BORE-HOLE SURVEY AT DYE 3, SOUTH GREENLAND

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Abstract. In 1983 three directional surveys were made in the bore hole from which a deep ice core was obtained in the summers of 1979–81. The inclination and azimuth of the bore hole were measured on three surveys, temperature was included on two surveys, fluid pressure and hole diameter on one of the surveys. Fluid-pressure measurements show that the ice-overburden pressure was undercompensated in the upper few hundred meters and overcompensated at the bottom of the hole. Diameter measurements show closure in the upper portion and expansion near the bottom beginning at the transition from the Holocene to Wisconsin ice at 1784 m. The hole expansion and increase in inclination correlate with dust and silt content in the Wisconsin ice. Changes in azimuth are due to flow of the ice and are consistent with the direction of flow at the surface. Temperature measurements show that the hole is at or near equilibrium. The gradient of 0.012 K/m below 1400 m is less than the 0.018 K/m at Camp Century. There is a slight reduction in gradient near the bottom from internal friction in the silty ice.

Résumé. *Relevés du trou de forage à Dye 3, Groenland du Sud.* En 1983, trois relevés de direction ont été réalisés dans le trou de forage à partir duquel des carottes profondes avaient été obtenues pendant les hivers de 1979 à 1981. Les inclinaisons et l'azimut du forage ont été mesurées pour trois relevés, la température pour deux relevés, la pression du fluide et le diamètre du trou au cours d'un des relevés. Les mesures de pression du fluide montrent que l'excès de pression de la glace était sous-compensée dans les quelques premières centaines de mètres et sur-compensée au fond du forage. Les mesures de diamètre montrent une fermeture dans la partie supérieure et un aggrandissement au fond, débutant à la transition entre l'Holocène au Wisconsin à 1784 m. L'agrandissement du trou et l'augmentation en incli-

naison sont corrélés avec la teneur en poussière et en sédiments de la glace du Wisconsin. Le changement en azimut est dû à l'écoulement de la glace et concorde avec la direction de l'écoulement en surface. Les mesures de températures montrent que le trou est à ou proche de l'équilibre. Le gradient de 0,012 K/m au-dessous de 1400 m est inférieur au 0,018 K/m de Camp Century. Il y a une légère diminution du gradient près du fond dû au frottement interne de la glace chargée en sédiments.

Zusammenfassung. *Bohrlochvermessung bei Dye 3, Süd-Grönland.* Im Jahre 1983 wurden drei Richtungsmessungen in dem Bohrloch vorgenommen, aus dem in den Sommern 1979–81 ein tiefreichender Eiskern geborgen worden war. Neigung und Azimut des Bohrloches wurden dreimal eingemessen, bei zwei Vermessungen wurde die Temperatur mitbeobachtet, bei einer Vermessung auch der Flüssigkeitsdruck und der Lochdurchmesser. Die Messungen des Flüssigkeitsdrucks zeigen, dass der Auflagedruck des Eises in den obersten Hektometern unterkompensiert, am Grunde des Bohrloches hingegen überkompensiert ist. Die Durchmessermessungen ergeben eine Schliessung im oberen Teil und eine Erweiterung nahe dem Grund, beginnend am Übergang vom holozänen zum Wisconsin-Eis bei 1784 m. Die Locherweiterung und die Zunahme der Neigung fallen mit dem Gehalt an Staub und Schlamm im Wisconsin-Eis zusammen. Azimutänderungen sind durch den Fluss des Eises verursacht und passen mit der Fliessrichtung an der Oberfläche zusammen. Temperaturmessungen zeigen, dass sich das Loch ganz oder nahezu im Gleichgewicht befindet. Der Gradient von 0,012 K/m unterhalb von 1400 m ist geringer als der von 0,018 K/m bei Camp Century. Eine geringe Abnahme des Gradienten tritt nahe dem Grunde infolge der inneren Reibung im schlammigen Eis auf.

INTRODUCTION

In the summers of 1979 to 1981, a deep (2037.63 m) ice core was obtained at Dye 3 (lat. 65°11'N., long. 43°49'W., H = 2490 m) in south Greenland. The drill site is on the eastern side of the ice sheet, in an area with a mountainous bedrock topography (Overgaard and Gundestrup, in press). The top 81.7 m was drilled thermally and cased with steel pipe by the Cold Regions Research and Engineering Laboratory (CRREL) (Rand, 1980), and the hole was drilled from 81.7 m to the bottom with an electromechanical drill (Gundestrup and others, in press). The drill, using neither melting nor solvents, produces a hole with a uniform diameter. The hole is filled with a liquid in order to minimize hole closure from the overburden pressure of the ice.

After the drilling stopped in 1980 at 901 m, a temperature profile was measured. Shortly before the end of the 1981 season, an inclination profile (Gundestrup and others, in press) was obtained using the inclinometers in the drill. The next day the drill was trapped at the bottom while drilling in silty ice. Four hundred liters of perchlorethylene (PCE) were added to the hole, and the drill was left with tension in the cable. In 1982, the drill had become loose. After recovery of the drill, a temperature profile was measured. Sonic logging was performed (Taylor, unpublished) and a 5 m by 0.08 m probe was used as radar target in an attempt to measure the azimuth of the hole inclinations, and the velocity of radar waves in ice (Jezek and Roeloffs, 1984). In 1983 three independent bore-hole surveys were made using different tools to measure inclina-

tion and azimuth. The hole diameter, fluid temperature, and pressure were also measured.

