Research Report 197

DEEP CORE STUDIES OF THE ACCUMULATION AND DENSIFICATION OF SNOW AT BYRD STATION AND LITTLE AMERICA V, ANTARCTICA

by

Anthony J. Gow

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PREFACE

This report was prepared by Mr. Anthony J. Gow, Geologist, of the Research Division (Mr. James A. Bender, Chief), U.S. Army Cold Regions Research and Engineering Laboratory.

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SUMMARY

Snow and ice cores from two deep drill holes in Antarctica were studied to determine past records of snow accumulation and density variations with depth in the Antarctic ice sheet. Data on the variation of porosity and ice load with depth were also obtained.

Byrd Station, located on the inland ice of West Antarctica, was the site of the first drill hole, which reached a depth of 309 m in ice estimated to be about 2500 m thick. Detailed analysis of the core stratigraphy to 88.6 m depth showed that the snow has been accumulating at an average rate of 15.6 g cm^{-2} annually since 1549 AD. Apart from a small but persistent decline in accumulation between 1839 and 1954 no major variations in snow accumulation were observed. The total absence of melt layers would indicate that surface air temperatures in the vicinity of Byrd Station have not risen above freezing for the last 1900 years – the estimated age of the ice at 309-m depth.

A second hole was drilled at Little America V at a point less than 3 km from the seaward edge of the Ross Ice Shelf. The ice at this location was about 258 m thick and cores were obtained to within 2 to 3 m of the bottom. No saline ice was encountered in any of the cores and all indications are that the bottom of the Ross Ice Shelf at Little America V is melting rather than accreting sea ice. Studies of core stratigraphy to 39-m depth revealed 105 years of snow deposition; the average rate of accumulation was 22.1 g cm^{-2} yr^{-1}. Occasional periods of intensive melt were observed throughout the stratigraphic sequence but no significant deviations in the accumulation record were detected. Three thin layers of debris, tentatively identified as volcanic ash, were observed at depths of 171, 219 and 223 m respectively. These ashes are thought to have been deposited from volcanoes in Marie Byrd Land more than 2000 years ago. Depth-density and surface elevation data show that the Ross Ice Shelf at Little America V is free floating and almost exactly five-sixths submerged. An anomalous increase in the rate of densification of firn below 35 m is attributed to large horizontal stresses in the ice shelf. At Little America firn transformed into ice at 51 to 52 m after only about 150 years. The same transformation at Byrd Station took nearly 300 years and was accomplished at 64-65 m depth. The densification process in polar snow is discussed and a method of predicting depth-density profiles from mean annual accumulation and temperature data is presented together with examples and other useful applications of the data.

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INTRODUCTION

Snow studies in Antarctica during the International Geophysical Year (1957-58) were confined largely to observations in shallow pits and hand augered holes. At two or three locations, however, these studies were extended to considerable depths in the ice by deep core drilling including two holes drilled by U.S. Army Snow, Ice and Permafrost Research Establishment (now U.S. Army Cold Regions Research and Engineering Laboratory) at Byrd Station and Little America V. Byrd Station, situated on the inland ice of West Antarctica, and Little America V, located near the edge of the floating Ross Ice Shelf (Fig. 1), were chosen because of their contrasting glaciological regimes. In addition to furnishing cores for studying the physical and petrographic properties of the ice at these two locations the holes themselves were also used to measure englacial temperatures and deformation. The deep hole at Byrd Station was drilled during the austral summer of 1957-58 and reached a depth of 309 m in ice estimated to be 2500 m thick. The following summer a second drill hole penetrated 258 m to the bottom of the Ross Ice Shelf at Little America V. Continuous sequences of undisturbed core were recovered from both holes which in the case of the Little America drilling represented the first time that samples had been obtained from the top to the bottom of a polar glacier. Details of the drilling including some preliminary results of core analysis are to be found in Patenaude et al. (1959) and in Ragle et al. (1960).

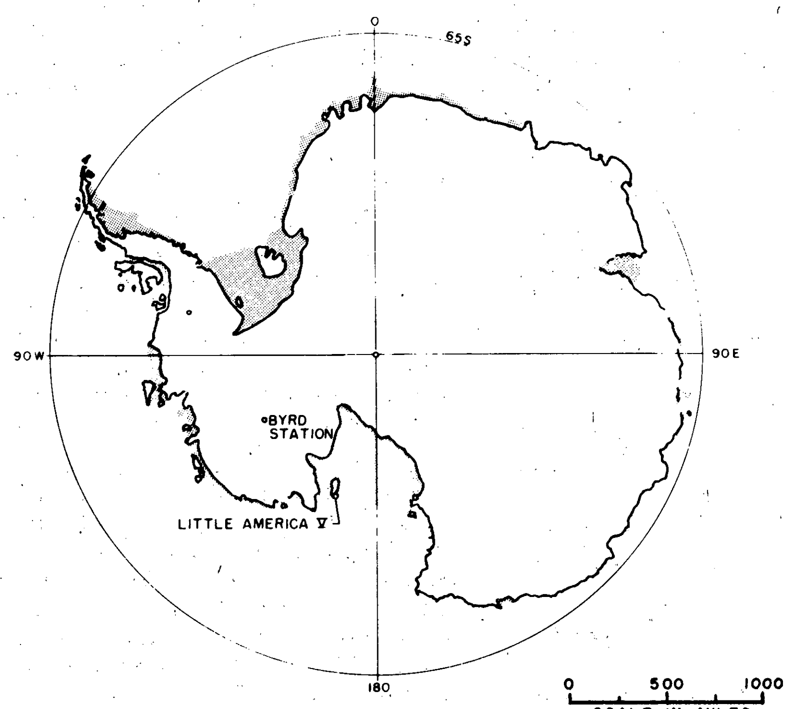


Figure 1. Map of Antarctica showing locations of deep drill holes at Byrd Station and Little America V.

Analyses made so far on cores from Antarctica have included detailed studies of the stratigraphy and accumulation rates, density measurements, crystal structure studies, petrofabric investigations and measurements of electrical conductivity. Preliminary results of some of these analyses have been presented by Bender and Gow (1961) and Gow (1963a, 1964). Results of measurements of the temperature and deformation in the drill hole at Byrd Station have been published by Gow (1963b). Data relating to the particulate content of various sections of core from Byrd Station are to be found in reports by Marshall (1962) and Bader et al. (1965a).

The purposes of this report are to furnish detailed descriptions of the core stratigraphy and to provide details of the accumulation rates based on this stratigraphy; to present the results of density measurements, and discuss the process of densification of snow on polar glaciers and outline a method of predicting density profiles from annual accumulation and mean annual temperature data.

DRILLING OPERATIONS

Location of drill holes

Byrd Station is situated at 80°S, 120°W at an elevation of 1500 m on the grounded ice sheet of West Antarctica. According to Bentley (1964) the ice in the immediate vicinity of Byrd Station is about 2500 m thick.

At Little America V the drill hole was located between the camp site (78° 10'S, 162°13'W in 1958) and Crevasse Valley at an elevation of 43 m above sea level and approximately 3 km from the ice front in Kainan Bay. The principal surface features of the Ross Ice Shelf in the general vicinity of Little America V are shown in Figure 2. The Ross Ice Shelf is essentially free floating at this location. Its thickness at the drill site was 257-8 m and the depth of sea water under it is estimated at nearly 400 m (Crary, 1961).

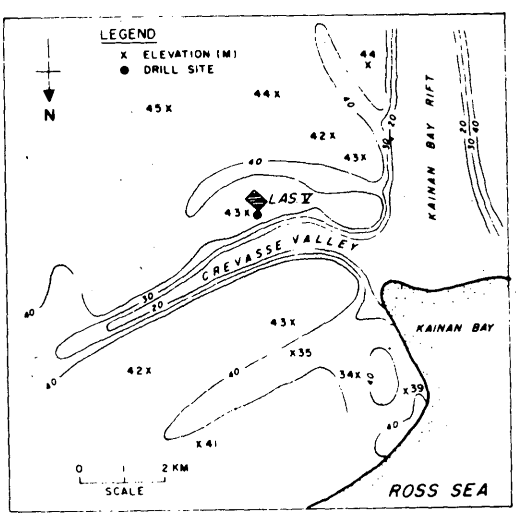


Figure 2. Sketch map of principal surface features of the Ross Ice Shelf at Little America V (adapted from Crary, 1961).

Core drilling

Deep drilling was performed at both locations with a Failing 1500 rotary well-drilling rig specially adapted for coring in ice (Fig. 3). Refrigerated compressed air was used as a drilling fluid. This rig cuts 9.8 cm diam cores from a 14.6 cm diam hole; most of the coring was accomplished with a 6 m long core barrel.

At Byrd Station the first core was cut at a depth of 18.4 m on 20 December 1957. When coring was terminated on 26 January 1958 the hole had been extended to a depth of 309 m with continuous coring throughout. Core recovery amounted to more than 98% of the footage drilled. Excellent cores were obtained in the first 200 m. In a number of runs in this interval unbroken cores up to 5 m in length were recovered from the core barrel. The ice became increasingly brittle below 200 m and the cores began

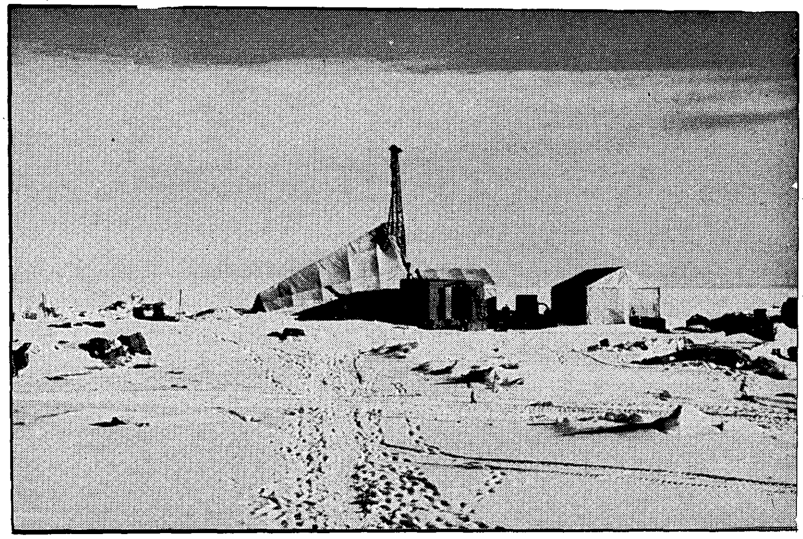


Figure 3. Failing rotary well drilling rig on the drilling site at Byrd Station. The height of the derrick is approximately 12 m.

to develop numerous fractures. This fracturing which invariably occurred in planes more or less normal to the axis of the core was triggered most probably by vibrations in the drill string after the core had been cut from its confining environment. In the deepest cores these fractures were usually spaced less than a centimeter apart but because of a certain amount of healing most of these cores tended to "hang together" in pieces up to 0.5 m in length. Variations in the condition of the cores with increasing depth in the ice sheet are demonstrated in Figure 4.

Coring at Little America V was begun at 6.7-m depth on 31 October 1958 and was continued without break to a depth of 255 m. At 249-m depth the hole was filled with diesel fuel after it had become evident from temperature measurements that the drilling had penetrated to within approximately 10 m of shelf bottom. Sea water entered the hole at 255-m depth. The ice shelf was estimated from temperature measurements to be 257-258 m thick at the drill site so that the sea water must have risen up a crack that formed between hole bottom and the bottom of the shelf. Since no trace of sea ice was observed in any of the cores it is concluded that the Ross Ice Shelf at Little America V is entirely glacial in origin.

Some mechanical breakage of cores occurred below 100 m but gross cross-fracturing due to stress relief did not occur until 160-170 m depth. A remarkable improvement in the condition of the ice was observed after the drill hole had been loaded with diesel fuel. Numerous cracks were observed on the surface of the core but they did not penetrate more than a centimeter beneath the surface. After all attempts to core the sea-ice plug below 200 m had failed because of repeated blocking off by ice particles of the fluid circulation in the core barrel it was decided to discontinue drilling on 17 December 1958. The core yield represented more than 98% of the footage cored and as indicated in the log of coring losses (Fig. 5) most of the loss was sustained in Run No. 20 when a new type of bit was being tested.

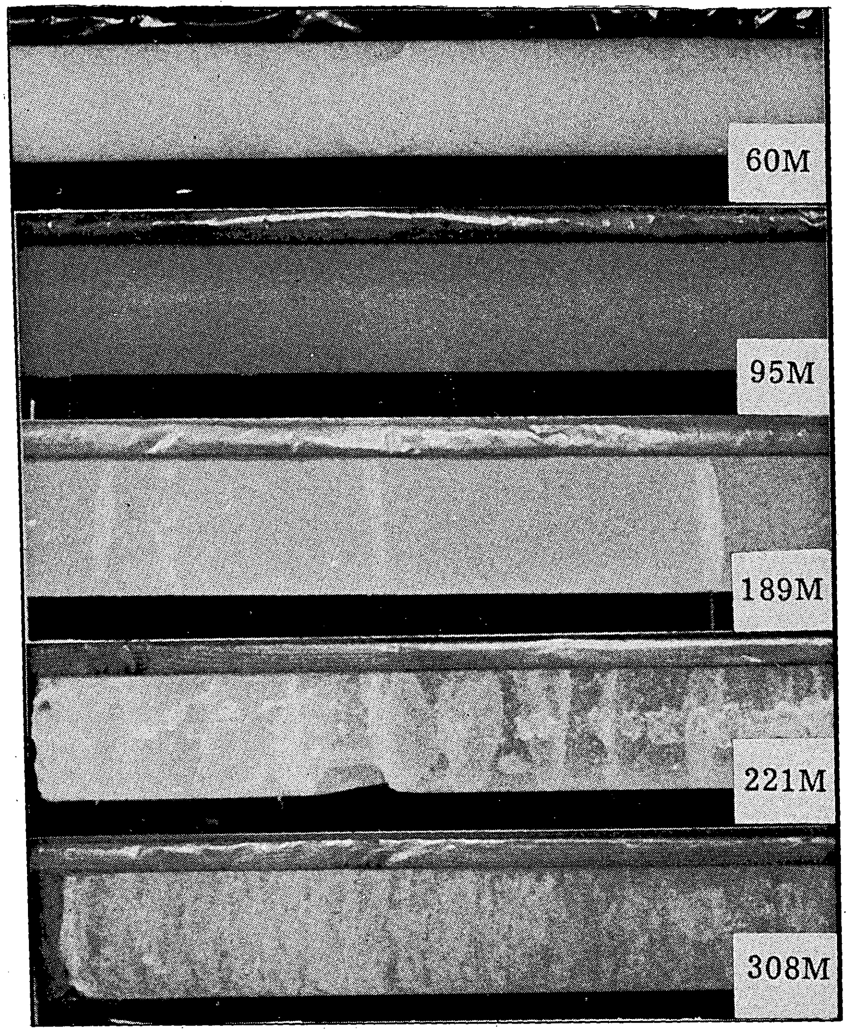


Figure 4. Sequence of ice cores from Byrd Station, Antarctica, showing variations in the condition of the core with increasing depth. Considerable cracking of the ice occurs in cores from below 200 m in unloaded holes.

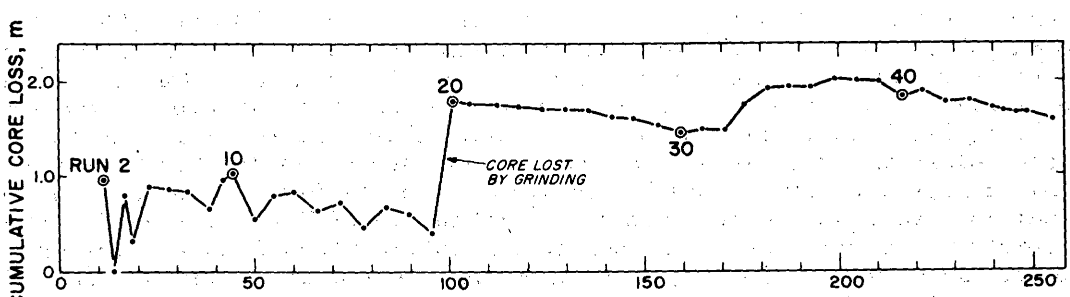


Figure 5. Log of cumulative core loss in the drill hole at Little America V. 98% of drilled core was recovered.

The Failing 1500 rig cannot be used successfully with compressed air circulation below about 450 m because of excessive shattering of the cores. This shattering can be attributed almost solely to rapid release of stresses in the ice following its removal from high confining pressures. However, the use of a liquid such as diesel oil to load the hole during drilling should greatly extend the coring depth. Already, reasonably good quality cores have been obtained with an electrodrill from a depth of more than 1000 m in the Greenland ice sheet at Camp Century. Hopefully, the electrodrill will be used to core holes to the bottom of both the Greenland and Antarctic ice sheets.* For a more detailed account of the technical aspects of ice coring in Antarctica and Greenland the interested reader is referred to Lange (in press).

CORE ANALYSIS

Core examination and preliminary measurements

After their removal from the core barrel the ice cores were carefully logged and then transferred to a trough where they were examined megascopically in transmitted light from a fluorescent light source placed directly beneath the core. This technique revealed even the subtlest of stratigraphic variations. At Byrd Station the exact position of a stratigraphic break was determined with a measuring tape laid along the edge of the trough. This measurement together with a brief description of the relevant stratigraphy was then carefully recorded. At Little America V it was found more expedient to transfer these data directly onto a roll of graph paper fed between reels placed at each end of the light table. At Byrd Station distinctive layering, particularly that associated with iced crusts, could still be discerned at 100 m depth. At Little America V, however, visual stratigraphy became very obscure beyond a depth of 50 m and only the occasional layer of clear ice, formed from refrozen melt water, could be detected in transmitted light below 100 m.

