INTERNAL FRICTION OF ANTARCTIC MIZUHO ICE CORES AT LOW FREQUENCY

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Abstract: Internal friction and shear modulus of Antarctic ice cores drilled at Mizuho Station were measured with an inverted torsion pendulum in a frequency range of 4 to 9 Hz and a temperature range of 96 to 272 K. As a function of temperature, the measured internal friction of every core showed two peaks: One around 265 K was considered due to the grain boundary and the other around 150 K to the mechanical relaxation, because the internal friction of a single crystal has only one peak around 170 K corresponding to the latter peak. The height of the former peak decreased with an increase in the density of the core. The shear modulus decreased very slowly with increase of temperature up to around 253 K, where internal friction begins to increase sharply. The decrease of shear modulus was more rapid above that temperature. The shear modulus increased linearly with the density.

1. Introduction

When an elastic solid is set into free vibration, amplitudes of the oscillation decrease with time due to internal friction. In such a case, the logarithmic decrement α as a measure of the free damping can be defined as follows:

$$\alpha = \ln(\theta_n/\theta_{n+1}), \tag{1}$$

where θ_n is the amplitude of the n-th mode of natural vibrations in free damping. The quantity α is connected with $\tan\delta$ as follows:

$$\tan\delta = \alpha/\pi, \tag{2}$$

where δ is the loss angle. The quantity α or $\tan\delta$ is a fundamental measure of the viscosity of solids; $\tan\delta$ will be used as a measure of internal friction in this paper.

The internal friction of natural ice crystals such as iceberg ice and glacier ice, as well as pure ice, doped ice and snow was measured in high frequency range with flexural vibration by KUROIWA *et al.* (YAMAJI and KUROIWA, 1954; KUROIWA and YAMAJI, 1956; KUROIWA, 1964). NAKAYA (1959) studied visco-elastic properties of the Greenland ice in detail with the same method as that used by KUROIWA *et al.*

The object of the present paper is to examine in detail visco-elastic properties of Antarctic Mizuho ice cores through the measurement of internal friction and shear modulus at low frequency. A part of the results of the measurements was reported by the present authors (1977). The ice cores were drilled from December 1974 to January 1975 and the measurements were carried out from July 1976 to April 1978.

2. Experiments and Calculations

2.1. Apparatus

Both the internal friction and the shear modulus of the Mizuho ice cores were measured in a frequency range of 4 to 9 Hz by the use of an inverted torsion pendulum apparatus (TAKESHITA, 1970) in a cold room kept at a temperature of 266 ± 2.5 K. Each sample was set in a cylindrical space (see Fig. 1) surrounded by two liquid-nitrogen containers. While the nitrogen was evaporating spontaneously the ice sample was vibrated. The rate of the temperature rise in the space was usually about 0.016 $K \cdot s^{-1}$. The free damping oscillation curves were recorded at the outside of the cold room.

In earlier experiments, ice samples fixed to the apparatus fractured occasionally due to the thermal contraction stress during the course of cooling by liquid nitrogen, because the length of the pendulum consisting of an ice sample and a wire was kept constant through one run. In later experiments, a constant axial load was applied

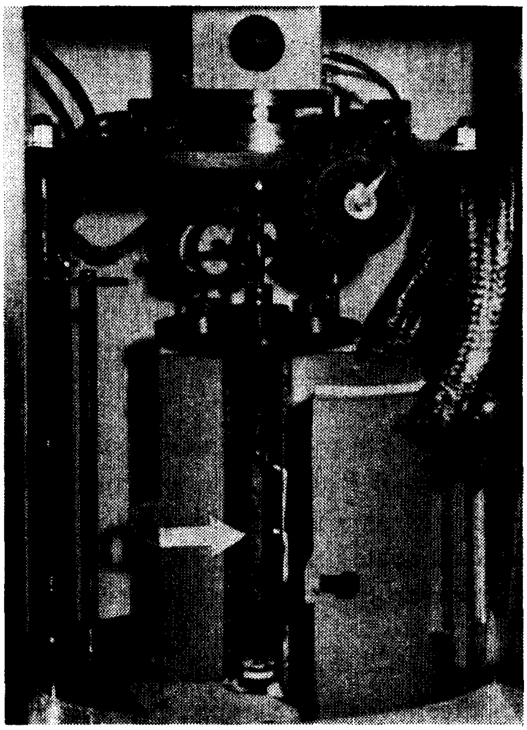

Fig. 1. Inside view of apparatus. The arrow indicates a specimen mounted on the apparatus.

to the ice sample throughout the test so that the sample did not fracture. The amount of the load ranged from 3×10^{-3} to 83×10^{-3} kg. The load showed no effect on the result.