While drilling, depth was measured as accumulated core length. The hole length changes with time due to the ice movement. In this work all slant hole depths measured on the logging winch in 1983 were scaled to comply with the 1981 core length which we believe to be the most accurate measurement of the length of the hole. This corresponds to a true vertical depth (TVD) of 2033.2 m as the difference between slant hole length and TVD was 4.4 m in 1981. In 1983, the difference was 7.4 m.

At the end of the 1983 season the casing was extended 2.29 m and 416 liters of diesel fuel was added to the hole.

EQUIPMENT

The temperature profiles measured in 1980 and 1982 were obtained with a lightweight probe 5 m below the drill antitorque section used to weight the cable. The probe presses the temperature transducer against the wall of the bore hole and resembles the surface sampling device described by Bird ([c1976]). The temperature transducer - the same both years - was a thermistor (Fenwal type UUA 32J3) calibrated by the manufacturer to 0.03 K at -40°C, -20°C, and 0°C. Resolution of the measurements was 0.002 K, and the sampling interval was 25 m. Interpolation was performed using the equation (Steinhart and Hart, 1968):

$$1/T = A + B \ln R + C(\ln R)^3 \qquad (1)$$

where R is thermistor resistance and T the absolute temperature. A, B, and C are constants. The first logging device used in 1983 was the University of Copenhagen (UCPH) experimental short unit (1.10 m from center to bottom of tool) measuring inclination, azimuth, temperature, pressure, and diameter.

This tool employs the same principles as the ISTUK drill: all measurements are performed in the logger controlled by a microprocessor. At 4 s intervals, the microprocessor transmits the information to a standard computer terminal at the surface. Here, the data are stored on magnetic tape for subsequent analysis.

The temperature transducer is similar to the type used in 1980 and 1982, however it measured the temperature of the fluid near the center of the hole at the bottom of the tool. The resolution of the sensor is 0.012 K.

Inclination is measured with a pair of Schaevitz LSRP-14.5 inclinometers, compensated to work from −50°C to 0°C. The nominal range of the inclinometers is 14.5°. Azimuth is measured with a magnetic compass (Aanderaa, type 1248).

The pressure transducer is a quartz sensor (Paroscientific type 75k-002), calibrated by the manufacturer with an accuracy of 0.04 per cent of the reading at 21°C and −25°C.

The tool has two calipers, one at each end. Due to a friction problem, only the lower caliper was operative. The caliper centers the tool using three points of contact with the hole wall. The range of measurements is 98-136 mm with a resolution of 0.1 mm.

The second logging device was owned and operated by "Sperry-Sun" of Canada. They used a gyro-accelerometer combination to give both inclination and azimuth. The distance from center to bottom of tool is 2.46 m.

The last logging device used was the Polar Ice Coring Office (PICO) survey tool. The compass and inclinometer are of the same brand and type as those used in the UCPH tool. In addition, a temperature transducer (thermistor) was mounted 0.25 m below the main body of the tool. The thermister (no. 1297) was calibrated at CRREL to 0.01 K at the following temperatures: −78.685°C, −38.867°C, 0.01°C, and 40.780°C. The resistance of the thermistor was converted to degrees Celsius using the calibration table for that thermistor. A rotary selector switch in the survey tool was actuated from the surface and the outputs of the various transducers were measured with a high-accuracy digital multimeter. The distance from the center to the bottom of the tool is 2.25 m.

A Gearhart-Owen 800 SUA winch was used for the three surveys. The winch has a hydrostatic drive powered by a diesel engine and is equipped with approximately 4000 m of prestressed seven-conductor steel-armoured logging cable 8 mm in diameter, a depth counter reading in feet, and a cable tension meter.

MEASUREMENTS

Hole liquid density

Using the measured depth of the logging tool and the pressure measured by it at that depth, the density of the hole liquid was calculated. The curve is slightly smoothed, the primary noise source being the resolution of the pressure gauge, approximately 1 m of depth. The density profile (Fig. 1) has three distinct regions; the density decreases from the surface of the liquid down to a depth of about 800 m, from 800-1800 m the density is nearly constant, then the density increases with depth. The high density in the upper region is caused by the excess 400 liters of PCE added in 1981. Two years later this PCE has only reached a depth of 800 m! The center region has a density close to 950 kg/m³ which was the nominal density chosen to compensate for the lack of liquid in the casing (the casing leaks at 68 m) and to produce
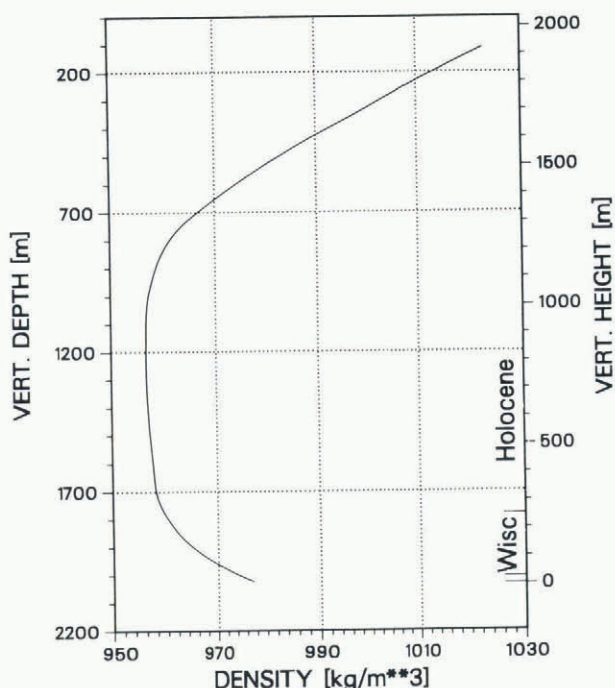

