A NEW EXPLANATION OF BENDING OF A SNOW DENSITY PROFILE

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Abstract: The physical meaning of bending of a snow density profile at G2 in Antarctica (665 kg/m³, 32 m depth below the snow surface) was investigated. It was found that the bending occurred at pressures around 0.1–0.2 MPa. Examination of snow densification mechanisms as a pressure-sintering phenomenon suggested that the bending is related to the initiation of dominance of the dislocation creep mechanism.

1. Introduction

Deposited snow is densified with time and finally changes into ice in polar glaciers and ice sheets. As the densification rate depends on the temperature, accumulation

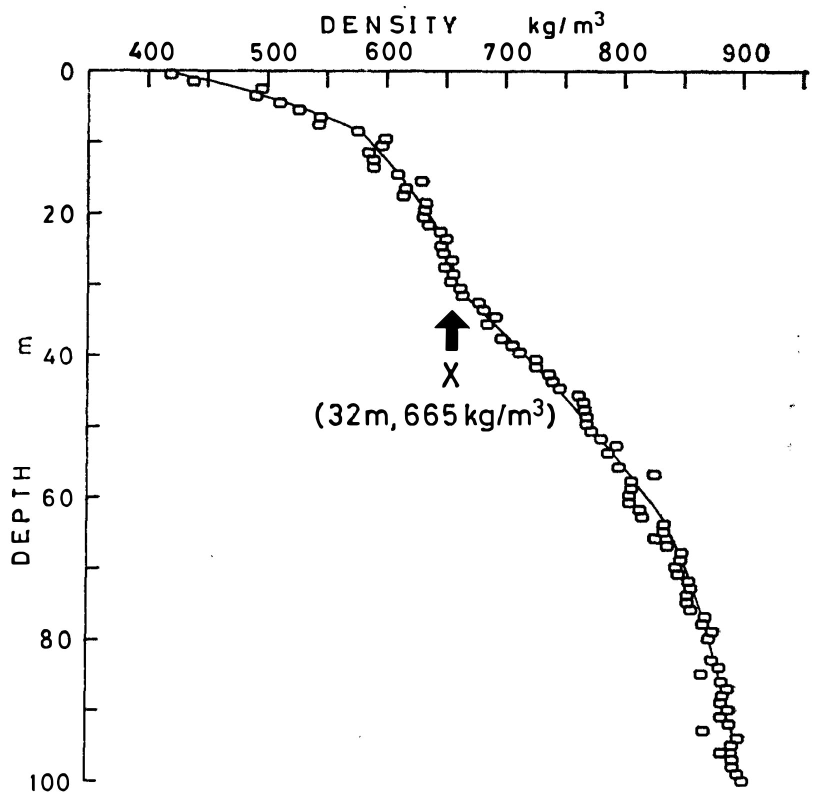

Fig. 1. Snow density versus depth at G2. Data are given in NISHIO (1984). An arrow indicates a bending-point newly found.

rate of snow, and others such as wind, the density profile (density-depth relation) at each site gives important information of the past climatic and meteorological conditions.

Figure 1 gives a snow density profile at point G2 (71°02′25″S, 39°51′47″E, 1787 m above sea level) in Mizuho Plateau, Antarctica; density data are given in NISHIO (1984). It appears that the profile shows peculiar bending, indicated by X, at the density of 665 kg/m³, that is 32-m depth below the snow surface, in addition to the two well-known bends near 550 and 840 kg/m³. The bending, however, does not seem to have been caused by a climatic event as was suggested by MAENO and NARITA (1979) for a constant-density (750 kg/m³) layer at 35-m depth of the Mizuho Station cores; the cause suggested was an colder climate period about 300 years before the present; HERRON and LANGWAY (1980) also found constant-density layers caused by a synchronous climatic event occurring in the 1880's. In the following sections, it

