ANISOTROPY OF ULTRASONIC WAVE VELOCITIES IN MIZUHO CORES*

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Abstract: The snow cover at Mizuho Station (70°41′53″S, 44°19′54″E, 2230 m in elevation), East Antarctica, is characterized by well-developed depth hoar. To clarify how the anisotropy of elastic wave velocities changes with densification process of the depth hoar having an anisotropic texture, the *P*- and the *S*-wave velocities were measured directly as a function of depth for both the vertical and the horizontal direction using the ultrasonic pulse method applied to deep core samples drilled to the depth of 145 m at Mizuho Station. As for the *P*-wave velocity, the upper part of the ice sheet from the surface to the depth of 25–30 m (0.72–0.73 Mg/m^3 in density) was found to be anisotropic, while below that depth the ice sheet became isotropic. The curve of *P*-wave velocity versus density disclosed discontinuities at the densities of 0.65 and 0.84 Mg/m^3, which correspond to the depths of 10～16 and 55～60 m respectively. The latter depth corresponds to the level of the pore close-off. These three levels in the ice sheet were in fairly good agreement with the levels of discontinuities located on the density-depth curve. The facts indicate that the process of densification and metamorphism of snow and ice may change at these levels in the ice sheet at Mizuho Station. As for the *S*-wave velocity, the ice sheet was isotropic through all depths, whereas on the curve of *S*-wave velocity versus density only one discontinuity was clearly noticed, at the density of 0.65 Mg/m^3.

1. Introduction

The development of depth hoar is characteristic, according to the stratigraphic observations, of the snow cover in the altitudes between 2000 and 3000 m on the Mizuho Plateau (WATANABE, 1978). In fact, the snow cover at Mizuho Station (70°41′53″S, 44°19′54″E, 2230 m in elevation) is composed of well-developed depth hoar except for newly deposited snow and sastrugi. It is well known that the depth hoar generally has an anisotropic texture with a vertically connected framework. Hence, the densification of the snow cover starts with the snow of anisotropic texture at Mizuho Station.

The snow texture should exert an influence on the elastic wave velocity, since this wave propagates through the framework of snow, although the elastic wave

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velocity of the snow mainly depends on the snow density. Consequently, the traveling time per unit distance in snow for the vertical direction may be different from that for the horizontal direction.

It has been revealed by previous investigators that seismic wave velocities in the Antarctic ice sheet are affected by anisotropy in crystal orientation and by differences in mode of densification (BENTLEY, 1971; ROBERTSON and BENTLEY, 1975). They did not, however, take into consideration the anisotropy of seismic wave velocities due to anisotropy in the snow texture.

Thus, for the purpose of clarifying how the anisotropy of the elastic wave velocity changes with the densification process of depth hoar having anisotropic texture, ultrasonic wave velocities were directly measured for the vertical and the horizontal direction as a function of depth using samples of the cores drilled to the depth of 145 m at Mizuho Station (SUZUKI and TAKIZAWA, 1978).

As the cores were damaged at depths between 80 and 145 m by a thermal shock during a drilling operation conducted by a thermal drill, many cracks were formed in the horizontal plane of the cores (NARITA *et al.*, 1978). Therefore, the number of samples obtained in this range of depths was extremely small because of a difficulty in preparing crackless samples.

2. Method

Each sample cut out from the cores was a rectangular block with dimensions of 4–10 cm on each side, with the top and the bottom face perpendicular and the other faces parallel to the core axis. Measurements were made of velocities of the longitudinal and the distortional wave, respectively denoted the *P*- and *S*-waves, by means of the ultrasonic pulse method with a pulse frequency of 100 kHz for both the vertical and the horizontal direction of a sample at the sample temperature of -10 ± 0.5°C. For measurements of *P*- and *S*-wave velocities, the sample was held between a transmitter-transducer and a receiver-transducer made from barium titanate, both 30 and 27 mm in diameter respectively. Then, an electric pulse generated by an ultrasonic pulse generator was transformed into a burst of a sonic wave by the transmitter-transducer in contact with one face of the sample. The sonic wave received at the opposite face was transformed into another electric pulse so that the received pulse was observed on a synchroscope screen. The traveling time was measured to the nearest 10^{-7}s by means of a universal counter (TR 5104, Takeda Riken Industry Co., Ltd.) connected with the pulse generator and the synchroscope. The traveling distance or the sample length between the two opposing faces was measured to the nearest 10^{-3} cm with a dial guage. The density was measured by the weight-volume method, in which the sample was weighed to the nearest 10^{-2} g.

