PARTICLE REARRANGEMENT AND DISLOCATION CREEP IN A SNOW-DENSIFICATION PROCESS

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PARTICLE REARRANGEMENT AND DISLOCATION CREEP IN A SNOW-DENSIFICATION PROCESS

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Résumé - La courbure caractéristique trouvée sur le profil de densité de la neige dans les couverts de glace polaire a été corrélée à la pression de frittage de la glace. La courbure apparait pour une densité d'environ 700 kg/m^3 et une pression de 0,1 MPa. Elle se produit lorsque le mécanisme de fluage par dislocations devient actif et que le réarrangement des grains ainsi que le mouvement des dislocations contribuent à la densification pour des densités comprises entre 550 et 700 kg/m^3 environ. La contrainte limite d'écoulement de la glace a été estimée à partir de la pression effective de contact entre grains. Les valeurs obtenues sont de deux ordres de grandeur plus petits que celles usuellement obtenues en laboratoire car la vitesse de déformation est très faible, égale à 10^{-11} s^{-1}.

Abstract: A characteristic bend found in a snow-density profile at polar ice sheets was investigated from a view point of pressure sintering of ice. The bend appeared at a density of about 700 kg/m^3 and a pressure of 0.1 MPa. It is concluded that the bend appears when the dislocation creep mechanism becomes effective, and that both particle rearrangement and dislocation creep contribute to densification at densities from 550 to about 700 kg/m^3.

The yield stress of ice was estimated from the effective pressure at the contact between particles. Obtained values are by two orders of magnitude smaller than usual laboratory results because the strain rate is as low as 10^{-11} s^{-1}.

I. Introduction

The densification of snow is understood as a process of pressure sintering or hot press of ice particles.[1,2] Important mechanisms working in the process are particle rearrangement, dislocation creep and diffusional creep, but the extent of contribution of each mechanism, especially that of the particle rearrangement, has not been made clear.

In the study of snow-density profiles at three sites on the East-Antarctic ice sheet, Ebinuma et al. [3] noted a characteristic bend around a density of 700 kg/m^3 and suggested that the bend was caused by the active contribution of dislocation creep to the densification process. The present paper aims to examine the above conclusion by using other snow-density profiles obtained in Antarctica and Greenland as well, and to discuss the physical meaning of the bend in reference to the pressure sintering and mechanical properties of ice.

II. New bends in snow-density profiles

Fig. 1 gives snow-densities measured by core analyses at eight sites on the Antarctic and Greenland ice sheets plotted against logarithms of overburden pressure (the integrated load at a depth due to overburden snow); This kind of plots gives more physical implication than usual density-depth plots [3]. In each profile a characteristic bend is indicated by an arrow around a density of 700 kg/m^3 and a pressure of 0.1 MPa; numerical values of density and pressure at the bend are tabulated in Table 1.

It is well known that snow-density profiles at polar glaciers usually show bends at densities around 550 and 820-840 kg/m^3; the two bends are considered to be related respectively to the attainment of stable mechanical packing of ice particles and the snow-ice transition.[9,10] The two bends, however, are clearly different from those indicated in Fig. 1.

Additional bends or characteristic points of snow-density profiles have been discussed by several researchers; Maeno and Narita [11] discussed a constant-density layer of 750 kg/m^3 at Mizuho Station, Antarctica, which was explained by the duration of a colder climate about 300 years before the present; Herron and Langway [12] also noted such constant-density layers in many snow-density profiles and explained them as caused by synchronous climatic events which might have taken place in the 1880's. It is clear in Fig. 1 and Table 1 that the pressure at the bend is larger at sites located farther inland from the coast. If the bends were caused by a synchronous climatic event, the bend pressure should be larger at sites near the coast than at inland sites because of larger coastal snow-accumulation rates; it is obvious that the bends in Fig. 1 cannot be explained by such climatic events. Gow [7] suggested a localized deformation near the seaward edge of a large ice shelf as a cause of bend in snow-density profiles. This still may apply at Little America, but cannot explain all of the results.