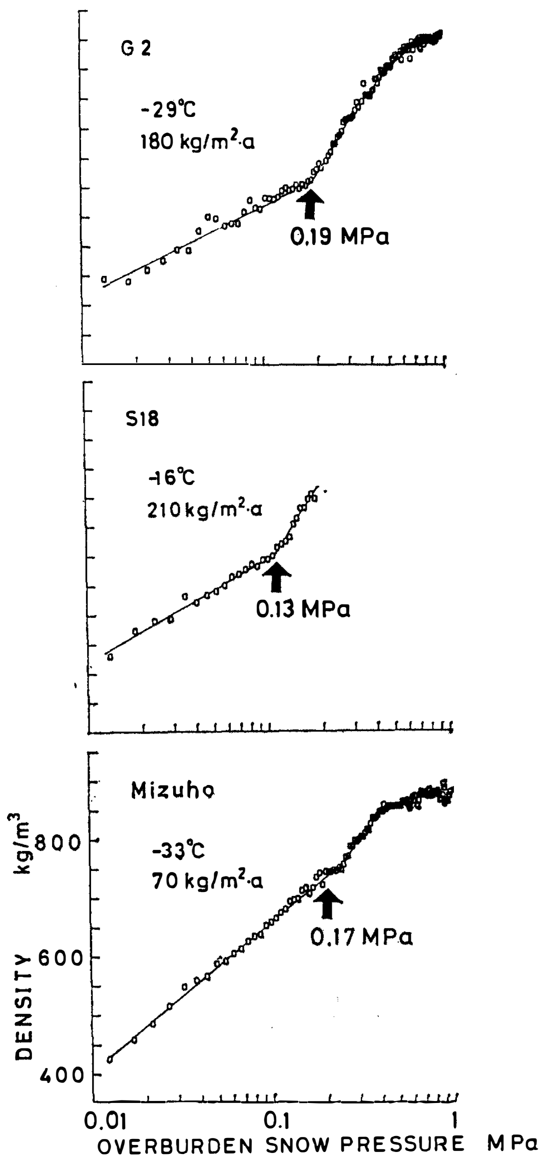

Fig. 2. Densities plotted against overburden snow pressures at G2, S18 (NISHIMURA et al., 1983), and Mizuho Station (NARITA and MAENO, 1978). Arrows indicate bending-points.

becomes clear that the bending of profile in Fig. 1 should be attributable to an intrinsic nature associated with the snow densification mechanism.

2. Bending-Point as Revealed by a Density-Pressure Plot

The bending appears more clear when the density is plotted against the logarithm of overburden snow pressure, which is calculated by summing the density from the surface. Figure 2 shows density-pressure plots for three sites in Mizuho Plateau; the bending is clear at the pressure of 0.19 MPa and the density of 665 kg/m^3 (G2), 0.13 MPa and 675 kg/m^3 (S18, 69°02′S, 40°07′E, 600 m above sea level) and 0.17 MPa and 730 kg/m^3 (Mizuho Station, 70°41′53″S, 44°19′54″E, 2230 m above sea level).

It is suggestive that the bending at the three sites occurs at similar pressures around 0.1–0.2 MPa. We have found by examining other available snow density profiles in Antarctica and Greenland that all the bending-point pressures are rather similar, only ranging from 0.1 to 0.5 MPa, and the bending-point densities are near 700 kg/m^3 though the depths are different depending on the sites.

3. Discussion

On the basis of the preceding results, we then discuss a possible mechanism to cause the characteristic bending around 0.1 MPa. According to the densification mechanism investigated by MAENO (1982) and MAENO and EBINUMA (1983) as a pressure-sintering phenomenon, the dislocation creep plays the most important role in the density range below about 900 kg/m^3 which includes the bending under discussion; the theory of pressure-sintering by dislocation creep at a constant pressure (WILKINSON and ASHBY, 1975) gives the strain rate of densification ($\dot{\varepsilon}$) as a function of the density (ρ) and pressure (P):

$$\dot{\varepsilon}=\frac{1}{\rho}\cdot\frac{\mathrm{d}\rho}{\mathrm{d}t}=\frac{2A(1-\rho/\rho_1)}{\{1-(1-\rho/\rho_1)^{1/n}\}^n}\left(\frac{2P}{n}\right)^n, \tag{1}$$

where A and n are creep constants of ice; A depends on the temperature and n nearly equals to 3. In the case of snow densification, the overburden snow pressure varies with time; the increasing rate of overburden pressure is related to the accumulation rate (a):

$$\frac{\mathrm{d}P}{\mathrm{d}t}=ag, \tag{2}$$

where g is the acceleration of gravity. Equation (1) is written by using eq. (2) as

$$\frac{\mathrm{d}\rho}{\mathrm{d}P}=\frac{1}{ag}\cdot\frac{2A\rho(1-\rho/\rho_1)}{\{1-(1-\rho/\rho_1)^{1/n}\}^n}\left(\frac{2P}{n}\right)^n. \tag{3}$$

Numerical integration of eq. (3) gives a density-pressure profile for a given temperature, accumulation rate and initial density.

