Mem. Natl Inst. Polar Res., Spec. Issue, **49**, 224–233, 1994

THE UCPH BOREHOLE LOGGER

Niels S. GUNDESTRUP[1], Henrik B. CLAUSEN[1] and B. Lyle HANSEN[2]

[1] *University of Copenhagen, Haraldsgade 6, DK-2200 Copenhagen N, Denmark*
[2] *Snow and Ice Research Group, University of Nebraska, Lincoln, Nebraska 68583-0850, U.S.A.*

Abstract: The University of Copenhagen (UCPH) logger measures borehole inclination, azimuth, temperature, diameter and pressure. Readings are made continuously by the logger, and the results are transmitted every 3 s to the surface. The tool remembers the maxima and minima of the diameters measured in each 3-s period. Thus, all extremes in diameter are recorded. The calliper is designed to give a resolution of 0.1 mm. A trade-off of this high resolution is that the tool cannot penetrate in a hole inclined more than 15°, and that the hole wall must be reasonably smooth in order to avoid hanging the tool on its callipers. The logger uses a single conductor coaxial steel cable, 3.1 mm in diameter. The winch has a standard 3-phase AC motor, which is powered by a variable frequency drive. The weight of the winch, including 3 km of cable, is 400 kg, and the total power consumption is less than 2 kW. This makes it possible to deploy the logger with light aircraft (Twin Otter or helicopter) support.

1. Introduction

The University of Copenhagen (UCPH) logger is specifically designed for logging the Dye-3 deep hole for temperature and deformation. An important consideration during the development of the logger system was that the logger could be transported by a Twin Otter aeroplane or a Bell 212 helicopter. This imposed restrictions in terms of maximum dimensions and weight both of single items and the total logging package. The most heavy individual item is the cable/winch. Therefore, a thin single-conductor coaxial cable is used instead of the customary 7-conductor logging cable. The information from the sensors in the logger is then read by a microprocessor in the tool, and transmitted at regular intervals to the console at the surface. The primary components of the system are the logger itself, the cable, the winch, the depth counter and power supply/modem. All electronics are custom designed.

2. Mechanical Design

The body of the logger (Fig. 1) is a brass tube, 68 mm inside diameter and 6 mm wall thickness. The brass type is Ms58, 270N/mm^2 0.2 flow value. Pressure rating is 600 bars. The material has relatively low strength, but only a few non-magnetic materials were available. At the top and bottom ends, a 3-legged calliper (Fig. 2) is mounted to a stainless steel body. The callipers centre the tool and resolve the diameter. The 3 legs are interconnected, and make the structure quite rigid. Because of this rigid construction, the tool can be centred in the borehole and the diameter can be measured with a resolution of 0.1 mm.

