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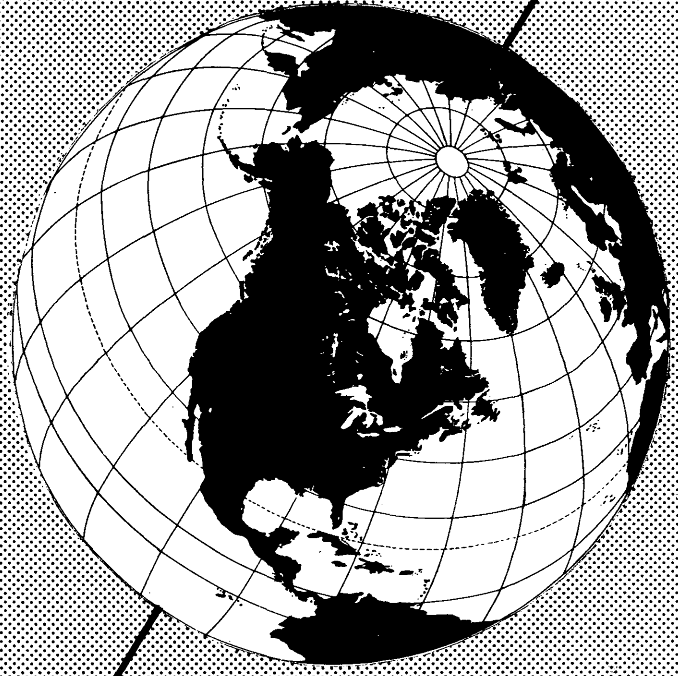
Drill-Hole Measurements and Snow Studies at Byrd Station, Antarctica



U. S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
Corps of Engineers

Technical Report 78
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Drill-Hole Measurements and Snow Studies at Byrd Station, Antarctica

by A. J. Gow

U. S. ARMY SNOW ICE AND PERMAFROST
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Wilmette, Illinois

PREFACE

This report summarizes the results of three years' studies in a deep drill hole in the ice at Byrd Station, Antarctica. The deep hole was drilled during the 1957-58 summer season by the U. S. Army Snow Ice and Permafrost Research Establishment* under sponsorship of the U. S. National Committee, International Geophysical Year. The drill hole was first fully instrumented by R. H. Ragle in December 1958. Subsequent measurements were carried out by A. J. Gow (Arctic Institute of North America), who participated in the initial drilling project as glaciologist. Since the end of the IGY, the project has been sponsored by the U. S. Antarctic Research Program Committee and supported by the National Science Foundation. Data reduction was carried out at USA SIPRE. Results of snow studies at Byrd Station in January 1960 are also included. The report was prepared for the Basic Research Branch, James A. Bender, chief, under SIPRE Task 022.01.038.

This report has been reviewed and approved for publication by the Office of the Chief of Engineers, U.S. Army.

W. L. NUNGESSER
Colonel, Corps of Engineers
Director

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* Redesignated U. S. Army Cold Regions Research and Engineering Laboratory, 1 February 1961.

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SUMMARY

Closure, temperature and inclination have been measured in a deep drill hole at Byrd Station, Antarctica. The deep hole was drilled to 1013 ft during the 1957-58 summer season, and was first fully instrumented in December 1958. The results of remeasurement in January 1960 and January 1961 indicate that temperatures in the uncased portion of the deep hole (below 150 ft) have stabilized; that the closure rate is increasing; and that insignificant inclination has occurred since the hole was drilled 3 yr ago. Results of snow studies in January 1960 show that the present rate of accumulation at Byrd Station is between 14 and 15 cm of water equivalent per year.

DRILL-HOLE MEASUREMENTS AND SNOW STUDIES AT BYRD STATION, ANTARCTICA

by

A. J. Gow

INTRODUCTION

During the Antarctic summer of 1957-58, a deep hole was drilled to 1013 ft in the Antarctic Ice Cap at Byrd Station. This drilling project formed part of the U. S. IGY glaciological program, and was carried out by USA SIPRE* (Patenaude, et al., 1959). The objectives of the project were twofold: (1) to recover a continuous sequence of ice cores for glaciological investigation, and (2) to provide a deep hole for studying temperature profiles and the flow properties of ice in the surface layers of a high polar glacier. In December 1958 the deep hole was instrumented for temperature, inclination, and rate of closure (Ragle, et al., 1959). Measurements were repeated in January 1960 and January 1961, and the results of this 3 yr study are embodied in this report.

Additional studies in 1960 included measurements of near-surface firn temperatures in a 19-m auger hole. The cores from this hole were utilized for stratigraphy and density studies, and three shallow pits were excavated and examined for recent accumulation.

METHODS AND RESULTS

In December 1958, hole diameters, inclination, and temperatures were measured separately, but for subsequent measurements the caliper, inclinometer, and thermistor probes were combined in a single instrument. This was attached to a three conductor steel insulated cable, and lowered into the drill hole by a hand-operated winch. The winch and recording equipment were set up in an unused undersnow laboratory and maintained at approximately -26C.

Temperature

Three thermistor type probes were used for recording temperatures in the deep hole. Resistance measurements were made with a Leeds and Northrup Wheatstone bridge and null detector. The December 1958 measurements were obtained with probe 4 only, but two additional probes (2 and 3) were used in January 1960; probe 2 was also used for measuring temperatures in a 19-m auger hole. Results with probe 4 in 1960 were calculated by more precise formulas than were available in 1958, but for comparative purposes the 1960 data were recomputed on the basis of the simple temperature resistance relation used in 1958 (See 4A in Table I). This formula gives temperatures which are 0.64 ± 0.001 higher than temperatures from the three constant formulas used in the 1960 tabulation (Table I, Fig. 1). During measurements in January 1961 probe 3 and probe 4 were both lost as the cable was being lowered down the hole. However,