After the stratigraphy of a piece of core had been examined and recorded the core was cut into several pieces at stratigraphic breaks and the density of each piece determined. Upon completion of the stratigraphic and density measurements the cores were wrapped in plastic tubing and then placed in 1.5 m long core tubes. Finally the cores were split lengthwise with a bandsaw. One-half of the core was retained at the drill site and the other half was returned to USA CRREL for additional analysis.

In addition to the deep drill cores supplementary studies were made in shallow snow pits and on cores obtained by hand augering to depths of 18-19 m.

Core stratigraphy - General remarks

The primary objective of stratigraphic studies in Antarctica is the identification of annual increments of accumulation. Even a cursory examination of the wall of a shallow pit dug in the snow will invariably reveal the existence of a layered sequence. This layering or stratification results from the discontinuous accumulation of snow at the surface. Each layer can be said to be composed of an aggregate of ice grains whose physical properties such as density, hardness, cohesion and texture reflect the conditions of deposition and early

*During July 1966 the electrodrill penetrated the bottom of the ice sheet at Camp Century. The thickness of ice was 1389 m (Hansen and Langway, 1966).

post-depositional change. This layering tends to be accentuated further by the existence of crusted surfaces between layers. Most of these crusts are formed at the surface by sun and/or wind when the surface is not accumulating snow.

The art of interpreting annual layering depends not so much on a grossly detailed analysis of the entire stratigraphic section but more on the identification of layers or groups of layers formed under specific conditions at specific times of the year. The first to demonstrate the effectiveness of these methods in Antarctica was Schytt (1958) who, relying largely on the sharp change in the grain size of the snow at the fall-winter boundary, was able to identify annual layering to the bottom of an 11-m pit at Maudheim. This work by Schytt has served as a model for later workers and essentially the same techniques were used in the present study for analyzing the stratigraphy of the deep cores to a depth of 88.56 m at Byrd Station and to 47.94-m depth at Little America V.

Core stratigraphy at Byrd Station

At Byrd Station delineation of the annual layering was usually facilitated by the identification of coarse grained summer layers overlain directly by fine grained snows of the ensuing fall or winter. Frequently this contact is further emphasized by a layer of loosely aggregated grains and crystals – depth hoar. Such layers of depth hoar were rarely thicker than 3 cm, but individual grains and crystals may measure as much as 5 mm in diameter. The average size of grains in coarse grained summer layers was between 1.0 and 1.5 mm but in the finer grained winter layers the grains were generally less than 0.5 mm in diameter. Much of the so-called summer layer was probably deposited during the winter; its subsequent coarsening of grain can be attributed to metamorphism during the ensuing summer. The extent of this metamorphism will vary from year to year, depending on the thickness of the winter layer and the duration of high temperatures during summer. In some years the winter layer appeared to have been entirely recrystallized.

Crusts which occur at frequent intervals in the stratigraphy proved particularly valuable in unraveling the annual accumulation in deeper cores. These included wind crusts (white granular crusts generally less than 0.5 mm thick) that are found in both summer and winter layers, and iced crusts (layers of bubble-free ice up to 1.0 mm thick). Iced crusts are especially useful since they tend to be associated with late summer surfaces and can be used to extend the accumulation record beyond the depth of normally resolvable stratigraphy. Occasionally iced crusts were observed in winter layers. These crusts were probably formed as a result of direct freezing of moist air onto the snow surface – glaze.

Glaze can form at any time of the year but most of the iced crusts found in the summer layers appear to have originated either by insolation to form sun crusts (sometimes referred to as radiation crusts) or by sublimation in association with thin layers of depth hoar formed just beneath the snow surface – sublimation crusts. Many of these subsurface crusts appear to have been molded upon pre-existing wind crusts and they probably would not have formed at all in the absence of wind crusted surfaces. The formation of sun crusts must involve some local radiational melting but sublimation crusts at Byrd Station are probably always formed at sub-melting temperatures.

Conditions favoring both the growth of depth hoar crystals and sublimation crusts are most likely to occur during the fall season when temperatures at the surface begin to drop rapidly, giving rise to fairly steep gradients in the surface snow layers. At this time of the year any movement of water vapor through the snow will be upward in response to this temperature gradient, which even in the absence of wind can produce considerable instability within the interstitial air. This ~~causes~~ convection ~~in the near-surface snow~~ layers ~~which is very~~ important because diffusion alone is probably not very effective at these vapor pressure gradients (Bader, 1939; Benson, 1962, p. 32). At Byrd Station convection does not occur from the temperature distribution in spring so that any abundant growth of depth hoar is necessarily restricted to the fall and winter.

Initially the upward migrating water vapor would either escape into the atmosphere or condense in the interstices between the grains of cold snow that may have been deposited on top of the insolated summer snow. In the event that the overlying snow should become impermeable any further condensation of water vapor would tend to take place at the junction between the warm and cold layers of snow. If these two layers were originally separated by some sort of crust this would impede the upward moving water vapor even more effectively, in which case an iced crust could almost certainly be expected to develop above the layer of depth hoar. The very porous and frequently vug-like character of the depth hoar is compatible only with a net loss of material, some of which probably contributes to the growth of the crust overlying the depth hoar. Useful discussions of the factors influencing the growth of depth hoar are to be found in Schytt (1958), Benson (1959 and 1962), and Bader (1962a) but it must be admitted that the actual mechanisms involved in the formation of depth hoar are as yet incompletely understood.

An examination of a number of ice crusts in thin section has shown that the great majority of crusts of this type are composed of just a single layer of equidimensional bubble-free crystals with their c-axes oriented vertically. Because of their clear glass-like appearance these crusts could still be detected in cores from as deep as 240 m. Since iced crusts tend to be associated with summer and fall layers extensive use was made of them (in combination with other layers) in extending the stratigraphic dating of the cores to a depth of nearly 89 m at Byrd Station. This greatly exceeds the depth to which the grosser elements of the stratigraphy could ever be sensibly resolved on their own. Apart from the iced crusts not a single layer or lens of ice, or any other evidence of melting, was observed in any of the cores from Byrd Station. Cores were also checked carefully for dirt layers but none were observed.

No shallow pits were dug at Byrd Station during the deep drilling in 1957-58 because of the delays in getting underway with the drilling. Hand augered cores were obtained to a depth of 21 m immediately after the main drilling had terminated. These cores were returned to the United States for further analysis but because of uncertainties as to the orientation of a number of the cores it was decided not to use them for stratigraphic studies. Additional studies were made 2 years later when three shallow pits were dug and analyzed in January 1960, and the stratigraphy at one of these pits was extended by coring to a depth of 18.69 m. Snow at this depth was estimated to have been deposited on the surface about the year 1894. The first deep core in 1957-58 was obtained from a depth of 18.36 m but because of the 2-year overlap some allowance must be made for this in the stratigraphic record of the deep drill cores. Two years' accumulation (with allowance for compaction) would drop the 18.36-m level of the deep drill core to close to 19.0 m below the 1960 surface. This would place the top of the deep core more than 30 cm below the bottom of the 1960 core. In order to bridge this gap a prominent crust at 19.03-m depth in the deep drill core was arbitrarily selected as the 1892 summer surface.

The stratigraphy observed in three pits at Byrd Station in January 1960 is presented in Figure 6. Details of the stratigraphy observed in the hand augered cores together with a number of representative sections of deep core stratigraphy are presented in Figure 7a. A detailed tabulation of data is given in Appendix A. It should be noted that only the diagnostic crusts and discontinuities are recorded in the sections of deep drill core in Figure 7b. The dates refer to the late summer (February) surfaces as interpreted from the stratigraphy, and the product of the thickness and average density of the accumulation between two such surfaces represents a year's accumulation in g cm^{-2} water equivalent.

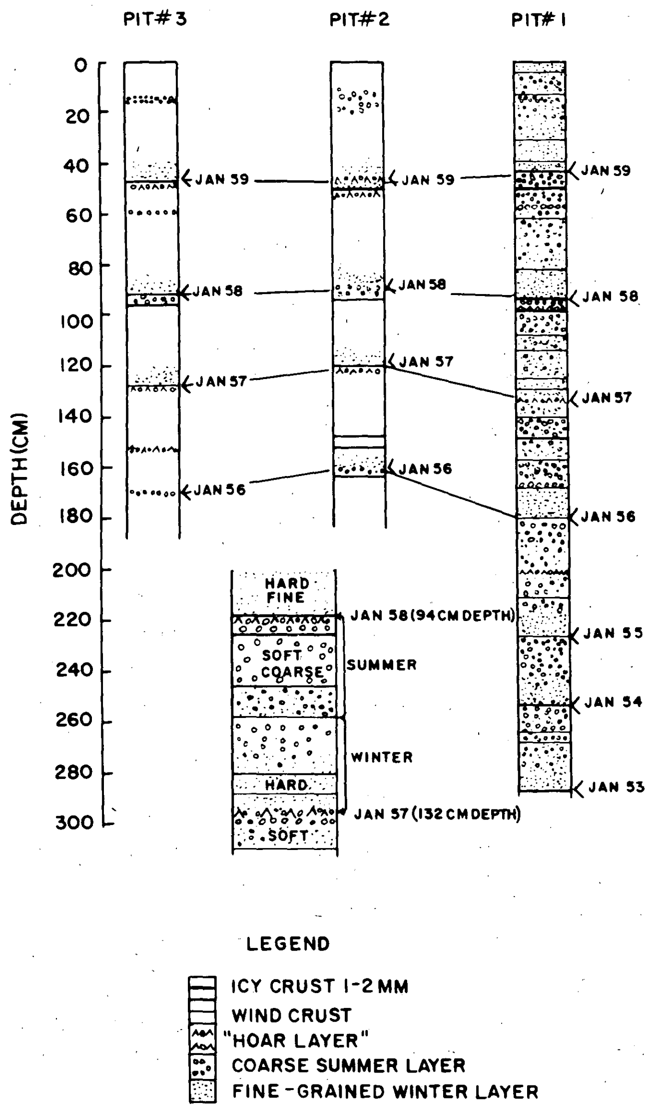


Figure 6. Stratigraphic data from three pits at Byrd Station, January 1960. A typical sequence of layers in a single year's accumulation at pit 1 is shown in the inset.

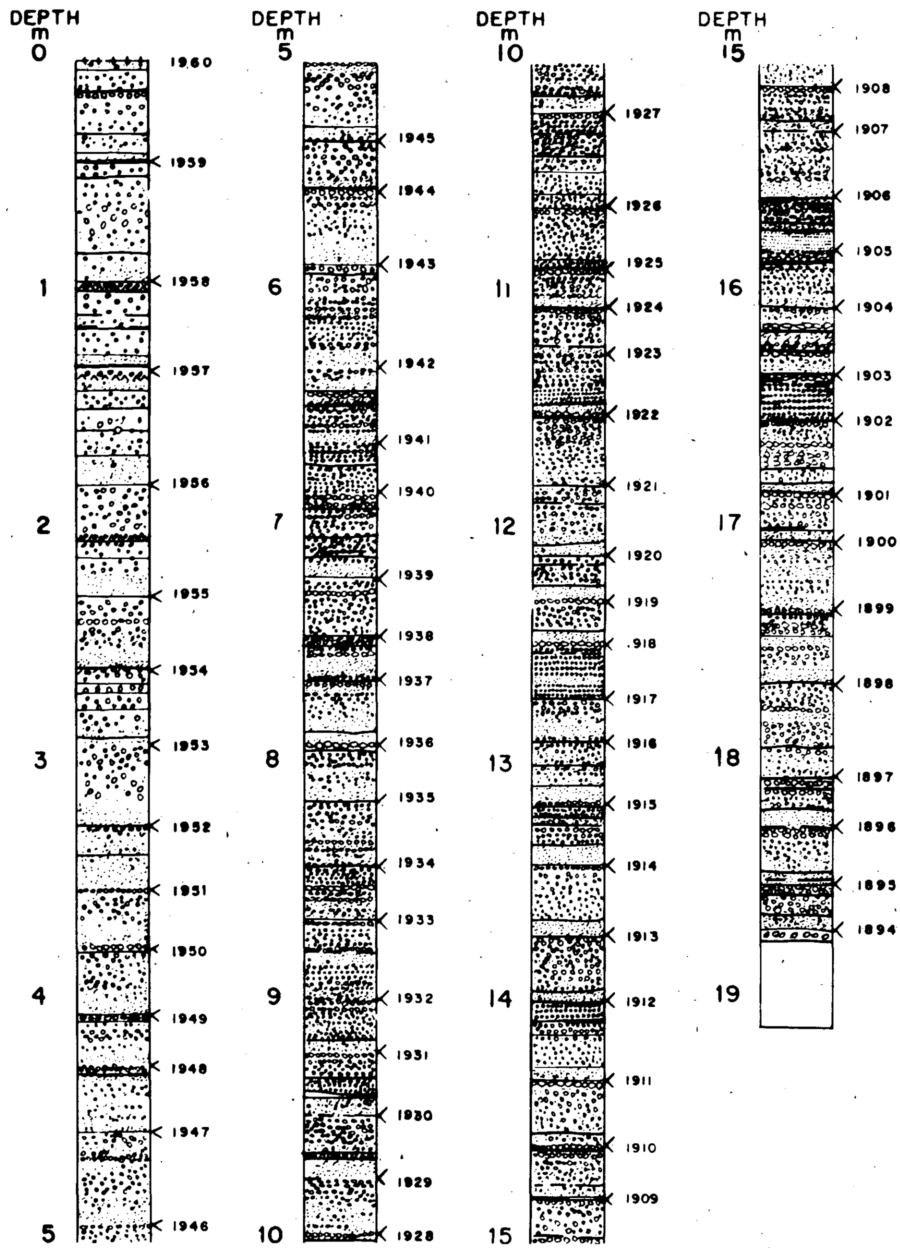


Figure 7a. Snow wall and core stratigraphy from pit 1, Byrd Station. See Figure 6 for explanation of symbols. The symbols in these and subsequent figures are purely representational and do not reflect actual sizes of grains in the individual layers.

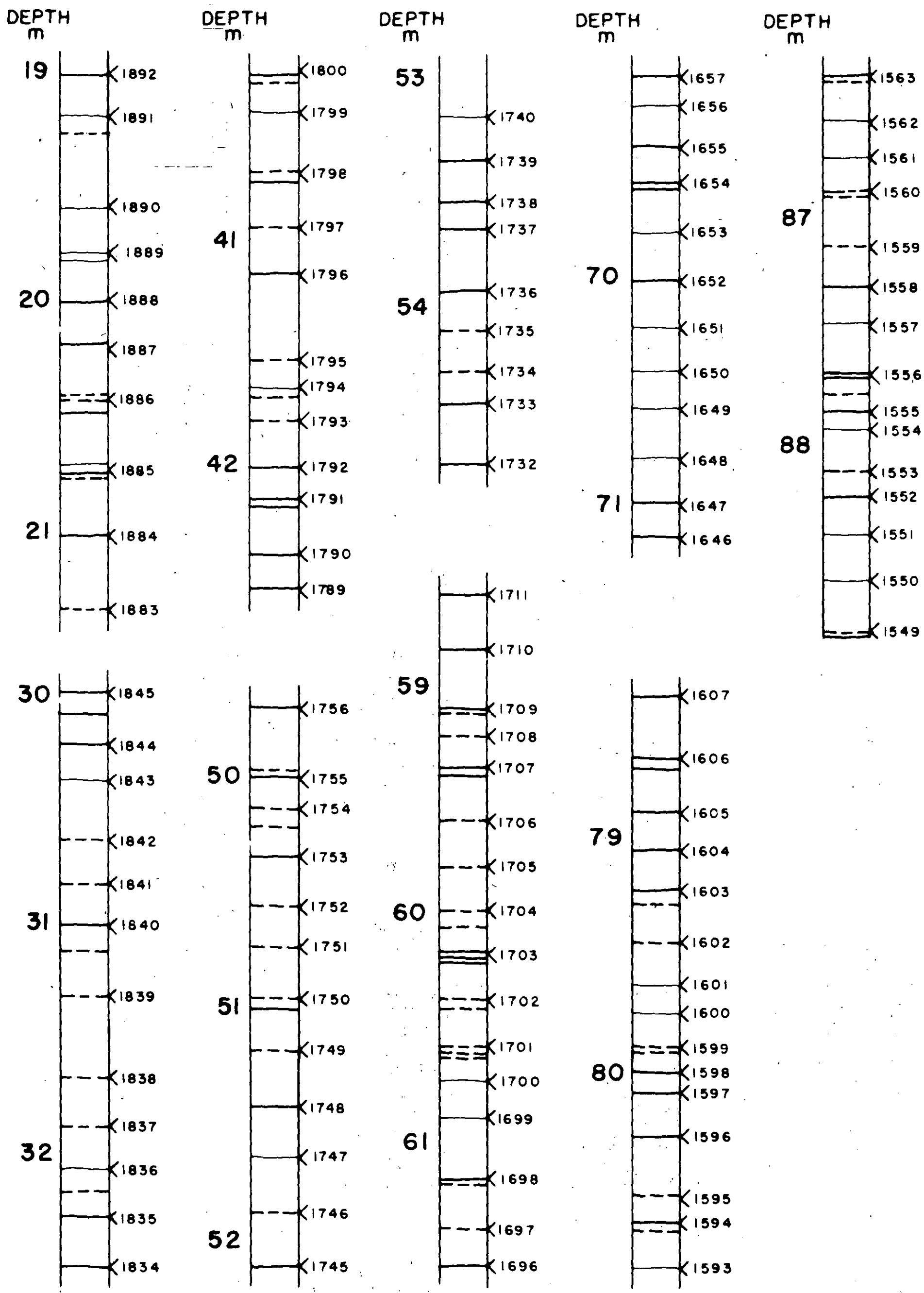


Figure 7b. Some representative sections of stratigraphically dated core from the deep drill hole at Byrd Station. Only the diagnostic crusts and discontinuities used for identifying the annual layers are indicated here.