Fig. 1. Hole-liquid density versus true vertical depth as measured in 1983. The upper high density is due to excess amount of heavy liquid added in 1981.

the correct pressure at the bottom of the hole. Repeated measurements showing the change in density with time may indicate the reason why the density increases with depth in the lower part of the hole.

Hole pressure

Due to addition of excess PCE in 1981, and a few hundred liters of diesel fuel in 1982, the pressure at the bottom should be at or above the hydrostatic pressure of the ice. This is confirmed by the diameter measurements. The absolute pressure 2 m above the bottom of the hole was 183.65 bars. The total vertical depth of the hole is 2033.2 m. Using a density correction for the firn of 24 m, and a barometric pressure of 0.74 bar, an average ice density of 928 ± 2 kg/m³ is calculated assuming that the liquid at the bottom is in hydrostatic equilibrium with the ice. This value is significantly higher than the 917-920 kg/m³ measured on the Byrd core (Gow, 1970). The difference is probably due to lack of hydrostatic equilibrium at the bottom. However, the Byrd density was measured on relaxed ice-core samples. These samples may have a low density due to formation of air bubbles. Future measurements can give the *in situ* ice density.

Diameter

The diameter was measured with a three-point caliper mounted 20 cm above the bottom of the UCPH tool which measures the diameter continuously and stores the maximum and minimum values. Every four seconds these values are transmitted to the surface and a new search for diameter extremes is initiated. Thus, any diameter anomaly will be detected. Apart from the caliper itself, errors may be introduced by accretion of ice on the caliper.

Figure 2 shows the measured diameter. Above 150 m, the diameter exceeds the maximum range of 136 mm. The spikes between 800 m and 900 m are caused by slippage of the antitorque springs during drilling. At 700 m the ice core started to be brittle, and at 800 m the ice core had several fractures. In an (unsuccessful) attempt to reduce these fractures, the drill rotation speed was slowed down. This reduction in drilling speed however disabled the fast automatic antitorque failure detector that normally would terminate the
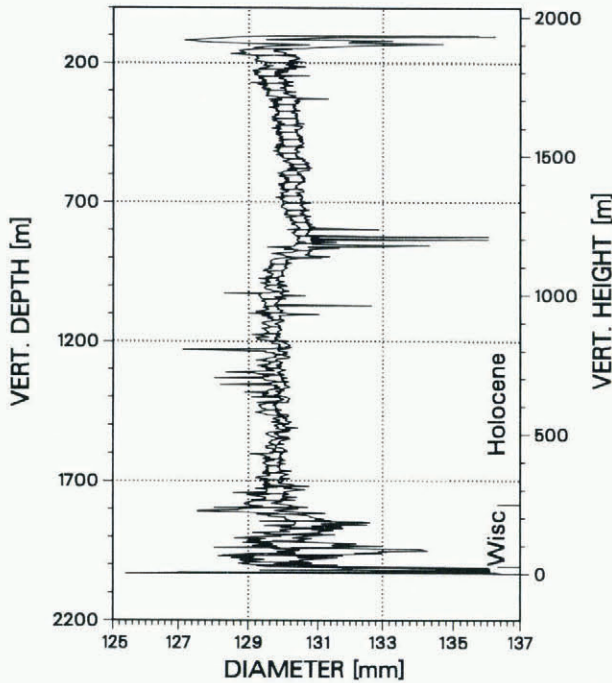
Fig. 2. *Hole diameter versus depth. The two curves indicate the maximum and minimum diameters. The low diameter near the top is due to hydrostatic underpressure in the liquid-filled hole. The shift at 901 m indicates end of reaming. The hole is distorted in Wisconsin ice, e.g. below 1784 m.*
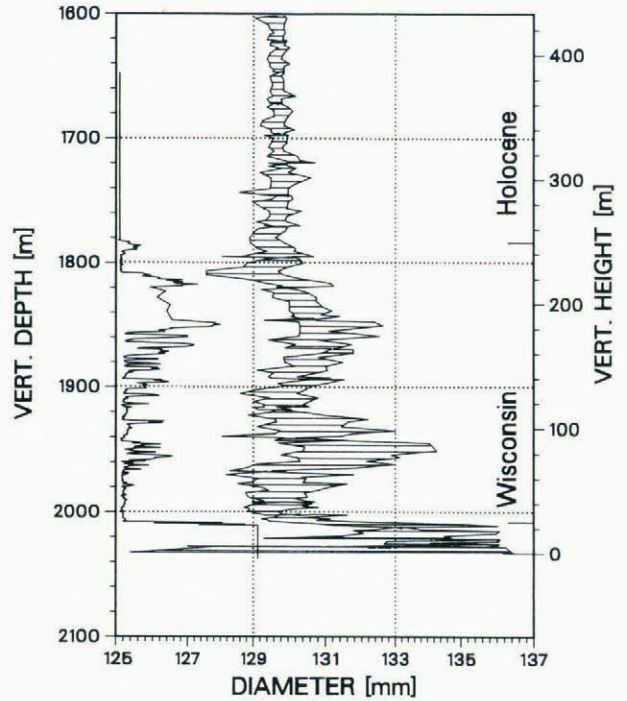