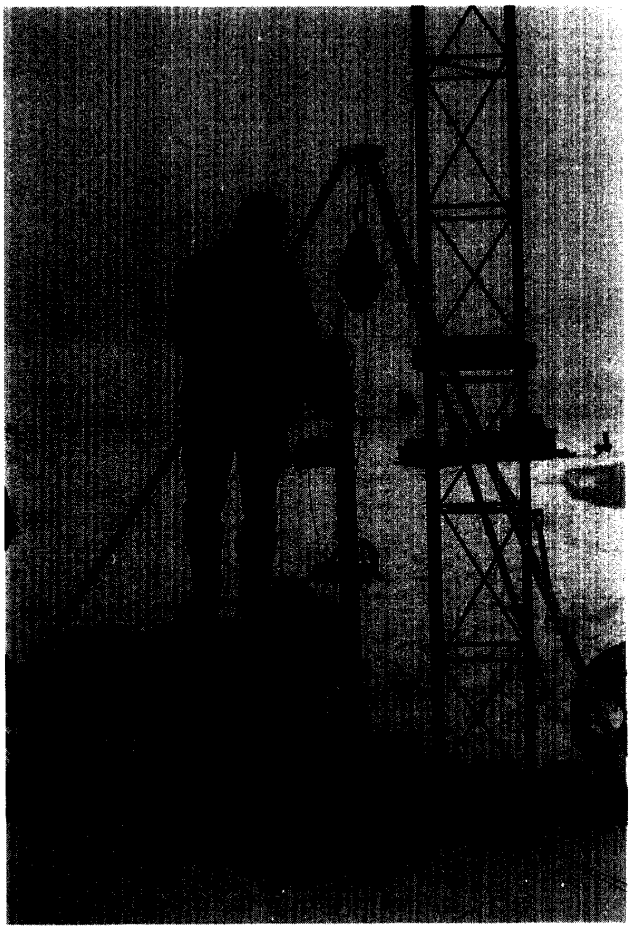

Fig. 1. Logger suspended on a tripod at the Dye-3 deep hole.

This rigid construction however, imposes the possibility of locking up the calliper during downhole movement. In order to minimise this risk, the callipers are mounted so that if locked up, an additional upward force will tend to disengage the callipers.

The distance between the centering devices is 1.9 m, and the maximum length is 2.1 m. The minimum diameter hole, through which the tool can pass is 98 mm.

3. Instrumentation

The tool has the following sensors:

1) Dual thermistor bridge which measures the temperature of the borehole liquid with a resolution of 0.01 K. The difference in temperature between the two sensors can be resolved with a resolution of 0.001 K. Both thermistors are calibrated by the manufacturer, and later by the National Danish Testing Board to 0.03 K.

2) A dual Schaevitz LSRP-14.5 inclinometer, compensated to work from –50°C to 0°C measures the hole inclination. Although the manufacturer defines the inclination range for these inclinometers to ±14.5°, they work well at inclinations up to ±30°.

3) Fluxgate directional sensor, mounted on a gimball allows inclinations up to 15° to be measured.

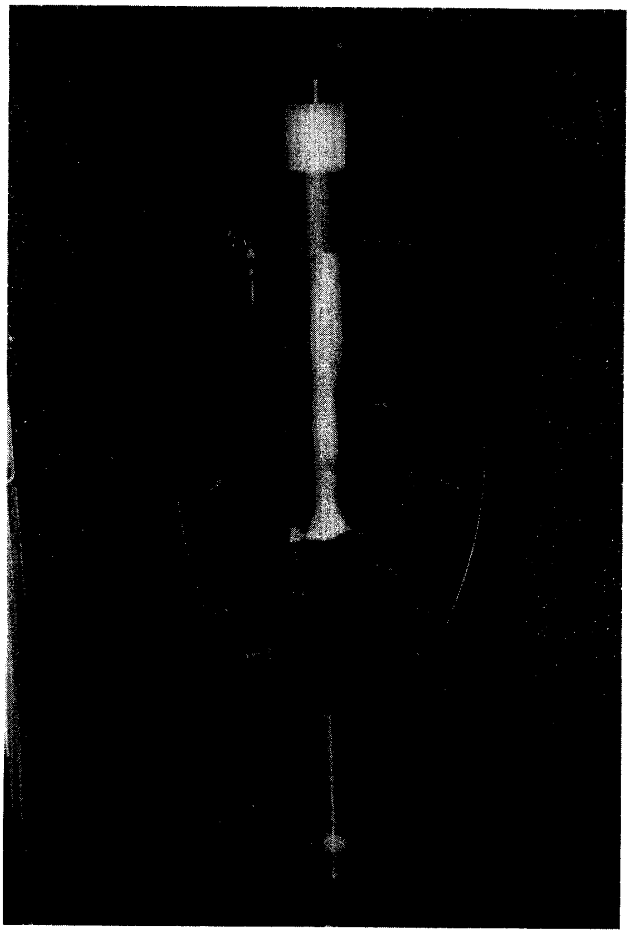

Fig. 2. The bottom of the logging tool, showing the 3-legged calliper and the bottom sensor. The black cylinder to the right is the linear potentiometer that measures the diameter.

