Reports

The Ross Ice Shelf Project

Abstract. *A hole was drilled through the Ross Ice Shelf 450 kilometers from the barrier. Scientific sampling through this hole revealed a sparse population of crustaceans, fish, and microbial biomass. The seabed consists of mid-Miocene glaciomarine mud. Geothermal heat flow is average. Oceanographic data indicate an active circulation and melting at the base of the ice.*

On 15 December 1977 an underwater television camera was lowered through 420 m of ice into the sea beneath the Ross Ice Shelf. Scientists were viewing for the first time this unique environment under the thick ice cover approximately 450 km from the open sea (Fig. 1). Sea bottom at the location (82°22.5′S, 168°37.5′W) is 597 m below sea level and the water column is 237 m thick. As the camera was slowly lowered for a close examination of the sea floor, an organism swam across the field of view. Life was discovered under the shelf. Over the next 3 weeks numerous biological, geological, and oceanographic measurements were made through this access hole.

The scientists had waited a long time for the opportunity to sample through the ice. Originally scheduled to begin in 1974, the drilling was delayed 2 years, at first because of engineering delays in preparing the drill and downhole instrumentation, and then because of fiscal and logistical constraints.

Drilling began in 1976. Engineers from the Ross Ice Shelf Project (RISP) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) attempted to drill through the shelf, using a wireline rotary drill system. In order to provide a clean access hole, no drilling mud or fluid was used. (Normally a mixture of diesel oil and trichloroethylene is used to equalize hydrostatic pressure in the hole.) Creep rates were higher than anticipated (*1*), and the drill became stuck in the ice about 90 m from the bottom. RISP scientists already in Antarctica were diverted to other research activities.

In 1977 attempts were made to melt out the drill with hot water to provide the clean hole desired. When these attempts failed, the group settled for a somewhat less suitable hole. A hole was drilled through the ice shelf in December 1977 with a flame-jet drill developed and operated by Browning Engineering Corporation, Hanover, New Hampshire. The drill delivered approximately 2×10^6 Btu's per hour and produced a hole averaging 50 cm in diameter at a penetration rate of 0.9 m per minute. The hole was redrilled every 3 to 4 days and was kept open by this method for a 3-week sampling period.

Since the turn of the century the Ross Ice Shelf has been used to establish bases for support of activities in Antarctica. Both Scott and Amundsen traversed the shelf in their race to the pole. Admiral Byrd's Little America and later stations (including the present-day McMurdo Station) were established on or adjacent to the ice shelf.

Extensive scientific investigation of the Ross Ice Shelf began during the International Geophysical Year (IGY) (1957–1958). A party of geophysicists and glaciologists circumnavigated the shelf; they measured elevations by altimeter, recorded seismic reflection shots, measured values of gravity and magnetism, and recorded snow temperatures and densities (*2*). During IGY, the shelf was penetrated by drilling at Little America V, less than 3 km from the Ross Sea; however, no measurements were made below the shelf through this hole (*3*). More recently, maps of ice thickness

