SNOW STRUCTURE AND DEPTH HOAR FORMATION IN MIZUHO PLATEAU, ANTARCTICA

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Abstract: The development of depth hoar was investigated for four 30-m snow cores in Mizuho Plateau, Antarctica, with measurements of specific area of internal free surfaces and air permeability. Both the specific area and air permeability increased with increasing porosity for the four cores. But the specific area at a given porosity was smaller for the core in a region having a smaller accumulation rate. The air permeability at a given porosity was larger in a region having a smaller accumulation rate. Degrees of orientation were extremely large in a region having a smaller accumulation rate, showing the development of vertical structure. It was concluded that the development of depth hoar was larger at a smaller accumulation rate.

The dominant factor of the development of depth hoar was discussed with reference to the variations of snow temperature at the four stations of core sampling. The development of depth hoar is essentially determined not only by the temperature gradient in snow but also by the staying period near the surface where the temperature gradient is largest. Thus the accumulation rate is an important factor in determining the characteristic structure of snow in polar regions. A physical quantity, *cumulative thermogradient*, is introduced to describe the degree of depth hoar development at a given site.

1. Introduction

Surface layers of snow cover in Antarctica are usually subjected to a large vertical temperature gradient, leading to the vertical transport of water vapor and formation of depth hoar. The characteristic structure thus developed is very important in determining physical properties. Several authors have reported on the development of depth hoar near the surface from stratigraphic observations (*e.g.* GOW, 1965; WATANABE, 1978), but no detailed description of physical properties seems to have been made.

In the present study, the development of depth hoar was evaluated by measurements of various structural parameters and air permeability for 30-m snow cores drilled at four sites on the Mizuho Plateau, Antarctica, and discussed to determine the most effective factor in depth hoar formation.

2. Measuring Method

Samples used for measurements were four 30-m snow cores drilled on the Mizuho Plateau, their densities being measured by NISHIMURA *et al.* (1983). The four drilling

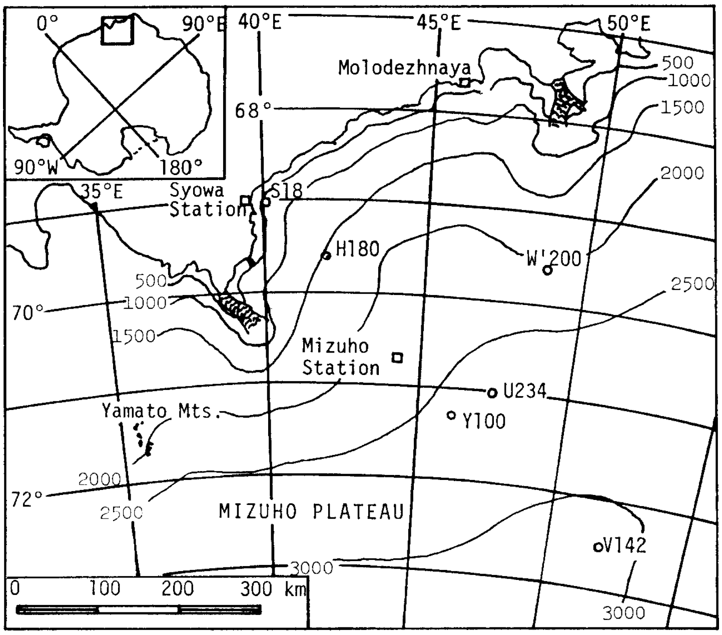

Fig. 1. Map of Mizuho Plateau showing locations of core-sampling sites (S18, W'200, U234, V142) and temporary meteorological stations (H180, Y100, V142): open circles.

stations are shown in Fig. 1. Snow temperatures at 10 m depth, which are considered to be mean annual air temperatures, are −15.9°C at S18, −33.1°C at W′200, −38.5°C at U234 and −48.1°C at V142. Annual mean accumulation rates were estimated from stratigraphic analyses of the snow cores: 210 kg/m^2·a at S18, 290 kg/m^2·a at W′200, 190 kg/m^2·a at U234, 90 kg/m^2·a at V142.

2.1. *Specific area of internal free surfaces*

Vertical thin sections were prepared by cutting aniline-reinforced samples. Thin sections planed to thicknesses about 0.2 to 0.4 mm and areas roughly 20×14 mm, were photographed under polarized light.

