Drilling Through Ice and into the Past

That the Earth's climate is changing is irrefutable. The future course, rate and ultimate effects of that change are less clear. Climatologists, glaciologists and engineers are retrieving ice cores from the Greenland and Antarctic ice sheets and from glaciers in temperate climes in an effort to learn from the past what the future may hold.

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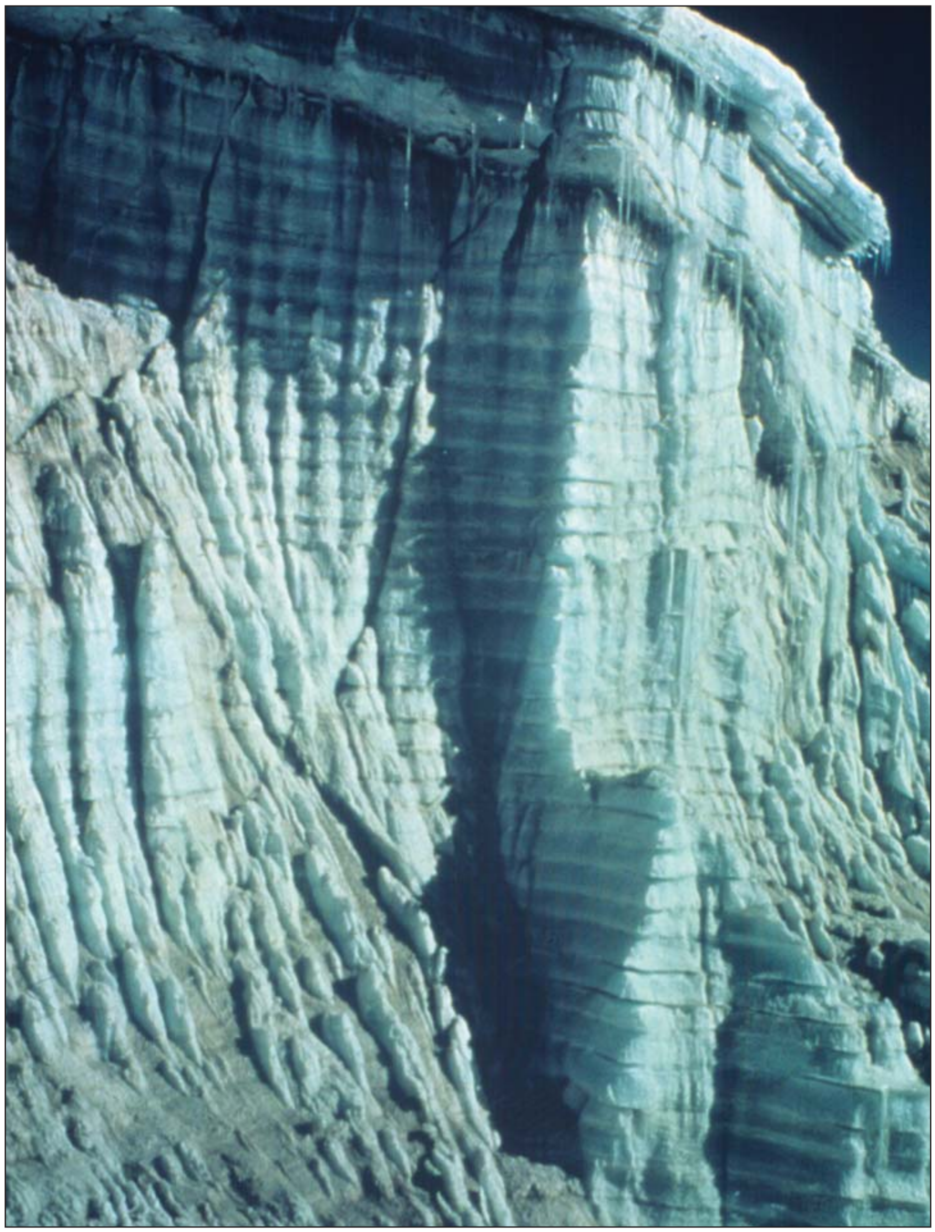


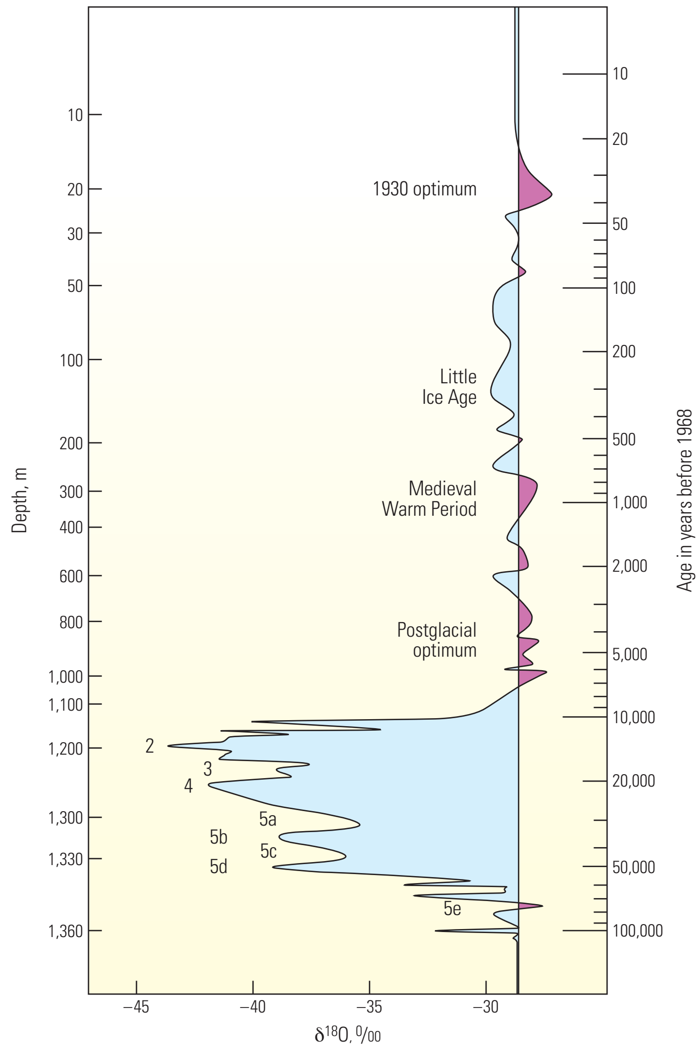
^ Quelccaya ice cap, 1977. (Photograph courtesy of Lonnie Thompson, The Ohio State University, Columbus, USA.)

Climatologists need to look back hundreds to many thousands of years to learn how the Earth's climate conditions have changed over those years. Doing so helps them better understand Earth's climate processes so they can make predictions of what is to come. In areas of ice sheets where snow does not melt but piles up over many hundreds of thousands of years, the resulting kilometers-thick ice forms an archive of clues to past climate.

Although the science of interpreting climate from ice cores is less than 70 years old, climatologists have made some remarkable discoveries.[1] For example, ice core science enabled the revelation that climate can change abruptly, in less than 10 years, and the realization that the carbon dioxide [CO_2] composition of the atmosphere is higher now than it has been in more than 800,000 years.[2]

The first drills for retrieving ice cores for scientific use were designed by the US Army Corps of Engineers in the 1950s. These drills, the design of which originated from concepts associated with geologic drilling, were used to drill a number of intermediate-depth and deep ice cores both in Greenland and Antarctica.[3] When the US Army created Camp Century in Greenland in the 1960s, army engineers built a new electromechanical drill for retrieving the first deep, continuous core to bedrock; for that core, Chester Langway, Jr., who was responsible for scientific analysis of the cores, formed an international team that included US, Danish and Swiss scientists to conduct an array of measurements on the core. Ice core science rapidly evolved in many nations, and even today, international, interdisciplinary endeavors continue to be a hallmark of ice core science.

Danish scientist Willi Dansgaard performed work that led to international collaboration on the analysis of the Camp Century ice core. Dansgaard made a discovery in the 1950s that enables analysts today to decipher the information etched into these ancient records. Dansgaard developed instrumentation that could rapidly measure the seasonal variations in climate conditions over short time intervals by measuring variations of stable oxygen isotope ratios, such as $^{18}O/^{16}O$ in ice cores. Dansgaard applied this technique to analysis of the 1,390 m [4,560 ft] long core recovered at Camp Century in 1966 (right).[4] Analysis of other chemical species, by a wide range of scientists from around the world, has since been performed on ice cores to extract such weather and climate information from dust, the results of volcanic activity, snow accumulation rate and, for natural and anthropogenic-related markers, a host of chemical tracers in the ice sheets.[5]

