THE MEASUREMENT OF VELOCITIES OF *P* AND *S* WAVES IN BOREHOLES AT MIZUHO STATION AND MINAMI-YAMATO NUNATAKS, EAST ANTARCTICA

Kenji ISHIZAWA[1] and Shinji MAE[2]

[1]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[2]*Department of Applied Physics, Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060*

Abstract: At Mizuho Station (70°42′S, 44°20′E) velocity profiles of *P* and *S* waves down to a depth of 208 m were measured on 30 July and 1 August 1983, the waves were generated by hitting an iron block set on the snow surface and traveled waves were detected by geophones set in boreholes. It was revealed that the velocities of *P* and *S* waves continuously increased with depth.

At Minami-Yamato Nunataks, velocities of both waves were obtained down to a depth of 100 m in a bare ice region on 29 December 1983. The obtained velocities were constant from the surface to a depth of 100 m, being 3.83 km·s^{-1} for *P* wave and 2.01 km·s^{-1} for *S* wave.

P and *S* wave velocities at a depth of 100 m at both sites were compared. It was found that the *P* wave velocity was almost the same at both sites, whereas the *S* wave velocity at Minami-Yamato Nunataks was larger than that at Mizuho Station, in spite of nearly identical ice density at both sites. The difference in the *S* wave velocity is discussed on the basis of difference in the crystal orientation.

1. Introduction

The velocities of the compressional waves (V_p) and shear waves (V_s) are important in the study of ice sheet. To obtain these velocities in the ice sheet, several methods have been used, such as the seismic reflection and refraction methods in the field and the ultrasonic wave measurement of ice core samples in the laboratory, however direct measurement of velocity values with the use of borehole is most reliable. BENTLEY (1972) made the first *in-situ* measurement of *P* wave velocity in the deep borehole at Byrd Station and obtained a profile down to 1550 m. ISHIZAWA (1981) conducted a borehole velocity logging of *P* and *S* waves down to a depth of 80 m at Mizuho Station, setting a geophone on the hole wall and giving a mechanical wave generation at the snow surface. This study gave the near-surface snow seismic velocities of *P* and *S* waves.

The physical properties of deep ice core are changed by rapid stress release from few hundred bars to the atmospheric pressure, so the velocities of *P* and *S* waves measured with cores are not representative unless the measurement is made immediately after the recovery. GOW and KOHNEN (1979) measured the ultrasonic *P* wave velocity of nine-year-old cores drilled at Byrd Station and they found the velocity decrease in comparison with the values obtained from *in-situ* logging by BENTLEY

(1972). They explained that the decrease of V_p could be attributed to the propagation of cleavage cracks along the basal plane of ice crystals.

At Mizuho Station (70°42′S, 44°20′E) a new borehole was drilled using a thermal drill down to a depth of 700.6 m in 1983–1984. The deep cores below 150 m contained many horizontal cleavage cracks which were probably due to thermal stress from the drill heater. Therefore, V_p and V_s of ice cores in the laboratory may be not reliable, so the borehole velocity logging down to 208 m was carried out in 1983. Another measurement down to a depth of 100 m in the borehole was made at Minami-Yamato Nunataks (72°05′S, 35°11′E), where the ice exposed to the surface.

2. Equipment

The measurement system employed was almost the same by Ishizawa (1981). As shown in Fig. 1, a transmitter for wave generation, recorders and an air-pressure control instrument for geophone fixation on the borehole wall were installed in a snow cave.