Core stratigraphy at Little America V

At Little America V the summer snow layers were frequently associated with ice crusts, pellets and ice lenses and less frequently with ice layers and ice glands. The relatively fine grained winter layers tended to be more homogeneously packed than the summer deposits, which, quite apart from any association with the above described melt water features, often possessed a "soaked" appearance when viewed in transmitted light. In general, the Little America V cores were somewhat simpler to analyze than those from Byrd Station. However, the dating could not be extended as deeply at Little America V because of the very rapid obliteration of decipherable stratigraphy below 50 m due in large part apparently to the effects of considerable deformation* in the upper part of the ice shelf.

The unconformable contact between the coarse grained summer layer and the overlying accumulation of the ensuing fall and/or winter was used for delineating annual layers. As at Byrd Station this contact zone was frequently accentuated by the growth of a thin layer of depth hoar. Grain sizes differed little from those observed at Byrd Station, with summer grains averaging between 1 and 2 mm in diameter and winter grains generally averaging less than 0.5 mm.

Recent records of accumulation were obtained at three widely separated pits. At pit no. 1 this record was extended to a depth of 17.59 m with the aid of hand augered cores, which provided considerable overlap with cores from the deep drill hole. These two cores were then successfully correlated on the basis of prominent melt zones located at approximately the same depth (10 m) in both cores (see Fig. 8a and 8b for pit and core stratigraphy and correlated sections). According to the stratigraphic measurements on the hand augered cores this melting occurred during the summer of 1937-38. The section of deep drill core extending from 10 m to 6.7 m was then updated independently of the hand augered core and the two analyses were found to agree almost perfectly. Another prominent melt zone was observed at 14.5-m depth in the hand drilled cores. This melting was estimated to have occurred during the 1927-28 summer and it can probably be correlated with the ice layers located between 13.75 and 14.12 m in the deep cores which were independently dated as having formed during the 1926-27 summer. Further analysis of the hand augered cores placed the 1919 summer (February) surface at 17.59 m. The corresponding date for the deep drill cores was located at 17.76 m. This 17 cm overlap was included in the accumulation for the year 1918 before transferring to the deep drill cores to continue stratigraphic studies. The stratigraphic analysis was then extended without break to a depth of 38.86 m (Fig. 9). The snow at this depth was estimated to have been deposited on the surface of the Ross Ice Shelf about the year 1855, i.e. it is now overlain by 104 years of accumulated snow.

The stratigraphy became increasingly difficult to interpret below 39 m and although interpolations were possible down to 47.94 m (see Fig. 9), it was not possible to identify annual stratification below this depth because of the rapid obliteration of diagnostic layering by recrystallization. The firn at 47.94 m was estimated to be about 133 years old, i.e., it fell as snow about the year 1825. The stratigraphic columns presented in Figures 8 and 9 are dated in exactly the same way as those at Byrd Station. A detailed tabulation of accumulation data from the Ross Ice Shelf cores is given in Appendix **A.**

*The evidence for this is discussed more fully in later sections of this paper.

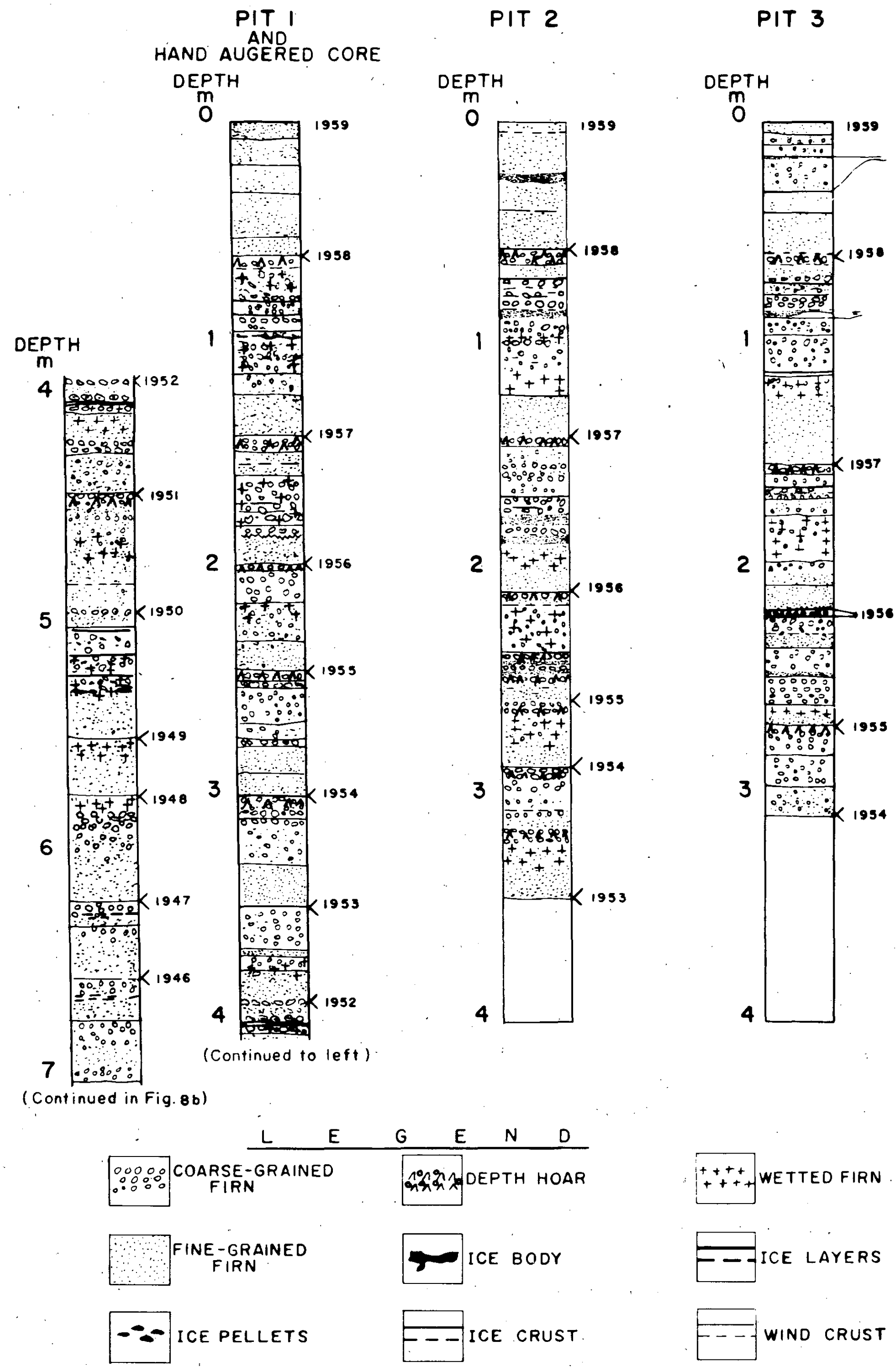


Figure 8a. Stratigraphically dated sections at three snow pits at Little America V.

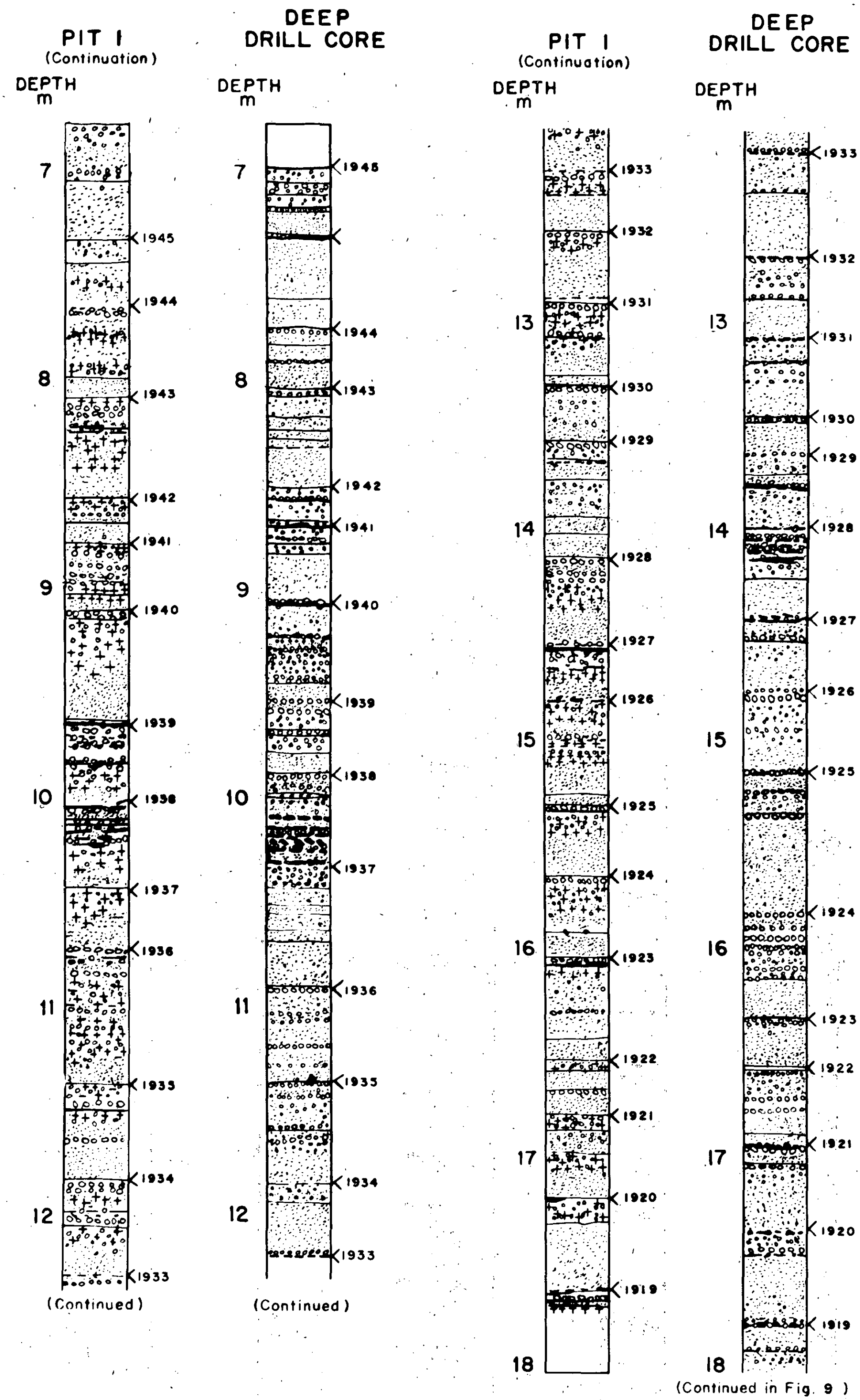


Figure 8b. Correlated sequences of core from the hand augered hole and the deep drill hole at Little America V. Stratigraphic symbols are the same as for Figure 8a.

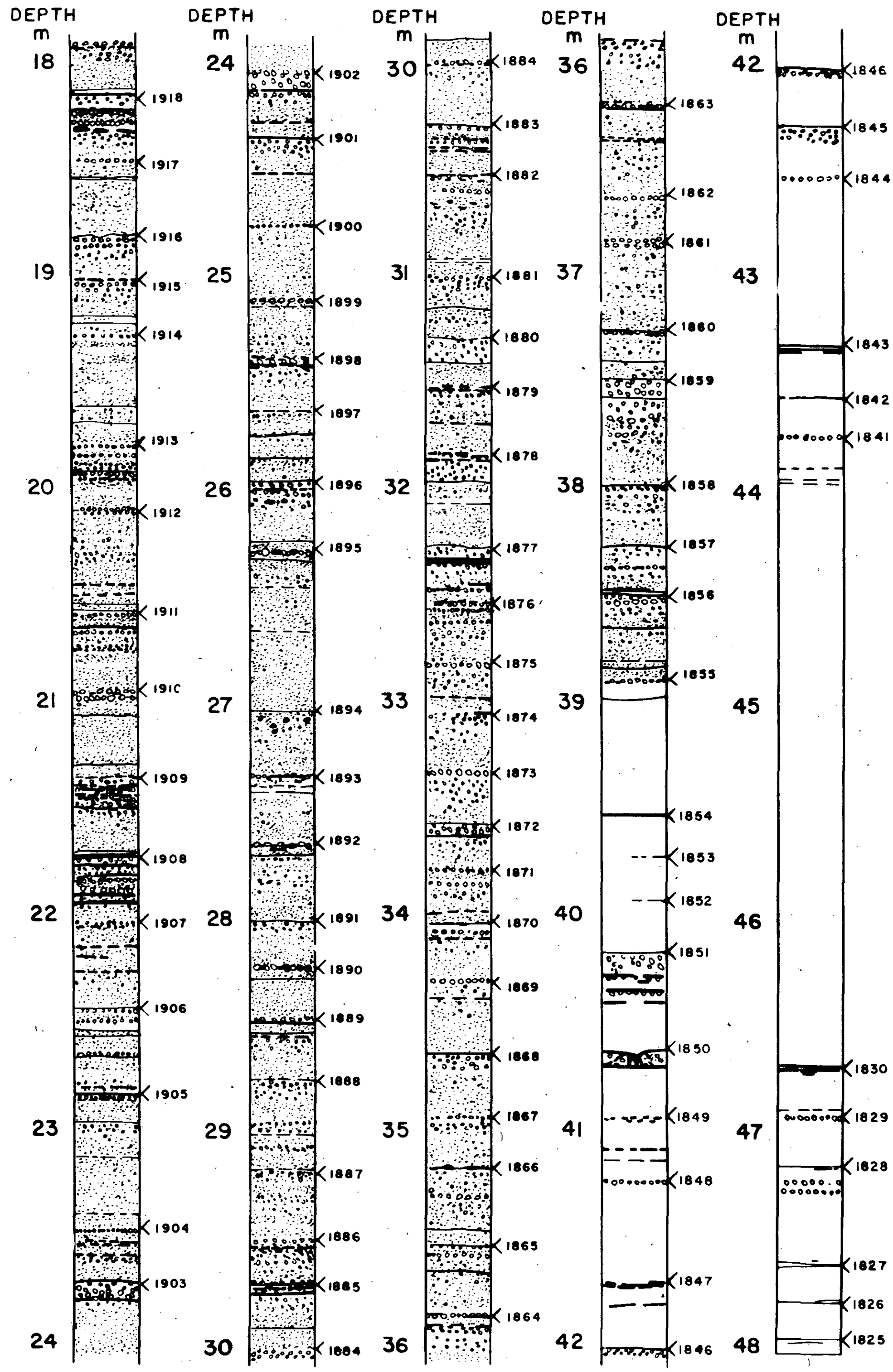


Figure 9. Continuation of stratigraphy of cores from the deep drill hole, Little America V, Ross Ice Shelf, Antarctica. See Figure 8a for explanation of symbols.

Density measurements at Byrd Station

At Byrd Station continuous density measurements were made to a depth of 100 m. More than 1000 cylindrical core samples ranging in length from 1 to 25 cm were measured. The volume-mass method was used to determine densities to 64-m depth – the depth at which the firn at Byrd Station transforms into bubbly ice. With this method the accuracy is probably no better than ± 0.003 g cm^{-3}. The densities of impermeable ice samples from below 64 m were determined by hydrostatic weighing in highly purified isooctane of density 0.7160 g cm^{-3} at -10 C. With this technique densities can be measured to an accuracy of at least ± 0.0003 g cm^{-3}. Additional measurements were made on more than 100 samples from between 100 and 308 m. Results of these measurements are presented in Figures 10 and 11 and Appendix B. All density values from below 64 m have been corrected for the *in situ* temperature of -28 C.

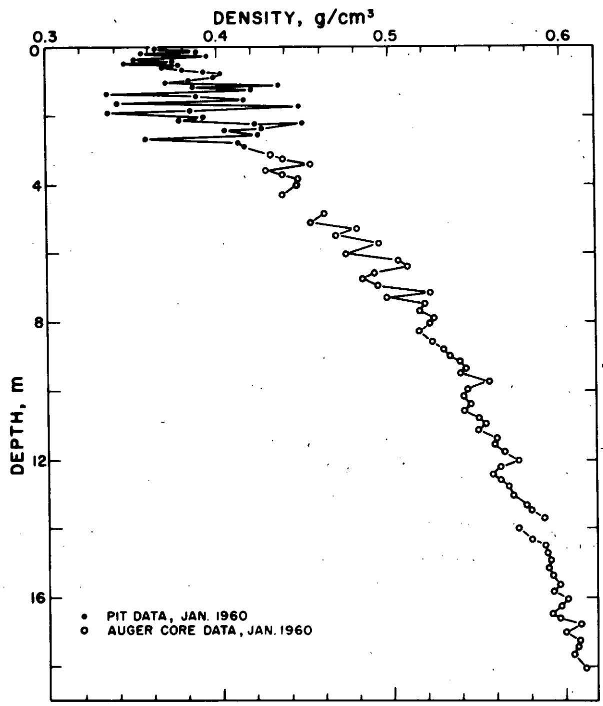


Figure 10. Plot of individual snow densities to 18.1-m depth at Byrd Station.

