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Is the Antarctic Ice Sheet Disintegrating?

by Barclay Kamb

The consequent rise in worldwide sea levels would have substantial impact on human activity elsewhere on earth.

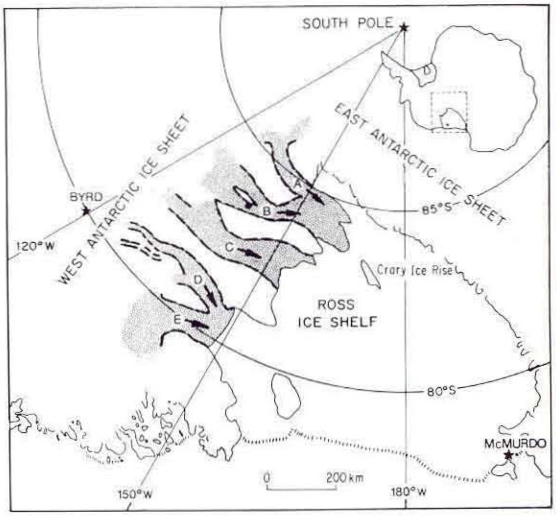
Traversing the Dragon on skis was not an ordinary cross-country outing for the Caltech/University of Alaska party that was the first to cross it. The Dragon is a 5-kilometer-wide swath of chaotically crevassed ice at the margin of Ice Stream B. The skiers here are Howard Conway (right) and Keith Echelmeyer (PhD '83) of the University of Alaska.

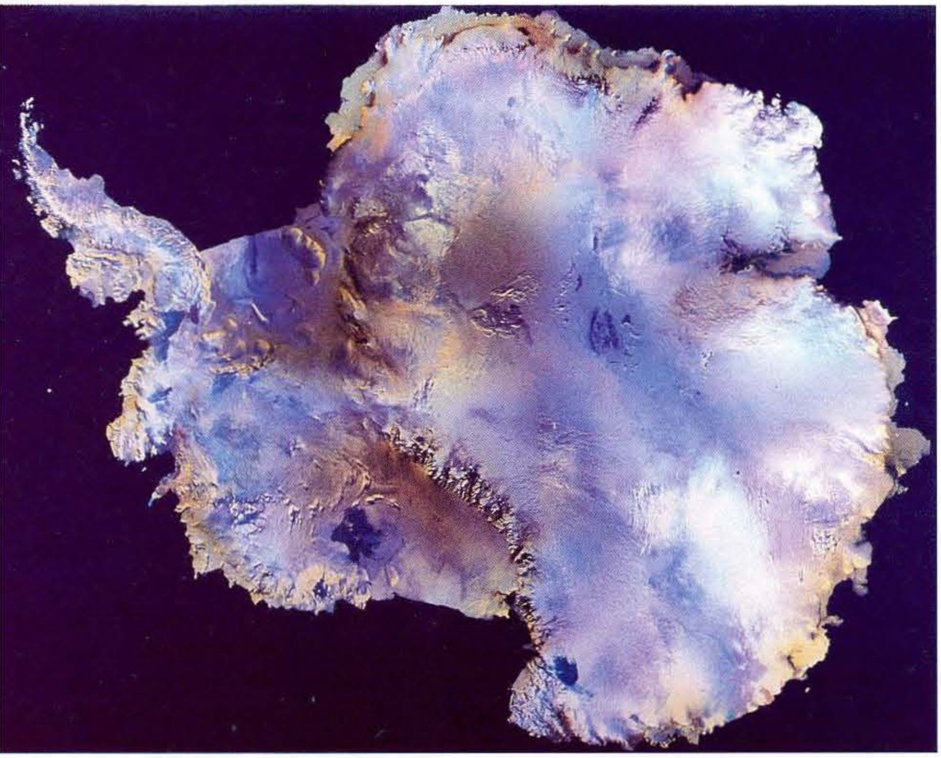
Disintegration of the Antarctic ice sheet is one of the more sensational scenarios associated with the greenhouse effect—the predicted global warming produced by an increase of carbon dioxide in the atmosphere. The consequent rise in worldwide sea levels from the melting of such a vast quantity of ice would have substantial impact on human activity elsewhere on earth. Is this happening or is it likely to happen?

The Antarctic ice sheet, which covers 98 percent of the Antarctic continent, is divided by the Transantarctic mountain range into two unequal and contrasting parts—the East Antarctic ice sheet covering 10 million square kilometers (a million larger than the United States), and the smaller West Antarctic ice sheet, a fifth the size and containing a tenth the volume of ice. If the West Antarctic ice sheet were to melt, worldwide sea level would rise 5 meters, which would already have serious consequences in coastal locations throughout the world. But if the East Antarctic ice sheet went, the sea-level rise would be a whopping 66 meters.

