Mem. Natl Inst. Polar Res., Spec. Issue, **45**, 66–73, 1986

BOREHOLE CLOSURE AT MIZUHO STATION, ANTARCTICA

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Abstract: The 400-m deep hole drilled in 1983 at Mizuho Station, East Antarctica, was used for measurements of the contraction of diameter in 1984. Depth-profiles of the diameter were obtained several times by using a three-contact-points caliper. Relationship between the stress and the strain rate of ice in the borehole was evaluated under the assumption that the strain rate was constant in the early stage of strain below approximately 0.08. Closure rates of the hole at Mizuho Station showed almost the same values as or slightly higher values than those in the same stress range derived by W. S. B. PATERSON (Rev. Geophys. Space Phys., **15**, 47, 1977) in Antarctica and other ice caps.

1. Introduction

The program of ice core drillings was conducted at Mizuho Station, East Antarctica, by the 24th and 25th Japanese Antarctic Research Expedition (JARE-24 and -25) in 1983–1984. A 411-m deep hole was drilled from April to July 1983 by JARE-24. Due to the intensive contraction of the hole in the deep layer, they stopped the drilling operation at this depth. A diameter gauge was provided to JARE-25, who continued the drilling operation from May 1984. Information of the closure-rates of borehole obtained by frequent measurements of its diameter helped JARE-25 for selecting the most appropriate technic and procedure for drillings. Finally they attained a depth of 700 m in August 1984.

HASEMI *et al.* (1985) predicted the contraction of the hole at Mizuho Station by computing the creep rate of ice. The present paper gives results of the above-mentioned measurements of the borehole diameter and evaluates the closure-rates of the hole for making a comparison with those derived by PATERSON (1977) from the data at Byrd Station in Antarctica, Site 2 in Greenland, and the Meighen and Devon ice caps.

2. Method of Diameter Measurements

A diameter gauge was newly developed by Institute of Low Temperature Science, Hokkaido University for the use of JARE-25 at Mizuho Station. The gauge has a single caliper which contacts at three points with the wall of borehold. Change in diameter can be detected by change in the output voltage of a linear potentiometer mounted in the gauge. The whole length of the gauge is 0.8 m; power supply is D.C. 6 V; the range of measurement is 125–200 mm.

Calibrations were made at Mizuho Station to convert the measured output to the diameter by using four steel pipes whose diameters were known. Judging from this result, the accuracy of the gauge is about ± 1 mm when the caliper contacts well with the borehole wall. A conditioner which controls the input voltage and a recorder were placed outside the hole. Measurements were carried out continuously with depth or intermittently.

Profiles of the borehole diameter down to a depth of 700 m were measured several times during January–July 1984. Successful data for the study of borehole closure were obtained from the surface to the 411 m depth on January 21, March 24 and May 2 in 1984. As the initial diameter of the hole drilled by JARE-24 were not measured, we assume it to be 17.5 cm, estimated from the results of test drillings with the same type drill.

The depth of diameter measurements in the hole was determined by reading the length of winch cable.

3. Results of Diameter Measurements

A depth-profile of the borehole diameter measured continuously in May 1984 is shown in Fig. 1. It indicates that the diameter decreases gradually from approximately 17 cm near the surface to approximately 13 cm at the depth of 400 m. It should be noted that the diameter fluctuates considerably in comparatively short distance of the