Fig. 3. *Hole diameter versus depth below 1600 m. The curve at left is a dust index. A high correlation between dust and hole deformation is visible.*

drilling. Thereafter the operator had to stop the drill in case of problems. The result is that the antitorque leaf spring scraped ice from the wall and in some positions increased the diameter beyond 136 mm.

The nominal hole diameter is 129.5 mm. In 1981 (before start of season) the diameter was reamed to 130 mm from the top down to 901 m. The 0.5 mm shift at 901 m is clearly visible. The decrease in diameter from 900 m towards the top is caused by the hydrostatic underpressure due to the stand of the liquid being below the top of the casing.

Below 901 m until the Holocene–Wisconsin transition at 1783.74 m vertical depth, the diameter is within a few tenths of a millimeter of the nominal diameter. The negative spike at 1231 m is not reproducible, it was probably caused by ice on the caliper.

The diameter of the lowest part of the hole (Fig. 3) deviates significantly from the original 129.5 mm. The PCE added in 1981 created a hydrostatic overpressure at the bottom of the hole up to 2.5 bars. This increase of the diameter caused by the overpressure starts at the transition from Holocene to Wisconsin. Part of the reason for the generally increasing diameter with depth in the Wisconsin ice is that the hydrostatic overpressure increases with depth.

The silty ice, starting at 2008.54 m vertical depth, has a diameter frequently exceeding 136 mm. The curve to the left in Figure 3 is a dust profile measured as the mean of 55 cm of core (Hammer and others, in press). A high correlation between dust and increased diameters (soft ice) is visible. The diameter anomaly at 1944–1951 m is connected with a narrow, visible layer. This layer hardly shows up in the dust profile. The reason is probably that the layer consists of relatively large particles that were removed in the laser dust equipment. Furthermore, the layer is narrow, giving little contribution to the 55 cm average value. The dust content in silty ice exceeds the range of the equipment.

Five meters above the bottom there appears to be a short constriction reducing the hole diameter to

125.4 mm. The constriction must have a relatively sharp edge as the logging tool tended to rest on the constriction. Having hydrostatic overpressure at that depth, the driving force cannot be the hydrostatic pressure difference between the ice and the liquid. We expect that the reason is a discontinuity in the ice creating a shift between the upper and the lower hole. If this explanation is correct, the lower 5 m of the hole will not be accessible in some years time.

Temperature

Temperatures were measured to the bottom of the hole, 901 m, in 1980, in 1982, and twice in 1983. Figure 4 shows the measured profiles, including the profiles from 0–901 m as measured in 1980 and 1982 in an expanded temperature scale. Close to the surface, above 150 m, the temperature profile is distorted due to the proximity of the steel casing. The cold peak around 200 m is assumed to be a climatic effect corresponding to a cold period 300 years ago (Dansgaard and others, 1975).

At 901 m, the bottom of the hole in 1980, the temperature had increased 0.1 K from 1980 to 1982. The same temperature probe was used in 1980 and 1982. The temperatures measured in 1980 and 1982 in the depth interval 200–300 m are reproducible with an accuracy better than 0.01 K, thus the shift is not caused by a measurement error.

After the drill was trapped at the bottom in 1981, power was removed from the drill. The next day the eight temperature transducers in the drill measured the hole temperature to -12 ± 0.5°C. In 1983, the bottom temperature was -13.22°C. This shift and the shift between the 1980 and 1982 temperatures are in opposite directions. The temperature was measured shortly after termination of drilling in 1980. Was the 1980 profile influenced by the drilling activities, e.g. addition of warm hole liquid? Most probably any disturbance from the drilling would have increased the hole temperature. Since no change is observed in the 200–300 m interval of the hole and the temperature in 1980 is lower than in 1982, no disturbances from the 1980 drilling activity is likely.

