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VOLUME EXPANSION OF A 413.5-M MIZUHO CORE AFTER ITS RECOVERY

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Abstract: The density of the core samples was measured soon after their recovery, and the measurement was repeated 1, 3, 6 and 27 months later. It was found that the density decreased significantly with time. The decreasing rate increased with depth, and decreased with time. The data have been analyzed on the basis of a stress-strain relationship, $\dot{\varepsilon} = K(\Delta p)^n$, where $\dot{\varepsilon}$ is the strain rate and Δp is the difference between the pressures of contained bubbles and of the atmosphere. It was found that $n \approx 3$, which is a generally accepted value. The value of K was found, on the other hand, of the order of 10^{-10} s^{-1} MPa^{-3} for a temperature of $-10°C$, which is much smaller than those obtained previously under deviated stress conditions.

1. Introduction

Ice in a deep portion of ice sheets is subjected to a high overburden pressure. Once the ice is taken out by drillings to the ice sheet surface, it starts to expand in volume, which is caused by the sudden drop of the applied pressure. The expansion would be attributed to the elastic expansion of ice matrix, the formation of cracks/cavities, the expansion of contained air bubbles in conjunction with the plastic deformation of ice matrix, and so on. Other structural changes such as recrystallization take place, which would be also due to the sudden release of pressure on the core samples.

Since the cores would have thus evolved after their recovery, the relaxation processes have to be taken into account when their physical properties, in particular structure sensitive ones, are investigated at some time after the drilling. The time dependent volume expansion, hence, is of great importance, and several works have been carried out in the past. GOW (1971), for example, measured the bulk density of core samples soon after the core recovery, and the measurements were repeated 8, 16, 27 months after. The results indicated a discernible decrease in density of the cores with increasing time. The amount of the volume expansion increased with depth in cores above around 800 m. Below about 800 m, it seems to decrease with, or to be independent of, depth, which would presumably be attributed to the presence of O_2- or N_2-hydrate in this depth range (MILLER, 1969; SHOJI and LANGWAY, 1982).

SHOJI and LANGWAY (1983) investigated the time dependent expansion of air bubbles entrapped in core samples; they analyzed the data in terms of general "flow law" of ice, since the plastic deformation of ice is considered the major process for the bubble expansion. The flow law parameters thus determined were generally compatible with those obtained by experiments or field measurements under deviated stress conditions (*e.g.* BARNES *et al.*, 1971; PATERSON, 1977). Similar results were obtained by JONES and JOHARI (1977), who observed the shrinkage of air bubbles in natural and artificial ice by applying a high hydrostatic pressure. The rate of volume change of air bubbles, caused by a change in the hydrostatic pressure, however, is different from bubble to bubble. The rate for a particular bubble is perhaps dependent on the location of the bubble, *i.e.* whether it is at a grain boundary or inside a crystal. The rate would also depend on the orientation of the host crystal in conjunction with the orientation of the surrounding crystals, when the bubble is in a crystal. For predicting quantitatively the volume expansion of the core samples after their recovery, hence, it would be desirable to measure the bulk density intermittently as was done by GOW (1971).

This paper describes the time variation of the density data of a 413.5-m long Mizuho core, which were collected 5 times during 27–28 months after its recovery, and presents a stress-strain relationship for the hydrostatic stress condition, which was obtained from the time dependent density data.

2. Thermal History of the Samples

The core was recovered during the period from May to July in 1983 at Mizuho Station (70°42′E, 44°20′S, 2230 m a.s.l.), where the annual mean temperature is about −32°C. The drilling was performed by a thermal drill, and the obtained core samples were stored at a temperature of about −35°C after their recovery. Samples for the density measurements were cut out from the core at the first measurement made in July 1983. The period in the storage was as long as 50 days for shallow samples but only one day for a bottom sample. After the first measurement, the density samples were kept in a container, where the temperature was maintained at about −30°C, until the 4th measurement was carried out in January 1984.

