Variations in microparticle concentration, size distribution and elemental composition found in Camp Century, Greenland, and Byrd station, Antarctica, deep ice cores

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Abstract. Two initial studies of the microparticle variation in the Byrd station and the Camp Century deep ice cores have been conducted to clarify the relationship between atmospheric turbidity and climate. First, an excellent correlation has been established between the microparticle concentration and size distribution and the stable isotope values for representative sections from the same depths in both ice cores. Second, the results of this work have led to the proposal of annual microparticle variations as a means of dating ice sheets. Further development of this technique should allow dating of ice cores at those depths where stable isotope variations are obscured by diffusion. Third, a significant aspect of this study is the determination of the elemental composition of the microparticles and their variation between Wisconsin and Holocene ice. Comparisons of particle concentration, size distribution and elemental compositions are made between the Northern Hemisphere and the Southern Hemisphere ice cores.

Variation de la concentration des microparticules, de la distribution selon la taille et de la composition en éléments de carottes de glace profonde trouvées à Camp Century, Groenland, et à station Byrd, Antarctique

Résumé. Deux études initiales de la variation des microparticules à Byrd station et à Camp Century sur les carottes de glace profonde on été conduites pour clarifier la relation entre la turbidité atmosphérique et le climat. Premièrement, une excellente corrélation a été établie entre la concentration des microparticules et la distribution selon la taille et les valeurs stables des isotopes pour des sections représentatives, prises de carottes de glace de même profondeur. Deuxièmement, les résultats de cette étude ont amené la proposition que les variations annuelles des microparticules pourraient servir de moyen pour dater les couches de glace. Un développement plus poussé de cette technique devrait permettre de dater les carottes de glace à ces profondeurs où les variations stables des isotopes sont rendues obscures par la diffusion. Troisièmement, un aspect significatif de cette étude est la détermination de la composition en éléments des microparticules et de leurs variations entre la glace du Wisconsin et celle de l'Holocène. Des comparaisons de concentration de particules, de la distribution selon la taille et de la composition en élements sont faites entre les carottes de glace de l'Hémisphère Nord et l'Hémisphère Sud.

INTRODUCTION

Recent theoretical studies and empirical evidence indicate that atmospheric turbidity is an important factor in the heat balance of the earth-atmosphere system. Some investigators (McCormick and Ludwig, 1967; Bryson, 1968; Rasool and Schneider, 1971; Schneider, 1971) have attributed the decrease in worldwide air temperature since the 1940s to the increase in aerosol load. Other scientists disagree as to whether aerosol concentrations in the lower troposphere lead to a net cooling (Neumann and Cohen, 1972) or to a net warming (Charlson and Pilat, 1969). Although the effects of aerosols concentrated close the the earth's surface is still one of speculation, most researchers do agree that the effect of aerosols at high altitudes, such as stratospheric dust veils of volcanic origin, is theoretically and unconditionally one of cooling near the surface (Budyko and Karol, 1975).

The ice sheets of the world provide ideal locations for the investigation of changes in such climatic parameters as ice, temperature and dust. The two major ice sheets, the Greenland and the Antarctic, are unique in that until recently they were completely remote areas in which were recorded, at least at some locations, annual variations of the atmospheric constituents. The stratigraphies of these ice sheets continually record the natural atmospheric particulate variations. Microparticle analysis which is the determination of the concentration and size distribution of microparticles in 14 diameter ranges

