VELOCITY DISTRIBUTION ON ICE SHEET IN PRINCE OLAV COAST, EAST ANTARCTICA

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Abstract: A refraction experiment with a 100-kg charge was carried out in the ice sheet in the Prince Olav Coast, East Antarctica by the 21st Japanese Antarctic Research Expedition (JARE-21) in 1980. Prominent Rayleigh waves were clearly recorded in a distance range of 2 to 8 km from the explosion point. The maximum period of Rayleigh waves was 0.7 s with a phase velocity of 1.8 km/s. A phase velocity of surface waves is considered to be most sensitive to the *P*- and *S*-wave velocity structures of ice layers to a depth of one-fourth of the wave length. Since the longest wave length of Rayleigh waves in the present experiment is estimated to be 1300 m for the maximum period of 0.7 s (1.8 km/s in phase velocity), *P*- and *S*-wave velocity structures of ice layers to a depth of 300 to 400 m may be inferred from the dispersion curves. Assuming velocity structures of ice sheet in the Mizuho Plateau based on the previous works of JARE, theoretical dispersion curves were calculated for three different velocity structures and they were compared with the observed ones. For example, the calculated phase velocities at the period of 0.4 s were 1.85 km/s for the highest velocity model, 1.7 km/s for the middle and 1.6 km/s for the lowest one, and the observed phase velocity at the period of 0.4 s was 1.75 km/s. The velocity structure of *P*- and *S*-waves in the upper part of ice sheet estimated from observed dispersion curves of Rayleigh waves is three percents higher than those of the averaged one in the Mizuho Plateau. The *P*- and *S*-wave velocities from 100 to 1000 m in depth range from 3.7 to 4.0 km/s, and from 1.8 to 2.0 km/s.

1. Introduction

In Antarctica, seismic prospecting experiments using reflection and refraction waves have been carried out for the study of the velocity structure of ice sheet (THIEL and BEHRENDT, 1959; THIEL and OSTENSO, 1961; WEIHAUPT, 1963; KOHNEN and BENTLEY, 1973). Similar experiments have also been carried out by the Japanese Antarctic Research Expeditions since 1957 (MURAUCHI *et al.*, 1958; ISHIDA, 1962; ETO, 1971). In recent years, a radio-echo sounding method has come to be adopted to a study on a thickness of ice sheet, but papers on a velocity structure of ice sheet by explosion experiments are few. ISHIZAWA (1981) made measurements of elastic wave velocities on the surface layer of ice sheet at Mizuho Station. He adopted a method of hitting a wooden plate fixed at the snow surface. By hitting vertically and horizontally with a hammer, he succeeded in determining the velocity structure of not only *P*-waves but also *S*-waves in the ice sheet down to a depth of 80 m.

The velocity-depth profiles so far obtained by refraction and reflection methods are limited to a depth of 200 m at the most. They cover still a very shallow part of the thick ice sheet in Antarctica.

In July 1980, the 21st Japanese Antarctic Research Expedition (JARE-21) carried out a preliminary explosion seismic experiment. The main object of the experiment was to test seismographs and boring machine to be used in the following long-range explosion seismic experiments to reveal the crustal structure to the Moho depth (IKAMI *et al.*, 1983). The shot sites were located at S22 (69°01′35.1″S, 40°18′46.2″E) and S27-3 (69°02′33.1″S, 40°34′31.6″E), 30 and 40 km east of Syowa Station, respectively. Ten observation stations were set up along the line between the two shot sites at intervals of 1 km. The detailed report of this experiments is given by ITO *et al.* (1983). After the experiment, we found unexpectedly remarkable later phases on seismogram.

MURAUCHI *et al.* (1958) reported that in explosion experiments in iceberg the most distinctive phase, the fourth phase, might be a surface wave of Rayleigh type, because the phase velocity of 1520 m/s was nearly equal to 0.9194 $V_p/\sqrt{3}$. As the later phases in the present experiment show some, though not so distinctive, dispersion characteristics, the phases seem to be surface waves of Rayleigh type.

So far as we know, there has been no study on velocity structure in ice sheet derived from surface wave analyses. In this paper, we present a velocity structure of ice sheet deduced on the assumption that the observed later phase is the fundamental mode of a Rayleigh wave.