4) Quartz pressure sensor, Paroscientific type 75K-002 measures borehole pressure. It was calibrated by the manufacturer to ±0.04%, and later by the Danish National Testing Board in the temperature range −50° to 0°C. This calibration indicated a hysteresis of 64 mbar, and a maximum scale error of 0.03% corresponding to 150 mbar. A temperature error of 2°C introduces an additional error of 60 mbar. The thin silicone oil that fills the transducer volume and capillary is Dow Corning type 200, 10 cSt at 20°C.

5) Two callipers, one at each end of the tool measure hole diameter. The range is 98–136 mm and the resolution is 0.1 mm.

6) Temperature transducers measure the temperature of the computer compartment in the logger, and the pressure sensor to ensure precise measurements.

4. Processor

Several of the parameters measured by the sensors, *e.g.* the hole diameter, should ideally be recorded continuously. Because all sensors share the same line of communication to the surface, the transmission speed is limited to one set of readings every 3 s. This corresponds to one sample per meter of hole, with a typical lowering speed of 30 cm/s. Typical anomalies in measured diameter occur over much shorter depths, and several irregularities could thus be missed. In order to make sure that all extremes in diameter are recorded, the computer measures the diameter 100 times a second, and stores the extreme values recorded since the previous transmission. At the next 3-s interval, the stored maximum and minimum diameter measured are transmitted to the surface. As a result, instead of one curve which shows the diameter, two curves show the maximum and minimum diameters in each 3-s interval. Sixteen analog channels, and a frequency which indicates the pressure, are recorded as shown in Table 1.

Table 1. Parameters measured by the UCPH logger.

CH0	1.9 V analog reference	CH9	Temperature of A/D converter
CH1	Inclinometer X	CH10	Pressure transducer temperature
CH2	Inclinometer Y	CH11	Input voltage
CH3	Azimuth	CH12	+5 V supply voltage
CH4	Upper diameter	CH13	Ground reference
CH5	Lower diameter	CH14	+12 V supply
CH6	Thermistor 1	CH15	–12 V supply
CH7	Thermistor 2	CH16	Pressure
CH8	10*(Term1-Term2)		

5. Surface Terminal

The information from the logger arrives at the surface as 300 baud audio modulation on top of the 70 V DC power to the unit. The audio signal is separated from the power current by a transformer in the power supply, and the signal is directed to a IC CMOS modem. The output from the power unit is a standard RS 232 computer interface which can be connected to a laptop PC. In order to record the depth reading as well as the information from the logger, the logger signal is relayed through the depth counter. This counter relays the information from the logger and listens for a carriage return character from the logger. When this character is received, the depth is added to the end of the message line from the logger. This system, based on a normal PC with only one serial port, acts as the logger terminal. The PC transforms the logger readings to engineering units, and displays the most important parameters. Of special interest is the hole pressure, because the increase in hole pressure with increased cable length verifies that the logging tool moves downward in the hole.

6. Cable

Because the information from the logger runs on top of the current which powers the tool, no special wires are needed for the transducers. This means that a thin single conductor coaxial cable is all that is needed. The selected cable is Rochester type 1H-125K, a tefzel-insulated 3.1 mm steel cable. The main specifications of the cable are:

Diameter: 3.15 mm
Weight in air: 40 kg/km
Weight in 930 kg/m^3 liquid: 33 kg/km
Breaking strength: 6.7 kN
Resistance of shield: 49 Ω/km

Resistance of center conductor: 79 Ω/km
Maximum voltage: 300 V
Elongation: 1.5 m/km/kN)

The cable is wound on the winch drum and is controlled by a Lebus groove on the drum and a front steering wheel. The spooling works well except for a small error in the reduction ratio used to position the front cable guide wheel. The cable worked very well, and hardly any memory effects occurred. The logger is routinely positioned within a few centimetres.