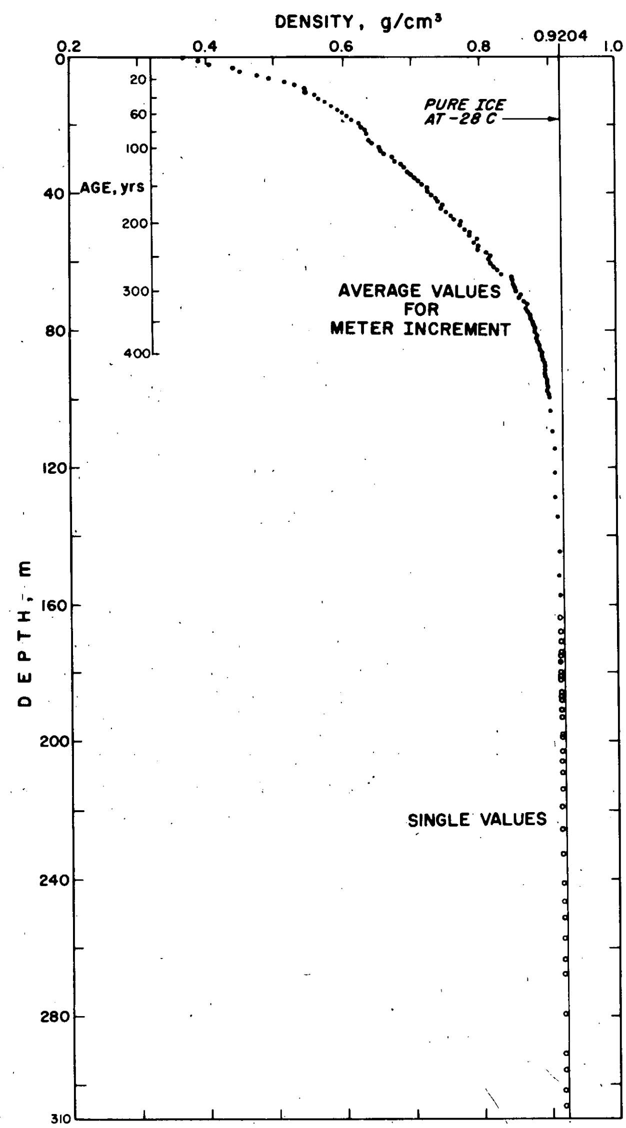


Figure 11. Depth-density profile from surface to 307 m at Byrd Station.

Density measurements at Little America V

Continuous measurements of density were conducted to 52 m, the depth at which firn transforms into bubbly ice at Little America V. Core samples averaged between 10 and 15 cm in length. Approximately 600 pieces of core were measured including 100 samples of ice whose densities were determined very accurately by hydrostatic weighing in isooctane. All ice densities have been corrected for *in situ* temperatures which increased from -21.5C at 52 m to approximately -3C at 255 m, i.e. within 3 m of shelf bottom. The results of density measurements at Little America V are given in Figures 12 and 13 and Appendix B.

Measurements of porosity and load

An accurately measured density profile also permits calculation of two additional parameters, porosity and load. The porosity (n) at any depth can be calculated according to the relation

$$n = 1 - \frac{\gamma_{st}}{\gamma_{it}}$$

where γ_{st} is the measured density at the *in situ* temperature t and γ_{it} is the density of pure bubble-free ice at the same temperature. The depth-porosity curves for both Byrd Station and Little America V are presented in Figure 14. Some individual values from below 130 m (porosities less than 1%) are also plotted.

The load (overburden pressure) can be obtained by integrating the depth-density curve, i.e., if the density can be expressed as some function of depth then the load σ at any depth h can be represented by an equation of the form

$$\sigma = \int_0^h \gamma(h)\, dh.$$

In practice, however, this can be closely approximated by simply taking the average density values for meter increments (say) and then summing to the desired depth. Smaller increments can be used, as was actually the case in the upper layers of firn and ice at Little America V and Byrd Station when water equivalents for each annual layer were being calculated. (These data are included in the columns of total accumulation in Appendix A.) Data from deeper cores are given in Appendix C and the depth load curves from both locations are presented in Figure 15.

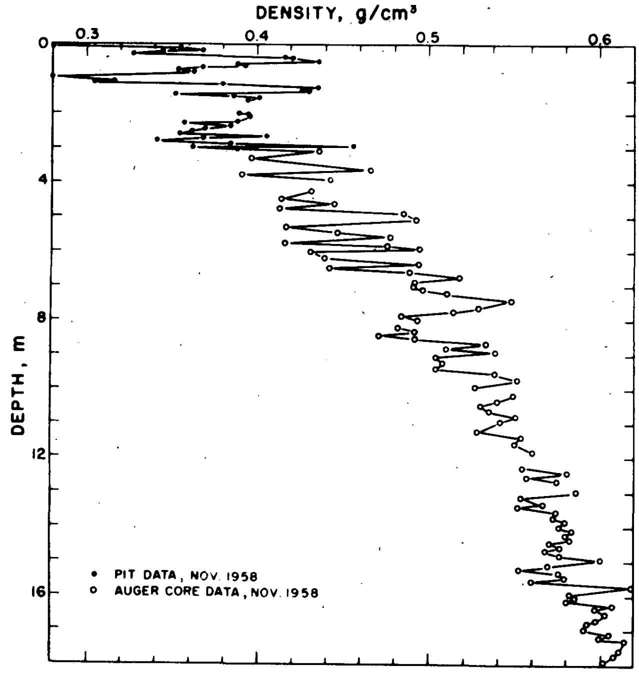


Figure 12. Plot of individual snow densities to a depth of 18.0 m in the Ross Ice Shelf at Little America V.

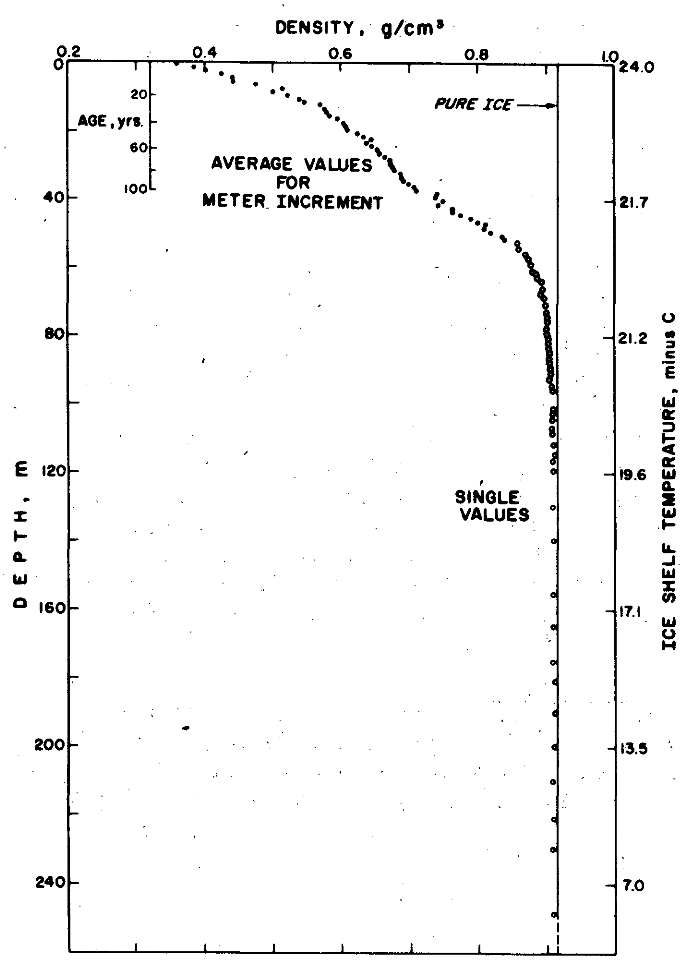


Figure 13. Depth-density profile from the surface to the bottom of the Ross Ice Shelf at Little America V.

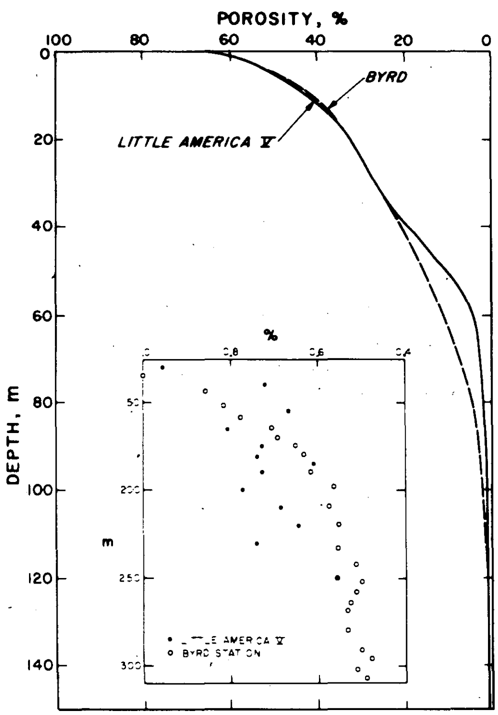


Figure 14. Depth-porosity curves for Byrd Station and Little America V, Antarctica. Individual values from below 130 m are included in the inset figure.

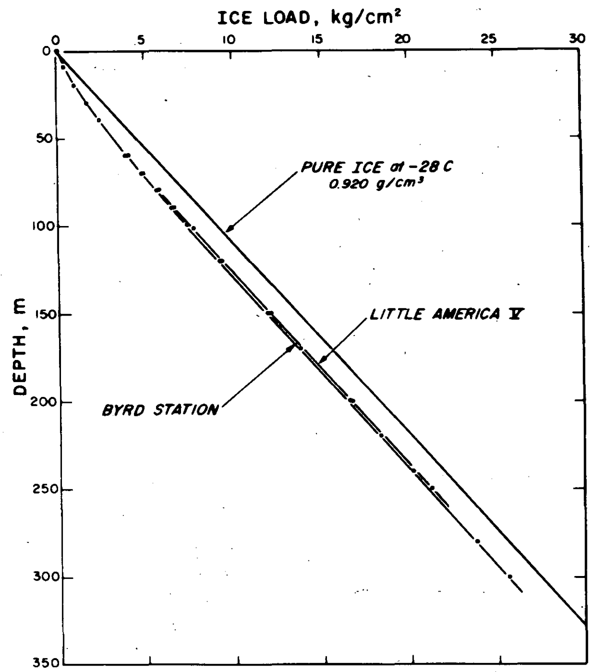


Figure 15. Depth-load curves from Byrd Station and Little America V, Antarctica.

RESULTS AND DISCUSSION

Snow accumulation at Byrd Station

At Byrd Station* accumulation has been measured at stakes since the beginning of the IGY (1957). Anderson (1958) obtained an average value of 41.7 cm snow for the period 12 March 1957 - 28 January 1958 which if extrapolated to one calendar year is equivalent to about 47 cm snow or 16 to 17 cm^{-2} yr^{-1}. During 1958 and 1959 Long (1961) and Pirrit and Doumani (1960) measured accumulation rates of approximately 18 g cm^{-2} yr^{-1} at 100 stakes. More recent measurements by Shimizu (1964) at the same stakes for the period 24 November 1960 - 9 February 1962 yielded a somewhat lower accumulation of 13.3 g cm^{-2} yr^{-1} and according to Koerner (1964) the average accumulation at all stakes at Byrd Station for the period 1957-63 has been 14.2 g cm^{-2} yr^{-1}. These measurements compare very favorably with accumulation records obtained at the three snow pits in 1960 (Table I).

*The data given above were all obtained in the vicinity of Old Byrd Station which was abandoned in 1961. Measurements of snow accumulation at the New Byrd Station, located approximately 10 km east of the original base, show a somewhat smaller rate of accumulation – 11 g cm^{-2} yr^{-1} over the past 3 years (Gow and Rowland, 1965).

Table I. Accumulation at snow pits, Byrd Station.

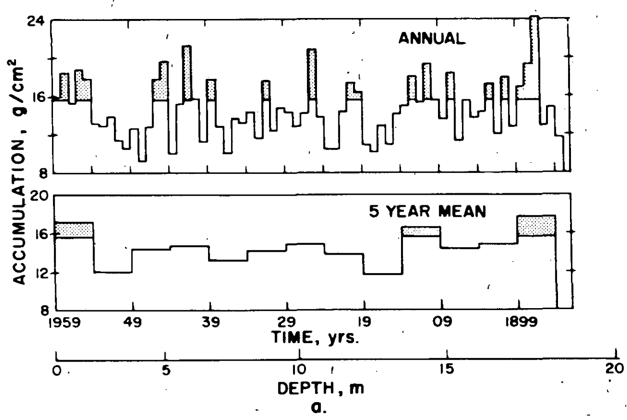
Year	Accumulation ($g\ cm^{-2}\ yr^{-1}$) Pit 1	Pit 2	Pit 3
1959	15.9	17.0	17.4
1958	18.4	15.7	15.8
1957	15.1	13.7	14.6
1956	18.8	14.8	15.1
Average	17.1	15.3	15.7

Stratigraphic studies of cores to a depth of 88.56 m indicate that ice at this depth was originally deposited on the surface as snow about the year 1549. This record of snow deposition extending back more than 410 years represents an average rate of accumulation of 15.6 $g\ cm^{-2}\ yr^{-1}$ (see Appendix A for detailed tabulation of these data). The results are also presented graphically in Figure 16. It can be seen from these results that for the period 1549-1839 there appears to have been no significant variation in the pattern of accumulation. Subsequently however the overall accumulation has declined somewhat including two periods, 1839-1879 and 1914-1954, when accumulation dipped appreciably. Between 1892 and 1959 the accumulation ranged from 24.4 to 9.3 $g\ cm^{-2}\ yr^{-1}$. For the past few years accumulation appears to have been slightly higher than average. An accumulation rate of 15-16 $g\ cm^{-2}\ yr^{-1}$ appears to be about average for West Antarctica, but it is more than double the accumulation observed in areas of the same latitude in East Antarctica where the ice sheet is considerably higher and colder.

Attempts to measure accumulation rates in deep cores by use of the stable isotopes have not proved too fruitful. O^{18}/O^{16} analyses of several lengths of cores from various depths all indicate accumulations in excess of 35 $g\ cm^{-2}\ yr^{-1}$ (Epstein et al., 1963), which is more than double the accumulation measured stratigraphically. An almost identical result was obtained with samples from 10.50 - 12.50-m depth in the deep pit at Byrd Station. This figure of 35 $g\ cm^{-2}\ yr^{-1}$ seems much too high, at least as an average value of the accumulation rate.

It might be noted here that the observed rate of change of firn density with depth at Byrd Station is not compatible at all with such an excessive rate of accumulation, but it is entirely compatible with the much smaller accumulation (15-16 $g\ cm^{-2}\ yr^{-1}$) derived from the stratigraphy of deep cores and confirmed by recent measurements at accumulation stakes.* The reason for the discrepancy is not fully understood, though it is possible that the isotopic maxima and minima (generally thought to reflect seasonal differences in precipitation in Greenland) may not be related to seasonal precipitation at all in Antarctica. Compared with Greenland the accumulation rates in Antarctica generally are much lower. This and the fact that wind may redistribute the year's accumulation entirely could so easily upset any orderly seasonal variation in the isotopes that estimates of accumulation based entirely on the occurrence of isotopic maxima and/or minima could be completely misleading.

*The reasons for this are discussed in a subsequent section of this paper dealing with the time-temperature relationships of densification of polar snow.



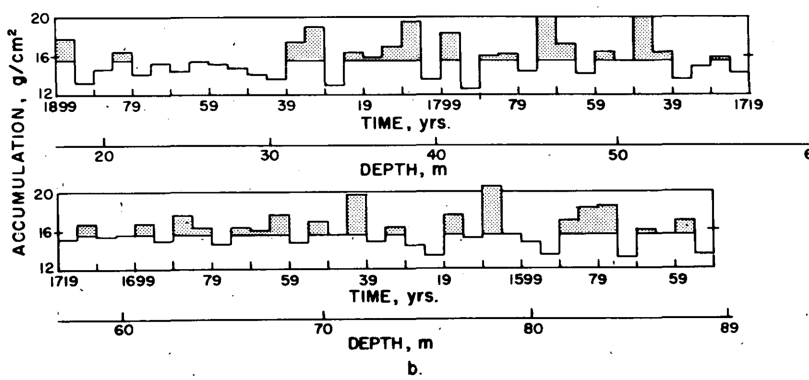


Figure 16. Variations in accumulation for the period 1959-1549 as interpreted from pit and core stratigraphy at Byrd Station.

Extrapolation to 309 m of the average rate of accumulation derived from stratigraphic studies (15.6 g cm^{-2} yr^{-1}) would yield an age of approximately 1700 years for the ice at the bottom of the deep drill hole. However, this does not take into account thinning of the ice due to plastic deformation. If it is assumed that the ice sheet at Byrd Station is 2500 m thick then according to the simple correction factor deduced by Nye (1963) the age of the ice at 309 m would be 1900 years and the thickness of the annual layer would have decreased to less than 14 g cm^{-2} yr^{-1}. Since the surface movement of the ice at Byrd Station is probably no greater than 10 m yr^{-1} it follows that ice now at the bottom of the drill hole must have been deposited originally less than 20 km from its present location.

Snow accumulation at Little America V

The only recent measurements of snow accumulation at stakes at Little America V were those obtained by Crary (1961) who measured an average accumulation of 23.7 g cm^{-2} yr^{-1} for the period February 1957 - October 1958.

At Camp Michigan, located approximately 40 km southwest of Little America V, Giovinetto (Zumberge et al., 1960) made measurements in a number of pits and found the accumulation to be of the order of 20 g cm^{-2} yr^{-1}. This agrees closely with the value of 19.6 cm^{-2} yr^{-1} that Vickers (1958) obtained in a pit study at nearby Little America III.

Table II. Accumulation at snow pits, Little America V.

Year	Accumulation ($g\ cm^{-2}\ yr^{-1}$) Pit 1	Pit 2	Pit 3
1958	22.2	20.3	19.3
1957	28.0	30.2	36.2
1956	21.8	27.7	26.1
1955	17.8	17.2	19.3
1954	20.1	12.8	15.7
Average	22.0	21.6	23.3

Data from three shallow pits at Little America V (see Fig. 8 for stratigraphy) for the period 1954-58 are given in Table II.

Relatively high accumulation was recorded at all three pits for 1957, but the accumulation during 1954 and 1955 was somewhat below average at each pit. It might be noted that the average value of a little more than 22 $g\ cm^{-2}\ yr^{-1}$ falls more or less in between the estimates based on pit studies by Giovinetto and Vickers and the stake measurements of Crary. This history of accumulation at Little America V was extended without break to a depth of 38.86 m and with interpolations can be extended with reasonable certainty to nearly 49 m (see Appendix A for detailed results). Variations in annual accumulation from the surface to 38.86 m and the 5-year means are plotted in Figure 17. Years with intensive summer melting are indicated in the same diagram. Particularly intensive melt was observed at 5 - 5.5 m (1949-50), 10 m (1937-38), 14-15 m (1926-29), 21-22 m (1907-09), 30 m (1883-84) and 40-41 m (1849-50). Such melting generally showed up in the stratigraphy as layers and lenses of ice up to 2 cm thick. Glands and bodies of ice were occasionally observed including an ice gland between 41.60 and 41.70 m which was more than 8 cm long. With the exception of the summer of 1928-29 the greatest melt appeared to occur in years of average or below average accumulation. None of these melt features were visibly associated with dirt layers or volcanic ash.

