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Antarctic Ice Sheet: Preliminary Results of First Core Hole to Bedrock

Abstract. *The Antarctic ice sheet at Byrd Station has been core-drilled to bedrock; the vertical thickness of the ice is 2164 meters. Liquid water—indicative of pressure melting—was encountered at the bed. Heat flow through the base of the ice sheet is estimated at 1.8 microcalories per square centimeter per second. The minimum temperature was − 28.8°C at 800 meters; maximum ice density, 0.9206 at 1000 meters. Core studies reveal the existence of a chemically pure, structurally stratified sheet comprising bubbly ice to 900 meters that transforms to bubble-free deformed ice, with substantially vertically orientated* c-*axis structure, below 1200 meters. Below 1800 meters the deformed ice structure gives way to large annealed crystals. Several thin layers of dirt between 1300 and 1700 meters are tentatively identified as volcanic ash, and horizontally banded debris, including fragments of granite, is present in the basal ice.*

On 29 January 1968 the first core hole to penetrate the bottom of the Antarctic ice sheet was drilled (*1*) at Byrd Station (80°01′S, 119°31′W; elevation, 1530 m) (Fig. 1). The vertical thickness of ice was 2164 m and more than 99 percent of the core was recovered. Cores were sought for investigations of the physical properties of the ice sheet, the nature of the ice-rock contact, and the composition of the underlying bedrock. Temperatures and deformation in the ice sheet are measured in the drill hole which will be used also for large-scale extraction of the englacial air required for radiocarbon dating of the ice sheet (see *2*).

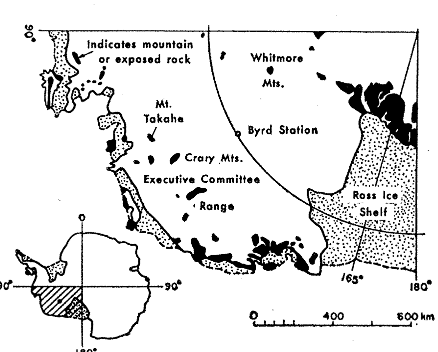

Fig. 1. Byrd Station and major outcrops of rock. Granites occur in Whitmore Mountains; Mt. Takahe, Crary Mountains, and Executive Committee Range are entirely volcanic.

Drilling was accomplished with a cable-suspended electromechanical rotary drill (*3*) that had been modified for coring in ice and had been tested in Greenland (*4*). The drill, driven by a 17.5-hp induction motor, was 26.5 m long, and weighed 1100 kg, and could be reeled in and out of the hole at a maximum rate of 46 m/min.

Drill cuttings were dissolved in ethylene glycol which was bailed after each coring run. The hole was cased to a depth of 88.4 m with 17.8-cm steel casing to prevent hole fluid from leaking into the permeable layer of firn. This fluid, a mixture of arctic diesel oil and trichlorethylene of the same density as ice (0.92), is required in the hole to prevent closure by plastic flow of the ice.

Cores 3 to 6 m in length and averaging 10.8 cm in diameter were recovered from the 16.2-cm hole. Drilling rates varied from 3.3 to 19.8 cm/min, the overall rate of coring averaging 20 m/day. The hole began to deviate from the vertical at 320-m depth, and the inclination had increased to 15 deg before bottom was reached.

Ice temperatures (Fig. 2), measured with a thermistor-type probe after completion of the drilling, are accurate within 0.1°C. Measurements of temperature below 1800 m were prevented by an accumulation of slush that could not be bailed before the end of the season. The minimum temperature was − 28.8°C at 800 m; the temperature at 1800 m was −13.0°C, and the pressure-melting point of the ice at the bottom, where the load pressure was 197 bars, was estimated at − 1.6°C. Extrapolating the temperature curve below 1800 m gives a temperature gradient of 3.25°C/100 m. Using an average ice temperature of −9.0°C in this region and Ratcliffe's (*5*) data for the thermal conductivity of ice, the basal heat flow is calculated at 1.8 μcal cm^{-2} sec^{-1}. An unknown proportion of this heat may be due to the flow of the ice.

Bedrock beneath the ice sheet was penetrated to a depth of 1.3 m, but a core could not be retrieved for reasons that remain uncertain; perhaps the material is unconsolidated sediment, such as glacial till, rather than solid rock. Glacial till underlies the Greenland ice sheet at Camp Century (*4*).

Liquid water was encountered at the ice-rock interface, clear evidence that the bottom of the ice sheet is at the pressure-melting point. Because of a slight deficiency in the density of the hole liquid, the bottom water flooded the hole to a height of about 50 m. Preliminary calculations indicate that this water was derived from a layer of water at least 1 mm thick.