Fortunately, glaciologists consider the East Antarctic ice sheet to be stable and not in danger of any rapid change. But the West Antarctic ice sheet is a different story. Unlike the East Antarctic ice sheet, which to a large extent rests on bedrock near or above sea level, the West Antarctic is a "marine ice sheet," meaning that its bed lies mainly well below sea level, so that the thinner, peripheral part of the ice sheet is afloat. The floating parts are called ice shelves. The famous Ross Ice Shelf—a floating plate of ice the size of Texas, ending against the open sea in a sheer ice cliff 750 kilometers long and 300 meters high (of which 90 percent is under water)—is formed mainly from ice that flows down from the West Antarctic ice sheet to the Ross Sea and goes afloat. If the ice were to melt away, all that would remain visible of West Antarctica would be a few islands, representing isolated high points in the bedrock surface. Glaciologists recognize that marine ice sheets are subject to a condition of potential instability. According to this concept, when climatic conditions cause a marine ice sheet to shrink, the thinning of the ice mass causes an increasing amount of the peripheral ice to lose contact with the bedrock and go afloat. This reduces the constraints holding the ice sheet together and results in an accelerating process of ice outflow and dispersal, which glaciologists call ice-sheet disintegration and collapse. Such collapse is believed to have struck the North American ice sheet at the end of the last ice age about 10,000 years ago.

My interest in marine ice sheet instability was aroused when it was realized that collapse might be greatly accentuated if the ice sheet were to go into a state of surge, such as occurs occasionally in glaciers elsewhere in the world. I had been working on the mechanism of surging in Alaskan glaciers (*E&S*, May 1984), and I wondered whether the concepts developed there might be applicable in Antarctica. At first the possibility that a huge polar ice sheet could surge seemed pretty remote, but then some features were discovered in the West Antarctic ice sheet that seemed to bear some resemblance to surging. Those features are the great ice streams.





This satellite mosaic image shows the Transantarctic Mountains dividing the much larger, and fortunately stable, East Antarctic ice sheet (right) from the West Antarctic ice sheet. The Ross Ice Shelf is visible under the curve of the mountains at lower left. Ice streams A, B, C, D, and E (F isn't shown) can be seen flowing into the Ross Ice Shelf in the detail of that area (above, right). The main US scientific base is at McMurdo.

An ice stream is a current of ice within the ice sheet, moving as much as a hundred times faster than the ice sheet around it. The ice streams are made visible by long belts of chaotic crevassing at their margins, where the fast-moving ice within the ice stream shears past the slow-moving ice outside. These belts look like the ice has been churned up by a giant eggbeater cutting a swath 5 kilometers wide along the margin of the ice stream. Antarctic pilots have come to recognize them and have given some of them fanciful names—"The Snake," "The Dragon," and "Valhalla," which are the chaotic zones on the margin of Ice Stream B, one of six great ice streams flowing from the West Antarctic ice sheet down into the Ross Ice Shelf. (They are perfunctorily designated "A" through "F.") Ice Stream B is about 50 kilometers wide and extends from the inner part of the West Antarctic ice sheet for about 500 kilometers to the place where the ice goes afloat and feeds into the Ross Ice Shelf.

At a camp on Ice Stream B called Upstream Bravo, where we have been working, the ice is moving 1.2 meters per day, and farther downstream its speed increases to more than 2 meters per day. The ice outside the ice stream is moving only a few meters per *year*. The extreme contrast in motion is reminiscent of surging, in which a glacier typically speeds up for a limited time from a few tenths of a meter per day to tens or even hundreds of meters per day.

The motions of Ice Stream B and the adjacent ice sheet have to be measured by satellite navigation, because there are no bedrock refer-

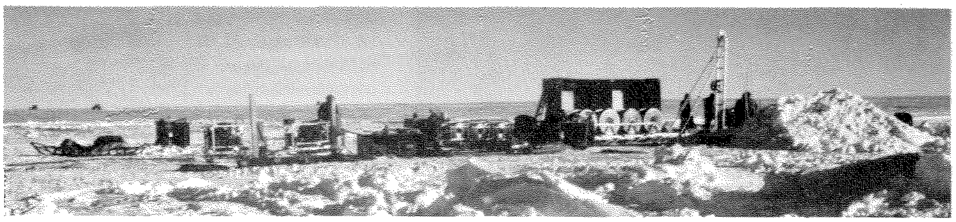
Left: from the air, ice streams are visible by the churned-up belts at their margins (bisected here by a cloud shadow). The landscape looks more daunting from a closer bird's-eye view (far left), and still more so from ground level (below), where Keith Echelmeyer poses above a deep crevasse.

ence points sticking up through the ice. The measurements were made by Ian Whillans at Ohio State University. One surprising thing they revealed is that Ice Stream C, which is otherwise fairly similar to Ice Stream B, has recently stopped moving. This shows that the rapid ice-stream motion can start and stop, another feature in common with surging.

