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Microparticles in "Byrd" station ice core: reply to comments by S. J. Johnsen, C. U. Hammer, N. Reeh and W. Dansgaard

We greatly appreciate the interest shown by Johnsen and others (1976), and also by Drs Gordon Robin, Robert Thomas and Ian Whillans, among others, in our preliminary studies of the microparticles in the Antarctic ice sheet (Thompson and others, 1975). Since that paper was submitted for publication we have established a new microparticle laboratory in which the particle counters are housed under "class 100 clean-room conditions" (complete description in Thompson, 1975). With this new facility we have analyzed eight additional 1.5 m segments of the "Byrd" core. Six of these additional core lengths were taken from depths below 1 200 m. Using these additional core data we can reply to some of the main points noted by Johnsen and others (1976) in our preliminary paper. The new core data continue to show that the microparticle method of stratigraphic analysis and age estimation has considerable potential but also show practical difficulties which at present are not completely resolved.

Johnsen and others (1976) are correct in pointing out the difficulties with vertical strain-rates in the "Byrd" core. The vertical strain-rate of $-28\times10^{-5}\ a^{-1}$ calculated in Thompson and others (1975), from the microparticle data, applies to the upper 200 m of the "Byrd" core. On the other hand, the vertical strain-rate over the lower 90% of the core, based on the current interpretation of the microparticle variations and assuming a constant accumulation rate, is about $-20\times10^{-6}\ a^{-1}$, only about 30% of the value of the vertical rate calculated from the current horizontal strain-rates measured up-stream from "Byrd" station (personal communication from I. Whillans).

If the West Antarctic ice sheet is unstable, as suggested by Hughes (1973) and Thomas (1976), then these vertical strain-rates obtained from the microparticle variations may not be unrealistic. The low strain-rate may reflect a long period during which the ice sheet was growing. On the other hand, if the ice sheet is nearly in equilibrium, as the studies of Whillans (1973, and personal communication) indicate, such a strain-rate in the lower portion of the core is difficult to explain. A partial explanation is possible, in terms of large temporal changes in accumulation rate and ice-sheet configuration. It is quite likely that the annual accumulation rate has changed significantly in the last 30 000 years, but such variations alone would not easily explain the apparent a_i pattern.

Part of the explanation for the small age estimated for the bottom ice may be due to the melting of the bottom, caused by geothermal and frictional heat. The temperature and temperature gradient at the bottom of the "Byrd" hole are known (Ueda and Garfield, 1968; Gow and others, 1968), and while the geothermal flux and the frictional heating are unknown, reasonable values of the geothermal heat, the sliding velocity and bottom stress (Whillans, 1973) suggest that small amounts of ice would be melted each year. Many other mechanisms could be adduced for removing many meters of ice from the bottom of the ice sheet, for example, through the ice flow associated with ascending convection patterns, as suggested by Hughes (1970, 1972).

Johnsen and others (1976) emphasized that with sample lengths of 2 cm, as used in our preliminary study, we might easily miss cycles of wavelength less than about 6 cm, a point which we also noted (Thompson and others, 1975, p. 442). The best data on this point come from a comparison of the annual accumulation at the Pole of Relative Inaccessibility estimated from the microparticle method, with that given by absolute methods (Hamilton, 1969). At that site, where near-surface values of a_i are about 7.5 cm (of snow), Hamilton found that with 2.5 cm samples the microparticle method overestimated the annual accumulation by about 14%. At that site some proportion of these "missing years" is due to the complete removal, after deposition, of a whole year's accumulation. In the "Byrd" core, even at depths where $a_i \approx 7$ cm, the percentage of missing years should be less than 14% because complete loss of a year's snowfall is unlikely. With such a correction factor, however, the age of the deepest samples becomes about 33 000 years.

Our new laboratory has enabled us to reduce the sample length to 0.7 cm, so that cycles of wavelength as short as 2 cm should be apparent. Even if the vertical strain-rate retains its near-surface value throughout the profile, and accumulation rates are unchanged, values of a_i should exceed 2 cm for 80% of the ice thickness. The results of such a small-sample study on a 1.5 m core length from 1 749 m depth in the "Byrd" hole (81% of the total depth), are shown in Figure 1. The smoothed profile shows a large-amplitude cycle with a wavelength of approximately 13 cm, which is probably the best estimate of the a_i value for this core section. The other five core sections from below 1 200 m yield a_i values between 12 and 14 cm.