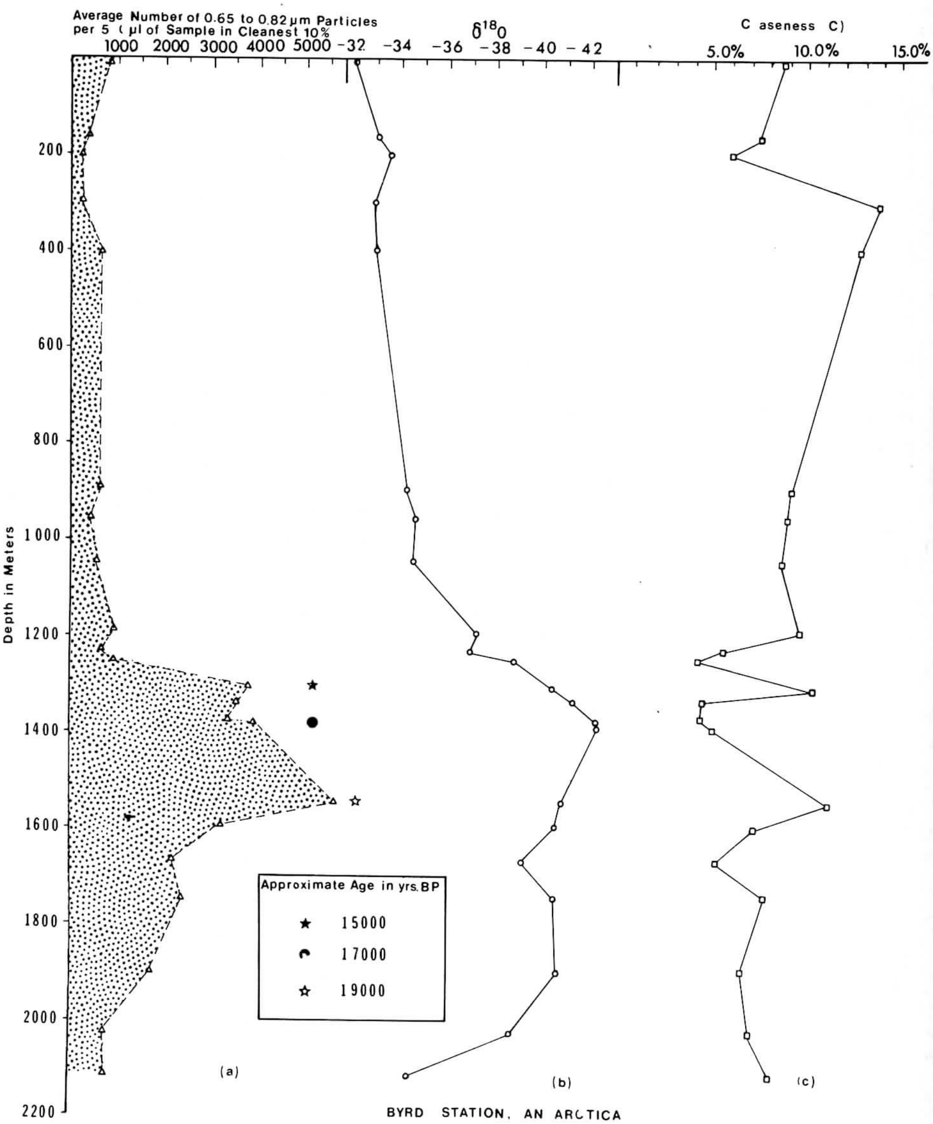

FIGURE 1. Data from the Byrd station, Antarctica, deep ice core. (a) Profile obtained by plotting the average number of 0.65–0.82 μm diameter particles per 500 μl of sample in the cleanest and unfractured 10 per cent of each core section. (b) Profile of Epstein's $\delta(^{18}O)$-values from the core sections analysed in 1(a). (c) Profile illustrating the change in per cent coarseness (C). Approximate ages given are microparticle determined (Thompson, 1973).

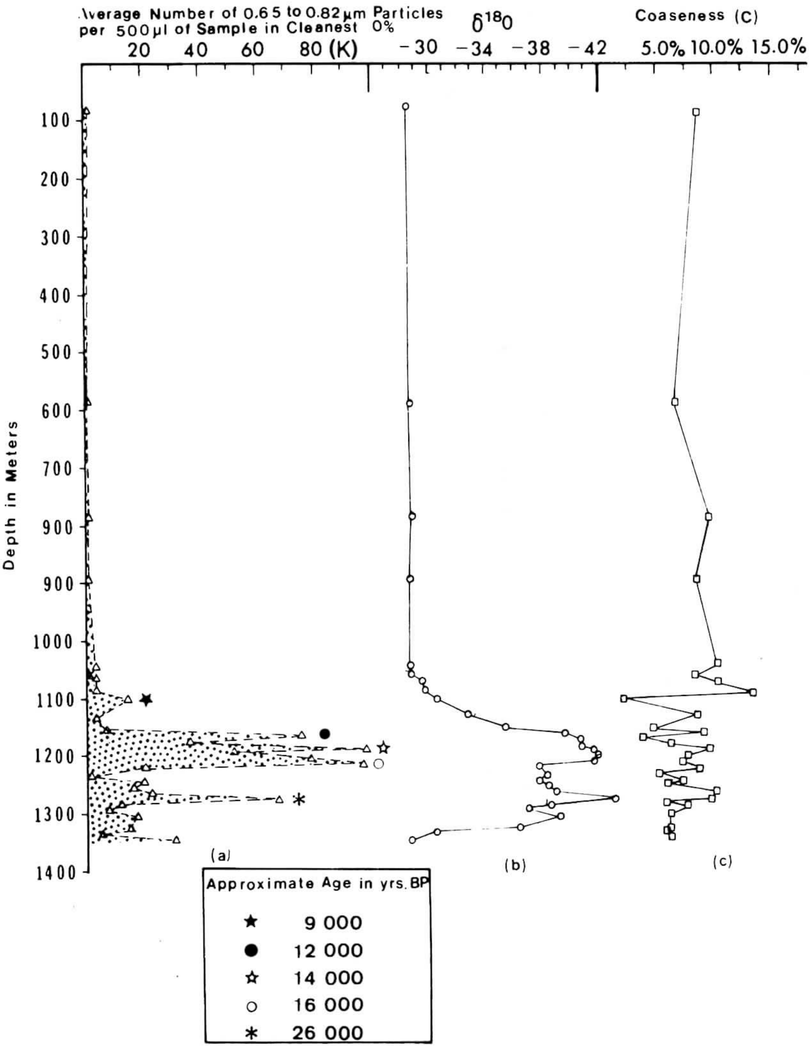

FIGURE 2. Data from the Camp Century, Greenland, deep ice core. (a) Profile obtained by plotting the average number of 0.65–0.82 μm diameter particles per 500 μl of sample in the cleanest and unfractured 10 per cent of each core section. (b) Profile obtained by plotting. Dansgaard's $\delta(^{18}O)$-values for the core sections analysed in 2(a) (c) Profile illustrating the change in per cent coarseness (C).

between 0.5 μm and 13.0 μm has been conducted for 21 representative* sections (a total of 22.91 m of ice) of the 2164-m deep Byrd station ice core and for 30 representative* sections (a total of 11.58 m of ice) of the 1387-m deep core from Camp Century. Sample sizes ranged from 2.5 cm in the upper sections of both cores to between 1.0 and 1.5 cm at greater depths where the annual layers are more compressed.

* In general, core sections were chosen to give a fair representation of depth. However, individual sections were chosen (i.e. core tube nos. 61 and 1016) because detailed $\delta(^{18}O)$-values for these same sections were available for comparison. In addition a greater number of core sections were selected between 1200 and 1400 m to better determine the nature of microparticle variations in the transition from Wisconsin to Holocene ice.

Techniques for the analysis were established by Marshall (1959) and were improved by Taylor and Gliozzi (1964), Bader *et al.* (1965), Hamilton (1969) and Thompson (1973). Epstein *et al.* (1970) and Johnsen *et al.* (1972) have measured ratios of the stable isotopes $^{18}O/^{16}O$ in samples from both deep cores. The variation of the ratios $\delta(^{18}O)$ has been used as a climatic change indicator and as a method for dating ice sheets. In general, snow deposited during the Wisconsin glacial stage (Würm) has more negative values of $\delta(^{18}O)$ than snow deposited before and after that period. Similarly, snow falling during the winter has lower $\delta(^{18}O)$-values than summer snow so that annual layering may be determined from detailed profiles.