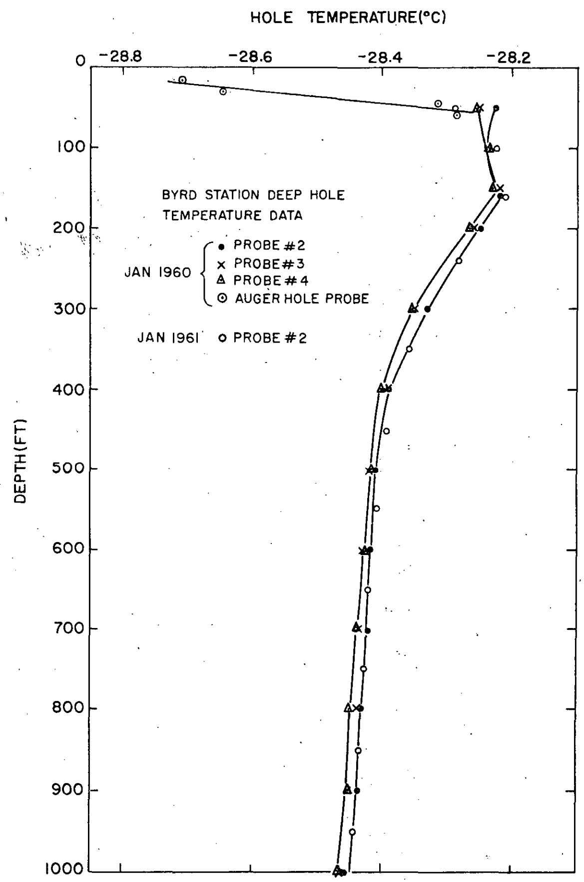


Figure 1. Temperature measurements at Byrd Station.

* Redesignated U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), 1 February 1961.

Table I. Deep-hole temperature measurements, Byrd Station, 1958-61.

Depth (ft)	Probe #4 Dec 1958 (C)	Probe #4 Jan 1960 (C)	4A Jan 1960 (C)	Probe #3 Jan 1960 (C)	Probe #2 Jan 1960 (C)	Probe #2 Jan 1961 (C)
1000	-28.40	-28.455	-28.391	-28.460	-28.455	
950						-28.438
900	-28.39	-28.450	-28.386	-28.450	-28.435	
850						-28.432
800	-28.38	-28.450	-28.386	-28.440	-28.430	
750						-28.425
700	-28.37	-28.440	-28.377	-28.435	-28.420	
650						-28.418
600	-28.36	-28.425	-28.361	-28.430	-28.415	
550						-28.409
500	-28.35	-28.415	-28.352	-28.420	-28.410	
450						-28.393
400	-28.32	-28.400	-28.337	-28.395	-28.385	
350						-28.357
300	-28.28	-28.355	-28.291	-28.350	-28.330	
250						-28.285
200	-28.18	-28.265	-28.201	-28.260	-28.250	
150	-28.13	-28.230	-28.165	-28.220	-28.220	-28.210
100	-28.16	-28.235	-28.170	-28.240	-28.240	-28.226
50	-28.17	-28.255	-28.191	-28.250	-28.225	-28.291
			Auger Hole Temperatures			
15					-28.730	
31					-28.645	
46					-28.315	
61					-28.285	

measurements were obtained with probe 2 and no apparent change in the temperature profile below 200 ft could be detected. The deep hole was cased to 120 ft during drilling in 1957-58 and this has had some effect on surrounding snow temperatures to at least 150 ft. Below 200 ft however, the temperatures appear to have stabilized.

Inclination

In December 1958 inclinations were measured at 100-ft intervals with a Parsons Survey Company single shot inclinometer. Measurements were repeated with a multiple shot instrument in 1960, but no significant bending of the hole could be detected on either occasion.

Diameter

The diameter of the hole was measured at 50-ft intervals with a caliper that varies an electrical resistance as a function of hole diameter. The diameter $\underline{d}$ of the drill hole was calculated from:

$$d = 2c + 2\sqrt{r\left(\frac{R - R_0}{k}\right) - \left(\frac{R - R_0}{2k}\right)^2}$$

where $\underline{c}$, $\underline{r}$, R_0 and $\underline{k}$ are constants and $\underline{R}$ is the measured resistance. A description of the caliper and the derivation of the equations are given by Hansen and Landauer (1958). Resistances were measured with the same bridge and null detector circuit used for temperature measurements. Results are given in Table II and Figure 2. The diameter of the hole measured 5.76 in. when drilled, but by January 1961 the hole had closed off to less than 2.5 in. at 950 ft. The caliper cannot be used to record diameters of less than 2 in., but measurements with a brass tube attached to a linen fishline showed that the hole had contracted to about 1.0 in. in diam at 1000 ft.

Table II. Deep-hole diameter measurements, Byrd Station 1958-61.

Depth (ft)	Diameter Dec 1958 (in.)	Diameter Jan 1960 (in.)	Diameter Jan 1961 (in.)
1000	4.78	3.27	≈1.0
950	5.00	3.81	2.44
900	5.05	4.25	3.19
850	5.28	4.45	3.62
800	5.38	4.74	4.02
750	5.44	4.98	4.43
700	5.51	5.14	4.74
650	5.56	5.28	4.98
600	5.61	5.41	5.19
550	5.65	5.48	5.33
500	5.68	5.57	5.44
450	5.69	5.65	5.53
400	5.69	5.66	5.59
350	5.74	5.69	5.64
300	5.74	5.71	5.68
250	5.75	5.76	5.70
200	5.76	5.78	5.75
150	5.79	5.79	5.73
100	6.04	6.07	6.06
50	6.04	6.07	6.06

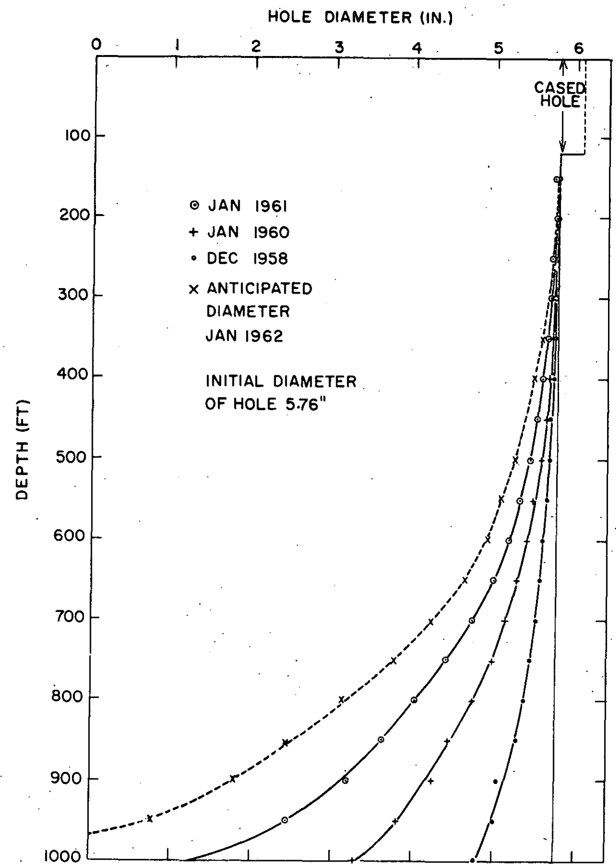


Figure 2. Hole diameter measurements at Byrd Station.

