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BEHAVIOR OF A DEEP HOLE DRILLED IN ICE AT VOSTOK STATION

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Abstract: A coring hole (5G) was drilled at Vostok station down to the depth of 2500 m using an electro-thermal drilling system. Relationships between ice core, hole diameters, and drill speed are presented. The hole was only partially filled with fluid (of density of 860 kg m^{-3}) so that ice pressure was not counter-balanced by the fluid column. After one year, diameter us, depth was measured. The hole deformation was found to be significant for depths below 1500 m. The hole closure rate is in agreement with the law proposed by PATERSON (Rev. Geophys. Space Phys., **15**, 47, 1977) and extrapolated to Vostok conditions as well as with previous studies from BLINOV and DMITRIEV (Antarktika, **26**, 95, 1987).

This information as well as the data from the fluid density properties is used to predict the hole closure for greater depths. Due to some drawbacks in using a high density fluid for thermal drilling operations a technical strategy for drilling toward 3000 m is presented.

1. Introduction

Drilling in East Antarctica at Vostok Station (78°28'S, 106°50'E, 3488 m a.s.l.) has been done to a depth exceeding 2000 m. Ice cores recovered at this site have allowed reconstruction of climate and ambient conditions over the last climatic cycle (*i.e.* 160000 years) (*e.g.* LORIUS *et al.*, 1985; JOUZEL *et al.*, 1987; BARNOLA *et al.*, 1987). The longest ice core sequence (2546 m) is believed to extend the record over the last 220000 years (JOUZEL *et al.*, 1993).

The ice thickness at Vostok is approximately 3600 m and the annual accumulation rate (2 cm of water equivalent) is very low. The ice near the bedrock is thought to be 500000 years old and recovering it represents a technical and scientific challenge.

The mean surface temperature is near –56°C and the ice deformation is very small. Thus drilling can be done without exactly counterbalancing the ice pressure (KUDRYASHOV *et al.*, 1984b). The fluid used is similar to kerosene and has a density of 840 kg m^{-3}. Its level in the hole was maintained below the ice firn transition, which lies at depth of about 105 m at Vostok. Three holes have been drilled with this technique. This allows operation without the use of a large amount of halogenated solvent as a densifier and without using a casing in the porous portion of the hole.

However, this technique has some limitations because both the ice temperature and the difference between ice and fluid pressure increase with depth. Thus, the hole closure speed is expected to become significant and may prevent drilling at depths greater than 2500 m.

In order to extend the coring of ice to a depth of 3000 m, we have studied the behavior of hole 5G which was started in 1990 and reached 2500 m in December 1991. A thermal drill TBZS-152 (KUDRYASHOV *et al.*, 1984a) designed by the St. Petersburg Mining Institute was used. We present the parameters obtained during drilling operations. Hole diameter measurements were performed in December 1992, and a study of the fluid density was done as well.

2. Some Characteristics of the Drilling Operations

Hole 5G was started in March 1990 on the 35th expedition and was completed in December 1991 on the 36th expedition. A thermal drill with a diameter of 180 mm was used for penetrating the porous firn down to a depth of 120 m. The drilling was then continued by using another thermal drill, TBZS 152 (KRUDYASHOV *et al.*, 1984a), designed for low temperature conditions. This drill has a head diameter of 152 mm and allows recovery of cores up to 3.5 m in length and with a diameter of about 110 mm. The hole diameter is about 160 mm and the drill speed is about 2.7 m per hour.

During routine operations, drill parameters are recorded daily. With a thermal drill, the ice is melted by the heater ring and water produced is pumped through a tube whose inlet is a few cm above the hot point. The fluid is stored in a tank. There, the water is separated from the drill fluid by gravity. The fluid used is a mixture of kerosene (TCN-1) and various amounts of halogenated solvent are included to increase the fluid density. During the drilling of hole 5G the concentration of the densifier was about 2% in mass and the fluid density was 860 kg m^{-3} at –50°C.

The water tank has a volume of about 35 *l*; the time to fill it depends directly on the electrical energy consumed by the heater ring.

