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RESURVEY OF BORE HOLE AT DYE 3, SOUTH GREENLAND

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ABSTRACT. The 2037 m deep bore hole at Dye 3 in south Greenland was surveyed in 1981, 1983, 1985, and 1986. The directional surveys show the ice flow is planar with a surface velocity of 12.2 m/year at an azimuth of 060°, which agrees with surface velocity measured by navigation satellites. Measurements of hole diameter and inclination are highly correlated with dust content in the ice. The temperature measurements show strong convection in the hole fluid with a cell height of about 20 m and an amplitude of 0.1 K. The calculated mean *in-situ* ice density is 921.3 ± 1.5 kg/m^3. Due to ice deformation, the lowest 4 m of the hole were not accessible in 1985 and the lowest 180 m were not accessible in 1986.

INTRODUCTION

The Dye 3 bore hole (lat. 65°11′N., long. 43°49′W., elevation = 2484 m) in south Greenland was surveyed just before the end of the drilling in 1981. It was resurveyed in 1983 (Gundestrup and Hansen, 1984), 1985, and 1986. The 1981 survey measured inclinations but not azimuth. The 1983 survey reached bottom. The bottom 4 m and 180 m were inaccessible in 1985 and 1986, respectively. In these two years slant-hole depths were calibrated using the previously measured depths of irregularities in the diameter and inclination. The 1985 and 1986 true vertical depths are accurate to 1.5 m assuming constant surface elevation (Reeh and Gundestrup, 1985). The casing length was 67.1 m when installed in 1979 (Rand, 1980). In 1981, 0.9 m was removed. In 1982 the casing was extended to the surface by adding 13.7 m. The casing was extended 2.3 m in 1983, 1985, and 1986 to a total casing length of 86.8 m. In 1981, 400 l of heavy liquid (perchlorethylene, PCE) was added to the bore hole to free the stuck drill. After the 1983 and 1986 surveys, 416 l of diesel fuel were added to keep the fluid pressure equal to the overburden pressure at the bottom of the bore hole. To keep this equilibrium, the fluid level is more than 100 m below the surface. This introduces an under-pressure of up to 8 bar in the upper part of the bore hole which leads to significant hole constriction.

In this paper, all depth references are given as vertical depths. The total vertical depth of the bore hole is 2033.2 m, the slant-hole depth in 1981 (which is the same as the depth used for the core logging) was 2037.63 m (Gundestrup and others, 1984; Gundestrup and Johnsen, 1985). The relation between 1981 slant-hole depth (SHD) and vertical depth (VD) is as follows:

if $VD < 1200$ m, then

$$\mathrm{SHD} = \mathrm{VD} - 0.013 + 2.63 \times 10^{-4} \times \mathrm{VD} - 5.88 \times 10^{-7} \times \mathrm{VD}^2 + 6.72 \times 10^{-10} \times \mathrm{VD}^3,$$

if $VD > 1200$ m, then

$$\mathrm{SHD} = \mathrm{VD} + 7.859 - 0.0179 \times \mathrm{VD} + 1.266 \times 10^{-5} \times \mathrm{VD}^2 - 2.31 \times 10^{-9} \times \mathrm{VD}^3.$$

EQUIPMENT

The equipment used in 1981 and 1983 was described by Gundestrup and Hansen (1984). The first logging device used in 1985 was the University of Copenhagen (UCPH) unit which measures inclination, azimuth, fluid pressure, temperature, and diameter. Some changes were made to the 1983 configuration. A fluxgate compass was used instead of the Aanderaa-type 1248 magnetic compass. A temperature-probe array was added to detect thermal convection in the bore-hole fluid. The thermistor electronics were modified to ensure a noise level significantly less than the resolution of the thermometer (0.009 K) without any smoothing. The UCPH serial numbers of the thermistors are: in 1980, No. 76-10; in 1982, No. 76-10; in 1983, No. 83-4; in 1985, No. 83-2; in 1986, No. 83-4. The resolution of the pressure transducer was increased to 15 cm. The transducer (Paroscientific type 75k-002) has been calibrated at −50°, −27°, −1°, and +18°C by the Danish National Testing Board, traceable to PTB, Braunschweig 1984. The calibration indicated the following error characteristics for the transducer: hysteresis 64 mbar; 2 K uncertainty in temperature introduces a pressure error of 60 mbar; and a maximum scale error of 0.03%. At the bottom, this corresponds to an estimated error of 150 mbar, which is equivalent to 1.5 m of depth. The sampling interval was reduced from 4 to 3 s. The tool was lowered into and retrieved from the bore hole by the UCPH winch built specially for that purpose. The winch carries 3500 m of Rochester-type 1H-125K double-armored, Tefzel insulated single-conductor cable. The cable has a diameter of 3.12 mm. The winch has a speed range of 0 to ±50 cm/s and a lifting capacity of 200 kg. A depth counter is interfaced to the console, making it possible to add the slant-hole depth to the logger's data stream.