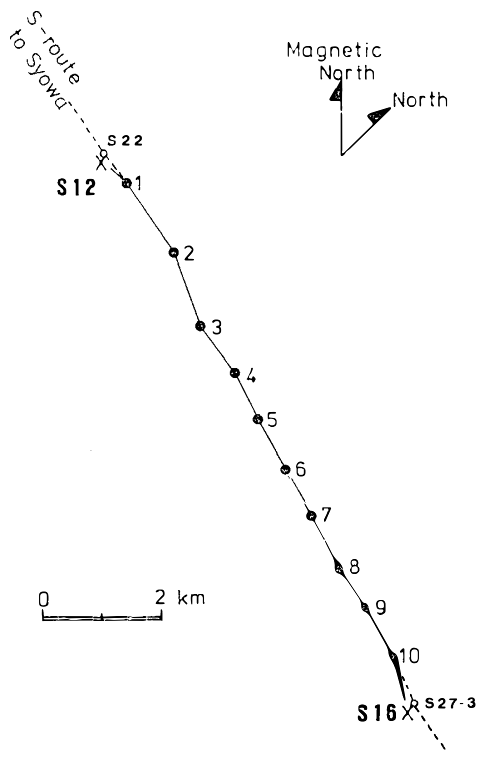

Fig. 1. Locations of shot points and observation stations. All stations were set along S-route, which was a part of the travel route from Syowa to Mizuho Stations. The crosses indicate the shot points, solid circles, observation stations, and open circles, guide-points of S-route.

2. Observed Surface Wave

The details of seismography and the operation procedure of our explosion seismic experiments are given in a separate paper (ITO *et al.*, 1983). All of the explosion seismic experiments operated by JARE-20, -21 and -22 were numbered in the firing order of explosives. The surface wave was observed in the two experiments named Shots 12 and 16.

Figure 1 shows the locations of Shots 12 and 16, and the locations of ten temporary observation points placed at intervals of about 1 km. We fired 100-kg charges at both shot points. Figures 2 and 3 show record sections observed in Shots 12 and 16. The numbers attached to the lead of each seismogram denote the station numbers shown in Fig. 1. Time axis for each seismogram is shifted by $\Delta/6$, where Δ is a shot distance in km. The upward direction on each seismogram indicates an upward movement of the ground. In order to make the record sections easy to see, the amplitude scale factor of each seismogram is modified. These record sections show that the ap-

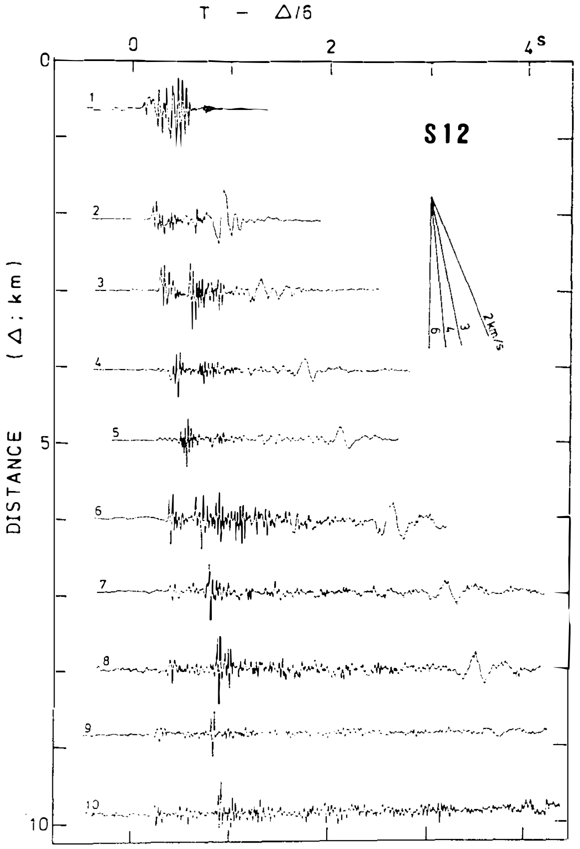

Fig. 2.