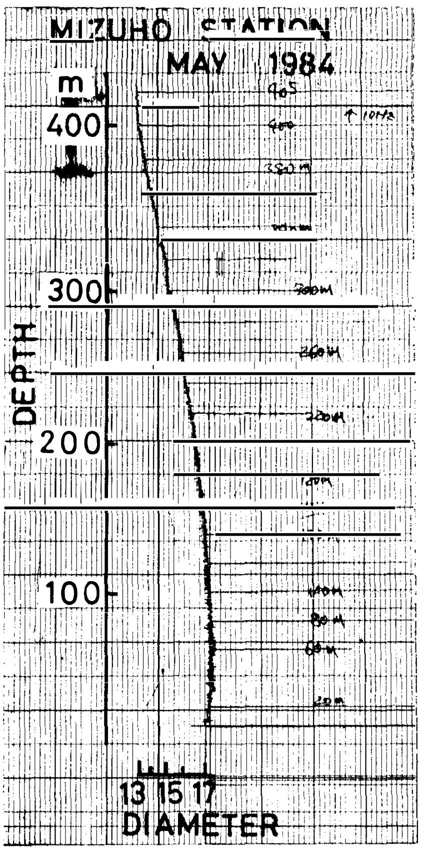

Fig. 1. Depth-diameter profile measured at Mizuho Station in May 1984.

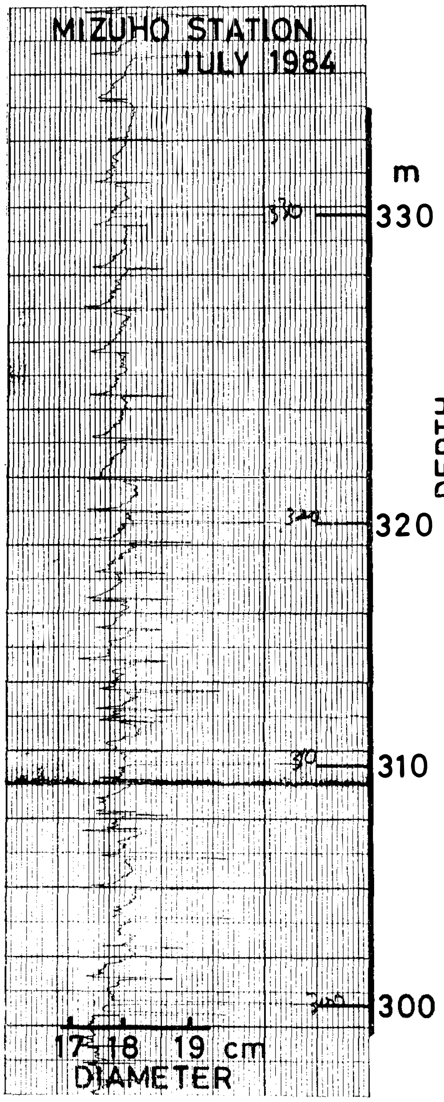

Fig. 2. A part of depth-diameter profile measured at Mizuho Station in July 1984.

depth. For example, a part of the diameter profile for the depth from 300 to 335 m which was measured just after the drilling is illustrated in Fig. 2, where we can recognize many peaks with narrow and wide diameters. Since we obtained almost the same profiles from both the measurements when the gauge proceeded downward and upward, these fluctuations cannot be ascribed to observational errors. The interval between two neighboring peaks, *i.e.* from 1.2 to 1.5 m, corresponds to the core length taken in one run of drilling. Therefore, the widening of the diameter has resulted from the extra-melting by the thermal drill at the bottom of each run of drilling to make the cut-off of the ice core easy.

For obtaining a smooth curve of the depth-profile of the diameter, we adopted an approximately central value of each fluctuation as a representative value of the diameter. Figure 3 shows three profiles of borehole diameter measured down to 400 m in January, March and May 1984. These curves were given by applying the moving average to the measured values at every 20 m in depth. From the figure, we can see that the greater the contraction the deeper the depth. It also shows that diameters in the