The second logging device used in 1985 was the Polar Ice Coring Office (PICO) survey tool which measures inclination, azimuth, and temperature. The configuration is the same as that used in 1983. The Gearhart–Owen 800 SUA winch used for all surveys in 1983 was used with the PICO tool in 1985.

For the 1986 surveys, the UCPH equipment was identical to that used in 1985. The PICO survey tool was modified to include a battery-powered microprocessor. The microprocessor-controlled data-acquisition package (DAP) transmits the information to a standard computer terminal at the surface. The inclination and azimuth sensors were those used in the previous surveys.

MEASUREMENTS

Hole-liquid density

Fluid density was calculated from measurements of depths and the pressure at that depth. The density profiles (Fig. 1) for 1985 and 1986 showed a significant decrease from the 1983 profile in the upper few hundred meters due to the addition of the light-density (≈850 kg/m^3) diesel fuel in 1983. There is a slight increase in fluid density in the bottom 200 m of the hole. The 1986 survey did not include that part of the hole.

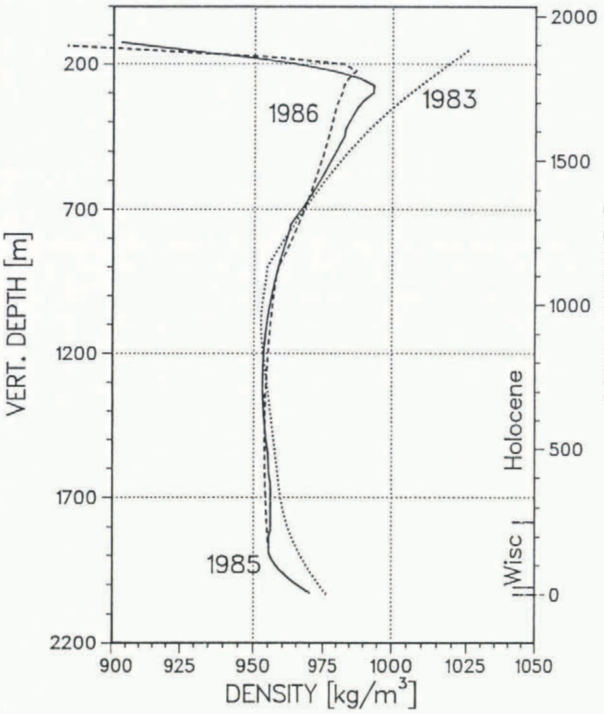

Fig. 1. Density of the liquid in the hole versus true vertical depth as measured in 1983, 1985, and 1986. The light liquid added after the 1983 season is clearly seen in 1985 and 1986.

Diameter

The diameter of the bore hole will decrease if the fluid pressure is less than the overburden pressure of the ice, and will increase if the fluid exceeds the overburden pressure.

The Wisconsin ice in the bottom 250 m of the hole deforms three to four times more readily than the Holocene ice above that level, and the silty ice in the lowest 25 m of the hole deforms an order of magnitude more readily than the Holocene ice.

The deliberate addition of 400 l of heavy fluid in 1981, in a successful attempt to expand the diameter at the bottom of the hole to free the drill stuck there, increased the hole fluid density so that a shorter liquid column is needed to match the overburden ice pressure at the bottom. This created large under-pressure in the upper part of the bore hole.