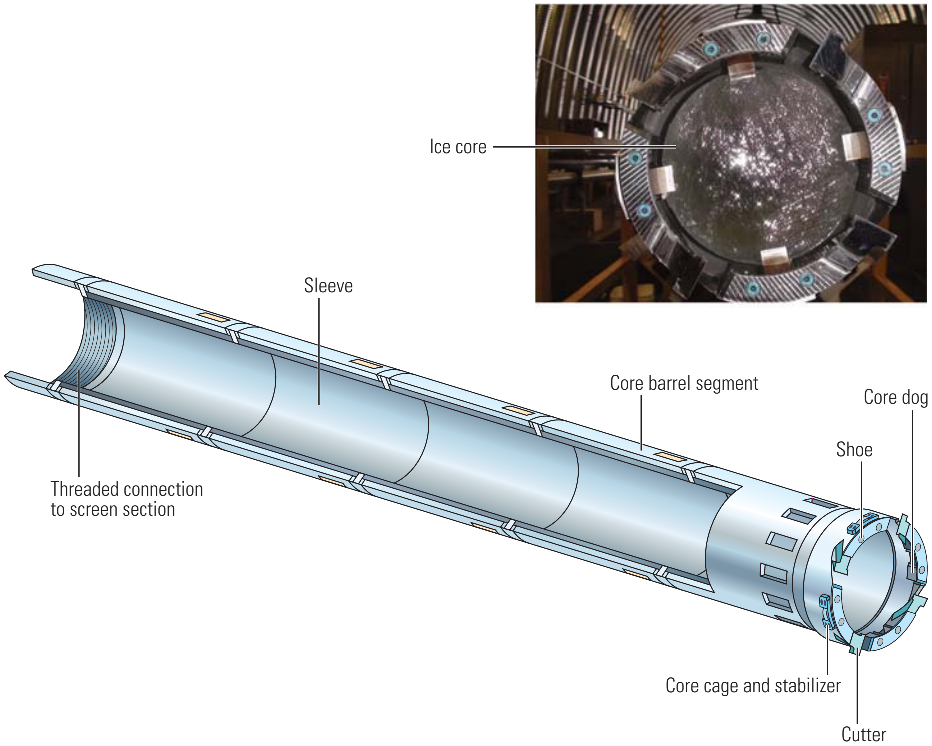


^ The first Camp Century ice core. Results from the analysis of the Camp Century ice core showed that past climate conditions could be derived from ice cores. The graph shows the amount, in parts per thousand (‰), by which the ratio of stable oxygen isotopes $^{18}O/^{16}O$ ($\delta^{18}O$) varies as a function of depth and age along the 1,390-m length of the ice core. Low $\delta^{18}O$ values (blue shading) are associated with low temperatures at the time, and high values (purple shading) are associated with warm temperatures. The large deviation of $\delta^{18}O$ values at around 1,100 m corresponds to the change from the last glacial to the current interglacial period. Various past climate events (2 to 5e) are also identified. These results demonstrate that ice core drilling and the oxygen isotope method are viable ways of reconstructing some past climatic conditions. [Adapted from "The History of Danish Ice Core Science," *University of Copenhagen, Centre for Ice and Climate, Niels Bohr Institute*, http://www.iceandclimate.nbi.ku.dk/about_centre/history/ (accessed June 5, 2013).]

This article describes the process of drilling through Arctic and Antarctic ice sheets and glaciers in tropical climates, the techniques used to retrieve intact ice cores and the way ice cores are stored and analyzed. Case histories include the results of efforts to capture cores from the Eemian interglacial period in Greenland, the West Antarctic Ice Sheet (WAIS) and the Quelccaya ice cap in Peru.

Building an Ice Drilling Rig

As scientists sought to acquire cores from greater depths in the thick ice sheets of Greenland and Antarctica, the equipment to do so has evolved to meet the challenges unique to those environments.[6] One of the most recent iterations in the development of ice drilling rigs is the electromechanical deep ice sheet coring (DISC) drill. The DISC drill, with its directional



^ Ice core cutter head. The ice core cutter creates an annulus between the ice and the sonde. As the tool moves downward, it captures a continuous column of ice for retrieval to the surface. Using this system, drillers have reached depths of about 3,800 m [12,500 ft] and can retrieve a core 12.2 cm [4.8 in.] in diameter and 4 m [13 ft] in length. The rotating core barrel consists of a series of mechanically connected tubes; the barrel can be fitted with a fiberglass sleeve, which helps keep fractured cores intact. Core dogs, which pivot into and break the ice when the drill is lifted, hold the core in the core stabilizer and cage (photograph) as the cutter is brought to the surface. Core shoes are small buttons on the bottom face of the cutter head that limit the penetration of the cutter blades. The vertical distance between the bottom surface of the shoes and the cutter tips sets the pitch, or rate of penetration, of the drill. (Adapted from Mason et al, reference 8.)

drilling capability, was designed and built by the Ice Drilling Design and Operations (IDDO) group at the Space Science and Engineering Center at the University of Wisconsin-Madison, USA. The drill was developed to retrieve cores in deep ice by incorporating, among other features, the ability to do the following:

- collect ice cores from depths to 4,000 m [13,000 ft]
- capture ice cores of more than 98 mm [3.9 in.] diameter
- maintain 5° or less borehole inclination
- collect replicate cores using directional drilling
- sample and record depth, drill rotation speed, torque, WOB, fluid temperature and core barrel acceleration 10 times per second.[7]

Designers also sought to reduce overall project duration by optimizing the balance between trip time and coring time; in deeper projects, moving the bit in and out of the hole is a larger contributor to overall project time than is coring on the bottom. The DISC unit is able to drill longer cores than were possible using earlier drills, thus is able to reach its depth objectives in fewer trips.

The DISC drill consists of a drill sonde, drill cable, drill tower, winch, surface power supply and control system. The modular drill sonde includes a cutter head assembly, core barrel, screen section, motor pump section and instrument section. The cutter head assembly, which has four replaceable cutters, incorporates a core barrel to protect the captured core (above). The cutter head, which cuts an annular ring of ice to produce the core, includes four core dog cages, or pawls, that break the core at the end of the coring run and keep it from slipping out the bottom of the barrel as it is brought to the surface. The cutter head assembly also includes buttons, or shoes, located on the bottom face of the cutter head. The buttons serve to limit the penetration of the cutters by setting the pitch of the cutters.[8]

The motor pump section of the DISC sonde contains two motors and a drill fluid pump that can operate in temperatures to –50°C [–58°F] and pressures to 40 MPa [5,800 psi]. One motor drives the pump and the other drives the core barrel and cutter head assembly.[9] Ice cuttings are collected in the screen section, which consists of a housing made of the same tubes as the core barrel fitted with screens in its center. Drilling fluid carries the ice chips created during coring operations up into the annulus of the core barrel to screens in the assembly, which brings them to the surface along with the core (next page, top).

The drill sonde is composed of antitorque, instrument and motor sections for motor control, data acquisition, power conditioning and communications. The system includes two motors, which operate independently and are controlled through a closed-loop current control system. Because motor torque in these systems is proportional to current, torque is controlled by moderating power to the motors.

Sensors within the sonde measure the temperature of the electronics, drilling fluid, cutter motor, pump motor and motor fluid. Because the instrument section must remain pressure sealed, sensors monitor the pressure between two redundant seals and each end cap of the assembly.[10]

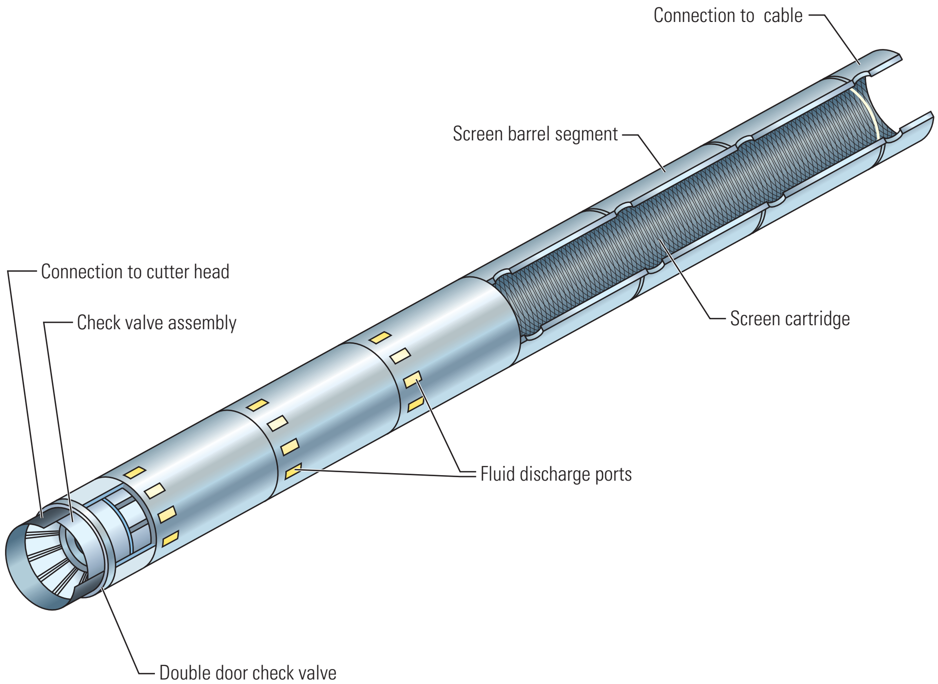
The upper section of the sonde includes the cable's mechanical, electrical and optical fiber terminations. Rotary joints allow the drill sonde to rotate relative to the cable. The cable physically supports the drill, supplies power to it and enables communication between the sonde and the surface. The DISC drill cable includes a central king wire, fiber-optic cables, copper wires and an outer wrapping of galvanized steel wires to provide the mechanical strength to lower and raise the sonde (next page, bottom).[11]