Apart from very brittle and badly fractured sections from between 400 and 900 m, the overall condition of the core varied from good to excellent. Dirt was abundant in the bottom 4 to 5 m of core, including bands of silt, sand, and pebbles, with scattered larger fragments—all interspersed with ice. Pending detailed analysis of these cores it was noted that the largest fragments

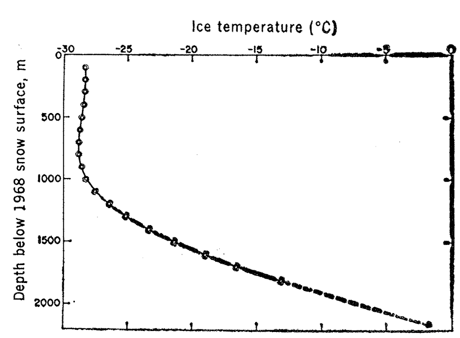

Fig. 2. Temperature profile of the ice sheet at Byrd Station. Open circles are measured values; the pressure-melting temperature (−1.6°C) at the bottom is marked by a solid circle.

(up to 5 cm in cross section) and some of the pebbles consisted of granite—both pink and light-colored. The nearest outcrops of granite occur in the Whitmore Mountains (6) about 360 km from Byrd Station; granitic rocks are also exposed at several other widespread localities in west Antarctica (7).

Several thin layers of dirt, as thick as 0.5 mm and overlain by variable thicknesses (up to 10 mm), of refrozen melt water, were encountered between 1300 and 1700 m. The melt can be attributed almost certainly to radiational heating of the snow by dirt particles exposed to the sun; apart from these debris-associated melt layers, no other signs of melt were observed in the cores. Six layers, containing particles large enough to be easily visible by eye, were tentatively identified as volcanic ash; such ash could have come from any of a number of volcanoes (no longer active) located within 300 km of Byrd Station —such as the Executive Committee Range (8).

The ages of these dirt layers can only be estimated at present. For an estimate of the age of a near-surface layer one simply divides the water equivalent of the snow above the layer by the mean annual snowfall, which at Byrd Station averages about 32 cm—equivalent to about 11 cm of water (9). At a depth of 100 m, for example, the equivalent column of water is 78 m and the age is approximately 700 years. With increasing depth of burial one must take account also of the thinning of annual ice layers by plastic deformation, the net effect of which is to increase the age of the ice. By use of Nye's (10) correction factor it was estimated that the layers of volcanic ash between 1300 and 1700 m were deposited on the surface of the ice sheet 15,000 to 25,000 years ago. Core from near the bottom of the ice sheet could be as old as 50,000 years.