Figure 2 shows the measured diameters in 1983, 1985, and 1986. There is pronounced hole closure in the upper 700 m. The spikes at 800–900 m and at 1050 m are due to slippage of the anti-torque springs during drilling.

Figure 3 is an expanded view of the hole diameter versus depth in the lower part of the bore hole. The original diameter of the hole was 130.0 mm (Gundestrup and others, 1984). The diameter increase in the period 1981–83 shows that the fluid pressure exceeded the overburden pressure. The diameter decrease in 1985 and 1986 shows that the fluid pressure was less than the overburden pressure, except at the bottom of the hole where the 1985 diameter shows that the pressures were very nearly equal. In 1985, both the UCPH and the PICO tools were unable to penetrate the lower 4 m of the bore hole. This possibility was foreseen and commented on in the 1983 survey (Gundestrup and Hansen, 1984).

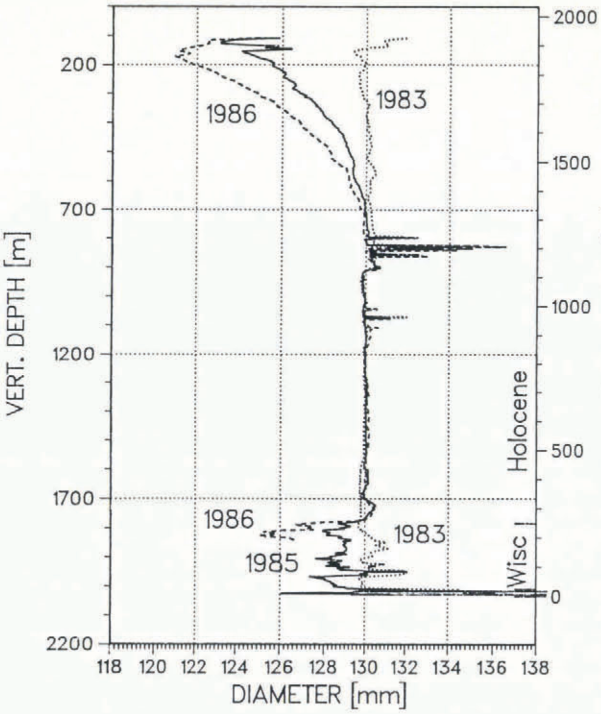

Fig. 2. Hole diameter versus vertical depth in 1983, 1985, and 1986. The profiles are slightly smoothed. The upper 900 m was originally 130.5 mm; below 900 m, the diameter was 130.0 mm.

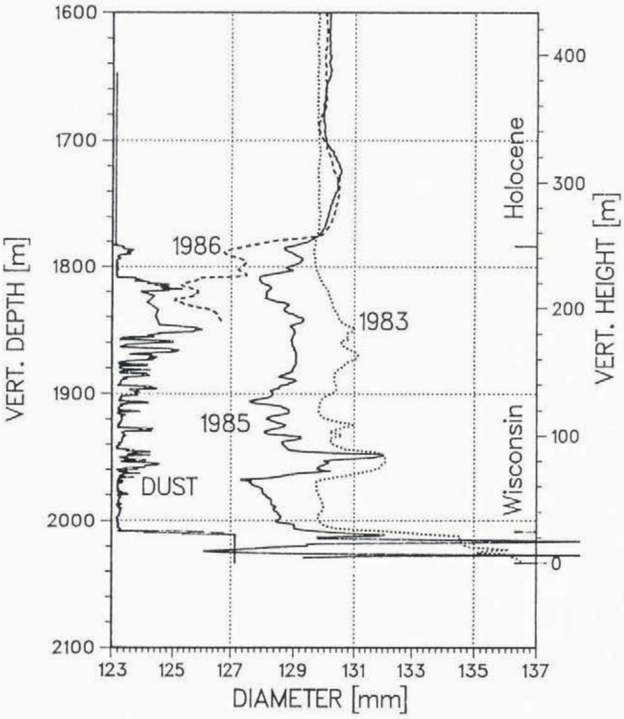

Fig. 3. Lowest part of Figure 2 shown expanded. The curve at the left is a dust index. The 1985 profile stops 4 m above the bottom of the hole. The 1986 profile stops at the highest dust peak in the Wisconsin.