Unlike oil and gas drilling unit arrangements, the axis of the DISC drill drum is parallel to the drill cable as it runs through a spooling device to the tower. The configuration allows the winch to be located at the base of the tower, resulting in a smaller footprint than those in which the cable runs perpendicular off the winch to the tower. Because of the tower-winch configuration, once the drill is on the surface, it must be laid down and the core barrel disconnected from the sonde. Rig workers then lift and rotate the core barrel 180° to allow the core to be pushed from the top of the barrel onto a processing tray. Removed from the core barrel, the cores are usually cut from their original 3.5-m [12-ft] lengths into 1-m [3-ft] lengths; they are then stored in a freezer for transportation to an archival storage and research facility. The DISC drill was field tested in Greenland and the designers implemented necessary modifications prior to the drill team's work in Antarctica.[12]

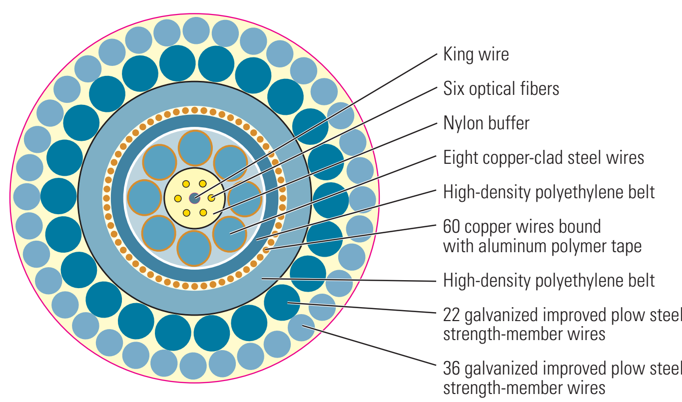
Similar to those used in the oil field, drilling fluids in ice coring serve multiple functions; in addition to lifting ice chips to the screens, drilling fluids used in ice drilling create a hydrostatic pressure that prevents the borehole from collapsing. Ice boreholes are not geopressured, but ice is plastic and will flow into the borehole in response to vertical and shear stresses imposed on wellbore walls. Vertical stress, or glaciostatic pressure, is caused by the overburden weight of the ice; shear stress, or glaciodynamic stress, is caused by glacier flow over rock.[13]

The density of ice core drilling fluids is designed to be as close as possible to the density of the ice being drilled; in the past, drillers used n-butyl acetate as drilling fluid. But driven by health concerns for personnel, project leaders at the WAIS Divide site in central West Antarctica opted for a mixture of about three parts Isopar K fluid to one part hydrochlorofluorocarbon. Fluid handling systems for ice coring contain a tank with measuring devices, valves, pumps and centrifuges to recover ice chips from the screens before returning the fluid to the system.

Development of new ice drilling technology in the US is driven by the Long Range Science Plan, which was the result of scientific community planning organized by the Ice Drilling Program Office (IDPO).[14] The IDPO oversees engineering

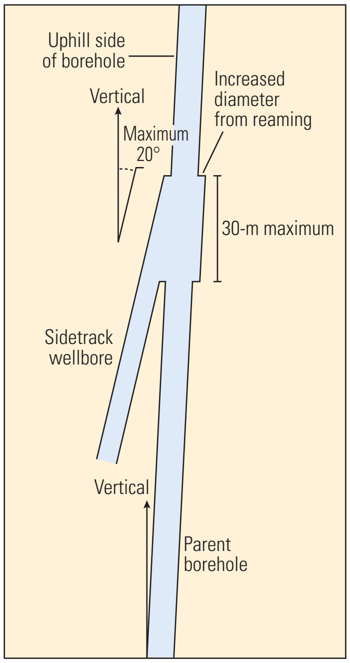


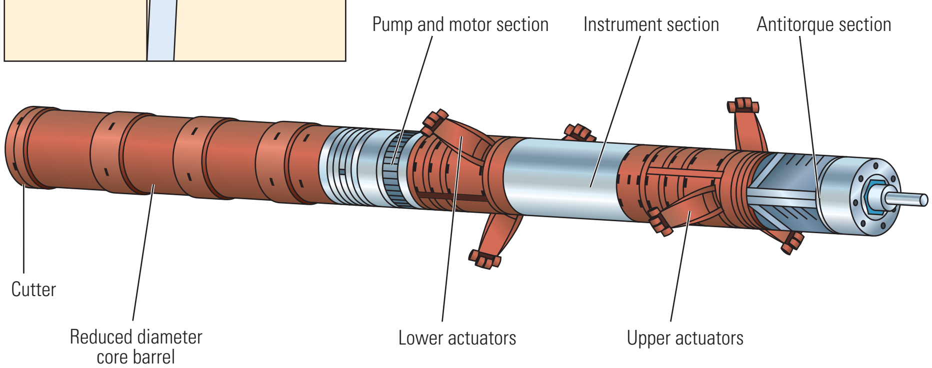
^ Screen section. The screen section filters ice chips produced by the cutters from the drilling fluid as it is circulated through the drill. The section also provides a compartment in which to collect and store the ice chips for transport to the surface. The ice chip screen is designed for maximum filter area and minimum pressure drop. A modular, interchangeable screen cartridge was developed for the DISC drill for speed and ease of cleaning during drilling operations. The DISC screen and barrel design are modular so that any number of screen cartridges can be used. Check valves control the direction of drilling fluid flow. The check valve assembly is connected to the screen section below the screens and held in place by a spring-loaded locking ring. The check valve assembly supports the weight of the screen cartridges that are above it and employs a set of double door check valves to allow the fluid-chip slurry that is pumped up from the cutters to enter the inside of the screen cartridge stack, where chips are filtered and collected from the drilling fluid; the filtered fluid is discharged into the wellbore. A concentric array of 12 openings allows one-way backflow of clear fluid to drain and bypass the screens in the opposite direction down through the drill as the tool is tripping out of the borehole. (Adapted from Mason et al, reference 8.)



^ DISC drill cable. The DISC drill cable is designed primarily for coring conditions at the WAIS site and engineered for requirements for weight, size and breaking strength. The cable is sized to fit on the winch spool that lowers the device into the core hole. The spool and cable are light enough to be handled by available cranes and shipping methods. The breaking strength is specified at 142 kN [31,900 lbf], which is greater than that of the mechanical fuse at the top of the sonde and less than the total winch pulling force. The cable is designed with void filler material around cable parts and outer layers that are impervious to drilling fluids used at the WAIS site. The cable has an operational life of five years. (Adapted from Shturmakov and Sendelbach, reference 11.)

7. Shturmakov AJ, Lebar DA, Mason WP and Bentley CR: "A New 122 mm Electromechanical Drill for Deep Ice-Sheet Coring (DISC): 1. Design Concepts," *Annals of Glaciology* 47, no. 1 (2007): 28–34.
8. Mason WP, Shturmakov AJ, Johnson JA and Haman S: "A New 122 mm Electromechanical Drill for Deep Ice-Sheet Coring (DISC): 2. Mechanical Design," *Annals of Glaciology* 47, no. 1 (2007): 35–40.
9. Mason et al, reference 8.
10. Mortenson NB, Sendelbach PJ and Shturmakov AJ: "A New 122 mm Electromechanical Drill for Deep Ice-Sheet Coring (DISC): 3. Control, Electrical and Electronics Design," *Annals of Glaciology* 47, no. 1 (2007): 41–50.
11. Shturmakov AJ and Sendelbach PJ: "A New 122 mm Electromechanical Drill for Deep Ice-Sheet Coring (DISC): 4. Drill Cable," *Annals of Glaciology* 47, no. 1 (2007): 51–53.
12. Johnson JA, Mason WP, Shturmakov AJ, Haman ST, Sendelbach PJ, Mortensen NB, Augustin LJ and Dahnert KR: "A New 122 mm Electromechanical Drill for Deep Ice-Sheet Coring (DISC): 5. Experience During Greenland Field Testing," *Annals of Glaciology* 47, no. 1 (2007): 54–60.
13. Aber JS, Croot DG and Fenton MM: *Glaciotectonic Landforms and Structures*. Amsterdam: Springer Netherlands (1989): 155–168.
14. The Long Range Science Plan was created by the US National Science Foundation to set goals and offer direction and logistical support for US ice coring and drilling science and to support ice drilling technology development and infrastructure.





^ Drilling a replicate core. The replicate drilling sonde (*bottom*) is a modified ice drilling and coring sonde with reduced diameter core barrel and screen sections and a lower actuator module that applies pressure against the borehole wall to initiate a sidetrack wellbore from the uphill, or high, side of the parent wellbore (*top*). Lower actuators are fitted with disk wheels (not shown) to reduce friction along the borehole wall. Upper actuators keep the sonde from spinning while the core is being cut by preventing transfer of torque to the sonde. [Adapted from Souney J: "Replicate Ice Coring System," *In-Depth* 6, no. 2 (Fall 2011): 7.]