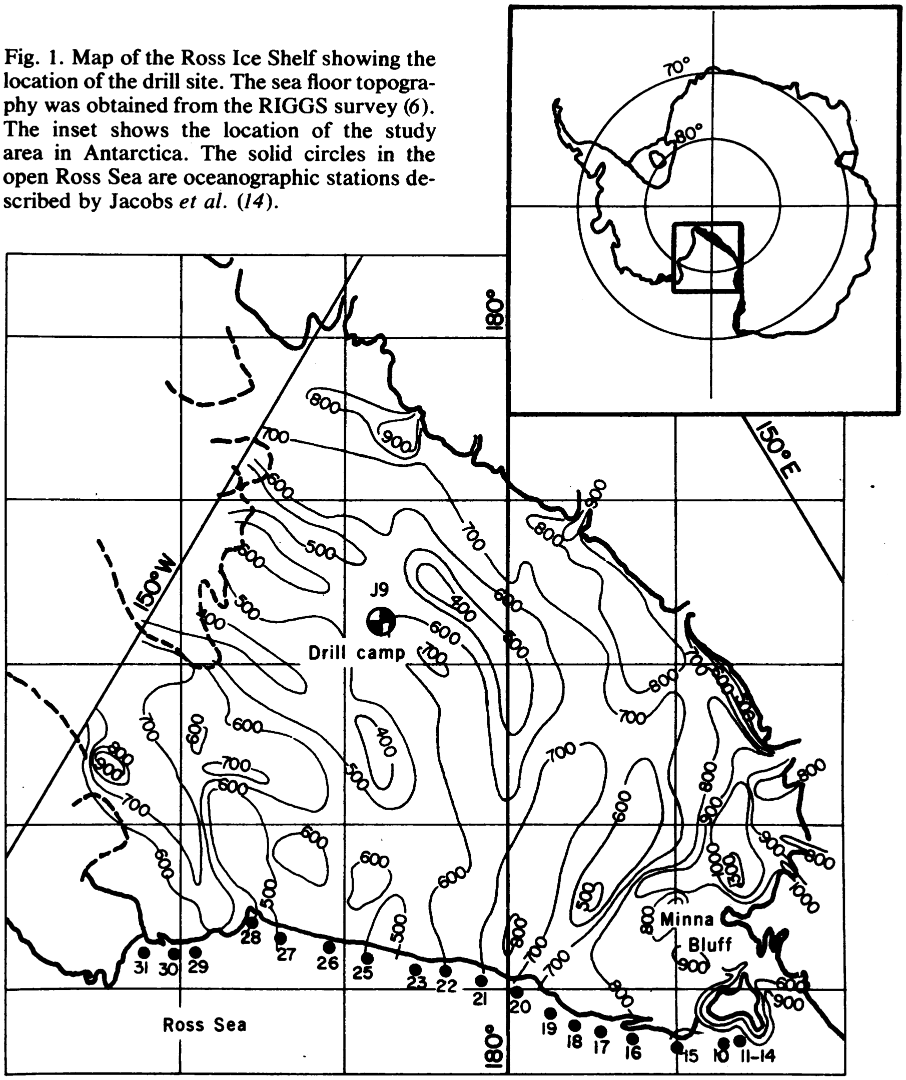

Fig. 1. Map of the Ross Ice Shelf showing the location of the drill site. The sea floor topography was obtained from the RIGGS survey (*6*). The inset shows the location of the study area in Antarctica. The solid circles in the open Ross Sea are oceanographic stations described by Jacobs *et al.* (*14*).

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and ice movement vectors for the ice shelf have been prepared, on the basis of extensive airborne radio-echo sounding conducted between 1972 and 1976 and glaciological traverses conducted in 1962-1963 and 1965-1966 (4).

A more detailed survey of the entire shelf region was conducted between 1973 and 1978 as part of the RISP program. This survey, the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS), visited nearly 200 sites during four field seasons, providing complete coverage of the shelf with measurements of ice thickness and velocity, surface strain rates, bottom depth, snow accumulation, mean annual temperature, and other geophysical measurements (5, 6). The topography of the sea floor obtained from RIGGS is shown in Fig. 1 (6). The RIGGS program included studies of snow precipitation mechanisms, tidal fluctuations of the shelf region and glaciochemistry of the ice and snow (7). Results of the access hole measurements are summarized below and described in more detail in the following reports.

Biology. Baited fishing traps were placed on the bottom several times for periods of 2 to 6 hours. More than 250 amphipods and one isopod (*Serolis trilobitoides*) were captured. Although no fish were caught, one or two species of fish were photographed (8). Several hours of videotape were recorded showing the activity of the amphipods around the baited traps. A mysid shrimp and euphausid were also observed (9). Estimates of microbial biomass were very low compared with the abyssal ocean. Bacteria, microplankton, and zooplankton were found in low abundance (10). No living animals were found in 1/3 m^2 of near-surface sediment collected (9).