In 1986, neither tool penetrated beyond a depth of 1850 m. A very marked increase in inclination, correlated with a dust layer at that depth, probably explains the failure to lower the tools beyond that depth. As seen in Figure 3, the penetration stopped at the highest dust peak in the Wisconsin.

The change in diameter is highly correlated with the dust content, as is the case in the Agassiz Ice Cap A77 hole (Fisher and Koerner, 1986). At Law Dome, Antarctica, *c*-axis enhancement factors and bore-hole closures have been measured (Russell-Head and Budd, 1979; Thwaites and others, 1984; Budd and Rowden-Rich, 1985; Morgan and McCray, 1985). They observed high closure at depth intervals with large-grain and multiple-maxima ice. There are a number of differences between the Dye 3 and Law Dome situations that make comparison complicated. The overburden pressure (≈20 bar) was higher at Law Dome than at Dye 3; the Law Dome ice contains less dust, the depth–shear relationship is more complicated at Law Dome, and Law Dome temperatures were close to the pressure melting-point.

Ice density

The hole pressure measured 2 m above the bottom of the hole in 1983 was 183.65 bar. In 1985, the absolute pressure 6 m above the bottom was 182.26 bar. Assuming that the 1985 fluid pressure is equal to the overburden pressure of the ice at that level, a density correction for the firn of 24 m (Clausen and others, 1988), a total vertical length of 2033.2 m, a surface barometric pressure of 0.74 bar, acceleration of gravity 9.823 m/s^2, and correcting for the 2.5 m rise in fluid due to the immersion of the cable and survey tool, the calculated mean *in-situ* ice density is 921.3 ± 1.5 kg/m^3. The compressibility of ice, 12×10^{-6}/bar (Dorsey, 1940) accounts for 1 kg/m^3 of the mean *in-situ* density. The calculated density is slightly higher than the 917–920 kg/m^3 measured on the relaxed Byrd Station core (Gow, 1970) and the 920.3 kg/m^3 at −20°C and 918.7 kg/m^3 at −10°C measured on artificial ice (Hobbs, 1974).

Temperature

The 1985 and 1986 temperature profiles were measured with a thermistor probe centered in the bore hole beneath the survey tool. The tool was lowered at a uniform speed of approximately 40 cm/s. The overall profile is identical to that shown by Gundestrup and Hansen (1984) for the hole wall. The temperature profile below 1600 m is shown expanded in Figure 4. Convective circulation of the fluid is evident. The amplitude of the temperature fluctuations is larger in 1985 than in the 1986 profile (dashed line). Gundestrup and Hansen (1984) stated that convective circulation would be consistent with the physical and thermal properties of the bore-hole fluid and the temperature gradient of 12×10^{-3} K/m in the depth interval shown. The reduced amplitude in 1986 may be due to the presence of a block of ice being pushed down-hole by the probe. The convection cells are about 20 m long with a temperature step between cells of 0.1 K. This change in temperature occurs over a depth range of less than 0.5 m. Similar convection cells were observed in the 340 m fluid-filled Agassiz Ice Cap bore hole (Fisher, unpublished).