MICROPARTICLE VARIATIONS OVER MILLENNIAL TIME INTERVALS

Figures 1 and 2 compare three different parameters in both ice cores (see Tables 1 and 2 for data). In the Byrd station ice core the major variations of

TABLE 1. Byrd station, Antarctica data

A	*B*	*C*	*D*	*E*	*F*
0	7.00	100.0	821	−32.0	8·60
61	180.00	31.0	391	−33.0	7.51
74	199.33	127.0	280	−33.5	5.86
144	298.75	32.0	231	−32.9	13.82
216	401.29	137.0	684	−32.8	12.00
553	896.94	101.5	650	−34.3	9.24
587	952.91	53.0	477	−34.7	9.00
651	1046.79	154.5	515	−34.5	8.67
751	1194.06	74.0	977	−37.3	9.80
767	1225.75	151.0	699	−37.0	5.82
785	1252.53	150.0	910	−38.8	4.33
820	1304.72	39.5	3770	−40.5	10.27
852	1342.71	151.0	3533	−41.2	4.60
875	1387.00	76.0	3345	−42.2	4.48
884	1389.66	150.0	3942	−42.2	5.10
982	1547.39	81.5	5586	−40.8	11.32
1016	1599.00	56.5	3186	−40.5	7.48
1049	1633.72	142.5	2130	−39.5	5.48
1115	1748.00	151.0	2390	−40.5	7.91
1229	1900.00	146.0	1710	−40.5	6.80
1297	2022.31	148.0	732	−38.7	7.12
1393	2139.61	139.3	771	−34.3	7.89

A = Core tube number.
B = Depth to top of core tube from 1968 surface [m].
C = Length of section analysed [cm].
D = Concentration of 0.65–0.82 μm diameter particles per 500 μl of sample in cleanest 10 per cent of each section.
E = Mean oxygen isotope values for core sections analysed in *C*.
F = Per cent coarseness defined as: $C = \dfrac{1.65\ \mu\text{m diamater}}{0.65\ \mu\text{m diameter}} \times 100.$

microparticle content [Fig. 1(a)] correspond closely with the major variations of the $\delta(^{18}O)$-values [Fig. 1(b)] as determined by Johnsen *et al.* (1972). The largest microparticle concentrations occur in those sections of core with the lowest $\delta(^{18}O)$-values. This same general relationship is found for the Camp Century ice core [Fig. 2(a, b)]. The large increase in microparticles within the two cores from different hemispheres and within sections of comparable age is remarkable and may suggest a higher global atmospheric particle content during the

Wisconsin. Observe that in both Figs. 1 and 2 the last large peak in the microparticle profiles occurs before the end of the glacial stage as defined by the $\delta(^{18}O)$-profile.

TABLE 2. Camp Century, Greenland data

A	*B*	*C*	*D*	*E*	*F*
141–145	82.50	400.0	1 678	−28.5	8.72
523	595.44	54.0	719	−28.9	6.77
655	791.05	28.0	1 146	−28.9	9.97
728	898.03	48.0	971	−28.4	8.85
828	1043.74	72.0	3 872	−28.8	10.73
839	1061.00	35.0	1 004	−28.8	8.24
842	1065.97	43.0	3 224	−29.5	10.88
858	1086.63	30.0	3 278	−29.6	13.52
873	1108.97	13.0	14 544	−30.7	2.02
893	1135.09	42.0	3 042	−32.6	8.89
908	1155.56	28.0	7 268	−35.2	4.76
915	1166.00	32.0	75 307	−39.4	9.32
921	1178.71	32.0	36 163	−40.6	3.72
929	1185.98	20.0	98 402	−40.9	6.44
937	1197.68	20.0	51 258	−41.6	9.82
942	1204.87	20.0	78 616	−41.6	7.87
949	1214.97	20.0	97 786	−41.5	7.26
955	1223.88	22.0	20 153	−37.4	8.68
962	1234.48	30.0	1 650	−38.2	5.07
969	1244.98	12.0	20 145	−37.9	7.43
976	1255.14	20.0	16 193	−38.4	5.65
983	1265.46	22.0	22 445	−38.5	10.17
992	1278.82	20.0	67 592	−42.8	9.92
997	1285.49	18.0	12 660	−38.5	5.16
1004	1295.59	20.0	7 731	−36.7	7.62
1011	1305.97	15.0	17 255	−39.2	6.35
1024	1324.76	17.0	14 568	−36.4	6.22
1031	1334.69	32.0	5 248	−30.4	5.92
1038	1345.43	20.0	31 613	−28.8	6.37

A = Core tube number.
B = Depth of top of core tube from 1966 surface [m].
C = Length of section analysed [cm].
D = Concentration of 0.65–0.82 μm diameter particles per 500 μl of sample in cleanest 10 per cent of each section.
E = Mean oxygen isotope values for core sections analysed in *C*.

$$F = \text{Per cent coarseness defined as: } C = \frac{1.65\ \mu\text{m diameter}}{0.65\ \mu\text{m diameter}} \times 100.$$

ANNUAL LAYERING OF MICROPARTICLES IN POLAR ICE SHEETS

Marshall (1959) was one of the first scientists to recognize a cyclical variation in particle concentration for Byrd station ice samples and he considered these cyclical variations to be annual layers. In general it has been found that the largest negative $\delta(^{18}O)$-values are associated with the highest particle concentrations, although the match is not perfect. This is due in part to the fact that the stable isotopes are subject to alteration by diffusion at depth and that some particle layers represent local volcanic activity which obscures seasonal concentration variations.