The specific area of the internal free surfaces was estimated by a method developed by SMITH and GUTTMANN (1953). For randomly distributed surfaces in a three-dimensional system, the specific area of internal free surfaces S_f is obtained as

$$S_f = \frac{2N}{L}, \qquad (1)$$

where L is the total length of lines drawn with spacing of about 1.0 mm on a test plane and N is the number of intersections of the lines with internal free surfaces. The test lines were drawn in vertical and horizontal directions on the test plane. The specific area of internal free surfaces was calculated by taking the mean of the values in the two directions.

When some orientation exists in the internal texture, values of the specific areas are different between vertical and horizontal directions. According to NARITA *et al.* (1978), degrees of orientation for the specific area, ω, were defined as

$$\omega=\frac{S_{fH}-S_{fV}}{S_{fH}+S_{fV}}, \qquad (2)$$

where S_{fV} and S_{fH} are the specific areas for vertical and horizontal test lines, respectively. When ω has a positive value, the internal free surface has a dominant plane of vertical direction, showing the development of vertical structure.

2.2. *Air permeability*

The air permeability of snow was measured with a permeameter used by MAENO *et al.* (1978). The permeameter is similar to that used by BENDER (1957). The air permeability was determined by measuring rates of air flow and pressure difference across a sample. Samples of snow were prepared by cutting into a cylindrical shape by using a lathe (about 40 mm in diameter and about 50 mm in length). The direction of air flow was vertical.

The air permeability k is defined by DARCY's law:

$$u=k\frac{\Delta P}{L}, \qquad (3)$$

where u is the air flow velocity, and $\Delta P/L$ is the pressure gradient in a snow sample. In the present measurements, a linear relation was found in the range of the flow velocities less than 8×10^{-2} m/s.

3. Results

3.1. *Specific area of internal free surfaces*

The specific area of internal free surfaces was measured using about 40 samples for each 30-m core. Figure 2 shows the relation between the specific area S_f and porosity p for the four cores. The porosity is defined as $p=1-(\rho/\rho_i)$ where ρ and ρ_i are densities of sample and ice, respectively. Each point in the figure is a running average of three data, which eliminates layer-to-layer fluctuations of snow structure.

S_f increases with increasing porosity or decreasing density at the four sites. But values of S_f at a given porosity are different among the four sites. They range from 2200 to 3000 m^2/m^3 at a porosity of 0.3 and from 2400 to 3500 m^2/m^3 at a porosity of 0.5. It is found that values of S_f at S18 and W′200, which are located in regions with larger accumulation rate, are larger than those at U234 and V142, which are located in regions of smaller accumulation rate.

Specific areas for Dome C (ALLEY *et al.*, 1982) and Mizuho Station (NARITA *et al.*, 1978) are also shown in Fig. 2, which are smaller than the present values. The accumulation rates at Dome C and Mizuho Station are smaller than those at the present four sites: 34 $kg/m^2\cdot a$ at Dome C (ALLEY *et al.*, 1982), 70 $kg/m^2\cdot a$ at Mizuho Station (NARITA and MAENO, 1979). It is concluded therefore that S_f is smaller in snow at smaller accumulation rates.