The samples were then shipped over the sledge from Mizuho Station to icebreaker SHIRASE, where they were kept in a cold room of −20°C in temperature. Experiencing a voyage for about 3 months, the density samples reached Japan and were stored in a cold room of National Institute of Polar Research (NIPR), maintained at −20°C. In September 1985, they were finally sent to our cold laboratory which is at a temperature of −20°C, where the 5th measurement was made in October 1985.

The temperature for sample storage was not controlled during the transportation from Mizuho to the SHIRASE, and from NIPR to our laboratory. The periods of the transportation, however, were very short, less than two days each. It is considered, therefore, the samples were kept at −30°C between the first and the 4th measurements, and essentially at −20°C between the 4th and 5th measurements.

3. Measurements and Analysis

The hydrostatic method (BUTKOVICH, 1953; LANGWAY, 1958) was employed for the density measurements. The samples were taken at depths of every about 20 m from the 413.5 m long core. Measurements were carried out 5 times during 28 months after the completion of the drilling; July, August, October in 1983, January in 1984, and October in 1985. Prepared for the first measurement were two block samples of 100 to 150 m*l* at each depth, and the both were subjected to the measurement. After this, one of the blocks (A series) was saved for the subsequent density determinations. The other (B series) was subsequently subjected to the measurement of the total gas content, *i.e.* the sample was melted in kerosene and the volume of the released air was measured (LANGWAY, 1958).

The Mizuho core was cracked considerably, which is presumably caused by the thermal shock during drilling, at depths below about 135 m (NARITA and NAKAWO, 1985). The density value obtained by the hydrostatic method is appreciably affected by the presence of the cracks. The cracks, however, were considered absent deep in the ice sheet. It is of interest, hence, to estimate the "crack-free density" of the core. NAKAWO and NARITA (1985) made this "crack correction", for which the data of the total gas content of the density samples *per se* were essential. The corrected density data were hence obtained only for the samples of B series. Samples of A series should not be melted, since their densities were to be measured further to see their time variation, and their total gas content was unknown. It was not possible, hence, to estimate the "crack-free density" for A samples, by applying NAKAWO and NARITA's method. At the time $t=t_1$ when the first density measurement was carried out, however, it would be reasonable to assume that the "crack-free density" of a sample of A series equal to that of B series at the same depth. The "crack-free density" of A sample at different time, $\rho(t)$, then, can be estimated by the following procedure.

Suppose a sample of A series, for which the mass is M and the total volume of air bubbles dispersed in the sample, and of bubbles exposed at the sample surfaces are v_b and v_s respectively. The volume of the cracks is defined by v_c, and the volume of bubbles exposed at the crack surfaces, v_{cs}. The following equations are then given, since, during weighing in the liquid for the density determination, v_s was filled with the liquid but v_c and v_{cs} were not (NAKAWO and NARITA, 1985).

$$\frac{M}{\rho_s(t)}=\frac{M}{\rho_i}+v_b(t)+v_c+v_{cs}, \tag{1}$$

$$\frac{M}{\rho(t)}=\frac{M}{\rho_i}+v_b(t)+v_s+v_{cs}, \tag{2}$$

where $\rho_s(t)$ is the measured density at t, and ρ_i is the density of pure ice. Equations (1) and (2) hold at $t=t_1$, and hence

$$\frac{1}{\rho(t)}=\frac{1}{\rho_s(t)}-\frac{1}{\rho_s(t_1)}+\frac{1}{\rho(t_1)}, \tag{3}$$

if v_c, v_s and v_{cs} are assumed independent of time. The value of $\rho(t)$ was estimated by this equation, where $\rho_s(t)$ and $\rho_s(t_1)$ were given by measurements, and $\rho(t_1)$ was taken from the data for B samples given by NAKAWO and NARITA (1985).

4. Results and Discussion

The temperature of the density measurements was in a range between $-24°$ and

$-30°C$ in the first 4 measurements, and about $-15°C$ in the 5th measurement. Using a density-temperature relationship given by BADER (1964), all the density data were converted to the values at $-27°C$ for comparison. The "crack-free density", $\rho(t)$, estimated by eq. (3), will be discussed in this section, where the values at $-27°C$ are used, unless otherwise mentioned.