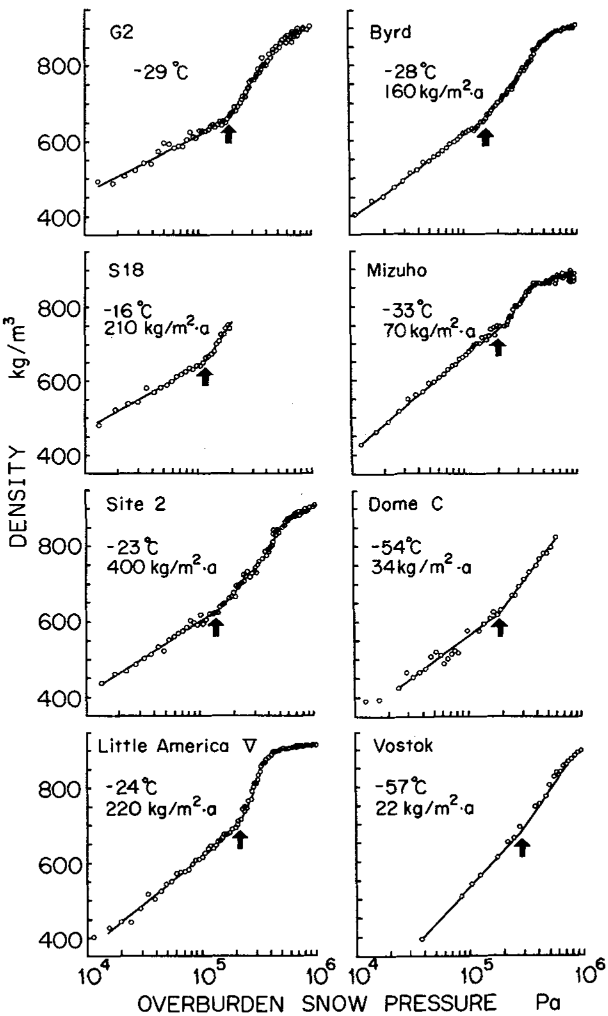

Fig.1 Density versus overburden snow pressure at eight sites in Antarctica and Greenland.[4-8] Numerals in each figure are annual temperature and snow-accumulation rate. A characteristic bend point is indicated with an arrow.

III. Physical characteristics of the bend

In the previous paper Ebinuma et al.[3] proposed that the bend corresponds to the initiation of dominance of the dislocation-creep mechanism. The conclusion suggests a close relation between the bend and a critical density of 730 kg/m^3, which was found by Maeno [13] in a snow-density profile at Mizuho Station, Antarctica, and was explained as a point at which snow has an optimum packing structure, i.e. contact areas between particles are maximum. In the following physical characteristics of the bend are discussed in reference to the theory of pressure sintering by the dislocation-creep mechanism at a constant pressure.

The strain rate of the densification ($\dot{\varepsilon}$) is given as a function of density (ρ) and pressure (P) as [14]

$$\dot{\varepsilon} = (1/\rho)(d\rho/dt) = \frac{2A(1 - \rho/\rho_i)}{[1 - (1 - \rho/\rho_i)^{1/n}]^n}(2P/n)^n \qquad (1)$$

Table I. Depth, density and pressure at the bend in snow density profiles.