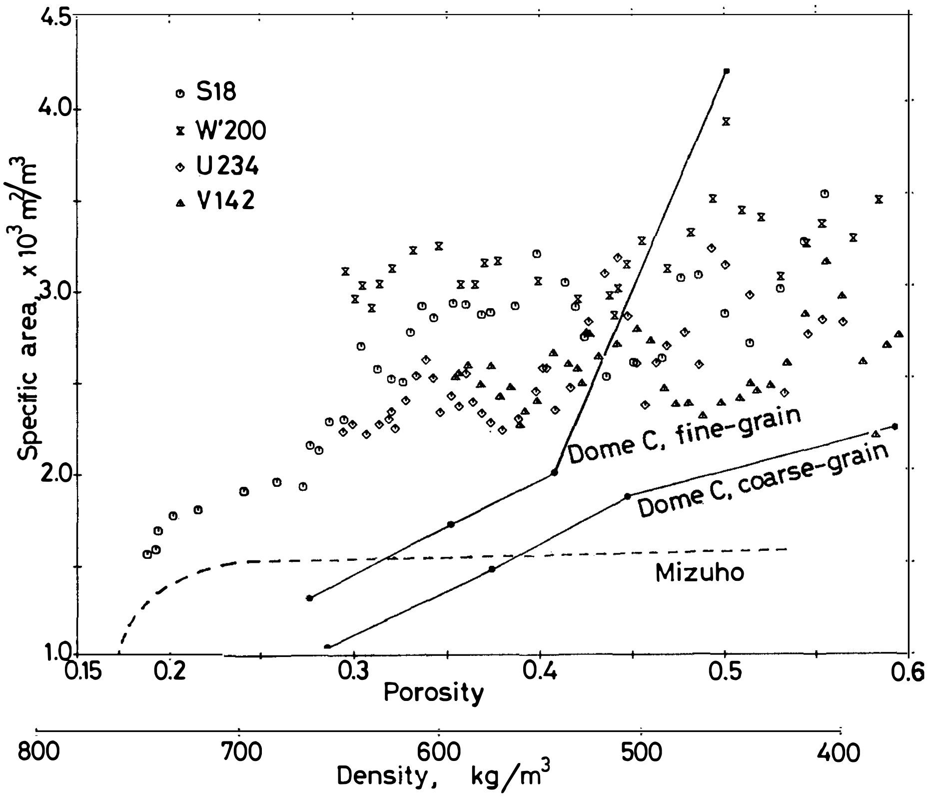

Fig. 2. Relations between the specific area of internal free surfaces and the porosity (or density) at the stations S18, W'200, U234 and V142. Each value is a running average of three data. Solid circles indicate data from fine-grained and coarse-grained snow of Dome C (ALLEY et al., 1982). Broken line indicates the result at Mizuho Station (NARITA et al., 1978).

3.2. Air permeability

Figure 3 shows the measured air permeability plotted against porosity; values are again running averages of three data. The air permeability observed at Mizuho Station (MAENO *et al.*, 1978) is also shown in the figure with a thick line. Air permeabilities at the four sites increase with increasing porosity. Just as in the case of S_f, values of air permeability at V142 and U234 are larger than those at W′200 and S18, and are rather similar to those at Mizuho Station. The result suggests that the air permeability of snow in areas of small accumulation rate (V142, U234 and Mizuho Station) is larger compared with those in areas of large accumulation rate.

3.3. Degrees of orientation

Degrees of orientation ω against depth are shown in Fig. 4: The values are also running averages of three measurements. The values of ω range from -5 to 5% at S18 and W′200, showing no strong anisotropy. But ω at U234 and V142 is definitely positive, and the positive values decrease with increasing depth. These large positive values are attributable to the development of vertical depth hoars during a prolonged period under a temperature gradient.

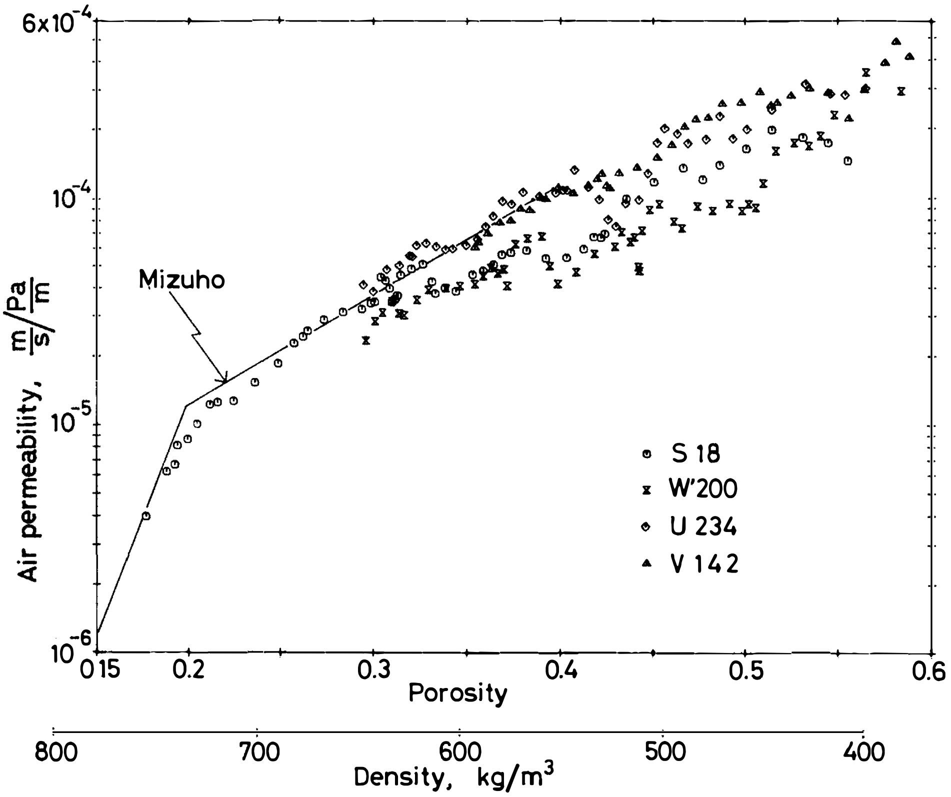

Fig. 3. Relations between the air permeability and porosity with running averages of three data. Solid line indicates data from Mizuho Station.