Why is all this happening? What are the physical conditions that make it possible for the ice streams to be moving at such high speed, and for the motion to start or stop? That is what we went to Antarctica to find out. The answers are needed in order to assess the potential role of the ice streams in the rapid collapse of the West Antarctic ice sheet. To do this we have to understand the mechanism of the ice-stream motion well enough to predict how extensively the ice streams may proliferate within the ice sheet and how fast they may ultimately move.

Not knowing the potential speed of these things is an unsettling feeling. I'm reminded of an experience on Variegated Glacier in Alaska, where we were camped as the glacier was going into surge. It was already moving 10 meters a day under our feet, but we didn't yet know how fast it could ultimately go. One night I felt a great shaking and thought, is this *it*? Is this what it feels like to go into full surge? As I bolted from my tent I heard rocks bounding down the mountainsides and realized that this was merely an earthquake, not the ultimate glacier surge!

There are three proposed explanations for the

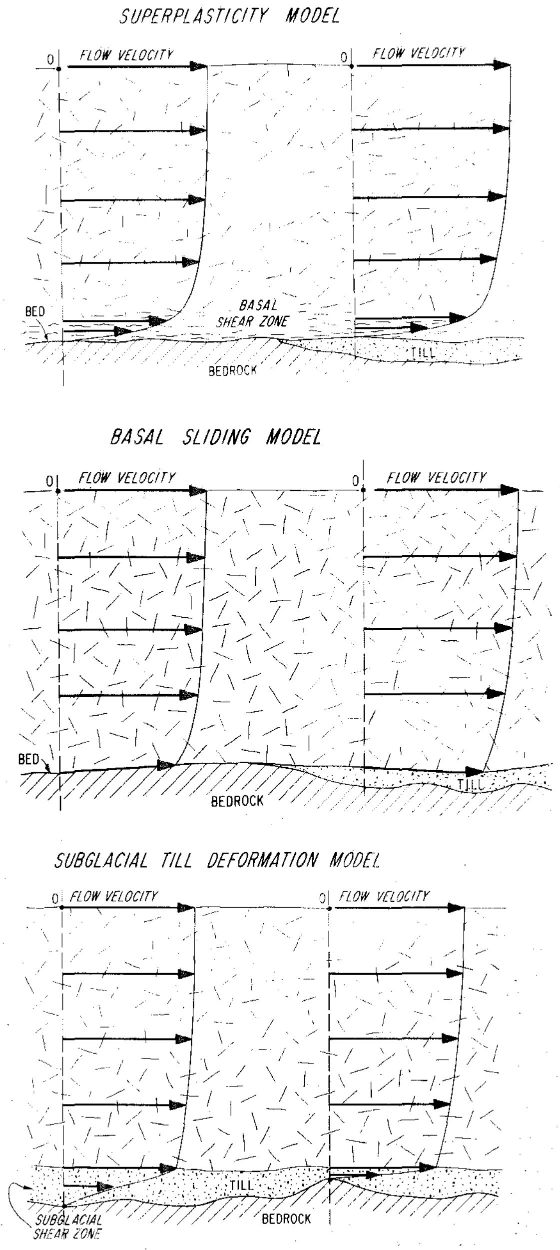


rapid motion of the Antarctic ice streams. The first ascribes a special property, "superplasticity," to the ice near the base of the streams. Ice in ordinary glaciers deforms as part of the flow process, especially near the base, but the deformation near the base of the ice streams would have to be extraordinarily rapid to allow them to move as fast as they do. The required enhancement in ice plasticity is particularly large because the shear stress near the base, which causes the ice deformation, is unusually small (0.2 bar) in comparison with typical glaciers (about 1.0 bar). The basal shear stress, which results from the downslope component of gravity acting on the ice mass, is small because the surface slope of the ice streams is very low (about 0.1°). If "superplasticity" were detected, we would be faced with the question of why the ice had changed and gone into the "superplastic" state.