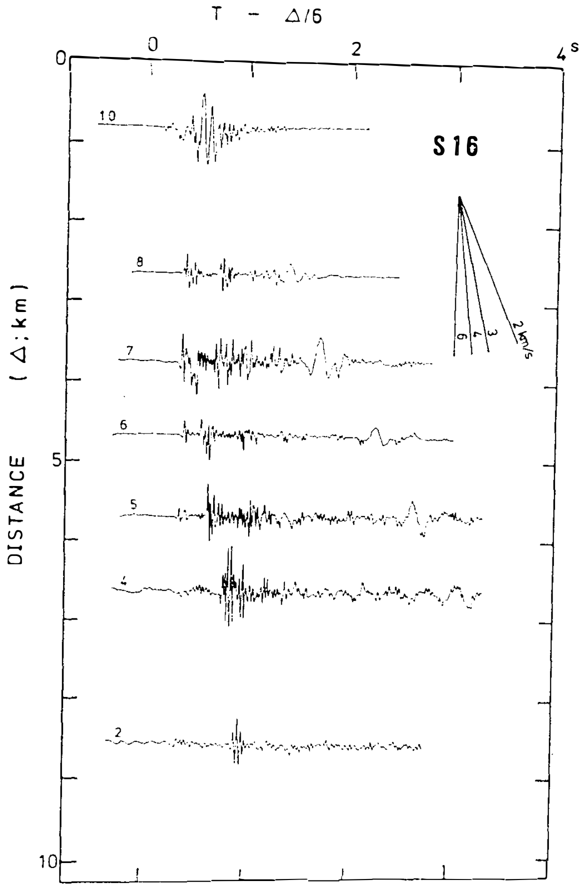

Fig. 3.

Figs. 2 and 3. Record section of Shots 12 (Fig. 2) and 16 (Fig. 3) experiments. Time axis is shifted by $\Delta/6$ (s), where Δ is the shot distance in km. Upward direction of each seismogram is concordant to the upward movement of the ground and the amplitude scale of each seismogram is modified. Numbers attached to the lead of each seismograms are the station numbers as shown in Fig. 1.

parent velocity of the initial phase at distances more than 3 km is nearly 6 km/s, a typical velocity in the upper crust, and the intercept time is 0.3 s.

The remarkable later phase, in which we are interested, is a wave group with a relatively long period as shown in the last part of each seismogram. It was observed in the distance range between 2 and 8 km. At the station nearest to each shot point, however, it was difficult to separate this phase from the direct *P*-wave. We note that the duration of the wave group was less than 1 s, and it was not dominant at distances more than 8 km. In spite of these observation results, we presumed that distinctive observed signals at stations Nos. 2 through 8 for Shot 12 and Nos. 5 to 8 for Shot 16 might be surface waves of Rayleigh type.

Criteria of a surface wave are based on (1) a dispersive characteristic, (2) a phase velocity less than an *S*-wave velocity, (3) ellipsoidal locus of ground motion, (4) an amplitude distribution with depth, and (5) a longer period than a *P*-wave and so on. Throughout our experiments, we used only a vertical seismometer, so the locus cannot be determined and the remarkable phase is Rayleigh wave but not Love wave if it is a surface wave. At stations Nos. 2 and 5, four seismometers were installed on the snow surface and at depths of 3, 5 and 10 m, though these depths are too shallow to judge whether the phase is a surface wave or not by the amplitude distribution. Therefore, in this paper we assumed that the phase was a Rayleigh wave only judging from the dispersion characteristic, though the duration of the wave was short and it was observed within a limited shot distance range.

3. Methods

We used direct analogue recorders to observe explosion seismic signals. These recorders worked continuously for several days, with a tape speed of 0.2475 mm/s. To reduce reproducing time, a data recorder with a tape speed of 200 or 400 times faster than that on recording and a digital oscilloscope were adopted. This oscilloscope is equipped with digital memories of 4 K words (12 bits/word) and a pre-triggering circuit. After picking up the signals by this apparatus, they were stored on a mini-floppy disk attached to the oscilloscope for the calculation of phase velocities. As the synchronized digitization of signals was not done at the present, resultant sampling intervals were different among seismogram. In order to equalize the intervals, the digital seismograms were interpolated by a cubic spline interpolation formula. After this process, phase velocities at each frequency were calculated using the Fast Fourier Transform. Since the Fourier Transform yields an ambiguity of $2\pi n$ in phase information, where n is an integer, it is necessary to make a phase delay by adding or subtracting $2\pi n$. The integer n can be determined directly if we have three or more stations (*e.g.*, DZIEWONSKII and HALES, 1972). In this study, $2\pi n$ corrections could be done easily, because observation stations were spaced at a constant distance. That is, the integer n is the same between the adjacent stations. After this correction, we could construct a relation between phase and shot distance and then calculated phase velocities by a least squares method.

4. Results

ISHIZAWA (1981) compiled the velocity structures of the ice sheet, which had been studied by explosion seismic experiments in Antarctica. The P-wave velocity of the ice sheet so far determined increases with depth and is nearly 4 km/s in the deepest part of the ice sheet. Based on the compiled data by ISHIZAWA (1981), we prepared three models, which have the highest, intermediate and lowest velocity distributions in his compiled data. In order to calculate the theoretical phase velocities, each model was divided into many horizontal layers. Thickness of each layer was different at shallower and deeper parts. Figure 4 shows three velocity profiles thus determined. The most sensitive factor for the dispersion is the velocity structure of S-waves. ISHIZAWA (1981), by the method of hitting the end of a wooden plate horizontally, determined an S-wave velocity structure without information of P-waves. The dispersion is less sensitive to the density structure than to the S-wave velocity structure but more sensitive than to the P-wave one. Referring to the relation between a P-wave velocity and density determined by NARITA and MAENO (1978), they showed that other elastic constants, such as Poisson's ratio and Young's modulus, are also depth dependent. In this paper, three models mentioned above were constructed from the P-wave velocity structure first and then obtained S-wave velocity and density structures according to ISHIZAWA (1981).