2.2. *Calculation*

Amplitudes and wave numbers of free damping oscillation curves recorded on a pen-recorder were read on a scale in 0.1 mm with the naked eye. For the samples, Nos. 152, 238 and 111-A, a frequency counter (Model FC-5132 made by Iwatsu Electric Co., Ltd., Tokyo) was used.

The strain of the torsion of the ice samples was in the order of 10^{-5}. The internal friction (tan δ) and the shear modulus (G) were calculated by the following equations:

$$\tan\delta = \ln(\theta_0/\theta_n)/(n\pi), \tag{3}$$

$$G \doteqdot 12\pi^2 Il/[(hb^3-0.63b^4)T^2], \tag{4}$$

where θ_0, θ_n are the 0-th and n-th amplitudes, respectively, n is the order of the amplutide, I the moment of inertia, l the length, h the width, b the thickness of a specimen and T the period.

3. Samples

3.1. *Mizuho ice cores*

Seven ice cores were supplied in the form of 12 cm in diameter and 23 to 26 cm in length. The samples were taken from 39 to 144 m below the ground surface, where the ice density increased from 770 to 900 kg·m^{-3} (Fig. 2). Cores Nos. 68-A, 93-A, 111-A and 128 had no cracks, while Nos. 152, 238 and 017 had many horizontal cracks.

As for the preparation of specimens, a core was at first sliced transversely and then a rectangular plate, 10 cm long, 1.2 cm wide and 1 cm thick, was cut out from the slice. Because the internal friction is structure sensitive, only the specimens with no visible cracks were chosen. The ice core density of the specimen was measured before it was shaped to the final thickness of about 2 to 3 mm with a specially designed tool (ABE, 1978) to an accuracy of ±0.1 mm.

3.2. *Diameter distribution of single crystal grains of specimens*

After measuring the internal friction, the size of single crystal grains of the same specimens was measured from their enlarged color photos ($\times1.5$), taken under polarized light, using a circle scale graduated to 0.5 mm. The grain size was defined as the diameter of a circle whose area was regarded to be equivalent to that of the grain.

The diameter distribution in Fig. 3 shows that the grain diameter increases gradually with the depth except for one sample, No. 017. For samples Nos. 68-A and 93-A, only the grain diameter range was determined. As shown in Fig. 3, the