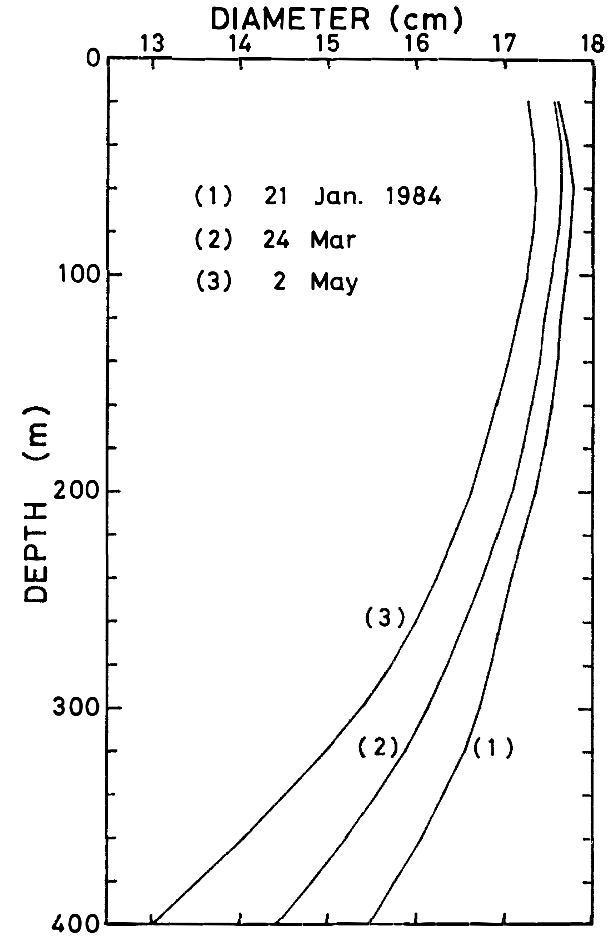

Fig. 3. Depth-diameter profiles obtained at Mizuho Station in January, March and May 1984.

upper 100 m part were wider on January 21, 1984, in the first measurement, than the original diameter estimated as 17.5 cm. The widening should have resulted from frequent passings of the thermal drill there.

4. Closure Rate of Borehole

If the ice is isotropic and incompressible, the stress-strain rate relation can generally be expressed as,

$$\dot{\varepsilon}=B\tau^{n}, \tag{1}$$

where $\dot{\varepsilon}$ is the effective strain rate, τ the effective shear stress, B a parameter which varies with temperature according to the Arrhenius relation, and n a constant which takes approximately 3. PATERSON (1977) showed that an appropriate measure of the strain ε for the closure of a cylindrical hole in the ice body is written as,

$$\varepsilon=-\ln(a/a_0), \tag{2}$$

where a_0 is the initial diameter of the hole and a the diameter at the time of measurement. NYE (1953) derived that on the wall of a hole, the effective shear stress τ is given by,

$$\tau(a) = -P/n, \tag{3}$$

where P is the overburden pressure in the ice. The value P at the depth h is calculated as,

$$P = g\int_0^h \rho(y)\mathrm{d}y, \tag{4}$$

where y is the distance in direction of depth, g the gravitational acceleration, and $\rho(y)$ the density of ice. The depth-profile of $\rho(y)$ was obtained from the *in situ* measurements of ice cores at Mizuho Station.

Applying eq. (2) to the data of three profiles of diameter given in Fig. 3 with the initial diameter 17.5 cm, strains in ice at every 20 m of depth were obtained. The strain *versus* the time after the drilling at each depth are shown in Fig. 4. It can be seen that the gradient of a strain-time curve is not constant with time but increases with time. GOW (1963) attributed the increasing of the borehole closure rate with time to the recrystallyzation of ice. It seems from the curves that the tertiary creep might have already begun until the first measurement made in several months after drilling. Since the initial stage of the closure drawn by broken lines in Fig. 4 is hypothetical, we cannot make clear the stage of secondary (stationary) creep in this figure. Therefore, to determine the onset of tertiary creep, we referred to the results analyzed by PATERSON (1977) at Byrd Station; namely, for overburden pressures below 1.6 MN/m^2 (corresponds to a depth of approximately 200 m) the onset of accelerating creep was found