In Figure 3 hole closures at various depths in the drill hole have been plotted against time. The closure is greatest at the bottom of the hole as would be expected, but it is also evident that the rate of closure is increasing at all depths. The curves in Figure 3 were used to compute average closure velocities for successive 12 month intervals, and results in Table III show that the closure is accelerating at all depths. This amounts to an increase in closure of about 20% per year below 600 ft, but at lower stresses the rate appears to diminish somewhat. At lower stresses however, the closure is perhaps too small to be analyzed with any certainty. Data at these depths will probably become more significant as deformation proceeds.

The writer has also studied the results of deformation in a 1400-ft hole at Site 2 Greenland, and a similar pattern of closure is apparent there also. In the Site 2 hole, however, the actual rate of closure was approximately 70-80% greater than that at Byrd Station and increased by about 50% in the deeper parts of the hole during the second year. On the basis of the first year's results at Byrd and Site 2 we might write

$$\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2} = \exp - \frac{E}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

where ε_1, and ε_2, are the strain closure rates at corresponding pressures in the Byrd and Site 2 drill holes respectively, T_1 and T_2 the corresponding drill hole temperatures in degrees Kelvin, E the energy of activation and R the gas constant. Accordingly,

$$0.59 = \exp - \frac{E}{1.98}\left(\frac{3.2}{244.6 \times 247.8}\right)$$

and E = 20 K cal/mole. This is somewhat higher than the generally accepted value of 14 K cal/mole for ice. In view of the small range of temperature and probable differences

Table III. Drill-hole closure, Byrd Station 1958-61.

Depth (ft)	$D_0 - D_1$ (in./yr)	$D_1 - D_2$ (in./yr)	$D_2 - D_3$ (in./yr)	$\frac{D_1 - D_2}{D_0 - D_1}$	$\frac{D_2 - D_3}{D_1 - D_2}$
1000	1.13	1.40	--	1.24	--
950	0.88	1.09	1.35	1.24	1.24
900	0.72	0.86	1.00	1.19	1.16
850	0.57	0.71	0.86	1.25	1.21
800	0.46	0.58	0.70	1.26	1.21
750	0.37	0.43	0.53	1.16	1.23
700	0.29	0.34	0.40	1.17	1.18
650	0.23	0.26	0.30	1.13	1.15
600	0.17	0.19	0.21	1.12	1.11
550	0.13	0.15	0.17	1.15	1.13
500	0.09	0.10	0.11	1.11	1.10
450	0.07	0.08	0.09	1.14	1.13
400	0.05	0.05	0.06	1.00	1.20
350	0.03	0.03	0.06	1.00	2.00
300	0.02	0.02	0.03	1.00	1.50

D_0 = Initial diameter of drill hole = 5.76 in.
D_1 = Diameter of drill hole after 1 year
D_2 = Diameter of drill hole after 2 years
D_3 = Diameter of drill hole after 3 years.

in the structure of the ice at Byrd and Site 2 the activation energy of 20 Kcal/mole should be considered an approximation only.

Before discussing the results of the measurements, a short account of the properties of the ice in the drill hole at Byrd Station is given. At Byrd Station the firn-ice transition occurs at a depth of about 65 m (213 ft), but the physical properties of ice below this depth are progressively changing. The density at the firn-ice transition is about 0.83 g/cm³. At 100 m (328 ft) the ice has attained a density of 0.900 g/cm³. It then densifies very slowly to 0.913 g/cm³ at 305 m (1000 ft). The density distribution in the first 1000 ft at Byrd has been accurately determined from ice cores, and the overburden pressure at any depth can be readily computed from the depth density profile. From additional studies on the ice cores it was found that grain size increased progressively with depth, grain shapes became more irregular, strained crystals became more numerous and bubble pressures increased. Petrofabric studies revealed only weak patterns of preferred orientation at depth. Temperature studies indicate that thermal conditions in the drill hole are particularly stable; below 400 ft the temperature remains almost constant at -28.4C (decreases by less that 0.01°/100 ft). Since no significant bending of the drill hole can be detected, it is assumed that the walls of the hole are deforming solely in response to the overburden pressure, considered everywhere to be hydrostatic. All measurements of the drill hole were made with reference to the 1958 summer surface (January). Only 5 ft of snow has accumulated in the vicinity of the drill hole since January 1958, so that the overburden pressure at any depth can be considered to have remained constant over the 3 yr period for which closure measurements were made.

According to Nye (1953), the rate of contraction of a vertical cylindrical hole in ice is $S = \left(\frac{\sigma}{nA}\right)^n$, where $\underline{S}$ is the rate of contraction, σ is the hydrostatic stress at some sufficient horizontal distance from the drill hole, and $\underline{A}$ and $\underline{n}$ are constants. This constitutes the simple power-law relationship between stress and strain rate for steady state creep in ice, and assumes that the flow rate is independent of the time for which the stress is applied. If the conditions of steady state flow are satisfied, then a double logarithmic plot of strain closure rate versus stress should give a straight line of slope $\underline{n}$. In laboratory tests on the deformation of ice, where the minimum creep rate has been observed, the value of n was found to vary between 1 and 4, depending on the stress. From the large number of creep tests performed on ice it appears that the creep rate obeys the Newtonian flow law at low stresses (<2.5 kg/cm^2) but at higher stress (up to about 7 kg/cm^2) the flow rate becomes constant after an initial period of decelerating creep. With continued application of stress and at stresses in excess of about 7 kg/cm^2, accelerated creep sets in. If closure in the drill hole at Byrd conforms to steady state creep then the rates of closure should remain constant and the hole should never close off. Results from 3 yrs' measurements (Fig. 3) show that closure is accelerating however, and that non-steady-state conditions prevail.