Station	Depth	Density	Pressure
S18	23 m	675 kg/m^3	0.13 MPa
Site 2	27	625	0.13
Little America V	35	690	0.19
Byrd Station	24	630	0.13
G2	32	665	0.19
Mizuho Station	30	730	0.17
Dome C	46	665	0.24
Vostok Station	76	760	0.41

where A and n are constants of the secondary creep of polycrystalline ice; the following values were used in the calculation [15]: n=3.08 and

$$A = 9.72 \times 10^7 \exp(-Q/RT) \qquad s^{-1}\ (MPa)^{-n} \qquad (2)$$

where Q is the activation energy (=74.5 kJ/mol) and R and T are the gas constant and absolute temperature respectively. In the case of snow densification, the overburden snow pressure (P) varies with time; the rate of the pressure increase is related to the snow accumulation rate (a):

$$dP/dt = ag \qquad (3)$$

where g is the acceleration of gravity. Eq. (1) is written by using Eq. (3) as

$$d\rho/dP = \frac{2A\rho(1 - \rho/\rho_i)}{ag\ [1 - (1 - \rho/\rho_i)^{1/n}]^n}(2P/n)^n. \qquad (4)$$

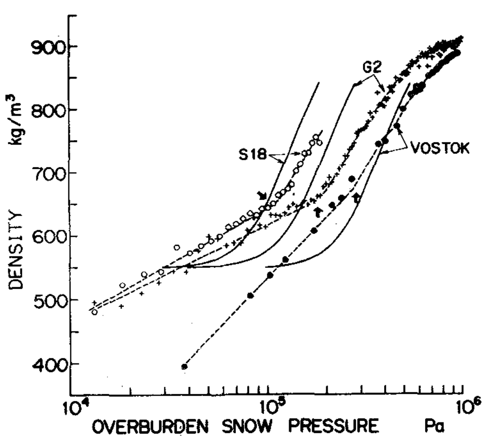

Fig.2 Calculated density-pressure profiles (solid lines) together with the measured data.

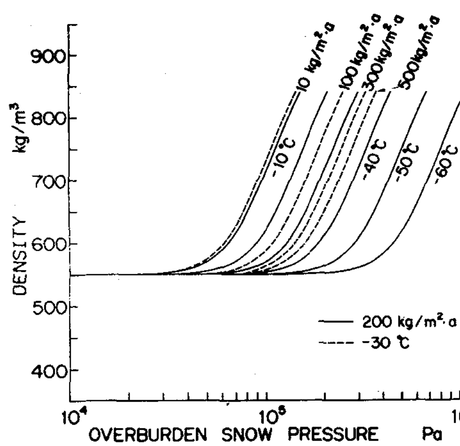

Fig.3 Calculated density-pressure profiles at constant temperature (dashed lines) and constant accumulation rate (solid lines).

Numerical integration of Eq. (4) was proceeded to get a density-pressure profile at a given temperature and accumulation rate. The initial density was assumed to be

550 kg/m^3 in the calculation, at which the primary mechanical packing is considered to be finished ; the initial pressure was assumed to be that at the density of 550 kg/m^3 at each site.

Fig. 2 gives calculated density-pressure profiles at the sites of G2, S18 and Vostok in Antarctica, together with the measured data; annual temperatures of S18 and Vostok are respectively the highest and lowest among sites considered in this paper. It is evident that the contribution of the dislocation creep becomes very effective to increase the density at a pressure around 0.1 MPa and that the pressure is nearly equal to that of the bend at each site. This result leads to a conclusion that the bend appears in a snow-density profile because of the predominant contribution of dislocation creep over that of other mechanisms.

A precise value of bend point cannot be determined because the quantitative extent of other contributions than dislocation creep cannot be estimated separately. However, particle rearrangement is known to be a main mechanism of densification below the density of 550 kg/m^3, and recently Ebinuma and Maeno [2] showed that particle rearrangement is still effective up to a density of about 700 kg/m^3. Consequently the densification of snow in a range from 550 kg/m^3 to about 700 kg/^{3} should be understood as a transition region in which the densification mechanism gradually changes from particle rearrangement to dislocation creep.