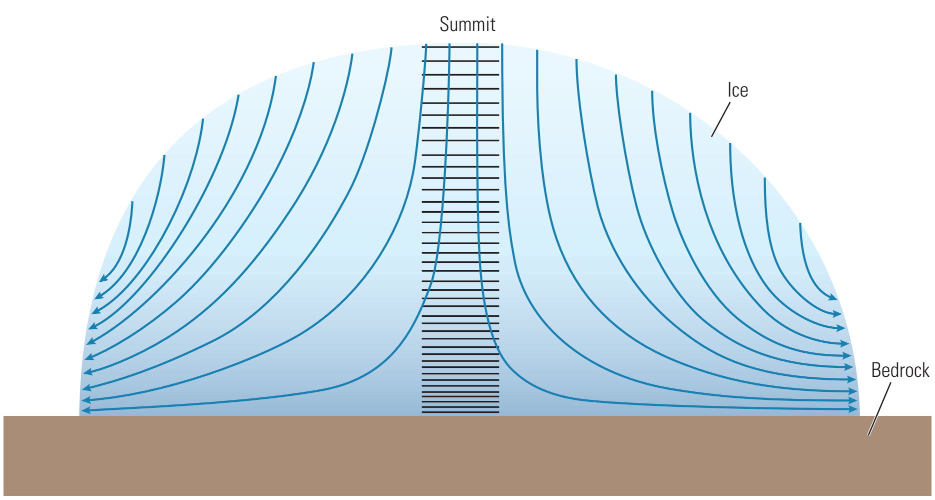
performed by IDDO.[15] Scientists in the ice core community have long wished for replicate cores from scientifically significant specific depths in ice sheets such as those at which abrupt climate changes have occurred. A replicate core is a core from a sidetrack wellbore that has been drilled nearly parallel to and very near a previously retrieved core so that the two will have exact depth and layer matches. In the last five years, engineers at IDDO have found a way to realize this possibility. In 2012, engineering adaptations to the DISC drill helped scientists recover replicate ice cores from multiple targeted depths at the WAIS drillsite. Because scientists wished to continue to deploy gravity-driven sensors in the borehole below the depth at which the replicate core was taken, the replicate core had to be taken from the uphill, or high, side of the hole.

To meet this requirement, the replicate coring technique uses actuators placed along the sonde that apply pressure to the sidewall of the main wellbore, which causes the wellpath to deviate (left). The deviated section becomes a separate borehole within 30 m [100 ft] of the point at which lateral forces are first applied. The sidetrack exits from the high side of a slightly deviated main wellbore. Once the sidetrack is established, cores are taken from a borehole that is drilled nearly parallel to the main wellbore. The replicate coring sonde includes actuators on its upper end that act as antitorque devices to keep the sonde from spinning; on the lower end of the tool, actuators with disk wheels allow the sonde to move smoothly along the deviated section. Coring is performed in repeated trips, each of which can capture a 10.8-cm [4.25-in.] diameter core, until the desired length of core section is acquired.[16]

Preparing the Take

Although the practices involved in drilling and coring ice may be comparable to those used in oilfield operations, rock and ice in place behave differently. Unlike rock, ice is plastic and flows downward and laterally (below left). Therefore to ensure true depth correlation of strata, drillers must site their equipment at the top of an ice structure, or dome. Additionally, ice composition differs depending on burial depth, and as a result, the ice must be handled accordingly. Glaciers are composed of ice containing chemical impurities and air bubbles. From about 600 to 1,200 m [1,970 to 3,940 ft], the cored ice is usually brittle when it is extracted from the borehole. Because the pressure of the air bubbles trapped in the ice is greater than the bond between the ice crystals, the ice core may spontaneously fracture and sometimes shatter. Deeper than about 1,200 m, the pressure and temperature of the ice force the air bubbles into clathrate hydrates, making them part of the ice crystal structure, and ice instability ceases to be an issue.[17]

Technicians electronically measure the length of cores brought to the surface and feed the measurements into a computer program so they may be tallied with measurements from previous cores brought up from the same wellbore. They then evacuate drilling fluid from around the core as it is pulled from the core barrel. Residual drilling fluid is then removed from the core in a



^ Ice flow. Because ice is plastic, it flows downward and outward (blue arrows) from the summit of a dome. Therefore, ice cores taken from the center of a dome (horizontal black lines) retain a true depth-age correlation. The black lines represent layers that become thinner with depth as they are compressed by increasing overburden weight.

drying booth, and the cores are then bagged, boxed and shipped. Brittle ice is captured in netting to minimize breakage, and when it does break into many pieces, scientists can still discern a great deal from it as long as the mass of the core is preserved in stratigraphic order.

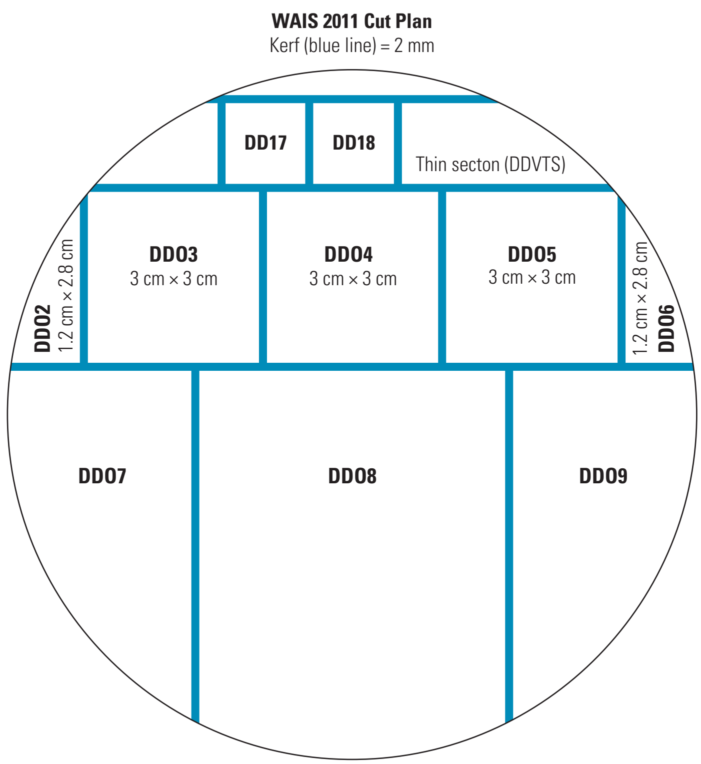
Many of the cores from the major ice sheets of Greenland and Antarctica are now shipped to the US National Ice Core Laboratory (NICL) in Denver. Managed by the US Geological Survey and funded by the US National Science Foundation (NSF), the NICL stores more than 17 km [11 mi] of ice cores from 34 drillsites at a storage temperature of –36°C [–33°F] (right).

The NICL area for examining cores is maintained at –24°C [–11°F]. The ice core to be analyzed is cut lengthwise, or slabbed. Slabs are further divided into sections to be distributed to scientists for various types of studies (below right). For example, because sections cut from the center of the core are least likely to have been contaminated by drilling fluids or other outside materials during capture, transportation and storage, scientists at the laboratory typically designate those sections for chemical analysis. Other sections are cut to size specifications or from certain locations within the core for bubble and layer counting, imaging or gas analysis using mass spectrometers.

Paleoclimatologists seeking information about past climates use proxy data gleaned from natural resources such as tree rings and ocean bottom sediment. The records they construct from these sources are paleoproxy records—indirect natural records of past climate or meteorologic variability. From the isotopic and chemical composition of ice and dust in ice cores, scientists are able to estimate past regional average air temperatures, atmospheric circulation variations, precipitation amounts, atmospheric composition, solar activity and volcanic eruptions. Proxy data include a variety of chemical species, stable isotopes, radioisotopes, dust composition, snow accumulation rate, volcanic ash and sulfur, which scientists use to determine past climate conditions.

15. Albert M, Twickler M and Bentley C: "A New Paradigm for Ice Core Drilling," *Eos Transactions, American Geophysical Union* 91, no. 39 (September 28, 2010): 345–346.
16. "Replicate Ice Coring System," *US Ice Drilling Program*, http://www.icedrill.org/equipment/replicate-coring-system.shtml (accessed July 6, 2013).
17. Clathrate hydrates are solids in which molecules, of air in this case, occupy cages in molecular crystals of hydrogen-bonded water molecules.

^ Cores in storage. The National Ice Core Laboratory in Denver serves as a center for preparation and storage of ice cores. The laboratory currently contains more than 17 km of ice cores from around the world.



^ Dividing the work. In the laboratory, technicians section the core for specific types of analysis. In this instance, sections DD17 and DD18 were used to determine stable isotopes (H and O) in water. Thin section DDVTS was used for crystal and fabric analysis for size, shape and axes orientation of ice crystals; these 10-cm [4-in.] sample sections are taken every 20 m [65 ft]. Sections DD02 and DD06 were used for beryllium-10 isotope analysis. Sections DD03, DD04 and DD05 were designated for chemical analysis. DD07 and DD09 were archived. DD08 was used for gas analysis, with samples taken every 10 to 50 cm [4 to 20 in.] depending on climate signature and time interval. Kerf is the width of the cut, which is dictated by the width of the saw blade and represents how much material is sacrificed during sectioning.