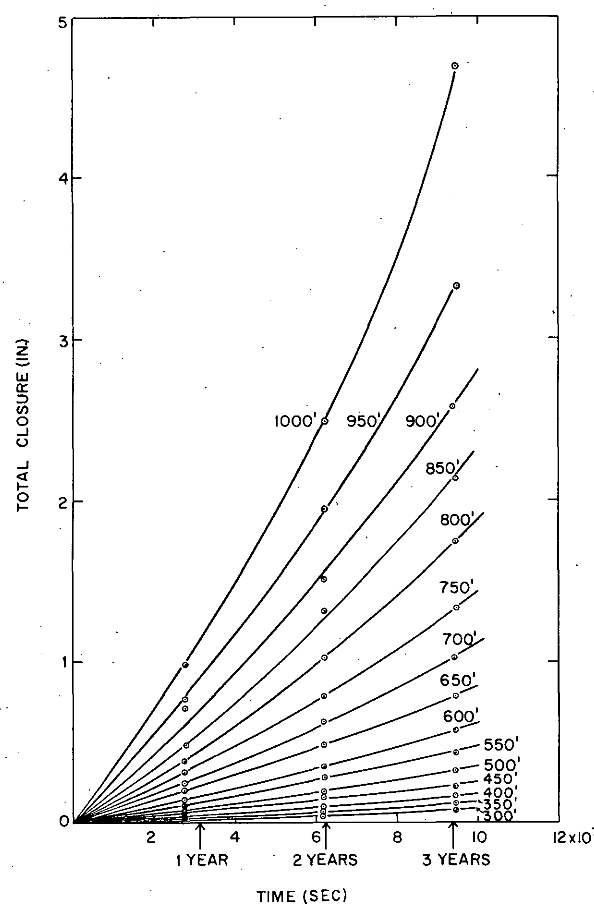


Figure 3. Hole closure at Byrd Station.

The double logarithmic plots of strain closure rate versus stress for the 3 yr data are presented in Figure 4, to give some idea of the departure from ideal power-law behavior. An approximate straight line with a slope value of 3 might be fitted to the first year's results, but it is not possible to obtain even approximate straight lines with data for the other 2 yrs' results. It is obvious that the strain closure rate is not proportional to some constant power of the stress, and that the value of n increases with increasing stress. Some of Glen's laboratory tests suggest similar behavior and results obtained by Butkovich and Landauer (1958), Landauer and Hansen (1958), Higashi (1959), and others on the plastic deformation of ice under a variety of stresses all show the same tendency for creep to accelerate at the higher stresses. Glen (1953) has also suggested that accelerated flow may well occur at lower stresses if the tests are continued long enough. This implies that flow in ice depends on time as well as stress. With time we associate the effects of recrystallization during flow, but just how this recrystallization modifies the original structure of the ice and what effect this has on the flow rate are not thoroughly understood. Glen (1958) has attributed accelerating flow in laboratory-deformed polycrystalline ice to the recrystallization of ice with a preferred orientation favorable to gliding. According to Butkovich and Landauer (1958), basal gliding in randomly oriented polycrystalline ice would be greatly inhibited by interference between neighboring grains. Steinemann (1954) observed that recrystallization of ice during deformation may lead to complexly interlocked grain structures and it would seem that basal gliding under these conditions would be rather limited. As already pointed out, the physical properties of the ice in the drill hole at Byrd are changing continuously with depth. Since the temperature and stress distribution have remained constant, recrystallization under stress will be affected by the original grain properties including grain size, grain shape, bubble structures, etc.

Actual granulation of crystals at high stresses or some process of crystal boundary migration with or without intracrystalline gliding, may be adequate to explain the observed closure in the Byrd drill hole. But it does appear that some process of continuous recrystallization (parakinematic crystallization), involving strain softening of the ice, must be invoked to account for the accelerating closure. One might reasonably expect recrystallization to be more effective at higher stresses, i.e., expect the rate of recrystallization

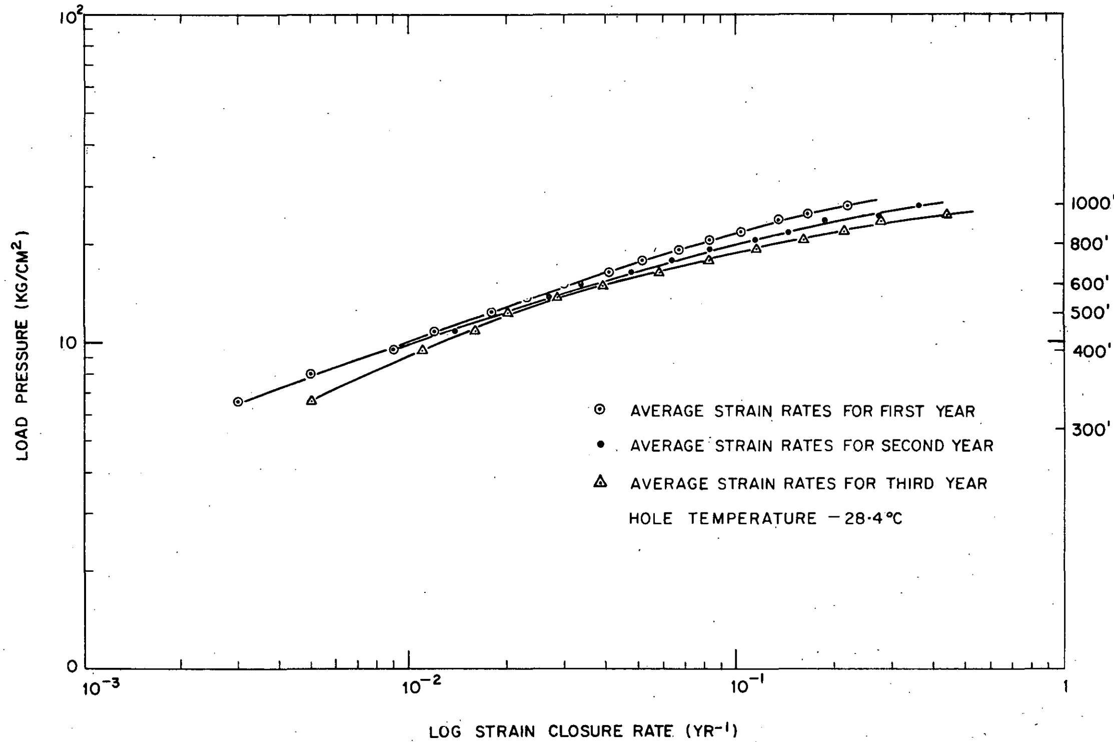


Figure 4. Stress-strain closure rates at Byrd Station.

