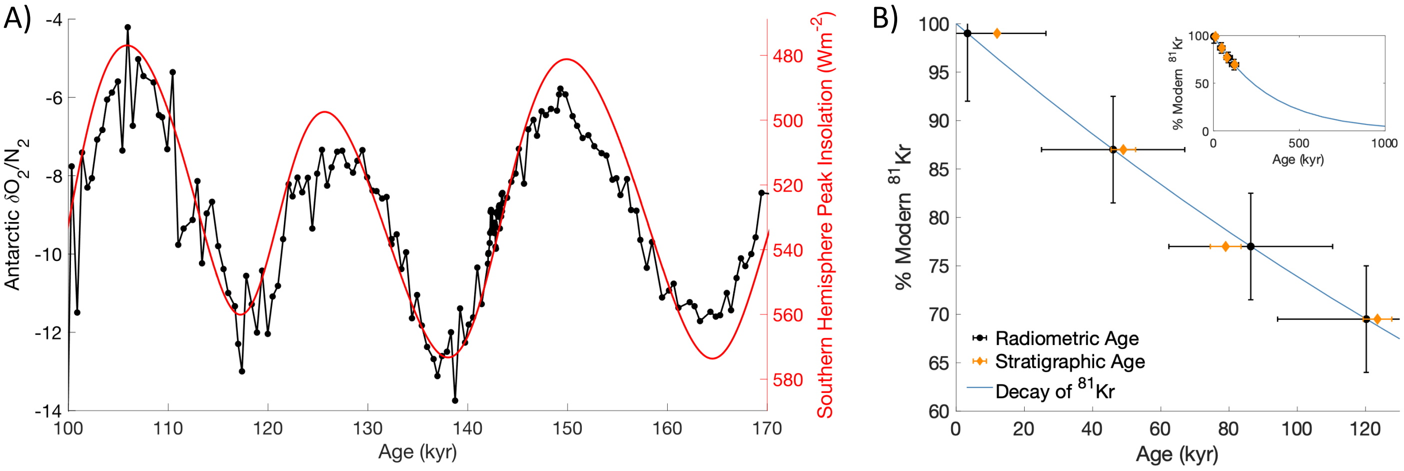

Figure 2: (A) The oxygen-to-nitrogen ratio ($\delta O_2/N_2$, black; Oyabu et al. 2021), measured from the Dome Fuji Ice Core in East Antarctica, and Southern Hemisphere peak summer sunlight, or insolation (red, note reverse axis; Laskar et al. 2004). The snow–ice transformation rate influences the $\delta O_2/N_2$, and this process correlates well with the location's amount of summer sunlight. By comparing $\delta O_2/N_2$ to past sunlight, age can be approximated. **(B)** Decay rate of ^{81}Kr (blue), and the comparison between conventional dating techniques (orange) and measurements of ^{81}Kr (black; Buizert et al. 2014). Inset: Same as in (B), but scaled to cover this technique's effective range.

age difference is not the same everywhere, nor is it constant for a given core. This is because Δage responds to changes in how fast snow turns into ice, which is set by local temperature and snowfall rate (Schwander et al. 1997).

As trapped air is younger than the ice surrounding it, dating gases requires different techniques. Because Δage is the ice–gas age difference, Δage and ice chronologies can be utilized to produce gas chronologies. Δage is accurately estimated during abrupt climate change events due to distinct features that occur in environmental indicators of both gas and ice (Buizert et al. 2015). During time periods without abrupt events, Δage is estimated by modeling the physics of snow compression, emulating how snow turns into ice given the climatic conditions at the time. Estimated and modeled Δages alongside annual-layer-counted ice chronologies are then used to calculate the gas chronology. Gas chronologies are also often dated using methane (CH_4). Due to rapid atmospheric mixing of CH_4, its atmospheric concentration is similar everywhere in Earth's lower atmosphere at any given time. This means that changes in one core can be matched to the same change in another core (Blunier and Brook 2001). This allows for the most accurate gas chronology to be transferred to any ice core (Fig. 1b, c).

As the array of well-dated ice cores and chronological information increases, data inversion techniques can be used to establish tie-points between different cores and bring their chronologies into agreement (Lemieux-Dudon et al. 2010). Such projects have successfully supported Antarctic chronologies (Parrenin et al. 2015). The key to data inversion is to utilize all available age constraints, like volcanic events, CH_4 matches, and annual-layer counts, in a mathematical framework. The framework then calculates a chronology that is within the bounds of the uncertainties and physical properties of the available data. This is a powerful technique, as it can overcome shortcomings of individual methods and reduce the time needed to construct new chronologies for recently recovered cores.

Dating the oldest ice

The oldest continuous ice-core records, found primarily in the East Antarctic Ice Sheet, have been dated by orbital tuning. This technique is necessary where annual layers become indistinguishable. Orbital tuning utilizes the known relationship between a proxy, like $\delta O_2/N_2$, and the cyclical variation of sunlight due to Earth's orbital cycles (Fig. 2; Oyabu et al. 2021). This method has been widely applied to marine sediment cores, where the variations in oxygen isotopes can be linked to changes in solar insolation and ice volume (Imbrie and Imbrie 1980).

Another technique for dating old ice utilizes radiometric dating, where the known decay rate of radioactive isotopes in preserved bubbles can be used to determine when they were isolated from the atmosphere. Two useful radioisotopes are Argon-41 (^{41}Ar) and Krypton-81 (^{81}Kr). ^{81}Kr is produced in the atmosphere by cosmic-ray interactions with the stable isotopes of Kr. As the atmospheric concentration of ^{81}Kr has been relatively constant over the last 1.5 million years, a measurement of an old sample will be less than the modern concentration due to radiometric decay. The difference in concentration between an old and modern sample is set by the decay rate of ^{81}Kr, and can be used to determine when the gas in the sample was trapped in the ice. The half-life of ^{81}Kr is 229 kyr BP, providing a dating range of 0.5 to 1.5 million years—useful when dating old ice (Fig. 2). Ar isotopes in ice cores record the decay and outgassing of radioactive potassium in the mantle, which provides a unique chronologic marker (Bender et al. 2008).

Outlook

Chronologies are critical to placing ice-core records into a global context, enabling direct comparisons between natural greenhouse-gas variations and records of environmental change in other archives. Chronology development is an ever-growing field, supported by advancements in instrumentation, new chemical measurements, and mathematical models as past cores are updated and new projects are planned. Techniques for absolute dating are being developed to support deep ice-core projects targeting continuous climate records of 1.5 million years, such as the new COLDEX and BeyondEPICA projects, and discontinuous climate records from blue-ice areas, like Allan Hills, Antarctica (Kehrl et al. 2018).

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Our frozen past: Ice-core insights into Earth's climate history

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Ice cores provide a unique window into Earth's climate history. This article explores the various climate indicators stored in ice cores and some of the scientific insights that have resulted from studying them.

Climate indicators

Ice cores contain an invaluable record of Earth's past climate. The climate information stored in ice cores, or climate indicators, can be broadly divided into three categories: (1) atmospheric composition, (2) regional atmospheric circulation, and (3) local temperature and snowfall. Past atmospheric composition is determined by directly sampling ancient air which was trapped during the transformation of snow to ice (McCrimmon et al. p. 112). As overburdened snow layers compact, the interconnected pores within old snow (firn) close and trap atmospheric gases (e.g. O_2, N_2, Ar, CO_2, CH_4) within the newly formed bubbles (Banerjee et al. p. 104). Analyzing the isotopes of atmospheric gases provides insight into their potential sources and sinks.

Past changes in regional atmospheric circulation (i.e. transport pathways) are inferred by examining mineral dust, volcanic ash, and ions in ice cores. The distribution of dust grain size indicates transport strength, and the geochemical composition of dust and ash reveals potential source areas. Dust concentrations can also provide insight into global aridity, while variations in ions (e.g. Na^+, Cl^-, Ca^{2+}, Mg^{2+}, NH_4^+) and organic compounds are used to infer regional changes, such as sea-ice extent and marine productivity.

Past changes in local air temperature are inferred from the analysis of oxygen ($\delta^{18}O$) and hydrogen ($\delta D = \delta^2H$) stable isotope ratios in the water molecules of ice. Air temperatures influence the degree of mass fractionation of water isotopes during the vapor condensation process inside clouds. Isotopic ratios of $\delta^{18}O$ and δD are translated to past temperatures using an empirical relationship derived from, for example, a spatial network of modern snowfall analysis or temperature–depth profiles within the ice sheet. During periods of rapid warming, a vertical temperature gradient within the porous firn column can form, causing gases to thermally fractionate. As a result, deviations in $^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$ provide an additional proxy for rapid temperature changes. Changes in temperature and snowfall accumulation influences the rate of ice formation, which provides further information about local climate conditions.

Long-term climate change

In the 1960s, glaciologists at Byrd Station (Antarctica) drilled an ice core that dated back to the last glacial period (Martin et al. p. 100). Their pioneering work revealed that cooler temperatures during the last glaciation coincided with lower greenhouse gas concentrations (Berner et al. 1980). This discovery led to a fundamental understanding of the link between global temperature and greenhouse gas concentrations.

Over the last five decades, a multinational effort to collect several deep ice cores from the East Antarctic Plateau has resulted in the now iconic 800-thousand-year (kyr) climate

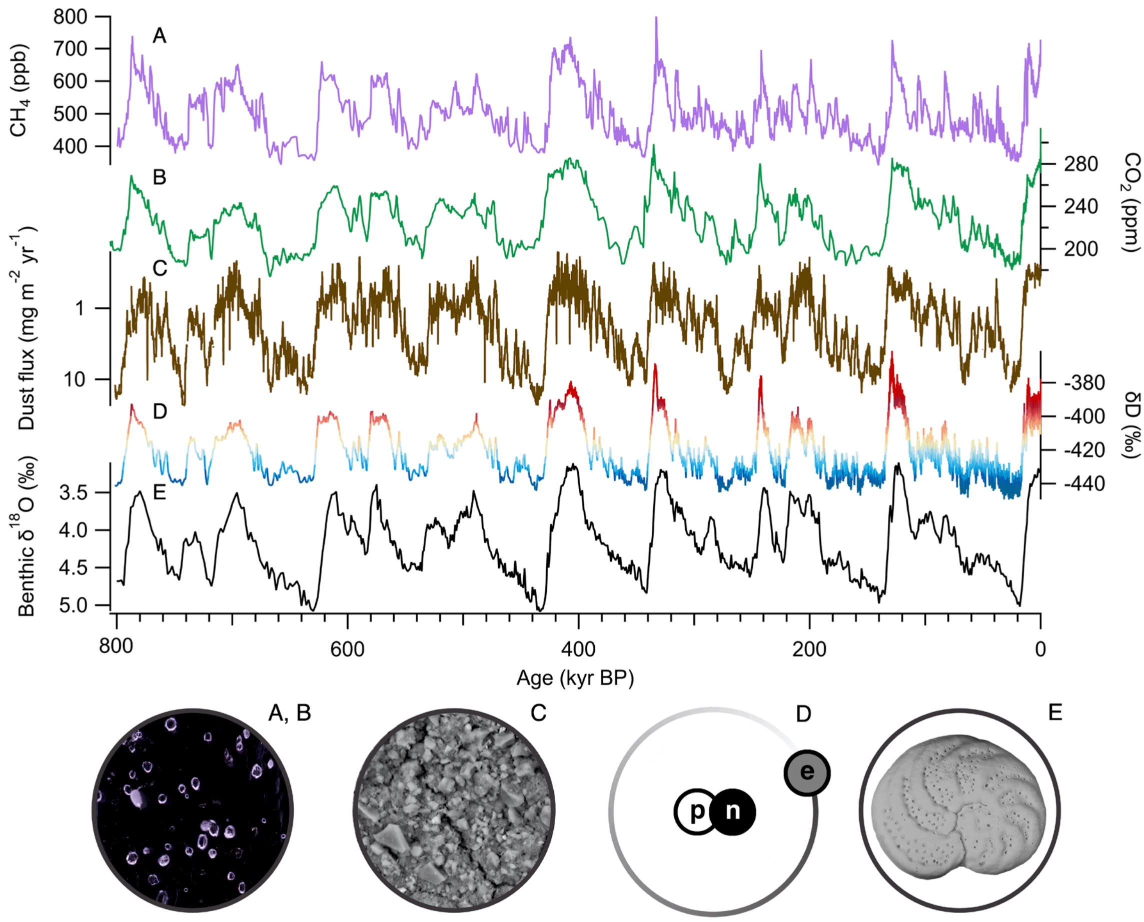

Figure 1: Climate indicators in Antarctic ice **(A-D)** and marine sediments **(E)** reveal climate change over the last 800 kyr. From top: **(A-B)** Atmospheric methane (purple, Loulergue et al. 2008) and carbon dioxide (green, Bereiter et al. 2015); **(C)** 250-year smoothed dust flux plotted on a reversed logarithmic scale (brown, Lambert et al. 2012); **(D)** Variations in δD (rainbow, Jouzel et al. 2007) which reflect Antarctic temperatures (red indicating warmer and blue indicating cooler); and **(E)** Variations in the $\delta^{18}O$ of benthic foraminifera in marine sediments (black, Lisiecki and Raymo 2005).

