

CLIMATOLOGICAL IMPLICATIONS OF MICROPARTICLE CONCENTRATIONS IN THE ICE CORE FROM "BYRD" STATION, WESTERN ANTARCTICA*

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ABSTRACT. The concentration of microparticles in the 2 164 m long ice core from "Byrd" station, Antarctica, varies cyclically. Highest concentrations of 0.65 µm diameter microparticles occur where oxygen-isotope studies show lowest paleotemperatures. The age of the bottom ice estimated from microparticle-concentration variations, assuming an annual cycle, is 27 000 years, much less than from oxygen-isotope studies.

RÉSUMÉ. *Conséquences climatologiques des taux de concentrations de microparticules contenues dans les carottes de glace de la station "Byrd", Antarctique Ouest.* Les concentrations de microparticules tout au long des 2 164 m de la carotte de glace provenant de la station "Byrd", Antarctique, varient périodiquement. La plus forte concentration en particules de diamètre 0,65 µm se produit lorsque l'étude de l'oxygène 18 conduit aux plus basses températures pour le climat de l'époque. L'âge des couches de glace les plus anciennes, estimé à partir des variations de concentration des microparticules, serait de 27 000 ans, valeur très inférieure à celle obtenue par ^{18}O .

ZUSAMMENFASSUNG. *Klimatologische Folgerungen aus Mikroteilchenkonzentrationen in der Eiskernprobe aus "Byrd"-Station, Westliche Antarktis.* Die Konzentration der Mikroteilchen in der 2 164 m langen Eiskernprobe aus "Byrd"-Station in der Antarktis variiert zyklisch. Die höchsten Konzentrationen der Mikroteilchen von 0,65 µm Durchmesser erscheinen dort, wo Sauerstoffisotopenuntersuchungen die niedrigsten Paleotemperaturen aufzeigen. Mit Annahme eines jährlichen Zyklus ist das aus Schwankungen der Mikroteilchen Konzentration geschätzte Alter des Bodeneises 27 000 Jahre, viel weniger als aus Sauerstoffisotopenuntersuchungen.

INTRODUCTION

The first bore hole through the Antarctic ice sheet was completed in January 1968, when engineers from the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) recovered most of the 2 164 m long ice core to bedrock drilled at new "Byrd" station (lat. 80° S., long. 120° W.) (Gow and others, 1968). At this site the annual positive balance of snow is about 14 g cm⁻² and the mean annual air temperature is -28° C (Bull, 1971), so that very little, if any, melting occurs at the surface, and the annual balance is sufficiently large to allow the preservation of the stratigraphic record of the deposition of microparticles.

Using modifications of techniques first developed by Marshall (1959, 1962), an analysis has been made of the size distribution and concentration of microparticles in the size range 0.518–13.1 µm diameter, in 15 representative continuous sections, averaging a little over 1 m in length, from the "Byrd" ice core (Table I). The sections are quarter-core segments sawn from 10.8 cm diameter core. Using a Model "T" Coulter counter, the number of particles in each of 15 size ranges was measured in 500 µl samples of melt water from specimens of the core, each 2.5 cm, or less, in length. Altogether, in this study, two or more counter runs were made on melt-water specimens from each of 821 samples from the ice core.

THE "BYRD" ICE CORE AND PREVIOUS WORK ON IT

Descriptions of the ice core have been given by Gow and Williamson (1971). In the upper 900 m of the core, crystal orientations are essentially random, but below 1 200 m the principal crystallographic axes (*c*-axes) of all ice crystals are orientated within 15° of the vertical. The

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TABLE I

Core number	Depth from surface m	Length of section cm	$\delta^{18}\text{O}$ values	Concentration of particles less than 0.65 μm		Coarseness equals $\frac{\text{No.} > 1.64 \mu\text{m dia.}}{\text{No.} > 0.65 \mu\text{m dia.}}$	Concentration of small particles 0.65–0.82 μm cleanest 10%
				T.	M.		
61	180.00	31.0	-33.0	1 665	0.075 1	0.075 1	391
74	199.33	127.0	T. -33.0 M. -34.0 B. -33.1	1 859	0.058 6	0.058 6	280
216	401.29	137.5	T. -33.0 B. -32.7	5 197	0.120 0	0.120 0	684
331	565.00	144.0	T. -34.3 B. -34.7	22 108	0.136 0	0.136 0	2 350
422	699.85	131.0	-33.3	14 346	0.148 0	0.148 0	2 890
552	896.94	101.5	T. -33.6 B. -35.1	3 928	0.092 4	0.092 4	650
651	1 046.79	154.5	T. -34.2 M. -34.8 B. -34.5	8 066	0.086 7	0.086 7	515
751	1 194.06	74.0	-37.3	3 556	0.098 0	0.098 0	977
852	1 342.71	151.0	T. -41.3 M. -41.1 B. -41.4	14 461	0.046 0	0.046 0	3 533
875	1 387.00	76.0	-42.2	19 151	0.044 8	0.044 8	3 345
884	1 389.66	150.0	T. -42.2 M. -42.1 B. -42.3	8 985	0.051 0	0.051 0	3 942
1 016	1 599.00	56.5	-40.5	24 700	0.074 8	0.074 8	3 186
1 049	1 633.72	142.5	T. -40.3 M. -38.9 B. -39.2	4 920	0.054 8	0.054 8	2 130
1 229	1 900.00	146.0	T. -40.2 M. -40.2 B. -41.0	3 079	0.068 0	0.068 0	1 710
1 393	2 139.61	139.3	-34.3	3 099	0.078 9	0.078 9	771