The hole diameter and the core diameter depend on the ice melting efficiency of the head and therefore on its thermal conductivity, its geometry and the quality of the contact between the head and the ice. These parameters also depend on drill speed which can be adjusted from the surface. Figure 1 shows the correlation between the ice core diameter and the drill speed. Figure 2 shows the correlation between the ice core length and ice core diameter. For a given amount of electrical energy supplied to the heater rings, a low drill speed allows melting of more ice around the hot point. Note that drill advance is stopped at the end of each run to reduce the core diameter and to facilitate the breaking of the ice core by the core catchers. However, at the same time, the hole diameter also increases, making a little cavern in the ice wall.

The initial hole diameter can be estimated from the volume of ice, and the volume of water collected in the tank, for each run. This value represents the hole diameter averaged over the total length of the run, usually about 3 m. Under normal drilling conditions when the ice caverns are reduced to their minimum volume, the accuracy of the hole diameter averaged over 3 or 5 runs is about 1 mm.

The hole diameter *versus* depth is plotted in Fig. 3 along with the core diameter. The average hole diameter is 159 mm. The free space between the hole wall and the drill head is about 6 mm. In Fig. 3, the ice caverns generally correspond to smaller ice core diameter. At the depth of 2360 m, the hole diameter reaches about 180 mm, which is 20 mm larger than normal, and the ice core diameter is about 102 mm or 8 mm smaller than normal.

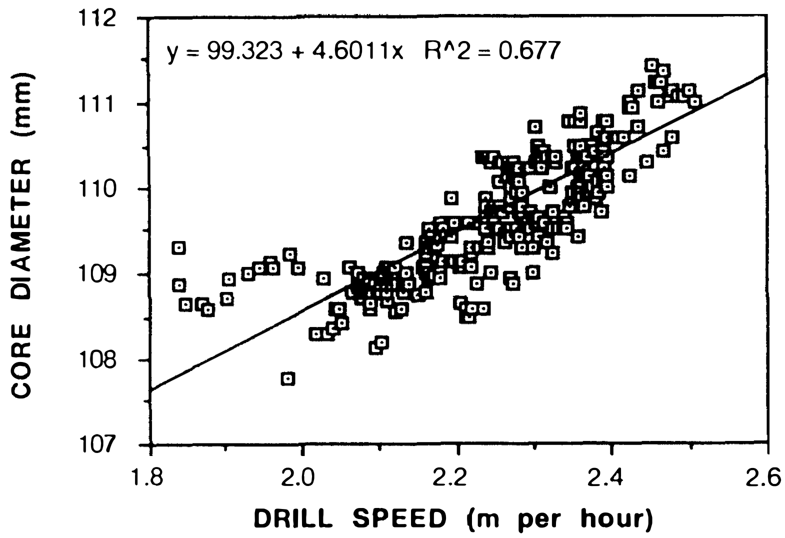

Fig. 1. Relationship between ice core diameter and drill speed obtained with an aluminum head.

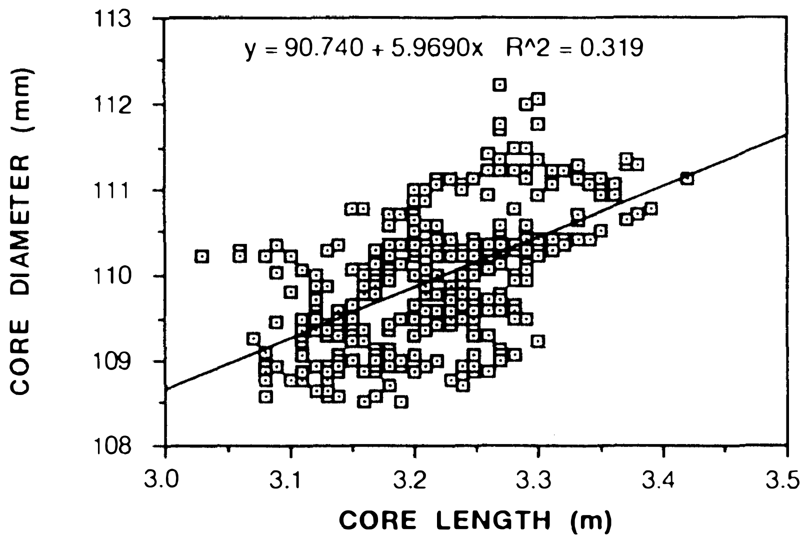

Fig. 2. Relationship between ice core diameter and ice core length.