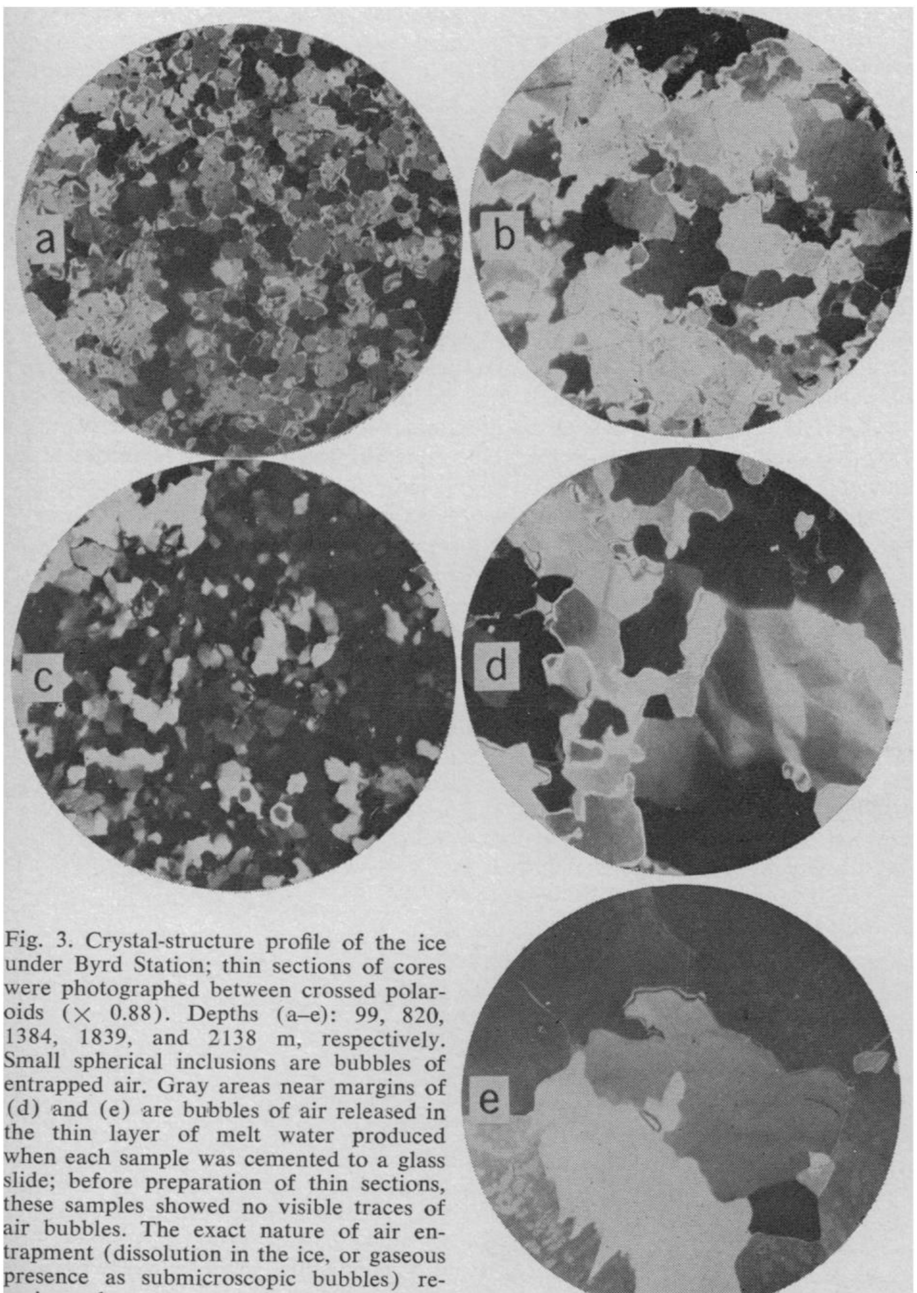

Fig. 3. Crystal-structure profile of the ice under Byrd Station; thin sections of cores were photographed between crossed polaroids (× 0.88). Depths (a–e): 99, 820, 1384, 1839, and 2138 m, respectively. Small spherical inclusions are bubbles of entrapped air. Gray areas near margins of (d) and (e) are bubbles of air released in the thin layer of melt water produced when each sample was cemented to a glass slide; before preparation of thin sections, these samples showed no visible traces of air bubbles. The exact nature of air entrapment (dissolution in the ice, or gaseous presence as submicroscopic bubbles) remains unknown.

Many air bubbles become trapped in ice formed by the compaction of dry polar snow. At Byrd Station, snow is converted (11) to ice at a depth of about 56 m, 1 cm^3 of ice containing between 150 and 200 bubbles. The density (12) of the ice increased from 0.8400 at 56 m to 0.9198 at a depth of 906 m where a definite decrease in concentration of bubbles was observed. Above 900 m the increase in density of the ice can be attributed substantially to compression (13) of the air bubbles which decreased in spherical diameter from 0.76 mm at 88 m to 0.27 mm at a depth of 906 m where calculated pressures within the bubbles exceed 80 bars. Ice density was maximum at 0.9206 (corrected for *in situ* temperature) at about 1000 m; at greater depth, increasing temperatures more than offset the effects of increasing pressure, and near the bottom the density had decreased to 0.9170.

The very dramatic improvement in cores from below 900 m (the ice was very brittle between 400 and 900 m) may be attributable to changes in the physical properties of the ice itself; the improvement was accompanied by (i) marked decrease in number of bubbles in the ice, and (ii) onset of preferred crystal orientation. Although no trace of bubbles was visible below 1200 m, the ice does contain air, as evidenced by bubbling of air from the thin layer of meltwater that is formed when an ice sample is pressed on a warm glass plate during preparation of thin sections.

While internal stresses, associated with highly pressurized bubbles, may be expected to decrease as the concentration of bubbles in the ice decreases (thus diminishing the occurrence of fractures in the cores), it seems that the increased plasticity of the ice below 900 m may correlate equally well with the onset of preferred crystal orientation. Fabrics are essentially random above 900 m. By a depth of 1200 m, however, basal glide planes of practically all crystals have become orientated within 15 deg of the horizontal plane of the ice sheet; that is, principal crystallographic axes are all orientated within 15 deg of the vertical. This structure persisted to a depth of 1800 m.