crystal size is smaller in bands in the depth range from 1 200 to 1 800 m, but otherwise generally increases from top to bottom of the core. Below 1 800 m the *c*-axis orientations become more dispersed. Between 400 and 900 m depth the ice core is fragile and badly fractured, an observation of significance to our studies.

"Dirt" bands occur at intervals along the core, the majority being between 1 100 and 2 100 m. Gow and Williamson (1971) identified 25 "ash bands" (containing macroscopic particles) and about 2 000 "dust bands" (containing particles not visible to the unaided eye). Both kinds of layers have been attributed by Gow and Williamson (1971) to volcanic eruptions. The interval of maximum volcanic ash fall, between 1 100 and 2 100 m, corresponds to the interval where the $\delta^{18}\text{O}$ data (Epstein and others, 1970; Johnsen and others, 1972) indicate maximum cooling of the Antarctic atmosphere. The concentration of major cationic constituents, Na^+ , K^+ , Ca^{++} and Mg^{++} , is also largest between 1 193 and 2 100 m, probably due to increased local volcanic activity (Ragone and Finelli, 1972).

Lamb (1970) noted that major historic volcanic eruptions are usually followed by periods of cooling in the lower troposphere, and Rasool and Schneider (1971), in model studies, demonstrated that increased atmospheric optical density (higher dust concentrations) would reduce surface temperatures. The variations in the ratio of oxygen isotopes ^{18}O and ^{16}O

in the ice cores from Camp Century, Greenland, and "Byrd" station, Antarctica (Epstein and others, 1970; Johnsen and others, 1972), together with some knowledge of the flow characteristics of ice at these locations, has allowed calculations of ages for the two ice sheets. Although the present study gives an alternative interpretation for the age of the west Antarctic ice sheet, the oxygen-isotope work shows that the most negative $\delta^{18}\text{O}$ values represent snow that fell during the Wisconsin II glaciation, and that younger and older snow has less negative $\delta^{18}\text{O}$ values.

Hamilton and Seliga (1972) consolidated these ideas, which point to a cause-and-effect relationship between atmospheric turbidity and temperature, and the present study is aimed at establishing the relationships more exactly, by comparing the particle concentrations in the "Byrd" core with the oxygen-isotope ratios.

LABORATORY TECHNIQUES

The basic procedures for analyzing the microparticles in ice samples were established by Marshall (1962), and greatly refined by Bader and others (1965). Taylor and Glioza (1964) modified the techniques for use in the clean-room facilities at the Institute of Polar Studies, Ohio State University, and further refinements have been described by Hamilton (1967, 1969). A full description of the techniques used in the present study has been given by Thompson (1973).

After careful annotation of the core sections, including orientation, size and number of air bubbles and fractures, color variations and "dirt" bands, they were cut into samples, usually of 2.5 cm length, but reduced to 2.0 cm for the sections from below 1900 m and to 1.0 cm for the 31 cm section from 180 m depth and the 76 cm section from 1377 m.

In the clean room, samples were decontaminated by thoroughly rinsing with water, which had been demineralized in an ion-exchange resin column and sequentially filtered through "Millipore" filters of 0.45 and 0.22 μm pore size. In this process, at least 2 mm of ice was melted from the samples, which were then melted in cleaned, covered, plastic containers in a vibrating water bath. About 20 ml of water was obtained from each 2 or 2.5 cm thick sample.

Analytically pure NaCl dissolved in pure filtered water was added to the melt water to convert it to 2.27% NaCl solution. Only one-half of each quarter-core section was analyzed at a time, the second half being analyzed about 2 months later.

The microparticles in two 500 μl samples of the melt water were counted with a 15 channel Model "T" Coulter counter, set so that the average particle volume counted in adjacent channels changes by a factor of two. For channel 14, the lower threshold diameter was 0.518 μm and the mean diameter of particles counted was 0.581 μm ; for channel 0 the upper threshold diameter measured was 13.1 μm .

Thompson (1973) has described the methods of calibrating the counter and of ensuring that the calibration does not change. He also discussed sources of contamination and error. We are convinced that contamination in the laboratory is not a problem, so that the results for sound ice samples are meaningful. However, with ice samples from the fractured zone of the core, 400–900 m depth, our washing techniques are not adequate to assure removal of contaminating particles from the network of internal fractures that may have been introduced during drilling, transport or storage.