Annual variations in microparticles in the Camp Century core are more distinct when compared to those of the Byrd station core because the annual snow accumulation is greater at Camp Century (36 g cm^{-2} year^{-1}; Mock, 1968) than at Byrd station [14 g cm^{-2} (Bull, 1971) to 10.4 g cm^{-2} year^{-1} (Cameron, 1971)]. In addition, Camp Century experiences a greater seasonal influx of particles due to the greater expanse of land masses in the Northern Hemisphere.

Figure 3 illustrates the microparticle and oxygen isotope data from nine representative sections of the Camp Century core. Core number 1 of Fig. 3 illustrates the correlation of the variations of microparticles (A) and $\delta(^{18}O)$-

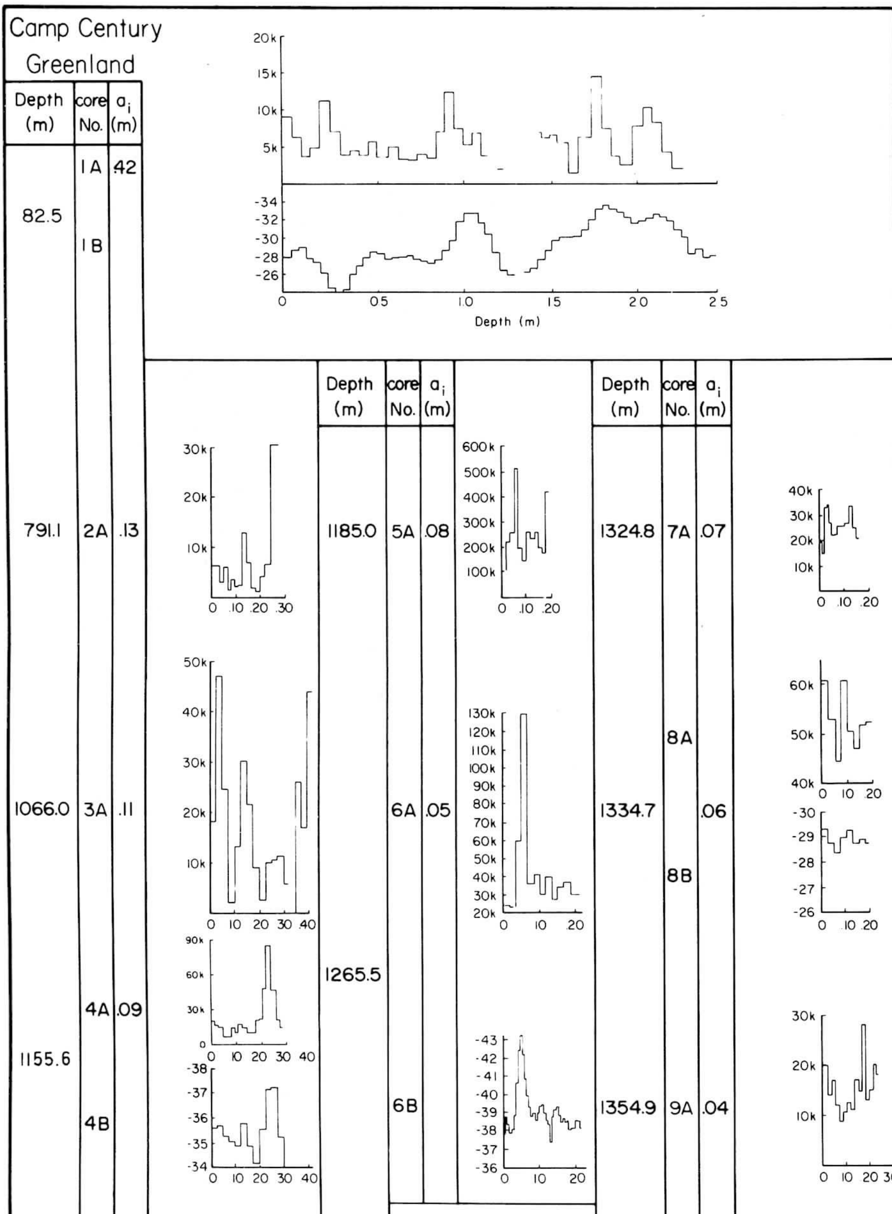

FIGURE 3. Detailed variation of microparticles and oxygen isotopes for increasing depths in the Camp Century, Greenland, ice core. (A) Detailed variations in the average number of 0.65–0.82 μm diameter particles per 500 μl of sample. (B) Detailed $\delta(^{18}O)$-data from identical sections of the ice where available (courtesy of W. Dansgaard).

values (B) for the ice from a depth interval of 82.51–84.76 m. The microparticle peaks lie stratigraphically above the $\delta(^{18}O)$-peaks by an average of 11 cm. If a uniform rate of snow deposition is assumed, then the particle peak represents an early spring deposition although some shifting of the peak location may be due to variations in seasonal precipitation and to the reworking of the snow after deposition. Microparticle variations in segments of ice from increasing depths in the Greenland core are presented in Fig. 3, core nos. 2–9. *Assuming* that the microparticle variations were *annual*, the corresponding values of annual layer thicknesses (a_i) were 41.8 cm for 82.51 m, 11 cm for 1065.97 m, 8 cm for 1185.98 m, 7 cm for 1324.76 m, and approximately 3.7 cm for 1354.56 m. Microparticles, however, yield a much younger age from the Greenland ice core. For example, between the circle and the asterisk in Fig. 2 there are 64 m of ice, which, for the a_i-value of 5 cm, should contain only 1280 years instead of the 10 000 years as suggested by the oxygen isotope ages. In order to better establish the a_i-values and to develop a better chronology for the Greenland core, much longer segments must be analysed for microparticle variations.

ELEMENTAL COMPOSITION

The microparticles retained from the Byrd station core were examined and analysed by light microscope, a Cambridge scanning electron microscope (SEM) and an Ortec X-ray energy dispersive system (EDS). The objective of this research is to classify the microparticles visually and chemically and to examine their stratigraphic variations. A total of 5000 particles from each core were visually classified using the light microscope with the random sampling of 350 particles per core section. Then 105 particles from the Byrd core and 97 particles from the Greenland core representing the particle groups observed during the visual classification were elementally analysed.