This corresponds to a run when the hole bottom was filled with dirt from the drilling fluid. This dirt degrades the thermal contact between the heating ring and the ice. This run was followed by a run using a conical head type which allows concentration of the dirt in the middle of the hole. The dirt is then retrieved in the middle of the following ice core.

Step-like changes in ice core and hole diameters can be observed in Fig. 3 at depths of 1480 m and 1760 m. These occurred when head types were changed. A head with an outer part made of copper was used for depths between 1260 and 1480 m; below 1480 m an aluminum head was used. The copper head resulted in high speed drilling and a large ice core diameter. But the hole diameter was small, which slowed down the extraction and insertion of the drill with the winch at greater depths.

During the drilling operations, the fluid level was kept between 150 m and 250 m below the surface with an average value of value 200 m. Drilling operations ended in

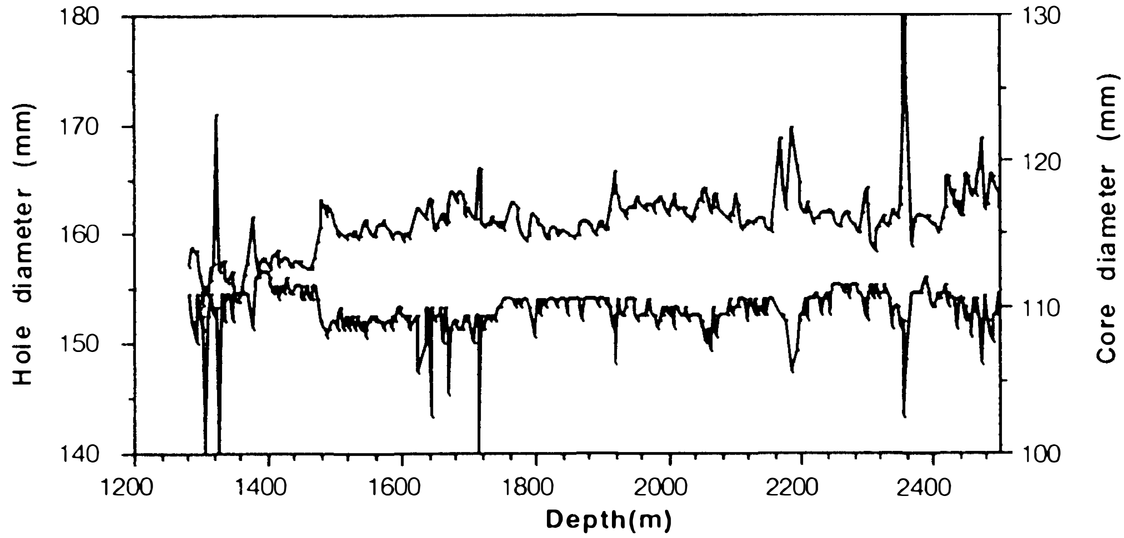

Fig. 3. Hole and ice core diameter versus depth (hole no. 5G).

December 1991 and the fluid level was raised up to 114 m. In June 1992 densifier was added in the hole in order to increase the fluid density to 885 kg m^{-3}. The fluid level was maintained at 114 m. Between October 1992 and January 1993, the fluid density was increased to 910 kg m^{-3} and the fluid level maintained at 95 m.

During the 1992-93 field season, a secondary winch was set up to allow a series of geophysical measurements to be made in this hole.