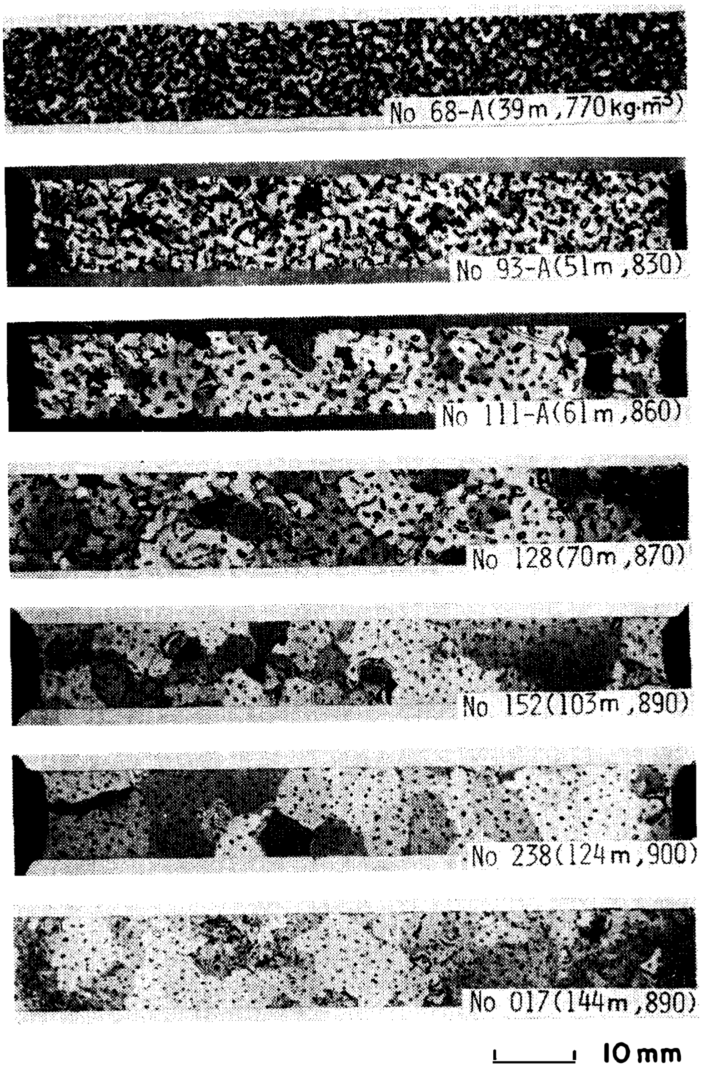

Fig. 2. Thin sections of ice specimens used for internal friction measurement. Black ends of the specimen show top and bottom holders. Figures at the right-hand side indicate sample number, depth and density.

weighted mean diameter of single crystal grains of the ice specimen increased from 0.7 to 5.5 mm. The largest diameter was 14 mm found in sample No. 238.

3.3. Size distribution of air bubbles in ice specimens

Air bubbles were included in all the core samples tested as shown in Fig. 2. The size of the air bubbles in sample No. 68-A was the largest among the seven samples and these air bubbles were linked to each other through the ice specimen. Bubbles became isolated and spherical with increase of depth as seen in Fig. 2.

An air bubble was defined as spherical when the ratio of the major axis to the

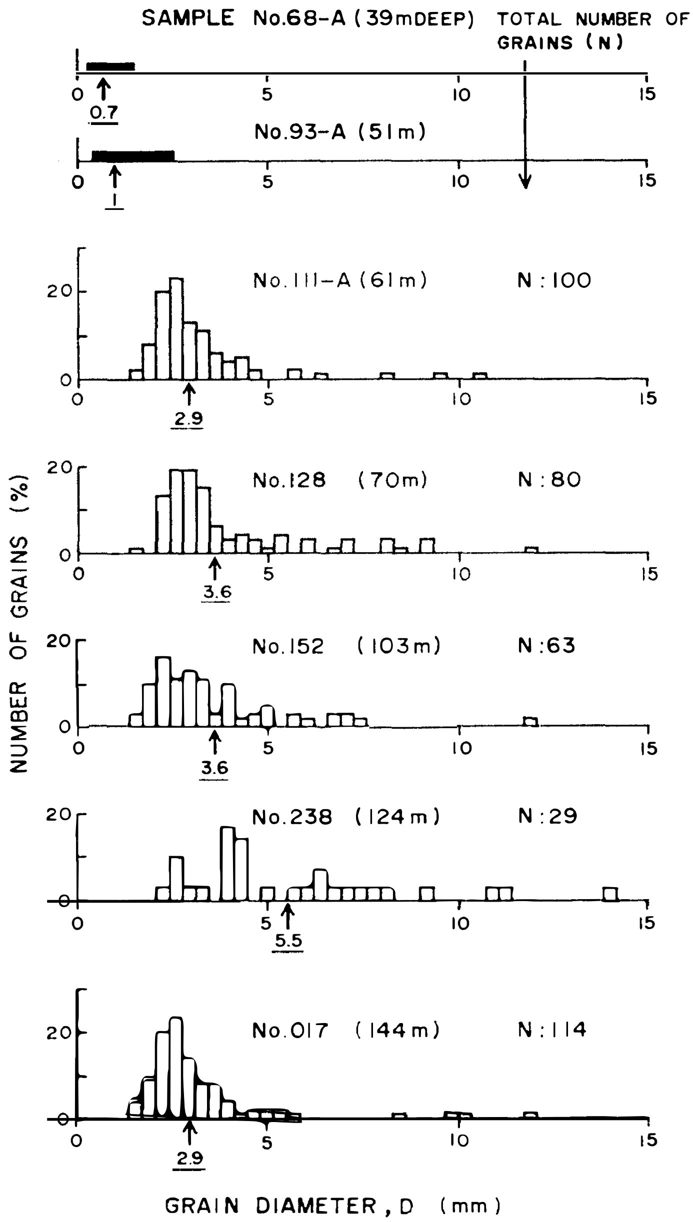

Fig. 3. Grain diameter distribution of ice specimens. Grading: $3.4 \leq D < 6.8$ mm, . . . (D: diameter). The weighted mean value of the diameter is indicated with an arrow.

minor axis of the bubble was smaller than 2. In this case the mean diameter of the air bubble was defined as the diameter of a circle, the area of which was the same as that of the air bubble. When the ratio was larger than 2, the air bubble was defined as longitudinal and the longest length of the bubble was defined as the length of the bubble. The scale used was a circular scale which was the same one used for grain size measurement.