A second explanation relates the rapid ice-stream motion to glacier surging. From our studies in Alaska we know that surging is due to enhancement not of ice deformation but of the sliding motion of the ice over its bed. This basal sliding can be clearly recognized in places such as New England or the Sierra Nevada where glaciation has occurred: you can see that the bedrock has been scoured and polished by the ice sliding over it. Basal sliding can occur only if the ice reaches the melting point at its base. The temperature of the ice mass near the surface at Upstream Bravo is about −25°C. A considerable source of heat at depth, greater than the normal geothermal heat, would be needed to raise the ice to the melting point at its base.

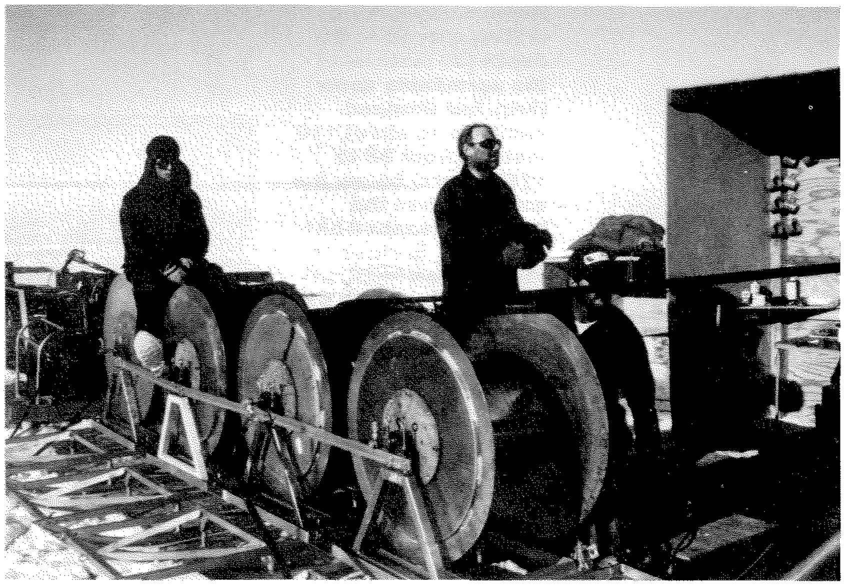
Recently a third explanation, the subglacial-till-deformation theory, has been put forward by a group of geophysicists led by Charles Bentley at the University of Wisconsin. From records of seismic-wave reflections off the base of the ice they inferred that there was a layer of ground-up rock, called glacial till, between the base of the ice and the bedrock. They theorized that the till was deforming and acting as a lubricant for the ice-stream motion; instead of a shear zone in the basal ice, there was a shear zone in the till beneath the ice, allowing the ice above to move forward rapidly.

All three of these theories concern things going on at or near the bottom of the ice stream. To test them requires observations in the basal zone. Therefore, in our study of the ice stream mechanism, my collaborators (senior research associate Hermann Engelhardt, research fellow Neil Humphrey, graduate student Mark Fahnestock, technician John Chadwick, and several capable field assistants) and I undertook the task



Three explanations for the unusually rapid flow of the Antarctic ice streams have been proposed. One of them (top) attributes the motion to rapid deformation at the base due to a "superplastic" property of the ice. The basal sliding model is similar to glacier surging, which is not due to greater ice deformation but to the sliding motion of the ice over its bed when the basal ice is at the melting point. The third explanation theorizes a layer of ground-up rock (till) between the base of the ice and the bedrock, which deforms easily and lubricates the ice-stream motion.

Opposite page: the drilling rig consists of heaters, pumps, four spools of hydraulic hose, and a derrick. Right: The spools, each of which holds 300 meters of hose, offer a rare place to sit (which, when drilling is under way, is also warm). The "coffee table" at right serves the additional function of strengthening the windbreak.



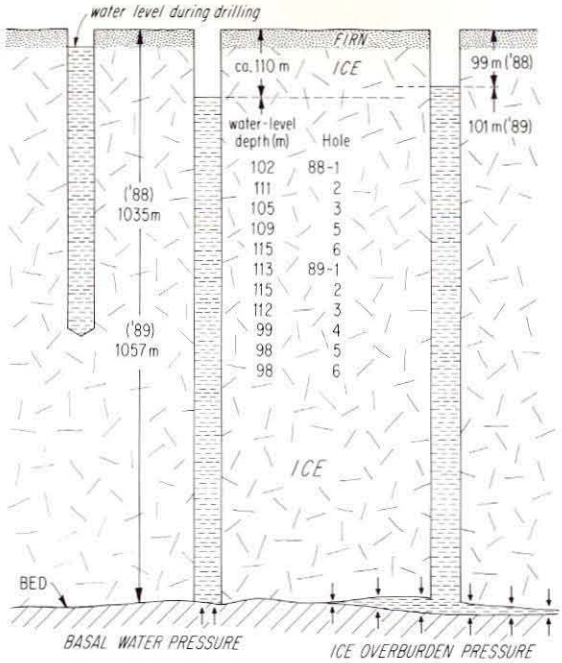
Our approach is what is known in the oil industry as "the truth of the drill."