3. Hole Diameter Measurements

Diameter measurements were made in December 1992 and January 1993, with a caliper designed by the LGGE. This device has three articulated arms which maintain skates, 20 cm long, in contact with the hole wall by a spring (Fig. 4). The arms are part of a 90° articulated (right ?) triangle. One end moves along a shaft and is connected to a linear potentiometer (1500 ohms and small temperature dependence). A potential of three

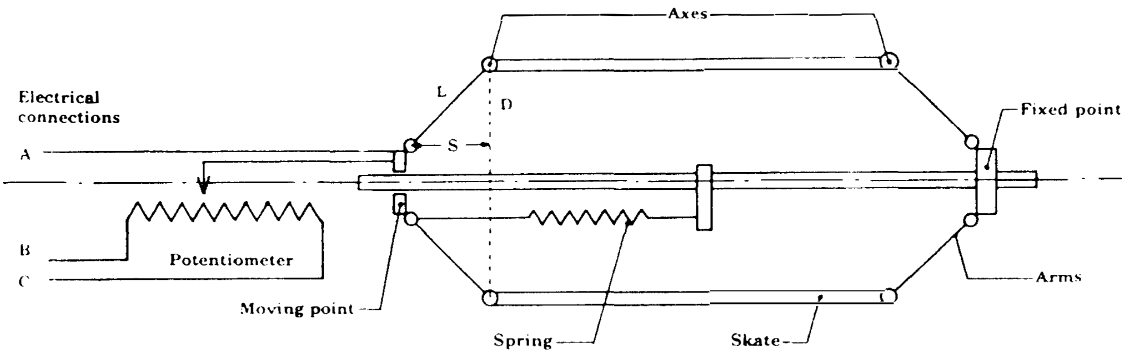

Fig. 4. Principle of the caliper. In the right triangle we can write: $(D-D_0)^2=L^2-S^2$ (D_0 and L are constants). For the linear potentiometer the voltage between ends A and B is: $V_{AB}=aS+b$ (a and b are constants). As D_0 is small, the equation of the caliper can be written $D^2= a' + b'V_{AB} - c'V^2_{AB}$ (a', b', c' are parameters adjusted from the calibration).

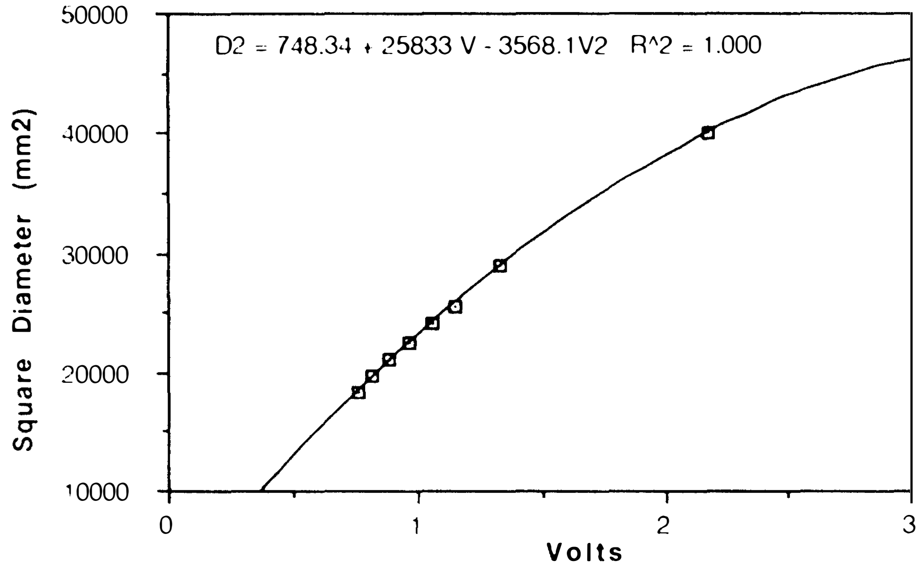

Fig. 5. Calibration curve obtained for the caliper.

volts is applied to the end of the potentiometer. The resulting current causes minimal heating. Calibration is done with various diameter standards (Fig. 5). When the caliper is used in the hole, its aperture is limited to a maximum value observed in only few hole caverns. This allows the calibration to be checked during the logging operation. The accuracy of diameter measurement is better than 0.4 mm.

4. Hole Closure Rate

To study the hole closure rate, we selected a section having only small or no caverns over 10 to 20 m lengths at depths below 1500 m where the deformation is already greater than 4 mm. We compared the data to the initial hole diameter estimated from the ice core and water volume at the time of drilling. This permits determination of the hole deformation with an accuracy of about 1 mm. As can be seen in Fig. 6, the hole deformation was about 10 mm at 2200 m one year after drilling.

