

Borehole drilling to the bed of ice stream B, Antarctica

HERMANN ENGELHARDT, MARK FAHNESTOCK,
NEIL HUMPHREY, and BARCLAY KAMB

*Division of Geological and Planetary Sciences
California Institute of Technology
Pasadena, California 91125*

The great ice streams flowing through and out of the west antarctic ice sheet move at speeds of hundreds of meters per year, while the ice sheet itself moves only a few tens of meters per year (Whillans, Bolzan, and Shabtaie 1987). What gives rise to the dramatic increase in the speed of the ice streams over the neighboring ice sheet? Our goal is to understand the basic physical mechanism that controls the rapid motion, both because it is an interesting glaciological phenomenon in its own right and because it may have important consequences for worldwide climatic change. A realistic understanding of the interaction of climatic and sea-level change with the west antarctic ice sheet will have to take into account the dynamics of this large ice mass, particularly the rapid motion of its ice streams.

The key to the rapid motion lies, it is thought, at or near the bottom of the ice. Three different mechanisms for rapid motion have been proposed:

- superplasticity of the basal ice (Hughes 1977);
- rapid basal sliding of the ice over its bed (Rose 1979);
- rapid deformation of a layer of subglacial till (Blankenship et al. 1987; Alley et al. 1987).

Determining which of these (if any) is the actual mechanism requires gaining access to the basal zone and making appropriate measurements there.

Over the last 10 years, a hot-water ice-drilling method has been developed that allows us to reach the bottom of glaciers more than 1,000 meters deep quickly, i.e., within 2–3 days. The boreholes are used for carrying out a range of borehole geophysical measurements, including temperature distribution, basal water pressure, and basal sliding. This method was used by our group on Variegated Glacier, a surge-type glacier in Alaska, which surged in 1982–1983 (Kamb et al. 1985; Kamb and Engelhardt 1987). It also proved successful in reaching the bottom of 1,000-meter-deep Columbia Glacier, Alaska, a large, fast-moving tidewater glacier (Kamb et al. in preparation).

Application of the method to the antarctic ice streams poses an additional complication. The Alaskan glaciers studied were at the pressure melting point near 0°C throughout, but the ice of the antarctic ice streams is well below freezing, except possibly very near the bed. As a result, water-filled boreholes drilled by the hot-water drilling method refreeze rapidly, making it difficult to make measurements other than those that can be done leaving instruments to freeze in. The method was, however, successfully used by Engelhardt and Determann (1987) to drill to the bottom of the central Ronne Ice Shelf (465 meters thick) and by the Polar Ice Coring Office to drill to the bottom of the Ross Ice Shelf (370 and 480 meters thick), at Crary Ice Rise (Bindschadler et al. 1989; Koci and Bindschadler 1989).

In field season 1988–1989, we carried out the first borehole geophysical study of an antarctic ice stream on ice stream B at

field camp “Upstream B” (83.5°S 138.1°W). At two sites 230 meters apart, we drilled a total of six boreholes, five of which reached the bottom, at depths between 1,030 to 1,037 meters. One stopped at a depth of 950 meters without reaching bottom. The boreholes as initially drilled were about 10 centimeters in diameter. Total time for drilling and reaming a borehole to completion averaged 55 hours. Drilling was done in steps of about 400 meters with intervening steps of reaming the borehole to the diameter of 10 centimeters. A borehole of 10 centimeters diameter in –26°C ice completely refreezes in 10 hours and is open for instrumental work for only 2–4 hours.

We tried to prevent refreezing by introducing antifreeze agent (ethanol) into one of the boreholes, but this did not work. Because of warming of the ice next to the borehole during drilling with hot water, the antifreeze is initially diluted by melting ice from the borehole wall; later, as a cold wave arrives from farther outside the borehole, the diluted antifreeze solution crystallizes frazil ice platelets, which float up and form slush, blocking the passage of instruments.