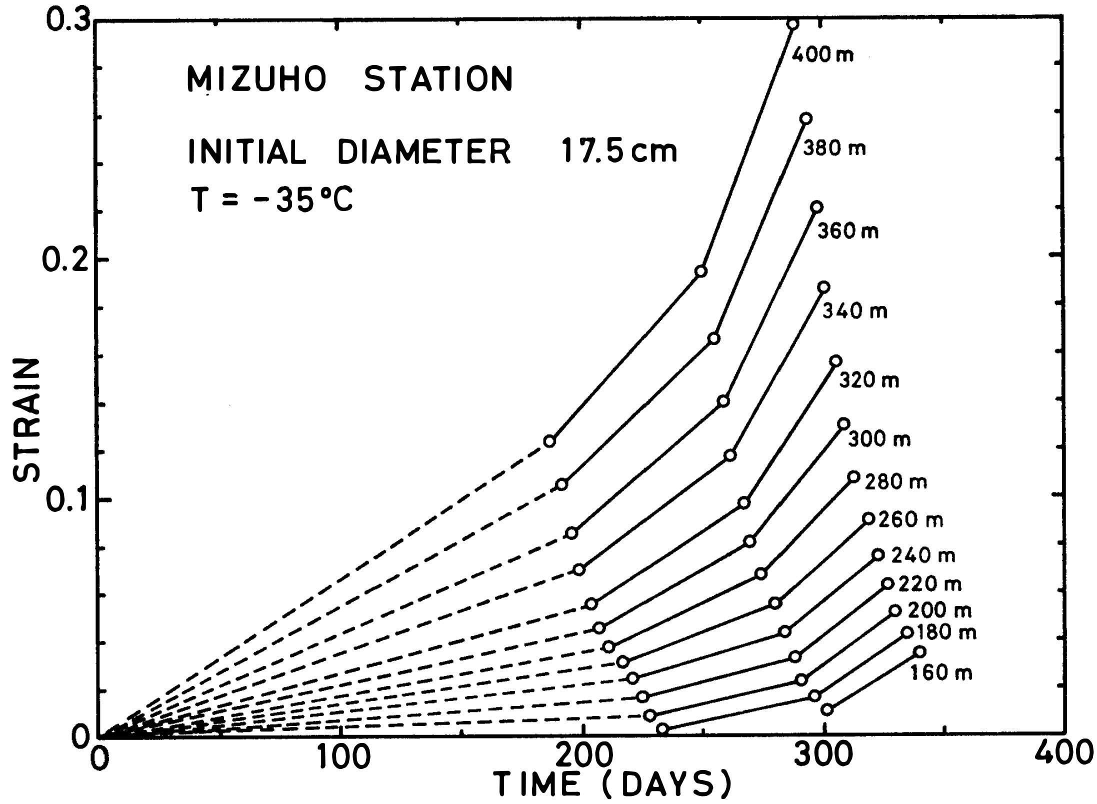

Fig. 4. Strain versus time for the borehole at Mizuho Station.

at strains between 0.06 and 0.17, and for pressures above 1.6 MN/m^2 the onset was at strains 0.08–0.17. The secondary creep rate was then determined in the present study as follows: in the upper layer above 200 m depth, the mean rate over one or more segments of each creep curve is in the range of strain smaller than 0.06; in the deeper layer below 200 m, the mean rate is in the range of strain smaller than 0.08.

A logarithmic plot of the effective strain rate $\dot{\varepsilon}$ in the secondary creep against the effective shear stress τ is shown in Fig. 5. Here τ was evaluated by eqs. (3) and (4): the possible effect of shear and longitudinal stresses in the ice sheet was neglected. Also illustrated by dotted lines in Fig. 5 are the relation derived by PATERSON (1977) for the temperature −22°C at the other boreholes in ice sheets and ice caps, and one adjusted to −35°C which is assumed as an uniform ice temperature at the Mizuho borehole. This result indicates that the closure rate in the borehole at Mizuho Station seems to be almost the same value as or slightly larger value than those in the same stress range at other sites. The value of B and n in eq. (1) were estimated by the least squares method, namely B is 4.05×10^{-9} when $\dot{\varepsilon}$ is measured by 1/s and τ in MN/m^2, and n is 2.3.