Evidence in the Ice

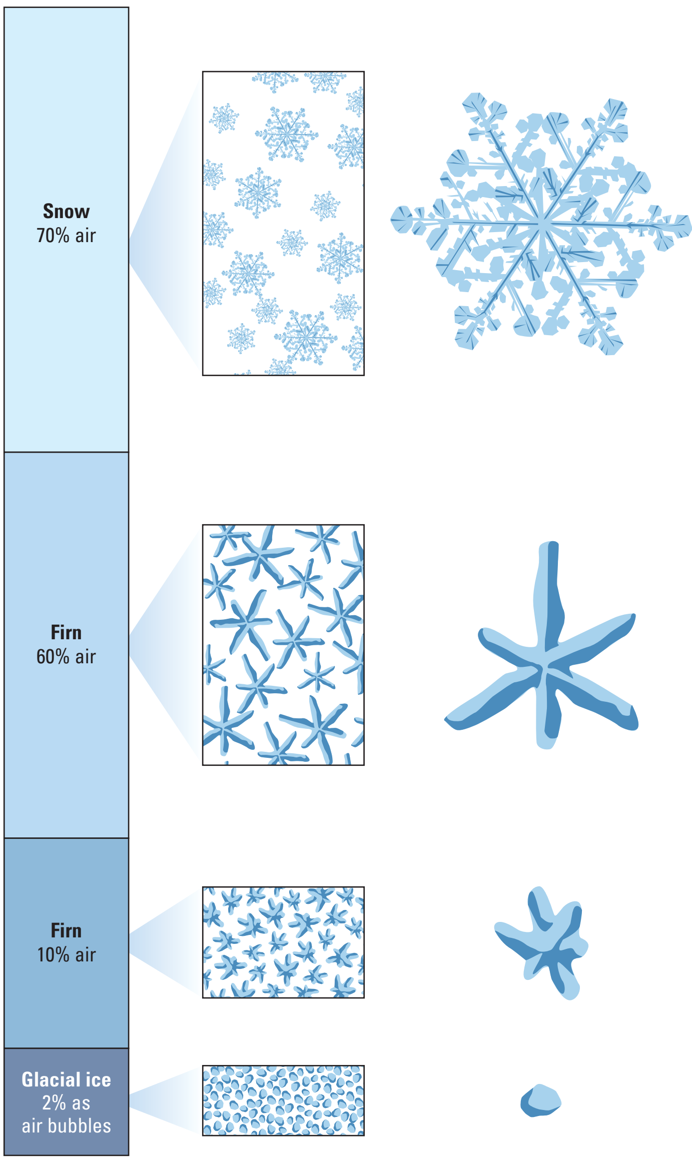
Since Dansgaard's work in the 1950s, use of radioisotopic ratios—primarily hydrogen 2 [δ^2H], or deuterium [δD], and oxygen 18 [δ^{18}O]—has further developed, and the ratios are common ice core proxies.[18] Isotopes are atoms of the same element with the same number of protons but an unequal number of neutrons. As with all oxygen atoms, the ^{18}O isotope has 8 protons. However, rather than the 8 neutrons of stable oxygen 16 [^{16}O], which makes up about 99.8% of all oxygen atoms, ^{18}O has 10 neutrons. Because ^{18}O is heavier than ^{16}O, water molecules made up of hydrogen and ^{16}O [$^1H_2{}^{16}O$] evaporate more readily than do molecules containing ^{18}O [$^1H_2{}^{18}O$]. The resulting vapor contains a high ratio of light-to-heavy water molecules. As an air mass cools, the heavier molecules condense more readily and fall from the clouds as snow and rain. Thus the oxygen isotopic ratio of rain and snow is strongly related to condensation temperature. If the temperature of the air continues to fall, the condensation will contain decreasing concentrations of heavy molecules, resulting in depletion of ^{18}O relative to precipitation that had previously condensed in a warmer environment. As a consequence, past warming and cooling trends have had a large influence on the heavy-to-light oxygen isotope ratio ($^{18}O/^{16}O$, or δ^{18}O) records within the ice core.[19]

Scientists also take into account other factors that might affect proxy values, and understanding relationships between proxies and climate factors is important to core analysis. Scientists, who gather data about past temperature, moisture source regions and hydrology from stable isotopes present in the snow and ice, have recently been tracking trace elements in the ice to assess the past and current contributions from anthropogenic and volcanic sources.[20]

Chemicals and dust found in ice cores also provide proxies that signal past atmospheric circulation, volcanic eruptions, wind speed and tropospheric turbidity. Evidence of a volcanic eruption in the form of ash layers and sulfate detected through chemical analysis and other tests can help scientists set dates of ice core layers.[21] Ion concentrations of certain chemicals in the ice reveal changes in atmospheric conditions and the causes driving those changes.[22]

Scientists interpret dust layers in ice cores to infer changes in climate and wind in the area near where the core is captured. Dust layers also help scientists mark instances of atmospheric turbidity; they then use this information to assign a date to the core. Dust concentration correlates well with δ^{18}O composition in glacial ice. Scientists have learned to interpret the value of δ^{18}O in glacial ice and in planktonic foraminifera in sea sediments as a measure of the amount of the Earth's water that is frozen in ice; plotting these data reveals the occurrence and duration of ice ages.[23] Paleoclimatologists use the oxygen isotope–to-dust concentration correlation to better understand the causes of ice ages by studying dust in ice that was buried deep enough to document climate variations in years before, during and after numerous past ice ages.[24]

Analysis of ions and trace elements has typically required technicians to progressively remove the potentially contaminated outer portion of the core under extremely clean conditions. This method has served researchers well but provides low resolution of 10 to 20 cm [4 to 8 in.] per sample, and because this process is labor intensive and time-consuming, datasets are often discontinuous. Scientists streamlined the process through the development of continuous ice core



^ Ice formation. Recently fallen snow layers are 70% air by volume but are compacted under succeeding layers of snow. Beneath the annual snowfall, which may range from 1 to 200 cm [0.4 to 80 in.] per year, the snow becomes firn, which resembles granular ice with interstitial air decreasing from about 60% to 10% with depth. Deeper than about 60 to 120 m [195 to 390 ft], the firn becomes glacial ice, with air remaining as bubbles within the ice matrix. As the burial process continues, bubble volume is further reduced and the ice becomes clear.

melting systems that reduced sample preparation time and increased sample resolution while providing continuous and coregistered data for a large suite of elements. These systems use inline continuous flow analysis (CFA) techniques or couple the melter to an ion chromatograph and inductively coupled plasma and field mass spectrometers. These innovations provided continuous measurements of isotopes in meltwater and in air trapped within ice core bubbles.

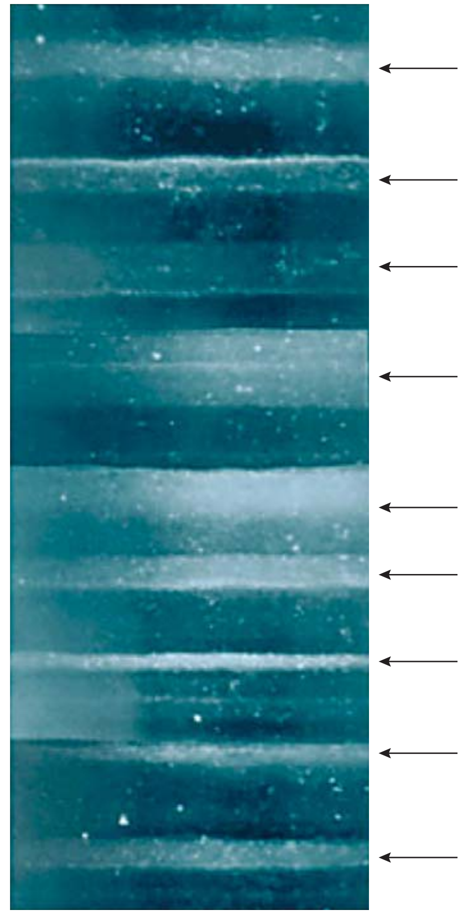
While the chemical and isotopic analysis of the ice matrix yields proxy evidence of past environmental conditions, ancient air trapped in bubbles within the ice provides the only direct samples of past atmospheres. Bubble formation results from the process of snow deposition, compaction and transition to ice at depth. In the extremely cold locations of Greenland and Antarctica where snow melt is rare, snowfall progressively piles up over many thousands of years, creating kilometers-thick ice sheets. As the snow continues to accumulate on the surface, the increasing overburden compresses the underlying snow. Snow that is more than one year old and still porous is called firn (previous page). With depth, the pore spaces between crystals in the firn become compressed. At a depth of 60 to 120 m [195 to 390 ft], the remaining pore space exists as bubbles in the matrix, which has become solid ice; this is known as close-off depth. Because air in the pore space can diffuse through the firn, the air trapped in the bubbles is younger than the ice in which it is enclosed.

A combination of in situ firn air gas measurements, measurements of gases in the bubbles in the ice, glaciological measurements and modeling is used to determine the difference between the age of the gas and that of the ice at pore close-off at a given site. Below pore close-off depth, the gases age at the same rate as the ice in which they are trapped. Measurement of the gas composition with depth of the core allows scientists to determine changes in past atmospheric composition for various gases, including changes in methane [CH_4] and carbon dioxide [CO_2] levels.[25] The air trapped in the bubbles deep in the polar ice sheets provides the only opportunity for direct measurements of the chemical composition of the ancient atmosphere.