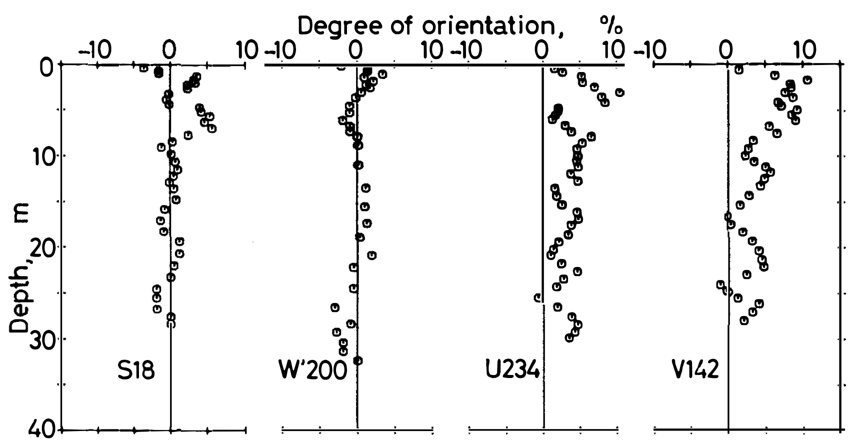

Fig. 4. Degrees of orientation for internal free surfaces at the four stations. Each value is a running average of three data.

4. Discussion

From measurements of specific area of internal free surfaces, air permeability and degrees of orientation, it is concluded that the development of vertical structures, which is the depth hoar formation, is promoted by a long stay at the surface layer where the temperature gradient is largest. This situation is often encountered in regions of smaller accumulation rates. We discuss next the thermal condition in a more quantitative way.

Depth hoars are formed in snow by vapor transport under a temperature gradient. We assume that the surface temperature T_0 of a snow layer changes with time t as

$$T_0=\bar{T}_0+A\cdot\cos\left(\frac{2\pi t}{\lambda}\right), \tag{4}$$

where λ is the period, and A and $\bar{T}_0$ are the amplitude and mean surface temperature, respectively. Then the temperature at a depth z is given by standard thermal conduction theory (CARSLAW and JAEGER, 1967):

$$T=\bar{T}_0+A\cdot\exp\left(-z\sqrt{\frac{\pi}{a\lambda}}\right)\cos\left(\frac{2\pi t}{\lambda}-z\sqrt{\frac{\pi}{a\lambda}}\right), \tag{5}$$

where a is the thermal diffusivity of snow given by

$$a=\frac{k}{C\rho}. \tag{6}$$

C and k are respectively the specific heat and thermal conductivity of snow.

The temperature gradient in snow at a depth z is given by differentiation of eq. (5),

$$\frac{\mathrm{d}T}{\mathrm{d}z}=-A\sqrt{\frac{\pi}{a\lambda}}\exp\left(-z\sqrt{\frac{\pi}{a\lambda}}\right)\left\{\cos\left(\frac{2\pi t}{\lambda}-z\sqrt{\frac{\pi}{a\lambda}}\right)+\sin\left(\frac{2\pi t}{\lambda}-z\sqrt{\frac{\pi}{a\lambda}}\right)\right\}. \tag{7}$$

From the experimental results by DEVAUX (1933), thermal conductivity of snow is expressed approximately as a function of density,

$$k=0.00007+0.007\rho^2 \qquad (\text{cal/cm}\cdot\text{s}\cdot{}^\circ\text{C}). \tag{8}$$

The thermal diffusivity of snow, a, for the four cores was calculated by using eqs. (6) and (8) and data of snow density (NISHIMURA *et al.*, 1983). Though it was found to increase slightly with depth, roughly 30% in the top 10-m layer to cause about 10% decrease in the calculation of gradients, it was assumed to be constant in the present estimate of temperature profiles. Values of thermal diffusivities used were means in the top 5-m: 3.6×10^{-3} cm²/s at S18, 3.2×10^{-3} cm²/s at W′200, 3.3×10^{-3} cm²/s at U234 and 2.9×10^{-3} cm²/s at V142.