The relative weight per cents of the elements present in each particle were compared objectively by the Ward Hygroup algorithm (Ward, 1963) which requires intervally scaled input. For the Byrd samples, Hygroup was able to distinguish the elemental differences between the Wisconsin and Holocene particles as illustrated by the bimodal distribution in Fig. 4(a). In Fig. 4(b, c) these two major groups are represented in terms of the relative weight per cents of the elements present in each and it is evident that relatively more Fe, S, P and Al is present in the particles from Holocene ice and more Si, K, Ca and Ti occurs in particles from the Wisconsin ice. Silicon tends to increase with depth in the core as the average for all the Holocene particles is 41.4 per cent while the average for all the Wisconsin particles is significantly greater at 54.5 per cent.

On the other hand, for the Greenland core particles, the Hygroup programme was unable to distinguish any marked stratigraphic change in the elemental compositions as illustrated by Fig. 5. In Fig. 6 these groups are broken into relative weight per cents of the elements present and as illustrated some sections of the Wisconsin ice did contain greater concentrations of Ca, Ti, Sn and Cu. Silicon tends to remain constant with depth in the core as the average for all the Holocene particles is 44.87 per cent while the average for all the Wisconsin particles is 41.98 per cent.

Our analyses indicate that the majority of the particles from the Wisconsin sections of the Byrd core are most probably volcanic in origin whereas the majority of the particles in the Camp Century core are more likely wind-blown terrestrial material. The significance of the volcanic particles which are present in the Wisconsin section of the Camp Century core is difficult to ascertain as the total particle concentrations are quite high as was illustrated earlier. Thus, if the