During drilling, the water level in the borehole stood high, at a depth of about 35 meters below the surface. Parallel to the main borehole, we drilled a second hole, in which the overflow of drilling water from the main borehole accumulated and from which the water could be pumped out and recycled. This feature greatly reduced the amount of ice melting required to produce hot water. When the drill reached bottom, the water level in the boreholes dropped to about 105 ± 5 meters below the surface. Water-level depths in the individual boreholes were 90.1, 101.8, 104.8, 111.2, and 115.0 meters. In four boreholes, the water-level drop occurred within about 10 minutes of reaching the bed; in one hole, it occurred 9 hours later. This shows, that the boreholes are connected to a basal hydraulic system capable of accepting appreciable amounts of water, about 2 cubic meters in each water-level-drop event. The differences in water pressures from borehole to borehole and the changes in pressure with time (figure 1) need further study to

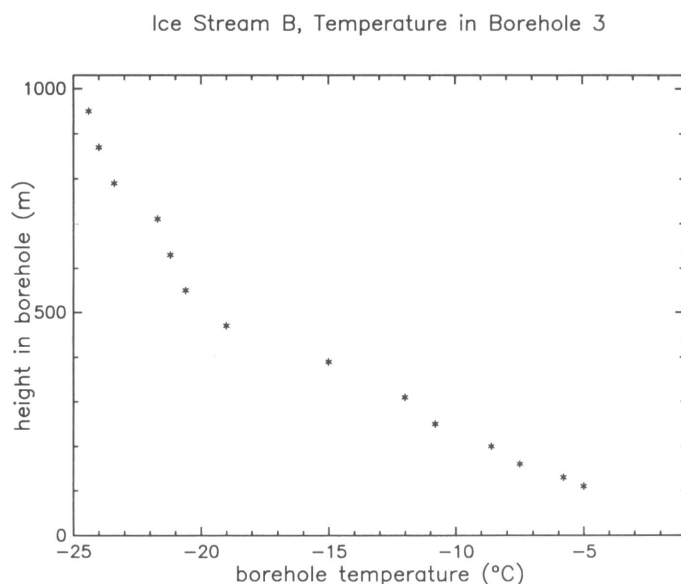


Figure 1. Water pressure at the bed of 1,030-meter-deep Ice Stream B, expressed as depth of water level in borehole 3. The curve shows the water level as a function of time after the initial drop to 104.8-meter depth. The floatation level is at about 100 meters. (m denotes meter.)

determine which effects are of general nature and which are attributable to the local borehole environment.

A preliminary temperature profile, extending down to within 110 meters of the bottom, was obtained in one borehole (figure 2). Extrapolation of the profile to the bottom suggests that the basal ice is at the pressure melting point, near -1°C , so that the ice stream is wet based.

The water level of 105 ± 5 meters indicates that the water pressure at the bed is high, near the floatation level, at which the water pressure is equal to the ice overburden pressure.

The fact that ice stream B is wet based and that the basal water pressure is high is of great significance for the mechanics of ice stream flow.

Samples of rock materials from the subglacial sediment layer consist of silt, fine sand, and some clasts up to 6 millimeters in size. Preliminary microscopic examination of the samples by R.P. Scherer (1989) reveal marine diatoms of Oligocene, Miocene, Pliocene, and possibly Pleistocene ages. This considerably extends the diatom age range found at Crary Ice Rise and RISP Site J-9, which is limited to Miocene ages (Scherer et al. 1988; Harwood et al. 1989). The mixture of diatom ages suggests mixing of a variety of bedrock source materials as could be expected in a deforming subsoil till. The presence of upper Pliocene marine diatoms suggests that the west antarctic ice sheet was absent at times as late as the late Pliocene.