The bend pressure is larger at inland than at coastal sites (Table I), which can also be explained reasonably. In Fig. 3 solid and broken lines give respectively the calculated density-pressure profiles at a constant snow-accumulation rate (200 kg/m^{2}a) and at a constant temperature (-30^o). The calculated bend pressure increases with decreasing temperature but decreases with decreasing snow-accumulation rate. Farther sites from the coast correspond to those of lower annual temperature and smaller snow accumulation rate; the observed result is then reasonably understood to reflect the temperature dependence of densification by dislocation creep.

IV. Discussion

The real or effective pressure at the contact between ice particles should be larger than the mean overburden snow pressure even if bonds between particles are relatively large because of their long ageing period. According to Swinkels et al. [16] the effective pressure during the pressure sintering of powders are described as

$$P_{eff} = (4\pi r^2 \rho_i / SZ\rho)P \qquad (5)$$

where S and Z are the contact surface area and the coordination number at a density ; ρ_i is the theoretical density of ice (917 kg/m^3). Assuming that snow is a randomly packed aggregate of ice particle, S and Z are expressed as [17]

$$Z = Z_0 + 9.5(\rho - \rho_0)/\rho_i$$
$$S = \pi x^2 = 3(\rho - \rho_0)r^2/\rho_i \qquad (6)$$

where Z_0(=7.3) and ρ_0 are the initial coordination number and density of snow; x and r are radii of the bond and particle respectively.

Fig. 4 shows the effective pressure plotted against the depth from the snow surface, together with the overburden snow

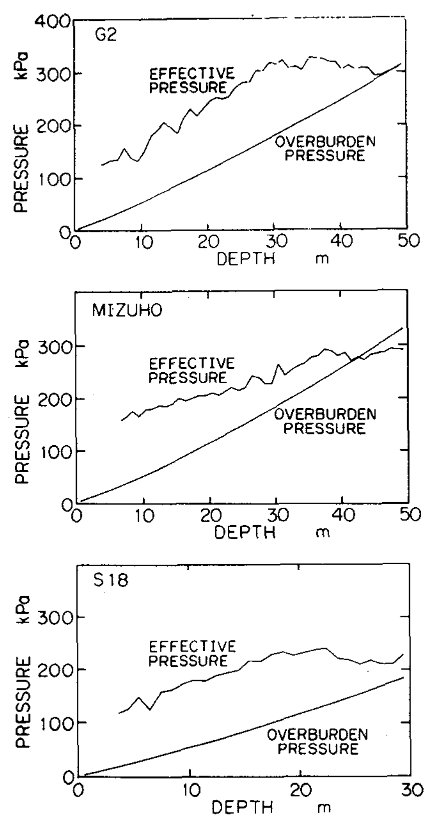

Fig.4 Effective and overburden pressures versus depth.

pressure. In each figure the effective pressure increases with increasing depth and becomes almost constant at a depth corresponding to that of bend found in a snow-density profile. The constant effective pressure suggests a steady state of deformation or yield at the contact. This result is in accordance with the above conclusion that the dislocation creep dominates at densities above the bend density. The yield strength (σ_y) of ice at the contact area can be estimated as one-third of the constant effective pressure in a steady state in consideration that the deformation is similar to that in an indentation test. Assuming that the snow-accumulation rate is constant, the strain rate of densification or that of the yield strength measurement can be estimated from the relation between the density and the overburden pressure :

$$\dot{\varepsilon} = (1/\rho)(d\rho/dt) = (ag/\rho)(d\rho/dP). \qquad (7)$$

Calculated values of strain rates around the bend are tabulated in Table II; they ranged from 1.8×10^{-11} to 1.5×10^{-10} s^{-1}. Laboratory measurements at such low strain-rates are almost impossible to be carried out.