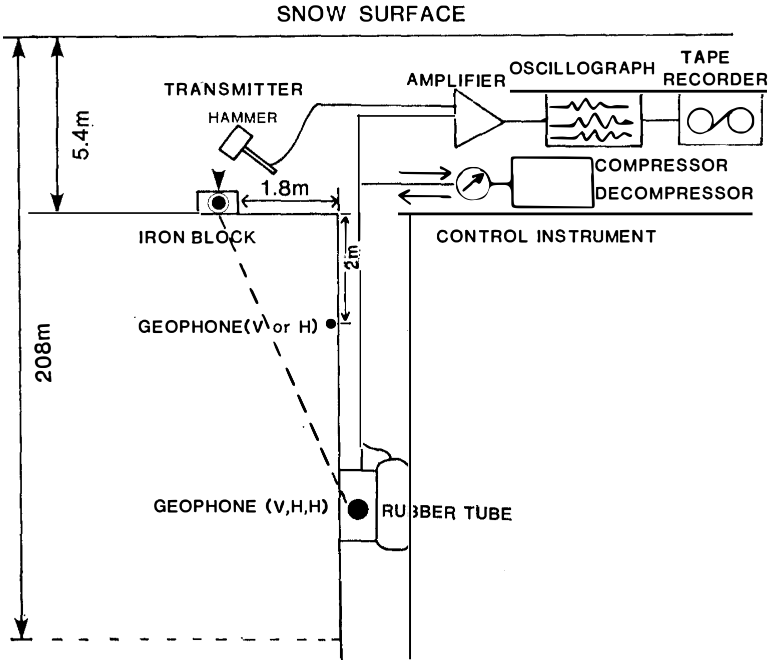

Fig. 1. Observation system of seismic waves in the borehole. The tube is inflated by compressed air of about 1 kg·cm^{-2}.

The *P* wave was generated mechanically by hitting a buried iron block vertically with a hard plastic hammer, and the *SH* wave was generated by hitting horizontally both sides of the block. Waves propagating in the ice were detected by a three-component geophone (one vertical and two horizontal) having a natural frequency of 28 Hz. The geophone was fixed to the borehole wall at an arbitrary depth by a natural-rubber tube inflated by compressed air. Two geophones, one vertical and one horizontal each (28 Hz), were set at 2 m below the shot point to record the amplitude and waveform of the wave source. The wave of vertical geophone was recorded for *P* wave measurement and that of horizontal one for *S* wave. Four signals (V, H, H in the borehole, V or H at 2 m depth) from geophones were amplified by a 6-channel amplifier and recorded on an electromagnetic oscillograph (SANEI, 5M21) and on an analogue tape recorder (TEAC, R81). Time break (shot break) by hammering was also recorded with 1 kHz time mark. The depth of geophone was measured by reading the scale of a graduated flexible wire including three pairs for signals and an air pipe.

The measurement of *P* and *SH* wave velocities at Mizuho Station was made on 30 July and 1 August 1983, placing an in-depth geophone at 4-m intervals to 208 m. The geophone in the borehole did not stuck since the improved natural-rubber tube was flexible at about −40°C and a new decompressor was effective. The signals were detected without being disturbed by the noise from the drifting snow and the electric generator about 22 m apart from the borehole. The measurement at Minami-Yamato Nunataks was made with the same method on 29 December 1983.

3. The Velocity Profiles of *P* and *S* Waves

3.1. *Mizuho Station*

Figure 2 shows five wave traces recorded at 50 m in depth. The first three traces show the wave trains of one vertical and two horizontal components in the borehole, and the fourth trace is the wave train recorded by a geophone installed at a depth of 2 m. The last trace is the time break detected by a geophone attached to the hammer. Time mark of 1 kHz is also recorded at the bottom. The initial motion of the vertical component is indicated by an arrow in Fig. 2, thus the travel time of *P* wave between the shot point and the geophone in the borehole is to be measured. In order to measure the travel time of *S* wave, the measurement was made twice by reversing the hitting direction. As shown in Fig. 3, the wave trains of *S* waves in the two *H* components are overlapped with small amplitude of *P* waves because the generation of pure *SH* wave was very difficult. Therefore, the wave trains of two horizontal components by reverse shots were compared and the initial motion of *S* wave was identified by observing the polarity of the waves as shown by arrows in Fig. 3.