The calculation of eq. (3) was carried out by using numerical constants obtained

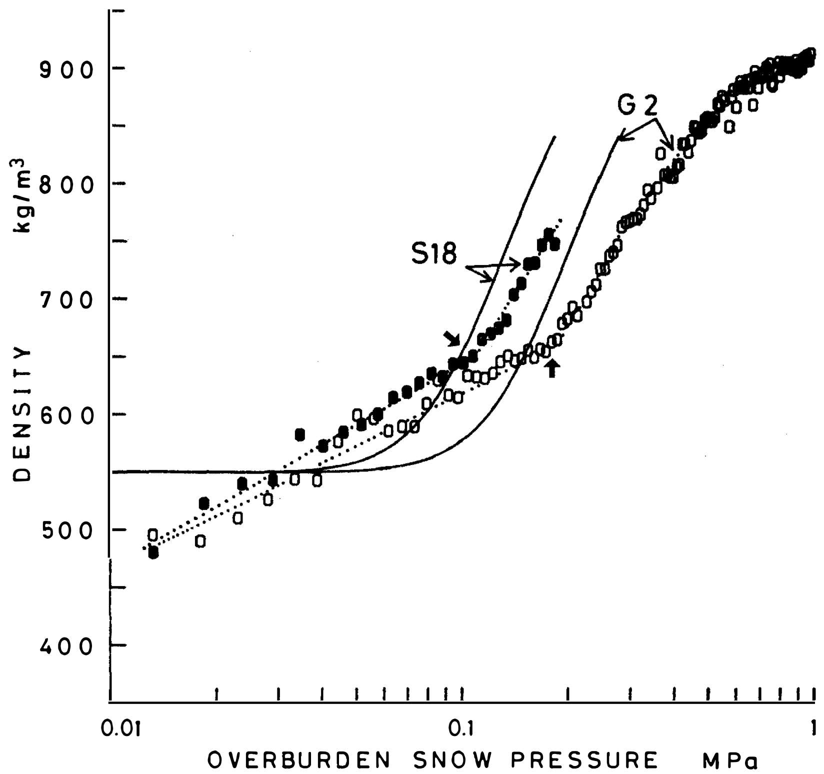

Fig. 3. Comparison of calculated and observed densities plotted against the overburden snow pressures (●: S18, ○: G2). Solid lines are calculation results of eq. (3).

by BARNES *et al.* (1971) at temperatures between −8 and −45°C as follows:

$$A=9.72\times10^{7}\times\exp(-Q/RT) \quad \mathrm{s^{-1}(MPa)^{-n}}, \tag{4}$$

where Q is the activation energy (74.5 kJ mol^{-1}), R is a gas constant, T is the absolute temperature and n=3.08; in the calculation the initial density was assumed to be 550 kg/m³ at which the mechanical packing is considered to be finished; the initial pressure was taken to be that at 550 kg/m³. The calculated density-pressure profiles are shown in Fig. 3 for S18 (T=257 K (−16°C), a=210 kg/m²a) and G2 (T=244 K (−29°C), a=180 kg/m²a). The result of Mizuho Station is not presented since its observed profile overlaps that of S18 at the density range from 600 to 750 kg/m³.

It is evident in Fig. 3 that the contribution of the dislocation creep becomes predominant at pressures above 0.1 MPa for S18 and 0.15 MPa for G2, which are close to the observed bending-point pressures. It is expected that if the calculation takes into account other predominant mechanisms as well as the dislocation creep at densities below the bending points, much better fitting of bending-point pressure will be obtained between the calculated and measured profiles.

It is concluded that the bending-point found in the density profile corresponds to a critical pressure at which the dislocation creep mechanism becomes dominant; the critical pressure is different at each site depending on temperature and accumulation rate. It is also suggestive to note that the bending-point coincides with the critical density 730 kg/m³ found by MAENO (1978) at Mizuho Station; at that density, snow has an optimum packing structure in which cylindrical air channels exist only along edges of polyhedral ice particles; the structure affords largest contact areas between ice particles, which may lead to the predominant role of the dislocation creep.

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