COMPARISON OF MICROPARTICLE CONCENTRATIONS AND $\delta^{18}\text{O}$ VALUES IN CORE SECTIONS FROM 180 AND 1377 m DEPTH

The early experiments of Marshall (1962) indicated a periodic variation in the micro-particle concentration in ice samples from the "Byrd" station area of Antarctica. He suggested that the variations were annual and that they could be used in detecting annual layering. At

the South Pole the spring and, to a lesser extent, the autumn snow precipitation is characterized by high concentrations of microparticles (Hamilton, 1969), so that, at that site (where the annual positive balance is quite small, about 8 g cm^{-2}) there are difficulties in determining the annual layering using only measurements of microparticle concentrations. At "Eights" station (lat. $75^{\circ} 14' \text{ S}$, long. $77^{\circ} 10' \text{ W}$), Taylor and Gliozzi (1964) also detected a periodic variation in microparticle concentration which was later (Bull, 1971) shown to be annual.

The most careful considerations of particle depositional mechanisms and patterns have been made by Hamilton (1969). Earlier Junge (1963, p. 111–202) had shown that most natural aerosols in the troposphere range from 0.1 to $20 \mu\text{m}$ and Kumai and Francis (1962) demonstrated the importance of these aerosols in the formation of snow crystals. A relatively large microparticle is almost always present at the center of a snow crystal, with many smaller particles in the remainder of the crystal. Hamilton (1969) proposed that variations in the microparticle depositional pattern can be caused by variations in the air temperature and saturation ratio because smaller particles can serve as nuclei at higher saturation ratios and lower temperatures.

Many investigators have used variations in the abundance ratio of the stable isotopes of oxygen and hydrogen in polar ice samples to determine variations in the air temperature at the time of crystallization, and hence to determine annual layering, for example, Dansgaard and others (1969), Epstein and others (1970), and Johnsen and others (1972).

The $\delta^{2}\text{H}$ and $\delta^{18}\text{O}$ variations in an ice core, however, do not necessarily provide a perfect record of near-surface air-temperature variations, because the temperature of the air mass in which the snow is formed may not be simply related to the near-surface air temperature where the snow is deposited. Furthermore, deflation and re-deposition, variations in the

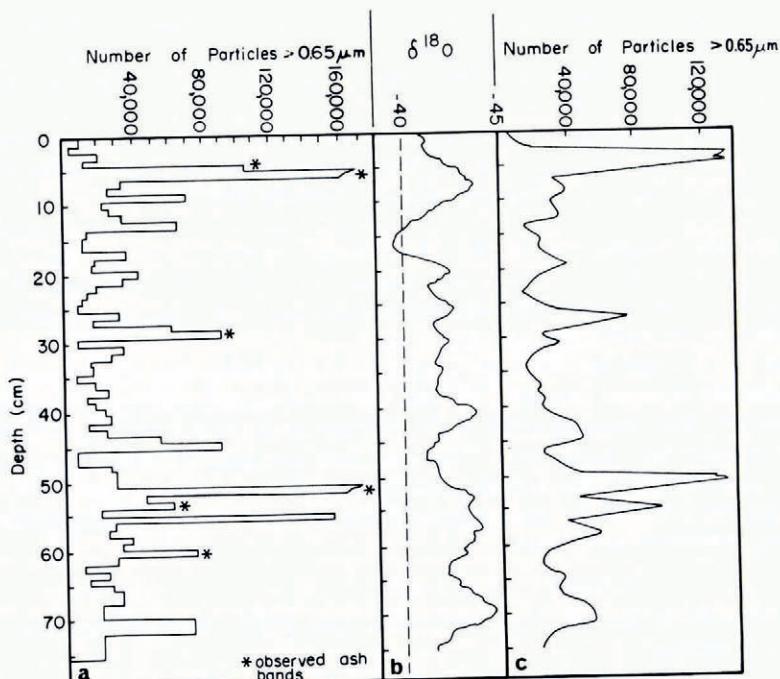


Fig. 1. Vertical profiles from the "Byrd" ice core: (a) Particle concentration for 1 cm samples; (b) $\delta^{18}\text{O}$ values after Johnsen and others (1972); (c) Particle concentration where the sample size has been mathematically increased to 2 cm for 15 500 year-old Antarctic ice. High particle concentrations tend to occur in ice with high negative $\delta^{18}\text{O}$.

amount of summer and winter snowfall, and isotopic diffusion after deposition may all affect the isotopic record.

In 700 year-old ice from Camp Century, Greenland, where the annual variations in the stable oxygen-isotope ratios are well marked, Hamilton and Langway (1967) obtained excellent correspondence between variations in the microparticle concentrations and those in the $\delta^{18}\text{O}$ values, the snow in late winter or early spring containing the highest microparticle concentrations. At this site, it appears that microparticle and stable-isotope stratigraphies yield reliable estimates of ice chronology, at least in the upper part of the ice sheet where diffusion has not erased the annual $\delta^{18}\text{O}$ variations.