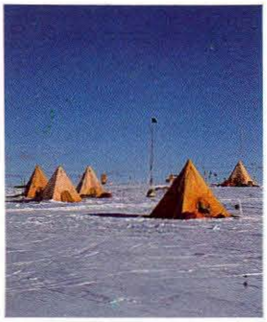
of drilling boreholes to the bottom and putting down instruments to register basal conditions. Our approach is what is known in the oil industry as "the truth of the drill." You can have seismic remote-sensing data and interpretations and theories of what is down there, deep below the surface, but until you drill there and get hold of the actual materials, you never really know.

In a project sponsored by the National Science Foundation we have carried out two field seasons of borehole work so far on Ice Stream B at camp Upstream Bravo (latitude 83.5°S, longitude 138.2°W). This site was chosen because it seems representative of the ice streams and because of logistical convenience, a camp and landing strip having been established there in 1983. We drill with a hot water jet. Water from melted snow is heated to about 90°C and pumped under a pressure of about 50 atmospheres through high-pressure hydraulic hose down to the jet tip at the lower end of a heavy drill stem. The drilling hose is handled in four spools of 300-meter length each, and on its way into the borehole it passes over a derrick where its tension is measured as a means of sensing when the drill reaches the bottom of the ice. At Upstream Bravo, where the ice is about 1,050 meters thick, we can drill a borehole to the bottom in about 24 hours, starting at a drilling speed of about 70 meters per hour, and decreasing to about 30 meters per hour near the bottom because of heat loss from the hose. The heat loss is beneficial because it counteracts refreezing of the borehole by heat conduction into the surrounding cold ice (−25°C near the surface). When the drill and hose are pulled out we have only a few hours, because of the refreezing, to work with instruments in the hole, but the useful life of the hole can be extended by hot-water reaming or by adding antifreeze. (It takes about 50 barrels of antifreeze to treat one borehole!) In the 1988-89 field season (November–January) we drilled five boreholes to the bottom, and in the 1989-90 season, six.

During drilling, each borehole holds water up to a level about 30 meters below the surface, which is the depth where permeable snow (firn) converts to impermeable glacier ice. Water fills up the hole to that level where it seeps out into the firn and freezes. But when the borehole reaches the bottom something dramatic happens: the water level drops suddenly, within a few minutes, down to about 110 meters below the surface. This happened in all eleven holes, except that in one case the drop started nine hours after the drill reached bottom. In two holes the downrush of water was so forceful that it jammed the drill stem into the bottom and we were barely able to pull it back up.

The drop in water level has three important implications. First, the escape of water into the bed indicates that the temperature there must be at the melting point; if everything were frozen solid, the water could not penetrate and the water level would not drop. Second, the basal zone must contain water-filled passageways or conduits of substantial size, to allow the water to escape from the hole so rapidly. Third, the water pressure in these conduits is near the over-