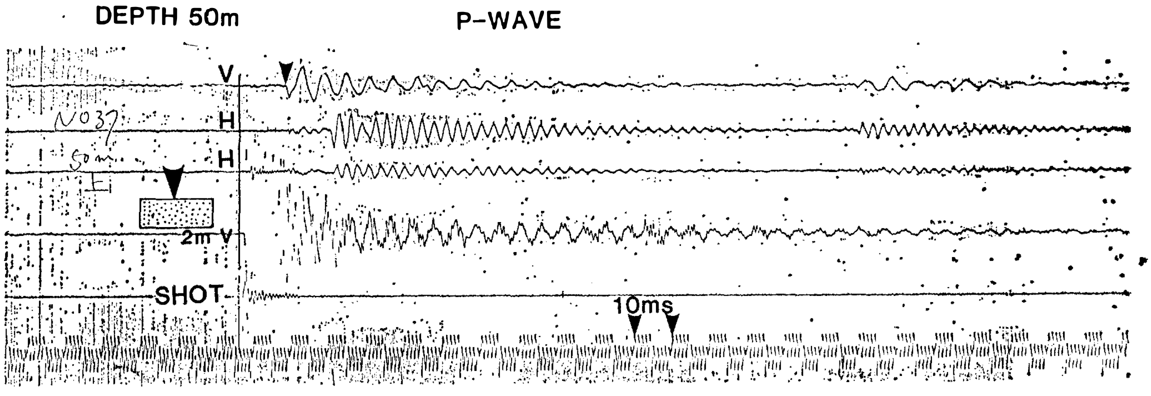

Fig. 2. P wave record.

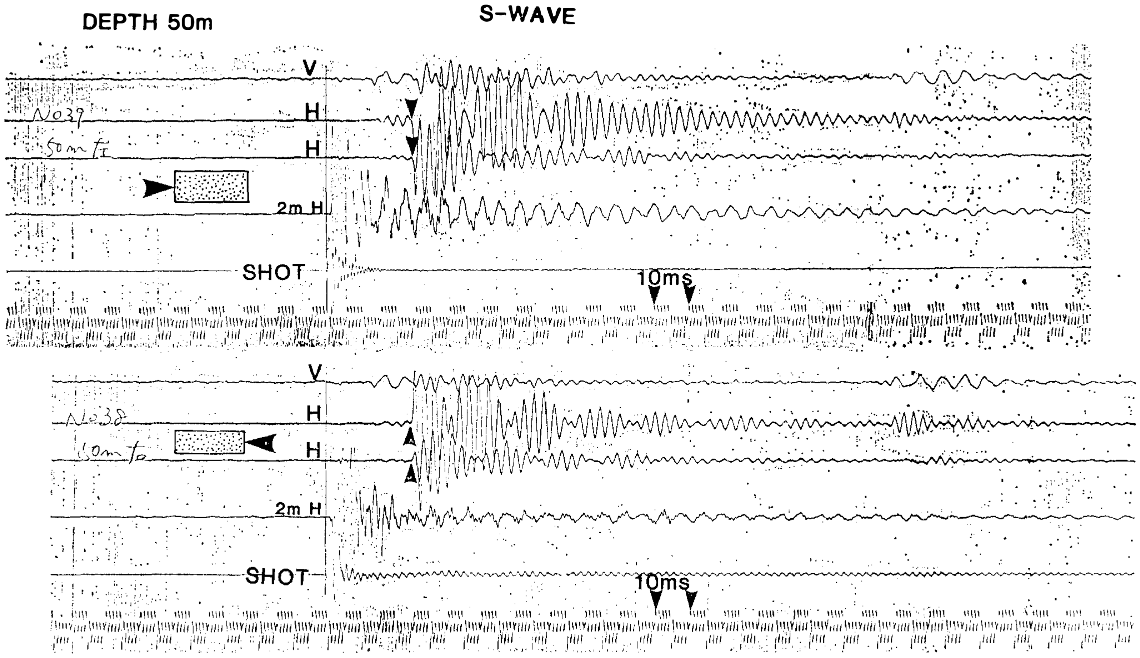

Fig. 3. A pair of S wave records.