7. Winch

The power requirement of the winch is based on these considerations:
Gravity on 3 km of cable in liquid: 1000 N
Gravity of logger: 300 N
Max nominal pull in cable: 1300 N
Power at 0.5m/s upward speed: 0.7 kW

Allowing for friction in the winch gearbox and a mechanical brake on the winch, 1.1 kW is the nominal mechanical power delivered by the winch motor.

Selecting a drive unit: For our shallow drill winch (JOHNSEN *et al.*, 1980), we are using a DC motor powered by a single-phase SCR drive. This system has worked well. This system is not safe enough for logging deep holes because the weight of the long logger cable means that the cable operates relatively close to its breaking strength. Thus, in case of an overtorque, the motor could break the cable. Therefore, it was decided to use a Variable Frequency Drive of a 3-phase motor. This system is basically safe: even in case of a malfunction in the electronic control, the maximum pull in the cable can never exceed

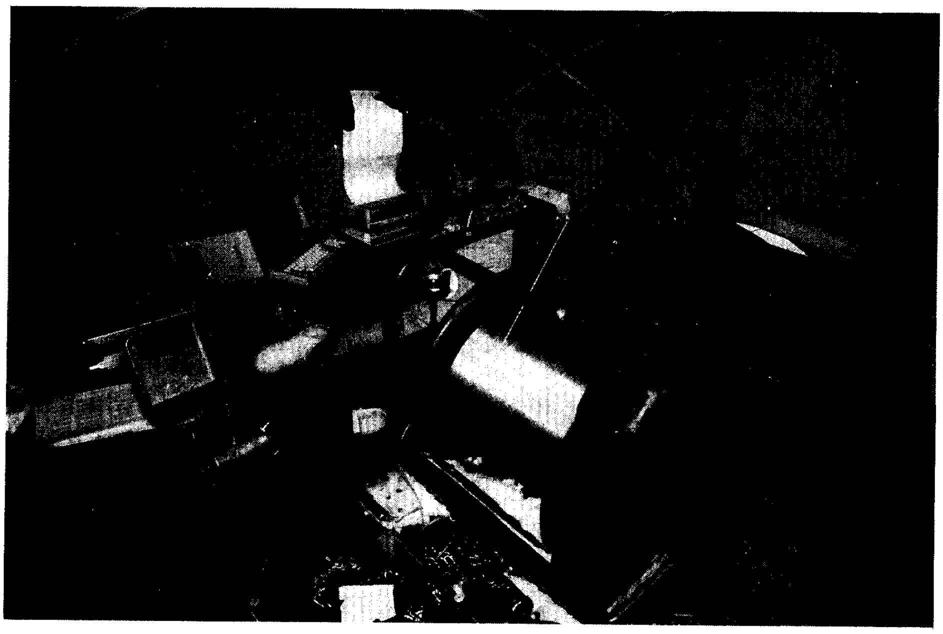

Fig. 3. The winch and surface electronics as used at Camp Century in 1989. The tent is a 2 m North Face dome. The cable extends through the door at the right to the casing 20 m away.

3 times the nominal pull. The system has worked well for several years and only requires routine lubrication. The weight of the winch and 2.5 km of cable is 400 kg.

8. Operation

In the original setup, a tripod was used to hold the tool. The winch was positioned next to the casing, and the cable went vertically from the winch up to the top wheel on the tripod and down into the hole (Fig. 1). Thus, the horizontal force on the tripod is quite small. In current configuration, a 2 m long beam with a wheel at each end is attached to the casing. The cable goes from the winch, horizontally to the lower sheave, up along the casing to the top sheave and down the hole. This setup with a strain gauge transducer built into the center bolt of the top sheave has the advantage that the winch can be placed in the operator's tent together with all electronics (Fig. 3). With everything inside a 2 m North Face dome tent, problems with blowing snow are minimised.