3. Results

To estimate the error of measurement, travel-time curves of several samples at different depths were obtained and two typical curves are shown in Fig. 1, in which the curves indicate good linearity. The error of measurement of sonic wave velocities assessed by deviations from a straight line was usually $\pm$10–30 m/s and did not exceed $\pm$50 m/s; it increased with increasing sonic wave velocity.

To confirm that the sonic wave velocity measured in the sample of a rectangular block with a limited size such as 4–10 cm on each side coincided with that in a great bulk of snow, two rectangular specimens different in dimension were prepared from the same layer of a seasonal snow cover composed of fine grained compact snow in Sapporo, Hokkaido. These two, having the same length of 20 cm, had different cross sections of 25×25 and 4×4 cm. Since the cross section of 25×25 cm of the first specimen was considered large enough in comparison with sonic wave lengths ranging from 0.8 to 3.8 cm depending on the wave velocity, it was assumed that the sonic wave velocity in this specimen equaled the bulk velocity. The cross section of 4×4 cm of the second specimen was the same as the smallest dimension of the samples used in this study. The two travel-time curves for the two specimens overlapped well each other into one line. As the result, the sonic wave velocity

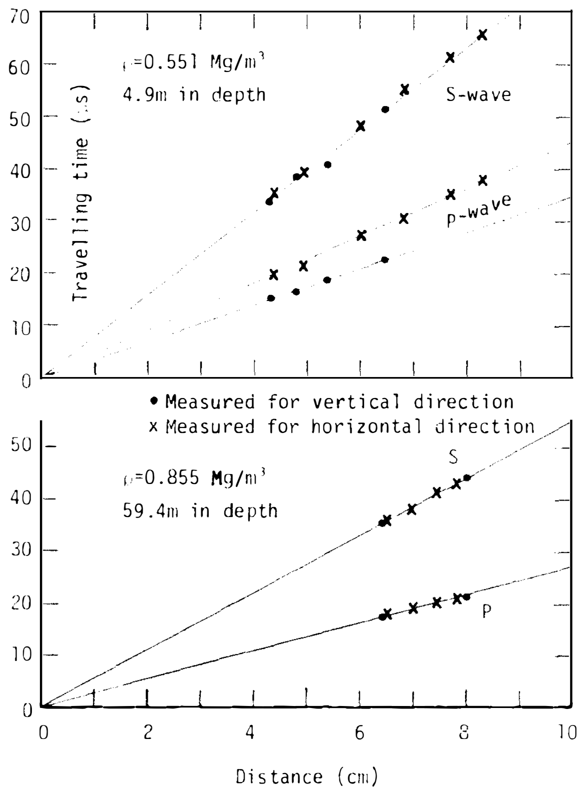

Fig. 1. *Travel-time curves for P- and S-wave in typical samples.*

measured in samples of limited size can be regarded as the bulk velocity.

Vertical distributions of sonic wave velocities are plotted in Fig. 2 together with the density, ρ, and the degree of anisotropy for P-wave velocity, γ. This figure shows the following: Velocity increases monotonically with depth. As for the P-wave velocity, V_p, a remarkable difference is found between the vertical and the horizontal direction in the upper part of the ice sheet. The velocity in the vertical direction, V_{pv}, is always greater than the velocity in the horizontal direction, V_{ph}. The degree of anisotropy for the P-wave velocity, γ, where $\gamma=(V_{pv}-V_{ph})/$

