

Warm Bedrock Forms Water beneath Rapidly Moving Ice Stream in Central Greenland

Ten years ago, glaciologists believed the great Greenland ice sheet was pretty much frozen to its bed of old, cold Precambrian crust. Thus anchored, the ice sheet crept viscously to the sea, where the ice melted away. Annual snowfall balanced whatever thinning the flow produced.

That appealingly simple paradigm was upset in 1992 when Mark Fahnestock, then at NASA's Goddard Space Flight Center, and his colleagues discovered a stream of fast-moving ice, tens of kilometers wide, running northeast from central Greenland to the Arctic Ocean 500 km away. Glaciologists had identified ice streams before in Western Antarctica, but not in Greenland.

Now, Fahnestock, who has since moved to the University of Maryland in College Park, has uncovered the source of the stream's rapid motion: a region of unusually warm bedrock at the head of the stream. Most likely volcanic in origin, the warm rock melts the ice, creating a lubricating layer of water for the stream to flow on.¹

It's not yet clear how big a role the northeast Greenland ice stream plays in the overall glacier dynamics of Greenland. But in West Antarctica, the seven known ice streams constitute the principal mass loss route for ice in that region, ultimately feeding the icebergs that break off the vast Ross Ice Shelf. If either the West Antarctic or Greenland ice sheet melted, the sea level would rise by 6 m. Understanding how ice streams form, particularly how they might respond to climate change, is a question of planetary importance.

Age-depth relations

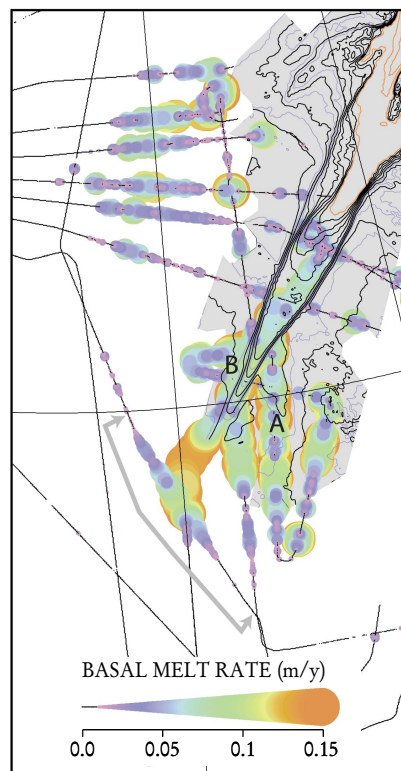
In Greenland, snow crystals are larger and fluffier in summer than in winter. A characteristic and convenient seasonal layering in the snow pack is the result. Distinctive layers also appear whenever dust from volcanoes, spewed upward into the atmosphere, falls back to Earth, thinly coating the snow.

Like the rings in a tree trunk, the layers can be used to trace back the annual pattern of snowfall year after year. And, because the rate of snowfall

▶ New measurements hint at the presence of a volcano underneath the Greenland ice sheet.

is pretty much the same from year to year, at least for the past 9000 years, the thickness of the layers reflects how the ice responds to the pressure of the load above.

Examining these layers requires boring a core sample, several of which have been taken in central Greenland over the years. Glaciologists can reliably time-tag the layers backward in time to about 40 000 years ago and less reliably to 130 000 years ago. But a typical ice core has a diameter of just 10 cm and takes two to three summers to painstakingly extract and analyze.

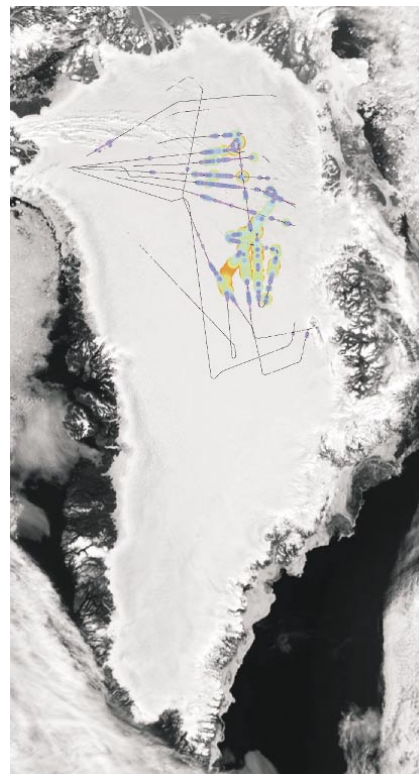


THE NORTHEAST GREENLAND ICE STREAM, as shown with speed contours in the left panel, originates in the center of the panel and flows upward and to the right. The black contours range from 10 to 90 meters per year in steps of 10 m/y. The red contours start at 100 m/y and increase in steps of 100 m/y. Also shown in the left panel are the color-coded rates of basal melting. Those same basal melting rates, and the flight paths along which they were determined, are shown on top of a satellite image of Greenland in the right panel. (Left panel adapted from ref. 1; satellite image courtesy of Jane Ferrigno, US Geological Service.)

Using ice cores to map the layers throughout an ice sheet is utterly impractical.

Layers also show up in ice-penetrating radar. When directed downward at the snow from an airplane, radar waves reflect strongly off the surface. And, thanks to the layers' differing conductivity, the waves also reflect off each of the layers in the ice. Measuring the intensities and travel times of these multiple reflections creates an image of the layers along the plane's flight path.

Fahnestock's collaborator Prasad Gogineni of the University of Kansas has created a particularly useful and public source of radar data. Carried aboard a specially modified Lockheed P-3, Gogineni's radar regularly flies



over Greenland. Much of the vast island has been mapped with radar, including the sites of several ice cores.