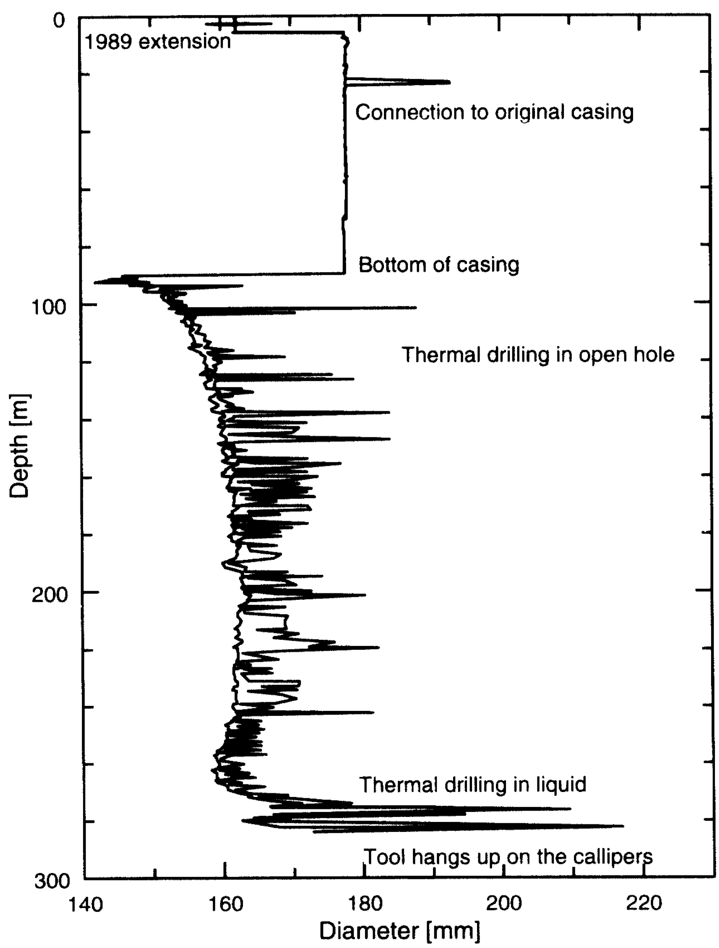

Fig. 4. The maximum and minimum diameters measured in the Camp Century deep hole in 1989. The figure shows the two casing extensions 2 mounted in 1988, the casing connection 23.8 m below the surface as attached after the drilling terminated in 1966, and the bottom of the casing at a depth of 90 m.
The reduced diameter just below the casing is caused by the low stand of the liquid (54 m below surface) in 1988.

9. Results

Figure 4 shows the hole diameter measured by one of the callipers at Camp Century in 1989 (GUNDESTRUP *et al.*, 1993). The two 3 m long fiberglass casing extension tubes mounted after the recovery of the hole in 1988 (HANSEN *et al.* 1989), are clearly seen. These casing sections have a slightly lower diameter than the steel casing below. At 23.8 m below the 1989 surface, a spike in the maximum hole diameter is seen. This spike corresponds to the connection between the original casing and the extension mounted after the drilling terminated in 1966. The bottom of the casing is at 90 m. The low diameter of the hole below the casing is caused by the pressure in the liquid being lower than the overburden pressure. With a stand of the liquid of 54 m below the surface (measured in 1988) and a firn correction of 24 m, the pressure in the liquid close to surface will be almost 3 bars less than the overburden ice pressure. Ideally, the hole liquid should have the same density as ice. In this case, the equilibrium level of the hole liquid would be the same as the firn correction or 24 m. The diameter of the hole, and thus the volume, will deform until pressure equilibrium is achieved at the depth where the ice is most readily