It is known that amplitudes of annual variations of air temperatures in the interior regions are larger than those in the coastal regions of Antarctica. Figure 5 shows the amplitude A_a plotted against mean annual air temperature $\bar{T}_{a0}$ for seven stations in Antarctica (DALRYMPLE, 1966; NISHIMURA *et al.*, 1982). A_a was defined as half of the difference between maximum and minimum monthly mean air temperatures. It shows an increase with $\bar{T}_{a0}$, which is described as

$$A_a=6.69e^{-0.0192\bar{T}_{a0}}. \tag{9}$$

According to this equation, amplitudes at the four stations are $A_a=9.1$°C at S18, 12.7°C at W′200, 14.1°C at U234 and 16.9°C at V142.

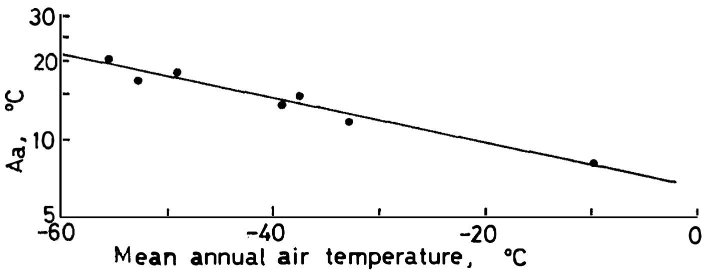

Fig. 5. Amplitude of annual air temperature variation A_a versus mean annual air temperature for seven stations in Antarctica (DALRYMPLE, 1966; NISHIMURA et al., 1982). Each value of A_a is a half of difference between maximum and minimum of monthly mean air temperature.

Diurnal temperature variations also differ among the four sites. The amplitudes A_d were measured at three temporary stations for a few weeks in 1981; the sites were H180 (69°40′S, 42°30′E), Y100 (71°18′S, 46°16′E) and V142 on the Mizuho Plateau. Measured values of A_d were assumed to be linearly related to those at Mizuho Station and found to be related to the mean annual air temperature $\overline{T}_{a0}$ by the following equation;

$$A_d = 0.62 A_{dM} e^{-0.015 \overline{T}_{a0}}, \qquad (10)$$

where A_{dM} is the amplitude of diurnal temperature variation at Mizuho Station: A_{dM} for 1981 is 4.2°C. Estimated values of A_d are 3.3°C at S18, 4.3°C at W′200, 4.6°C at U234 and 5.3°C at V142.

Figure 6 shows variations of snow temperature profiles calculated at intervals of one month by using eqs. (5) and (9). In the calculation, the mean surface temperature of the snow layer was assumed to be identical to the mean air temperature. Amplitudes of the temperature variation decrease with increasing depth. Figure 7 shows variations of snow temperature profiles calculated at intervals of two hours by using eqs. (5) and (10). Diurnal variations of temperature only occur in the top 0.5-m layer.

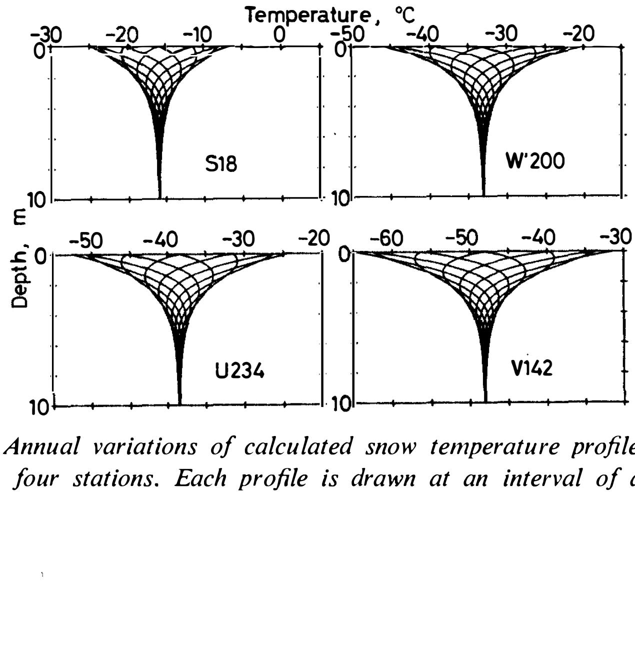

Fig. 6. Annual variations of calculated snow temperature profiles at the four stations. Each profile is drawn at an interval of a month.