Oceanography. Water samples were collected and temperatures were recorded at several depths with modified Niskin bottles and reversing thermometers. Water samples were also pumped to the surface from several depths. Vertical profiles of temperature and conductivity were repeatedly measured (11, 12). The temperature and salinity profiles show a nearly isothermal layer of relatively fresh cold water (temperature, −2.16°C; salinity, 34.39 per mil) just below the shelf and a layer of relatively warm water (temperature, −1.86°C; salinity, 34.83 per mil) near the seabed (13). The temperature-salinity data suggest melting rather than freezing at the bottom of the shelf in the vicinity of this southern location (11, 14). Combined with continuous measurements made from an icebreaker along the Ross Ice Shelf Barrier in the Ross Sea, thermohaline observations beneath the ice shelf show that melting is the dominant phase change occurring over the entire base of the ice shelf (14).

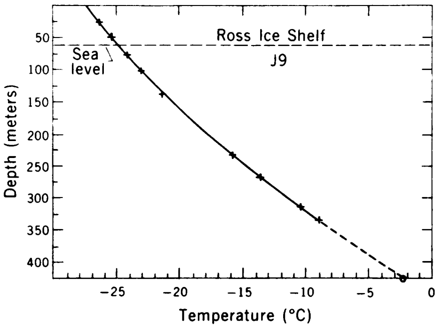

Fig. 2. The temperature profile through the ice shelf at the drill site. Below 330.3 m, the curve is extrapolated to the freezing point at the base of the shelf.

Measurements of current were obtained at three depths during several measuring periods; however, continuous recordings were obtained for no longer than 6 hours. Velocities up to 17 cm sec^{-1} were recorded. The main current component appears to result from tidal oscillation. The net current flux cannot be determined from the available data. Turbidity measurements were scheduled; however, the nephelometer was lost before data could be obtained.

Geology. Eleven gravity cores, up to 1 m in length, were collected. An equal number of surface samples (up to 14 cm in length) were obtained with a sphincter sampler. The cores were dated by microfossils as mid-Miocene (15). The thermal gradient in the sediment was measured by a heat probe, and thermal conductivity was measured on one of the sediment cores. Heat flow was found to be 1.3×10^{-6} cal cm^{-2} sec^{-1} (12).

Ice temperatures. Temperatures were measured in the ice to a depth 330.3 m below the surface. Measurements were made at the bottom of the hole as it was being drilled during 1976. A cooling curve was observed at each depth to assure that the thermometer was in equilibrium with the ice and that all thermal disturbance caused by the drilling had dissipated. The temperature profile is shown in Fig. 2. The curve is extrapolated to the freezing point temperature at the base of the ice shelf (420 m) using $T_f = -0.036 \quad -0.0499S \quad -0.000112S^2 -0.00759P$ (16). Using a measured salinity, S, of 34.39 per mil and estimating a pressure, P, of 36.3 bars, this equation yields $T_f = -2.16$°C at the base of the shelf. Using the measured temperature of −9.02°C at 330.3 m, the temperature gradient in the lower portion of the shelf is 7.6×10^{-4}°C cm^{-1}. Multiplying this gradient by the thermal conductivity of ice (5×10^{-3} cal cm^{-1} sec^{-1} °C^{-1}) gives a value for the heat flux into the ice of 3.8×10^{-6} cal cm^{-2} sec^{-1} (120 cal cm^{-2} $year^{-1}$). From a value of 1.3×10^{-6} cal cm^{-2} sec^{-1} (40 cal cm^{-2} $year^{-1}$) for the geothermal heat flux through the seabed (12), a balance of 80 cal cm^{-2} $year^{-1}$ must be accounted for. The 80 cal cm^{-2} $year^{-1}$ can be accounted for by freezing ice onto the base of the ice shelf at a rate of 1 cm $year^{-1}$, assuming no other source of heat input; however, the heat input by advection in the water column is apparently an order of magnitude greater than the geothermal flux (14).