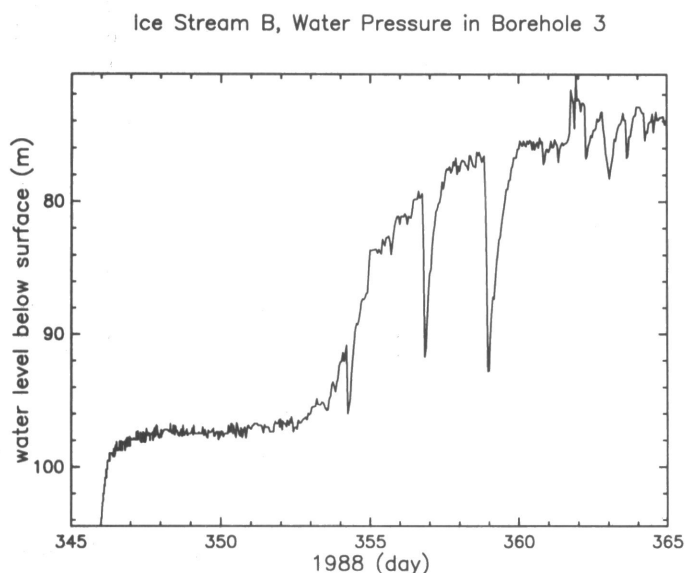


Figure 2. Temperature in borehole 3 to a depth of 110 meters above the bottom. (m denotes meter.)

We thank our tireless field assistants Mark Wumkes, John Chadwick, and Jim Berkey for their great efforts, without which this work could not have been accomplished. We also thank the many people in the long logistical support chain necessary for this work. The work was supported by National Science Foundation grant DPP 85-19083 and by a subcontract from the National Science Foundation Polar Ice Coring Office 88-02/DPP 83-18538.

References

- Alley, R.B., D.D. Blankenship, C.R. Bentley, and S.T. Rooney. 1987. Till beneath ice stream B. 3. Till deformation: Evidence and implications. *Journal of Geophysical Research*, 92, 8,921–8,929.
- Bindschadler, R., B. Koci, S. Shabtaie, and E. Roberts. 1989. Evolution of Crary Ice Rise, Antarctica. (Abstract) *Annals of Glaciology*, 12, 199–200.
- Blankenship, D.D., C.R. Bentley, S.T. Rooney, and R.B. Alley. 1987. Till beneath Ice Stream B. 1. Properties derived from seismic travel times. *Journal of Geophysical Research*, 92, 8,903–8,911.
- Engelhardt, H., and J. Determann. 1987. Borehole drilling through the central Ronne Ice Shelf. *Nature*, 327, 318–319.
- Hughes, T. 1977. West Antarctic Ice Streams. *Review of Geophysics and Space Physics*, 15, 1–46.
- Harwood, D.M., R.P. Scherer, and P.-N. Webb. 1989. Multiple Miocene marine productivity events in West Antarctica as recorded in upper Miocene sediments beneath the Ross Ice Shelf (Site J-9). *Marine Micropaleontology*, 15, 91–115.
- Kamb, B., and H. Engelhardt. 1987. Waves of accelerated motion in a glacier approaching surge: The mini-surges of Variegated Glacier, Alaska, U.S.A. *Journal of Glaciology*, 33, 27–46.
- Kamb, B., M. Fahnestock, N. Humphrey, and H. Engelhardt. In preparation. Relation between basal water pressure and sliding in a large tide water glacier, Columbia Glacier, Alaska.
- Kamb, B., C.F. Raymond, W.D. Harrison, H. Engelhardt, K.A. Echelmeyer, N. Humphrey, M.M. Brugman, and T. Pfeffer. 1985. Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska. *Science*, 227, 469–479.
- Koci, B., and R. Bindschadler. 1989. Melt-water drilling on Crary Ice Rise, Antarctica. (Abstract) *Annals of Glaciology*, 12, 214.
- Rose, K.E. 1979. Characteristics of ice flow in Marie Byrd Land, Antarctica. *Journal of Glaciology*, 24, 63–75.
- Scherer, R.P. 1989. Microfossil assemblages in "deforming till" from Upstream B, West Antarctica: Implications for ice stream flow models. *Antarctic Journal of the U.S.*, 24(5).
- Scherer, R.P., D.M. Harwood, S.E. Ishman, and P.N. Webb. 1988. Micropaleontological analysis of sediments from the Crary Ice Rise, Ross Ice Shelf. *Antarctic Journal of the U.S.*, 23(5), 34–36.
- Whillans, I.M., J. Bolzan, and S. Shabtaie. 1987. Velocity of Ice Stream B and C, Antarctica. *Journal of Geophysical Research*, 92, 8,895–8,902.