Unusually fine grained firn was observed between 20 and 30 m. This snow probably originated under somewhat cooler conditions than exist on the Ross Ice Shelf at the present day, but detailed examination of the stratigraphy gave no indication of any radical change in accumulation rates at these depths.

Cores to a depth of 38.86 m at Little America V represent 105 years of continuous accumulation, the firn at 39 m having been deposited on the surface of the ice shelf about the year 1854. Accumulation varied from 11.6 to 48.9 g $cm^{-2}\ yr^{-1}$ with the annual average amounting to 22.1 $g\ cm^{-2}\ yr^{-1}$. Apart from some periods of exceptionally high accumulation between 1894 and 1939 the record is rather uniform. Firn at a depth of 48 m is estimated to have been deposited on the surface about the year 1825 and the snow at the firn to ice transition depth (51-52 m) is believed to be approximately 150 years old. At Byrd Station this transformation was observed to take place at a depth of approximately 64 m in snow nearly 300 years old, approximately twice as old as the snow at the firn-ice transition at Little America V.

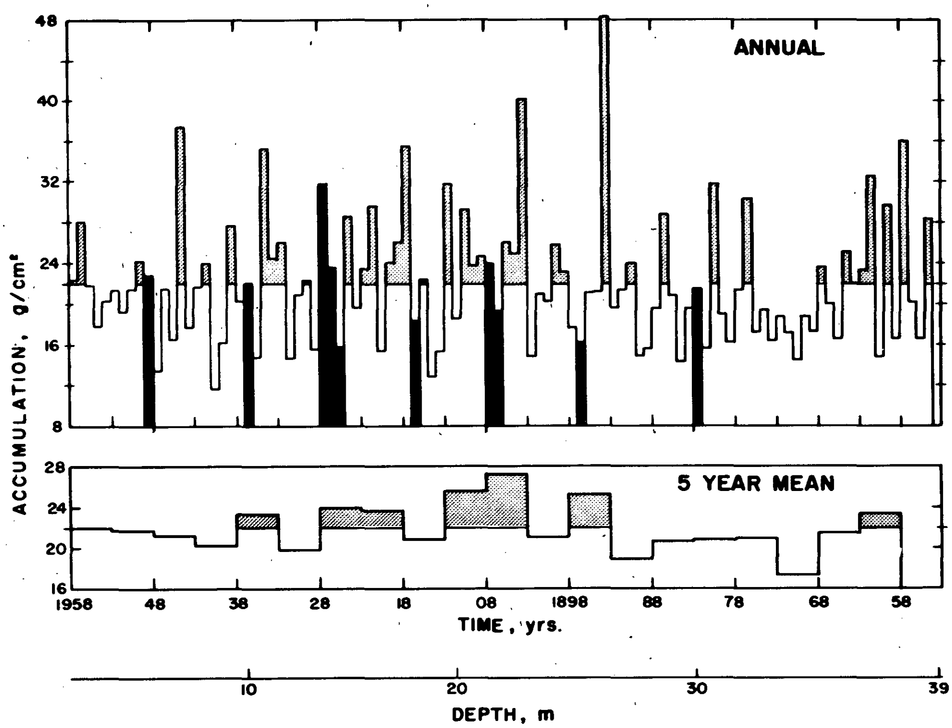


Figure 17. Variations in accumulation for the period 1958-1855 at Little America V. Dating based on analysis of deep core stratigraphy. Blacked in portions of diagram denote years of extensive melt.

The accumulation rate at Little America compares very closely with that observed at Ellsworth Station on the Filchner Ice Shelf (Aughenbaugh et al., 1958) but it is appreciably smaller than the accumulation of 36-38 g cm^{-2} yr^{-1} recorded at Maudheim (Schytt, 1958) and at Base Roi Baudouin (Gonfiantini et al., 1963) on the ice shelf bordering Dronning Maud Land. None of the cores from Little America V have been used for measuring stable isotope variations. However, measurements of oxygen isotopes in the deep pit at Little America V have been interpreted as indicating an accumulation rate of about 30 g cm^{-2} yr^{-1} (Epstein et al., 1963). Stratigraphic studies of deep cores from the same depth (15-19 m) gave an average value of 23-24 g cm^{-2} yr^{-1}. This is only slightly higher than the value obtained with the entire length of dated core, but it is still appreciably smaller than the accumulation rate based on isotopes. However, the maximum (40.5 g cm^{-2} yr^{-1}) and minimum (15.8 g cm^{-2} yr^{-1}) values obtained with isotopes are well within the range of values 49.9 to 11.6 g cm^{-2} yr^{-1} based on core stratigraphy.

In a floating ice shelf, as in the deeper parts of a thick grounded ice sheet, the effects of plastic deformation must be taken into account when estimating the age of the ice. A recent calculation by Crary (Crary et al., 1962), based on Glen's flow law and using actual measurements of surface strain at Little America V, indicates that plastic thinning of the ice could have reduced the thickness of annual layers near the bottom to less than 1/10 of their original surface values. According to Crary the ice at the bottom of the shelf could be as old as 5000 years.

Despite the existence of relatively old ice at the bottom of the shelf at Little America V it would appear from an examination of the particle paths deduced by Crary (Crary et al., 1962, Fig. 40, p. 132) that the bulk of the ice at Little America V has been derived from snow deposited on the surface of the ice shelf. Whether the very abrupt change in the texture and fabric of the ice at approximately 150-m depth (Gow, 1963a) represents a discontinuity between shelf derived ice and ice from the interior is difficult to determine. However, it is of interest to note that Schytt (1958) has attributed a similar increase in crystal size of the ice at 70-75 m at Maudheim to a change in source of ice, material below 75 m being derived from the inland ice sheet and that above being composed of shelf accumulation. In the case of the ice shelf at Maudheim these two components are present in the ratio of 5:3 but as Schytt concedes the inland ice could be expected to wedge out in the largest ice shelves, e.g., Ross Ice Shelf, because of bottom melting. The temperature gradient observed near the bottom of the ice shelf at Little America V is compatible only with appreciable bottom melting and according to Crary's analysis of particle paths in the direction of ice flow this melting should have eliminated all but 20 m or so of the original land ice in the shelf at Little America V. However, apart from the alternative evidence afforded by the abrupt change in the structure and size of crystals below 150 m there is still too little data on the absolute movement, rates of strain and bottom melting to determine at all confidently the relative contributions of ice shelf accumulation and continental ice in the cores at Little America V. Petrographic and conductometric analyses of cores from near the bottom of the ice shelf (Gow, 1963a; in press, a) revealed no trace of sea ice or any evidence of bottom freezing at Little America V.

Three layers of discolored ice were observed at depths of 172.1, 219.4, and 222.8 m. Up to 4 cm thick, these layers contained particles of dirt as large as 0.5 mm in diameter. The fact that the particles were suspended in and underlain by melt water ice clearly shows that the debris was originally deposited on top of the ice shelf (or ice sheet). Angular particles predominated and several of the more readily identified minerals included magnetite, hornblende and glass fragments. Chemical and mineralogical studies have yet to be completed but all indications are that the dirt is volcanic ash. The only active volcano in Antarctica at the present day is Mt. Erebus. However, it is located more than 700 km to the west of Little America V and it is not considered a likely source of the dirt in the cores at Little America V. First, Mt. Erebus is not the type of volcano normally associated with large scale eruptions of volcanic ash. Second, the prevailing winds on the Ross Ice Shelf blow from the direction of Marie Byrd Land, not from McMurdo Sound where Mt. Erebus is located. Third, if the ash layers are more than 2000 years old as Crary's particle path analysis would indicate then these ashes must have traveled a distance of at least 200 km since falling onto the ice shelf. Since this movement can only have been from the direction of Marie Byrd Land it follows that the ashes must have been deposited on the surface at least 900 km from Mt. Erebus. Fourth, the existence of particles as large as 0.5 mm in the ash layers would tend to indicate that this debris was not deposited any great distance from its source. A number of recently active volcanoes are known to exist in Marie Byrd Land (Doumani, 1960) and the dirt layers observed in deep ice cores at Little America V are inferred to have originated from one of these volcanoes.

It is unlikely that this debris was derived from secondary volcanic sources, i.e., blown onto the shelf from exposed rock surfaces during the ablation season. If this had been the case, the cores could reasonably have been expected to contain numerous layers of dirt. No such layers were observed.

Snow densification at Byrd Station

It has already been shown how cyclical property variations of the summer and winter snow layers can be used to determine annual increments of accumulation to considerable depths in the firn at Byrd Station and Little America V. However, overall changes in the bulk physical properties of the snow pack do occur as the layers of snow become more deeply buried. One such property that is both readily determined and a useful index of the continually changing conditions in the snow pack is density.

Near the surface snow densities can vary considerably from layer to layer. However, these variations tend to dampen quite rapidly with increasing depth. At Byrd Station (Fig. 10), layer to layer densities near the surface were found to vary by as much as 0.10 g cm^{-3}. At depths of between 3 and 4 m successive pieces of core 10-15 cm long generally varied by less than 0.03 g cm^{-3}. This variation had been reduced to about half at 10 m and at 20 m the variation between successive core samples rarely exceeded 0.01 g cm^{-3}. Below 200 m density differences between one sample and the next were never greater than 0.0005 g cm^{-3}.

In regard to gross changes of density with depth three distinctive regions are clearly indicated in the depth density curve at Byrd Station (Fig. 11). These are separated by major breaks of slope at depths of approximately 10 m and 64 m and at densities of 0.54 and 0.83 g cm^{-3} respectively. Between the surface and 10 m the average rate of increase of density with depth is about 0.02 g cm^{-3} per m. A fairly abrupt change occurs around 10 m; between 10 m and 60 m the density increases almost linearly with depth at a rate of approximately 0.005 g cm^{-3} per m. In bubbly ice below 64 m further densification, at a very slow rate, occurs primarily by compression of the entrapped air bubbles which build up pressure and become spherical in an effort to establish equilibrium with the overburden pressure. These breaks in slope of the density profile are clearly related to changes in the principal mechanism of densification. These mechanisms and their relationship to the ever-changing structure of the firn as it transforms into glacier ice are discussed more fully in a later section of this report.

Snow densification at Little America V

At Little America V densities in the upper snow layers were found to fluctuate in much the same way as at Byrd Station although the amplitude of fluctuation is appreciably greater at Little America V and they tend also to persist to somewhat greater depth (Fig. 12). This can be attributed most probably to more variable layer structure and larger density differences initially in the snow at Little America V. The most unusual feature of the depth density profile at Little America V (Fig. 13) is the very marked increase in the rate of densification below 35 m. Between 35 m and 50 m the density increased at an average rate of 0.009 g cm^{-3} per m, more than double the rate between 20 m and 35 m and about equivalent to the rate of densification between 10 m and 20 m.

A very similar profile has been observed at Ellsworth Station on the large Filchner Ice Shelf (Aughenbaugh et al., 1958). In fact the two profiles overlap one another almost exactly down to a depth of 26 m (see Fig. 18). This is not too surprising since both these locations have virtually identical regimes with mean annual temperatures of -24 C and accumulation rates of 22 g cm^{-2} yr^{-1}. Much more puzzling is the anomalous increase in the rate of densification of the firn at a depth where it is already highly densified. This anomaly

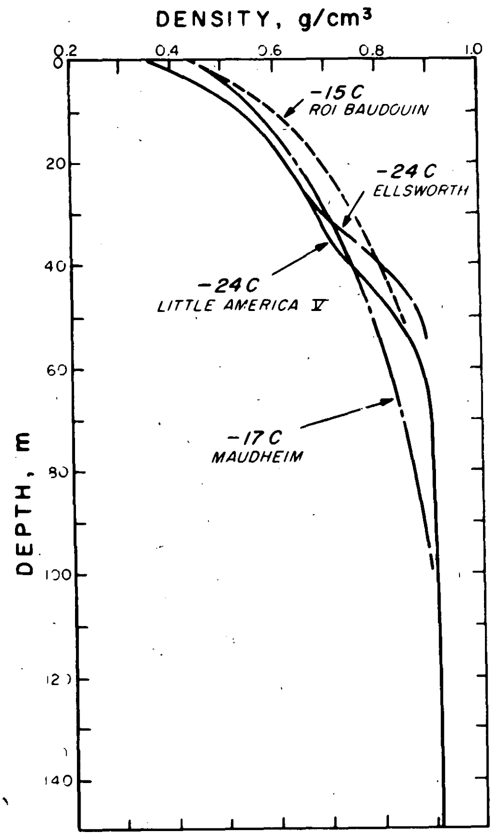


Figure 18. Depth-density profiles of a number of Antarctic ice shelves.

develops somewhat sooner at Ellsworth Station (26-m depth) than at Little America V (35 m) but it is not observed at all in the depth-density profiles from smaller ice shelves such as at Maudheim (Schytt, 1958) and Base Roi Baudouin (Tongiorgi et al., 1962) or in depth-density curves on the inland ice sheet. It seems most unlikely that anomalies of this magnitude at these depths could ever have originated at the surface. In any event detailed stratigraphic studies of the cores at Little America V gave no indication of any radical changes in rate of accumulation or temperatures around 35-m depth. However, a very rapid obliteration of stratigraphy was observed below 40 m.

It is perhaps significant that both Little America V and Ellsworth Stations were located near the seaward edges of large ice shelves in areas characterized by inlet rifts, undulations, crevasses and other obvious signs of localized deformation. The fact that the deep drill hole at Little America V was located only a short distance from Crevasse Valley is perhaps very significant, since the very existence of such a feature would imply considerable deformation in this region of the ice shelf. Since large horizontal stresses could be expected in such a region excessive densification below 35 m can probably be attributed to these additional sources of stress acting in conjunction with the compactive pressure of the overburden. The appearance of strain shadows in crystals below 65 m, the rapid rate of growth of these crystals, and their recrystallization into a highly oriented fabric by 100 m would tend also to indicate the presence of considerable deformation in the upper layers of the Ross Ice Shelf at Little America V.

Predicting depth-density profiles

On polar glaciers where melting is negligible or nonexistent the process of snow densification is the same at all places regardless of the temperature or rate of accumulation. However, the rate of densification will depend very much on the temperature in the snow and the speed with which it is deposited. In some cases the effects of englacial deformation must also be considered, e.g., Little America V.

During the past 10-15 years, depth-density profiles have been obtained from deep pits and from corings at a number of locations on both the Greenland and Antarctic ice sheets. These measurements have covered such a wide range of mean annual temperatures and accumulation rates that the relative effects of these two variables on densification can now be evaluated on a semiquantitative basis. Although the best attempts to formulate an adequate theory of snow densification have met with only a moderate measure of success (Bader, 1960 and 1962b; Kojima, 1964) this does not mean that the existing data cannot be usefully analyzed from a judicious inspection of the depth-density curves themselves.

It is quite obvious, even from a cursory examination of density curves from the inland ice of Greenland and Antarctica (Fig. 19), that the smaller the rate of accumulation and/or the higher the mean annual temperature the greater the density increase over a given increment of depth, and vice versa. In general, it is a relatively simple matter to determine mean annual temperature and rate of accumulation at any given location so that it should be possible to use existing depth-density curves to obtain a reasonably reliable estimate of density distribution at any given location on a polar glacier when only the mean annual temperature and average rate of annual accumulation at that place are known.

The effects of temperature can best be illustrated with reference to the density profiles from Maudheim (Schytt, 1958), Roi Baudouin (Tongiorgi et al., 1962), and Site 2 (Langway, 1958) presented in Figure 20. Snow accumulation at all three locations is approximately the same (36-41 g cm^{-2} yr^{-1}) but because of the much warmer temperatures at Roi Baudouin (mean annual temperature -15 C) the density there at any given depth is significantly greater than at Maudheim (-17 C) or Site 2 (-24 C). As expected Site 2 with the coldest mean annual temperature has the least densified snow at any given depth.

The Wilkes S-2 curve (Cameron et al., 1959) is also included to demonstrate the effect on densification rate of a marked decrease in the rate of accumulation. Although the mean annual temperature at Roi Baudouin is more than 4 C warmer than at Wilkes S-2 (mean annual temperature -19 C) it can be seen that this temperature difference has been more than compensated for by the approximate three-fold decrease in the rate of accumulation at Wilkes (annual average 13 g cm^{-2} yr^{-1}). Of course, snow of any given density will be considerably younger at Roi Baudouin than at Wilkes S-2 so that the really important effect of decreasing the rate of accumulation is to increase the time for which densification, a strongly temperature dependent reaction, can proceed.

An additional illustration of the importance of the time factor in depth densification of snow is provided by data from Site 2 and Camp Century, Greenland (Mock and Langway, personal communication). Both locations have the same mean annual temperature (-24 C) but the accumulation at Camp Century is only about 33 g cm^{-2} yr^{-1} compared to 40 g cm^{-2} yr^{-1} at Site 2. As would be anticipated, densities at any given depth at Camp Century are somewhat higher than at Site 2. Data from these two locations are all the more interesting because over a considerable range of densities (up to 0.75 g cm^{-3}) snow of the same age has much the same density at both locations. Table III was prepared from data kindly furnished by Mr. S. Mock and Dr. C. Langway.

Apparently the time required to attain a given density at a slightly greater depth at Site 2 is more or less balanced by the increased rate of densification associated with the somewhat smaller rate of accumulation at Camp Century. It would be of some interest to know if this holds generally, i.e., that for places with the same mean annual temperature the time required to attain a given density will be the same whatever the rates of accumulation might be.