and hence the rate of flow to increase with increasing stress. There is some indication that this is so at Byrd, for the closure does appear to accelerate more rapidly at the higher overburden pressures. It would be very interesting to obtain samples of wall ice to determine the mode and extent of recrystallization in different parts of the drill hole. However, backdrilling the hole for this purpose does not seem feasible at the present time. In view of the results already obtained, further measurements of closure in the drill hole at Byrd Station are advocated.

It has been assumed that the hole has remained cylindrical during closure. There is no way of determining whether this is so or not, but experiments by Higashi (1959) on the plastic deformation of hollow ice cylinders under hydrostatic pressure have shown that the cylinders generally retain their circular shape during deformation. Part of the closure in the hole may be attributed to two other causes: (1) hoar frost accretion in the drill hole, and (2) relaxation of the ice in the walls of the drill hole.

Measurements in the 120-ft section of the drill casing show no change in its internal diameter since its emplacement 3 yr ago. This would indicate negligible accretion of hoar frost, and there is no reason to suspect any deposition of hoar frost on the walls of the drill hole either. Langway (1958) has shown that glacial ice with bubble pressures exceeding about 10 atm does relax when removed from its confining environment. It is possible that sufficient relief of stress may take place in the deeper parts of the hole to allow expansion of entrapped air bubbles and subsequent increase in the specific volume of the ice in the walls of the drill hole. The effect is probably small in comparison to the true plastic contraction of the drill hole.

SNOW STUDIES

Stratigraphy

To supplement the glaciological studies conducted by Marshall and Gow during drilling in 1957-58 (Patenaude, et al., 1959), three shallow pits were dug during January 1960, and examined for recent records of accumulation. Results are shown in Figure 5.

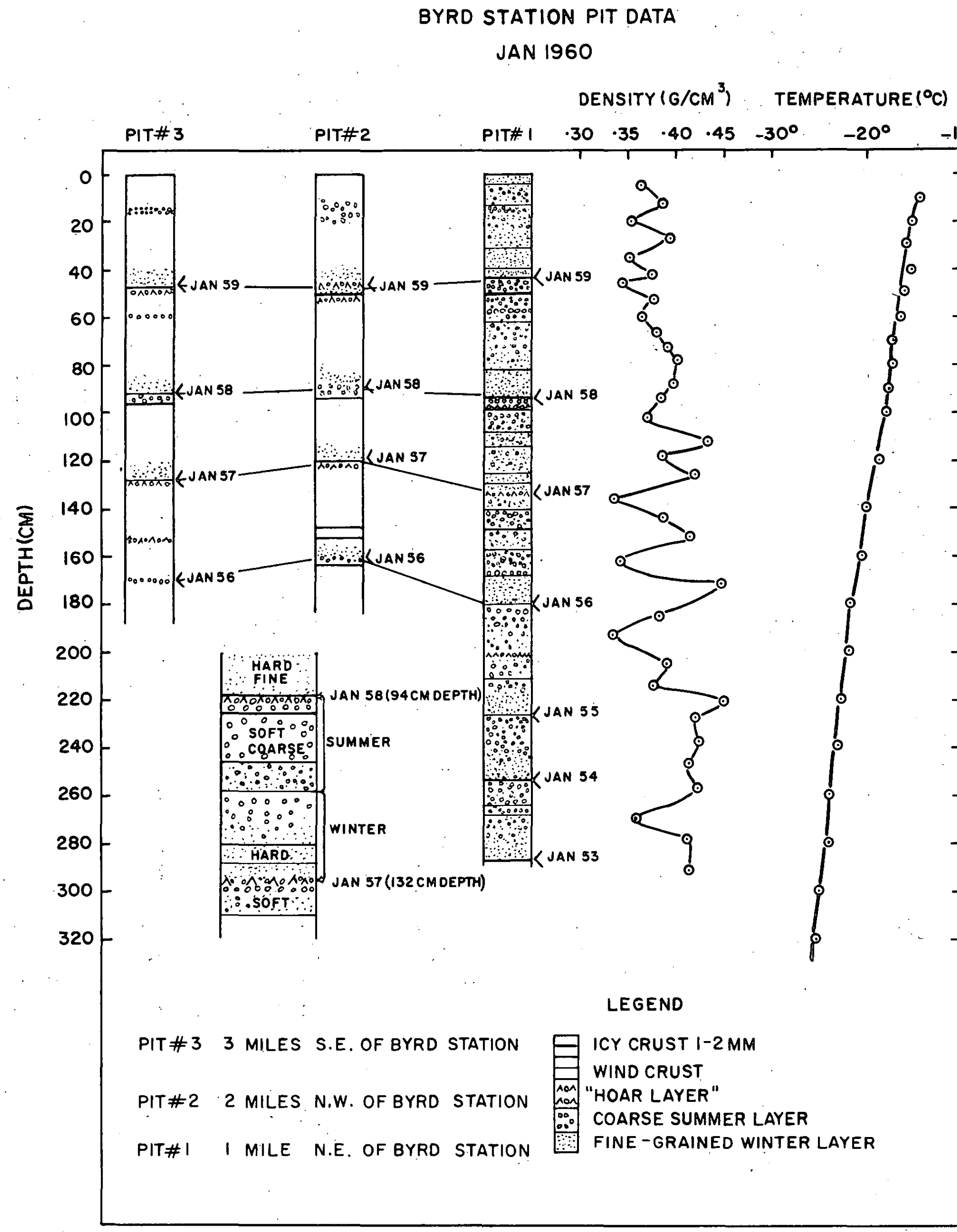


Figure 5. Pit data at Byrd Station.