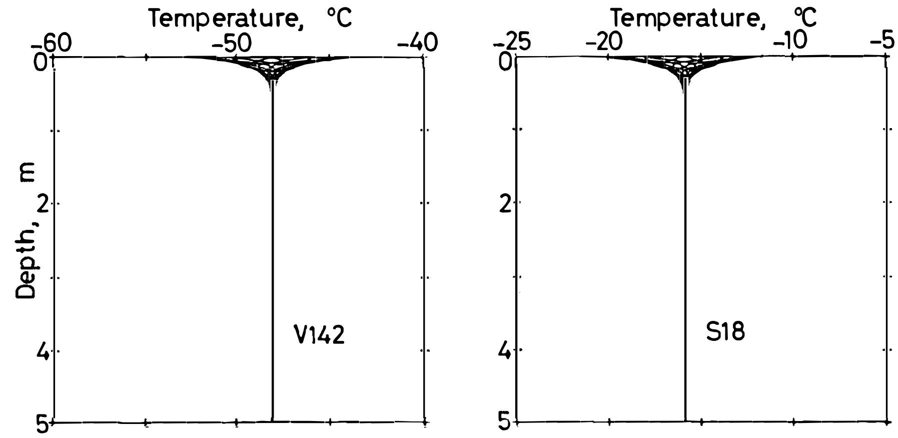

Fig. 7. Diurnal variations of calculated snow temperature profiles at S 18 and V 142, assuming no annual variation. Each profile is drawn at an interval of two hours.

Depth hoars are formed in snow by the deposition of water vapor transported under a temperature gradient. If we assume that the vapor is transported only by diffusion, the vapor flux f is given by

$$f=-D\frac{\mathrm{d}\rho_{\mathrm{v}}}{\mathrm{d}z}=-D\frac{\mathrm{d}\rho_{\mathrm{v}}}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}z}, \tag{11}$$

where D is the diffusion coefficient of water vapor and ρ_{v} is the saturated water vapor density. Depth hoars develop both by upward and downward fluxes (WATANABE, 1978). Then the degree of the depth hoar formation is proportional to the cumulative vapor flux in both the upward and downward directions to which the snow has been subjected after deposition on the snow surface. Assuming that D and $\mathrm{d}\rho_{\mathrm{v}}/\mathrm{d}T$ vary only slightly with time, t, the cumulative flux, F, is expressed as

$$F=c\int_0^t\left|\frac{\mathrm{d}T}{\mathrm{d}z}\right|\mathrm{d}t=cG, \tag{12}$$

where c is a numerical constant depending upon the structural property of the snow in question. The integral G describes conveniently the extent of depth hoar development, and may be named the *cumulative thermogradient.*

The cumulative thermogradient was estimated both for annual and diurnal temperature variations using eq. (7) and the sum is plotted against depth in Fig. 8; in the calculation the staying time of snow at each depth was estimated from the accumulation rate and density data reported by NISHIMURA *et al.* (1983). The cumulative thermogradient increases rapidly with increasing depth in the uppermost layer above 0.5-m depth at all four sites, suggesting that the depth hoar develops mostly in this surface layer. With further increase in depth, the value of G increases and becomes almost constant between about 5 m and 10 m in depth where there are only small temperature gradients. The constant values of G are larger at V142 and U234 than those at S18 and W′200, in accordance with the observed result that the depth hoars

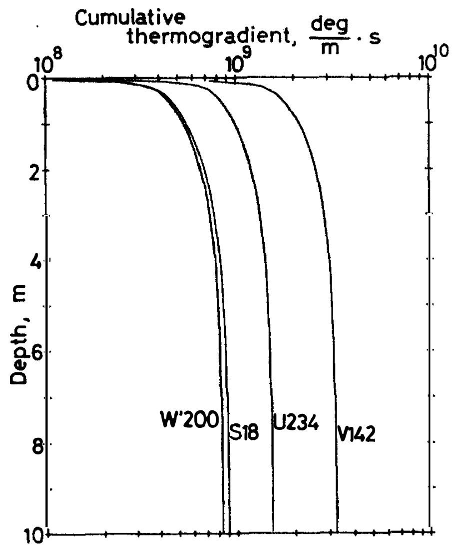

Fig. 8. Computed results of the number of cumulative thermogradient against depth.

were found to develop more actively at V142 and U234. Consequently the number of cumulative thermogradients can be used as an index to estimate the degree of the depth hoar formation in any snow cores. This is because the depth hoar formation is promoted not only by a temperature gradient but also by a prolonged period of staying there. Thus the development of depth hoars is considerably assisted by a small accumulation rate.

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