Figure 4 illustrates the relation between the travel time of waves and the depth. The measured values are shown by dots and solid lines are drawn by the least square method. The travel time of *P* and *S* waves changes continuously with depth. The travel time (t), whose reading accuracy is 1 ms, is given by the following equation:

$$t=a\cdot z^{b}+c, \qquad 16\ \mathrm{m}\leqq z\leqq 200\ \mathrm{m} \tag{1}$$

where z is the depth from the snow surface and a, b and c are numerical constants determined by non-linear regression analysis. Therefore, the velocities of propagating waves at a depth of z, $V(z)$, can be given by the following equation:

$$V(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=(a\cdot b\cdot z^{b-1})^{-1}\,. \tag{2}$$

Substituting the constants of a, b and c obtained by eq. (1) into eq. (2), $V_{\mathrm{P}}(\mathrm{km\cdot s^{-1}})$ and $V_{\mathrm{S}}(\mathrm{km\cdot s^{-1}})$ are given as,

$$V_{\mathrm{P}}(z)=2.41\ z^{0.098}, \tag{3}$$

$$V_{\mathrm{S}}(z)=1.35\ z^{0.077}. \tag{4}$$

The calculated results of $V_{\mathrm{P}}(z)$ and $V_{\mathrm{S}}(z)$ are shown in Fig. 5, which indicating velocity increase with depth. The error of absolute values of V_{P} and V_{S} in the present study is estimated to be 100 $\mathrm{m\cdot s^{-1}}$ from the accuracy of reading of time and measurement of depth but the error of relative values is estimated not to exceed 50 $\mathrm{m\cdot s^{-1}}$. Equations (3) and (4) are approximately consistent with the result obtained by the previous work (ISHIZAWA, 1981).

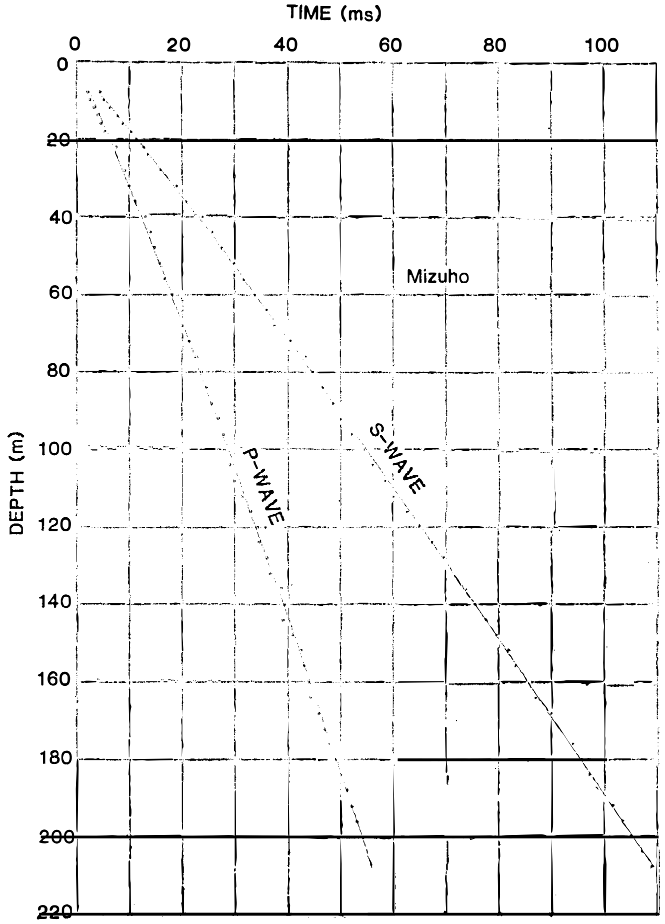

Fig. 4. Travel time versus depth for P and S waves at Mizuho Station.