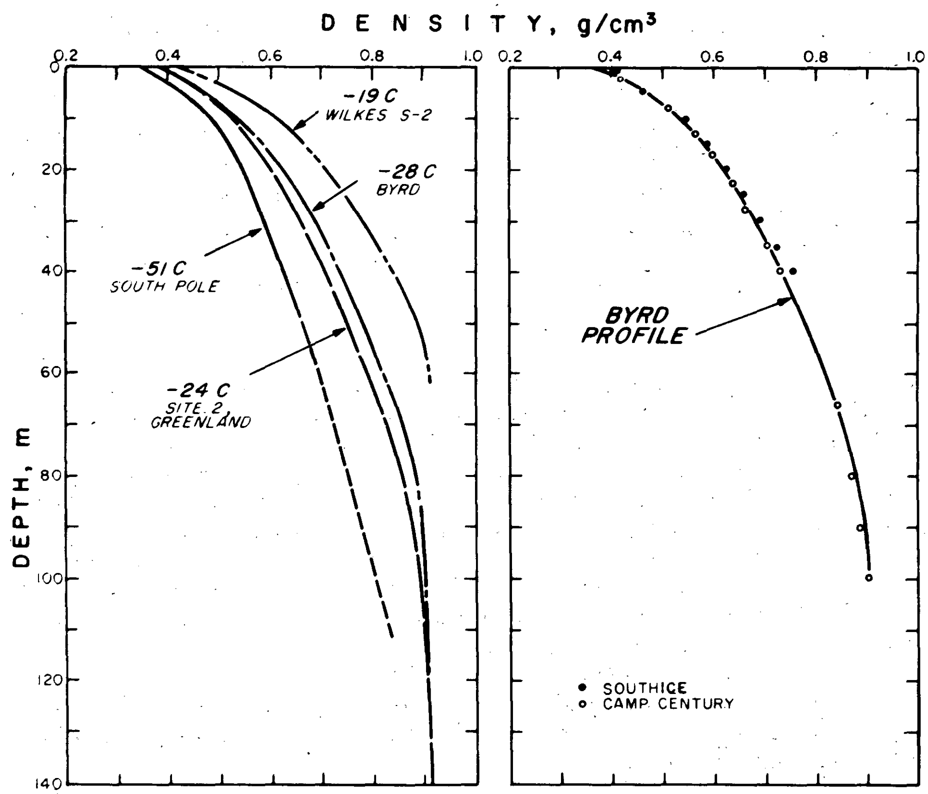


Figure 19. Depth-density curves from the inland ice of Antarctica and Greenland.

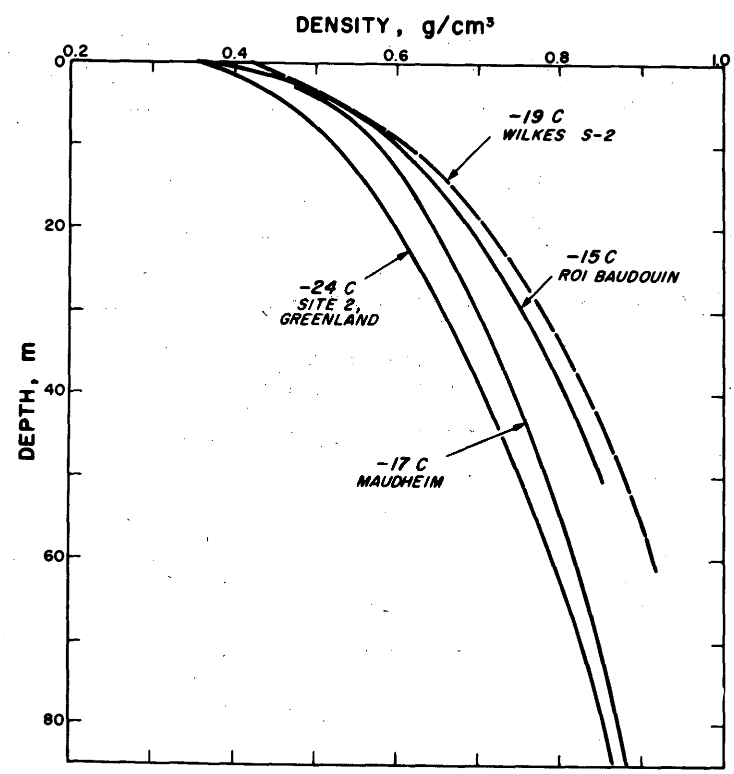


Figure 20. Depth-density profiles for locations with approximately the same rate of accumulation, **38-40 cm^{-2} yr^{-1}, but different mean annual temperatures.**

Table III. Age-density relations in firn at Site 2 and Camp Century, Greenland. The numbers in parentheses are depths in meters.

Age (yr)	Site 2	Camp Century
25	.600(20)	.600(16)
40	.655(32)	.645(24)
58	.710(41)	.700(32)
77	.750(52)	.740(42)
110	.830	.810

Of considerable analytical interest are the very closely matched density profiles observed at Byrd Station and Southice (Stephenson and Lister, 1959) in the Antarctic and at Camp Century, Greenland (Fig. 19). The Camp Century densities overlap the Byrd Station profile almost perfectly and the Southice profile deviates only slightly near the bottom. From an examination of the temperature-accumulation data for these three locations (Table IV), it would seem that doubling the rate of accumulation exerts much the same effect on densification as a temperature decrease of 4C, and vice versa, i.e., if the accumulation was suddenly doubled the mean annual temperature would need to rise about 4C to maintain the same density profile. If this exponential relationship were to hold over a more extended range of temperatures and accumulation rates then the temperature-accumulation values listed in Table V including those from Byrd Station, Southice and Camp Century should all give rise to identical depth density profiles.

Table IV. Temperature and accumulation data for three locations with similar depth-density profiles.

Location	Mean annual temperature (°C)	Mean annual accumulation (g cm^{-2} yr^{-1})
Southice	-31	10
Byrd Station	-28	16
Camp Century	-24	34

Table V. Temperature-accumulation data based on Table IV relationship.

Mean annual temperature (°C)	Mean annual accumulation (g cm^{-2} yr^{-1})
-52	$\frac{1}{4}$
-48	$\frac{1}{2}$
-44	1
-40	2
-36	4
-32	8
-28	16
-24	32
-20	64
-16	128

Whether or not these should lead to reasonable results can, perhaps, be best tested against the observed density curves at the two extreme locations Wilkes S-2 and the South Pole.

At Wilkes S-2, either the accumulation would need to be increased to more than 64 g cm^{-2} yr^{-1} or the temperature would have to drop to about -29 C if the density profile were to match that at Byrd Station. At the South Pole, however, where densities are very much lower than at Byrd Station either the temperature would need to be increased to about -33 C at the current rate of accumulation or the accumulation would have to be reduced to $\frac{1}{2}$ - $\frac{1}{4}$ g cm^{-2} yr^{-1} without changing present day temperatures to produce a matching profile. Such orders of change at both the South Pole and Wilkes S-2 appear entirely reasonable.

This exponential relationship between the rate of accumulation and the mean annual temperature, which requires that the accumulation be decreased by a factor of 2 for each 4 C rise in temperature and vice versa, seems to hold also for density data from Wilkes S-2 and Roi Baudouin Base. If the temperature at Wilkes S-2 were to increase by 4 C to -15 C then according to the above "rule" the rate of accumulation would have to be doubled, i.e., from 13 g cm^{-2} yr^{-1} to 26 g cm^{-2} yr^{-1}, in order for the density profile to remain the same. Although the temperature at Wilkes S-2 would then be the same as at Roi Baudouin, the accumulation would still be smaller so that the density at any given depth at Wilkes should still be greater, as is actually observed. Conversely, at Roi Baudouin either the temperature would have to be increased to -13 C or the rate of accumulation would need to be decreased to about 26 g cm^{-2} yr^{-1} if the density profile were to match that at Wilkes S-2. To bring the densities at Byrd Station into line with values at Wilkes S-2 either the temperature at Byrd Station would have to be raised to about -18 C, an increase of 10 C, or the accumulation would need to be decreased five-fold to about 3 g cm^{-2} yr^{-1}

There are, of course, an infinite number of combinations of mean annual temperatures and accumulation values that will satisfy any given depth-density curve. However, from the examples given above it now seems that there are already enough depth-density data at hand to permit density profiles for other locations to be derived with some precision when only the mean annual temperatures and average rates of accumulation of the locations are known. Both parameters can be readily measured at most places on the Antarctic and Greenland ice sheets. However, at those locations where it has proved difficult to measure accumulation directly in pits, e.g., South Polar plateau, it should be possible to reverse the process; one should be able to derive a reasonably reliable value of the average accumulation rate by simply coring a hole to 20 m and measuring the density profile and mean annual temperature.

Depth-porosity profiles

The depth-porosity curves at Byrd Station and Little America V (Fig. 14) match almost exactly down to a depth of 36 m. Below 36 m the rate of change of porosity increases appreciably at Little America V due apparently to the existence of abnormal strains in the upper part of the ice shelf. When the firn transforms into ice it still contains approximately 10% by volume of air. This transition occurs at 52 m at Little America V. It occurs somewhat deeper at Byrd Station - approximately 64 m, at which depth the porosity at Little America V has already decreased to less than 4%. Porosities become equalized at about 130-m depth (1% porosity) and continue to diminish slowly with increasing depth of burial. At Byrd Station the measured porosity at 308-m depth was 0.5%. This value is somewhat higher than would actually be found in in situ ice because of the "relaxed" nature of cores obtained at depth. This relaxation, invariably accompanied by some cracking of the ice, occurs when a core is cut from confining pressures exceeding about 15 kg cm^{-2}. Calculations based on the gas law indicate that the porosity of undisturbed ice at 308 m should be about 0.4%. From further calculations, which also included consideration of the effects of compressibility of ice at high overburden pressures, it can be shown that if the ice at the bottom of the ice sheet at Byrd Station (estimated thickness 2500 m) is at the pressure melting point (-2 C) its in situ density would be 0.9183 ± 0.0003 g cm^{-3} and its porosity would be less than .05%. It can also be shown that all ice below 400 m at Byrd Station must have an in situ density greater than 0.9180 g cm^{-3}. A full discussion of bubbles and bubble pressures in Antarctic glacier ice is to be presented in a forthcoming paper (Gow, in press, b).

Depth-load profiles

The ice load at the bottom of the Ross Ice Shelf at Little America V is estimated at 22.03 kg cm^{-2}. The thickness of ice as determined seismically is estimated to be 257-258 m, which for the above value of the load gives an average density of 0.853 g cm^{-3} for the ice shelf at Little America V. The freeboard can be computed from the relationship $E = H(\gamma_w - \gamma_i)/\gamma_w$ where H is the total thickness of floating ice and γ_i is its average density, E is the elevation of the ice shelf above sea level, and γ_w is the density of sea water of known temperature and salinity. Using the value of 1.0275 g cm^{-3} for the density of sea water actually measured at the edge of the Ross Ice Shelf (Crary et al., 1962) the elevation E works out at 43.5 m. This figure agrees closely with the value of 43 m that Crary (1961) obtained by surface leveling at Little America V in 1958. In addition, the seismically sounded thickness of ice at Little America (Thiel and Ostenso, 1961) agreed almost perfectly with the thickness derived from temperature measurements in the drill hole. Since estimates of thickness based on temperature data are not likely to be in error by more than a meter or two it is concluded that the Ross Ice Shelf in the vicinity of Little America is free floating.

Since the temperature and accumulation conditions over the surface of the Ross Ice Shelf don't appear to vary greatly from one place to another (Crary et al., 1962) the thickness of the snow-firn veneer should not vary too much either. The results obtained at Little America V thus constitute a convenient source of data for estimating ice thicknesses and elevations on other parts of the Ross Ice Shelf. Results of these calculations are given in Figure 21 together with the curve of the thickness to elevation ratios. At Little America V this ratio is almost exactly 6:1 (258 m:43.5 m). The ratio increases as the thickness of the ice shelf increases; for a 1000 m thick shelf the ratio would be 8:1; this decreases to about 4:1 for an ice shelf only 100 m thick.

In Greenland, Benson (1962) has successfully used density and load data to distinguish between the various snow facies. When load values from the top 15 m at Byrd Station and Little America V are plotted on Benson's diagram both sets of data are found to fall within the percolation field (Fig. 22). Occasional percolation of melt water was observed at Little America V, but at Byrd Station the snow is entirely dry and it most certainly cannot be included in the percolation facies. Even more interesting is the fact that the Little America V data are disposed more closely to the dry snow boundary than data from Byrd Station.

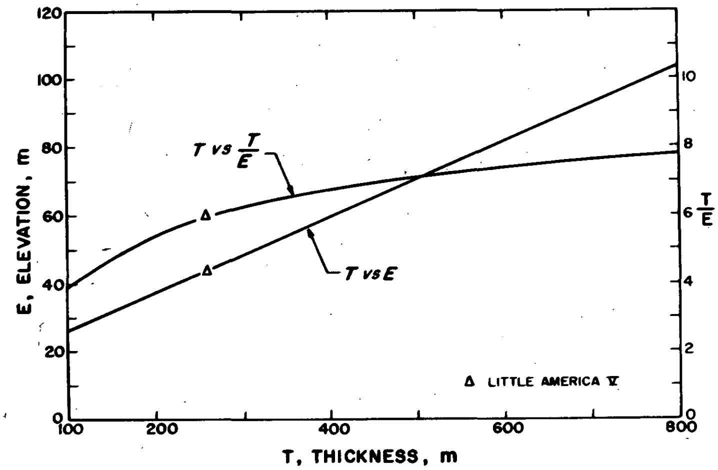


Figure 21. Relationship of elevation (E) to thickness (T) in a free floating ice shelf; based on depth density data from Little America V. At Little America V the Ross Ice Shelf is almost exactly five-sixths submerged.

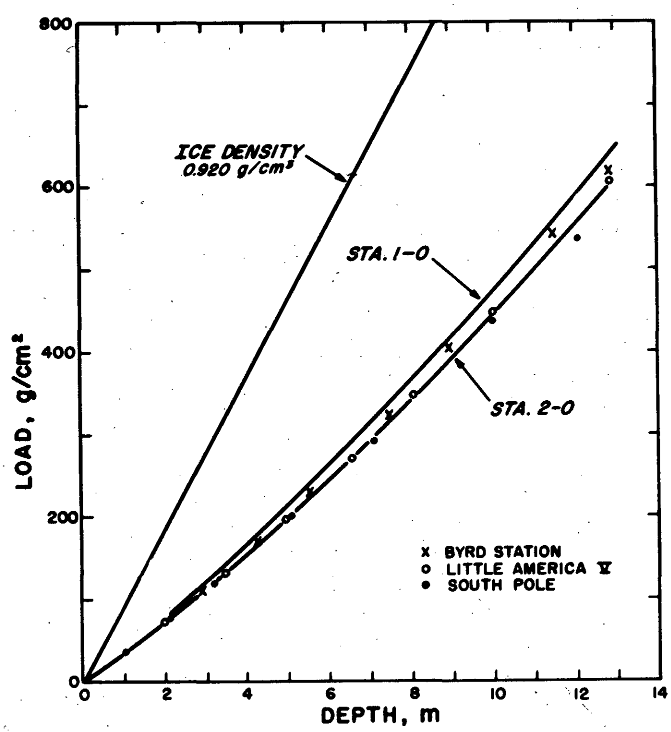


Figure 22. Snow load data from Byrd, Little America V and South Pole Stations. The curves for Sta. 1.0 and Sta. 2.0 inclose all areas included in the percolation facies in Greenland.

According to Benson the dry snow facies in Greenland should include only those areas where the mean density of the top 5 m is less than 0.375 g cm^{-3}. However, if this criterion was applied to Antarctica then even the South Pole with a mean density of 0.395 g cm^{-3} in the top 5 m would have to be included in the percolation facies. These data clearly point up a fundamental difference in the location of the dry snow - percolation facies boundary in Antarctica and Greenland.

It is important to note that snow facies as defined by Benson are classified according to the intensity of melt and so are essentially temperature dependent. However, as we have already observed, the density (and hence the load) of the snow at any given depth depends on rate of accumulation as well as the temperature. Because accumulation in Antarctica is generally much smaller than it is for areas of comparable mean annual temperature in Greenland, densities (and hence the loads) should tend to be higher at any given depth in Antarctica than in Greenland. It is for this reason that load data from Byrd Station and other low accumulation areas in Antarctica tend to fall into the percolation facies on Benson's Greenland diagram.

In Greenland as well as Antarctica all areas with mean annual temperatures below -25C are confined to the dry snow facies. However, according to Giovinetto (1964) there are some dry snow areas in Antarctica where mean annual temperatures can rise as high as -15C. Since no such areas have been reported from Greenland this would tend to indicate that rather gross differences in seasonal distribution of temperature do exist on the two ice sheets. Apparently the seasonal extremes of temperature, particularly the summer temperatures, are not as great and/or of as long duration in Antarctica as they are in Greenland.

The snow-ice transformation

The Antarctic Ice Sheet is veneered by a relatively thin blanket of snow that is slowly transformed into bubbly ice at depth. During this transformation the snow undergoes two principal changes. The most obvious change — densification — is concerned simply with the elimination of permeable pore space from between the grains of snow; the other has to do with progressive changes in the granular and crystalline structure of the snow, a process which might loosely be referred to as recrystallization. The overall transformation has been described variously as diagenesis (Paulcke, 1934; Benson, 1959, 1962; Anderson and Benson, 1963), metamorphism (Bader *et al.*, 1939) and sintering.

Of the two terms, diagenesis and metamorphism, the latter seems to be the more inclusive of the processes involved in the transformation of snow to glacier ice. Recently Anderson and Benson have argued in favor of diagenesis but their preference for this term seems to be predicated more on the sedimentary origin of snow rather than on the nature of the post depositional changes. The important point here (and geologists are in general agreement on this point) is that diagenesis should not include those changes that take place at elevated temperatures. Such changes fall within the metamorphic realm and there is perhaps no better example of metamorphism of a sediment than snow itself simply because it is deposited at temperatures very close to its melting point even on the coldest of polar glaciers. One might also object on similar ground to Benson's use of the term "diagenetic" in his snow facies classification (Benson, 1959, 1962). This objection reflects in no way on the immense value of the facies concept but since the various facies are classified according to the intensity of melt, e.g., soaked facies, etc. it is a misnomer to refer to them as diagenetic facies. They should simply be referred to as snow facies.