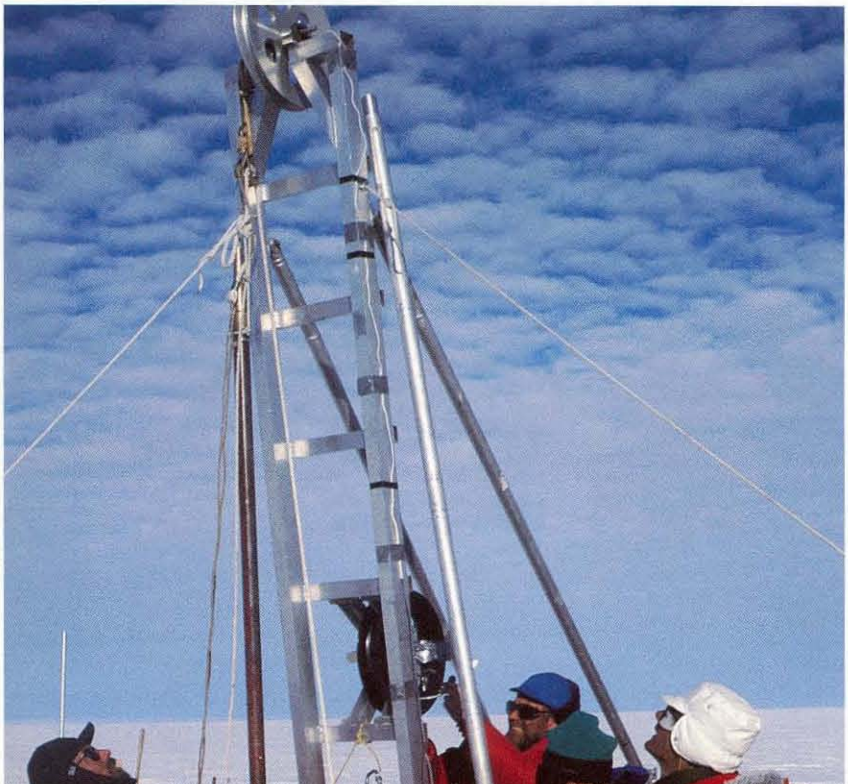
Right: water during drilling stayed at the depth (30 meters) of the permeable snow (firn), but dropped suddenly to about 110 meters (from 98 to 115 meters) below the surface when the borehole reached bottom. This is close to the flotation level, at which there would be a balance between the basal water pressure and the ice overburden pressure.
Left: John Chadwick tests the reamer, necessary to keep the borehole from freezing up soon after it's drilled.
Below: Sleeping accommodations at Upstream Bravo were in Scott tents.

burden pressure of the ice—the pressure due to the weight of the overlying ice. This follows from the depth to which the water level drops (about 110 meters). It is near the flotation level—the water level for which the basal water pressure would be just sufficient to float the ice off its bed because basal water pressure and ice overburden pressure are balanced. Just as an iceberg floats with about one tenth of its mass above the water line, so the flotation level in a glacier borehole is about one tenth of the way from the surface to the bed. An accurate figure for the depth of the flotation level requires careful calculation, taking into account the gradual downward increase in density of the snow as it changes to ice, and of the ice as the air bubbles trapped in it are progressively compressed. Such calculation indicates a flotation-level depth of 100 meters at Upstream Bravo. The observed borehole water levels range from 98 to 115 meters' depth, which means that the pressure of water in the basal conduit system ranges from 1.5 bar (1.5 atmosphere) below the ice overburden pressure to 0.2 bar above it.

This finding is very significant mechanically because high basal water pressure, near the ice overburden pressure, promotes rapid basal sliding, as we found in the surge of Variegated Glacier. At the same time, high water pressure will reduce the mechanical strength of any subglacial till that may be present and will thus promote the lubricating action of shear in this material. So we know now that the conditions required for rapid basal motion, either by basal sliding or by sub-basal deformation, actually exist at the bottom of the ice stream.

With a string of temperature transducers, we measured the temperature at a succession of points in one of the holes after it had frozen closed and cooled down to near the ambient temperature. We could not measure the temperature all the way to the bed because our transducers failed in the bottom 100 meters of the borehole, but extrapolation from higher in the hole pointed to a temperature of about −1°C at the bed. The melting point under the ice overburden pressure at the bed is −0.7°C. The temperature measurements are thus compatible with the conclusion above that the base is at the melting point.

How is the basal temperature raised to the melting point? The geothermal heat flowing up out of the earth hasn't been measured in this region, but elsewhere it is typically about 1 heat-flow unit (hfu; 1 microcalorie per square centimeter per second). Our temperature measurements indicate that in the lower half of the ice mass the ice is conducting 1.9 hfu of heat upward from the bed. Thus the addition of an extra 0.9 hfu at or near the bed, added to a geothermal heat flow of 1.0 hfu, is necessary to supply the 1.9 hfu flowing upward and thus to maintain the basal temperature at the melting point. In fact, if the ice is sliding over its bed at 1.2 meters per day, or if this motion is accommodated by deformation of subglacial till, under a basal shear stress of 0.2 bar, frictional heating amounts to 3.7 hfu, much more than needed to supply the extra 0.9 hfu. The remainder of the frictional heat (2.8 hfu)



Preparing to lower a core drill to the base of the ice stream are (from left) Howard Conway, Hermann Engelhardt, Judy Zachariasen, and Neil Humphrey.