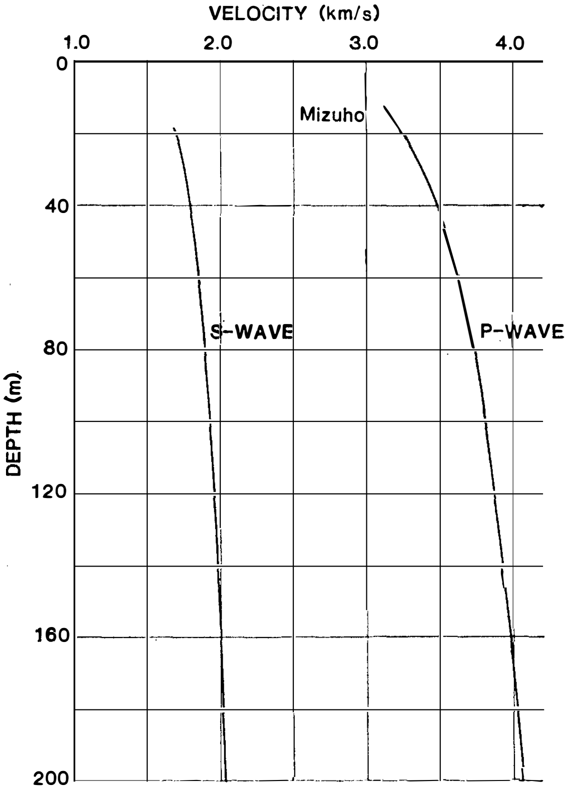

Fig. 5. P and S wave velocity profiles with depth at Mizuho Station.

3.2. *Minami-Yamato Nunataks*

A 100 m deep hole was opened with a mechanical drill in the bare ice field at Minami-Yamato Nunataks (72°05′S, 35°11′E) in December 1983. The velocity logging was carried out down to the bottom by the same method used at Mizuho Station. In Fig. 6, the relation between the travel time and the depth is given by a straight line; V_P and V_S did not change with depth, contrary to the case of Mizuho Station. V_P and V_S were 3.83 km·s^{-1} and 2.01 km·s^{-1} respectively.

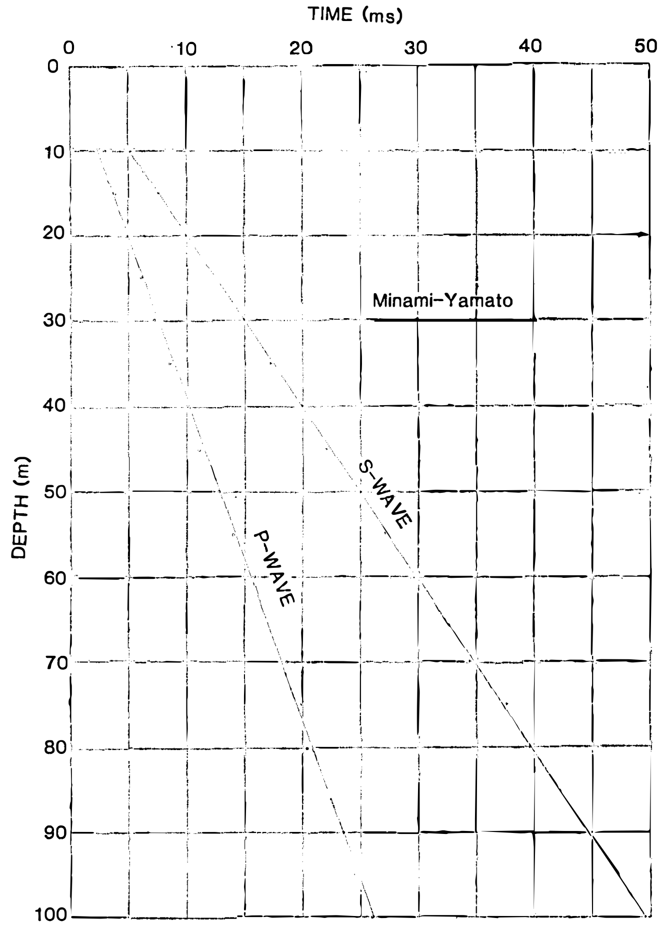

Fig. 6. Travel time versus depth for P and S waves in the bare ice field at Minami-Yamato Nunataks.