The transformation of snow to glacier ice probably fits the definition of sintering more accurately than either diagenesis or metamorphism. Sintering occurs when an aggregate of fine particles is heated and, to the ceramacist at least, this sintering results in both a densification (shrinkage) and recrystallization (welding and grain growth) of the aggregate. On polar snow fields this sintering takes place under conditions of constantly increasing load and at essentially constant temperatures over most of the firn density range. The word firn is defined generally to denote the material that exists between unconsolidated snow and bubbly ice regardless of what the mechanism of its actual transformation to ice might have been. For this reason this writer would favor the term firnification in lieu of such terms as metamorphism, sintering etc., to describe the overall process by which snow is transformed into ice on polar glaciers. Seligman (1939), in using the same term to describe the analogous transformation in a temperate glacier, also implied the operation of two principal processes, densification and recrystallization. Since changes in the density and crystal structure of the firn are relatively easy to measure they collectively serve to characterize firnification in its very simplest terms.

Attention has already been drawn to certain characteristic breaks of slope in the depth-density curves from Antarctica and Greenland and it would seem reasonable to assume that these slope changes are related directly to changes in the mechanisms of densification. This problem has been examined most recently by Anderson and Benson (1963). They concluded that "grain packing, enhanced by the grain rounding action of other mechanisms" is the dominant mechanism of densification of snow of less than so-called critical density. The concepts of critical density and critical depth were introduced by Anderson and Benson to characterize the density and depth at which the rate of densification is observed to decrease rather abruptly in both Greenland and Antarctica. On most depth-density curves this change occurs at a density of 0.50 - 0.55 g cm^{-3} and at a depth of about 10 m. Anderson and Benson note that this density, equivalent to a porosity of about 40%, corresponds rather closely with the maximum packing densities that can be attained with granular aggregates in the laboratory. Largely on this basis and without any supporting evidence from thin sections Anderson and Benson conclude that the critical density also represents the limit beyond which grain packing is no longer effective. However, examination of many thin sections of snow at Byrd Station by the writer reveals little evidence for the formation of a simply mechanically packed structure at the critical density, nor is there any indication that the critical density can be associated with any radical change in snow structure as is also contended by Anderson and Benson. The textural relations of several representative sections of snow and firn from Byrd Station are amply demonstrated in Figure 23. An obvious feature of all sections is the existence of intergranular bonds. Though only weakly developed in the sample of near surface snow these bonds can be seen to increase both in number and size as the depth increases. This growth of bonds is important as it should inhibit to an increasing degree any approach to a simply mechanically packed structure at the so-called critical density. This, of course, does not preclude some rupture of bonds and subsequent mechanical adjustment of individual grains in lower density snow. However, there is additional evidence from thin sections that even at densities as low as 0.44 g cm^{-3} the over-all bonding is already strong enough to prevent any widespread collapse of the structure. The fact that snow at the critical density possesses very considerable strength is clearly indicative of a relatively strongly bonded structure. This strength, of the order of 10 kg cm^{-2}, is more than an order of magnitude greater than the overburden pressure at the critical depth (approximately 0.45 kg cm^{-2} at Byrd Station).

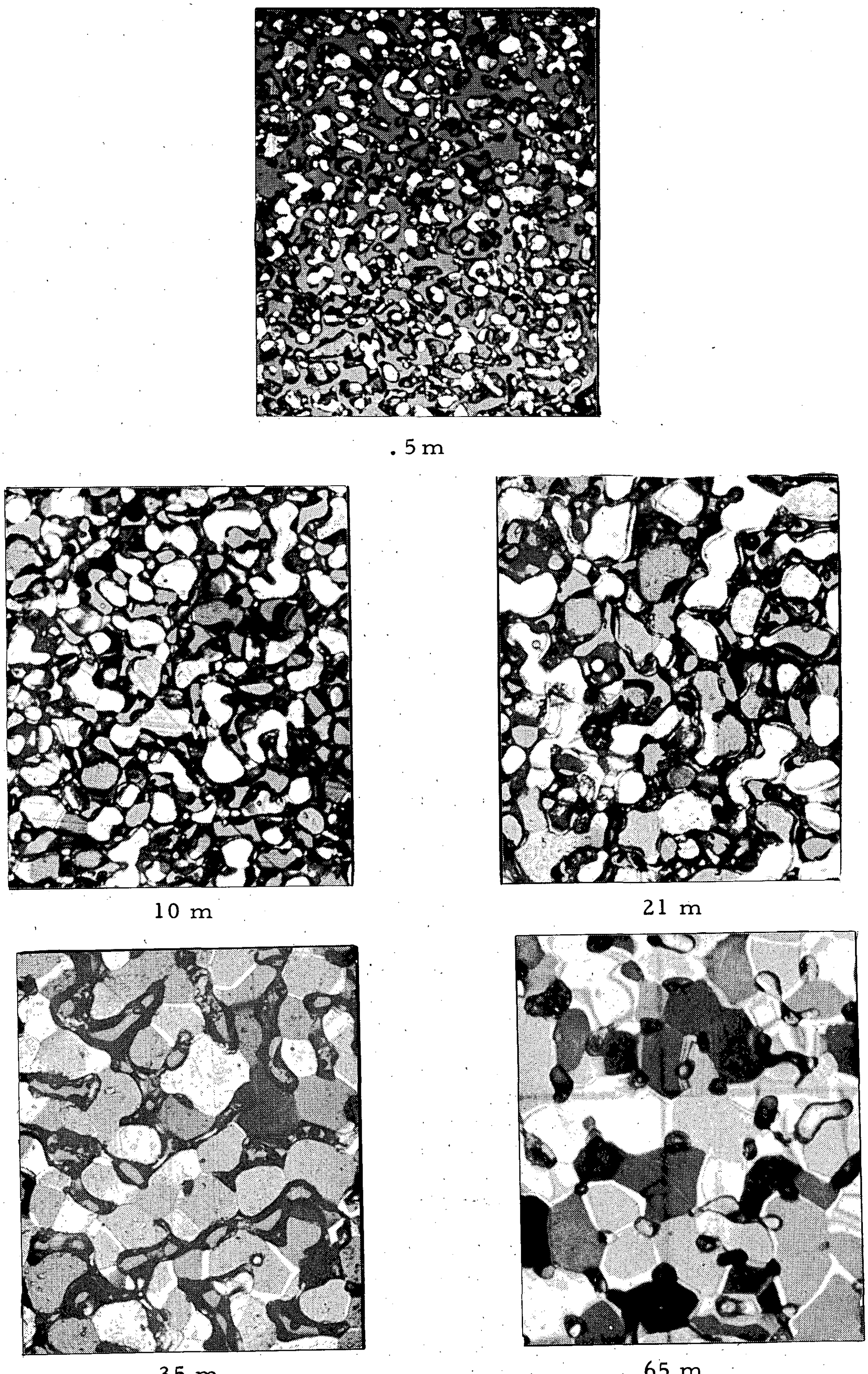


Figure 23. Thin section photographs of snow and ice from Byrd Station illustrating the progressive changes in structure accompanying firnification. All photographs were taken between crossed polaroids to reveal the crystal outlines. The clear gray areas between grains are pore spaces.

No abrupt changes in snow structure were observed below the critical density at Byrd Station. In fact, the transformation to glacier ice was found to proceed so gradually that if the marked reduction in the rate of densification at the critical density is to be explained at all in terms of the structure then it must be due to the establishment of a relatively stable structure that changes only very slowly after the critical density is reached. It is of additional interest to note that changes in the velocity of seismic waves through the snow pack tend to parallel the density profile quite closely. A fairly rapid increase in the P wave velocity in the first 10 m seems consistent with the idea of an increasing structure continuity associated with increased intergranular bonding. The significant decrease in the rate of velocity observed around 10 m also tends to confirm the existence of a thoroughly bonded aggregate at the critical density which thereafter changes its structure only very slowly.

In dry snow areas the temperature below about 10 m varies by less than ±1.0 C from the mean annual surface air temperature so that the bulk of firnification takes place under essentially isothermal conditions. The snow at 10 m is thoroughly permeable and structurally it resembles a sponge. Further evolution of this structure can only proceed as a result of deformational recrystallization of the constituent grains. Depth of burial is an important factor in that solubility at grain contacts will tend to increase with pressure. This will cause a migration of material from the contact areas into the interstices or pressure shadow regions. The net result of this process is to straighten out grain to grain boundaries and to cause permeable pore space to diminish progressively with depth. At a density of about 0.72 g cm^{-3} the firn structure converts from a cellular to a sieve-like structure, i.e., the structure in thin section begins to take on the appearance of a solid sheet perforated by tubular bubbles. Crystal size increases concomitantly with densification and at Byrd Station this growth of crystals was observed to proceed linearly with depth at the rate of 0.045 mm^2 per m. The average cross sectional area of crystals increased from approximately 1.0 mm^2 at 10 m to 3.5 mm^2 at 64 m at which depth all remaining pore space had become sealed off and the firn had now, by definition, transformed into bubbly glacier ice. The texture at this stage can be described as mosaic – composed essentially of equidimensional polyhedral crystals inclosing tubular air bubbles that are now located principally at the intersections of crystals rather than along their boundaries. Many of the grain boundaries still show some curvature, but where three crystals meet at a point their intersecting boundaries tend to radiate at angles of about 120°. This is especially true of straight boundary intersections. Newly formed ice of density around 0.83 g cm^{-3} still contains about 10% by volume of air but since the compressibility of ice is very small any further increase in the bulk density of the ice must take place at the expense of the air bubbles. This compression of the entrapped air proceeds extremely slowly so that the rate of densification drops fairly abruptly after close-off. Since bubble pressures at close-off are essentially the same as atmospheric (0.82 bars at Byrd Station) a considerable lag exists between bubble pressure and the absolute overburden pressure which at Byrd is approximately 5 bars at close-off. However, calculations of bubble pressure from density data at Byrd Station indicate that this pressure lag reduces to less than 1.0 bars at 200-m depth (Bader, 1965; Gow, in press, b).

The depth (and age) of the firn-ice transition will depend on both the temperature of the snow and the speed with which it is deposited. The change will tend to occur earlier and closer to the surface on peripheral parts of the ice sheet mainly because of the warmer temperatures. In the interior of Antarctica, however, where the greatly increased elevation of the ice sheet causes the temperature to drop drastically, snow will tend to persist to much greater depth. Since the inland ice is invariably associated with low accumulation rates this transformation to glacier ice may take as much as a thousand years to accomplish. Some representative values of the depth and age of this transition on both the Greenland and Antarctic ice sheets are given in Table VI.

Table VI. Firn-ice transition depths and ages for some representative locations on the Antarctic and Greenland ice sheets. The transformation is assumed to occur at a density of 0.83 g cm^{-3}.

Location	Depth (m) of transition	Age (yr) of transition	Accum. rate (g cm^{-2} yr^{-1})	Mean ann. temp. (°C)
South Pole	110 (est.)	1000	7	-51
Southice	58 (est.)	300	11	-31
Byrd	64	280	16	-28
Little America V	51	150	22	-24
Ellsworth	43	130	22	-24
Site 2	71	110	40	-24
Camp Century	67	140	34	-24
Wilkes S-2	40	220	13	-19
Maudheim	64	120	37	-17
Roi Baudouin	46	80	38	-15

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APPENDIX A. ACCUMULATION RECORD AS INTERPRETED FROM THE STRATIGRAPHY OF DEEP DRILL CORES

Byrd Station

(Accumulation for period 1959-1894 derived from pit and auger core data; transferred to deep core at 1892.)

Accum yr	Depth (m)	Accum ($g\ cm^{-2}$)	Total accum ($g\ cm^{-2}$)	5-yr mean ($g\ cm^{-2}\ yr^{-1}$)	Running mean ($g\ cm^{-2}\ yr^{-1}$)
1959	.43	15.9	15.9		15.9
1958	.94	18.4	34.3		17.2
1957	1.32	15.1	49.4		16.5
1956	1.80	18.8	68.2		17.1
1955	2.26	17.7	85.9	17.2	17.2
1954	2.58	13.3	99.2		16.5
1953	2.90	13.0	112.2		16.0
1952	3.24	13.9	126.1		15.8
1951	3.51	11.4	137.5		15.3
1950	3.76	10.5	148.0	12.0	14.8
1949	4.04	12.6	160.6		14.6
1948	4.25	9.3	169.9		14.2
1947	4.54	12.9	182.8		14.1
1946	4.93	17.8	200.6		14.3
1945	5.35	19.5	220.1	14.4	14.7
1944	5.56	9.9	230.0		14.4
1943	5.87	15.2	245.2		14.4
1942	6.31	21.4	266.6		14.8
1941	6.62	15.6	282.2		14.8
1940	6.85	11.2	293.4	14.7	14.7
1939	7.19	17.8	310.4		14.8
1938	7.44	12.7	323.1		14.7
1937	7.63	9.9	333.0		14.5
1936	7.89	13.5	346.5		14.4
1935	8.14	13.1	359.6	13.2	14.4
1934	8.42	14.4	374.0		14.4
1933	8.64	11.6	385.6		14.3
1932	8.97	17.5	403.1		14.4
1931	9.20	12.4	415.5		14.3
1930	9.47	14.7	430.2	14.1	14.3
1929	9.73	14.2	444.4		14.3
1928	9.96	12.7	457.1		14.3
1927	10.22	14.1	471.2		14.3
1926	10.60	20.7	491.9		14.4
1925	10.85	13.7	505.6	15.1	14.4
1924	11.04	10.5	516.1		14.3
1923	11.23	10.5	526.6		14.2
1922	11.49	14.5	541.1		14.2
1921	11.80	17.4	558.5		14.3
1920	12.09	16.5	575.0	13.9	14.4
1919	12.28	10.8	585.8		14.3
1918	12.46	10.1	595.9		14.2
1917	12.69	12.9	608.8		14.1
1916	12.88	10.8	619.6		14.1
1915	13.13	14.2	633.8	11.8	14.1
1914	13.39	14.9	648.7		14.1
1913	13.70	18.0	666.7		14.2
1912	13.97	15.4	682.1		14.2
1911	14.31	19.3	701.4		14.3
1910	14.58	15.5	716.9	16.6	14.3
1909	14.81	13.6	730.5		14.3
1908	15.12	18.3	748.8		14.4
1907	15.31	11.2	760.0		14.3
1906	15.58	15.5	775.5		14.3
1905	15.81	13.6	789.1	14.4	14.3
1904	16.05	14.3	803.4		14.3
1903	16.34	17.4	820.8		14.4
1902	16.54	11.9	832.7		14.3
1901	16.84	18.0	850.7		14.4
1900	17.05	12.7	863.4	14.9	14.4
1899	17.33	17.0	880.4		14.4
1898	17.65	19.4	899.8		14.5
1897	18.05	24.4	924.2		14.7
1896	18.26	12.9	937.1		14.6
1895	18.50	14.7	951.8	17.7	14.6
1894	18.69	11.6	963.4		14.6
1893	Transferred to deep cores				
1892	19.03	20.9	984.3		14.5
1891	19.21	11.2	995.5		14.4

Accum yr	Depth (m)	Accum ($g\ cm^{-2}$)	Total accum ($g\ cm^{-2}$)	5-yr mean ($g\ cm^{-2}\ yr^{-1}$)	Running mean ($g\ cm^{-2}\ yr^{-1}$)
1890	19.55	21.1	1016.6	13.0	14.5
1889-85	20.71	72.6	1089.2	14.5	14.5
1884-80	22.00	81.4	1170.6	16.3	14.6
1879-75	23.12	70.0	1240.6	14.0	14.6
1874-70	24.33	76.2	1316.8	15.2	14.6
1869-65	25.45	71.5	1388.3	14.3	14.6
1864-60	26.64	76.9	1465.2	15.4	14.7
1859-55	27.80	75.7	1540.9	15.1	14.7
1854-50	28.91	73.3	1614.2	14.7	14.7
1849-45	29.96	70.7	1684.9	14.1	14.7
1844-40	30.97	68.3	1753.2	13.7	14.6
1839-35	32.24	86.9	1840.1	17.4	14.7
1834-30	33.61	94.8	1934.9	19.0	14.9
1829-25	34.53	64.4	1999.3	12.9	14.8
1824-20	35.68	81.4	2080.7	16.3	14.9
1819-15	36.78	78.8	2159.5	15.8	14.9
1814-10	37.97	85.2	2244.7	17.0	15.0
1809-05	39.32	97.5	2342.2	19.5	15.1
1804-00	40.26	68.2	2410.4	13.6	15.1
1799-95	41.49	91.6	2502.0	18.3	15.2
1794-90	42.34	62.7	2564.7	12.5	15.1
1789-85	43.42	80.1	2644.8	16.0	15.1
1784-80	44.51	81.2	2726.0	16.2	15.1
1779-75	45.48	72.6	2798.6	14.5	15.1
1774-70	46.81	100.5	2899.1	20.1	15.3
1769-65	47.94	86.1	2985.2	17.2	15.3
1764-60	48.86	71.1	3056.3	14.2	15.3
1759-55	49.93	82.5	3138.8	16.5	15.3
1754-50	50.92	77.3	3216.1	15.5	15.3
1749-45	52.19	99.8	3315.9	20.0	15.4
1744-40	53.21	81.7	3397.6	16.3	15.4
1739-35	54.06	67.7	3465.3	13.5	15.4
1734-30	55.00	74.3	3539.6	14.9	15.4
1729-25	55.99	79.0	3618.6	15.8	15.4
1724-20	56.88	71.0	3689.6	14.2	15.4
1719-15	57.81	75.2	3764.8	15.0	15.4
1714-10	58.83	83.1	3847.9	16.6	15.4
1709-05	59.77	76.5	3924.4	15.3	15.4
1704-00	60.72	77.4	4001.8	15.5	15.4
1699-95	61.73	82.8	4084.6	16.6	15.4
1694-90	62.63	74.2	4158.8	14.8	15.4
1689-85	63.69	87.7	4246.5	17.5	15.4
1684-80	64.66	81.0	4327.5	16.2	15.5
1679-75	65.52	72.6	4400.1	14.5	15.4
1674-70	66.47	80.5	4480.6	16.1	15.5
1669-65	67.53	79.9	4560.5	16.0	15.5
1664-60	68.56	87.7	4648.2	17.5	15.5
1659-55	69.40	73.6	4721.8	14.7	15.5
1654-50	70.38	84.3	4806.1	16.9	15.5
1649-45	71.29	78.0	4884.1	15.6	15.5
1644-40	72.43	98.7	4982.8	19.7	15.6
1639-35	73.28	73.8	5056.6	14.8	15.6
1634-30	74.22	81.5	5138.1	16.3	15.6
1629-25	75.05	72.2	5210.3	14.4	15.6
1624-20	75.82	67.2	5277.5	13.4	15.5
1619-15	76.82	87.4	5364.9	17.5	15.6
1614-10	77.68	75.3	5440.2	15.1	15.5
1609-05	78.85	102.8	5543.0	20.6	15.6
1604-00	79.73	77.5	5620.5	15.5	15.6
1599-95	80.56	73.0	5693.5	14.6	15.6
1594-90	81.32	67.0	5760.5	13.4	15.6
1589-85	82.28	84.8	5845.3	17.1	15.6
1584-80	83.31	90.9	5936.2	18.2	15.6
1579-75	84.35	92.0	6028.2	18.4	15.7
1574-70	85.09	65.6	6093.8	13.1	15.6
1569-65	85.99	79.9	6173.7	16.0	15.6
1564-60	86.86	77.4	6251.1	15.5	15.6
1559-55	87.81	84.6	6335.1	16.9	15.6
1554-50	88.56	66.9	6402.6	13.4	15.6

Little America V

(Accumulation for period 1958-1919 derived from pit and auger core data; transferred to deep core at 1918.)