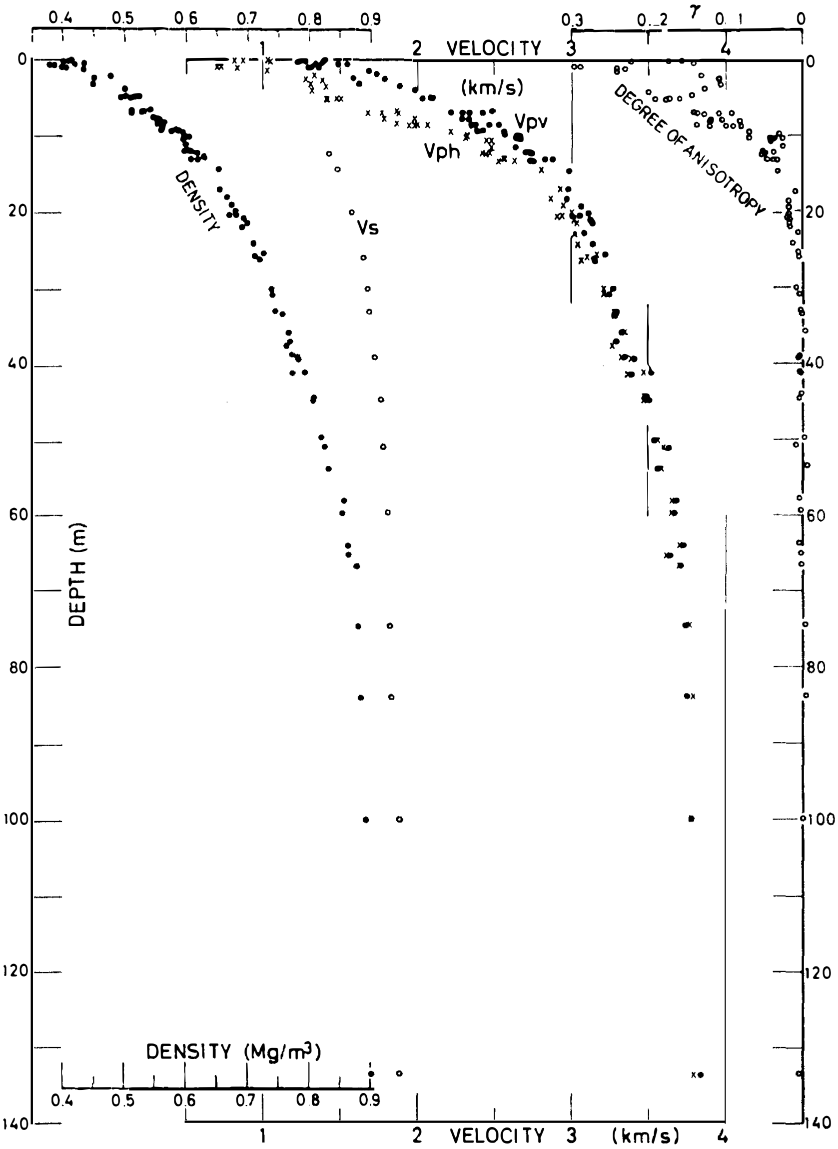

Fig. 2. Vertical distributions of P- and S-wave velocities, degree of anisotropy for P-wave velocity and density.

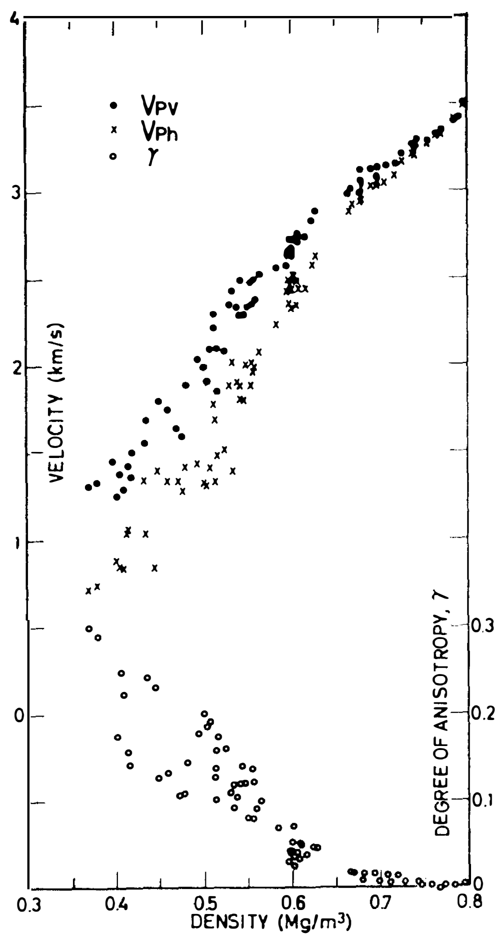

Fig. 3. P-wave velocity and its degree of anisotropy versus density.