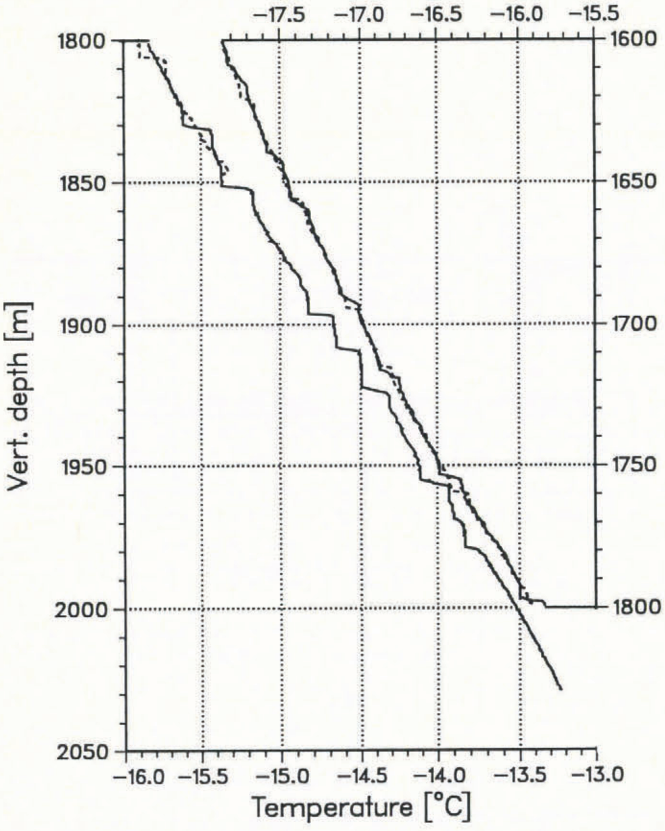

Fig. 4. Temperature below 1600 m in the center of the bore hole. The full line is the 1985 measurement; dashed line is 1986 measurements. The profiles show distinct convection in the hole liquid, except for below a depth of 1980 m where the liquid density increases.

DIRECTIONAL SURVEY

Directional surveys of the Dye 3 bore hole were made in 1983, 1985, and 1986. The inclination of the bore hole over the entire depth is shown in Figure 5. This figure includes the 1981 data from the inclinometers mounted inside the drill, and it is obvious that those readings are slightly too low. This possibility was discussed earlier (Gundestrup and Hansen, 1984). Figure 6 is an expanded view of the lower part of the inclination profiles compared with a dust profile at the left. The marked increase in deformation in the Wisconsin ice and in the silty ice below it is shown by the 1983 and 1985 surveys.

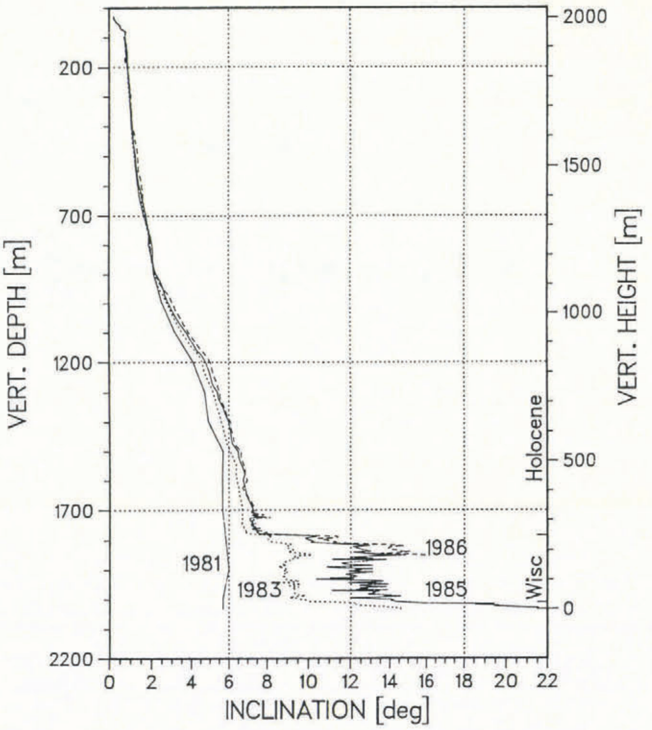

Fig. 5. Inclination versus vertical depth in 1981, 1983, 1985, and 1986.

The azimuth of the bore hole over the entire depth is shown in Figure 7. The azimuth is essentially constant down to the Wisconsin ice, where significant changes are evident.