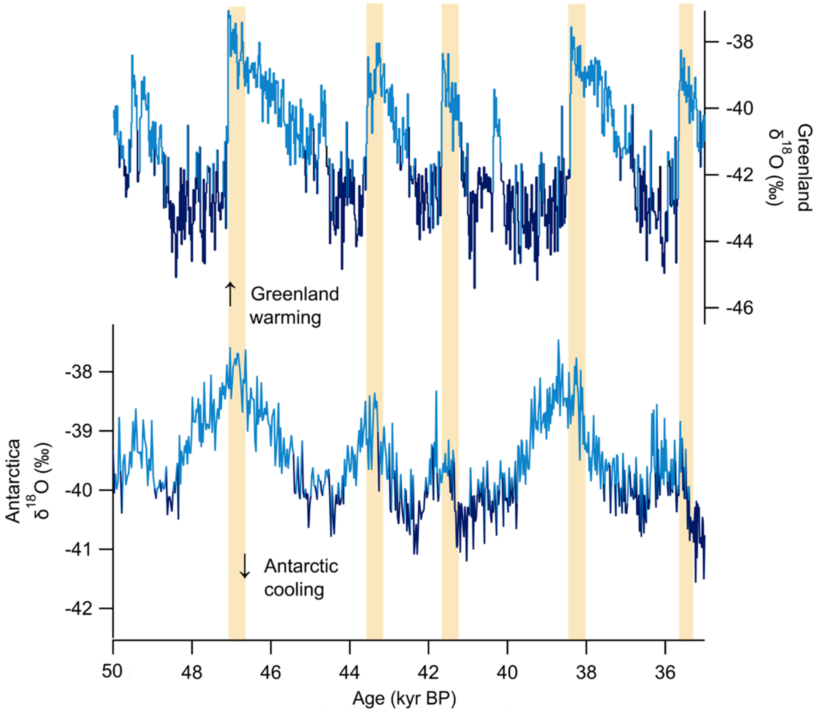

Figure 2: Example of abrupt climate change during the last glacial period. Top panel shows ice $\delta^{18}O$ from North Greenland (NGRIP Members 2004) plotted on the adjusted GICC05 chronology. Bottom panel shows ice $\delta^{18}O$ from West Antarctica (WAIS Divide Project Members 2015) plotted on the WD2014 chronology. Yellow bars indicate the timing of D-O events, during which Greenland warms rapidly. Shades of blue illustrate how relatively cold atmospheric temperatures were at each location, with darker blues showing colder temperatures.

record (Fig. 1). The compiled record offers a window into past greenhouse gas concentrations, Antarctic temperatures, and atmospheric transport properties over the last eight glacial cycles. Climate indicators within the ice reveal major synchronous variations on glacial–interglacial timescales (Fig. 1). The recorded variations resemble the blade of a jagged saw with the troughs representing glacial periods. When compared to warm interglacial periods, glacials are characterized by cooler Antarctic temperatures, lower greenhouse gas concentrations, and dustier winds blowing over Antarctica (Fig. 1a-d). For example, Antarctic temperatures were between 4 and 10°C cooler (e.g. Buizert et al. 2021) and atmospheric CO_2 concentrations were over 100 ppm lower (Lüthi et al. 2008) during the Last Glacial Maximum (20 kyr ago) relative to pre-industrial conditions.

The 800-kyr ice-core record shows remarkable similarities to other paleoclimate records worldwide. Most notable is the $\delta^{18}O$ of benthic foraminifera in deep ocean sediments (Fig. 1e), which is widely used as an index for global ice volume (Lisiecki and Raymo 2005; Christ et al. p. 116). Examining synchronous variations provides a complete picture of the global changes that occur on glacial–interglacial timescales and, most importantly, what drives them. The study of ice cores and other long-term climate records have contributed to the understanding that glacial cycles are paced by Earth's orbital configuration. Climate changes caused by variations in incoming solar radiation are further amplified by a cascade of feedbacks within the climate system. This is best observed during a glacial termination, when climate records worldwide show a systematic and rapid transition to interglacial conditions (Fig. 1). Ice cores have been instrumental in revealing the order, timing, and magnitude of these key climate shifts.

Abrupt climate change

Ice cores also provide unique insight into past periods of abrupt climate change (Alley 2000). Evidence from ice cores suggests that Greenland experienced large swings in temperatures at millennial-scale intervals throughout the last glaciation (Fig. 2; Dansgaard et al. 1993). Abrupt warming periods, known as Dansgaard-Oeschger (D-O) events, are defined by a ~10°C increase in Greenland temperatures over the short period of a few decades (Severinghaus and Brook 1999). Approximately 200 years after an abrupt warming in Greenland, Antarctic temperatures begin to cool (WAIS Divide Project Members 2015; Fig. 2). Similarly, abrupt cooling in Greenland ultimately gives way to Antarctic warming. This phenomenon is known as the thermal bipolar seesaw (Stocker and Johnsen 2003). It can be explained by perturbations in the northward heat transport via the Atlantic Ocean, which exert opposite temperature effects on both hemispheres. The 200-year delay in Antarctic temperatures is the result of a north-to-south propagation of the climate signal through oceanic processes that operate on centennial timescales.

Recent work on high-resolution Antarctic ice cores have revealed variations in CH_4, CO_2, and the relationship between $\delta^{18}O$ and δD that are near-synchronous with Northern Hemisphere D-O events (e.g. Bauska et al. 2021). The timing of these coeval changes suggests a rapid atmospheric response that is uncoupled from ocean circulation. Shifts in the distribution of tropical precipitation or the meridional position of midlatitude westerlies could rapidly propagate signals between hemispheres. These interhemispheric mechanisms are the focus of ongoing research. Resolving these finer-scale changes shed important light on fast-acting feedbacks within Earth's climate system.

Climate sensitivity

Ice cores support our understanding of past climatic changes and play a critical role in future climate projections. Since Eunice Foote's discovery of CO_2's warming properties in 1856 (Foote 1856), the study of greenhouse gases and their influence on Earth's radiative balance has remained a cornerstone of climate sciences. The study of past atmospheric greenhouse gas concentrations drastically improved our understanding of their role in amplifying climate changes that result from variations in incoming solar radiation due to rhythms in Earth's orbit. For example, approximately 40% of the radiative forcing associated with the last glacial termination has been attributed to changes in atmospheric CO_2 and CH_4 (Lorius et al. 1990). Greenhouse gas records from ice cores can also be used in conjunction with reconstructions of global temperature to quantify equilibrium climate sensitivity (i.e. the magnitude of temperature change associated with a given change in greenhouse gas concentration). Future climate projections that aim to quantify the global temperature response to fossil-fuel emissions require accurate estimates of climate sensitivity. If not for the ancient atmosphere encapsulated in ice cores, predicting future climate change would be far more uncertain.

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Ice-core records of atmospheric composition and chemistry

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All authors contributed equally and are considered joint first authors.

Ice cores record fundamental information about past atmospheric composition and chemistry, its intricate relationship with global climate, and recent changes to the atmosphere's composition due to anthropogenic activities.

As snow accumulates and compacts on ice sheets, ambient air is trapped within the ice, making glacial ice a direct archive of past atmospheric composition (McCrimmon et al. p. 112). The extraction and measurement of gases trapped in ice cores provide continuous, direct observations of atmospheric composition going back hundreds of thousands of years. These records show changes in atmospheric composition on timescales ranging from decades to hundreds of millennia (Martin et al. p. 100). Ice cores have provided high-resolution records of greenhouse gas (GHG) concentrations including carbon dioxide (CO_2) and methane (CH_4), and their influence on, and relation to, global climate.

In addition to trapped gases, ice cores also provide a unique archive of major ions and non-gaseous compounds including sulfate (SO_4^{2-}), nitrate (NO_3^-), and halogens (e.g. chloride, bromide, iodide); atmospheric acidity; and other measurements that provide information about atmospheric chemistry and anthropogenic pollution. In the following sections, we describe these ice-core records of Earth's atmosphere.

Long-term records of greenhouse gases

The fidelity of ice-core air as a record of past atmospheres is confirmed by the precise agreement between ice-core-derived records of GHGs and instrumental records over the last 40–60 years (Fig. 1a; Macfarling Meure et al. 2006). Ice cores from Antarctica have provided 800,000-year-long records of major GHGs in high resolution (CO_2, CH_4), covering eight complete glacial–interglacial cycles, with recent efforts aimed at recovering ice, and subsequently atmospheric composition, up to several million years old (Dahl-Jensen 2018). These data confirm that the modern atmospheric concentrations of GHGs and their rates of increase are unprecedented in at least the last 800,000 years.

Ice-core CO_2 records have established the fundamental relationship between atmospheric CO_2 and climate (derived from stable isotopes of H_2O in the ice surrounding the bubbles, which are temperature proxies; Wendt et al. p. 102) on glacial–interglacial timescales (Fig. 1a, c; Jouzel et al. 2007). GHG records on centennial and millennial timescales provide strong evidence of abrupt changes to Earth's climate system and atmosphere. For example, ice-core CH_4 records from Greenland and Antarctica reveal dramatic variability on decadal timescales that coincides with similarly abrupt Northern Hemisphere climate changes recorded in Greenland ice cores, highlighting the sensitivity of CH_4 to abrupt climate change (Chappellaz et al. 1993).

Measurements of the stable and radioactive isotopic composition of atmospheric GHGs can reveal which sources contributed to changes in concentration over time. Because major GHG sources often have distinguishable isotopic compositions, variability in the strength of these sources over time had measurable impacts on the past atmospheric isotopic signature. Recently, the suite of trace gas measurements made on ice-core samples has expanded to include these isotope measurements, providing valuable constraints on the causes of past GHG variability and the complex dynamics of Earth's climate system. For example, records of stable isotopes in CO_2 suggest that land-based CO_2 sources caused abrupt CO_2 rises during the last deglaciation (20,000-10,000 years ago), while ocean-based sources were responsible for a more gradual rise (Bauska et al. 2016). Records of CH_4 isotopes strongly suggest that changes in microbial sources, rather than abrupt releases of geologic CH_4, dominated the deglacial CH_4 change (Dyonisius et al. 2020).

Modern records of anthropogenic change

Ice cores preserve changes in atmospheric chemistry and pollution over human history (Wensman et al. p. 108). For example, they record how atmospheric sulfate, which causes acid rain and influences global climate, tripled between 1900 and 1980 due to fossil-fuel burning, and then declined from 1980 to present day following clean-air policies in North America and Europe (Mayewski et al. 1986; Fig. 2a). They also show how atmospheric nitrate concentrations have doubled since the 1950s due to increased

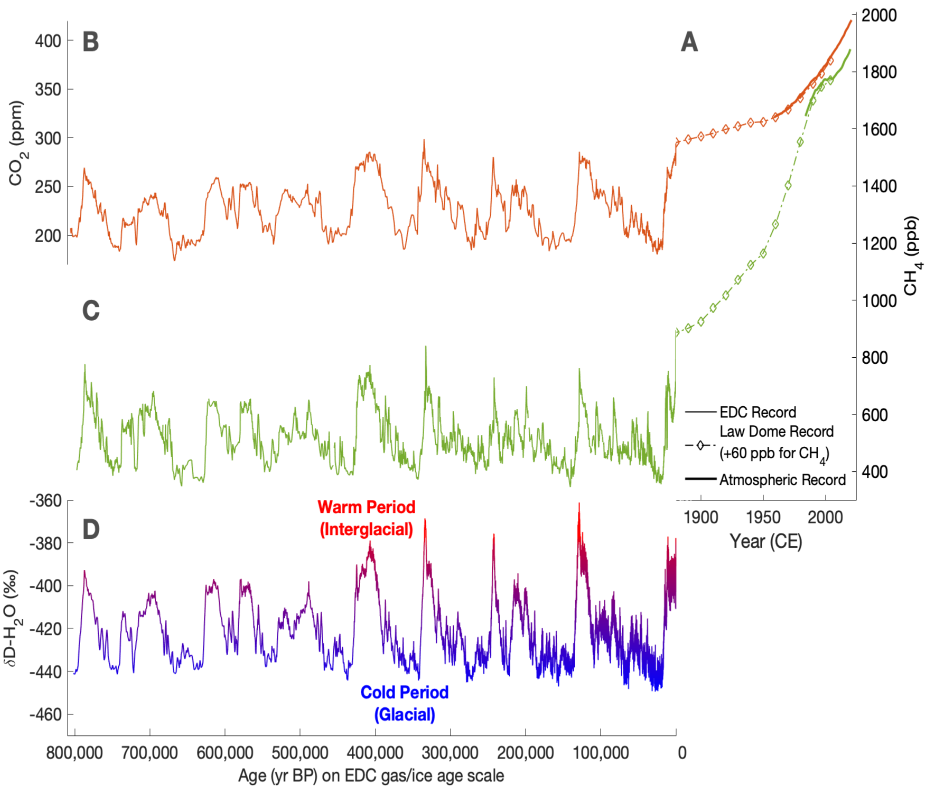

Figure 1: (A) CH_4 and CO_2 records from the Law Dome ice core (Macfarling Meure et al. 2006; dot/dashed lines) and the global mean atmospheric records (Hofman et al. 2006; solid lines) from 1875 to 2020 CE. In the modern atmosphere, Antarctic CH_4 is roughly 60 ppb lower than the atmospheric mean CH_4 because CH_4 sources are concentrated in the Northern Hemisphere. To account for this, the Law Dome CH_4 record was increased by 60 ppb. **(B-D)** 800,000 year Antarctic records of **(B)** CO_2, **(C)** CH_4, and **(D)** δD-H_2O, a proxy for temperature, all from the EPICA Dome C (EDC) ice core (Jouzel et al. 2007).