($V_{pv}+V_{ph}$), decreases with depth, becoming practically zero at the depth of 25–30 m. The fluctuation of γ at a given depth is high in the surface snow layers and gradually decreases with depth.

To examine the density dependence of anisotropy of P-wave velocities, values of V_{pv}, V_{ph} and γ are plotted as a function of ρ in Fig. 3. The differences between V_{pv} and V_{ph} decrease with increasing density, falling within a range of the accuracy of velocity measurement at the densities of 0.72–0.73 Mg/m^3, where γ becomes practically zero. The fluctuations of V_{pv}, V_{ph} and γ are clearly larger at low densities than at high densities. The great fluctuation of V_p at low densities in this figure is considered to reflect a wide variability of snow texture, because of large porosity in low density snow. Densification of snow causes the porosity to decrease, resulting in a decrease in freedom of variability of textures. Consequently, the fluctuation of V_p at a given density, gradually decreases with increasing density.

While the anisotropy-isotropy boundary for the P-wave velocity can be found at the depths of 25–30 m and at densities of 0.72–0.73 Mg/m³, the *S*-wave velocity, V_s, has no directional difference in all of the samples (Figs. 1 and 2).

Densities of measured samples are plotted semi-logarithmically against depth in Fig. 4. The density-depth curve can be separated in to four sections, AB, BC, CD and DE, representing four straight lines. Densities and depths at three discontinuity points, B, C and D, are 0.60, 0.73 and 0.86 Mg/m³, and 10, 27 and 58 m, respectively. Such discontinuities probably occur at depths where the predominant densification process changes.

Corresponding to these discontinuities in the density-depth curve, almost identical discontinuities can be found in the curves of V_p versus ρ and V_s versus ρ as indicated in Fig. 5, where $V_p=(V_{pv}+V_{ph})/2$. A plot falls into any of three sections AB, BD and DE for V_p, or either of two sections AB and BE for V_s. The densities at B and D of the V_p curve are around 0.65 and 0.84 Mg/m³. On the curve for V_s, a discontinuity point B can be found at almost the same density of 0.65 Mg/m³ as on the V_p curve, but the discontinuity point D is not present. The densities of 0.65 and 0.84 Mg/m³ at B and D in Fig. 5 agree fairly well with the densities of 0.60 and 0.86 Mg/m³ at B and D in Fig. 4. No discontinuity corresponding to that at point C in Fig. 4 is found on the V_p and V_s curves in Fig. 5.

The density of 0.73 Mg/m³ at C in Fig. 4 is identical to the density of 0.72–0.73 Mg/m³ found in Fig. 3 as the density of the anisotropy-isotropy boundary at the depth of 25–30 m for the *P*-wave velocity. At depths near the anisotropy-isotropy boundary found in this study, NARITA *et al.* (1978) also reported an abrupt change in crystal structures and other physical properties. Thus, this depth (or corresponding density) may be considered as a newly found "critical depth" (or density) in the ice sheet. A detailed study will provide some physical meanings for it.

It is concluded that in the ice sheet at Mizuho Station, the densification process changes at the three depths around 10, 27 and 58 m which correspond to the densities of 0.60, 0.73 and 0.86 Mg/m³ respectively.