The decrease of $\rho(t)$ is plotted against depth in Fig. 1, where only $\rho(t_1)$-$\rho(t_4)$ and $\rho(t_1)$-$\rho(t_5)$ are shown for simplification. The suffixes of 1, 4 and 5 indicate the 1st, 4th and 5th measurements respectively. It is seen that the amount of density decrease

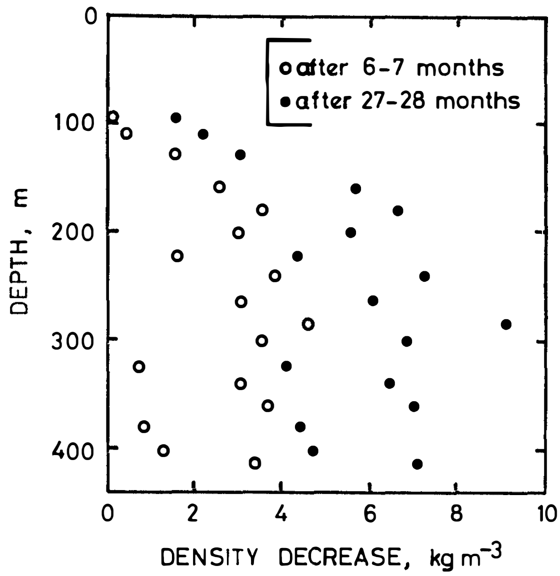

Fig. 1. Density decrease versus depth. Open and solid circles indicate respectively the decrease in periods between the 1st and the 4th measurements and between the 1st and the 5th measurements.

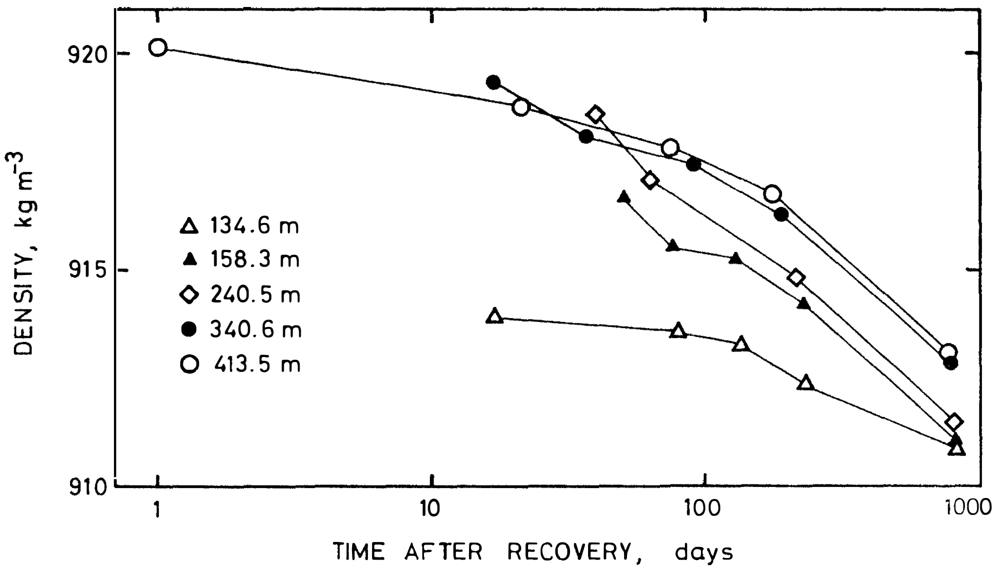

Fig. 2. Density decrease with time. Note that the samples were stored at a temperature of —30°C before the 4th measurement (about 200 days after the core recover), while at —20°C between the 4th and the 5th measurement.

increases with depth. This trend is more pronounced in the shallow portion, say above 150 m, than at deeper depths where the scatter of the data is large.