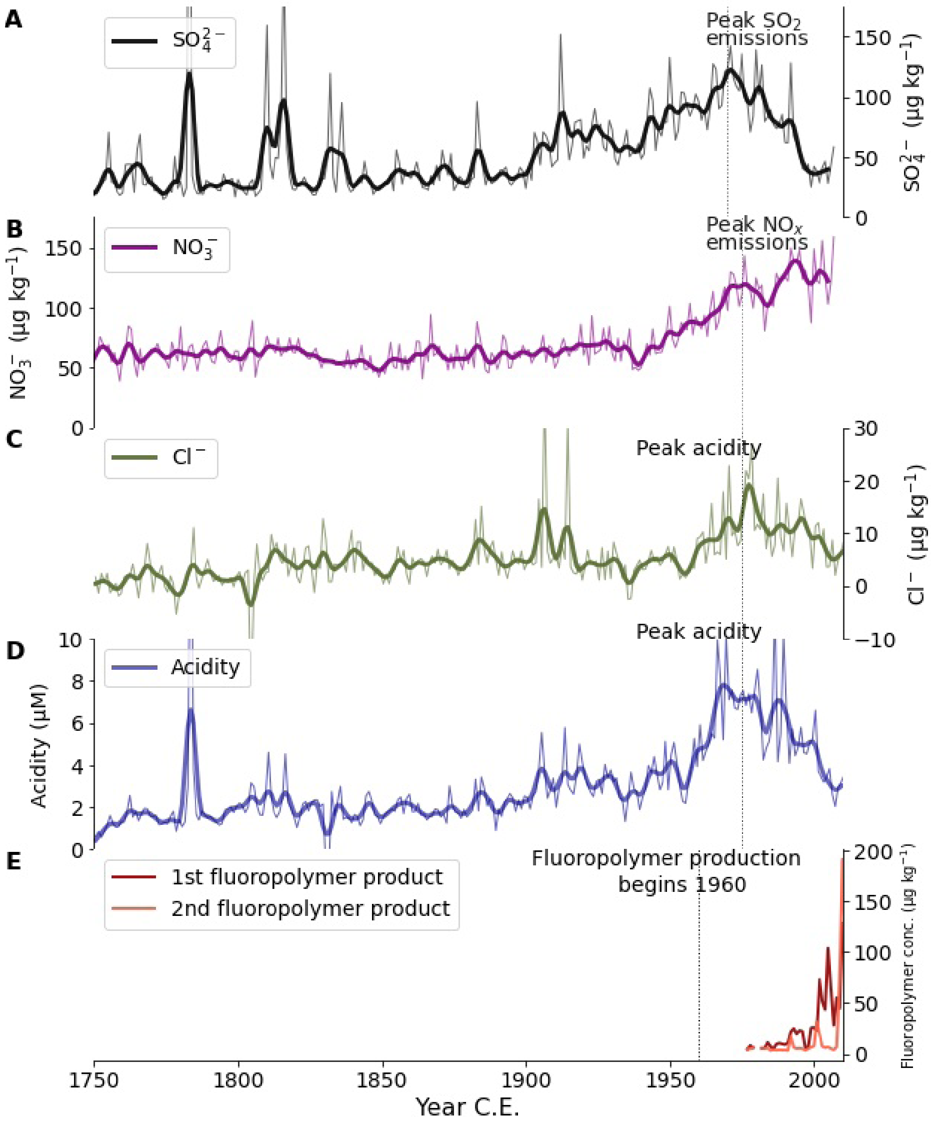

Figure 2: Recent measurements of dissolved ice-core species that tell us about atmospheric chemistry and pollution. Thin colored lines show annual measurements and bolded lines show multiyear averages. These ice cores are from the Greenland Ice Sheet and the Canadian Arctic. **(A)** Summit sulfate from Cole-Dai et al. (2013); **(B)** Summit nitrate from Geng et al. (2014); **(C)** Tunu chloride from Zhai et al. (2021); **(D)** Tunu acidity from Zhai et al. (2021); and **(E)** Devon Ice Cap and Mt. Oxford (northern Canada) perfluoroalkyl carboxylic acids from Pickard et al. (2020).

NO and NO_2 (collectively NO_x) emissions from fossil-fuel combustion and agriculture, which have changed the biogeochemical cycling of nitrogen since the pre-industrial era (Hastings et al. 2009; Fig. 2b).

Ice cores also provide information about the past and current abundance of atmospheric oxidants, which are chemicals that react with air pollutants (e.g. SO_2) and hydrocarbons (e.g. CH_4), yielding products that can cool (e.g. SO_4) or warm (e.g. CO_2) the atmosphere. These reactions can determine the lifetime of GHGs such as CH_4, so investigating how oxidants have changed can help estimate the warming potential of GHGs at different times in Earth's history. Although many oxidants such as ozone and the hydroxyl radical are too chemically reactive to be recorded in ice-core gas bubbles, proxies for these oxidants can indicate how oxidants have varied in the past. For example, clumped oxygen isotopes (i.e. $^{18}O^{18}O$ instead of $^{16}O^{16}O$ or $^{16}O^{18}O$) constrain how ozone concentrations increased in the 20th century due to industrialization (Yeung et al. 2019).

Atmospheric halogens (elements including chlorine, bromine, and iodine) are some of the most reactive oxidants in the atmosphere and influence important species such as sulfate, volatile organic compounds, mercury, and ozone. It is difficult to know how atmospheric halogens have varied because measurements of reactive halogens have only been possible in the past few decades, but ice-core records combined with models can provide insight into how atmospheric halogen chemistry has changed due to anthropogenic pollution. For example, ice-core records of chlorine excess (i.e. chlorine that comes from a source other than sea salt; Fig. 2d) show how chlorine is correlated with atmospheric acidity (Fig. 2e) since the pre-industrial, and atmospheric models indicate this correlation is due to acidity reacting with sea-salt aerosols (Zhai et al. 2021).

Ice cores also record pollutants that only exist due to anthropogenic activities. Figure 2e shows ice-core concentrations of perfluoroalkyl carboxylic acids, which are byproducts of refrigerants that have been found in ice cores starting in the mid-20th century and increasing rapidly after 1990 (Pickard et al. 2020). Records of these pollutants, along with concentrations of short-lived species such as sulfate, nitrate, and halogens, show how profoundly human activities have affected the chemistry and composition of the atmosphere, especially in the past 100 years.

Conclusions

Ice-core records provide unique archives of past changes in atmospheric composition and chemistry due to natural and anthropogenic causes. Ice-core gas records have provided information about past GHG concentrations and their relationship with global climate on glacial–interglacial and millennial timescales, as well as unprecedented increases in GHGs over the last century due to fossil-fuel burning. Analyses of major ions and other non-gaseous compounds have improved our understanding of anthropogenic pollution and its influence on atmospheric chemistry and climate. As older ice-core records are recovered and measurement techniques continue to improve, so too will our knowledge of past atmospheric composition and its interaction with climate and chemistry—knowledge that is essential for understanding the modern climate system and predicting future change.

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Fire trapped in ice: An introduction to biomass burning records from high-alpine and polar ice cores

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All authors contributed equally and are considered joint first authors.

Paleofire research is crucial for understanding long-term wildfire trends for fire and air quality management. Future work should close geographic gaps and incorporate cross-disciplinary collaborations for a holistic understanding of wildfires and their role in the climate system.

Fires are a unique element of the climate system. They are highly sensitive to regional climate, vegetation, and human factors, and serve as a significant driver of global climate and atmospheric composition (Legrand et al. 2016). Recent years were marked by devastating fire seasons worldwide with severe consequences for human health, economies, and ecosystems across continents. Yet, current biomass burning trends are a result of complex interactions between changing land-use practices, ecosystem dynamics, and climatic factors. Paleorecords provide a crucial context for both trends and drivers of burning, which help us understand how fires are changing now and how they might change in the future.

Efforts to build paleofire records began almost 100 years ago with charcoal analyses from Greenland sediments (Stutzer 1929). Early efforts to study paleofire in ice cores focused on black carbon (soot), but modern ice-core paleofire studies employ a range of proxies for biomass burning (Legrand et al. 2016) and utilize the long, accurate chronologies unique to ice cores (Martin et al. p. 100).

Paleofire proxies in ice cores

Fires yield products that are transported from the fire source region and deposited on ice. These fire tracers are preserved in the ice matrix as particulate matter, water-soluble species, and gases. They have varying levels of dilution, preservation potential, and specificity to biomass burning (Fig. 1). For example, black carbon is comprised of submicron-sized particles which can be produced by incomplete biomass combustion or by fossil-fuel burning (McConnell et al. 2007). Ammonium and potassium ions (which are water-soluble) also have multiple sources and thus correlate with wildfire activity only after accounting for the naturally occurring background (Rubino et al. 2016). Certain soluble organic molecules can present greater specificity to biomass burning—levoglucosan, for example (Simoneit 2002)—but atmospheric processes in gaseous and aqueous phases (Li et al. 2021) limit how well one can quantify past fire emissions from these ice-core records at present. Other small organic molecules produced in fires, such as acetylene and ethane (gaseous proxies), have simpler and better-understood atmospheric budgets that result in additional insights into burning history (Nicewonger et al. 2020). Finally, the isotopic compositions of gases such as methane are sensitive to changes in their emission sources, facilitating unique constraints on hemispheric- and global-scale biomass burning (Bock et al. 2017).

Note that while each proxy system has its unique advantages and shortcomings, the evidence for changes in paleofire regimes has been corroborated by multiple proxies in many cases, lending confidence to qualitative trends inferred for the last 2000 years. Recent reviews by Legrand et al. (2016) and Rubino et al. (2016) provide more comprehensive discussions about individual proxy systems.

Spatial coverage of ice-core paleofire records

The spatial distribution of available ice cores is skewed towards the poles, with a few high-alpine ice cores in temperate and tropical mountain ranges (Davidge et al. p. 98). Likewise, the coverage of ice-core-based paleofire reconstructions in polar regions is relatively extensive and includes many different particulate, water-soluble, and gaseous proxies (Fig. 2). Outside the polar regions, several multi- proxy paleofire reconstructions have been developed from the tropical South American Andes and the Himalayan region showing millennial-scale changes in fire regimes. Large-scale fire reconstructions based on black carbon, ammonium, nitrate, and microscopic charcoal in the temperate regions are concentrated in the Altai mountains in Central Asia and the European Alps. However, some regions with massive modern fire activity have not yet been investigated. For example, to our knowledge, there is not a single study investigating fire

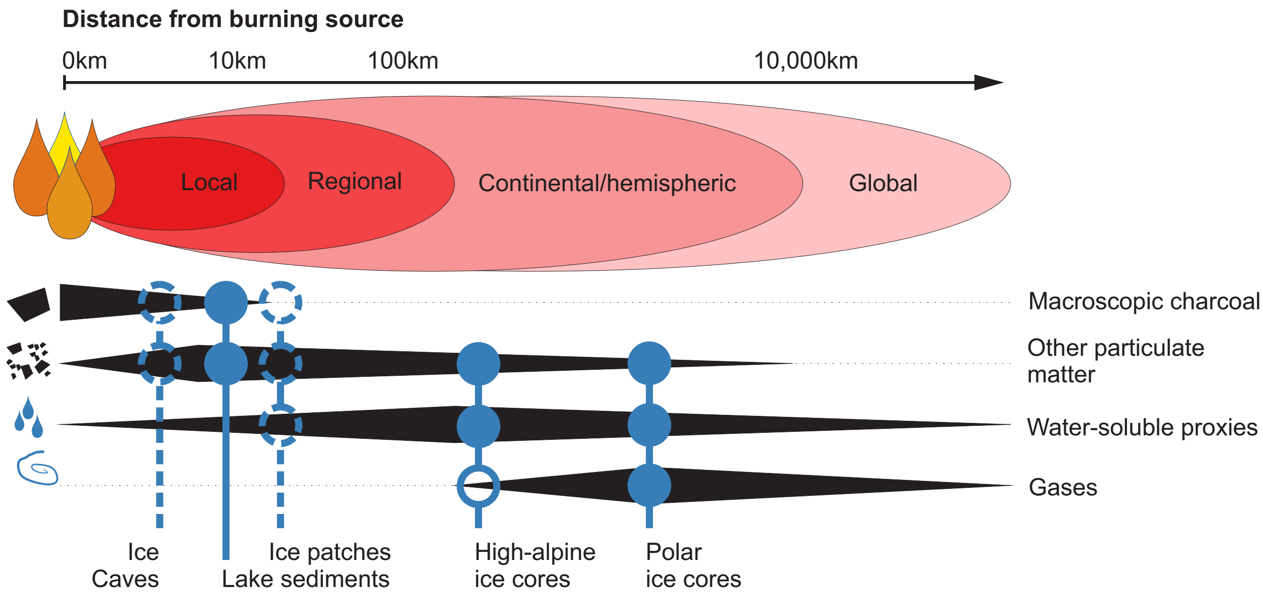

Figure 1: Atmospheric footprint of fire tracers in natural archives. Full circles indicate established fire proxies in a certain archive. Dashed circles indicate future directions of proxies in a certain archive. Note that high-fidelity gas records in high-alpine glaciers have been elusive.