According to the time scale of Johnsen and others (1972), the ice at 1377 m depth at "Byrd" station is approximately 15 500 years old. In Figure 1 are given the profiles of $\delta^{18}\text{O}$ values, determined from very thinly sliced samples at 1377 m (Johnsen and others, 1972) and of the microparticle concentrations (here defined as the number of particles larger than $0.65 \mu\text{m}$ diameter per 500 μl of melt water) in 1 cm slices of the same piece of core. In Figure 1a, these concentrations are shown as measured on the 1 cm samples; in Figure 1c, they are smoothed, binomially, to give 2 cm running means for comparison with the $\delta^{18}\text{O}$ variations of Figure 1b. The match is good but not perfect; part of the mismatching probably arises because some of the particle-concentration peaks are in ash bands representing local volcanic activity which obscure seasonal variations.

In the 31 cm long section from 180 m (800 years b.p.) the variations in $\delta^{18}\text{O}$ (Fig. 2) are not sufficiently pronounced to allow the unambiguous identification of annual layering, but the microparticle-concentration profile does show periodic variations which may be related to the annual layering.

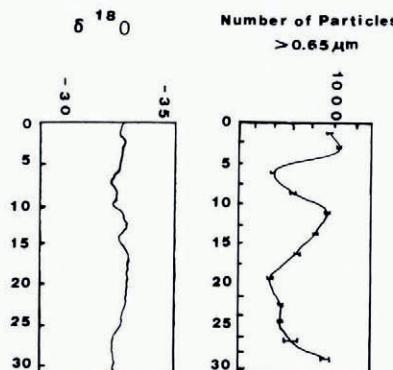


Fig. 2. Vertical profiles of particle concentration and $\delta^{18}\text{O}$ values in 800 year old Antarctic ice. Note the small variations in particle concentration and in $\delta^{18}\text{O}$.

VARIATIONS IN MICROPARTICLE CONCENTRATIONS AND OXYGEN-ISOTOPE RATIOS OVER MILLENNIAL TIME INTERVALS

Following the conclusions of Hamilton and Seliga (1972), on the relationships between atmospheric turbidity and temperature, representative samples from the entire "Byrd" core have been examined. The two main objectives were to determine: (i) how the microparticle concentrations and size distributions vary over the time period represented by the core, and (ii) whether these variations are related to variations in the paleotemperatures as indicated by the $\delta^{18}\text{O}$ values. We felt that it might be possible to distinguish between local microparticles (derived from local land surfaces and volcanic eruptions) and global microparticles being carried by atmospheric circulation from distant sources, in terms of ratios of numbers of coarse and fine particles. The diameter of natural tropospheric particles ranges from 0.1 to

20 μm (Junge, 1963, p. 111–202) and the effect of gravity is negligible on particles smaller than 1 μm . Hence, in the “Byrd” core, the global microparticles are concentrated in the smaller particle sizes, while the local microparticles show greater concentrations in the coarser fraction. Table I gives the basic data on the 15 core sections measured. The numbers of microparticles refer to 500 μl samples.