Crystals between 1200 and 1800 m were appreciably smaller than crystals observed directly above and below this zone (Fig. 3) which also contained numerous cloudy bands (as thick as 2 cm) of very fine-grained ice that resembled shear layers. All fabric elements observed in this zone, together with the widespread occurrence of "strain shadows" in crystals, are entirely consistent with some process of shear deformation in this part of the ice sheet. "Smearing out" of entrapped air bubbles by such a process may possibly explain the decrease and ultimate disappearance of air bubbles at about 1200 m. The very rapid increase in size of crystals below 1800 m (crystal cross sections of 30 cm^2 or more are not uncommon) is probably attributable to annealing at elevated temperatures near the bottom of the ice sheet; practically identical structure occurs in ice from near the bottom of the Ross Ice Shelf (*14*).

Measurements of electrolytic conductivity of melted samples indicate very low levels of dissolved solids at all depths; conductivities varied between 1.7 and 3.1 μmho/cm, the 45 samples of dirt-free ice tested averaging 2.1 μmho/cm. No systematic changes in conductivity with depth (time) were detected.

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12. Ice densities were determined by hydrostatic weighing, with very pure isooctane (2-2-4 trimethyl pentane) used as the immersion liquid; they are accurate to within 0.0003.
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Turbidity Maximum of the Northern Chesapeake Bay

Abstract. *The turbidity maximum near the head of the Chesapeake Bay is produced primarily by the local resuspension of bottom sediments, and by the estuarine "sediment trap" which is formed in the upper reaches of the estuarine circulation regime by the net nontidal circulation.*

Zones of turbidity maximums in the upper reaches of a number of coastal plain estuaries throughout the world have been reported. These zones begin in the estuary where a vertical gradient of the salinity first appears and extend downstream for 20 to 40 km. They are characterized by tubidities and suspended sediment concentrations greater than those found either upstream in the source river or farther seaward in the estuary. Their formation has been attributed both to the flocculation (*1*) and to the deflocculation (*2*) of river-borne sediment, and to hydrodynamic processes (*3, 4*). Although there have been numerous reports of turbidity maximums, the turbid zone extending from the head of the Chesapeake Bay at Turkey Point seaward for about 32 km (nearly to Tolchester) (Fig. 1) is the first of such features to be comprehensively studied.

From 1 April 1966 through 31 March 1967 samples were collected fortnightly from several depths at each of the stations shown in Fig. 1 for determinations of the concentration of the total suspended solids, the concentration of combustible organic matter, the mineralogy, and the size distribution of the suspended particles (*5*). Supplementary samples were also collected at stations farther seaward in the estuary, and at a

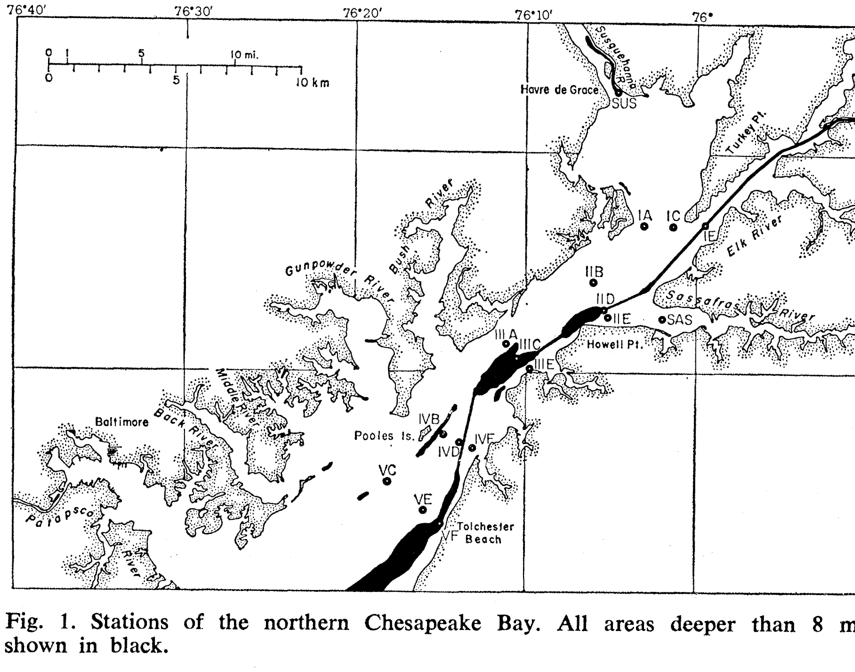

Fig. 1. Stations of the northern Chesapeake Bay. All areas deeper than 8 m are shown in black.