Getting the Dates Right

In addition to correcting for the age difference between the air trapped in ice and the ice itself, scientists face the task of depth-age correlation in ice cores. They accomplish this by comparing profiles of chemical species that exhibit seasonal variation at the time of deposition and gases of known past atmospheric composition, correlating core depth to the depth of volcanic deposition for known eruptions and, for some locations, by visually counting layers. Visual stratigraphy, which relies on differences in brightness, texture, air bubbles and color between core layers, is a direct means of correlating depth and age at sites with high snow accumulation rates where melt has not occurred and where dust serves to enable layer identification (right).

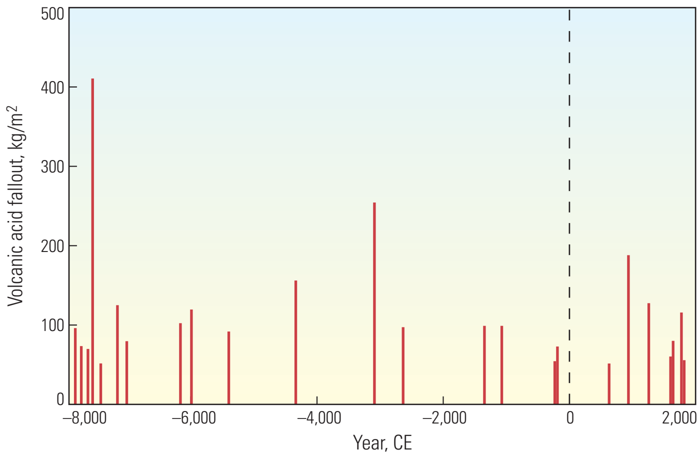
Because counting layers visually is not always possible, scientists most often use dating methods that compare chemical variations and gas composition profiles. In 2003, scientists dated 50 m [165 ft] of ice at Siple Dome, Antarctica, by sending a camera with an LED down the wellbore. Image brightness was filtered digitally. The results of the depth-age relationship derived using digital imaging were close to those derived by manually counting layers and by electrical conductivity measurement (ECM) in a core from a nearby location.[26]



^ Visual stratigraphy. Annual layers are clearly visible in this ice core sample. Summer layers (arrows) appear lighter because they contain less dust. (Photograph courtesy of the University of Colorado Boulder, USA.)

Direct current ECM, one of two methods analysts use in the process of electrical stratigraphy, measures the low-frequency conductivity of cores. In this process, laboratory workers pull two electrodes of relatively high potential difference along the surface of a prepared slab and measure the current flowing through the core. The measurements are digitized at every millimeter along the length of the core; these data are stored along with other information such as depth, time of recovery, ice temperature and locations of breaks and fractures. Because the ECM conductivity measurement is a reflection of the acidity of the ice, it is a direct indicator of the volcanic activity influence on the chemistry of the core. Scientists interpret ECM measurements to reveal a stratigraphy of volcanic eruptions,

18. $\delta D = \{[(^2H/^1H)_{sample} - (^2H/^1H)_{VSMOW}]\ (^2H/^1H)_{VSMOW}\} \times 1000$, where $(^2H/^1H)_{sample}$ is the ratio of deuterium to ordinary hydrogen in a sample corresponding to a particular datum, and $(^2H/^1H)_{VSMOW}$ is the ratio of deuterium to ordinary hydrogen in Vienna Standard Mean Ocean Water (VSMOW).
19. In the 1960s, the Vienna Standard Mean Ocean Water was developed for the isotopic composition of freshwater. Scientists studying ice cores use the standard to estimate the temperature of condensation at the time the snow fell.
20. Osterberg EC, Handley MJ, Sneed SB, Mayewski PA and Kreutz KJ: "Continuous Ice Core Melter System with Discrete Sampling for Major Ion, Trace Element, and Stable Isotope Analyses," *Environmental Science & Technology* 40, no. 10 (May 2006): 3355–3361.
21. Scientists have commonly used chemical testing to detect sulfate in ice cores and to detect preindustrial volcanic activity. However, because rising volumes of anthropogenic sulfates create background signals that obscure the chemical signal from natural sources, the technique is less accurate for post-Industrial Revolution samples.
22. Osterberg et al, reference 20.
23. Planktonic foraminifera are single-celled shelled animals that live on the surface of the ocean. When they die their shells fall to the seabed. Depending on their species, planktonic foraminifera, which can be differentiated by their shells, flourish in various ocean waters, from the warmer surface to the colder depths. Therefore, scientists can use the planktonic foraminifera remains found in the strata of ocean floor to infer the ocean's temperature at the time a sediment layer was laid down.
24. Miocinovic P, Price PB and Bay RC: "Rapid Optical Method for Logging Dust Concentration Versus Depth in Glacial Ice," *Applied Optics* 40, no. 15 (May 20, 2001): 2515–2521.
25. Bender M, Sowers T and Brook E: "Gases in Ice Cores," *Proceedings of the National Academy of Sciences of the United States of America* 94, no. 16 (August 5, 1997): 8343–8349.
26. Hawley RL, Waddington ED, Alley RB and Taylor KC: "Annual Layers in Polar Firn Detected by Borehole Optical Stratigraphy," *Geophysical Research Letters* 30, no. 15 (August 2003): HLS1-1–HLS1-3.



Electrical stratigraphy graph. Using the Greenland Crete and Camp Century ice cores, technicians calculated the volcanic stratigraphy of the last 10,000 years from the size of the direct current electrical conductivity method (ECM) peaks (red lines). ECM responds to the acidity of ice, which varies with acidic input from volcanic activity. Scientists can date the ice by matching the dates of these peaks with those of known volcanic eruptions. (Adapted from Wolff, reference 27.)

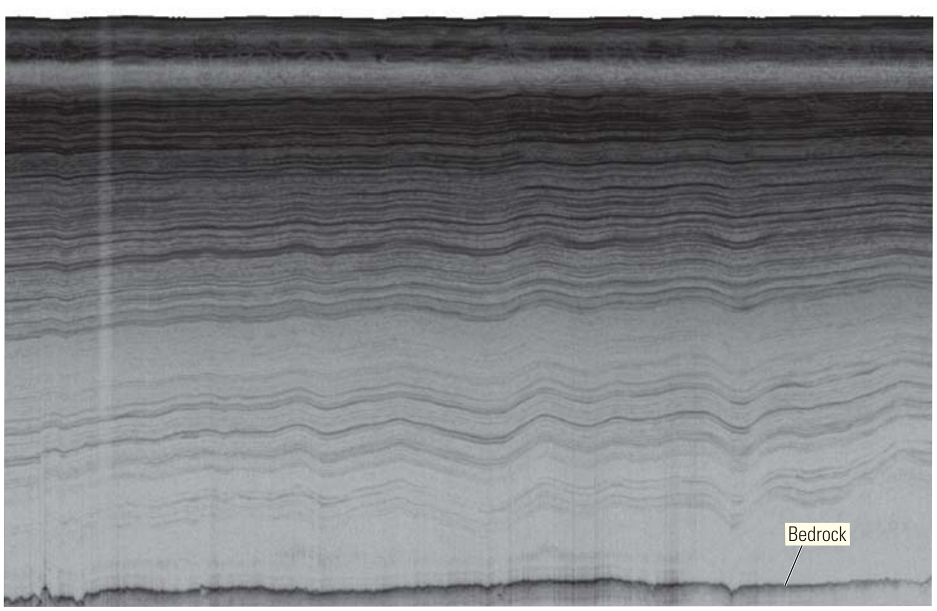
which can be used to date ice cores. They use these findings, along with chemical dating, to establish depth-age relationships (above).[27] Scientists also use these measurements to determine depth correlations between cores; these correlations may be used to determine or clarify annual layers that are difficult to discern because of droughts.[28]

A second method for electrical stratigraphy—dielectric profiling (DEP)—employs high-frequency, alternating current to measure ice conductivity. Dieletric profiling conductivity is an indication of the amount of acid present in the ice, but unlike the ECM method, the DEP measurement may be influenced by chemicals such as ammonium and chloride. In the DEP method, whole ice cores are placed between curved electrodes, lending the method several advantages over ECM. DEP conductivity tests may be performed without touching the ice core and without removing the core from the plastic shipping sheath, which makes the method particularly useful on unstable, brittle core sections.

Ice core depth-age correlation is also affected by ice flow and base rock deformation. Ice flow around basal deformities can cause melting, folding and other ice sheet deformations. These events can affect how scientists interpret dates and in some cases can destroy the physical record.

Because of these and other difficulties, scientists must sometimes indirectly establish a depth-age relationship of a core. In 1968, the Byrd ice core in Antarctica was drilled to bedrock. But because the top 88 m [290 ft] of the core were damaged or missing, scientists could not establish a correlation by counting layers. Chronology was established instead by first identifying the horizon at 97.8 m [321 ft] below the surface as a layer created by volcanic activity known to have occurred in 1259 CE. Mean annual accumulation at the Byrd site was 1.12 cm [0.44 in.] per year for the 709-year period prior to 1968.[29] The timescale for the remainder of the core was established using ECM. Because measurements were sparse in the brittle zone from 300 to 800 m [980 to 2,600 ft], the measurements were fitted with linear functions and the depth-age relationship obtained by integrating the layer-thickness profile from surface to depth. The timescale for older sections of the core was subsequently adjusted by correlating measurements of methane concentration in the Byrd ice core with those in layer-counted chronologies from Greenland ice cores.[30]

Researchers may also extend depth-age relationships established from chemical and visual studies from ice cores over larger, adjacent geographic areas by applying ice-penetrating radar that uses time domain electromagnetic pulses. Radar reflections received at the antennae are caused primarily by conductivity contrasts in the ice that indicate distinct snowfalls (left). By extrapolating radar-determined isochrones from a dated ice core to the geographic area of interest, scientists can determine the lateral extent of key stratigraphic layers in places that are distant from the ice coring site.