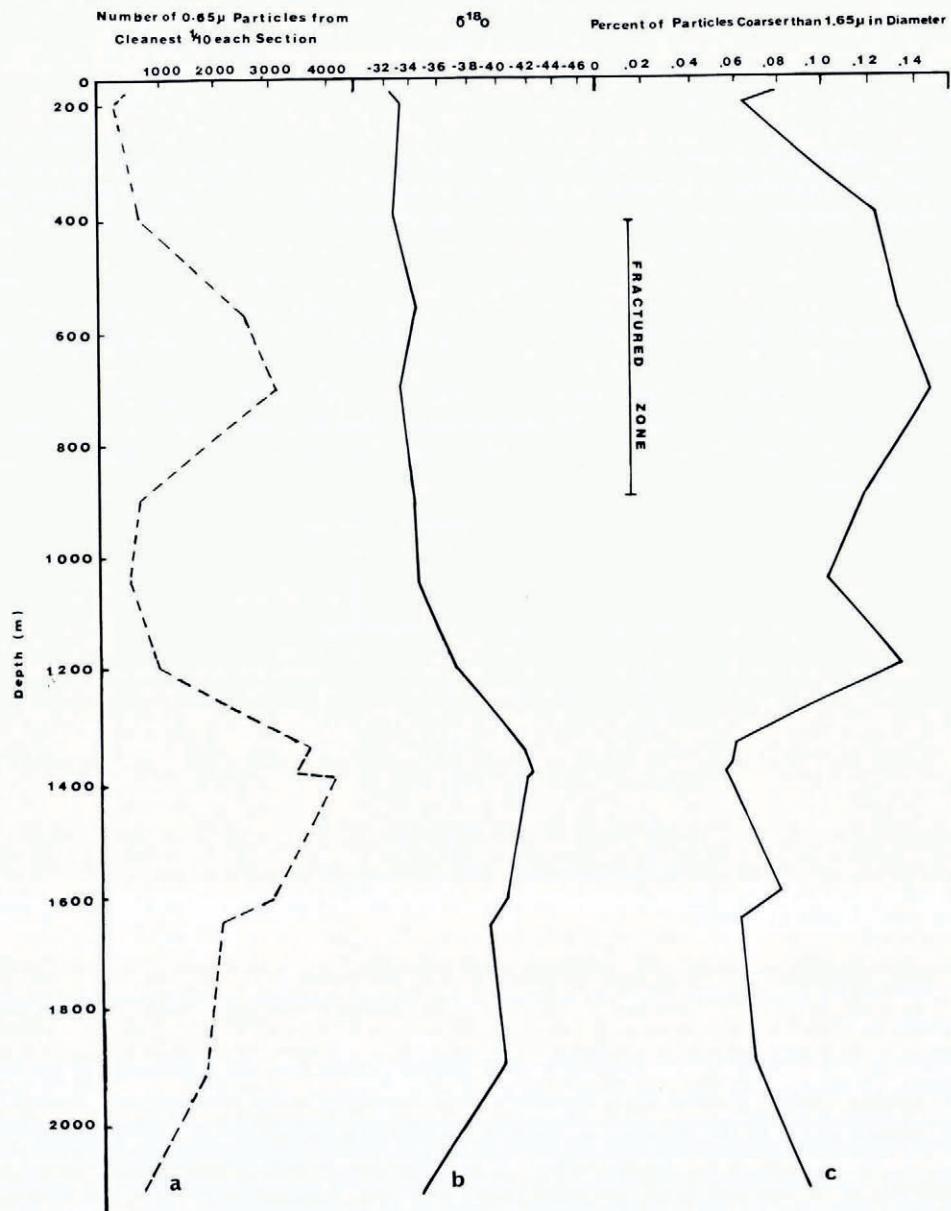


Fig. 3. Data from the “Byrd” station ice core: (a) Profile obtained from plotting the number of 0.65–0.82 μm diameter particles for the cleanest 10% of the samples from each of the core sections against depth. (b) Profile resulting from plotting Epstein and others (1970) $\delta^{18}\text{O}$ values for the core sections analyzed in Figure 4. (c) Average percentage of particles coarser than 1.65 μm for the sections of the “Byrd” core analyzed.

An attempt to restrict our considerations to the global particle concentrations, by disregarding ice samples containing large particles and high total concentrations of particles, has been made by examining the numbers of small microparticles (0.653–0.822 μm diameter) per 500 μl of melt water, in the cleanest 10% of the samples cut from each core section. These would presumably represent snow accumulation in the periods when the Antarctic atmosphere contained least amounts of locally derived dust or short-duration global dust clouds. In Figure 3 these concentrations are compared with Epstein and others (1970) $\delta^{18}\text{O}$ values for the same sections. The profiles match well except for the peak in the microparticle concentrations at 400–900 m depth. This is the fractured part of the core (Gow and others, 1968) and the high concentration of microparticles is probably contamination. The relationship between small-diameter microparticle concentrations in these cleanest samples and $\delta^{18}\text{O}$ values is shown in Figure 4. Except for the two samples from the fractured zone, the number of microparticles increases approximately exponentially as the $\delta^{18}\text{O}$ values become more negative.

In Figure 3c the profile is given of the coarseness of the microparticles, expressed as the average percentage, for all of the samples from a section, of the number of microparticles greater than 1.65 μm diameter, compared with the total number of microparticles. Again,