We compare these results to the estimate made with the closure law proposed by PATERSON (1977) and BLINOV and DIMITRIEV (1987). The hole closure rate (D' in mm per year) for secondary creep given by PATERSON (1977) can be written:

$$D' = 0.4774 \times D \times A\ (P/30)^3, \qquad (1)$$

where D is the initial hole diameter in mm; A is the temperature factor and equals exp $(-7500(1/T-1/251))$ assuming an activation energy of 60 kJ mole^{-1}; P is the pressure difference (in bars) between the ice and the fluid column; T is the temperature in K.

The hole temperature at Vostok *versus* depth (z in m) was taken from BLINOV and DMITRIEV (1987) and can be fitted by a polynomial:

$$T = 216.0 + 6.5493\ 10^{-3} z + 1.1829\ 10^{-6} z^2 + 3.7477\ 10^{-10} z^3. \qquad (2)$$

The ice pressure was calculated from the density measurements of firn and ice. The firn portion (100 m) represents 66 m of ice equivalent. The ice density is 920 kg m^{-3} at

–50°C. For each selected depth from 1500 m down to 2200 m, we have integrated the hole deformation taking into account the ice temperature, the time since the drilling and the change in the density and fluid level (Table 1). The calculated hole deformation values are reported in Fig. 6 and with the observed values. The good agreement suggests that we can use eq. (1) to estimate the behavior of the hole for deeper depth.

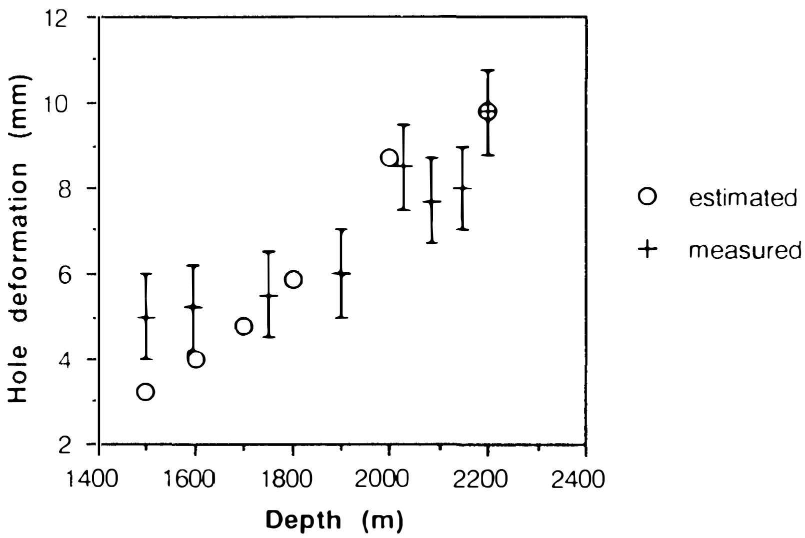

Fig. 6. Hole deformation obtained for the 5G hole. Crosses are measured values with an accuracy of about 1 mm. Open dots are the estimated hole deformation from eq. (1) and reported in Table 1.

Table 1. Hole deformation estimated from eq. (1) taking into account the times of changing the fluid level and density.

Depth (m)	from drill date to 02/01/92	from 02/01/92 to 06/01/92	from 06/01/92 to 10/01/92	from 10/01/92 to 01/01/93	total
	fluid level:200 m density=0.860	fluid level:114 m density=0.860	fluid level:114 m density=0.885	fluid level:95 m density=0.91	mm
1500	2.60	0.40	0.21	0.02	3.23
1600	3.14	0.52	0.27	0.02	3.95
1700	3.78	0.67	0.35	0.03	4.83
1800	4.54	0.87	0.45	0.04	5.90
2000	6.46	1.46	0.75	0.05	8.72
2200	5.98	2.49	1.28	0.07	9.82