^ Ice-penetrating radar. This 150 km [95 mi] long section of radar data collected around the North Greenland Ice-Core Project (NGRIP) drillsite in Greenland shows fairly flat bedrock (dark line at bottom) at a depth of about 3 km [2 mi] and undulating ice layers. The shape of these layers is created by variations in basal melt rates. Where the layers dip down, the basal melt rate is highest. (Photograph used with permission from the Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, USA.)

Looking Back at the Future

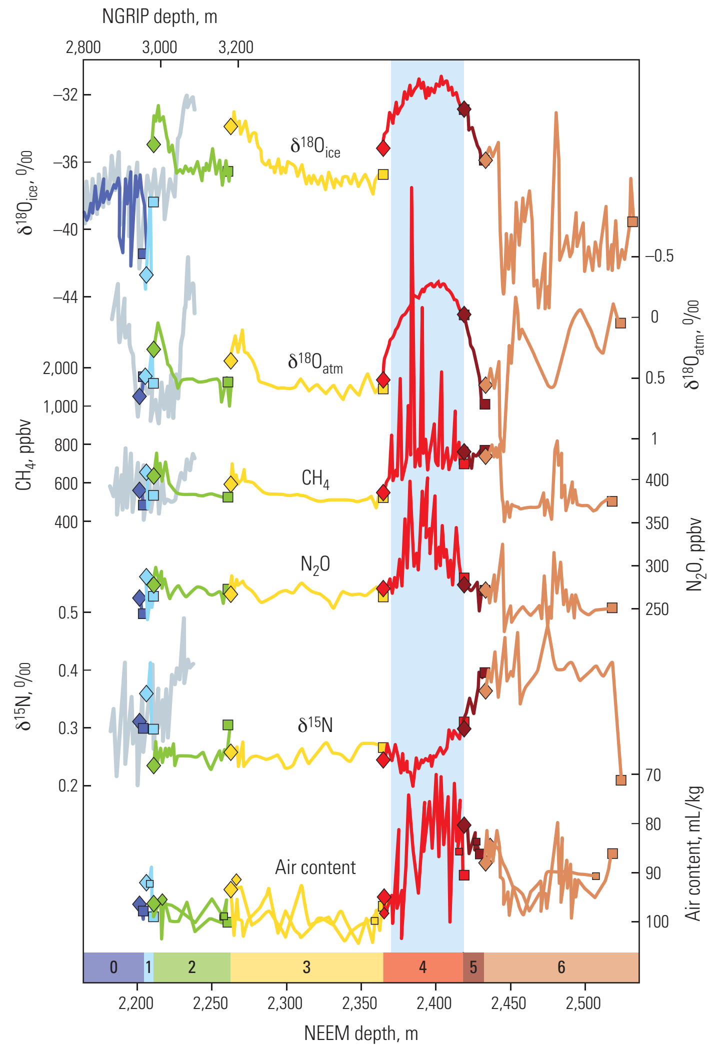
Many climatologists consider capturing an ice core from the last interglacial period—the Eemian, which lasted from 130,000 to 115,000 years ago—

to be crucial to understanding the Earth's current climate warming trend. The Eemian interglacial period was a warm period similar to that which the Earth may be trending toward today. Although the warming then was not caused by anthropogenic emissions, results of the warming on the glaciers and ice sheets do provide clues to climate processes and may help scientists improve predictions about the future. For example, some climate models suggest the Greenland ice sheet will disappear if today's apparent warming trend continues; proxy records from the Eemian interglacial period provide a test of that hypothesis.[31]

Until recently, efforts to extract an ice core with the complete record from the Eemian period have been unsuccessful. That hurdle was recently overcome at the North Greenland Eemian Ice Drilling (NEEM) site when scientists extracted a 2,540-m [8,330-ft] ice core. The NEEM project, an international collaboration led by investigators at the Niels Bohr Institute, University of Copenhagen, Denmark, took from 2008 to 2012 to acquire the core. The top 1,419 m [4,656 ft] are from the current Holocene interglacial period. The glacial ice below that can be matched to the glacial ice of the North Greenland Ice-Core Project (NGRIP). Below NGRIP depth, the Greenland Ice Core Chronology 2005 extended timescale can be used to a depth of 2,206.7 m [7,239.8 ft], which correlates to 108,000 years before present, assuming 1950 as present.[32]

Deeper than 2,206.7 m, annual layering in the Eemian ice core becomes more difficult to discern because the ice near the bottom of the ice sheet is folded. This lower section does, however, contain zones with relatively high stable isotope values of H_2O [$\delta^{18}O_{ice}$], which, as a proxy for condensation temperature, indicates the ice is from the Eemian interglacial period (right). This conclusion is supported by the fact that ice deeper than 2,537 m [8,323 ft] is near bedrock and has low $\delta^{18}O$ values, which indicate it is from the glacial period that preceded the Eemian.[33]

The NEEM ice core is the first ice core record from the entire Eemian period. Scientists will continue their studies in an attempt to further decode the folded ice; however, it is clear that Greenland during the Eemian was about 8°C [14°F] warmer than it is today. From the analysis of the core, scientists have concluded that melting occurred at the edge of the ice sheet and the flow of the entire ice mass caused the ice sheet to lose mass and become reduced in height. Although the ice sheet was shrinking at a rate of



^ Observed NEEM records. The observed records of isotopes $\delta^{18}O_{ice}$, $\delta^{18}O_{atmosphere}$ and $\delta^{15}N$ along with traces of CH_4 and N_2O in parts per billion volume (ppbv) and air content from 2,162 m [7,093 ft] and deeper are plotted here on the NEEM depth scale. Each zone (0 to 6) represents a section of the NEEM ice core record. Symbols mark the start (diamond) and end (square) of each zone. There is no discontinuity between Zones 4 and 5, but spikes of CH_4, N_2O and air content occur in Zone 4 (shaded blue), which indicate a period of surface melting or wet surface conditions. For comparison, the NGRIP data are plotted as light grey curves on the NGRIP depth scale on top of the plot. The NEEM and NGRIP depth scales are synchronized between the NEEM depths of 2,162 and 2,207.6 m [7,093 and 7,242.8 ft]. (Adapted from NEEM Community members, reference 32.)

27. Wolff E: "Electrical Stratigraphy of Polar Ice Cores: Principles, Methods, and Findings," in Hondoh T (ed): *Physics of Ice Core Records*. Sapporo, Japan: Hokkaido University Press (2000): 155–171.

28. Taylor K, Alley R, Fiacco J, Grootes P, Lamorey G, Mayewski P and Spencer MJ: "Ice-Core Dating and Chemistry by Direct-Current Electrical Conductivity," *Journal of Glaciology* 38, no. 130 (1992): 325–332.

29. Langway CC Jr, Clausen HB and Hammer CU: "An Inter-Hemispheric Volcanic Time-Marker in Ice Cores from Greenland and Antarctica," *Annals of Glaciology* 10 (1988): 102–108.

30. Neumann TA, Conway H, Price SF, Waddington ED, Catania GA and Morse DL: "Holocene Accumulation and Ice Sheet Dynamics in Central West Antarctica," *Journal of Geophysical Research: Earth Surface* 113, no. F2 (June 2008): F02018-1–F02018-9.

31. Wilhelms F, Schwander J, Mason B, Augustin L, Azuma N, Hansen SB, Fitzpatrick J and Talalay PG: "Ice Core Drilling Technical Challenges," International Partnerships in Ice Core Sciences white paper, http://www.isogklima.nbi.ku.dk/nyhedsfolder/engelske_nyheder/centre-people-to-antarctic-2013/IPICS_Technical_Challenges.pdf/ (accessed January 15, 2014).

32. NEEM Community members: "Eemian Interglacial Reconstructed from a Greenland Folded Ice Core," *Nature* 493, no. 7433 (January 24, 2013): 489–494.

33. NEEM Community members, reference 32.

^ West Antarctic Ice Sheet core. Because snowfall at the WAIS Divide rarely melts, ice layers for the past 40,000 years are unbroken, and their divisions are visible and easily counted. The ice also contains much less dust than other ice sheets do. A dark ash layer, however, in this 2 m [6.5 ft] long core section is clearly visible. (Photograph courtesy of Heidi A. Roop, WAIS Divide Science Coordination Office, University of New Hampshire.)

about 6 cm [2.5 in.] per year, it did not disappear, and the research team estimates the volume of the ice sheet was not reduced by more than 25% during the warmest years of the Eemian period.[34] This may indicate that high sea levels during the Eemian period are primarily attributable to the collapse of the West Antarctic Ice Sheet (WAIS).