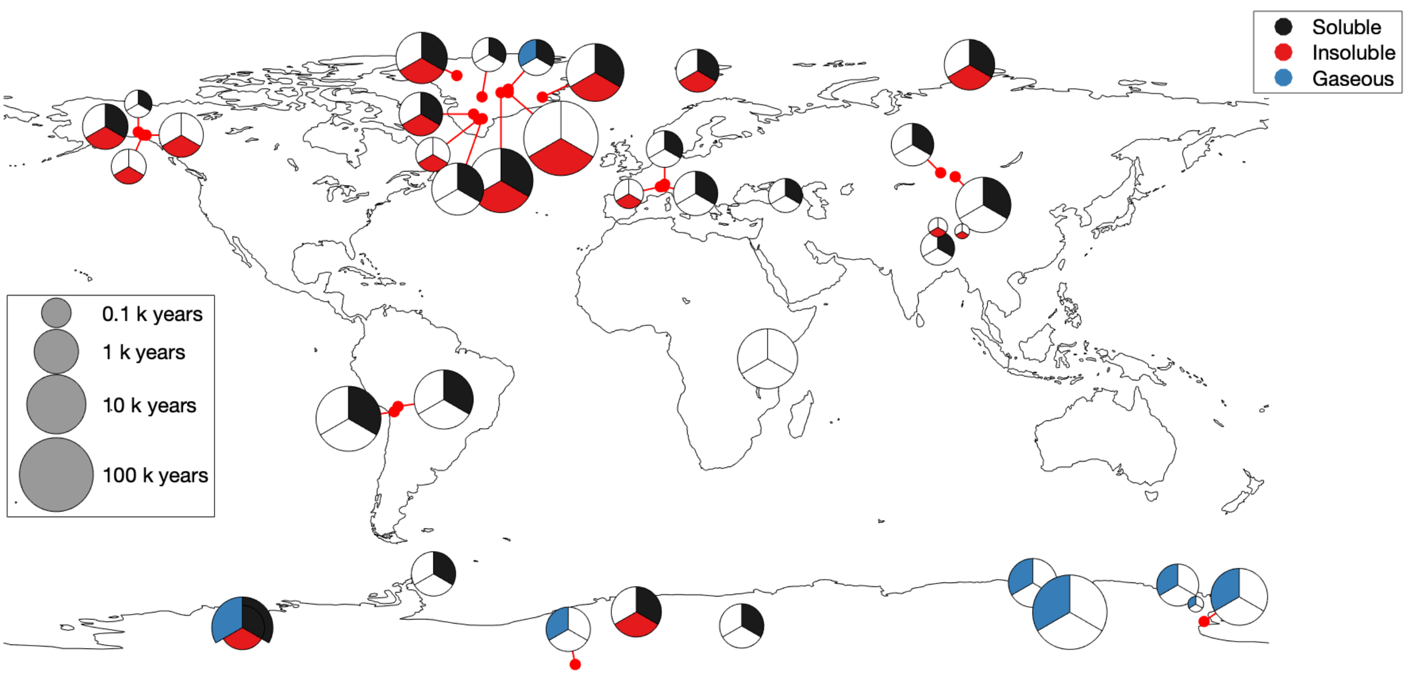

Figure 2: The distribution, temporal range, and type of paleofire records derived from ice cores. White sections indicate sites with a missing group of proxies. Note Kilimanjaro, shown as a notable missing archive for paleofire reconstructions. References to original datasets available from Brugger et al. (2022).

activity trends from the African continent, although Kilimanjaro, Tanzania, could provide a suitable ice archive.

Insights from ice fire records

Ice-core paleofire records show important trends for the last 2000 years, although a few records provide context from the late Pleistocene glacial cycles (Fig. 2). Two broad trends from these records are notable. First, decadal- to millennial-scale variability in fire activity has been inferred for the past 2000 years, arising from human activities and climatic driving forces. For example, global fire activity was higher during the Medieval Climate Anomaly (ca. 950–1250 CE) and then decreased into the Little Ice Age (ca. 1400–1850 CE, Rubino et al. 2016). Second, on glacial–interglacial timescales, large variations in land ice coverage, hydroclimate, and vegetation yielded higher amplitude changes in biomass burning compared to the Holocene (ca. 9700 BCE–modern). The stable isotopic composition of methane suggests that global biomass burning emissions increased between 115 kyr BP and 18 kyr BP, perhaps due to the extinction of megaherbivores that led to an increase in plant biomass (Bock et al. 2017). However, much remains to be learned about glacial–interglacial trends in biomass burning.

Future directions and conclusions

Ice-core records have most clearly illuminated the history of Northern Hemisphere paleofires over the past ~2000 years. Yet, key records from the Southern Hemisphere and Africa are still missing. In addition, proxy measures distinguishing between paleofire frequency and severity, on local to global scales, are needed. Filling in these gaps will improve our understanding of the relationship between fire, climate, ecosystems, and human activities. Fortunately, ice-core science is well suited for cross-disciplinary syntheses, which integrate paleofire reconstructions with atmospheric and ecological dynamics and past human impacts. Such research may incorporate multidisciplinary approaches and collaborations with experts in other fields.

New ice-core archives, such as from ice caves or alpine ice patches (Leunda et al. 2019), that have already yielded promising ice-core records could extend the spatial coverage of ice-core-based biomass-burning reconstructions. Comparison of paleofire records from ice cores with peat-, lake- and marine-sediment cores, as well as tree rings, also helps close geographic gaps and adds to a holistic understanding of past fire regimes. Sharing methodologies such as the application of black carbon methods to lake sediments (Chellman et al. 2018) and incorporating the measurements of traditional sediment-charcoal methods in ice-core science may facilitate comparison across paleoarchives. Due to the much larger particle size, charcoal fragments have a much shorter atmospheric lifetime and, thus, provide more local information compared to the more regional records derived from the smaller particles and gases recorded in ice cores (Fig. 1).

The use of multiple approaches is key to understanding regional patterns of past fire dynamics, fire severity, and sources for the individual biomass-burning proxies. Disentangling proxy sources is particularly important in the industrial period, given the influence of fossil-fuel and land-use emissions on individual fire proxies. Indeed, humanity's relationship with fire has likely been as variable as the cultures that comprise it; through time and space, social needs, traditions, and technological advances together have shaped the role of fire in society. Indigenous and local communities, in particular, should be included in the current fire dialogue to understand the role of fire in cultural traditions and oral histories. The broader paleofire community in the Global Paleofire Working Group highlighted the importance of combining paleofire research with traditional and Indigenous knowledge systems (Colombaroli et al. 2018).

We conclude that research on establishing paleofire records from ice cores is a relatively young field that is rapidly evolving. It has the potential to provide a much-needed long-term global and regional context for current fire adaptation strategies of society and natural systems (Watts and Brugger 2022) in a rapidly changing climate.

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Ice-core records of human impacts on the environment

Sophia M. Wensman[1], J.D. Morgan[2] and K. Keegan[3]

Ice cores can provide high-resolution records of anthropogenic activities, observable in gas and impurity records, for at least the last few millennia. Such archives demonstrate the ubiquity of human influence and the importance of legislation in mitigating these impacts.

Ice cores archive direct and proxy records of human impacts on the environment. The impact of human activity on the environment is clearly visible in ice cores as: increasing concentrations of methane and other greenhouse gases (e.g. Banerjee et al. p. 104; Mitchell et al. 2013); spikes in radionuclides from atomic bomb explosions (e.g. Gabrielli and Vallelonga 2015); and elevated concentrations of pollutants like lead, microplastics, and black carbon (e.g. Materić et al. 2022; Gabrielli and Vallelonga 2015; Fig. 1).

Ice-core records also extend much further into the past than modern observations, revealing the widespread extent of historical anthropogenic impacts. Here, we focus on methane and lead, two chemical species that record some of the earliest ice-core evidence of human impacts on the environment, beginning at least 2500 years ago. Additionally, we discuss examples of ice-core records that show the impact of remediation actions including legislation and technological advancements in reducing anthropogenic influence.

Methane emissions from early agriculture

Ice cores record changes in the composition of the atmosphere in air bubbles that get trapped as snow and ice accumulate. Air bubbles in ice cores from both Greenland and Antarctica record a steady 100-ppb increase in atmospheric methane concentrations beginning around 5000 years ago. There has been much debate about whether this reflects natural variability or is evidence of early human influence on the environment via land clearance and agriculture, such as rice and livestock farming. Fortunately, ice cores offer tools to investigate this question. For example, the difference in methane concentration between Arctic and Antarctic ice cores tells us which hemisphere has larger emissions. Additionally, the isotopic composition of methane in the ice preserves a fingerprint of where and how it was produced. Using these techniques, ice cores reveal that the increase between 5000 and 2000 years ago likely came from stronger monsoons in the Southern Hemisphere, rather than rice farming in East Asia (Beck et al. 2018). Studying these natural variations allows us to better identify the impact of human activity.

Anthropogenic methane emissions became truly significant during the last 2000 years (Fig. 1). During this period, the rise in methane concentrations in the ice cores cannot be explained without the increase of emissions from human activity, such as rice and cattle farming and decomposition in landfills (Mitchell et al. 2013). The sensitivity of methane emissions to human population and industry is also evident in the sharp dips in Northern Hemisphere emissions coinciding with the fall of the Roman Empire and Han Dynasty (Sapart et al. 2012), the arrival of the Black Plague in Asia (Mitchell et al. 2013), and the deaths of Indigenous Americans resulting from European invasion and subsequent disease introduction (Ferretti et al. 2005).

Human impacts on lead pollution

Anthropogenic emissions of lead, a toxic heavy metal emitted from industrial activities including mining and fossil-fuel burning, are first observed in Arctic ice cores approximately 3000 years ago (e.g. Murozumi et al. 1969), with earliest evidence of lead pollution attributed to the expansion of the Phoenician society (McConnell et al. 2018). Antarctic ice cores record anthropogenic lead pollution only during the last 130 years due to lower emissions in the Southern Hemisphere, with earliest emissions from mining and smelting of lead ores in Australia (Vallelonga et al. 2002). High-resolution ice-core records demonstrate the sensitivity of ice cores to year-to-year and decade-to-decade changes in anthropogenic emissions corresponding to major historical events including plagues, wars, and periods of economic stability (e.g. McConnell et al. 2018).

Arctic lead pollution rose rapidly during the industrial period, peaking in the 1960s, when leaded gasoline use was most prevalent. Indeed, Greenland ice cores indicate that

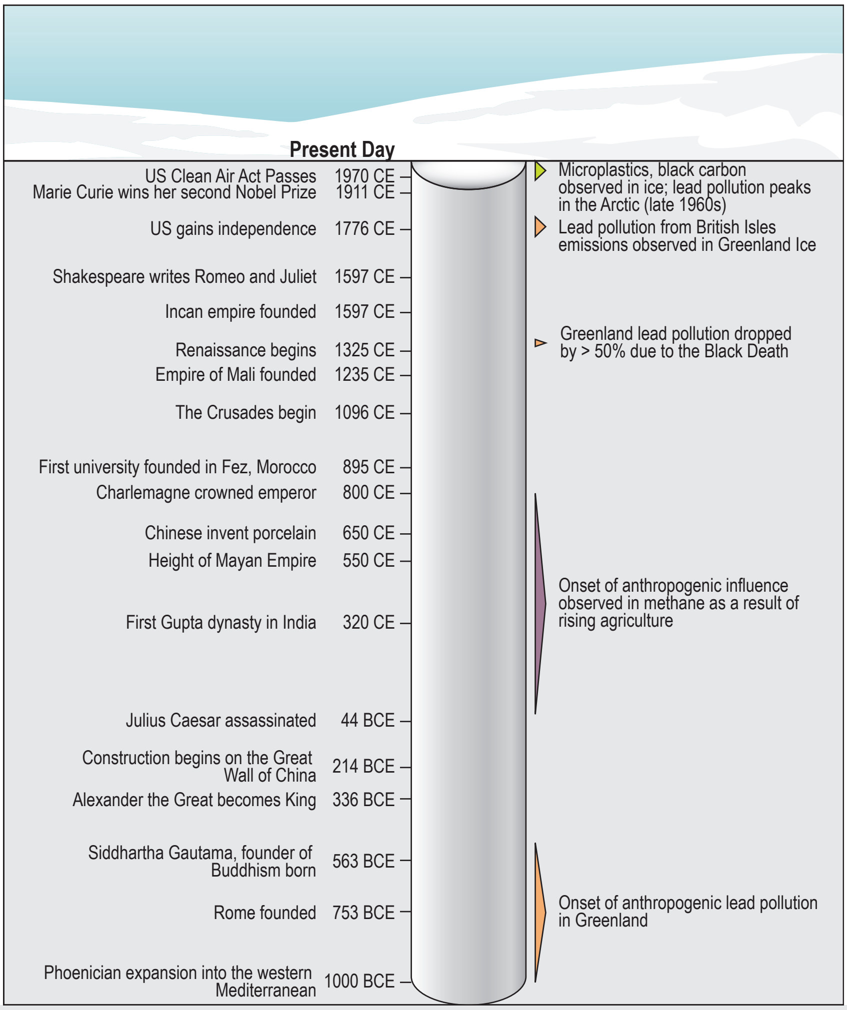

Figure 1: Schematic of an ice core, with present day representing the surface of an ice sheet or glacier, relevant historical markers on the left, and, on the right, a timeline of human activity archived in ice cores including anthropogenic methane (Mitchell et al. 2013; Beck et al. 2018), lead (Wensman et al. 2022; McConnell et al. 2018; 2019), microplastics (Materic et al. 2022) and black carbon (Gabrielli and Vallelonga 2015 and references therein). Triangles represent the timeframe of each event.