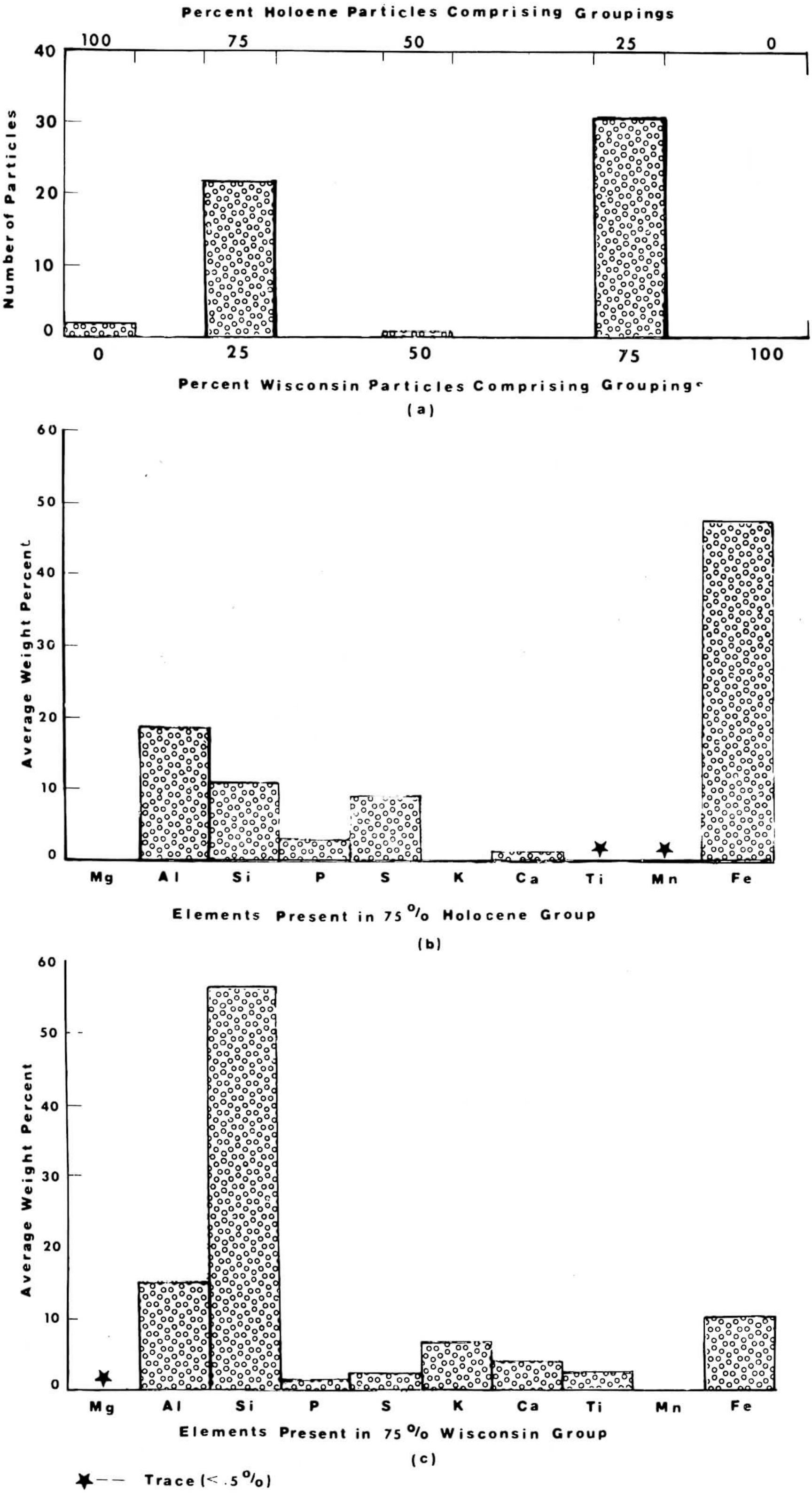

FIGURE 4. *Caption opposite.*

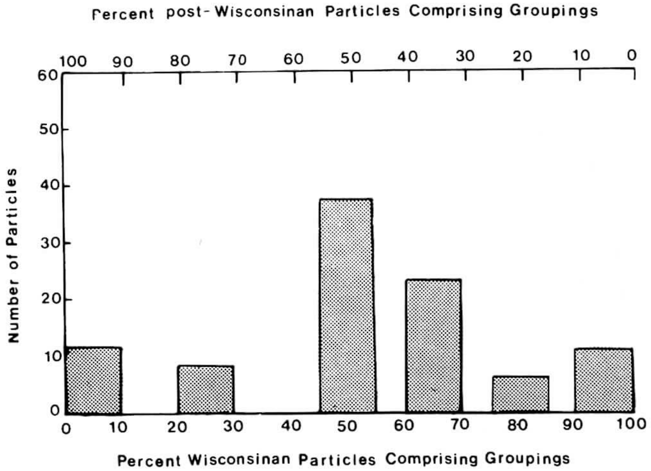

FIGURE 5. Elemental data from the Camp Century, Greenland, deep ice core. The Hygroup programme was unable to distinguish any marked stratigraphic change in the elemental compositions.

volcanic fraction of the Camp Century core was of the same concentration as found in the Byrd core they would only make up 5 per cent of the total particle population. Further, the rather constant occurrence of extraterrestrial microspheres throughout the entire stratigraphy of both cores suggests that the high concentration of particles during the Wisconsin is not a function of decreased accumulation but rather of a higher degree of atmospheric particle loading during the Wisconsin period. These data coupled with the variation in particulate size and concentration may prove to be climatologically significant to the investigation of the relationship between changing source regions and atmospheric circulation during past climatic periods.

DISCUSSION OF RESULTS FROM THE BYRD AND CAMP CENTURY MICROPARTICLE ANALYSES

The study of microparticle variations in these ice cores was initiated primarily to examine the relationship between atmospheric turbidity and climate by comparing the microparticle concentration and stable isotope profiles and to establish annual microparticle variations as a means of determining annual layering and thus of dating ice sheets. The second objective should allow the development of a chronology for deep ice cores, where $\delta(^{18}O)$-variations are obscured by diffusion. Following Johnsen (1972) in principle dating of the Camp Century ice core by counting annual layers is possible to about 1060 m depth, going back 8300 years. However, it is also possible that the oxygen isotope variations noted at greater depth represent annual variations. The microparticle profile shows distinct variations even at 1354.9 m depth. The author only wishes to point out here that microparticles being solid particles are less likely to be subject to diffusion. It is possible in the deeper sections of the core illustrated in Fig. 3 that these variations in microparticles represent periods of time greater

FIGURE 4. Elemental data for the Byrd station, Antarctica, deep ice core. (a) Analysis of groupings obtained by the Ward Hygroup algorithm and illustrating the bimodal distribution of the particles upon the basis of elemental compositions. (b) Average weight per cent of the elements present in the 75 per cent Holocene group of 4(a). (c) Average weight per cent of the elements present in the 75 per cent Wisconsin group of 4(a).

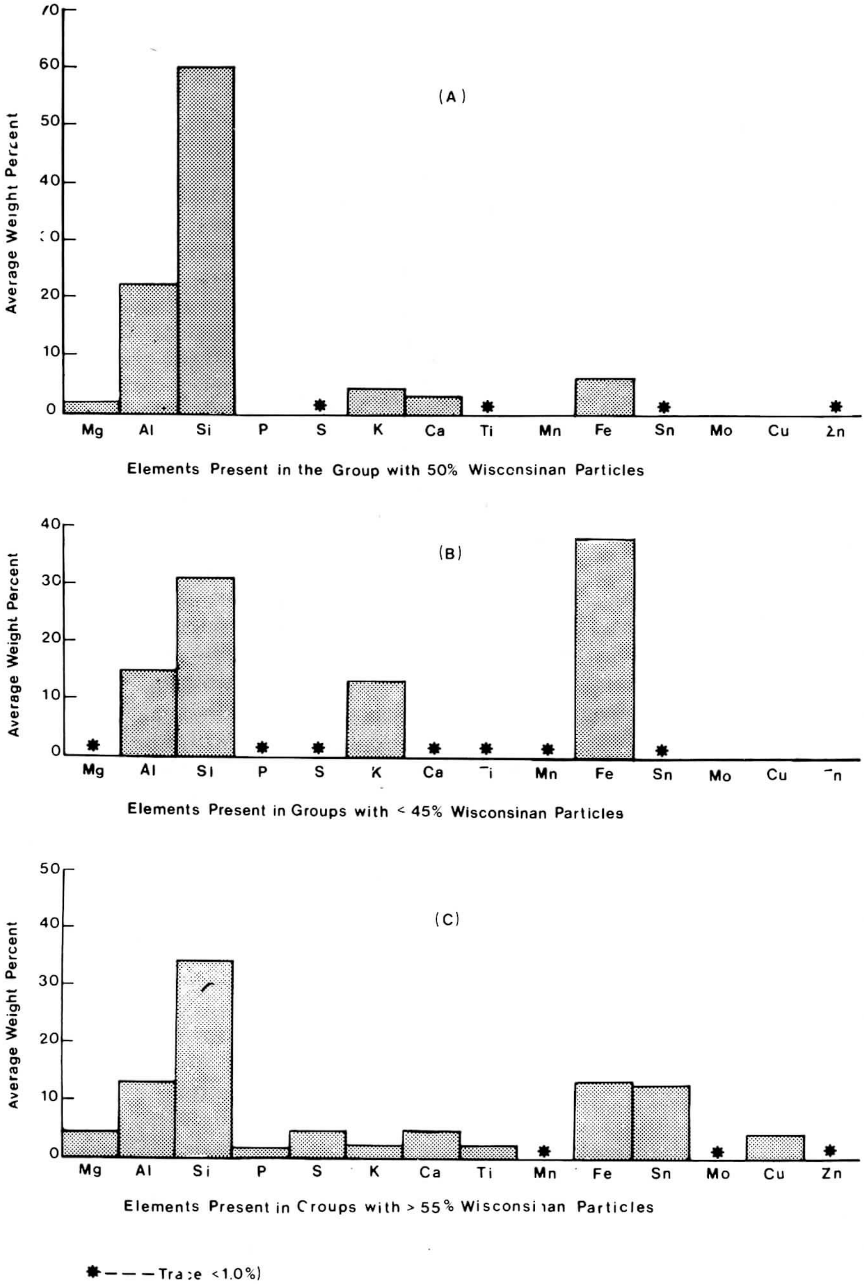

FIGURE 6. Average weight per cent of the elements present in groups illustrated in Fig. 5 for the Camp Century core. (a) Elements present in the group with 50 per cent Wisconsin particles. (b) Elements present in groups with less than 45 per cent Wisconsin particles. (c) Elements present in groups with more than 55 per cent Wisconsin particles.