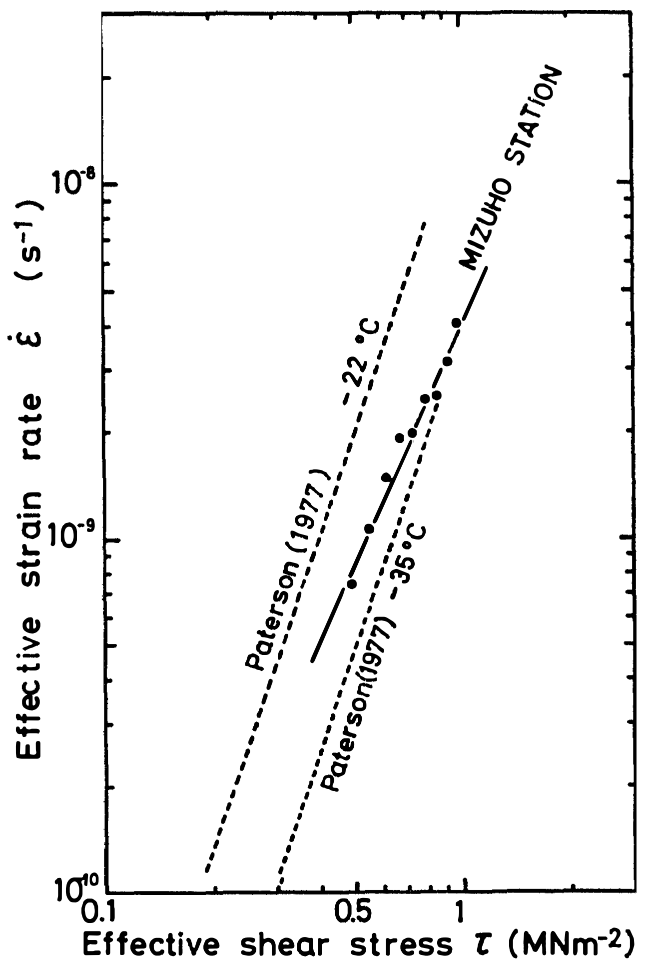

Fig. 5. Relation between the effective strain rate and the effective shear stress for the borehole at Mizuho Station.

5. Concluding Remarks

From the deduced results of borehole contraction in Fig. 4, it is inferable that the tertiary creep occurred at the deep layer within one year. Due to scarce measurements in one year after the drilling, we could not detect the boundary between the secondary and the tertiary creeps. Therefore, the secondary creep rate was determined assuming the onset of tertiary creep on the basis of the critical values of strain derived by PATERSON. However, the obtained effective strain rate was well related to the effective shear stress by the form of a power law.

If the measurement of borehole diameters can be carried out more accurately and more frequently, the depth-profile of the contraction rate should be related to the properties of ice, *e.g.* crystal fabrics and dust contents of ice in glaciers or ice sheets (THWAITES *et al.*, 1984; GUNDESTRUP and HANSEN, 1984). For more accurate measurements, an instrument which has a better aligment with the axis of the hole is necessary. An improved gauge, that is a tandem gauge with two calipers 0.53 m apart (NARUSE *et al.*, 1985), has been developed after this work and is utilized by JARE-26 in 1985 (OKUHIRA *et al.*, in preparation).

Another information to be derived from a deep borehole is the vertical strain rate which can be obtained from the measurements of length of a vertical section of the hole. The section may be distinguished by recognizable pattern of diameter variations as shown in Fig. 2 (PATERSON, 1976). Therefore, analysis of such fluctuating profile of diameter will be important in future studies. An accurate gauge to measure the depth in a hole is also greatly demanded.

Acknowledgments

We would like to thank the wintering members of JARE-24 and -25 at Mizuho Station for their help in the diameter measurements and providing the data. We are particularly grateful to Dr. Y. FUJII, National Institute of Polar Research, for giving us the chance to study borehole closure and to Mr. T. HASEMI, Institute of Geo-Technology, for his helpful suggestions. We are also indebted to an anonymous reviewer whose comments resulted in considerable improvements of this paper.

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(Received May 6, 1986; Revised manuscript received September 20, 1986)