To analyze these data, Fahnestock and Waleed Abdalati of NASA headquarters have developed a sophisticated computer program that matches the radar-observed reflection layers at one of the ice core sites with the time-tagged layers in the core itself. Thus calibrated, reflection layers, which rise and fall depending on the local snow accumulation rate and other factors, can be followed away from the core along the flight paths. The result is a direct measurement along each flight path of what glaciologists call an age–depth relation, a key probe of ice models.

Modeling the flow of ice is challenging. Glacial ice is a non-Newtonian fluid. The harder you push it, the softer it gets. Moreover, its properties depend not only on its current temperature, but on its thermal history. The Greenland ice sheet still “remembers” the colder temperatures from the last Ice Age.

Despite these complications, elementary models have been successful at capturing basic ice-sheet rheology. In the simplest model, devised in the 1950s by John Nye, accumulation is balanced by horizontal flows that thin the ice in such a way that vertical strain is constant with depth and the sliding occurs only at the bed. In Greenland, where most of the ice is stuck to the bed, Willi Dansgaard and Sigfus Johnsen found they had to modify the Nye model. Their 1969 revision incorporates a shearing zone just above the bed where the vertical strain rises from zero to a constant.

Dansgaard and Johnsen’s model yields the age of a layer in terms of the annual accumulation rate, the height above the bed, and the thickness of the sheet and the shearing layer. Having already measured the age–depth relation, Fahnestock and company inverted the model to derive the

thickness of the shear layer. This technique gives sensible values for the shearing layer thickness along most of the radar tracks, but not everywhere. At certain locations, layers appear to collapse toward the bed, as if the underlying layers had been knocked from under them. Applying the Dansgaard–Johnsen model to the disturbed layers yields negative values for the shearing layer thickness.

To account for the disturbed layers, Fahnestock made a simple adjustment to the model. He replaced the shearing layer with a term that removes ice at a constant rate from the bed, presumably by melting. As a result, the amount of thinning that horizontal flows would have to produce for a given ice load is reduced. This simple model fits the data from the disturbed layers well and, as the figure on page 17 shows, can be used to map the basal melting rate along the radar tracks.

Comparing the basal melt map with the disposition of the northeast Greenland ice stream proved especially revealing. Ian Joughin of NASA’s Jet Propulsion Laboratory, another of Fahnestock’s collaborators, had mapped the ice stream using space-based radar interferometry. As the figure shows, the head of the ice stream coincides with an area of intense basal melting—strongly suggesting that meltwater loosens the ice’s hold on the bedrock and sets the stream in motion.

Over the volcano

According to the radar data, a layer tens of centimeters thick turns to water each year beneath the ice stream. Melting that much ice requires nearly a watt per square meter of thermal power—20 times more than what Greenland’s ancient bedrock typically puts out. Only an unusually concentrated heat source, such as a volcano or some other magmatic structure, can do the job.

Does a volcano lurk under the ice?

Indirect evidence suggests the answer is yes. John Brozena of the Naval Research Laboratory, another of Fahnestock’s collaborators, has surveyed the gravitational and magnetic fields in the ice-stream region. Close to the region of rapid basal melting, there appears to be a structure whose gravitational signature is reminiscent of the huge caldera in Yellowstone National Park. And not far away is an area of stronger than normal magnetization of the sort expected when magmatic rock cools and crystallizes.

If confirmed, the Greenland caldera won’t be the first volcano implicated in basal melting. In 1993, a team led by Don Blankenship of the University of Texas at Austin uncovered evidence of a volcano under the West Antarctic Ice Sheet, close to the source of one of the ice streams that feed the Ross Ice Shelf. Water is certainly necessary for ice streaming to occur, but in West Antarctica, where the snow pack lacks easy-to-measure layering, it’s unclear how much meltwater underlies the streams. Also uncertain in the case of the West Antarctic ice streams is the role played by glacial till, a soft muddy mixture of clay, sand, pebbles, cobbles, and boulders that lies between the ice and the bedrock. Till could act either as a lubricant or as a soft, easily deformed shearing layer.

Perhaps the most intriguing implication of the Greenland discovery is that the crust beneath Greenland is warm in places, rather than cold and dead throughout. Greenland lies hundreds of miles from the Mid-Atlantic Ridge, the closest seismically active zone. But, points out Caltech geophysicist Don Anderson, the Greenland crust is likely to be under tension, a condition that could make it vulnerable to a magmatic hemorrhage. **CHARLES DAY**

Reference

1. M. Fahnestock et al., *Science* **294**, 2338 (2001).

From Superfluid to Insulator: Bose–Einstein Condensate Undergoes a Quantum Phase Transition

Bose–Einstein condensates (BECs) have opened yet another promising avenue of experimental research. This time, the road leads to an opportunity to study quantum phase transitions in a very clean and controlled manner. Specifically, researchers from the Max Planck Institute for Quantum Optics in Garching, Germany, and the University of Munich

The atoms in a BEC assemble gregariously into a coherent whole, but in a periodic potential that’s sufficiently strong, they can separate into an array of isolated atoms.

have shown that they can take a dilute gas of cold atoms from a superfluid to an insulator—and back again—simply by varying the intensi-

ty of a laser beam.¹ Daniel Kleppner of MIT said it was “breathhtaking” to witness a quantum fluid move back and forth between its superfluid and insulating phases.

Matthew Fisher, a condensed matter theorist from the University of California, Santa Barbara, was excited to see BECs getting into the regime in which interactions between the