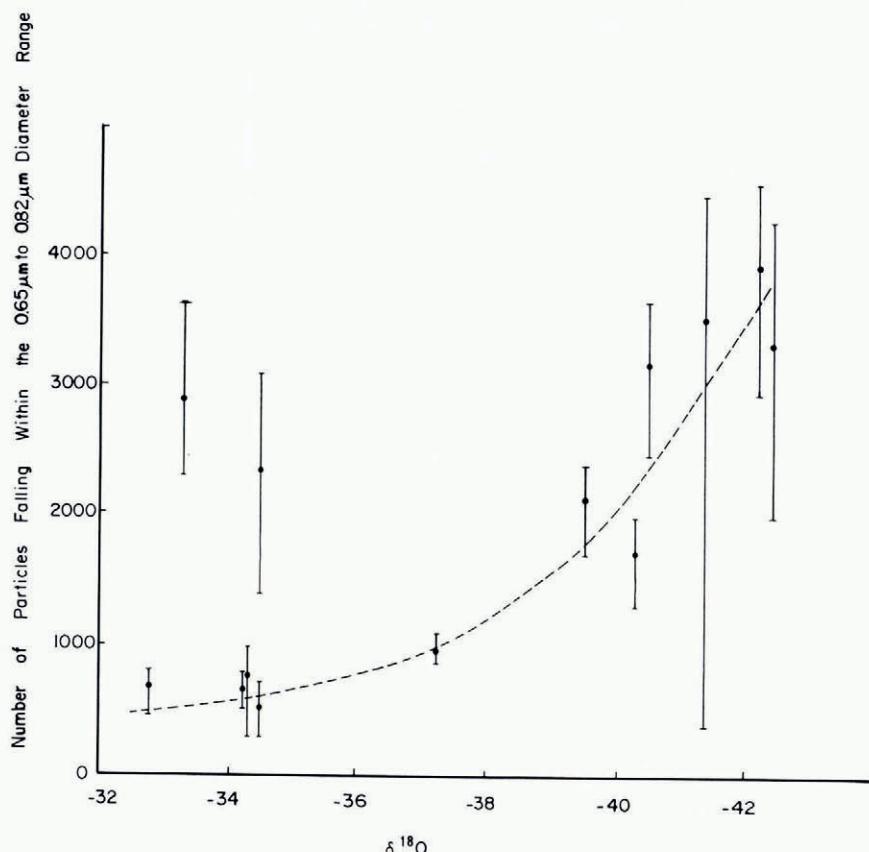


Fig. 4. Illustration of $\delta^{18}\text{O}$ values plotted against the number of 0.65–0.82 μm diameter particles per 500 μl in the cleanest 10% of the samples from each core section. The length of the vertical line indicates the variance of values within each core section and the small circle indicates the average value. There is an exponential increase in the number of particles with a linear decrease in $\delta^{18}\text{O}$.

a close relationship exists between this percentage and the $\delta^{18}\text{O}$ variations; the largest percentages of coarser microparticles occur in ice with the least negative $\delta^{18}\text{O}$ values, corresponding to warmer temperature intervals.

CHRONOLOGY FOR THE "BYRD" CORE DERIVED FROM VARIATIONS IN MICROPARTICLE CONCENTRATIONS

Although conclusive proof is lacking that the short-period variations in microparticle concentrations are annual, the earlier work referred to above, and the detailed studies on the sections at 180 and 1377 m give strong presumptive evidence. (In the 1973-74 Antarctic

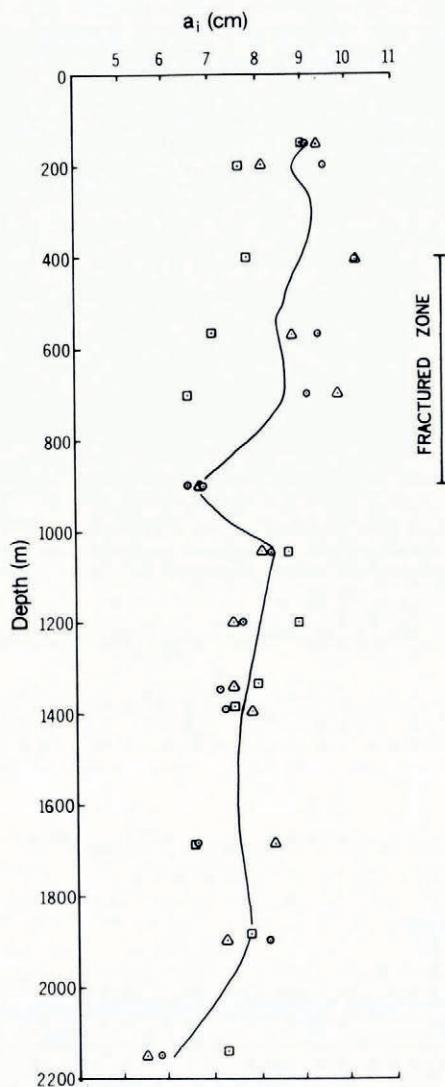


Fig. 5. The annual accumulation of ice in cm (a_1) for each core section plotted according to depth in meters as determined from particle peak counts. The solid line represents the average a_1 values for the three parameters.

The a_1 values are determined from variations in the following: 0.65–0.82 μm diameter particles, \triangle ; 1.65–2.07 μm diameter particles, \square ; particles greater than 1.65 μm in diameter, \circ .

field season one of us (L.G.T.) collected samples for microparticle analysis from areas near "Byrd" station where the snow stratigraphy and chronology are well known.)

If, however, one assumes that the cycle of microparticle concentrations is annual, the age for the ice at the bottom could be obtained by counting the peaks throughout the core. Such an analysis is not practical at present. Instead, we have counted the numbers of peaks in the profiles of microparticles of selected sizes for the 13 analyzed sections and have assumed that the thickness, a_i , of the annual accumulation, for the measured sections may be applied to the unanalyzed parts. The variations of a_i for three ranges of microparticle diameters is shown in Figure 5. Thinning by vertical strain causes a reduction in a_i with increasing depth. Assuming that the balance at the surface has remained constant, the vertical strain-rate is about $-28 \times 10^{-5} \text{ a}^{-1}$, in remarkable agreement with the near-surface vertical strain-rate of $-27 \times 10^{-5} \text{ a}^{-1}$ calculated by I. Whillans (personal communication) from measurements on the "Byrd" station strain net. In fact, the ice now at depth under "Byrd" station fell as snow at the surface farther up the flow line, where the balance is now greater than at "Byrd" station (Whillans, 1975).

The ages calculated from the values of a_i for the different size ranges of microparticles are shown in Figure 6, together with Johnsen and others (1972) age-depth curve calculated from variations in $\delta^{18}\text{O}$ values. In comparing the records from "Byrd" station and from Camp Century, Greenland, Johnsen and others pointed out that, while the $\delta^{18}\text{O}$ record is very well preserved in the Greenland core, so that their age estimates are reliable, the $\delta^{18}\text{O}$ record from the "Byrd" core does not show well-preserved short-period cyclic variations, so that their age estimates are questionable, as they recognize.