The velocity profile computed from the 1981, 1983, 1985, and 1986 directional surveys is shown in Figure 8. It was computed using seven sets of measurements (Dahl-Jensen and Gundestrup, 1987). The azimuth calculations show that the ice flow is unidirectional within the accuracy of the measurements (±5°). The calculated surface velocity (assuming zero at the bottom) is 12.2 m/year at an azimuth of 060°. This is consistent with the results of the navigation-satellite position determinations. Mock (1976)

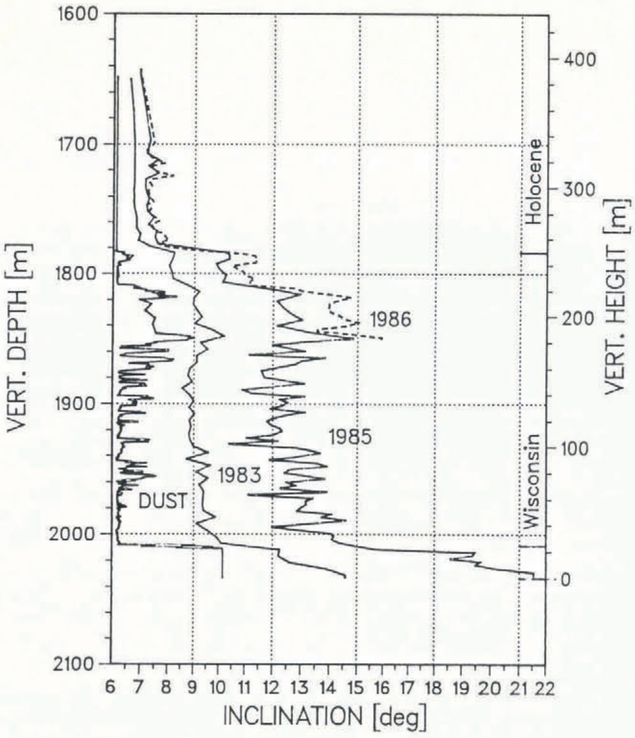

Fig. 6. Inclination versus vertical depth for depth below 1600 m. The curve to the left is a dust index. These curves indicate a high correlation between tilting rate and dust content.

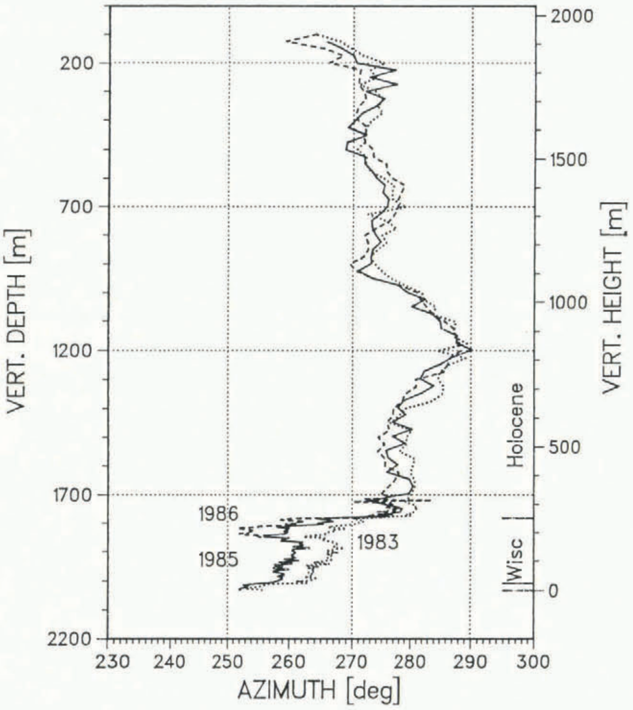

Fig. 7. Azimuth versus vertical depth in 1983, 1985, and 1986. There is very little change with time for Holocene ice. For Wisconsin ice, the azimuth goes towards 240°.

established in 1972 a station 450 m from the drill site. The position of the antenna at this station has been measured by satellite several times (Table I).

This table is an extension of that provided by Reeh and Gundestrup (1985). The antenna height over the WGS-72 ellipsoid is 2528.4 ± 1.3 m. With an antenna height over the surface of 1 m, and a geoid height of 43.4 m (Rapp, 1978), the surface elevation is 2484 ± 2 m above mean sea-level.