From the Deep South

At a field camp 1,045 km [650 mi] from the magnetic South Pole, engineers and scientists have recently recovered an ice core that dates 68,000 years into the past. The WAIS Divide Ice Core Project provides southern hemisphere climate and greenhouse gas records that are of comparable time resolution and duration to the Greenland ice cores. This ice core allows scientists to compare environmental conditions between the northern and southern hemispheres with greater detail than before and allows them to study the levels of greenhouse gases present in ancient atmospheres.

Researchers are using the ice core to understand the history of the WAIS to provide further insights into past atmospheric composition and abrupt climate change and to investigate the biological signals contained in deep Antarctic ice cores. Because the WAIS Divide core has an order of magnitude less dust than the Greenland ice core has, scientists expect it to provide them with a more detailed atmospheric CO_2 record than was possible from Greenland ice. Many other gases (both greenhouse and nongreenhouse) and their isotopes are being measured at unprecedented precision and resolution.

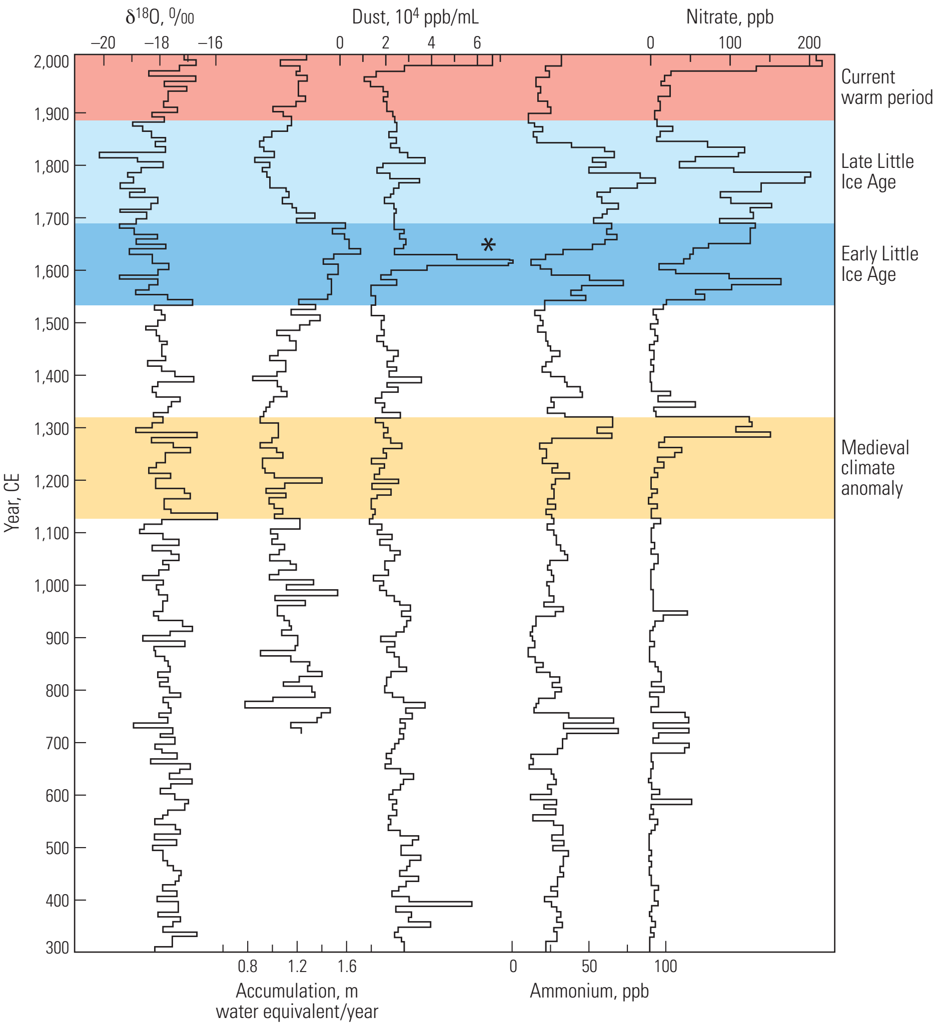
The research team recovered the ice core from ice that is more than 3,460 m [11,300 ft] thick; they stopped drilling just 50 m [165 ft] above bedrock to avoid contaminating water at the bottom of the ice that has remained isolated from the environment for at least 100,000 years. Because snow falling at the WAIS Divide rarely melts, each of the past 40,000 years can be identified in individual layers of ice (above). Deeper than that depth, individual annual layers are not as readily identifiable, but the core contains a higher time resolution record than any previously recovered cores. Results from the analysis of this

34. "Greenland Ice Cores Reveal Warm Climate of the Past," *University of Copenhagen, Niels Bohr Institute* (January 22, 2013), http://www.nbi.ku.dk/english/news/news13/greenland-ice-cores-reveal-warm-climate-of-the-past/ (accessed October 23, 2013).

35. Thompson LG: "Ice Core Evidence for Climate Change in the Tropics: Implications for Our Future," *Quaternary Science Reviews* 19, no. 1–5 (January 2000): 19–35.

36. Thompson LG, Mosley-Thompson E, Davis ME, Zagorodnov VS, Howat IM, Mikhalenko VN and Lin PN: "Annually Resolved Ice Core Records of Tropical Climate Variability over the Past ~1800 Years," *Science* 340, no. 6135 (May 24, 2013): 945–950.

37. Fischer H, Severinghaus J, Brook E, Wolff E, Albert M, Alemany O, Arthern R, Bentley C, Blankenship D, Chappellaz J, Creyts T, Dahl-Jensen D, Dinn M, Frezzotti M, Fujita S, Gallee H, Hindmarsh R, Hudspeth D, Jugie G, Kawamura K, Lipenkov V, Miller H, Mulvaney R, Parrenin F, Pattyn F, Ritz C, Schwander J, Steinhage D, van Ommen T and Wilhelms F: "Where to Find 1.5 Million Yr Old Ice for the IPICS 'Oldest Ice' Ice Core," *Climate of the Past* 9 (November 5, 2013): 2489–2505.



^ Identifying climate events. Decadal averages of $\delta^{18}O$, net accumulation, insoluble dust, ammonium and nitrate in the Quelccaya Summit Dome ice core from the Quelccaya ice cap of Peru allowed scientists to identify specific climatological periods (shading). The asterisk on the dust profile indicates the 1600 CE eruption of Huaynaputina in Peru. (Adapted from Thompson et al, reference 36.)

core have resolved a scientific debate concerning relationships between climate change in the northern and southern hemispheres and confirmed that the WAIS is very sensitive to conditions in the southern oceans. Scientists expect additional significant results from further analysis now that drilling of the ice core is complete.

To the Top of the Mountain

Ice coring is not restricted to extreme polar climes and has been performed in high-altitude, low-latitude glaciers. The wellbores in these tropical locations are shallower than those drilled in ice sheets at high latitudes, but these ice cores effectively reveal details of the Earth's tropical climate history. Tropical ice cores have been retrieved from such geographically disparate locations as the Himalaya and the Andes mountain ranges.

In 2003, scientists from The Ohio State University, Columbus, USA, retrieved ice cores 1.92 km [1.19 mi] apart from two wellbores—Quelccaya Summit Dome and Quelccaya North Dome—drilled to bedrock in the Quelccaya ice cap of the Peruvian Andes. Researchers analyzing the cores found that each of the 1,800 years spanned by the cores was clearly defined by alternating dark and light layers. The dark layers are tinted by dust accumulated during dry seasons; the light layers are the result of snowfall during wet seasons.[35]

In addition to the unprecedented clarity of the annual layers, the Quelccaya ice cap cores are important to climatologists because they were formed in the high Andean plain of southern Peru. The snow that became the ice that formed the cores originated to the east of the Quelccaya ice cap; this snow was also affected by El Niño weather effects originating in the west. Because El Niño is a temporary climate change that is driven by sea surface temperatures, the chemical signature in the Quelccaya ice cap is a proxy for sea surface temperatures in the equatorial Pacific Ocean over the past 1,800 years (left).[36] Chemical and isotopic records from these tropical ice cores provide historical evidence of the nature of climate change in the lower latitude regions of the planet and a context for current changes.

Perfecting the Tools

Although early ice coring drills were based on concepts from geologic drilling, current state-of-the-art units include advances not attempted in rock drilling. For example, the DISC drill's ability to retrieve replicate cores from the high side of the borehole, while leaving the original hole accessible for borehole logging studies, is an innovation that is unique to ice core drilling.

Enabled by a number of advances in technology, the relatively young science of using ice cores to understand past climates and environments has yielded societally relevant and important discoveries. As it matures, the science is certain to provide climatologists with increasingly clear insight into the future of Earth's climate.

These technological advances in ice core drilling may also help answer a question that has plagued scientists for decades. Currently, ice coring experts are working to choose the optimal surface location in the East Antarctic Ice Sheet from which to drill into 1.5 million–year-old ice.[37] Proxy records from such an ice core may help solve the mystery behind a climate transition that analyses from marine sediments indicate took place between 900,000 and 1.2 million years ago. Before this Middle Pleistocene event, the time between Earth's warming periods and ice ages was about 41,000 years; since the climate change during the Pleistocene, the time between these temperature extremes has been about 100,000 years. To this date, the cause of this transition is unknown, and scientists hope the answer is in the air bubbles and chemistry of this now reachable ancient ice. —RvF