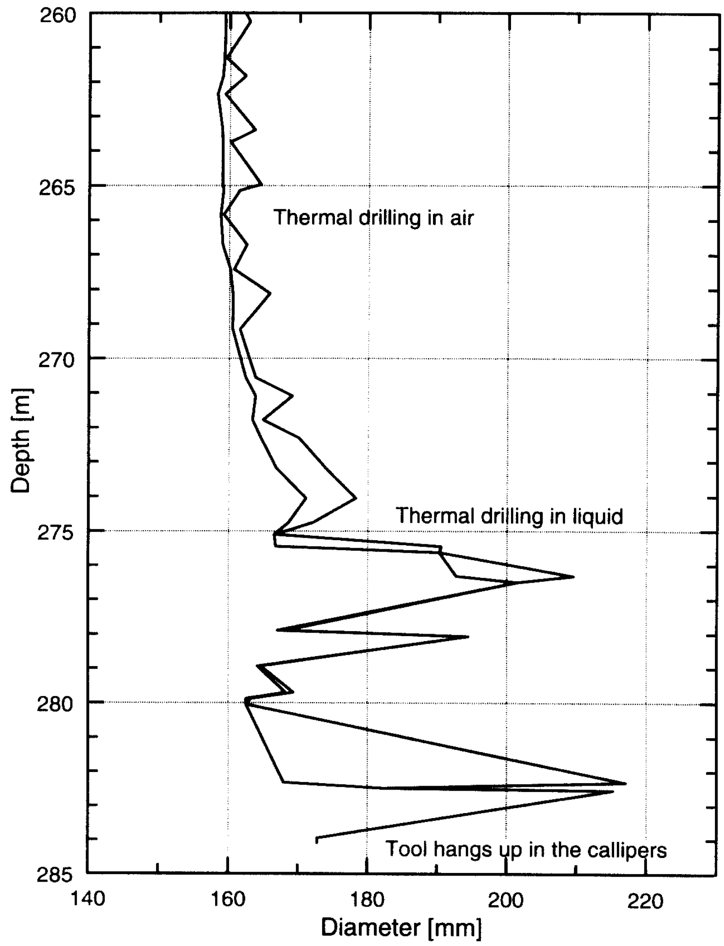

Fig. 5. The lower part of Fig. 4 expanded. It clearly shows the increase in diameter at the core breaks, and the unstable drilling when the operation changed from drilling in a dry hole to thermal drilling in a liquid-filled hole.

deformed. From measurements at Dye 3 and Camp Century, it is known that the silty ice is far more readily deformed than the ice at other depths. Thus, the diameter of the hole in the silty ice will change until the hole liquid pressure is the same as the overburden ice pressure. Assuming that the pressure equilibrium exists at the bottom of the hole at a depth of 1390 m, and with a firn correction of 24 m and an ice density of 920 kg/m^3, we calculate an average hole liquid density of 941 kg/m^3.

Figure 5 shows the depth range from 260 to 285 m. Every core-break is clearly visible, and the change from thermal drilling in an open hole to thermal drilling in a liquid-filled hole is reflected in a highly varying hole diameter, which changes between 160 and 220 mm. The thermal drilling in liquid had numerous problems, which caused changes in penetration rate. The excess heat from the drill head increased the hole diameter. In fact, these corrugations caused the logging tool to hang on its callipers, thereby preventing the tool from moving downward.

The friction between the logging tool and the hole wall is measured by fitting the reading of the depth counter (h) at the surface to a polynomial evaluation of the pressure measured by the tool (p). Figure 6 shows for a logging at Dome GRIP the difference