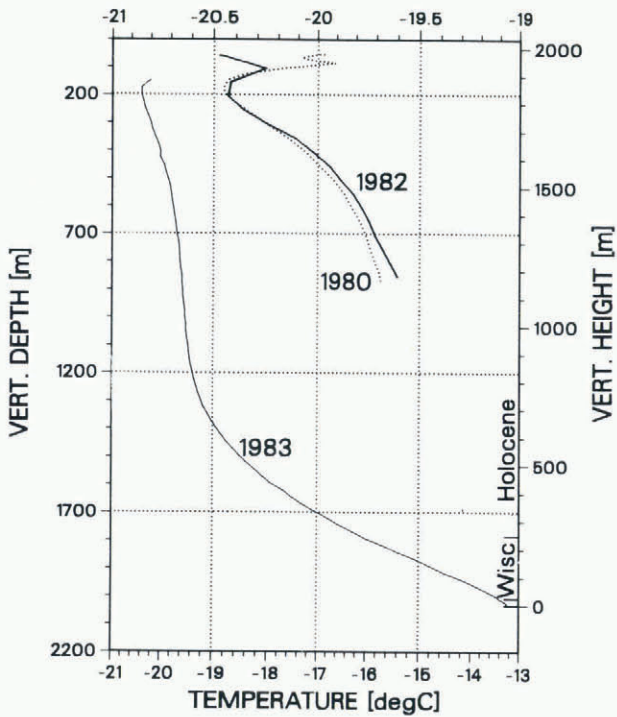Below 1400 m the temperature gradient approaches

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*Fig. 4. Hole-liquid temperature versus depth. The ex-
panded figure is hole temperature as measured in
1980 and 1982 at the hole wall.*

0.012 K/m compared to 0.018 K/m at Camp Century
(Hansen and Langway, 1966; Weertman, 1968; Robin,
1983). This gradient is half the 0.024 K/m expected
in case of steady state (Paterson, 1981). There is no
reason to believe that the geothermal heat is smaller
in south Greenland than in Camp Century, therefore
the temperature profile must be highly influenced by
the past history of the ice sheet. In the last few
meters above bedrock, a slight reduction in gradient
is observed corresponding to the internal friction
in silty ice. The temperatures in 1982 and 1983 were
identical within 0.03 K. This corresponds to the
calibration accuracy of the two thermistors used.
Thus, the hole is now considered to be in thermal
steady state.
      Since the temperature increases downwards there
is a possibility of convective circulation in the
hole. Based on Hales' (1937) original work, Diment
(1967) and Gretener (1967) published papers on con-
vective circulation in bore holes. Diment's nomen-
clature is used in the following calculation of the
critical temperature gradient:

$$G_C = \frac{g \alpha T}{C_p} + \frac{C \nu k}{g \alpha d^4}$$ (2)

"where G_C is the critical gradient, g the
acceleration due to gravity, T the absolute
temperature, α the coefficient of thermal
expansion, C_p the specific heat, ν the kine-
matic viscosity, k the thermometric conduc-
tivity (diffusivity), a the radius of the
tube, and C is a constant which has the value
216 for a tube whose length is great com-
pared with its diameter.
      The first term in this expression is the
adiabatic gradient which is about 0.2°C/km
for water and about 10°C/km for dry air at
20°C."

The drill hole was filled with a mixture of jet
fuel (Jet A-1) and perchlorethylene (PCE) (Gundestrup

and others, in press). The thermal expansion co-
efficient α and the kinematic viscosity ν of the hole
fluid at a temperature of -15°C (T = 258) are
9.26×10^{-4} K^{-1} and 3×10^{-6} m^2/s respectively. The rad-
ius of the hole was 0.065 m.
      Data on the specific heat C_p and diffusivity k
of the hole fluid are not available. Estimated values
are 1.6×10^3 W s/kg K and $10^{-7} m^2/s$ respectively. Using
these figures, we obtain a critical gradient of
2×10^{-3} K/m. The measured temperature gradient in the
bore hole from 1750-1950 m is 12×10^{-3} K/m, so con-
vective circulation is not unreasonable.
      On the Devon Island ice cap, Fisher (private
communication) has measured convection with an ampli-
tude of 0.1 K and a cell height of 8 m in a liquid-
filled hole with a temperature gradient of 0.024·K/m
or double that of the Dye 3 hole.
      The UCPH temperature profiles did not show any
sign of convection, however these profiles were ob-
tained with a 25 m sampling interval. The 1982 pro-
files were measured with the thermistor against the
hole wall so convection would not have been seen.
The gradient of 0.0007 K/m in the interval 600-900 m
is one-third of the calculated critical gradient. But
Samuel (1968) states "field measurements have shown
that convective flow occurs at gradients at least an
order of magnitude smaller than the calculated"
(critical) "gradients". The possibility that convec-
tive flow is responsible for the 0.1 K warming ob-
served at 901 m cannot be ruled out at this time.