5. Drilling Fluid

A study was done of the mixture of the kerosene and a halogenated solvent available at Vostok Station. The fluid density varies with the concentration of halogenated solvent as well as with the temperature (Fig. 7). The use of the densifier has some drawbacks for drilling with the thermal system. The first one is that a black material (called "grease") appears in suspension in the fluid column. The origin of this component is unknown. It may be due to the fact that the two liquids are not perfectly pure or that the solvent interacts with the cable and cleans it. This grease can produce some electrical short circuits in the drill and it needs to be removed. This was done by using a filter with 200 μm porosity, which was pulled up and down in the fluid column. The mixture also results in a less efficient separation in the tank of the water produced during drilling from the fluid. For efficient separation, the density of the drilling fluid near the drill must be significantly different from the water density. This can be achieved by keeping the drilling fluid density at the bottom part of the hole lighter than that above. This is done by filling the tank with pure kerosene before each run. The kerosene is injected in to the hole near the drill when

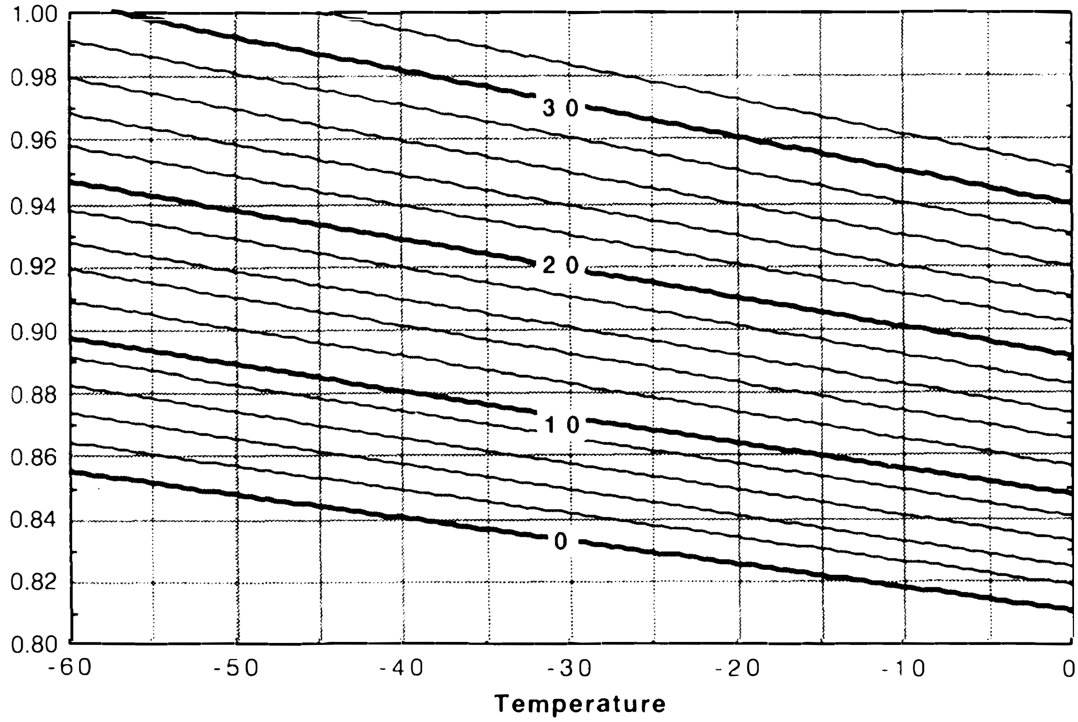

Fig. 7. Plot of fluid density versus temperature for different concentration (% in mass) of halogenated solvant.