Fig. 4 shows the decrease in the size of air bubbles with increasing depth from 51 to 144 m. The decrease is also seen in Fig. 2. Both longitudinal and spherical air bubbles are seen in the samples above 70 m in depth but only spherical air bubbles are observed below this depth.

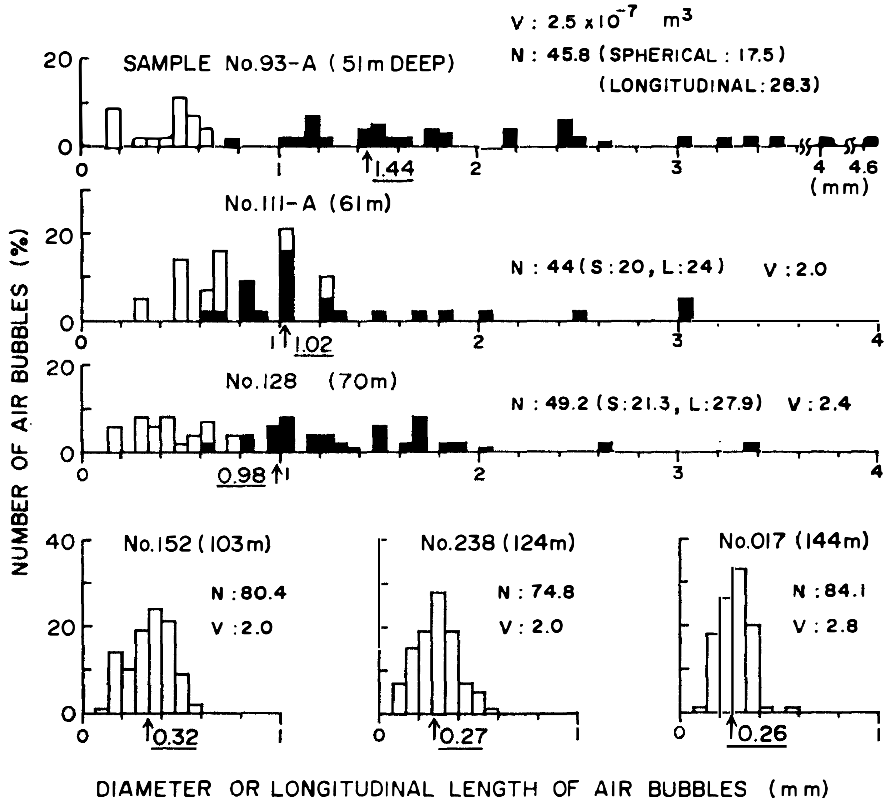

Fig. 4. Size distribution of air bubbles in ice specimens subjected to internal friction measurement. Spherical air bubbles are shown in white and longitudinal ones in black. Grading: $6.7 \leqq s < 13.4$ mm, . . . (s: size). V means a sample volume where the number of air bubbles (N) was counted. The weighted mean value of the size of air bubbles is indicated with an arrow.

3.4. *Electric resistivity of molten cores*

An ice block of about $3.5 \times 10^{-5} m^3$ was taken from each ice core, and was melted. The electric conductivity of the water was measured with a common electric conductivity bridge (Model CM-3M, manufactured by TOA Electronics Ltd., Tokyo). To avoid contamination due to handling, the surface of the ice block was rinsed in de-ionized water and only the inner part of the block was melted for use. The electric resistivity was measured at room temperatures (295 to 296.6 K) and the values were converted to 298.15 K by the use of a nomograph attached to the instrument.

Summary of the specifications of ice samples is shown in Table 1.

Table 1. Specifications of ice samples subjected to internal friction measurements.