4. Discussion

V_P and V_S at a depth of 100 m at Mizuho Station given by eqs. (3) and (4) are

$$V_P = 3.80 \text{ km·s}^{-1}, \quad V_S = 1.93 \text{ km·s}^{-1},$$

whereas, at Minami-Yamato Nunataks they are

$$V_P = 3.83 \text{ km·s}^{-1}, \quad V_S = 2.01 \text{ km·s}^{-1}.$$

V_P's at a depth of 100 m are approximately equal at both sites, but V_S at Minami-Yamato Nunataks is 4.1% large.

NAKAWO and NARITA (1985) gave the ice density of 910 $\text{kg}\cdot\text{m}^{-3}$ at a depth of 100 m at Mizuho Station. On the other hand, NAKAWO (personal communication) reported that the ice density between the surface and 100 m at Minami-Yamato Nunataks changed from 890 to 910 $\text{kg}\cdot\text{m}^{-3}$.

ROBIN (1958) gave an empirical formula of snow density as a function of V_p and snow temperature:

$$\rho=221\left(\frac{V_\text{p}}{1-0.00061T}\right)+59\,, \tag{5}$$

where ρ is the snow density ($\text{kg}\cdot\text{m}^{-3}$), V_p the P wave velocity ($\text{km}\cdot\text{s}^{-1}$) and T the snow temperature (°C). Substituting -35.0°C to T and 910 $\text{kg}\cdot\text{m}^{-3}$ to ρ in eq. (5), V_p at a depth of 100 m at Mizuho Station is 3.93 $\text{km}\cdot\text{s}^{-1}$. Calculated V_p at Minami-Yamato Nunataks is 3.91 $\text{km}\cdot\text{s}^{-1}$ substituting -26.0°C and 910 $\text{kg}\cdot\text{m}^{-3}$. The measured V_p values at both sites were almost the same but they were smaller than calculated values by eq. (5).

At Mizuho Station V_p and V_s measured at 200 m are 4.07 and 2.03 $\text{km}\cdot\text{s}^{-1}$ respectively. NAKAWO and NARITA (1985) gave the ice density of 918 $\text{kg}\cdot\text{m}^{-3}$ at 200 m. The calculated value of V_p from eq. (5) was 3.97 $\text{km}\cdot\text{s}^{-1}$ which is smaller than the measured value; the reason of this difference is not clear yet.

The V_s value of 2.01 $\text{km}\cdot\text{s}^{-1}$ at 100 m at Minami-Yamato Nunataks is larger than that of 1.93 $\text{km}\cdot\text{s}^{-1}$ at Mizuho Station, but it is almost the same as 2.03 $\text{km}\cdot\text{s}^{-1}$ at a depth of 200 m at Mizuho Station. V_p and V_s of the ice largely depend on the crystal orientation of the ice (THIEL and OSTENSO, 1961). In general, seismic wave velocities traveling parallel to the c-axis are a few per cent larger than the velocities perpendicular to the c-axis. GOW and KOHNEN (1979) made V_p measurement of cores at Byrd Station and found that the velocity difference was in excess of 140 $\text{m}\cdot\text{s}^{-1}$. The relationship between V_s and the crystal orientation of the ice has not been clarified yet because of insufficient measurement of V_s in the field.

It is well known that the c-axis distributions are concentrated in the vertical direction when the ice sheet flows plastically. The flow trajectry inside the ice sheet suggested that the ice at Minami-Yamato Nunataks experienced much larger plastic deformation than the ice at Mizuho Station even though they were at the same depth, so the c-axis distribution at Minami-Yamato Nunataks may be expected to concentrate in the vertical direction. Therefore, although the ice fabric of the cores at both sites is not examined yet, the difference in the fabric pattern of the c-axis may explain the fact that V_s at a depth of 100 m at Minami-Yamato Nunataks is larger than V_s at Mizuho Station.

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