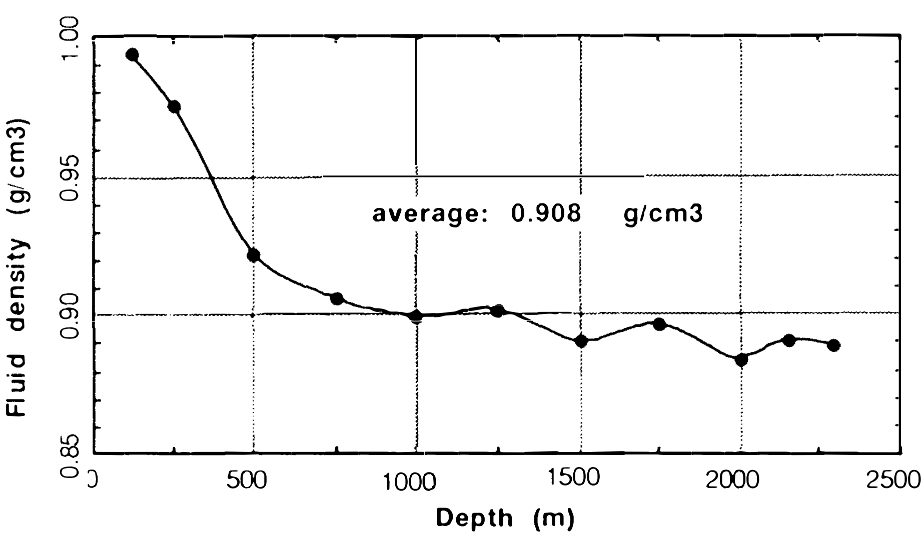

Fig. 8. In situ density profile of the drilling fluid in hole 5G measured in January 1993.

the drill is operating and when the water replaces it in the tank. The fluid densifier is added at the top of the fluid column far from the drill.

Fluid in the hole was sampled to determine the filtration efficiency as well as the density. The *in situ* density profile is given in Fig. 8, taking into account the ice temperature. The fluid column appears highly stratified with the highest value in the first 500 m of the hole. The mixing with underlying layers occurs very slowly. The average in-situ density was 910 kg m^{-3} in January 1993.

6. Prospect for Deeper Drilling

In order to reach depth beyond 2500 m using the same thermal drilling technology, it is necessary to reduce the hole closure. In addition, since the thermal drill cannot work in high density fluid, the fluid level needs to be raised to its maximum value.

In Table 2 we present the calculation of the hole closure rate assuming a fluid density of ~ 910 kg m^{-3}, a fluid level at 100 m and extrapolating eqs. (1) and (2) to greater depth. If we accept a closure of the hole of 2 mm/year representing about one third of the free space between the drill and the wall, a depth of 2800 m could be reached. For greater depth, the casing of the firn part of the hole will have to permit the fluid level to approach the surface. In such conditions for a fluid level maintained at 50 m of depth, a depth of 3300 m could be reached (Table 2).

Table 2. Estimate of the hole closure rate versus depth for deep drilling at Vostok Station assuming a fluid density of 910 kg m^{-3} and a fluid level maintained at 100 and 50 m respectively. A is the temperature factor. P is the pressure difference (in kg cm^{-2}) between ice and the fluid column.

Depth	Hole temperature	*A*	Level 100 m *P*	Closure rate mm/a	Level 50 m *P*	Closure rate mm/a
1500	−43.5	0.061	7.8	0.1	3.2	0.0
1600	−42.2	0.073	7.9	0.1	3.3	0.0
1700	−40.9	0.088	8.0	0.1	3.5	0.0
1800	−39.5	0.107	8.1	0.2	3.6	0.0
1900	−38.0	0.131	8.2	0.2	3.7	0.0
2000	−36.5	0.161	8.4	0.3	3.8	0.0
2100	−34.8	0.200	8.5	0.3	3.9	0.0
2200	−33.2	0.249	8.6	0.4	4.1	0.0
2300	−31.4	0.313	8.7	0.6	4.2	0.1
2400	−29.6	0.395	8.8	0.8	4.3	0.1
2500	−27.7	0.502	9.0	1.0	4.4	0.1
2600	−25.7	0.642	9.1	1.4	4.5	0.2
2700	−23.6	0.825	9.2	1.8	4.7	0.2
2800	−21.5	1.067	9.3	2.4	4.8	0.3
2900	−19.2	1.389	9.4	3.3	4.9	0.5
3000	−16.9	1.817	9.6	4.5	5.0	0.6
3100	−14.5	2.390	9.7	6.1	5.1	0.9
3200	−11.9	3.159	9.8	8.4	5.3	1.3
3300	−9.3	4.198	9.9	11.5	5.4	1.8
3400	−6.6	5.604	10.0	16.0	5.5	2.6
3500	−3.8	7.516	10.2	22.2	5.6	3.7
3600	−0.9	10.123	10.3	31.0	5.7	5.4

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