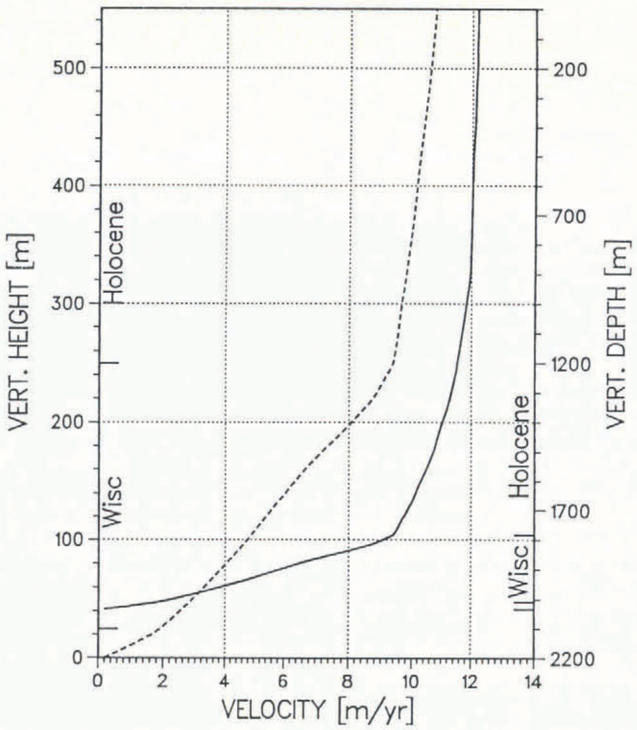

Fig. 8. Horizontal velocity versus vertical depth based on seven surveys in the period 1981–86.

TABLE I. POSITIONS OF MOCK STATION 1 IN WGS-72 COORDINATES

Year	*Lat.* °N.	*Long.* °E.	*Elevation* m
72.586	65.187391	316.169520	2526.76
80.626	65.187814	316.171377	2526.45
81.548	65.187878	316.171618	2529.68
83.422	65.187977	316.172051	2529.36
85.479	65.188092	316.172560	2529.21
86.408	65.188139	316.172755	2528.72

A linear fit to these data gives the velocity: $V_1 = 12.56 \pm 0.06$ m/year, azimuth 061.2° ± 0.3°.

This velocity must be corrected for the local strain when moving the velocity to the drill site. This correction is 10 cm/year. Thus, the corrected velocity (V_d) at the drill site is:

$$V_d = 12.6 \pm 0.1 \text{ m/year, azimuth } 061.2^\circ \pm 0.5^\circ.$$

This compares favorably with the independent result from the directional surveys.

The velocity profile (Fig. 8) is similar to the preliminary profile (Gundestrup and Hansen, 1984), which was based on lower-resolution inclinometer data. The higher-resolution data from recent surveys show that the deformation in the upper half of the hole is smaller than the preliminary estimate. This was foreseen by Gundestrup and Hansen (1984).

SUMMARY AND CONCLUSIONS

Results from the 1985 and 1986 resurveys of the bore hole at Dye 3 have confirmed and refined the preliminary results based on the 1981 and 1983 surveys.

The convective circulation of the hole fluid which was anticipated in 1983 was observed in the 1985 and 1986 surveys.

The diameter measurements have been disturbed by the changing fluid pressure in the bore hole. The addition of heavy liquid in 1981 made rapid closure of the upper parts of the bore hole unavoidable. It will be necessary to ream the 100–300 m depth interval in future years. The measurements in the Wisconsin ice and in the underlying silty ice show that the most rapid diameter increases (in 1983) and decreases (in 1985 and 1986) correlate with the layers with high dust content and high shear deformation rates.

The major features of the estimated velocity profile based upon the 1981 and 1983 surveys (Gundestrup and Hansen, 1984) are confirmed. The standard deviation of shear deformation rates is halved. The Wisconsin ice deforms more readily than the Holocene ice and there is a high correlation between dust content and shear deformation rate. This is in agreement with results from Canadian ice caps (Fisher and Koerner, 1986, 1987).

Future directional surveys in the upper 1800 m of the bore hole are needed to provide data for shear deformation rates in the Holocene ice. The differences between the 1983 and 1986 surveys are too small to do this for the upper 1200 m. This depth interval, where only a few per cent of the deformation occurs, is of great value for the determination of flow properties.

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