than annual. Only by looking at smaller sample sizes can this be determined, something which currently is being done. It may well be that the Camp Century core bottom ice is somewhat younger than previously claimed.

Junge (1963) found that the predominant size of natural tropospheric aerosols ranged in diameter between 0.1 and 20.0 μm and that particles with diameters $\leqslant 1.0$ μm have the longest residence time; therefore, they are most likely to have the greatest effect upon world temperature. So as to restrict the analyses to global particle concentrations, the larger particles have been disregarded and attention has been focused upon the smaller particles (0.65–0.82 μm diameter) within 500 μl of meltwater from only the cleanest 10 per cent of the samples cut from each section. Presumably these sections represent snow accumulation during periods of reduced concentrations of locally derived material and therefore the data should represent the true background aerosol load. No data are presented for the fractured portion of the Byrd core (400–900 m) as it is impossible to differentiate naturally occurring particles from contamination introduced during drilling, transport and storage.

The comparison of microparticle variations and $\delta(^{18}O)$-values yields an excellent relationship over millennial time intervals such that increased concentrations are correlated with more negative $\delta(^{18}O)$-values [Figs. 1(a, b) and 2(a, b)]. In addition a direct positive relationship [i.e. an increase in particle concentration corresponds to a decrease in $\delta(^{18}O)$-values] exists between microparticle and isotopic variations in both cores over cyclical time intervals, which are annual near the surface and the reason for which at depth is undetermined yet. Figure 3 illustrates this correspondence for Camp Century and similar data for Byrd station are presented by Thompson (1973).

It is evident from Figs. 1(a) and 2(a) (the raw data for these figures are presented in Tables 1 and 2) that the atmospheric solid particle content over Greenland and Antarctica during the Wisconsin was 100 times and 4 times greater, respectively, than during the Holocene period. As solar insolation must traverse considerably more atmospheric mass in the polar regions, their climatic regimes are more sensitive to atmospheric turbidity than are those of other geographic regimes. An increase in cloud cover or the presence of a stratospheric dust veil in the polar areas could serve to reduce the annual temperature range by reducing the receipt of summer insolation (cooler summers) and by increased trapping of longwave (>4.0 μm) radiation (warmer winters). The above condition of a reduced annual temperature range and more importantly cooler summers are thought to favour the growth of ice sheets (Flint, 1971; Budyko and Karol, 1975).

The size distribution of microparticles deposited during the Wisconsin is different from that deposited during the Holocene. In general, the total number of particles within the cores increases greatly in Wisconsin ice while the fraction of large particles (diameter $\geqslant 1.65$ μm) decreases [Figs. 1(c) and 2(c)]. These variations in microparticle coarseness may be explained by a change in the concentrations of local and global atmospheric components. It has been found that the larger percentages of coarse particles correspond to warmer temperature intervals within the core and this may be a function of the increased continentality of the Northern Hemisphere which provides an extensive source for 'local' microparticles. These coarseness observations may be explained if the circulation pattern during the cold intervals corresponded more closely with the present winter circulation (predominantly high altitude convection, subsidence and katabatic surface flow) and during the warm intervals corresponded with the present summer circulation (more cyclonic).

SUMMARY

The above relationships provide conclusive evidence that the stratigraphic record of microparticle size distributions, concentrations and elemental variations preserved within ice and snow contains a wealth of climatic information

especially when coupled with the corresponding stable isotope data. The relatively short time interval involved in the transition from the Wisconsin with high particle content to the Holocene with low particle content is of great importance. In the Camp Century core this transition occurs within less than 10 m of ice encompassing less than 100 years which indicates that climatic transitions may occur rather suddenly. It is necessary to note that recent solid particle deposition in West Antarctica [Fig. 1(a)] has not increased significantly over mean Holocene values and thus the natural processes which occurred during the Wisconsin must have been of monumental magnitude.

The results of these analyses indicate an urgency for man to investigate the possible causes of climatic change. The continued analysis of microparticle elemental compositions and temporal concentration and size variations will provide more detailed knowledge of their sources and about the atmospheric circulation patterns which existed during the various past climatic regimes. The ultimate goal is to determine precisely the role of microparticles in world climate.

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REFERENCES

Bader, H., Hamilton, W. L. and Brown, P. L. (1965) Measurement of natural particulate fall-out onto high polar ice sheets; part I: Laboratory techniques and first results. *US Army Cold Regions Research and Engineering Laboratory, Research Report no. 139,* 86 pp.

Bryson, R. A. (1968) All other factors being constant. . . . *Weatherwise* **12**, 56–61.

Budyko, M. I. and Karol, I. L. (1975) Man's impact on the global climate. In *Proceedings of the WMO/IAMAP Symposium on Longterm Climatic Fluctuations* (held in Norwich, England, August 1975), pp. 465–472: WMO Publ. no. 421.

Bull, C. (1971) Snow accumulation in Antarctica. In *Research in the Antarctic* (edited by L. O. Quam), pp. 367–421: American Association for the Advancement of Science, Washington, DC, USA.