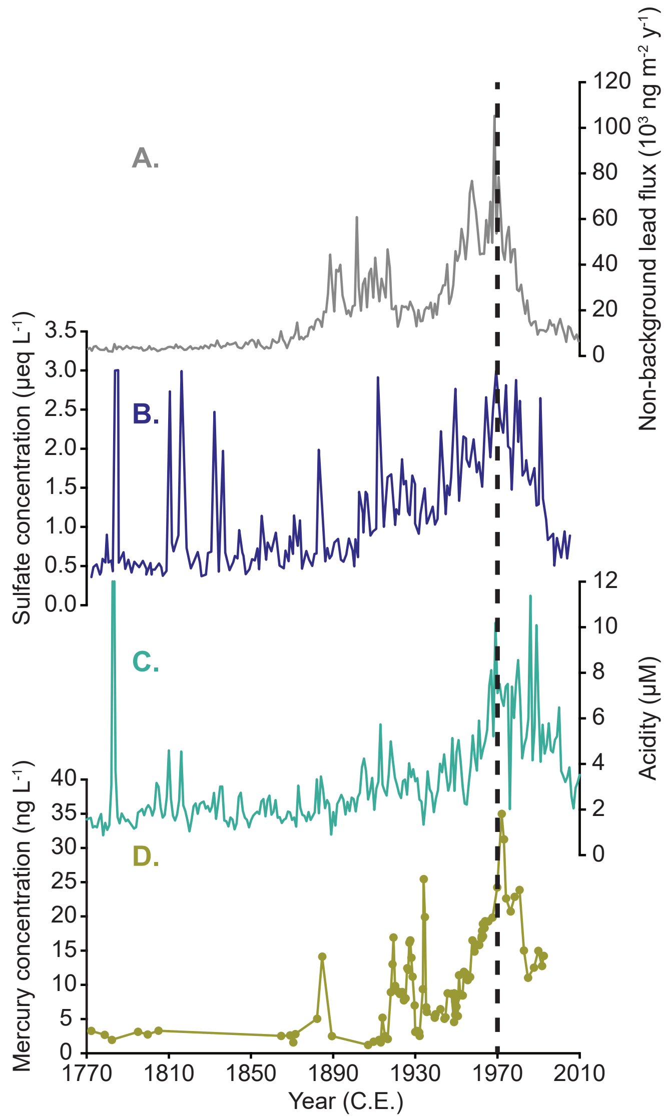

Figure 2: Ice-core records of environmental pollutants before and after enactment of the US Clean Air Act in 1970 (dashed line). **(A)** Lead flux from southern Greenland ice cores (McConnell et al. 2019); **(B)** Summit, Greenland, sulfate concentrations (Geng et al. 2014); **(C)** Acidity levels from northern Greenland (Maselli et al. 2017); and **(D)** Mercury concentrations from Upper Fremont Glacier in Wyoming, USA (Chellman et al. 2017).

Arctic lead pollution increased 250- to 300-fold between the Early Middle Ages and the 1960s (McConnell et al. 2019), with lead isotopic records suggesting predominantly US-derived sources (e.g. Wensman et al. 2022). Clair Patterson and colleagues first noted large-scale increases in lead pollution in Greenland ice associated with leaded gasoline use (e.g. Murozumi et al. 1969). Using ice cores to determine pre-industrial levels of lead pollution, they demonstrated that increased lead deposition was caused by anthropogenic emissions; these results influenced the passage of the US Clean Air Act in 1970.

Impact of environmental legislation

Following enactment of legislation in North America and Europe in the 1970s and 80s, ice cores show lead pollution declined rapidly, with current levels approximately 80% lower than during the height of leaded gasoline use, though deposition remains 60-fold higher than pre-industrial levels (McConnell et al. 2019; Fig. 2a). In addition to decreases in lead pollution, other pollutants also record evidence of positive human impacts following the US Clean Air Act, and similar legislation enacted around the world (e.g. Environment Action Programme in Europe). One example is the concentration of sulfates in ice from Summit Station in central Greenland. Sulfates primarily originate from coal burning, and therefore their atmospheric concentration increased after the Industrial Revolution. This increase was recorded in the Greenland Ice Sheet (Geng et al. 2014) until the enactment of the Clean Air Act, following which ice-core sulfate concentrations returned to pre-industrial levels (Fig. 2b). Measurements in ice cores also show decreased acidity levels following the Clean Air Act and ensuing market-based cap-and-trade systems (which set limits on allowable pollutant emissions for companies) for sulfur dioxide and nitrogen oxides, which are key chemical species in the formation of acid rain, produced as a byproduct of fossil-fuel burning (Fig. 2c; Maselli et al. 2017; Geng et al. 2014). At Upper Fremont Glacier in Wyoming, USA, there has been a sharp decrease in mercury levels (a toxic heavy metal and anthropogenic pollutant) recorded in the ice since the 1970s, due to the lack of recent volcanic activity and legislation requiring the addition of pollutant scrubbers to industrial flue-gas stacks (Fig. 2d; Chellman et al. 2017).

Ice-core records of pollutants demonstrate the importance of legislation regulating anthropogenic emissions and suggest further environmental legislation may result in continued reductions in anthropogenic emissions. As far as we are aware, no ice-core studies to date have incorporated Indigenous knowledge in interpretation of ice-core data; however, Indigenous experts can enhance our understanding of the role humans have played in shaping the environment and improve effectiveness of legislation. Previous examples of studies within the Earth sciences provide mechanisms for working across knowledge systems to create respectful, inclusive, and effective collaborations with Indigenous experts (e.g. Hill et al. 2020), including tracking sea-ice extent and thickness (Tremblay et al. 2008). Such collaborations could be impactful in ice-core science in, for example, expanding understanding of early pollution histories or impacts of long-range pollution transport, as observed in ice cores, on Indigenous Arctic populations.

Conclusion

The exponential acceleration and vast extent of anthropogenic disruption of the environment is uniquely recorded by a vast array of ice-core datasets. The historical context ice cores provide, by extending contemporary measurements into the past, will continue to be invaluable as previously undiscovered impacts emerge. Ice cores provide unique long-term records, highlighting both the level to which humans have altered remote environments, and the role legislation can have in reducing human influence.

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The living record: Considerations for future biological studies of ice cores

Madelyne C. Willis[1,2], N. Chellman[3] and H.J. Smith[2,4]

This article highlights the state of knowledge of glacial microorganisms, focusing on englacial habitats, challenges associated with studying cells in these environments, and considerations for future ice-core projects seeking to advance biological studies as part of their scientific objectives.

Once thought to be inhospitable to life, glaciers and ice sheets are now considered microbially dominated biomes. Anesio et al. (2017) estimated there may be on the order of 10^{29} cells in all of Earth's glaciers and ice sheets, on the same order of magnitude as the reported total cell abundance for all aquatic systems on Earth (1.2 x 10^{29} cells; Whitman et al. 1998). Originally assumed to be preserved in a dormant state, studies over the past 20 years have demonstrated many of these cells are likely viable, and their presence and function have profound implications for a wide range of scientific fields including paleoclimatology, bioprospecting, and exobiology (D'Andrilli et al. 2017; Balcazar et al. 2015; Tung et al. 2005). Despite this shift to a perception of glaciers as habitable, methodological challenges and the fact that biological studies are often secondary to other scientific goals on deep ice coring projects have limited the study of microorganisms in englacial ice. Looking forward, recent advancements in lab- and field-based methods have created new opportunities for investigating life in these unique ecosystems.

Implications of ice as a habitable space

Glaciers and ice sheets contain liquid water features which may be habitable for microorganisms throughout all three glacial zones (supraglacial, englacial and subglacial) (Boetius et al. 2015). Investigations of glacier microbial communities have focused primarily on the relatively dynamic supraglacial and subglacial zones, emphasizing surface features such as ephemeral meltwater streams and ponds, and cryoconites (depressions in the surface filled with dust and liquid water; Cook et al. 2015), and subglacial hydrological systems (Mikucki et al. 2016; Walcott et al. p. 114). Much less is known about the biology of englacial ecosystems, despite these environments comprising the bulk of glacier ice mass (Boetius et al. 2015).

Within the englacial environment, habitable spaces may be found on the micron scale in water-filled pore spaces between ice crystals and in thin layers of liquid water surrounding dust particles trapped within ice (Tung et al. 2005). While a lack of energy sources and nutrients in these microhabitats may inhibit optimal growth, it is widely accepted that under these conditions microbes can maintain the low levels of activity needed to support basic housekeeping functions (Dieser et al. 2013). These functions, for example DNA repair, allow the cell to remain viable and may result in the uptake or production of some greenhouse gases (Fig. 1). Over geologic timescales, the activity required for cellular maintenance may be adequate to offset ice-core gas records by producing anomalous, non-atmospheric signals of gases e.g. nitrous oxide, methane, and carbon monoxide (Miteva et al. 2016; Fain et al. 2022; Banerjee et al. p. 104). At present, our understanding of in-situ microbial activity within glacier ice is limited to either theoretical (Tung et al. 2005), or in-vitro laboratory studies (Dieser et al. 2013); there has been no direct measure of microbial activity within deep glacial ice. Studies providing empirical evidence of microbial activity or quiescence would facilitate more robust paleoclimatic reconstructions, and understanding the resilience of these organisms may inform our search for life on Mars or other planetary environments containing water ice.

Challenges and considerations

The gap in knowledge regarding in-situ biological activity is largely due to the difficulty of performing biological measurements on ice-core samples. The primary hurdle for most studies is the inherently low biomass within glacier ice. Although cell concentrations as high as 10^6 cells/mL have been reported (Miteva et al. 2016), these high numbers correlate with high dust concentrations and, in general, englacial cell numbers tend to be much lower: between 10^1 and 10^4 cells/mL (Santibáñez et al. 2018).

The challenge of low biomass is exacerbated by limited sample volumes available from deep ice-core projects, contamination, and

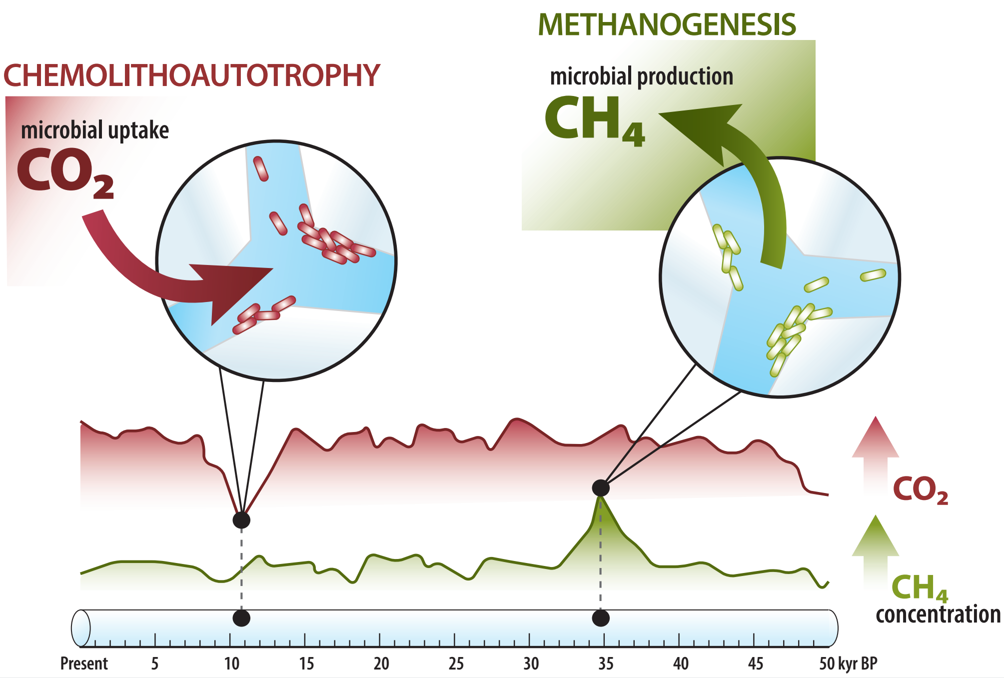

Figure 1: Schematic of ice-core gas records and corresponding in-situ microbial metabolic strategies illustrating the potential for microbial metabolic activity to impact paleoclimatic records. Methanogenesis results in the release of methane (CH_4) outside of the cell and chemolithoautotrophy results in the consumption of carbon dioxide (CO_2).