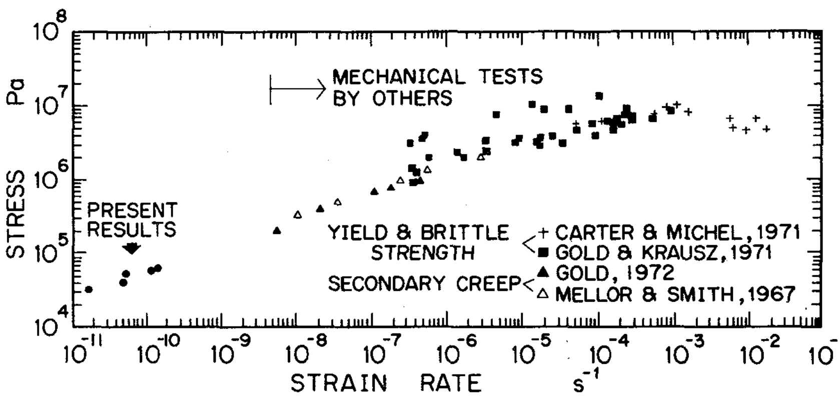

Fig.5 Yield strengths of ice plotted against strain rate. Results of mechanical tests are also shown.[18]

Table II. Strain rate evaluated from pressure-density plot.

Station	Strain rate	
	Below the bend	Above the bend
G2	5.2×10^{-11} s^{-1}	5.4×10^{-11} s^{-1}
Mizuho Station	3.6×10^{-11}	1.8×10^{-11}
Byrd Station	8.7×10^{-11}	5.2×10^{-11}
Little America V	9.3×10^{-11}	1.1×10^{-10}
S18	1.1×10^{-10}	1.3×10^{-10}

The yield strength thus estimated is compared with other laboratory results [18] in Fig. 5; in the plot the values were converted to those at -9.5°C by using the following Arrhenius-type equation:

$$\sigma_y/\sigma_0 = \exp[(Q/nR)(1/T-1/T_0)] \qquad (8)$$

where σ_0 is the yield strength at temperature T_0 and the creep constant (n) is the same as Eq.(2). It is shown in Fig. 6 that the yield strength estimated is in fairly good agreement with the extrapolation of laboratory results obtained at strain rates from 10^{-9} to 10^{-1} s^{-1}, and that the values are by one or two orders of magnitude smaller than the mechanical tests.

This work was carried out as a part of Doctorate Thesis of T. Ebinuma at the Institute of Low Temperature Science, Hokkaido University.

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COMMENTS

Remark of A. GOW :

The bend in the density depth profile of Little America V (Ross Ice Shelf) has been attributed to localized deformation related to crevasse formation in the immediate area of the Little America V drill hole. Such deformation is confirmed by the presence in the deeper firn and early-formed ice of widespread undulose extinction in the ice crystals. This behaviour may be typical of locations near the edges oflarge floating ice shelves, since a similar sharp bend in the density-depth profile was also observed at Ellsworth Station located at the edge of the Filchner Ice Shelf. The effect you describe may contribute to the bend but I think localized deformation is the principal cause if the bend in the density depth profiles at the above mentioned sites.

R.B.ALLEY

Could you tell us how you determine neck size for estimating effective pressures ? We have been measuring neck sizes in firn and find that necks are quite large (average neck radius / average grain radius = 0.6 to 0.7) even in very shallow firn (upper 50 cm), so that although effective pressure exceeds overburden pressure, the difference is not extremely large.

Answer :

The neck was assumed to grow with density according to the formula proposed by Swinkels and others (1983) in powder metallurgy. If your results of measurements may also be applicable to our case, the effective pressures and yield strengths may be slightly larger than those estimated here. It should be emphasized that the order of magnitude of yield strength of ice at such low strain rates is only significant.

L. LLIBOUTRY

Is not your critical density 0.7 about the density of close-packed equal spheres of ice ?

Answer :

Two critical points (A and B) have been found in snow-density profiles in polar regions in addition to the snow-ice transition point (C)(see Figure). Point A is considered to correspond to the random close-packing of snow particles ; at point B, which we are discussing, contact areas between particles are maximum so that the dislocation creep mechanism predominates since the particle-rearrangement mechanism cannot contribute more.