Directional survey
      A directional survey of a drill hole consists in
measuring the inclination angle I from the vertical
and the azimuthal angle A from either true north or
magnetic north at measured depths D along the axis of
the drill hole.
      The position of points along the axis of the drill
hole is calculated with respect to a coordinate refer-
ence frame that has its origin at the top of the drill
hole. The positive X direction is east, the positive
Y direction is north and Z is measured vertically
downward.
      The X, Y, and Z coordinate of the drill hole at
any measurement point n are computed using the "bal-
anced tangential equations" (Walstrom and others,
1972):

$$X = \frac{1}{2} \sum_{i=1}^{n} (S_i - S_{i-1})(\sin I_i \sin A_i + \sin I_{i-1} \sin A_{i-1}),$$ (3)

$$Y = \frac{1}{2} \sum_{i=1}^{n} (S_i - S_{i-1})(\sin I_i \cos A_i + \sin I_{i-1} \cos A_{i-1}),$$ (4)

$$Z = \frac{1}{2} \sum_{i=1}^{n} (S_i - S_{i-1})(\cos I_i + \cos I_{i-1}),$$ (5)

where I_i, A_i, and S_i are the inclination, azimuth and
slant hole depth at measurement i. The slant hole
depths are measured to the middle of the survey tool
(Blythe, 1975) which is centered in the hole by springs
near top and bottom of the tool.
      The PICO and UCPH survey tools contain a pair of
inclinometers and a magnetic compass to measure the
drill-hole inclination and azimuth. The outputs from
the two inclinometers and the compass reading are
used to calculate inclination and azimuth of the bore
hole from magnetic north. Measurement of the magnetic
deviation (36° W.) using sun-shot and satellite-
determined positions made it possible to have the azi-
muth referenced to true north.
      Figure 5 shows the inclination versus depth on 9
August 1981 and 2 July 1983. Above 900 m no change in
inclination with time is visible. From 900-1784 m
there is a gradual increase in the difference between
the inclinations. Part of the difference may be due
to the 1981 reading being too low. The 1981 inclina-

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tion was measured with the inclinometers in the drill. The drill however is not rigid and the upper part of it may not have been centered. As a consequence, readings from the drill tend to be too low, in particular at inclinations approaching the upper limit of the inclinometers (6°).

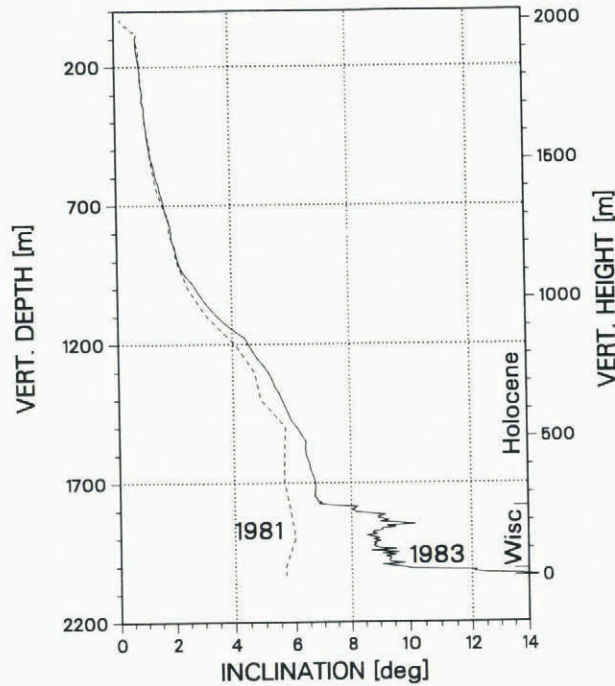The lower part of the inclination profile is expanded in Figure 6 together with a dust profile. The profile reveals the same feature as the diameter measurements (Fig. 3). There is a sharp change at the transition from the Holocene to the Wisconsin at 1783.74 m vertical depth, the Wisconsin ice showing much more deformation. Again a high correlation between dust and change in inclination is visible. The 4° maximum change in inclination, occurred in the 25 m of silty ice over a period of 1.88 years.

Due to the c-axis of the ice crystals becoming more vertical with depth (Herron and others, in press) the ice is expected to creep faster with depth. Although a few measurements of the c-axis orientation in Wisconsin ice exists, and significant changes in c-axis orientation have been observed within 30 m (Russell-Head and Budd, 1979), change in crystal orientation can hardly explain the fast creep changes displayed in diameter and inclination. We conclude that dust, and/or some substance that varies in proportion to dust, is dominating the creep-rate, even though other physical and chemical properties vary significantly in the Wisconsin ice (Shōji and Langway, in press). This observation is supported by measurements on the Canadian ice cores (Koerner and Fisher, 1979).

The azimuth is shown in Figure 7. The drilling was performed at nearly constant azimuth 292° ± 10° determined by the azimuth of the casing. There is no tendency to screw shape as in the Byrd hole (Garfield and Ueda, 1976). The end of the Wisconsin corresponds to a shift of 14° and silty ice to an additional 10°. The bottom azimuth of 260° is quite consistent with the measured surface flow.

Knowing the inclination and azimuth at various depths, the X,Y,Z coordinates of the drill hole were computed and plotted on a three-dimensional graph (Fig. 8). The bottom of the hole is 128.7 m west and 45.4 m north of the top of the casing. The shift between the 1980 and 1981 season at 1130 m, and the end of the Wisconsin at 250 m above bedrock are clearly visible.