Å-scale **Elements**	nm-scale **Biomolecules**	µm-scale **Cells**	mm-scale **Structure**
The elemental composition of ice may be linked to the underlying biology. Bio-relevant elements include carbon, hydrogen, nitrogen, oxygen, phosphorous, sulfur and their isotopes.	Biomolecules are compounds produced by living organisms. Examples of biomolecules include lipids, carbohydrates, nucleic acid polymers such as DNA and RNA, and amino acids both free and bound in the form of proteins.	Intact microbial cells and spores have been isolated from deep ice cores and current methods may allow for future investigation of individual cells to determine physiological function and phylogenetic identity.	The physical structure of ice may also be linked to the underlying biology. The presence of cells as impurities, and the possible expression of ice-binding proteins by microbial cells may alter ice lattice structure.
Geochemical measurements (of C, N sources and electron acceptors/donors) may offer insight into the habitability of ice. The concentration and distribution of key elements may indicate the availability of nutrient and carbon sources required to sustain life in ice. One example analysis is **Total organic carbon** (TOC) which measures the complete organic carbon content, including cells and their carbon sources, within the ice.	**Meta-omics** are sequencing techniques which examine the pooled genetic material, DNA or RNA, of a whole microbial community. These methods can be used to study the function and structure of a microbial community. Complementary **single cell genomics** techniques can determine the metabolic potential and taxonomic identity of individual cells within a larger community, potentially revealing the communities functional and genetic diversity.	**Raman microspectroscopy** (RM), **nano scale secondary ion mass spectrometry** (nanoSIMS), and **microautoradiography** (MAR) are minimally invasive and, in combination with isotopic tracers, can provide quantitative information on substrate assimilation of an individual microbial cell. Of note, RM is a non-destructive method that may be used without tracers to produce a unique fingerprint of an organism's native chemical composition.	**Cross polarized light and micro-CT scanning** can be used to study the physical structure of ice by visualizing crystal structure, bubble structure, inclusions, lithic matter, and temporal stratigraphy. When combined with geochemical and molecular measurements, physical measurements could offer insight into the habitability of ice.

Table 1: Analytical targets relevant to biology are categorized with examples of techniques for measuring these analytes in ice cores.

insufficient sensitivity of analytical methods. Core fracturing is a source of contamination that can easily be introduced during ice-core breaking and inconsistent temperature storage. Contamination from mechanical drilling practices that use hydrocarbon-based drilling fluids is of particular concern, as these fluids can contaminate both cores and the subglacial environment. Existing ice-core decontamination protocols are effective but can result in appreciable sample loss. Once samples have been transported to the laboratory and decontaminated, many traditional microbiological approaches lack the sensitivity required for low biomass englacial ice. Depending on final cell concentrations, relatively large sample volumes (5–500 mL meltwater) are often required for these approaches.

Recent developments

Fortunately, recent advancements in drilling systems, microbial analytical methods, and in-situ technology make this an exciting moment for probing questions about microbiology in ice. Hot-water drilling and air-reverse circulation are alternatives to mechanical drilling with organic fluids and have been demonstrated to be effective and to limit contamination (Talalay and Hong 2021). In addition, engineering solutions which prevent vertical and diagonal fracturing of cores during drilling processes preserve more core sections suitable for microbial analysis (Talalay and Hong 2021). Use of a replicate ice-coring system can provide additional sample volume at depths with high community demand for core sections by drilling replicate cores slightly deviated from the original borehole. Use of these systems could provide the sample volume required for microbial analyses.

In the lab, continuous flow analysis provides detailed temporal resolution of decontaminated ice (Santibáñez et al. 2018), which is particularly useful for biological applications to monitor contamination (e.g. the detection of drilling fluids or other anomalies). Innovative and highly sensitive analytical techniques, such as nanoSIMS, stable isotope probing, and other next-generation physiology measurements can reveal cellular function on the single-cell level (Fig. 2). Excitingly for ice-core studies, many of these next-generation approaches are also nondestructive, which enables crucial downstream analyses of individual cells such as cultivation, sequencing, and "omics" approaches. These methods have been demonstrated for studies of microbial diversity and physiology in a variety of low-biomass natural samples; however, they have yet to be applied to studies of deep ice cores. Hatzenpichler et al. (2020) provide a full review of next-generation physiology techniques.

Field-deployable technologies are complementary to lab-based methods and are capable of detecting cells or biorelevant compounds within the solid ice matrix (Eshelman et al. 2019). Cells and compounds that may become too dilute once melted (ex: 10^2–10^4 cells/mL), can be concentrated at detectable levels (10^6–10^8 cells/mL) within the grain boundaries of solid ice (Mader et al. 2006). Since most biological measurements traditionally require samples to be melted before analysis, the development of non-destructive technologies could result in new approaches to studying englaciated life in situ. Additionally, the incorporation of these technologies into the drilling process creates the potential for real-time data collection within the ice borehole. This could provide a means to detect areas of interest based on organic or microbial content during the drilling process and allow for data-driven decision-making during ice-core collection, for instance in determining the depths of interest for replicate coring.

Conclusion

Ice-core research has traditionally focused on reconstructing Earth's climate and environmental history using measurements of stable water isotopes, gases, and other inorganic compounds preserved within the ice. However, we now have the capability to better understand the abundance and function of microbial communities in ice. These organisms may have a profound impact on paleoclimatic records preserved in ice chemistry, may be used as additional indicators of past depositional events related to climate, and may serve as proxies for life in extraterrestrial water ice elsewhere in our solar system. If considerations for biological measurements are taken into account early in planning future drilling projects, there will be greater opportunities to discover the englacial microbiome.

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Firn: Applications for the interpretation of ice-core records and estimation of ice-sheet mass balance

Drake McCrimmon[1,2], A. Ihle[3], K. Keegan[1] and S. Rupper[4]

Firn—old snow slowly densifying into glacial ice—provides valuable information for interpreting ice-core records, modeling meltwater runoff and sea-level rise, and improving our understanding of glacier dynamics through the interpretation of remote-sensing signals.

A glacier's cross section can be split into three main components: (1) a low-density layer of fresh snow at the surface, (2) a ~50–100-m-deep transition zone of densifying old snow called firn, and (3) hundreds to thousands of meters of high-density glacial ice at the bottom (Fig. 1). Firn is an important section of a glacier or ice sheet because the densification process and the grain structure impact how climate information is preserved by glacial ice. The microstructure of the firn (the size and shape of snow grains and pore space within the firn, Fig. 1c) influences both the movement and fate of air and water through the firn (Blackford 2007). These processes affect the interpretation of ice-core paleoclimate records, estimation of the capacity for firn to store glacier surface meltwater, and the use of remote sensing to study ice-sheet mass balance.

Interpretation of ice-core records

Gases trapped in ice cores generally reflect the atmosphere at a time in the past, thus allowing scientists to use ice-core gas records to reconstruct past atmospheric composition (Banerjee et al. p. 104), including greenhouse gases, extending back hundreds of thousands of years (Wendt et al. p. 102). The densification of firn is a major control on how gases are preserved in ice, so understanding this process is imperative for studying past climate.

Like surface snow, firn contains pore space between ice grains in which air can flow and liquid water can infiltrate. As firn density increases with burial depth, the space between snow grains shrinks until pores are closed off from one another (Fig. 1b, c). This depth, called the pore close-off depth, is the point when atmospheric gas becomes permanently trapped as bubbles enclosed in ice. Since gas is not trapped until the pore close-off depth, the air that is trapped in bubbles is younger than the surrounding ice (Schwander and Stauffer 1984). This difference in age is called Δage (delta age) and must be known to accurately date gas records from ice cores (Martin et al. p. 100). The Δage makes it possible to determine what the atmospheric composition was at specific points in Earth's climate history. Firn densification models, annual layer counting, and gas-diffusion models allow us to estimate Δage by determining the time it takes for firn to transition into glacial ice, as well as the time it takes for atmospheric gas to move through the firn to reach the pore close-off depth.

Since the densification rate of firn is strongly controlled by local climate, empirical firn densification models rely predominantly on site temperature and snow accumulation rate (Herron and Langway 1980). Typically, sites with higher temperatures densify more quickly, and sites with higher accumulation rates tend to have thicker layers of firn. While temperature and accumulation are the strongest controls on the compaction rate and these empirical models predict firn density well, there are other physical processes that also impact firn compaction (Fujita et al. 2014). An active area of firn research is the development of physics-based firn-compaction models that take into account firn microstructure and the underlying physical processes driving firn densification (Keenan et al. 2021). Improved firn-compaction models will allow us to better interpret ice-core paleoclimate records and estimate ice-sheet mass balance from remote sensing, especially in locations where empirical firn compaction models do not predict firn density well enough.

The movement of gas through the firn can also be modeled to help determine Δage. This becomes complicated as atmospheric gas composition is altered as it flows through firn pore spaces. Several physical processes alter how gas moves through firn, such as the settling of heavy gasses due to gravity and temperature-gradient-driven gas separation (Severinghaus et al. 1998). This means that the heavier isotopes of gases settle deeper into the firn and also towards cooler

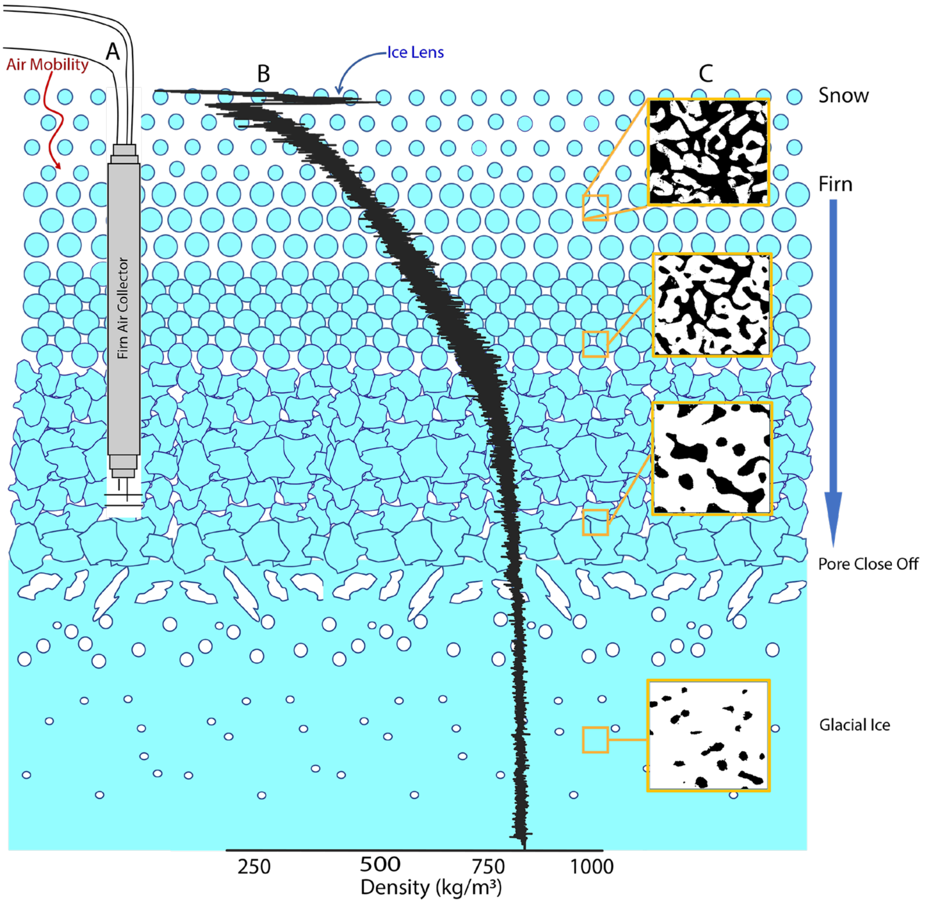

Figure 1: Background illustration shows the evolution of snow to firn to ice. **(A)** The firn-air collection apparatus. **(B)** Example density profile from snow surface through pore close-off to glacial ice (Burgener et al. 2013). **(C)** Example microCT images at differing densities, with black denoting pore space and white denoting ice grains.

temperatures. This results in a slight difference in gas composition between when the gas enters the firn column and when the gas reaches pore close-off. Gas diffusion models are tuned to many different gas species in order to accurately model the movement of different gasses through firn (Buizert et al. 2012). Optimizing these models allows researchers to correct for the change in gas composition within the firn and improve the age estimation of gases. In addition, the air that is traveling through the firn column can also be collected and measured to understand the atmospheric composition in recent history (Fig. 1a; Butler et al. 1999). This firn air is a link between current atmospheric composition and that which is trapped within ice-core bubbles, which may be hundreds to thousands of years old.