Adjusting the time scale of Johnsen and others (1972) $\delta^{18}\text{O}$ profile from "Byrd" station to the 27 000 year age estimate for the bottom ice from Figure 6, one obtains the profile shown in Figure 7b. This shows a much greater correspondence with the Camp Century profile (Fig. 7a) than does the original "Byrd" profile (Fig. 7c). It is tempting to conclude that the close similarity between Figure 7a and b lends support to the microparticle method

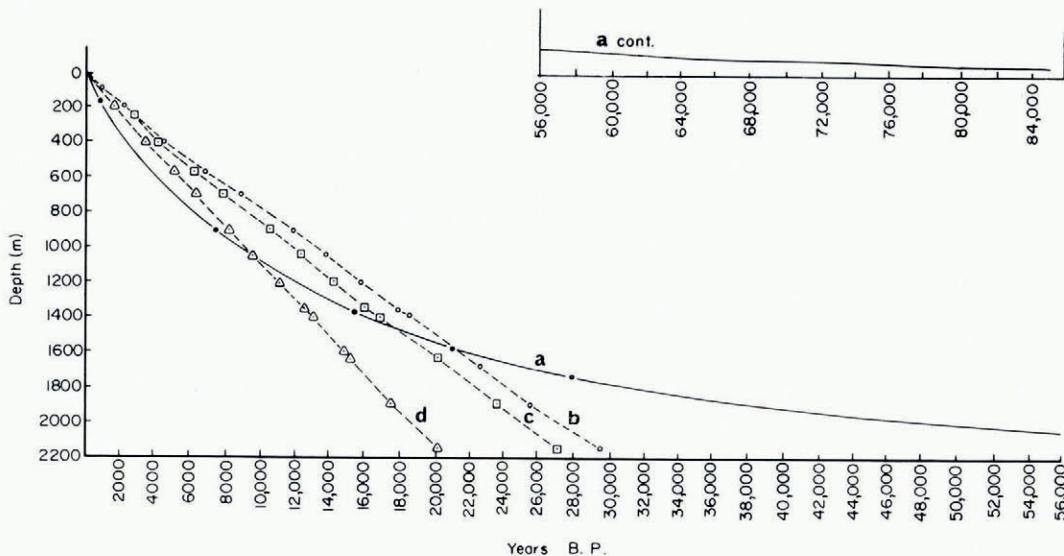


Fig. 6. Time-depth relationships for the "Byrd" core: (a) Johnsen and others (1972) as determined from $\delta^{18}\text{O}$ values; (b) Established by using the minimum a_i values obtained from the particle variations; (c) Established by using the average a_i values as determined from Figure 5; (d) Established by using a_i values determined by variations in particles coarser than $1.65 \mu\text{m}$.