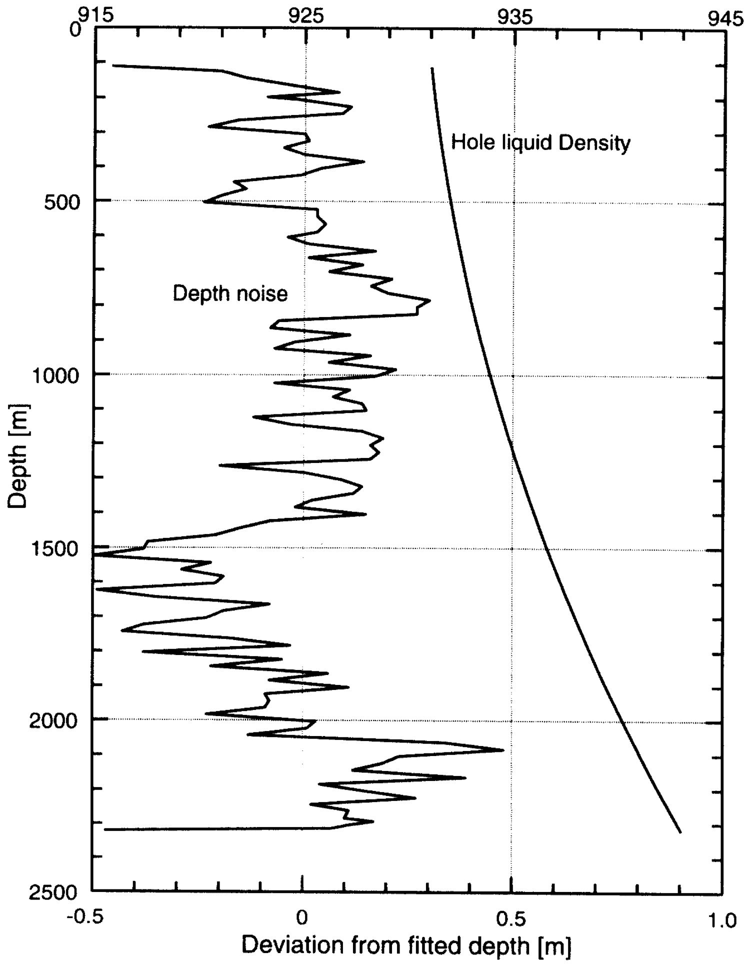

Fig. 6. The difference between the cable counter depth and the depth calculated from the probe pressure as measured by the probe and the hole liquid density profile at the right. The profile is from the logging at Dome GRIP, 1992.

between the depth counter at the surface and the depth calculated from the pressure at the probe. The left curve shows that the probe position in the hole closely follows the cable counter at the surface. The standard error in the position is 19 cm, quite close to the resolution of the pressure transducer. This resolution corresponds to 15 cm of depth change. Knowing the pressure versus depth, the hole liquid density (ρ) shown at right is calculated from the equation $p = \rho * g * h$, where g is the acceleration of gravity (9.822 m/s^2). Close to the surface, the density is 930 kg/m^3, increasing to more than 940 kg/m^3 at 2.3 km depth. The drillers used a more dense liquid at this depth in order to stabilise the drilling.