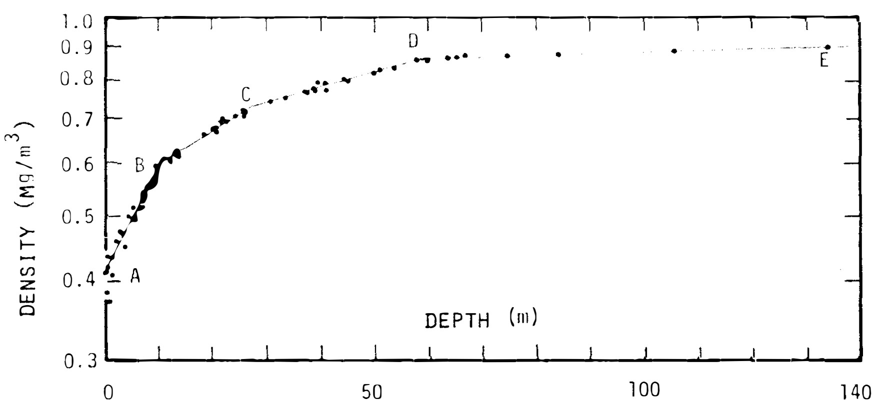

Fig. 4. Density versus depth.

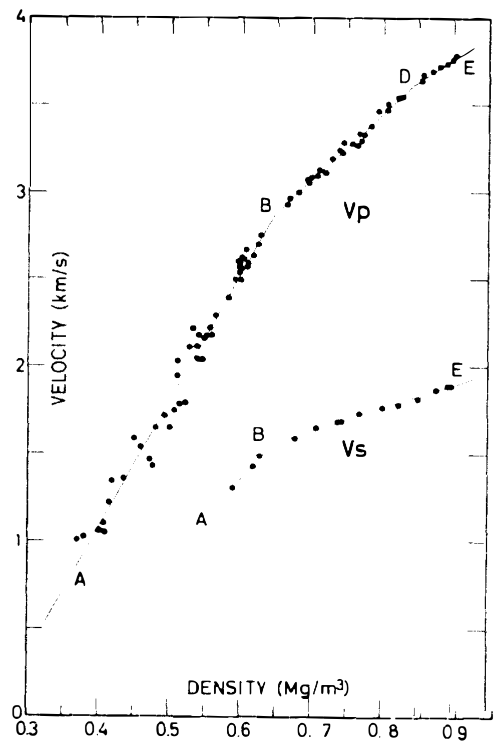

Fig. 5. P- and S-wave velocities versus density.

From Fig. 5, the following regression equations can be given between sonic wave velocity (km/s) and density (Mg/m^3): in case of the *P*-wave, for $\rho \leqq 0.65$ Mg/m^3,

$$V_p = 7.23\rho - 1.81,$$

and for $0.65 < \rho \leqq 0.84$ Mg/m^3,

$$V_p = 3.80\rho + 0.42,$$

and for $\rho > 0.84$ Mg/m^3,

$$V_p = 2.62\rho + 1.41.$$

Meanwhile, in the case of the *S*-wave, for $\rho > 0.65$ Mg/m^3,

$$V_s = 1.30\rho + 0.71.$$

4. Discussion

According to ice fabric measurements by NAKAWO (1974), the direction of the *c*-axis showed a vertical concentration above the depth of 35 m. The degree of anisotropy, γ, for V_p derived from this *c*-axis concentration does not exceed 0.04. Therefore, the value of γ obtained from the present study is too large to be explained solely in terms of the *c*-axis concentration.