As the core was being pulled to the surface, the elastic expansion would have already taken place (GOW, 1971). Also, the amount of this elastic relaxation is considered relatively small (BADER, 1964). It is considered, therefore, the decrease of the "crack-free density" is essentially due to the plastic deformation of ice matrix. The depth dependence of the density decrease shown in Fig. 1 would be caused by the internal pressure of air bubbles in the cores, which increases with depth. The bubble pressure, however, is a function not only of the depth but also of the time after the core recovery.

Figure 2 shows the time variation of the "crack-free density", $\rho(t)$ at 5 selected depths. It shows that the density decreases with time at all depths. The rate of decrease becomes small with increasing time (note that the time is plotted with a logarithmic scale), which would be due to the successive decrease of bubble pressure in association with the volume relaxation with time. Assuming the volume expansion takes place uniformly, the one-dimensional strain rate $\dot{\varepsilon}(t)$ can be given by

$$\dot{\varepsilon}(t) = -\frac{1}{3\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}. \quad (4)$$

The pressure difference between the internal bubbles and the atmosphere, Δp is expressed by

$$\Delta p = \left(\frac{\rho_\mathrm{i}-\rho_\mathrm{c}}{\rho_\mathrm{i}-\rho}\right)\left(\frac{\rho}{\rho_\mathrm{c}}\right)p_\mathrm{c} - p_\mathrm{s}, \quad (5)$$

where ρ_c and p_c are the density and the atmospheric pressure respectively when the sample ice was originally transformed from firn to ice, *i.e.* the bubbles were closed off, and p_s is the atmospheric pressure during the storage.

Average strain rate is calculated with eq. (4) from the density decrease in a period between i-th and $(i+1)$th measurements, where $i=1$, 2, 3 or 4. In the calculation, the mean value is used for ρ, namely $(\rho(t_i)+\rho(t_{i+1}))/2$. Between 4th and 5th measurements, the samples were stored at about $-20°$C. Obtained average strain rates were hence transformed to those for $-30°$C by using an activation energy of 78 kJ mole^{-1} (HOBBS, 1974), in order to compare them with the strain rates obtained for the previous periods while the storage temperature was about $-30°$C. The average pressure difference for each corresponding period was also estimated by the use of eq. (5), where ρ_c and p_c were taken to be 829.62 kg m^{-3}, and 73.9 kPa respectively (HIGASHI *et al.*, 1983), and p_s is 73.4 kPa in periods between the 1st and the 4th measurements, and essentially 1 atm. or 101.3 kPa between the 4th and the 5th measurements.

In Fig. 3 are plotted the average values of $\dot{\varepsilon}$ and Δp thus estimated for each depth and each period between the measurements. A positive correlation can be seen between $\dot{\varepsilon}$ and Δp, although the data scatter considerably. A general expression for the plastic deformation of ice indicates the following relation:

$$\dot{\varepsilon} = K(\Delta p)^n, \quad (6)$$

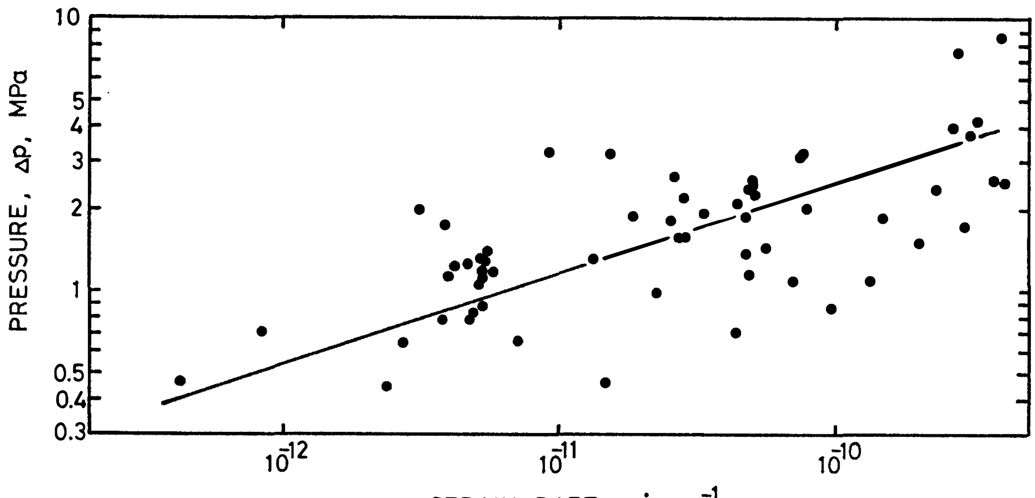

Fig. 3. Strain rate $\dot{\varepsilon}$ versus pressure difference Δp at $-30°C$. Solid line indicates a linear regression with a slope of 1/3.

where K and n are constants. Taking a value $n=3$, which is generally accepted (*e.g.* WEERTMAN, 1983), K was determined, by a least square fit to the data, to be 6.3×10^{-12} s^{-1} MPa^{-3} for $-30°C$. When strain rate is normalized to $-10°C$ with an activation energy of 78 kJ $mole^{-1}$, K becomes 1.2×10^{-10} s^{-1} MPa^{-3}.

Various workers obtained the values of K from laboratory experiments or field measurements with deviated stress conditions. They vary in a range from 5.7×10^{-8} to 5.6×10^{-7} s^{-1} MPa^{-3} when normalized to $-10°C$ (PATERSON, 1981). They are much larger by two to three orders of magnitude than the value obtained in the present study.

This large difference might indicate that the Mizuho core is much harder than the ices used for the other investigations. A preliminary study with the Mizuho core, however, resulted in K value of about 8×10^{-8} s^{-1} MPa^{-3}, which was obtained by uniaxial compression tests (S. FUJITA, personal communication). Also, values of K obtained from the closure rate of the Mizuho bore hole (KAWADA *et al.*, 1986) fit into the range of K value compiled by PATERSON (1981). It is considered, hence, the Mizuho core was by no means extraordinarily hard to deform.

In the present study, the volume of crack v_c was assumed not to change with time, as described in Section 3. If it decreases with time, however, the decreasing rate of "crack-free density" decreases apparently (see eqs. (1), (2) and (3)), which would have lead to smaller value for K. To see the effect of cracks, prepared were thin plate specimens, which included essentially no cracks, at 5 depths from cracked core samples. These small specimens were also subjected to the density measurements repeated 5 times for 28 months after the core recovery, as the samples of A series. The same analyses with the plate samples resulted in K value of 2.4×10^{-11} for $-10°C$, which was smaller by about one order of magnitude than the value from samples of A series. This indicates that the volume of cracks in A sample did not decrease but rather increased with time, although the density data with the thin plates were much less accurate because of their small sample size.

Another possibility for the smaller K value than the values in the literature would lie in that the bubble pressure would have already decreased significantly when the 1st measurement was carried out, since the values of $\rho(t_1)$ substituted into eq. (3), taken from NAKAWO and NARITA (1985), is the densities estimated not for the values at $t=t_1$ but for the *in situ* values before the samples were pulled up to the ice sheet surface. Taking into account this density differences at $t=t_1$, re-calculations were carried out, which resulted in an increase of K value by about one order of magnitude. The crack effect mentioned in the previous section, however, tends to decrease K value by the similar amount. The most probable value for K, therefore, would still be of the order of 10^{-10} s^{-1} MPa^{-3} for a temperature of -10°C.

This value is extremely smaller than those found in the literature by two to three orders of magnitude. It is considered that the large difference would be attributed to the difference in stress conditions, *i.e.* the hydrostatic pressure in the present study, while deviated stress conditions in the other investigations. To confirm this tentative conclusion, however, further studies are necessary in particular mechanical tests with the hydrostatic condition, in which the stress would not be uniform in the sample but different from place to place. The stress during the volume expansion would be high near a bubble but low near the sample surface.

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