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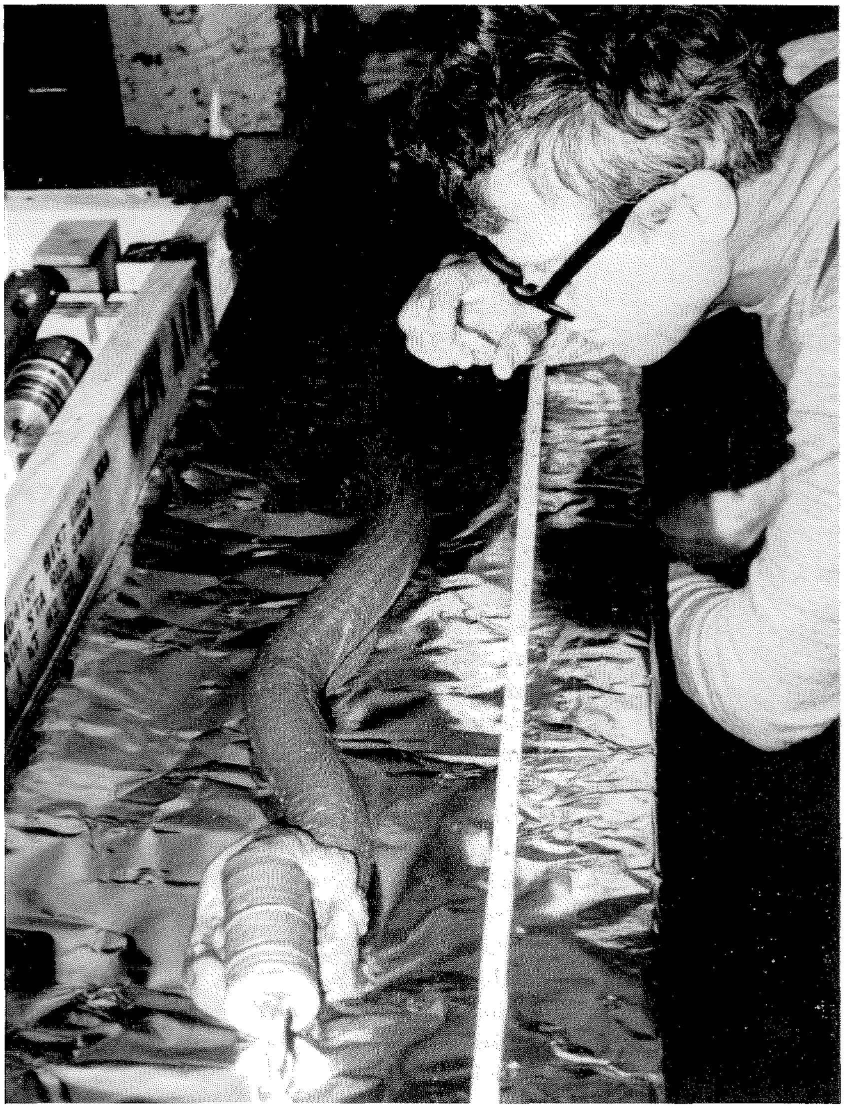
must go to melting ice off the base of the ice mass, thus generating water that enters the basal water conduits, through which it ultimately is conducted to the sea under the Ross Ice Shelf.

What about the supposed till under the ice? With a piston coring device we obtained four cores of the subglacial material, three cores 2 meters long and one 3 meters long, all 5 centimeters in diameter, from three different boreholes. The core material is a highly plastic but cohesive, sticky mud (not a slurry) containing abundant rock fragments of pebble size and smaller. In texture and structure, especially the wide range of grain sizes abundantly present, it strongly resembles the type of glacially deposited pebbly mud called till by geologists. The till inferred by the University of Wisconsin geophysicists is really there (truth of the drill)! They estimated it to be 6.5 meters thick under Upstream Bravo, and our cores verify a thickness of at least 3 meters. We tried to drill through it with a hot water jet; the drill penetrated about 5 meters, but we could not sense a bedrock bottom beneath the till.

Our till samples contain fossils, from shell fragments visible to the naked eye down to microscopic sponge spicules, diatoms, and other organic remains. Ages of the diatoms, determined by Richard Scherer of Ohio State University, range from 2 million to 50 million years. The till is therefore derived from a wide mixture of marine sedimentary rocks, which were deposited at times when the West Antarctic ice sheet was absent. The mixing is reasonable if the till material were picked up from an extensive area



Opposite page: A tranquil view of the Antarctic Peninsula, a part of West Antarctica where the base of the ice sheet is above sea level.

Left: Barclay Kamb inspects a core sample of till from beneath the base of the ice stream—a plastic, sticky mud that can be cut with a knife.

and transported with the movement of the ice stream. This is compatible with the till lubrication theory.