Modeling meltwater runoff and sea-level rise

The fate of ice-sheet surface meltwater depends strongly on firn. Instead of running off the ice sheet directly into the ocean, surface meltwater can percolate into the open pore spaces in firn, leading to the development of firn aquifers (Fig. 2a). Remote sensing has shown that there are large areas on both the Greenland and Antarctic ice sheets that have conditions conducive to forming firn aquifers. These conditions include high rates of melting and snow accumulation (Forster et al. 2014). High snow accumulation leads to a thicker layer of firn pore space and insulation to retain meltwater (Kuipers Munneke et al. 2014). In Greenland, large firn aquifers are found on the perimeter of the ice sheet (Fig. 2b) where such conditions are met (Koenig et al. 2014; Miller et al. 2022). Because firn aquifers can slow or entirely prevent meltwater runoff, determining the conditions under which firn aquifers develop will ultimately lead to more accurate estimates of how much surface meltwater will be stored within the firn, versus how much will runoff to the sea (Christ et al. p. 116).

Remote sensing for ice-sheet mass balance

Changes in the thickness and density of firn are a significant uncertainty in estimates of ice-sheet mass change using satellite measurements of surface elevation (Smith et al. 2020). For satellite measurements using microwave radiation, scattering related to snow grain and pore sizes can limit the ability of microwave radiation to penetrate into the ice sheet (Rott et al. 1993). This scattering complicates the use of remote sensing to understand the underlying structure of firn, its meltwater buffering capacity, and changes in ice-sheet surface elevation. Current work aims to use firn microstructure to inform the interpretation of microwave remote sensing on ice sheets in order to improve our understanding of ice-sheet mass balance, both today and in a warming future (Keenan et al. 2021).

Conclusion

Understanding the firn transitional zone is crucial to the accurate reconstruction of past climates, realizing the fate of ice-sheet surface meltwater, and improving estimates of ice-sheet mass balance. Firn provides an important link between processes in the modern atmosphere and ancient atmosphere that is trapped in deep glacial ice. The structure of firn also has major controls on the interpretation of remote sensing signals of glacier surfaces. Ultimately, improving our understanding of firn will deepen our insight of many processes on glaciers and ice sheets.

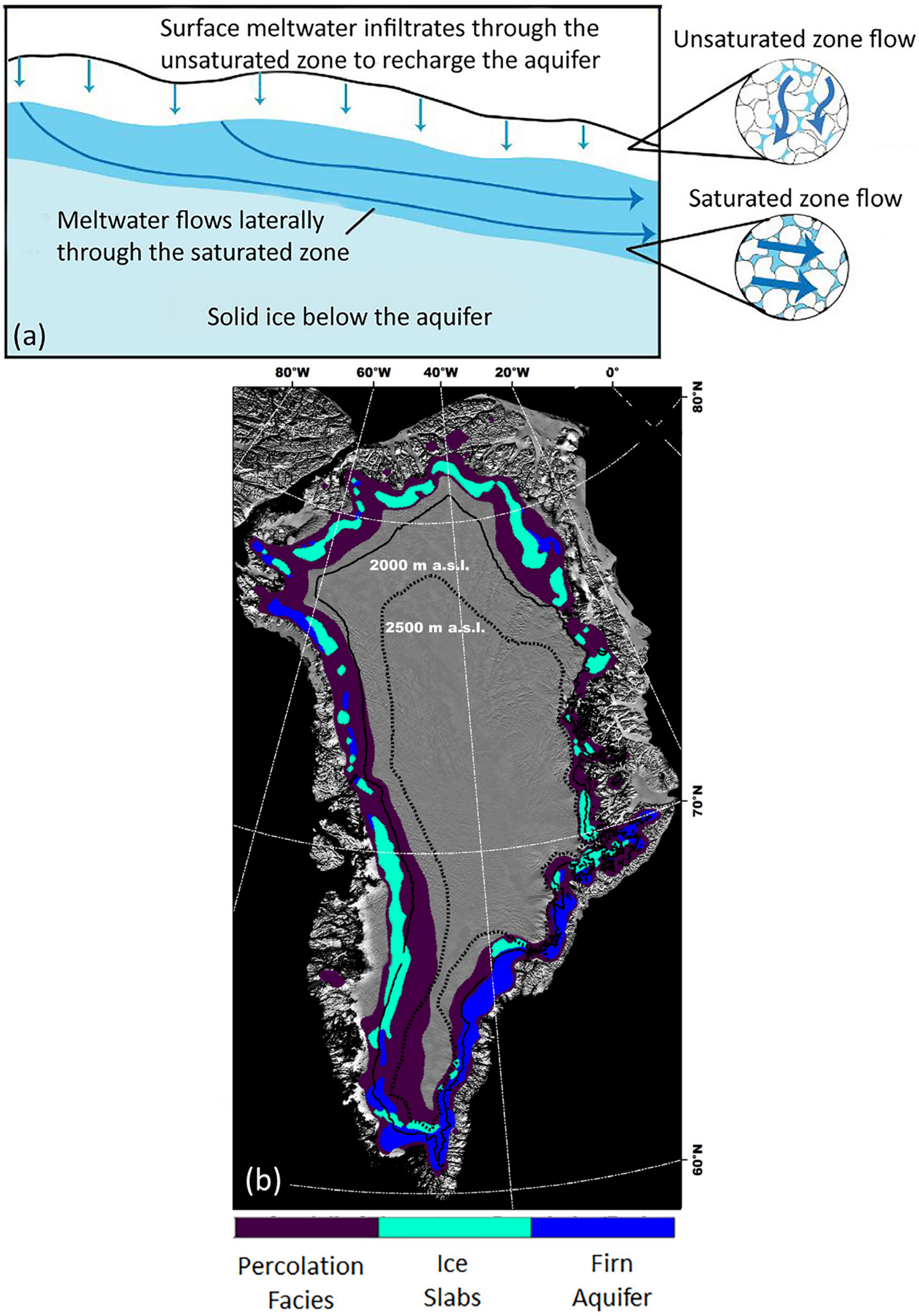

Figure 2: (A) A conceptual illustration of meltwater percolation into a firn aquifer (adapted from Miller et al. in review); and **(B)** Current firn aquifer extent in Greenland (adapted from Miller et al. 2022).

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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

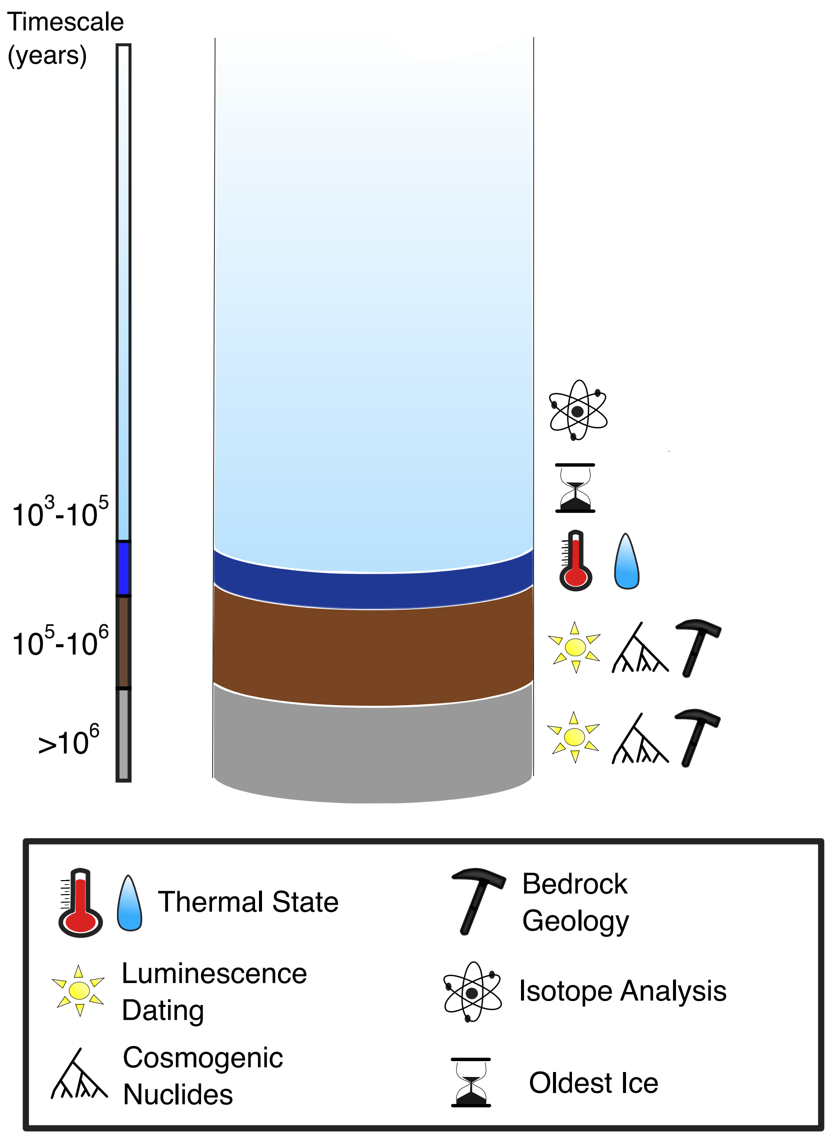

Figure 1: Schematic of a deep ice-core sample, including the subglacial melt (dark blue), sediments (brown), and bedrock (gray). Icons indicate the scientific approaches relevant to deep ice and subglacial materials.

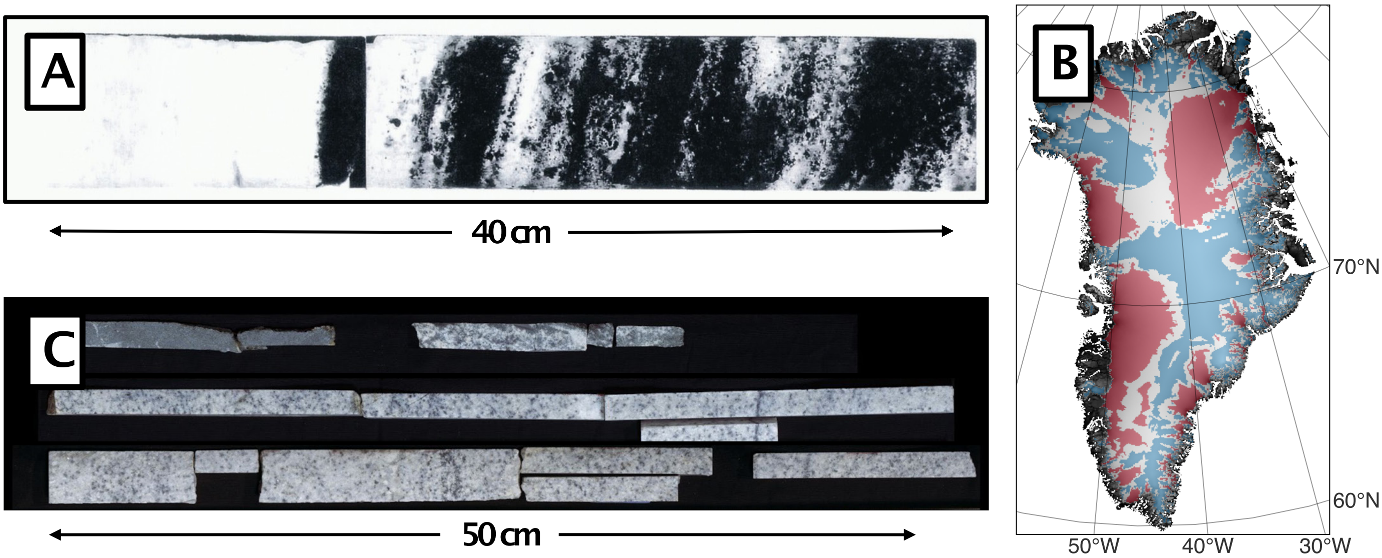

Figure 2: (A) Basal ice from the Byrd ice core, Antarctica (Gow and Meese 1996); **(B)** Bedrock core from GISP2, Greenland (Image credit: Geoffrey Hargreaves); and **(C)** A Greenland-scale product of inferred basal thermal state (blue is frozen, red is melting, gray is not confidently constrained; 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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Ice-core constraints on past sea-level change

Andrew J. Christ[1], J.R. Andreasen[2] and J. Toller[3]

Ice-core records from Antarctica and Greenland reveal how ice sheets responded to past climate changes and contributed to sea-level rise. These archives are critical for understanding how ice sheets may respond and raise sea level due to climate change.

Anthropogenic climate warming threatens to melt portions of the Greenland Ice Sheet (GIS) and Antarctic Ice Sheet (AIS) and raise sea level 0.2–2.4 m by the end of this century (Fox-Kemper et al. 2021; McCrimmon et al. p. 112). During the Pleistocene (2.58 Myr BP–11.7 kyr BP), cyclical changes in Earth's orbit paced the expansion and retreat of Earth's ice sheets, with corresponding drops and rises in global sea level measuring hundreds of meters. These climate oscillations imprint onto Greenland and Antarctic ice cores, which inform ice-sheet contributions to past sea-level rise.