Ice cores from the 19-m auger hole were used to date annual layers below 3 m; results of the combined analyses are given in Table IV. Breakdown into annual increments was usually facilitated by the identification of coarse-grained summer layers in contact with fine-grained snows of the ensuing autumn and/or winter. The transition from winter to summer, however, was not usually so abrupt because of the variable degree of recrystallization that took place in the winter layer during the ensuing summer. In some annual strata, the winter-summer boundary had disappeared entirely, apparently because of abnormally low winter accumulation and/or exceptionally warm summers. Accumulation stake measurements at Byrd during 1959 and early 1960 (J. H. Pirret, personal communication) showed that the greater part of the annual snowfall (February 1959 - February 1960) occurred during the winter. That only the topmost part of the 1959 winter layer underwent any appreciable grain growth during the summer was readily observed in all three pits.

Table IV. Snow accumulation record at Byrd Station, 1960-1893.

Summer surface	Depth below 1960 surface (cm)	Thickness of annual layer (cm)	Annual accu-mulation (g/cm²)	Total accu-mulation (g/cm²)	Running mean accu-mulation (g/cm²)	Depth to middle of annual layer (cm)	Density of annual layer (g/cm³)
1960	0						
1959*	43	43	15.9	15.9	15.9	22	.370
1958*	94	51	18.4	34.3	17.2	68	.360
1957	132	38	15.1	49.4	16.5	113	.395
1956	180	48	18.8	68.2	17.1	156	.390
1955	226	46	17.7	85.9	17.2	203	.385
1954	258	32	13.3	99.2	16.5	242	.415
1953	290	32	13.0	112.2	16.0	274	.405
1952*	324	34	13.9	126.1	15.8	307	.410
1951	351	27	11.4	137.5	15.3	338	.420
1950*	376	25	10.5	148.0	14.8	363	.420
1949*	404	28	12.6	160.6	14.6	390	.450
1948	425	21	9.3	169.9	14.2	415	.440
1947	454	29	12.9	182.8	14.1	439	.445
1946	493	39	17.8	200.6	14.3	474	.455
1945	535	42	19.5	220.1	14.7	514	.465
1944*	556	21	9.9	230.0	14.4	546	.470
1943*	587	31	15.2	245.2	14.4	572	.470
1942	605	18	8.6	253.8	14.1	596	.475
1941	631	26	12.8	266.6	14.0	618	.490
1940	662	31	15.6	282.2	14.1	647	.505
1939	681	19	9.2	291.4	13.9	672	.485
1938	719	38	19.0	310.4	14.1	700	.500
1937	744	25	12.7	323.1	14.0	732	.510
1936	763	19	9.9	333.0	13.9	754	.520
1935*	789	26	13.5	346.5	13.9	776	.520
1934*	814	25	13.1	359.6	13.8	802	.525
1933	842	28	14.4	374.0	13.9	828	.515
1932*	864	22	11.6	385.6	13.8	853	.525
1931	897	33	17.5	403.1	13.9	881	.530
1930	920	23	12.4	415.5	13.9	909	.540
1929*	947	27	14.7	430.2	13.9	933	.545
1928*	973	26	14.2	444.4	13.9	960	.545
1927	996	23	12.7	456.2	13.8	985	.550
1926*	1022	26	14.1	470.3	13.8	1009	.540
1925	1060	38	20.7	491.0	14.0	1041	.545
1924*	1085	25	13.7	504.7	14.0	1073	.550
1923	1104	19	10.5	515.2	13.9	1095	.550
1922	1123	19	10.5	525.7	13.8	1103	.550
1921*	1149	26	14.5	540.2	13.9	1136	.555
1920*	1180	31	17.4	557.6	13.9	1164	.560
1919	1209	29	16.5	574.1	14.0	1195	.570
1918*	1228	19	10.8	584.9	13.9	1218	.570
1917*	1246	18	10.1	595.0	13.8	1237	.560
1916*	1269	23	12.9	607.9	13.8	1258	.560
1915	1288	19	10.8	618.7	13.7	1278	.570
1914	1313	25	14.2	632.9	13.8	1300	.570
1913*	1339	26	14.9	647.8	13.8	1326	.575
1912	1370	31	18.0	665.8	13.9	1355	.580
1911*	1397	27	15.4	681.2	13.9	1384	.570
1910	1431	34	19.3	700.5	14.0	1414	.570
1909*	1458	27	15.5	716.0	14.0	1444	.575

* Layers showing strongly developed summer surfaces.

Table IV (cont.)

Summer surface	Depth below 1960 surface (cm)	Thickness of annual layer (cm)	Annual accu-mulation (g/cm^2)	Total accu-mulation (g/cm^2)	Running mean accu-mulation (g/cm^2)	Depth to middle of annual layer (cm)	Density of annual layer (g/cm^3)
1908*	1481	23	13.6	729.6	14.0	1469	.590
1907*	1512	31	18.3	747.9	14.1	1597	.590
1906	1531	19	11.2	759.1	14.1	1521	.590
1905	1558	27	15.5	774.6	14.1	1544	.575
1904	1581	23	13.6	788.2	14.1	1569	.590
1903	1605	24	14.3	802.5	14.1	1593	.595
1902	1634	29	17.4	819.9	14.1	1619	.600
1901*	1654	20	11.9	831.8	14.1	1644	.595
1900*	1684	30	18.0	849.8	14.2	1669	.600
1899	1705	21	12.7	862.5	14.2	1695	.605
1898	1733	28	17.0	879.5	14.2	1719	.605
1897*	1765	32	19.4	898.9	14.3	1749	.605
1896	1805	40	24.4	923.3	14.4	1785	.610
1895*	1826	21	12.9	936.2	14.4	1815	.615
1894*	1850	24	14.7	950.9	14.4	1838	.615
1893	1869	19	11.6	962.5	14.4	1859	.610

* Layers showing strongly developed summer surfaces.