Cameron, R. L. (1971) Glaciological studies at Byrd station, Antarctica, 1963–1965. *American Geophysical Union; Antarctic Research Series* **16**, 317–332.

Charlson, R. J. and Pilat, M. J. (1969) Climate: the influence of aerosols. *J. Appl. Met.* **8**, 1001–1002.

Epstein, S., Sharp, R. P. and Gow, A. J. (1970) Antarctic ice sheet: stable isotope analyses of 'Byrd' station cores and interhemispheric climatic implications. *Science* **168**, 1570–1572.

Flint, R. F. (1971) *Glacial and Quarternary Geology*, p. 801: John Wiley, New York.

Hamilton, W. L. (1969) Microparticle deposition on polar ice sheets. *The Ohio State University Research Foundation, Institute of Polar Studies, Report no. 29.*

Johnsen, S. J., Dansgaard, W., Clausen, H. B. and Langway, C. C. Jr (1972) Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature* **235**, 429–434.

Junge, C. E. (1963) *Air Chemistry and Radioactivity*, pp. 119–202: Academic Press, New York,

Marshall, E. W. (1959) Stratigraphic use of particulates in polar ice caps. *Bull. Geol. Soc. Amer.* 70, p. 1643.

McCormick, R. A. and Ludwig, J. H. (1967) Climatic modification by atmospheric aerosols. *Science* **156**, 1358–1359.

Mock, S. J. (1968) Snow accumulation studies on the Thule peninsula, Greenland. *J. Glaciol.* **7**, no. 49, 59–76.

Neumann, J. and Cohen, A. (1972) Climatic effects of aerosol layers in relation to solar radiation. *J. Appl. Met.* **11**, 651–657.

Rasool, S. I. and Schneider, S. H. (1971) Atmospheric carbon dioxide and aerosols: effects of a large increase on global climate. *Science* **173**, 138–141.

Schneider, S. H. (1971) A comment on climate: the influence of aerosols. *J. Appl. Met.* **10**, 840–841.

Taylor, L. D. and Gliozzi, J. (1964) Distribution of particulate matter in a firn core from Eights station, Antarctica. *American Geophysical Union; Antarctic Research Series* **2**, 267–277.

Thompson, L. G. (1973) Analysis of the concentration of microparticles in an ice core from 'Byrd' station, Antarctica. *Institute of Polar Studies, Ohio State University Research Foundation, Report no. 46.*

Ward, J. H. (1963) Hierarchial grouping to optimize an objective function. *J. Amer. Statist. Assoc.* **58**, 236–243.

DISCUSSION

Koerner:
So far all investigations on cores which reach Wisconsin (Camp Century, Byrd, Devon Island) have shown in the Wisconsin ice unique characteristics—unique in time, but not in space. This ice has high dirt content, high Ca and Mg content, and consists of fine crystals. Have you comments on the high particle content of Wisconsin ice?

Thompson:
I agree fully that the characteristics of Wisconsin ice in both the Northern and the Southern Hemispheres are unique. The result of this study indicates that the high particle counts are probably of two different origins. For Greenland the particles of the Wisconsin are mostly clay-like in morphology and composition. Their high abundance in the Camp Century core is related most likely to a very intense circulation in the Northern Hemisphere during the Wisconsin period. The particles have been carried by wind from the unglaciated land areas. In the Southern Hemisphere the circulation must have been less intense to account for the low concentration of particles within the Byrd core. In addition the particles of Wisconsin age are mainly of volcanic origin. This large increase in volcanic particles may have large climatic implications. It is difficult to determine the importance of the volcanic fraction of particles in the Wisconsin of the Greenland core, for if they had the same abundance as is found in the Byrd core, they would still only make up 5 per cent of the total particle population.

Warburton:
What is your explanation of the relationship between the low $\delta(^{18}O)$-values and the higher concentration of small particles in both the Camp Century and Byrd cores?

Thompson:
This is a difficult question to answer based on present data. However, it seems very unlikely that the association of high particle concentrations being associated with lower $\delta(^{18}O)$ can be a matter of chance. The data indicate that both of these parameters are directly related over both small (annual) time intervals as well as over millenial time intervals. It may be that there is a causal effect relation or that both parameters are only the effect of some third as yet undefined process. A lot depends on the determination of the exact role particles play as a determinate in world climate. I believe the question can be better answered with more data from climatology and meteorology coupled with more data from deep ice cores on small particle variation during known periods of climatic change, such as the Little Ice Age.

Herron:
What was the reason for looking at the particle distribution of the 'cleanest 10 per cent'?

Thompson:
There is nothing magical about '10 per cent'. We wanted to look at a representative 'background' aerosol content. If we look at say the total number of small particles, there is a great chance that one or two large inputs of particles as from volcanic eruptions could cause large notations, which do not represent the background levels. In the analyses we have used a relatively small portion of the total length of the two cores. Even though I feel the sections are representative, it is impossible to say what the particle variations were in core sections just preceding those core sections we analysed. If there was an unusually high particle input, then looking at the total small particle population could be misleading. Just as sampling snow in a geographical area close to a small volcanic eruption would give a very large particle count which is in no way related to the global distribution of particles from that eruption.

Herron:
Were enough particles examined by energy dispersive X-ray to justify your conclusions about the change in Byrd morphology and absence of change in the Camp Century morphology upon the transition from Wisconsin ice?

Thompson:
Yes. We analysed a total of 5000 particles from each deep ice core, randomly selecting 350 particles from each core section. The method used has been applied many times in pollen analysis and has proven statistically valid. It is important to analyse the particles in additional sections of both cores. However, for the sections analysed we feel the conclusions are justified.

Comment by Newell:
Meteorological considerations suggest that atmospheric kinetic energy was much larger in the Wisconsin than in the Holocene, which would support more dust pick-up in the former than in the latter. Furthermore the *kinetic energy difference* was much larger in the Northern Hemisphere than in the Southern Hemisphere. These two considerations are borne out by the dust concentration differences reported.