Ice core No.		68-A	93-A	111-A	128	152	238	017
Depth from the ground surface (m)		39	51	61	70	103	124	144
Density* (kg·m^{-3})		770	830	860	870	890	900	890
Single crystal grains								
Sample area ($\times 10^{-4}$ m^2) for grain number and diameter measurement		10.8	9.8	8.9	11.0	9.0	9.2	10.5
Number of grains		**	**	100	80	63	29	114
Diameter range (mm)		0.3–1.5	0.4–2.5	1.5–10	1.5–12	1.5–12	2–14	1.5–12
Weighted mean grain diameter (mm)		0.7	1.0	2.9	3.6	3.6	5.5	2.9
Air bubbles [sample volume for number and diameter: $(2.0\text{–}2.8)\times 10^{-7}$ m^3]								
Linked (L) or Isolated (I)		L	I	I	I	I	I	I
Spherical air bubbles	Number ($\times 10^9$ m^{-3})	none	0.7	1.0	0.89	4.0	3.7	3.0
	Weighted mean diameter (mm)	none	0.41	0.67	0.41	0.32	0.27	0.26
Longitudinal air bubbles	Number ($\times 10^9$ m^{-3})	***	1.1	1.2	1.2	none	none	none
	Weighted mean length (mm)	—	2.07	1.32	1.41	none	none	none
Both kinds of air bubbles	Number ($\times 10^9$ m^{-3})	—	1.8	2.2	2.1	4.0	3.7	3.0
	Weighted mean size (mm)	—	1.44	1.02	0.98	0.32	0.27	0.26
Electric resistivity (kΩm)		2.9	5.3	4.3	5.6	5.8	4.4	4.5

* All the specimens have no cracks except for sample No. 017.
** Not measured.
*** Measurement impossible.

4. Results and Discussion

Three examples of the measurements of internal friction (tan δ) and shear modulus (G) of Mizuho ice cores as a function of temperature in a frequency range of 4 to 9 Hz are shown in Figs. 5 and 6. Although the storage time in a cold room was different in each sample, there was no distinguishable difference in the results of the internal friction and shear modulus measurements. A curve of internal friction of Antarctic iceberg ice (KUROIWA, 1964) obtained by a flexural vibration method and another curve of pure single crystal ice (NAKAMURA and ABE, 1977) obtained by the same pendulum apparatus used in the present work are also shown in Fig 6.

Two remarkable peaks of internal friction were observed on all the Mizuho ice cores, while KUROIWA (1964) observed only the rapid increase of tan δ at the melting point of ice. The higher peak of the two peaks is at around 265 K, which is close to the melting point of ice, and the lower one at around 150 K. The higher peak is not observed in the pure single crystal ice, as shown in Fig. 6. The higher peak

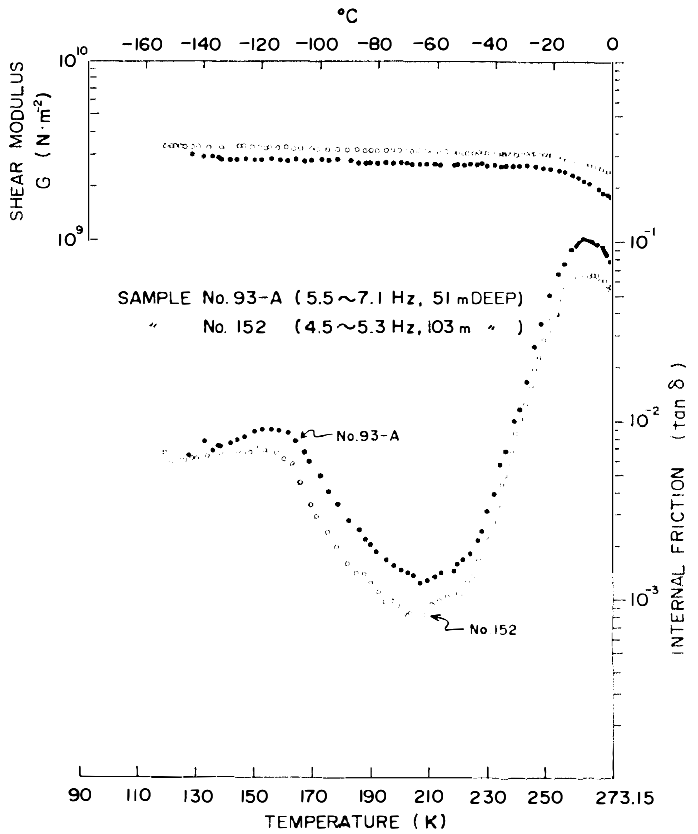

Fig. 5. Internal friction and shear modulus as a function of temperature. Samples No. 93-A and No. 152. Figures in parentheses indicate frequency in Hz from low temperature (for example, 7.1 Hz in No. 93-A) to high temperature (5.5 Hz).