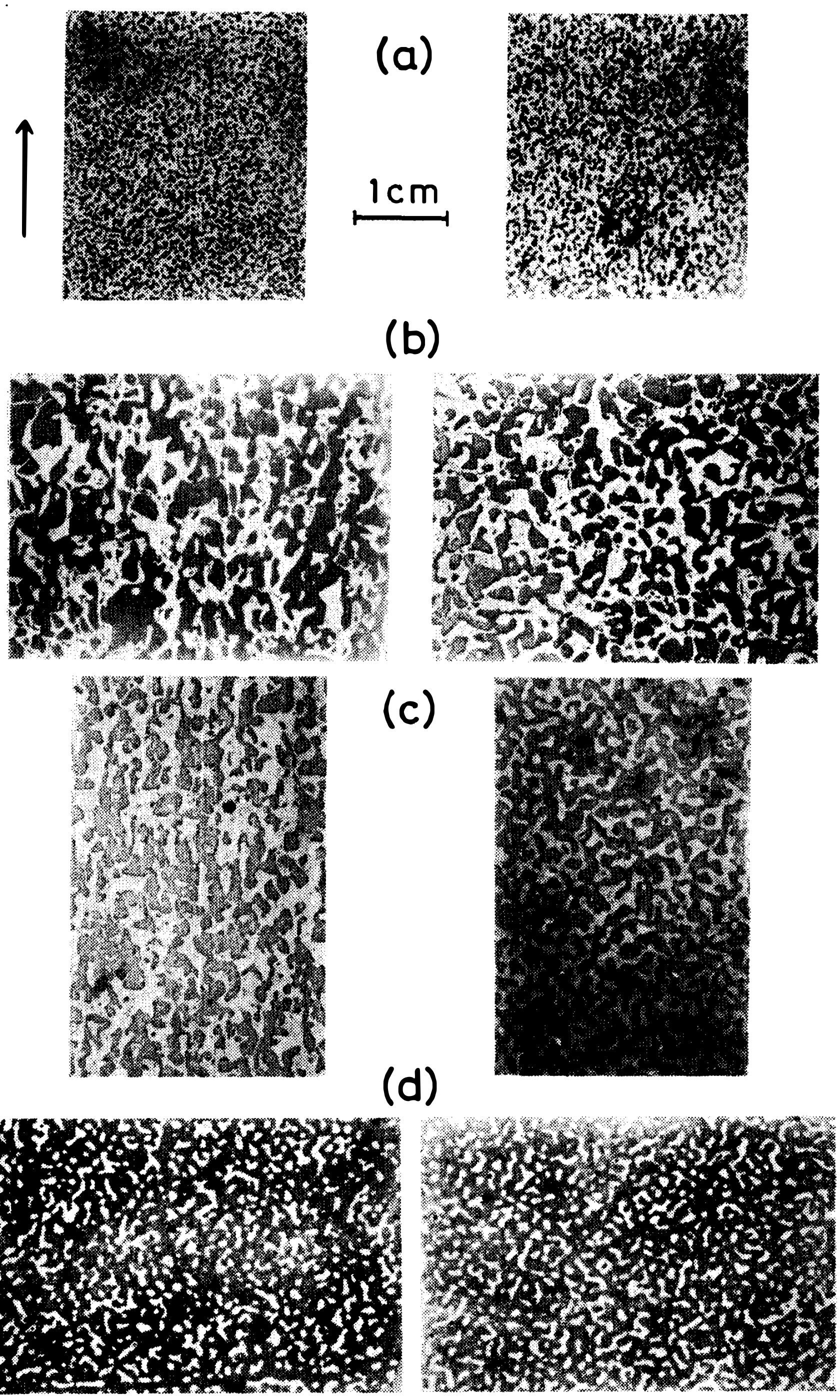

Fig. 6. *Vertical and horizontal cross sections of several samples.*
(*a*) *Newly deposited snow with isotropic texture at surface* (ρ=0.41 Mg/m^3).
(*b*) *Anisotropic texture of depth hoar at 4.2 m* (ρ=0.51 Mg/m^3).
(*c*) *Anisotropic texture of firn densified from depth hoar at 8.0 m* (ρ=0.57 Mg/m^3).
(*d*) *Slightly anisotropic texture of firn looking almost isotropic at 20.0 m* (ρ=0.69 Mg/m^3).