The till contains 40 percent water by volume, remarkably high for a material with so large a grain-size range. The high water content probably is an indication that the till is undergoing shear deformation as the ice stream moves. The till cores came out of the boreholes unfrozen—another proof that the bed of the ice stream is at the melting point.

We tested the shear strength of the fresh till with a small test cell put together in the field. The tests showed normal plastic behavior, with a yield stress of about 0.03 bar. This is only about a tenth the shear stress at the base of the ice stream (0.2 bar). Thus the till could very readily deform under the shear stress at the base of the ice stream, as visualized in the till lubrication theory. But there is a problem: the lubrication is *too* good; the till is too weak to support the shear stress at the base of the ice, low as it is. We hope to resolve this problem with more detailed laboratory tests of the till's mechanical properties.

While our observations have revealed that conditions suitable both for rapid basal sliding and for subglacial till deformation are present at the base of Ice Stream B, we have not succeeded in getting fully unambiguous and complete measurements of basal sliding and till deformation rates, which could show with certainty which process actually predominates in causing the ice-stream motion.

The clearest indication so far comes from a

"tethered stake" experiment carried out in January 1990 in borehole number 5. A heavy steel stake attached to a steel cable (the tether) was lowered to the bottom and driven into the bed; if basal sliding occurs, the stake will move laterally away from the bottom of the hole, and the tether cable will be pulled into the hole after it. We observed a pull-in of 20 cm in the first 3.3 hours of the experiment. (Shortly thereafter the tether became frozen in at shallow depth, and the pull-in stopped.) The observed pull-in corresponds to a basal sliding rate of 1.5 meters per day. This is somewhat faster than the surface motion of 1.2 meters per day from satellite navigation measurements in 1984-86, so either the ice stream has sped up since then, or else the observed pull-in is erroneously large. On face value we have here an indication that basal sliding is the predominating process, in spite of the other indications mentioned above that till deformation is probably involved also.

It is certainly doing some rather remarkable things in these ice streams, but that does not yet constitute disintegration.

What does all this mean as far as ice sheet disintegration is concerned? By identifying the mechanism of ice-stream motion and developing a quantitative formulation of it, we aim to provide a concrete and reliable basis for assessing how ice streaming will respond to changing environmental conditions. In this response it makes quite a difference whether the till behaves as a plastic material, as our tests show, or as a linearly viscous fluid, as has been assumed in some geophysical models of the ice stream. It also makes quite a difference whether the rate-controlling mechanism is till deformation or basal sliding. The role of water pressure in controlling the mechanical behavior of the till and basal sliding, and the role of the basal conduit system in controlling the water pressure, are probably crucial elements of the ice-stream mechanism. An instability may be lurking there: if the ice stream starts to move faster, more frictional heat will be generated, hence more water will be produced by basal melting, which will tend to increase the basal water pressure, and that will weaken the till and promote a further increase in ice-stream motion—a positive feedback loop.

The principal factors that could bring about rapid disintegration of the ice sheet are widespread proliferation of ice streams throughout the ice sheet and acceleration of the ice streams to high speeds, perhaps comparable to the approximately 100 meters per day sometimes seen in surging glaciers. At such speeds the ice sheet could disintegrate in a matter of decades. We don't yet know what the potentialities for such motions are, but the borehole data that we are gathering are beginning to build a basis for considering these problems.

Is the Antarctic ice sheet disintegrating? No, not obviously, at present. It is certainly doing some rather remarkable things in these ice streams, but that does not yet constitute disintegration. The fact that Ice Stream C has stopped shows that the whole thing is not just running away. Would the greenhouse effect provide enough of a perturbation to provoke disintegration sometime in the near future? That's what we hope the truth of the drill will eventually help us decide. ☐

Barclay Kamb has spent a good portion of his professional life camped on top of glaciers studying their physical properties and dynamics, a research experience that can be somewhat more exciting than ordinary lab work when the glacier surges at 65 meters per day. When he hasn't been on the ice, he's been in southern California—his career at Caltech has spanned four decades. He received his BS (physics) in 1952 and PhD (geology) in 1956, the same year he joined the faculty as assistant professor of geology. He has been professor of geology and geophysics since 1963, was chairman of the Division of Geological and Planetary Sciences from 1972 to 1983, and provost from 1987 to 1989. Last month he was named the first Barbara and Stanley R. Rawn Professor. Kamb hopes to return next year for a third summer at Upstream B to continue plumbing the depths of the West Antarctic ice streams.