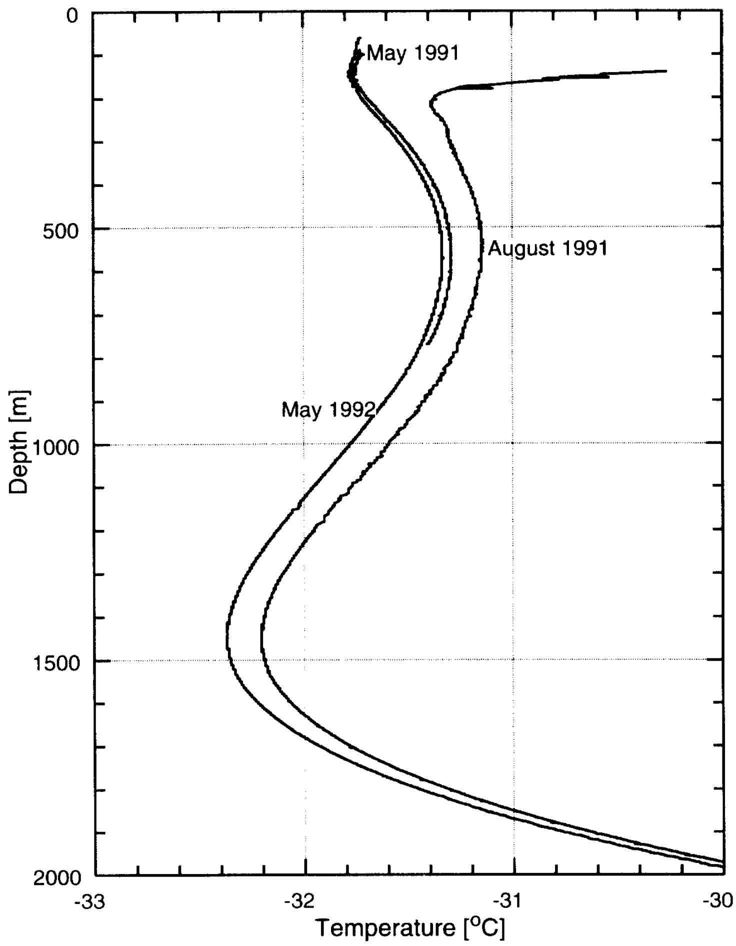

Fig. 7. The temperature in the GRIP hole, as measured in May 1991, August 1991 and May 1992.

Figure 7 shows the measured temperature of the GRIP 1991 hole at the start of the drilling in 1991, after the drilling, and in the spring of the following year, prior to commencement of drilling, after the hole had been at rest for 9 months. It is apparent, that the drilling activities increased the hole temperature 0.2°C in August 1991. By comparing the May 1991 to the May 1992 temperature curves, a disturbance on the order of 0.03 K is observed after one year.

By repeated measurements of inclination and azimuth in the deep bore hole at Dye 3 in south Greenland, GUNDESTRUP and HANSEN (1984) and HANSEN and GUNDESTRUP (1988) showed, that the Wisconsin ice at Dye 3 is a factor of 3 softer than Holocene ice. This change in ice flow properties is most likely a general feature of the Greenland ice sheet, and is associated with the higher concentration of impurities in the ice, ice smaller crystal size and a vertically aligned *C*-axis in the ice age ice.

10. Conclusion

The UCPH logging tool is a lightweight instrument that is transportable by small aircraft or helicopters. It measures hole inclination, diameter, pressure and temperature with high accuracy. Azimuth is measured with a typical accuracy of 1°. Together with the long Snow and Ice Research Group (SIRG) borehole logging tool described by GUNDESTRUP and HANSEN (1984) which has 4 m between the centering devices, and the new short SIRG/UCPH 1 m long logger (presented at this conference), a range of tools are available to provide maximum accuracy in different kind of holes. The main disadvantage of the UCPH tool is that it requires a relatively smooth hole wall for the callipers not to hang up. For boreholes with rough walls, the SIRG tools are better suited.

The UCPH tool works well. Although there are no immediate plans for improving it, future modifications may increase the resolution of the temperature sensor. Also, the fluxgate sensor should be replaced with the KVH sensor as used in the short SIRG logger. This sensor has a higher accuracy, and can work at higher inclinations than the present sensor. In addition, by compacting the information from the logger, the sampling time interval can be reduced from 3 s to 1 s which corresponds to 1 m to 30 cm depth resolution.

Acknowledgments

This work is a contribution to the Greenland Ice Core Project (GRIP), a European Science Foundation Programme with eight nations collaborating to drill through the central Greenland ice sheet.

References

GUNDESTRUP, N.S. and HANSEN, B.L. (1984): Bore-hole survey at Dye-3, south Greenland. J. Glaciol., **30**, 282–288.

GUNDESTRUP, N. S., DAHL-JENSEN, D., HANSEN, B.L. and KELTY, J. (1993): Bore-hole survey at Camp Century, 1989. Cold Reg. Sci. Technol., **21**, 187–193.

HANSEN, B.L. and GUNDESTRUP, N.S. (1988): Resurvey of bore-hole at Dye 3, south Greenland. J. Glaciol., **34**, 178–182.

HANSEN, B.L., GUNDESTRUP, N.S., and CLAUSEN, H.B. (1989): Camp Century hole reopened. Cold Reg. Sci. Technol., **16**, 315–317

JOHNSEN, S.J., DANSGAARD, W., GUNDESTRUP, N.S., HANSEN, S.B., NIELSEN, J.O. and REEH, N. (1980): A fast light weight core drill. J. Glaciol., **25**, 169–174.

(Received May 25, 1993; Revised manuscript received January 17, 1994)