As shown in Fig. 6 (a), snow deposits in patches as the drift of fine grained compact snow with an isotropic texture at the surface of the ice sheet at Mizuho Station, where the mean annual accumulation is less than 5 g-water/a (YAMADA and WATANABE, 1978): the mean air temperature is −32°C and constant katabatic wind of 10 m/s blows throughout the year (INOUE *et al.*, 1978): accumulation sometimes stops for long periods, occasionally several years, during which time a glazed surface develops widely (WATANABE, 1978). Since the snow surface is exposed to violent weathering for a long time under such a climatic condition, the surface snow layers are subjected to negative and positive temperature gradients in summer and winter respectively for a long enough time to change to well-developed depth hoar. In the case of the depth hoar, it is well known that its texture becomes anisotropic, as the framework elongates vertically and the medium is connected better vertically than horizontally, as shown in Fig. 6 (b). As seen from (b) to (d) in Fig. 6, the anisotropic texture which has developed near the surface gradually loses its anisotropy under the processes of densification and metamorphism. Finally, the texture becomes isotropic at the depths of 25–30 m, which correspond to the densities of 0.72–0.73 Mg/m^3. The anisotropy for the *P*-wave velocity is explainable in terms of the shorter path of the *P*-wave in the depth hoar in the vertical direction than in the horizontal direction. Therefore, V_{pv} is greater than V_{ph}. The true path length of the *P*-wave per unit distance in the snow and firn, *i.e.*, *P*-wave velocity varies with the snow texture, which fluctuates widely at a given density since the mode of densification differs depending on climatic conditions. It is considered consequently that previous investigators have yielded various density-velocity functions in linear and logarithmic relationship (BROCKAMP and PISTOR, 1968; KOHNEN and BENTLEY, 1973; ROBIN, 1958; SMITH, 1965).

Development of depth hoar is limited in the surface snow layers from the surface to several meters in depth because the temperature gradient decreases rapidly with depth, but the snow texture retains its anisotropy further down to the depths of 25–30 m, as observed from the sonic wave. This fact means that snow and firn layers above these depths are also initially depth hoar layers before undergoing densification. Firn in such depths is estimated to be approximately 230–300 years old from stratigraphic and oxygen isotope analyses (WATANABE *et al.*, 1978). It is thus likely that over two centuries in the past the climatic condition in which depth hoar develops has continued in Mizuho Station and vicinity.

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References

BENTLEY, C. R. (1971): Seismic anisotropy in the West Antarctic ice sheet. Antarctic Snow and Ice Studies II, ed. by A. P. CRARY. Washington, Am. Geophys. Union, 131–178 (Antarct. Res. Ser., **16**).

BROCKAMP, B. and PISTOR, P. (1968): Ein Beitrag zur seismichen Erforschung der Struktur des grönländischen Inlandeises. Polarforschung, **6** (37), 133–146.

INOUE, M., YAMADA, T. and KOBAYASHI, S. (1978): Effects of synoptic scale disturbance on seasonal variations of katabatic winds and moisture transport into Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 100–114.

KOHNEN, H. and BENTLEY, C. R. (1973): Seismic refraction and reflection measurements at "Byrd" Station, Antarctica. J. Glaciol., **12**, 101–111.

NAKAWO, M. (1974): Ice fabric studies on a 75 m-long core drilled at Mizuho Camp, East Antarctica. Nankyoku Shiryo (Antarct. Rec.), **50**, 29–34.

NARITA, H., MAENO, N. and NAKAWO, M. (1978): Structural characteristics of firn and ice cores drilled at Mizuho Station, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **10**, 48–61.

ROBERTSON, J. D. and BENTLEY, C. R. (1975): Investigation of polar snow using seismic velocity gradients. J. Glaciol., **4**, 39–48.

ROBIN, G. de Q. (1958): Glaciology. III. Seismic shooting and related investigations. Sci. Res. Norw.-Br.-Swed. Antarct. Exp., 1949–52, **5**, 1–135.

SMITH, J. L. (1965): The elastic constants, strength and density of Greenland snow as determined from measurements of sonic wave velocity. CRREL Tech. Rep., **167**, 1–16.

SUZUKI, Y. and TAKIZAWA, T. (1978): Outline of the drilling operation at Mizuho Station. Mem. Natl Inst. Polar Res., Spec. Issue, **10**, 1–24.

YAMADA, T. and WATANABE, O. (1978): Estimation of mass input in the Shirase and the Sôya drainage basins in Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 182–197.

WATANABE, O. (1978): Stratigraphic studies of the snow cover in Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 154–181.

WATANABE, O., SATOW, K., OKUHIRA, F. and KATO, K. (1978): Stratigraphic analyses of firn and ice at Mizuho Station. Mem. Natl Inst. Polar Res., Spec. Issue, **10**, 25–47.

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