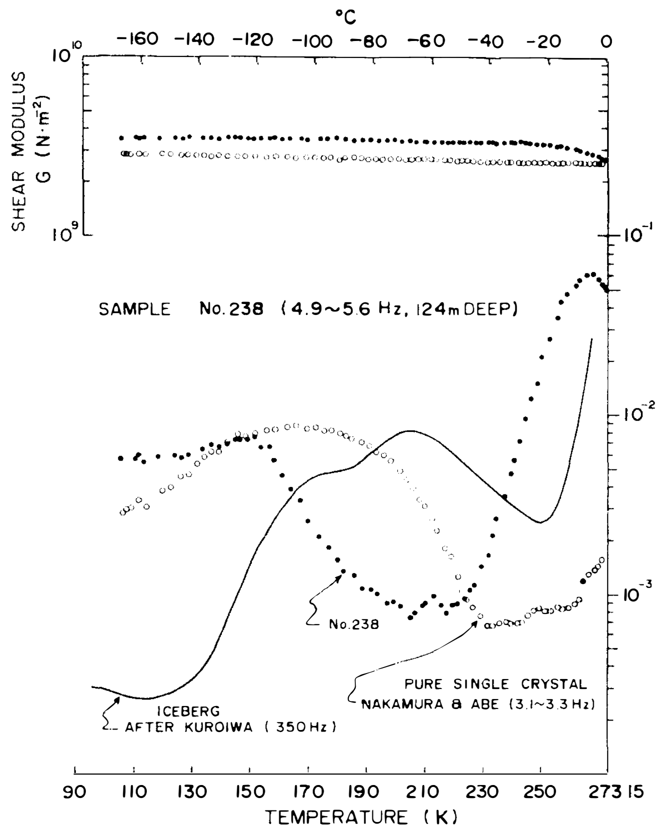

Fig. 6. Internal friction and shear modulus as a function of temperature. Sample No. 238. Two internal friction curves for a pure ice single crystal (NAKAMURA and ABE, 1977) and Antarctic iceberg ice (KUROIWA, 1964) are also shown.

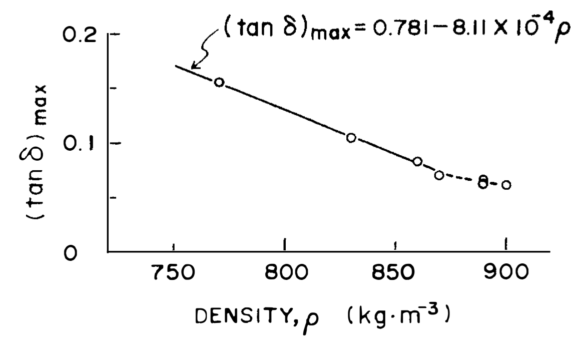

Fig. 7. Density dependence of maximum internal friction at about 265 K.

is the grain-boundary peak (NAKAMURA and ABE, in preparation) and the lower one the mechanical relaxation peak. The grain-boundary peak decreased with the density increase. The grain-boundary peak, *i.e.*, the maximum tan δ, was therefore plotted as a function of density as shown in Fig. 7. An empirical equation to express the relation for the density range 750 to 870 $kg\cdot m^{-3}$ was derived as follows:

$$(\tan \delta)_{\max}=0.781-8.11\times10^{-4}\rho, \qquad (5)$$

where ρ is the density in $kg\cdot m^{-3}$.

A mechanical relaxation peak was observed at temperatures around 150 K for the Mizuho ice cores and 170 K for pure ice single crystal as shown in Fig. 6. This difference in temperature is considered to be due to the presence of impurities in the Mizuho ice cores, as HF-doped ice single crystals (VASSOILLE *et al.*, 1977; NAKAMURA and ABE, 1977); natural snow and ice grown on roads (NAKAMURA and ABE, 1977) have shown a similar phenomenon.

An ice core whose internal friction was comparatively small over the whole temperature range showed a larger shear modulus, as shown in Fig. 5. Gradual decrease of the shear modulus with the increase in temperature towards the melting point has also seen in Figs. 5 and 6 for every sample except for pure single crystal ice, whose shear modulus showed no remarkable temperature dependence. The noticeable decrease in shear modulus existed near the melting point where internal friction has a maximum. The shear modulus (G) increased with the core density. The density dependence of two sets of shear modulus is shown in Fig. 8.