On the other hand, it may be argued that the short wavelength fluctuations in microparticle concentration in this profile are the annual cycles and that the cyclicity of 13 cm wavelength represents the

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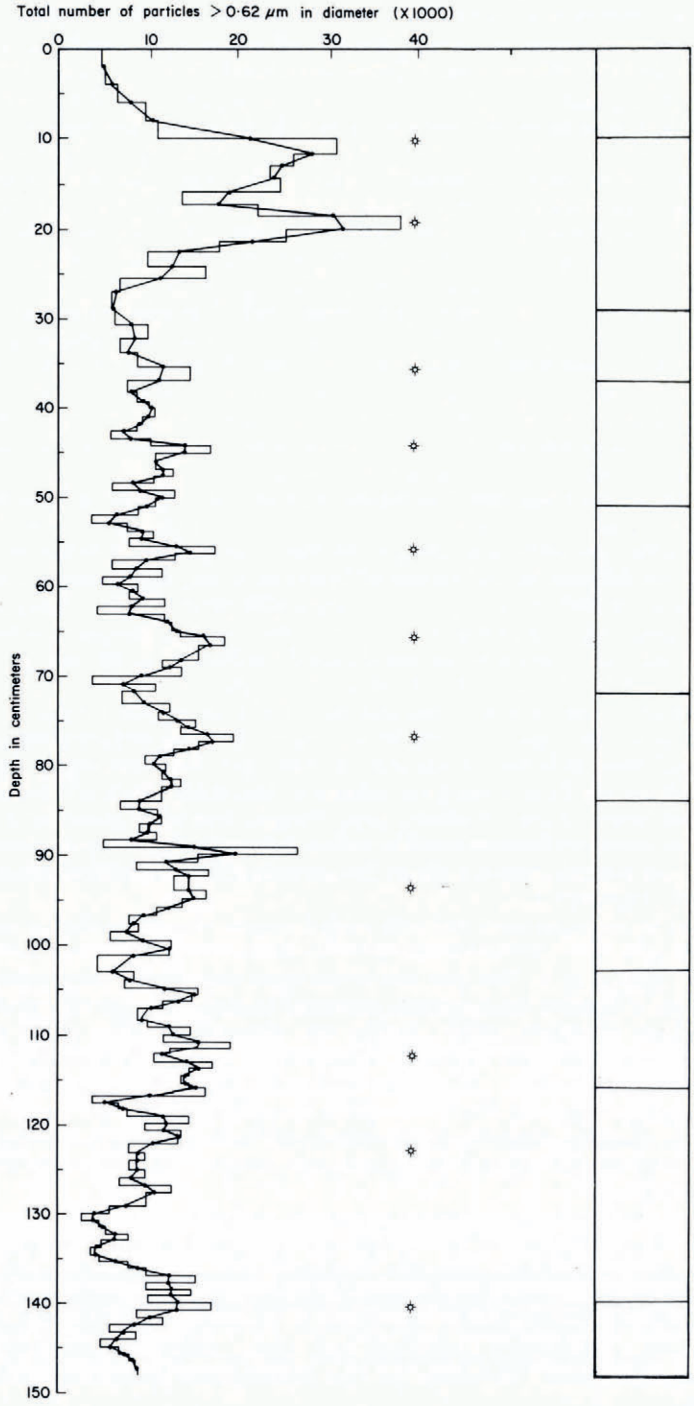

Fig. 1. Vertical particle profile from the "Byrd" core. The top of this core section is 1 748.65 m below the 1968 surface. The left profile indicates variations in total particles greater than 0.62 μm in diameter per 500 μl of sample. The sample thickness for 75% of the samples analyzed was 0.7 cm. Open stars indicate peaks in total particle concentration used to calculate the 13 cm a_i value. The physical breaks in this core length are indicated in the column on the right.

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concentration of particles in specific horizons due to migration of particles during recrystallization. The question arises whether it is possible for one-micrometer-diameter dirt particles to be transported during the recrystallization of ice. This point should be tested. In any event, the problem of distinguishing annual layers is not simple and cannot be solved just by reducing the sample size. Incidentally, one of our reasons for assuming that the variations in the microparticle profile from 1 387 m were annual was the similarity with the $\delta^{18}O$ profiles from the same core (fig. 3d of Johnsen and others, 1972).

In the preliminary studies we used the comparison of the oxygen-isotope profiles at Camp Century, Greenland, and at "Byrd" station (with modified time scale) to support our age estimate. Mercer (1969) has pointed out that by 11 000 B.P., South American mountain glaciers between lat. 40° and 50° S. were as small as they are now; he finds no hint of the glacial advance known as the Younger *Dryas* (11 000–10 000 B.P.) which is well established in Europe (Iversen, 1954). Such evidence indicates that some climatic variations may not be world-wide. Johnsen and others (1972) dated the "Byrd" core, in part, by matching variations in the oxygen-isotope profile with similar variations in the Camp Century profile. Obviously, there are still major difficulties with estimating the age of the ice core and it is apparent that further work on both the stable-oxygen-isotope and microparticle methods is needed in this very important study. We are pleased that our plans for further cooperation with our Danish colleagues are moving ahead. The problems, described above, also illustrate the need for ^{14}C or other "absolute" age determinations for samples of ice from deep under "Byrd" station.

We are grateful to Drs Mercer and Whillans for stimulating discussions on many aspects of this subject.

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