The horizontal velocity profile cannot be calculated due to lack of information about the 1981 hole geometry; no azimuth is known. However an estimated

Fig. 5. *Inclination versus depth. The solid line was measured 2 July 1983, dashed 9 August 1981. The 1981 inclination may be too low at higher inclinations (see text). The main part of the hole deformation occurs in Wisconsin ice.*
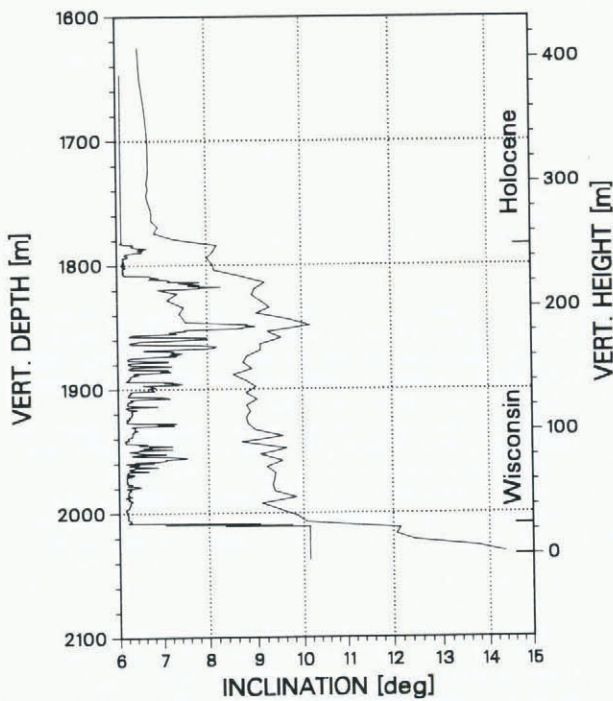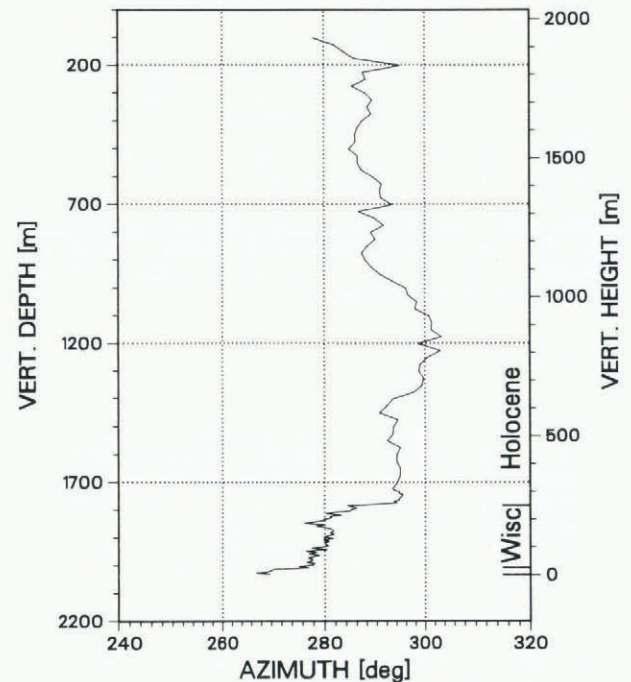

Fig. 6. *Inclination versus depth below 1600 m. The curve at left is a dust index.*

Fig. 7. *1983 azimuth versus depth. The drill hole lies almost in a plane at 290° azimuth. The change in azimuth due to ice flow in Wisconsin and silty ice is clearly visible.*
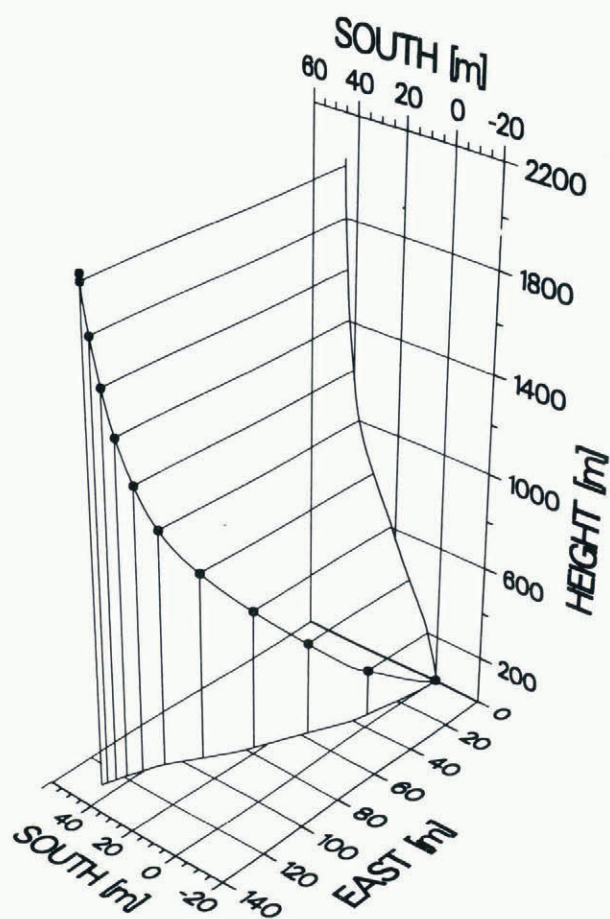
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Fig. 8. *Three-dimensional plot of 1983 hole position. The bottom of the hole is located north-west of the top.*