Fig. 9 shows the vertical profiles of the maximum internal friction, shear modulus G at the maximum tan δ, ice core density ρ, ice grain diameter D and the weighted mean size of air bubbles. The ice grain diameter, density and shear modulus increase with the increase of the depth. On the other hand, the maximum internal friction and size of air bubbles decrease with depth. Among these five properties, the maximum internal friction changes rapidly at about 70 m depth.

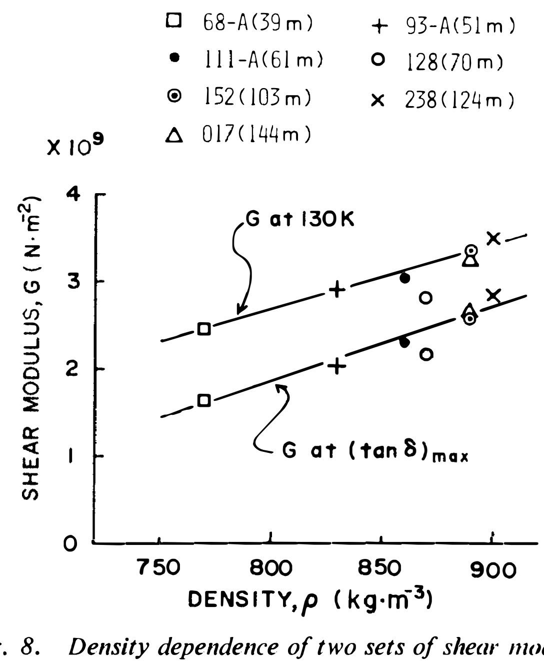

Fig. 8. Density dependence of two sets of shear modulus.

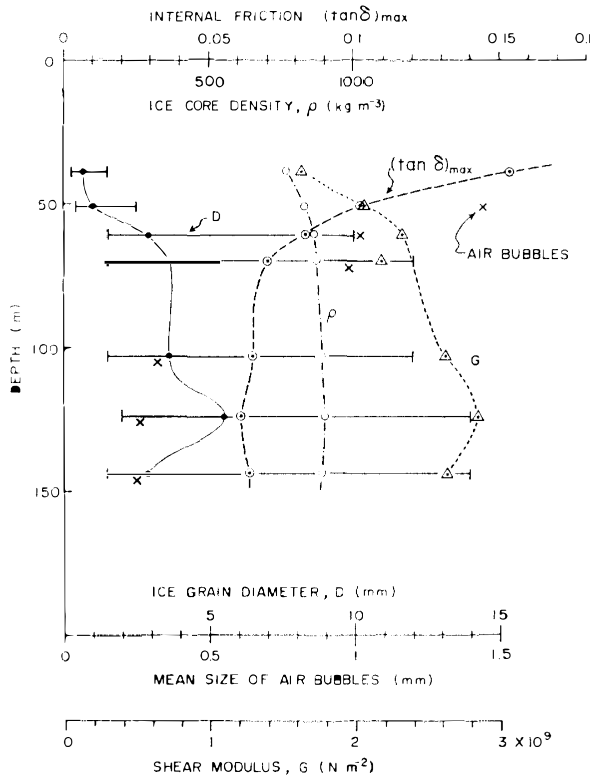

Fig. 9. Vertical profiles of the maximum internal friction (tan $\delta)_{\max}$, ice core density ρ, ice grain diameter D, mean size of air bubbles and shear modulus G at the maximum internal friction. Since sample No. 128 (70 m in depth) had three minute thermally introduced cracks during the measurement, the value of the shear modulus (shown in the triangle) is smaller than the expected value.

The value 0.1 of tan δ corresponds to about 60% energy loss in every frequency of the elastic wave propagation. The amount of 60% is a significant value when we consider the propagation of the elastic waves in the ice sheet.

Acknowledgments

The authors are indebted to Prof. K. KUSUNOKI of the National Institute of Polar Research, Drs. Y. SUZUKI and N. MAENO of Hokkaido University and Mr. N. OHHIRA of the National Research Center for Disaster Prevention for their comments in preparing this paper. Ice cores were provided by the Japanese Antarctic Research Expedition through the Institute of Low Temperature Science, Hokkaido University. This work was supported by the Science and Technology Agency of Japan.

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(Received June 5, 1978; Revised manuscript received October 5, 1978)