The frequently encountered crusted surfaces were of considerable value in interpreting the annual stratification. Two principal types were recognized: (1) windcrusts that occurred in both summer and winter deposits, and (2) icecrusts (1 - 2 mm thick). The latter were usually associated with summer deposits though occasional icy crusts developed in winter layers, probably as a result of contact freezing of moist air (condensation crusts). The summer crusts appear to have originated either as a result of insolation (surface radiation crusts) or in association with thin layers of sublimation crystals just beneath the snow surface (sublimation crusts). Large temperature gradients are implied for the development of these subsurface crusts. These conditions could develop during the autumn where cold, fine-grained snow overlying insolated summer deposits would tend to impede the upward migration of water vapor and cause condensation at the warm-cold snow contact. A previously formed crust (either a radiation or wind crust) would intensify the process, but in any case the development of an iced crust above a layer of sublimating snow (depth hoar) could reasonably be expected. The 1957-58 summer-winter transition in Pit 1 is considered an ideal example of this phenomenon (see enlargement in Fig. 5). The development of more than one summer surface was occasionally observed, as in Pit 3, where two layers of sublimation crystals were formed during the summer of 1956-57. They probably represent early and late summer surfaces respectively.

Ice lenses, glands, pellets, soaked firn, and other obvious melt-water features were not observed. Certain annual layers (marked with asterisks in Table IV) exhibit strongly developed summer surfaces. The average rate of accumulation for these layers is 14.2 cm of water/yr, which agrees well with the actual rate of 14.4 cm water/yr computed for the total 19-m sequence. Variations in the accumulation for the period 1960-1893 are shown in Figure 6.

Density

Figures 7 and 8 illustrate the variations of density with depth. Mean densities of the annual layers are plotted in Figure 7, and mean densities for meter increments in Figure 8. Both profiles reveal a marked change in the rate of densification at a depth of approximately 10 m, and a corresponding density of 0.55 g/cm^3. This change in rate probably reflects an actual change in the densification process. The depth-density profile of Byrd Station has yet to be completely analyzed, and further details of densification mechanisms will be included in a later report. The load-depth curve, computed from depth-density data, is given in Figure 9.

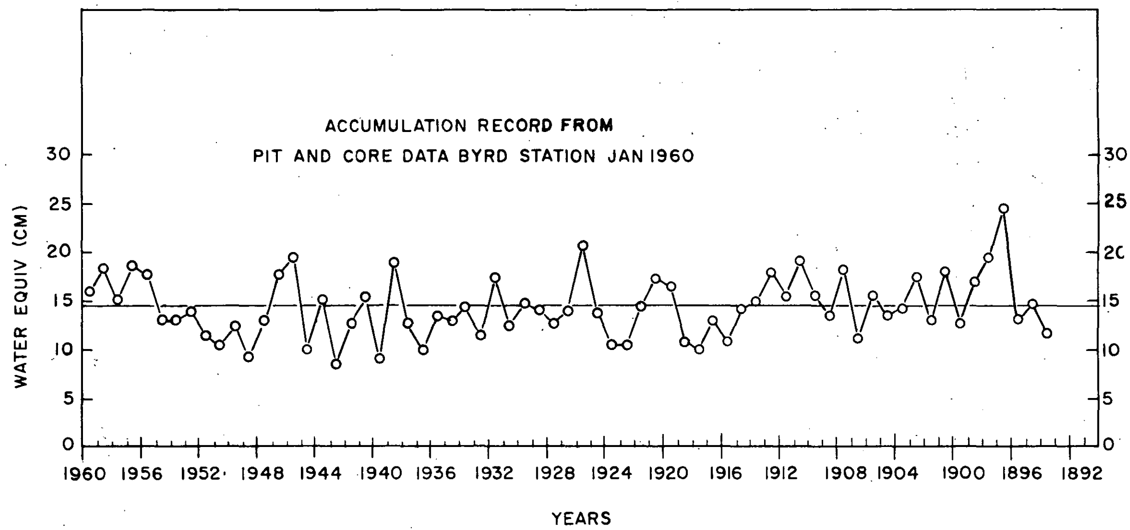


Figure 6. Accumulation at Byrd Station from 1960-1893.

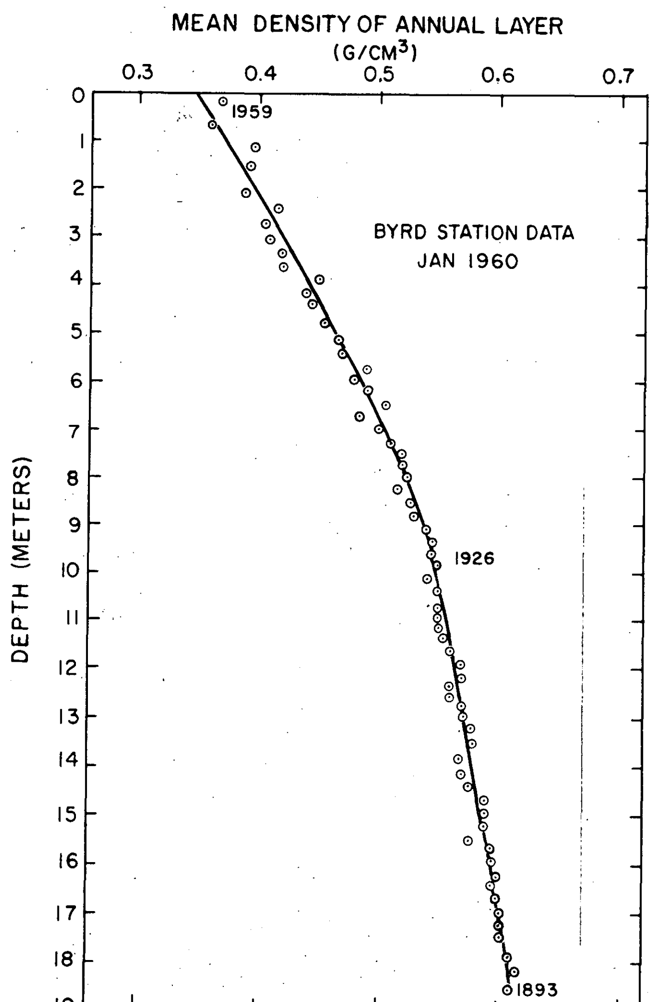


Figure 7. Depth-density curve (annual layers).