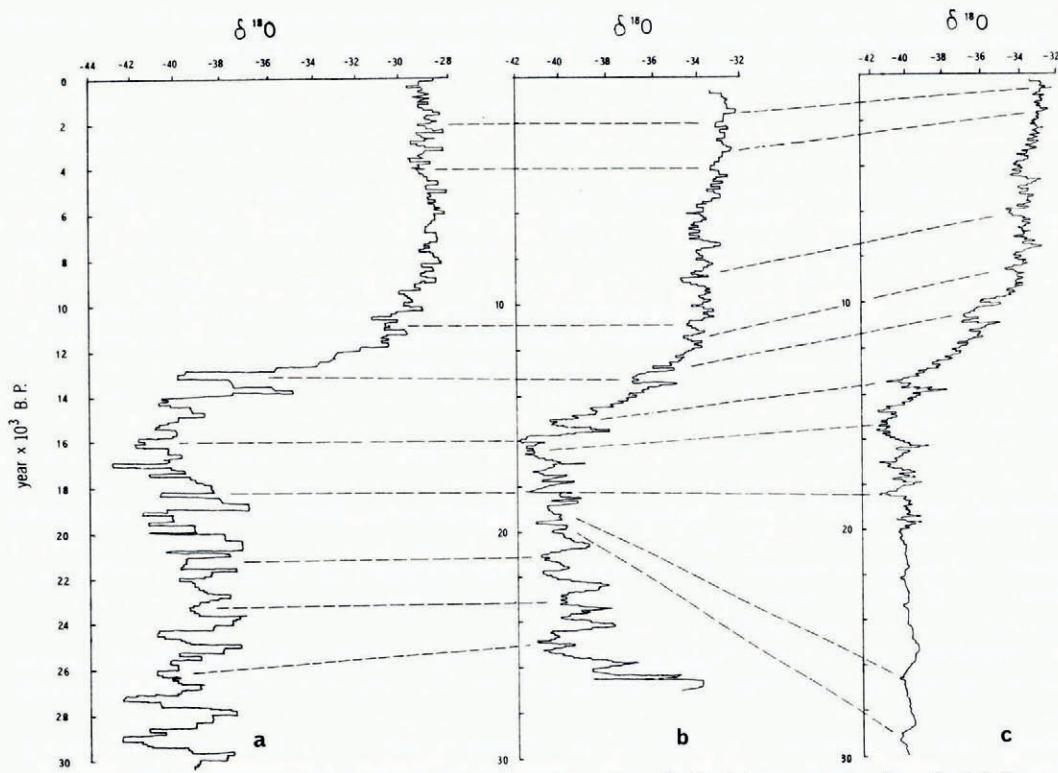


Fig. 7. The "Byrd" station and Camp Century oxygen-isotope values as determined by Johnsen and others (1972). (a) Oxygen-isotope values for the Camp Century, Greenland, ice core; (b) Oxygen-isotope values for the new "Byrd" station, Antarctica, ice core adjusted to the 27 000 year-old time scale determined from particle variations; (c) Oxygen-isotope values for the new "Byrd" station, Antarctica, ice core as determined by Johnsen and others (1972) adjusted to the time scale they derived using $a_1 = 21.4$ cm and $d = 2.5$. Comparison of the three profiles thus obtained suggests that the Camp Century $\delta^{18}\text{O}$ profile is more closely related to the "Byrd" $\delta^{18}\text{O}$ profile adjusted to the 27 000 year-old particle time scale than the $\delta^{18}\text{O}$ profile adjusted to the Johnsen and others (1972) time scale.

of age determination and, particularly, to the assumption of an annual period for the variations of microparticle concentration.

It must be emphasized, however, that the age calculation from the separation of peaks in the microparticle-concentration profiles depends on the extent of post-depositional change in the stratigraphy, as well as on the persistence of an annual cycle. In this preliminary study, a sample size of 2 cm has been used, which may be too large to resolve all of the annual variations. Experiments are now under way to test this point. Furthermore, it must be remembered that a lacuna may exist in the core. We still need dates by the ^{14}C method.

In the meantime, some support for the estimate of 27 000 years for the age of the bottom ice comes from two sources. Budd and others (1971, p. 149–51), from a profile for the "Byrd" flow line, calculated a maximum age of less than 40 000 years for the ice near the base of the ice sheet at "Byrd" station, and Hollin (1962), with reasonable assumptions, showed that the ice sheet could build up from ground level in less than 15 000 years.

DISCUSSION AND CONCLUSIONS

These preliminary studies on concentrations and size distributions of microparticles, and their relationships with $\delta^{18}\text{O}$ values, add several points which must be explained in any

successful hypothesis on the causes of glaciation and climatic change, but do not themselves provide unequivocal evidence for a particular cause.

The variations in coarseness of the microparticles may be explained in terms of changing amounts of local and global components. Larger percentages of coarse particles correspond to warmer temperature intervals in the core, which may indicate that more of Antarctica was exposed, providing a larger source for "local" microparticles. Alternatively, atmospheric circulation patterns over Antarctica may change with time. At present in many areas of the continent a greater amount of cyclonic snowfall occurs in the summer than in the winter (Alt and others, 1959, p. 185–95; Markov and others, 1968, English translation, p. 147–248); and Hamilton (1969) found, at the Pole of Inaccessibility, that the summer precipitation contains a larger number of particles greater than 3.5 μm in diameter than does the winter snowfall. Our observation on coarseness may be explained if the circulation pattern during the cold intervals of the core corresponded more closely to the present winter circulation (predominantly high-altitude convection, subsidence and katabatic surface flow); and that in the warm intervals, to the present summer circulation (more cyclonic).

As a second alternative, during the colder intervals the ice sheet should have been more extensive; large particles are favored as condensation and freezing nuclei over smaller ones (Kumai and Francis, 1962). The first deposition from cyclones occurs near the coast, so that with a larger ice sheet only the small nuclei would be deposited inland near "Byrd" station.

The peak in the concentration of small microparticles occurs in the interval of 14 800–25 000 years B.P. according to the chronologies of Johnsen and others (1972) or rather less than that according to our microparticle-based estimate (12 000–21 000 years B.P.) but still within the period generally accepted for the Wisconsin glaciation.

Gow and Williamson (1971) considered that large quantities of dust injected into the Antarctic stratosphere, by impeding solar radiation, could reduce troposphere temperatures by 2 or 3 deg. On the other hand, LeMasurier (1972), from studies of the ash bands in the "Byrd" core, has shown that it was unlikely that large quantities of ash originated from local volcanoes. The small percentages of large microparticles supports this conclusion. Perhaps the small particles originated from the ash-rich explosive eruptions characteristic of the circum-Pacific volcanoes, and the small particles remained in the atmosphere long enough to reduce solar radiation sufficiently to affect world climate.

Alternatively, the Antarctic temperatures may have been reduced by some other cause; the cooling would have produced a more intense global atmospheric circulation and, hence, an increased number of small (global) particles in the Antarctic atmosphere. It appears unlikely, however, that meridional exchange, and hence global particle flux in Antarctica, could have changed by more than a factor of two, which is insufficient to explain the four-fold variations in Figure 3. Moreover, no mechanism is apparent by which increased exchange, by itself, could cause a reduction in the mean size of microparticles carried to Antarctica.

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