JOHN W. CLOUGH
B. LYLE HANSEN

Ross Ice Shelf Project Management Office, University of Nebraska, Lincoln 68588

References and Notes

1. J. Weertman, "Anticipated closure rates for a proposed drill hole Ross Ice Shelf, Antarctica," *Special Report 190 Cold Regions Research and Engineering Laboratory*, Hanover, N.H., 1973.
2. A. P. Crary, E. S. Robinson, H. F. Bennett, W. W. Boyd, Jr., "Glaciological studies of the Ross Ice Shelf, Antarctica, 1957–60," *I.G.Y. Glaciological Report 6, I.G.Y. World Data Center A, Glaciology* (American Geographical Society, New York, 1962); H. F. Bennett, "A gravity and magnetic survey of the Ross Ice Shelf Area, Antarctica, Research Report 64-3" (Geophysical and Polar Research Center, University of Wisconsin, Madison, 1964).
3. R. H. Ragle, B. L. Hansen, A. J. Gow, R. W. Patenaude, "Deep core drilling in the Ross Ice Shelf, Little America V, Antarctica," *U.S. Army Snow Ice and Permafrost Research Establishment Technical Report 70* (Willmette, Ill., 1960).
4. G. D. Robin, *Nature (London)* **253**, 168 (1975); J. H. Zumberge, *Am. Geophys. Union Antarct. Res. Ser.* **2**, 65 (1964); E. Dorrer, W. Hofmann, W. Seufert, *J. Glaciol.* **8**, 67 (1969).
5. Summary reports of RISP and RIGGS activities are included in *Antarct. J. U.S.* **9** (No. 4), **10** (No. 4), **11** (No. 4), and **12** (No. 4) (1974–77); R. H. Thomas and C. R. Bentley, *J. Glaciol.* **20**, 84 (1978). C. R. Bentley, J. W. Clough, K. C. Jezek, *ibid.*, in press.
6. J. D. Robertson, C. R. Bentley, J. W. Clough, L. L. Greischar, "Sea bottom topography and structure below the Ross Ice Shelf, Antarctica," in *Antarctic Geoscience*, C. Craddock, Ed. (Univ. of Wisconsin Press, Madison, in press); C. R. Bentley, J. D. Robertson, L. L. Greischar, "Isostatic gravity anomalies on the Ross Ice Shelf, Antarctica," in *ibid.*; R. H. Thomas, *J. Glaciol.* **16**, 11 (1976).
7. G. O. Linkletter and J. A. Warburton, *J. Glaciol.* **17**, 351 (1976); R. T. Williams and E. S. Robinson, *Science* **203**, 443 (1979); C. C. Langway and E. Chiang, *Eos* **59** (No. 4), 308 (1978); M. M. Herron and C. C. Langway, *ibid.*, p. 308; *J. Glacial.*, in press.
8. P. M. Bruchhausen, J. A. Raymond, S. S. Jacobs, A. L. DeVries, E. M. Thorndike, H. H. DeWitt, *Science* **203**, 449 (1979).
9. J. H. Lipps, T. E. Ronan, Jr., T. E. DeLaca, *ibid.*, p. 447.
10. F. Azam, J. R. Beers, L. Campbell, A. F. Carlucci, O. Holm-Hansen, F. M. H. Reid, D. M. Karl, *ibid.*, p. 451.
11. A. E. Gilmour, *ibid.*, p. 438.
12. T. D. Foster, The temperature and salinity fields under the Ross Ice Shelf, *Antarct. J. U.S.* **13** (No. 4) (1978).
13. S. S. Jacobs, J. L. Ardai, P. M. Bruchhausen, Thermohaline stratification and the seafloor below the Ross Ice Shelf, *Eos* **59** (4), 308 (1978).
14. S. S. Jacobs, A. L. Gordon, J. L. Ardai, Jr., *Science* **203**, 439 (1979).
15. P. N. Webb, T. E. Ronan, Jr., J. H. Lipps, T. E. DeLaca, *ibid.*, p. 435.
16. K. Fujino, E. L. Lewis, R. G. Perkins, *J. Geophys. Res.* **79**, 1792 (1974).

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JOHN W. CLOUGH and B. LYLE HANSEN

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