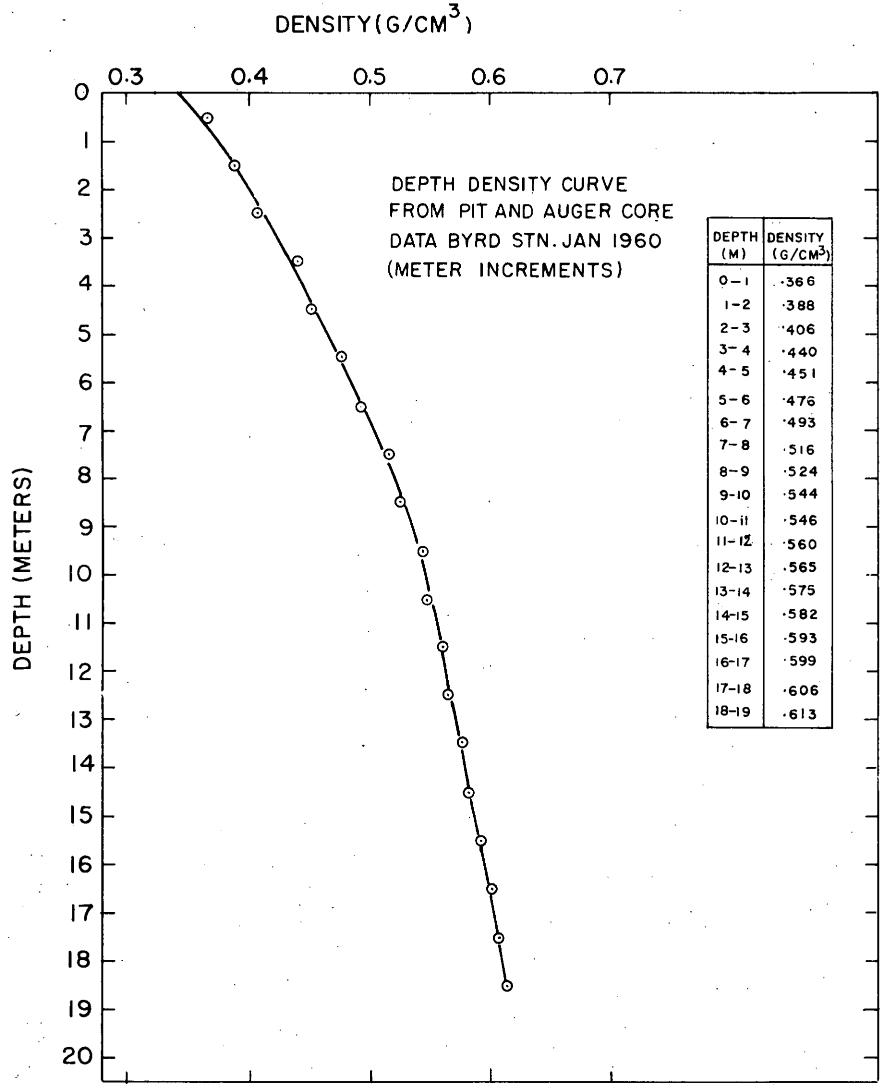
CONCLUSIONS

1. Temperatures below 200 ft appear to have stabilized in the deep hole at Byrd Station. It is not known to what extent the drill casing has affected surrounding snow temperatures, but this might be profitably investigated in a 200-ft uncased hole. The mean annual temperature at Byrd is approximately -28.2C (-18.8F). The temperature decreases to about -28.4C (-19.1F) at 400 ft. Below 400 ft, the temperature decreases almost linearly at a rate of 0.01C/100 ft.

2. The 1960 and 1961 hole diameter data show that closure is accelerating. The strain rate is not proportional to some constant power of the stress, but increases with increasing stress and time of application of stress. Accelerating closure is attributed to some process of continuous recrystallization in ice under high stress.

3. Inclinations (less than 2/3°) have been detected at various depths, but data do not appear to be significant at this stage.

4. Pit measurements and results of a 19-m core study show that since 1893 snow has been accumulating at an average rate of 14.4 cm water/yr at Byrd Station. Annual layering was identified on the basis of detailed stratigraphic studies. Recognition of summer surfaces assisted greatly in the actual dating of annual layers. Depth-density and load-depth profiles were also obtained.



DEPTH (M)	DENSITY (G/CM³)
0-1	.366
1-2	.388
2-3	.406
3-4	.440
4-5	.451
5-6	.476
6-7	.493
7-8	.516
8-9	.524
9-10	.544
10-11	.546
11-12	.560
12-13	.565
13-14	.575
14-15	.582
15-16	.593
16-17	.599
17-18	.606
18-19	.613

Figure 8. Depth-density curve (meter increments).

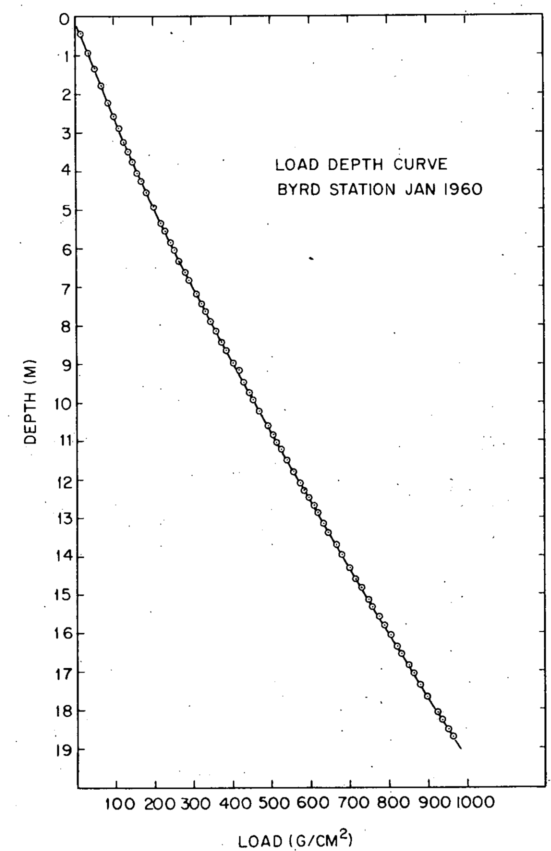


Figure 9. Depth-load curve at Byrd Station.

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