Here, we summarize how continuous and discontinuous ice-core records are used to understand past sea-level changes. Chronologically continuous records can be compared to regional and global paleoclimate datasets to resolve the interplay between ice sheets and sea level up to 800,000 years ago. Chronologically discontinuous records can directly determine past ice-sheet configurations and thus inform ice-sheet contributions to sea level at timescales spanning into the Pliocene (5.3–2.6 Myr BP) and possibly older.

Continuous ice-core records

Ice cores with continuous records preserve paleoclimate data that is sustained through time. All continuous Greenland deep ice cores document Earth's climate through the Holocene (11.7 kyr BP–present) and the last glacial period (118–11.7 kyr BP), with some ice cores reaching into the last interglacial period (128-118 kyr BP; Seierstad et al. 2014; Fig. 1). In Antarctica, continuous ice cores capture much longer records that span multiple glacial–interglacial cycles up to 800 kyr BP (Wendt et al. p. 102) The time resolution of continuous ice cores can vary. For example, due to high snow accumulation rates, the West Antarctic Ice Sheet (WAIS) Divide Core (WDC; Fig. 1) contains annually resolved ice layers since 68 kyr BP (WAIS Divide Project Members 2013), while ice cores from the interior of East Antarctica, such as the European Project for Ice Coring in Antarctica (EPICA) Dome C, have lower resolution but reach 800 kyr BP and possibly as far back as 1.5 Myr BP (EPICA community members 2004; Parrenin et al. 2017).

Continuous ice cores can record changes in ice volume. Ice-core oxygen stable isotopic ($\delta^{18}O$) profiles document the elevation at which frozen precipitation fell onto the ice sheet. In Greenland, vastly different $\delta^{18}O$ trends between ice cores near the ice margin (Camp Century and DYE-3) and those near the ice-sheet center (Greenland Ice Sheet Project (GRIP) and North Greenland Ice Core Project (NGRIP)) indicate significant elevation decrease along the ice-sheet periphery (Fig. 1), and thus ice-sheet thinning, during the last deglaciation (Vinther et al. 2009). In Antarctica, the oxygen isotopic profile of the WDC reveals temperature changes and subsequent ice advection and thinning (WAIS Divide Project Members 2013). Changes in ice-surface elevation from continuous ice cores can be compared against geologic records of ice-sheet thinning and retreat (Briner et al. 2020) to reconstruct changes in ice-sheet volume.

Temperature records extracted from continuous ice cores help to resolve the interplay between ice-sheet behavior and sea level during abrupt millennial-scale climate events. For example, during the last deglaciation from 14.7 to 13.0 kyr BP, Greenland ice cores record intense warming, while Antarctic ice cores show cooling due to hemispheric differences in ocean heat transport. These hemispheric differences in temperature demonstrate how the Antarctic and Greenland ice sheets respond to global warming in the context of the entire climate system.

Continuous ice-core records can also be compared against regional and global records of sea level deduced from coastal geomorphology, tectonic, and isostatic records, and isotopic analyses of marine sediments. The compilation of continuous ice-core records with far-field records of sea level captures both periods of rapid sea-level rise during deglaciation, as well as stability in sea level following the mid-Holocene (Lambeck et al. 2014). Over glacial–interglacial timescales, continuous ice-core records from Antarctica can be compared to the global ice volume reconstructed from benthic foraminifera in deep marine sediment.

Discontinuous ice-core records

Discontinuous ice-core records, such as folded ice, uplifted ice, basal ice, subglacial materials, and ancient buried ice, offer snapshots of the past that can directly constrain ice-sheet configurations at timescales reaching into the Pliocene (5.3–2.6 Myr BP; Fig. 2). Ice-core records become discontinuous due to ice deformation, glacial erosion, or disconnection from the wider ice sheet. Ice flowing across its bed can fold, complicating simple stratigraphic interpretations of ice chronology. When the ice deformation

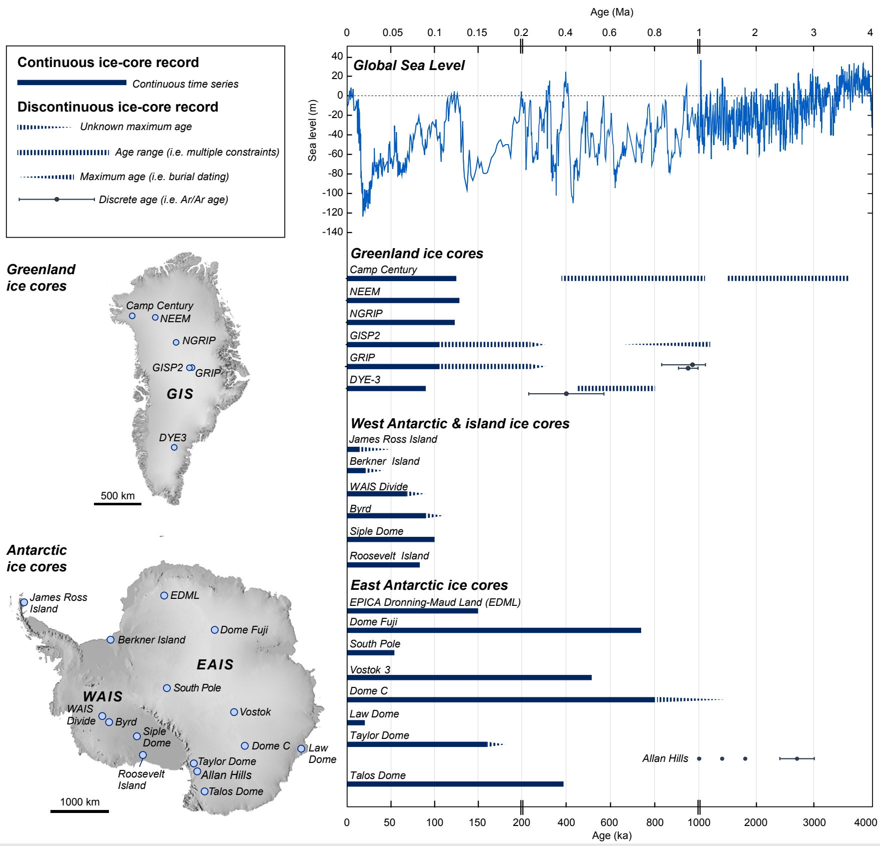

Figure 1: Continuous and discontinuous ice-core records from Greenland and Antarctica (locations shown in map insets) compared to a multi-proxy reconstruction of global sea level since 4 Myr BP (Miller et al. 2020) (note changes in timescale).

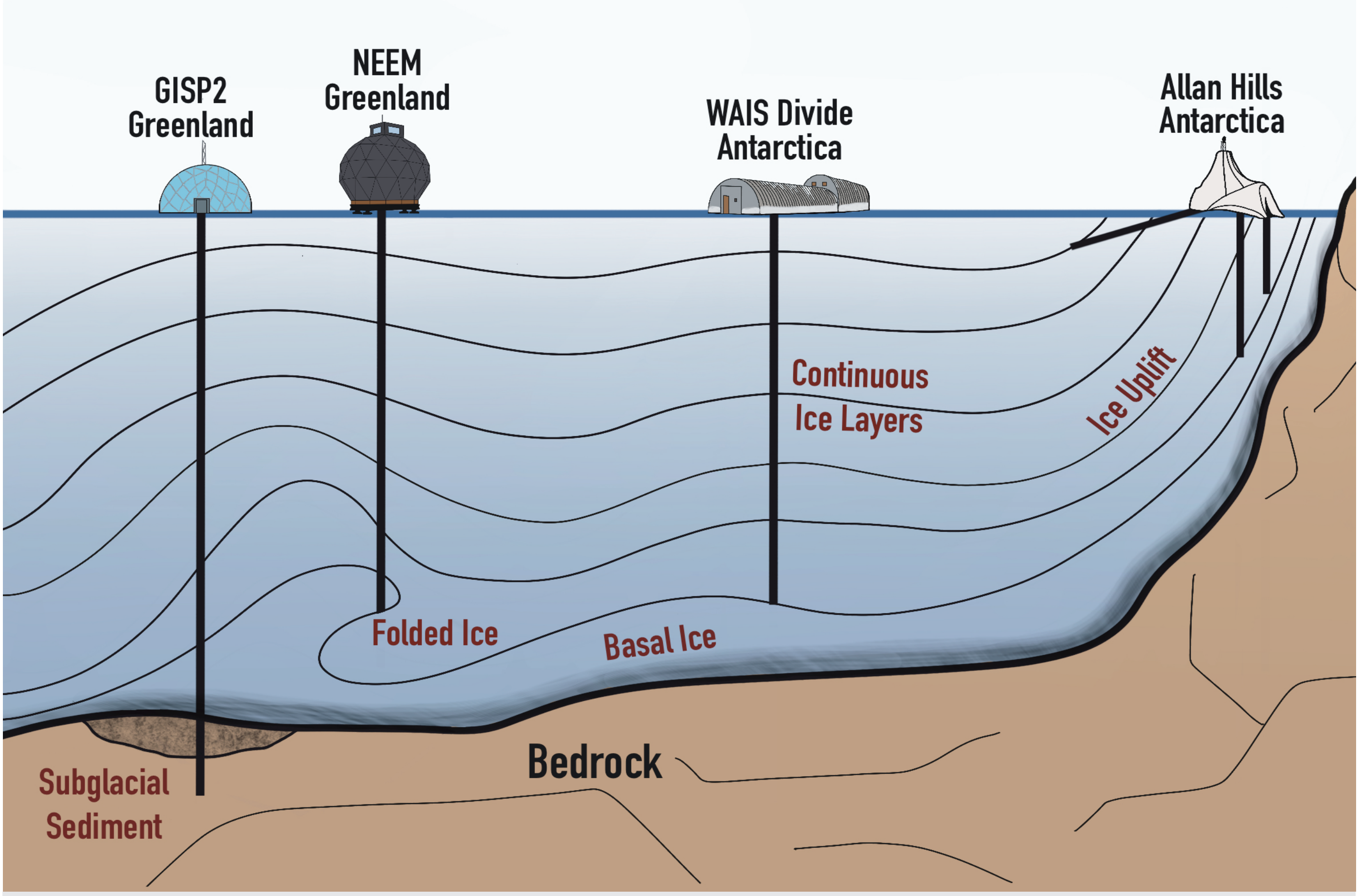

Figure 2: Schematic of ice-core drilling settings that recover continuous and discontinuous ice-core records showing several examples from existing ice-core sites.

history is disentangled, ice-core records can be tied to time periods older than the overlying ice. For example, the North Greenland Eemian Ice Drilling (NEEM) ice core from northeast Greenland contains folded ice from ~130 kyr BP during the warm Marine Isotope Stage 5e interglacial period, when sea level was 4–6 m higher than today (NEEM community members 2013). Older ice can be uplifted to the surface where ice flowing across the bed encounters mountainous topography, providing a snapshot of atmospheric composition older than continuous ice-core records provide. In the Transantarctic Mountains, uplifted ice in the Allan Hills (Figs. 1, 2) contains trapped atmospheric gasses from 1.0, 1.2, 2.4 Myr BP, and older, which is further back in time than any continuous ice-core record (Yan et al. 2019).

As drilling approaches the ice-sheet bed, ice cores can recover sediment-rich basal ice (Walcott et al. p. 114). Dating basal ice can provide a maximum age of ice cover. In the GRIP ice core, basal silty ice as old as 970 ± 140 kyr (Willerslev et al. 2007) has been found, suggesting that part of central Greenland remained ice-covered for the past ~1 Myr. Ice cores that recover subglacial sediment and bedrock from the bed of an ice sheet can be dated to directly constrain when a presently ice-covered landscape was deglaciated in the geologic past. In West Antarctica, radiocarbon analysis of subglacial lake-sediment core samples demonstrated that the grounding line in the Ross Sea retreated relative to its present position, and thus the West Antarctic Ice Sheet was smaller, in the Early Holocene (Venturelli et al. 2020). Dating of subglacial sediment from the Camp Century ice core in northwest Greenland (Christ et al. 2021) and subglacial bedrock from the GISP2 ice core (Schaefer et al. 2016) in central Greenland both require ice-free exposure at least once since ~1 Myr BP, implying that much of the GIS melted and contributed to sea-level rise within that time frame.

In ice-free valleys in Antarctica, ancient ice from the Pliocene and possibly older periods remains frozen below a relatively thin layer of overlying glacial till (Bergelin et al. 2022). Although exceptionally challenging to date (Martin et al. p. 100), ice cores from debris-covered glaciers can provide snapshots far into the geologic past when atmospheric CO_2 concentrations may have exceeded those observed today.

The future

The future of ice-core drilling aims to recover continuous ice-core records older than 800 kyr and discontinuous ice-core records that constrain past ice-sheet configurations. In Antarctica, several ongoing projects led by different international teams aim to recover the oldest ice to reveal the size and behavioral characteristics of the AIS during the Early Pleistocene (2.6–0.8 Myr BP). In Greenland, the GreenDrill project will drill several ice cores near the margin of the GIS to recover subglacial sediment and bedrock. These discontinuous records will resolve when and how often the GIS was smaller in the past than it is today. As Earth's ice sheets respond to continued climate warming, continuous and discontinuous ice-core records both offer important information on ice-sheet responses to past warming periods and contributions to sea-level rise.

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