Accum yr	Depth (m)	Accum ($g\,cm^{-2}$)	Total accum ($g\,cm^{-2}$)	5-yr mean ($g\,cm^{-2}\,yr^{-1}$)	Running mean ($g\,cm^{-2}\,yr^{-1}$)	Accum yr	Depth (m)	Accum ($g\,cm^{-2}$)	Total accum ($g\,cm^{-2}$)	5-yr mean ($g\,cm^{-2}\,yr^{-1}$)	Running mean ($g\,cm^{-2}\,yr^{-1}$)
1958	0.60	22.2	22.2		22.2	1906	22.41	26.4	1181.9		22.3
1957	1.40	28.0	50.2		25.1	1905	22.80	25.0	1206.9		22.4
1956	1.97	21.8	72.0		24.0	1904	23.45	41.7	1248.6	27.3	22.7
1955	2.44	17.8	89.8		22.4	1903	23.68	14.7	1263.3		22.6
1954	3.00	20.2	110.0	22.0	22.0	1902	24.01	20.9	1284.2		22.5
1953	3.49	21.4	131.4		21.9	1901	24.33	20.3	1304.5		22.5
1952	3.91	19.2	150.6		21.5	1900	24.73	25.8	1330.3		22.5
1951	4.41	21.4	172.0		21.5	1899	25.08	23.1	1353.4	20.1	22.6
1950	4.93	24.1	196.1		21.8	1898	25.35	17.6	1371.0		22.5
1949	5.45	22.8	218.9	21.8	21.9	1897	25.60	16.2	1387.2		22.4
1948	5.74	13.4	232.3		21.0	1896	25.92	21.0	1408.2		22.4
1947	6.21	21.4	253.7		21.1	1895	26.24	21.1	1429.3		22.3
1946	6.55	16.5	270.2		20.8	1894	27.00	49.9	1479.2	25.2	22.8
1945	7.28	37.4	307.6		22.0	1893	27.30	19.7	1498.9		22.7
1944	7.62	17.7	325.3	21.3	21.7	1892	27.62	21.4	1520.3		22.7
1943	8.06	21.6	346.9		21.7	1891	27.98	23.9	1544.2		22.7
1942	8.54	23.9	370.8		21.8	1890	28.20	14.8	1559.0		22.6
1941	8.76	11.6	382.4		21.2	1889	28.43	15.5	1574.4	19.1	22.5
1940	9.08	16.2	398.6		21.0	1888	29.72	19.5	1594.0		22.5
1939	9.60	27.6	426.2	20.2	21.3	1887	29.15	28.9	1622.9		22.6
1938	9.99	20.3	446.5		21.3	1886	29.46	20.9	1643.8		22.5
1937	10.41	22.0	468.5		21.3	1885	29.67	14.4	1658.2		22.4
1936	10.68	14.7	483.2		21.0	1884	29.96	19.6	1677.8	20.7	22.4
1935	11.33	35.2	518.4		21.6	1883	30.28	21.5	1699.3		22.4
1934	11.77	24.5	542.9	23.4	21.7	1882	30.51	15.6	1714.9		22.3
1933	12.24	26.0	568.9		21.9	1881	30.98	31.8	1746.7		22.4
1932	12.51	14.6	583.5		21.6	1880	31.26	19.0	1765.7		22.4
1931	12.88	20.8	604.3		21.6	1879	31.50	16.2	1781.9	20.8	22.3
1930	13.28	22.3	626.6		21.6	1878	31.81	21.5	1803.4		22.3
1929	13.55	15.5	642.1	19.8	21.4	1877	32.25	30.3	1833.7		22.4
1928	14.10	31.8	673.9		21.7	1876	32.50	17.2	1850.9		22.3
1927	14.51	23.6	697.5		21.8	1875	32.78	19.2	1870.1		22.3
1926	14.78	15.8	713.3		21.6	1874	33.02	16.4	1886.5	20.9	22.2
1925	15.28	28.5	741.8		21.8	1873	33.29	18.7	1905.2		22.2
1924	15.61	19.6	761.4	23.9	21.8	1872	33.54	17.2	1922.4		22.1
1923	16.01	23.4	784.8		21.8	1871	33.76	14.5	1936.9		22.0
1922	16.50	29.5	814.3		22.0	1870	34.02	18.7	1955.6		21.9
1921	16.76	15.4	829.7		21.8	1869	34.27	17.3	1972.9	17.3	21.9
1920	17.16	24.1	853.8		21.9	1868	34.61	23.6	1996.5		21.9
1919	17.59	26.1	879.9	23.7	22.0	1867	34.90	20.0	2016.5		21.9
1918	18.14	35.4	915.3		22.3	1866	35.14	16.6	2033.1		21.9
1917	18.44	18.3	933.6		22.2	1865	35.50	25.1	2058.2		21.9
1916	18.80	22.4	956.0		22.2	1864	35.82	22.5	2080.7	21.5	21.9
1915	19.01	12.8	968.8		22.0	1863	36.15	23.2	2103.9		21.9
1914	19.26	15.3	984.1	20.8	21.9	1862	36.60	32.6	2136.5		22.0
1913	19.78	31.8	1015.9		22.1	1861	36.81	14.8	2151.3		22.0
1912	20.08	18.5	1034.4		22.0	1860	37.23	29.7	2181.0		22.0
1911	20.55	29.3	1063.7		22.2	1859	37.46	16.6	2197.6	23.4	22.0
1910	20.93	23.8	1087.5		22.2	1858	37.96	36.0	2233.6		22.1
1909	21.32	24.6	1112.1	25.6	22.2	1857	38.24	20.2	2253.8		22.1
1908	21.70	24.1	1136.2		22.3	1856	38.47	16.7	2270.5		22.0
1907	22.00	19.3	1155.5		22.2	1855	38.86	28.3	2297.8		22.1

APPENDIX B. DEEP CORE DENSITIES

Byrd Station

(All values below 64 m corrected for in situ temperatures.)

Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})
0-1	.366	36-37	.710	72-73	.8677	157-158	.9133
1-2	.388	37-38	.715	73-74	.8666	164	.9139
2-3	.406	38-39	.723	74-75	.8700	168	.9142
3-4	.440	39-40	.724	75-76	.8731	171	.9140
4-5	.451	40-41	.729	76-77	.8738	174	.9145
5-6	.476	41-42	.736	77-78	.8749	175	.9144
6-7	.493	42-43	.738	78-79	.8788	177	.9141
7-8	.516	43-44	.746	79-80	.8807	180	.9146
8-9	.524	44-45	.743	80-81	.8796	182	.9145
9-10	.544	45-46	.750	81-82	.8825	186	.9148
10-11	.546	46-47	.757	82-83	.8833	187	.9148
11-12	.560	47-48	.762	83-84	.8853	188	.9149
12-13	.565	48-49	.773	84-85	.8865	191	.9147
13-14	.575	49-50	.771	85-86	.8875	193	.9148
14-15	.582	50-51	.781	86-87	.8896	198	.9152
15-16	.593	51-52	.786	87-88	.8905	199	.9152
16-17	.599	52-53	.786	88-89	.8916	203	.9155
17-18	.606	53-54	.796	89-90	.8939	206	.9153
18-19	.613	54-55	.790	90-91	.8944	209	.9151
19-20	.624	55-56	.798	91-92	.8943	214	.9152
20-21	.626	56-57	.798	92-93	.8961	219	.9153
21-22	.632	57-58	.809	93-94	.8952	226	.9153
22-23	.634	58-59	.815	94-95	.8957	233	.9153
23-24	.630	59-60	.813	95-96	.8972	242	.9157
24-25	.638	60-61	.816	96-97	.8983	247	.9154
25-26	.643	61-62	.820	97-98	.8978	252	.9158
26-27	.653	62-63	.825	98-99	.8998	258	.9157
27-28	.655	63-64	.830	99-100	.9001	264	.9156
28-29	.660	64-65	.8456	103-104	.9026	268	.9155
29-30	.673	65-66	.8471	109-110	.9055	280	.9155
30-31	.676	66-67	.8505	115-116	.9074	284	.9155
31-32	.684	67-68	.8510	121-122	.9084	291	.9158
32-33	.690	68-69	.8529	128-129	.9104	296	.9160
33-34	.695	69-70	.8595	134-135	.9111	302	.9157
34-35	.699	70-71	.8568	144-145	.9125	307	.9159
35-36	.704	71-72	.8645	151-152	.9129		

Little America V

(All values below 52 m corrected for in situ temperatures.)

Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})	Depth (m)	Density (g cm^{-3})
0-1	0.360	26-27	0.657	53.0	0.8578	91.0	0.9061
1-2	0.385	27-28	0.664	54.0	0.8601	92.0	0.9044
2-3	0.402	28-29	0.673	56.0	0.8692	94.0	0.9095
3-4	0.426	29-30	0.673	57.5	0.8740	95.0	0.9081
4-5	0.442	30-31	0.675	59.0	0.8778	101.0	0.9084
5-6	0.441	31-32	0.680	61.0	0.8810	102.5	0.9084
6-7	0.476	32-33	0.687	61.5	0.8863	104.5	0.9080
7-8	0.515	33-34	0.690	63.0	0.8874	107.0	0.9074
8-9	0.501	34-35	0.692	64.0	0.8934	108.5	0.9082
9-10	0.522	35-36	0.699	66.0	0.8926	111.5	0.9078
10-11	0.541	36-37	0.708	67.5	0.8920	116.5	0.9089
11-12	0.548	37-38	0.711	69.0	0.8960	119.5	0.9103
12-13	0.569	38-39	0.741	70.0	0.8976	130.0	0.9104
13-14	0.572	39-40	0.738	71.0	0.8994	140.0	0.9125
14-15	0.574	40-41	0.750	73.5	0.9011	144.5	0.9131
15-16	0.579	41-42	0.743	74.5	0.9011	155.0	0.9129
16-17	0.595	42-43	0.763	76.5	0.9021	165.0	0.9115
17-18	0.605	43-44	0.764	78.0	0.9012	175.0	0.9121
18-19	0.608	44-45	-	79.0	0.9014	181.0	0.9119
19-20	0.611	45-46	0.790	80.5	0.9028	190.0	0.9118
20-21	0.624	46-47	0.800	82.0	0.9035	200.5	0.9113
21-22	0.635	47-48	0.812	83.5	0.9031	210.5	0.9119
22-23	0.644	48-49	0.811	85.0	0.9032	221.0	0.9121
23-24	0.638	49-50	0.820	86.5	0.9038	229.5	0.9109
24-25	0.644	50-51	0.834	88.0	0.9049	249.0	0.9120
25-26	0.655	51-52	0.840	89.0	0.9055		

APPENDIX C. DEPTH-LOAD VALUES FROM DEEP CORE DENSITY DATA

Byrd Station

Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})
1	0.0366	30	1.691	59	3.860	88	6.360
2	0.0754	31	1.759	60	3.941	89	6.449
3	0.116	32	1.827	61	4.023	90	6.538
4	0.160	33	1.896	62	4.105	91	6.627
5	0.205	34	1.966	63	4.187	92	6.717
6	0.253	35	2.036	64	4.270	93	6.806
7	0.302	36	2.106	65	4.355	94	6.896
8	0.354	37	2.177	66	4.439	95	6.986
9	0.406	38	2.249	67	4.524	96	7.076
10	0.460	39	2.321	68	4.609	97	7.165
11	0.515	40	2.393	69	4.695	98	7.255
12	0.571	41	2.393	70	4.781	99	7.345
13	0.628	42	2.540	71	4.866	100	7.436
14	0.685	43	2.614	72	4.953	110	8.838
15	0.743	44	2.688	73	5.040	120	9.245
16	0.803	45	2.763	74	5.127	130	10.154
17	0.862	46	2.838	75	5.214	140	11.066
18	0.923	47	2.913	76	5.301	150	11.978
19	0.984	48	2.990	77	5.388	160	12.892
20	1.047	49	3.067	78	5.476	170	13.805
21	1.109	50	3.144	79	5.564	180	14.720
22	1.173	51	3.222	80	5.652	190	15.635
23	1.236	52	3.301	81	5.740	200	16.549
24	1.299	53	3.379	82	5.828	220	18.380
25	1.362	54	3.459	83	5.916	240	20.211
26	1.427	55	3.538	84	6.004	260	22.042
27	1.492	56	3.618	85	6.094	280	23.873
28	1.558	57	3.697	86	6.182	300	25.705
29	1.624	58	3.778	87	6.271	309	26.529

Little America V

Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})	Depth (m)	Load (kg cm^{-2})
1	0.0360	21	1.090	41	2.457	95	7.175
2	0.074	22	1.153	42	2.531	100	7.629
3	0.115	23	1.217	43	2.608	110	8.537
4	0.157	24	1.281	44	2.684	120	9.447
5	0.202	25	1.346	45	2.762	130	10.357
6	0.246	26	1.411	46	2.841	140	11.268
7	0.293	27	1.477	47	2.921	150	12.180
8	0.345	28	1.543	48	3.002	160	13.092
9	0.395	29	1.611	49	3.083	170	14.004
10	0.447	30	1.678	50	3.165	180	14.916
11	0.501	31	1.745	51	3.248	190	15.828
12	0.556	32	1.813	52	3.332	200	16.740
13	0.613	33	1.882	55	3.590	210	17.651
14	0.670	34	1.951	60	4.026	220	18.563
15	0.727	35	2.020	65	4.470	230	19.474
16	0.785	36	2.090	70	4.917	240	20.386
17	0.845	37	2.161	75	5.367	250	21.297
18	0.905	38	2.232	80	5.818	258	22.027
19	0.966	39	2.306	85	6.269		
20	1.027	40	2.383	90	6.722		

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Anthony J. Gow

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13. ABSTRACT
Snow and ice cores from two deep drill holes in Antarctica were studied to determine past records of snow accumulation and density variations with depth in the Antarctic ice sheet. Data on the variation of porosity and ice load with depth were also obtained. Byrd Station, located on the inland ice of West Antarctica, was the site of the first drill hole, which reached a depth of 309 m in ice estimated to be about 2500 m thick. Detailed analysis of the core stratigraphy to 88.6 m depth showed that the snow has been accumulating at an average rate of 15.6 g cm^{-2} annually since 1549 AD. Apart from a small but persistent decline in accumulation between 1839 and 1954 no major variations in snow accumulation were observed. The total absence of melt layers would indicate that surface air temperatures in the vicinity of Byrd Station have not risen above freezing for the last 1900 years - the estimated age of the ice at 309-m depth. A second hole was drilled at Little America V at a point less than 3 km from the seaward edge of the Ross Ice Shelf. The ice at this location was about 258 m thick and cores were obtained to within 2 to 3 m of the bottom. No saline ice was encountered in any of the cores and all indications are that the bottom of the Ross Ice Shelf at Little America V is melting rather than accreting sea ice. Studies of core stratigraphy to 39-m depth revealed 105 years of snow deposition; the average rate of accumulation was 22.1 g cm^{-2} yr^{-1}. Occasional periods of intensive melt were observed throughout the stratigraphic sequence but no significant deviations in the accumulation record were detected. Three thin layers of debris, tentatively identified as volcanic ash, were observed at depths of 171, 219 and 223 m respectively.

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Abstract (Cont'd)

These ashes are thought to have been deposited from volcanoes in Marie Byrd Land more than 2000 years ago. Depth-density and surface elevation data show that the Ross Ice Shelf at Little America V is free floating and almost exactly five-sixths submerged. An anomalous increase in the rate of densification of firn below 35 m is attributed to large horizontal stresses in the ice shelf. At Little America firn transformed into ice at 51 to 52 m after only about 150 years. The same transformation at Byrd Station took nearly 300 years and was accomplished at 64-65 m depth. The densification process in polar snow is discussed and a method of predicting depth-density profiles from mean annual accumulation and temperature data is presented together with examples and other useful applications of the data.