Fig. 9. *Estimated horizontal ice velocity versus depth. The dashed line is the lower 500 m in expanded depth scale. The difference in flow enhancement factor for Holocene and Wisconsin ice is clearly visible.*

profile can be computed. Figure 7 shows that the azimuth is almost constant, making it possible to estimate the 1981 azimuth: in the upper 1400 m above the bottom, the azimuths in 1981 and 1983 are assumed to be identical. Below 1400 m the azimuth in 1981 is assumed to be constant. Using this estimate, and assuming zero velocity at the bottom of the hole, the estimated horizontal velocity profile in Figure 9 is obtained. The calculated surface velocity is 13.4 m/year compared to the measured surface velocity of 12.3 m/year (Overgaard and Gundestrup, in press).

The calculated azimuth is 89.5° compared to a measured flow direction of 60°. The high surface velocity is probably due to a too small 1981 inclination below 900 m as explained above. Under the present circumstances, the agreement between the calculated and measured surface velocity is considered very good. Shōji and Langway (1984) have calculated a velocity profile based on estimated enhancement factors of the core, dividing the core into five sections. The profile is in reasonable agreement with the present work.

The drill did not penetrate the material below the ice. However as the calculated surface flow indicates, not many meters of ice between the bottom of the hole and the sub-ice material are missing.

The calculated velocity profile differs significantly from the theory (Dansgaard and Johnsen, 1969) where ice of temperature-dependent shear strength is assumed. Based on the calculated velocity profile and the inclination profile, four distinct flow regimes are observed: (1) above 250 m above bedrock corresponding to Holocene, (2) from 250-88 m above the bottom this region is assumed to contain "ordinary" Wisconsin ice, (3) from the first layer containing
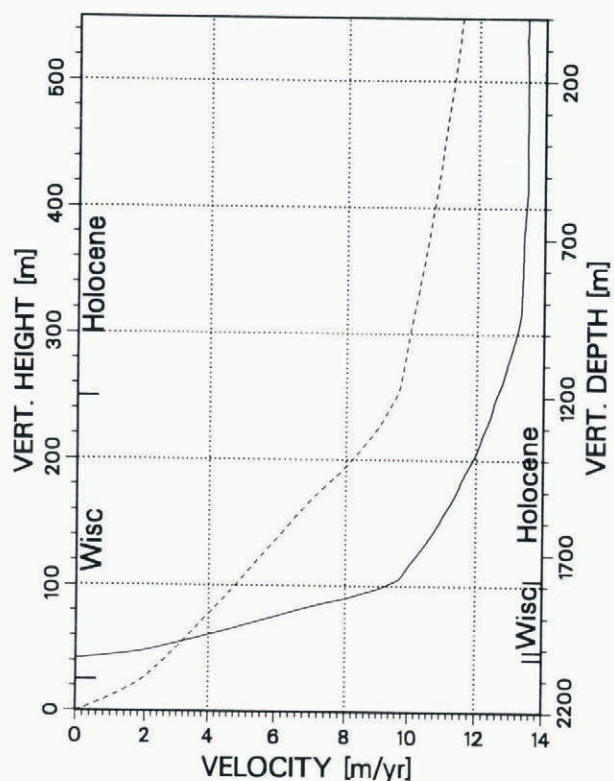
bottom material at 88 m to silty ice at 25 m, and (4) silty ice below 25 m above the bottom.

SUMMARY AND CONCLUSION

Due to the use of a two-component hole fluid, the hole fluid is inhomogeneous. Initial density differences in the hole liquid smooth very slowly and some fractionation close to the bottom cannot be excluded.

Repeated temperature measurements show the hole temperature to be in a steady state. The maximum change of temperature with depth is 0.012 K/m. The bottom temperature is -13.22°C. Measurements indicate that the present hole temperature may deviate from that of undisturbed ice due to thermal diffusion and possible convection in the hole liquid.

The Wisconsin ice shows about an order of magnitude higher creep-rate than Holocene ice. There is a high correlation between dust and creep-rate, meaning that dust and/or some substance that varies together with dust has a major impact on the ice properties.

A velocity profile was estimated based upon assumptions about the 1981 hole position. The estimated surface velocity is 9% larger than the measured surface velocity. Holocene ice seems to flow as a homogeneous medium. Wisconsin ice and silty ice have a much higher deformation rate. The flow calculations support the assumption that the bottom of the hole is close to the sub-ice material.

Paterson (1977) and Fisher (quoted by Paterson, 1981, p. 35) found that the late Wisconsin sections of bore holes in ice caps on Devon and Ellesmere Islands, Arctic Canada, closed more rapidly than the Holocene sections. On the other hand, Paterson (1983) interpreted inclinometer measurements at Camp Century, Greenland, and Byrd Station, Antarctica, as indicating that the Wisconsin ice there deformed less readily than the Holocene ice. However, new survey of these bore holes, combined with additional surface data, might change this conclusion.

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Repeated logging of the hole will provide the data necessary to compute a measured velocity profile and possibly the average *in situ* ice density.

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