Figure 5 shows the theoretical dispersion curves thus calculated and observed phase velocities. Dashed lines are the theoretical curves and closed circles are phase velocities derived from observed data. At short periods, two or more phase velocities are plotted as observed ones. These are due to uncertainty in correction of n. Therefore, to construct a velocity model of the ice sheet, by the dispersion of a surface wave,

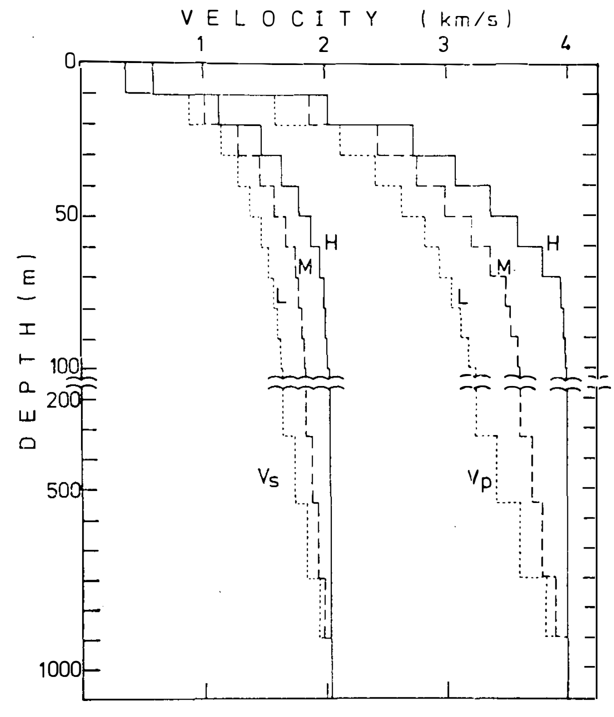

Fig. 4. The velocity profiles of P- and S-waves in ice sheet, for which theoretical dispersion curves were calculated. H, M and L mean a high, intermediate and low velocity model, respectively.

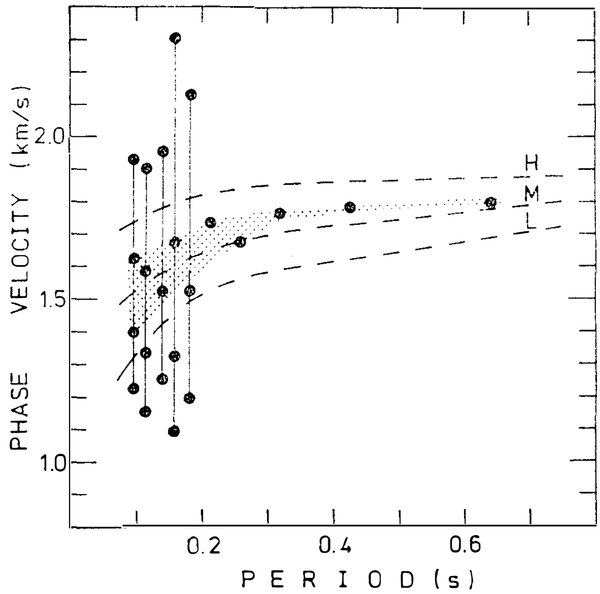

Fig. 5. Theoretical and observed dispersion curves. Dashed lines mean the theoretical ones for three models shown in Fig. 4. Solid circles indicate the observed phase velocities at the respective periods. Because of uncertain phase correction, two or more phase velocities are plotted.

especially at shallow depths, denser observation-station intervals would be desirable. The velocity structure in our explosion experimental site was the structure corresponding to a hatched area in Fig. 5. This structure has a slightly higher velocity distribution than the intermediate velocity model shown in Fig. 4. In order to discuss the difference between observed and theoretical phase velocities, it must be inferred that what a depth range of the ice sheet the observed dispersion curves reflect. In Fig. 5, the phase velocity at a period of 0.7 s was 1.8 km/s, so its corresponding wave length is 1.3 km. Although the surface wave goes through into the depth nearly equal to the wave length, the most sensitive depth is the depth corresponding to 1/4 of the wave length (KNOPOFF *et al.*, 1966), it is a depth of 300 m in our case. A phase velocity of a surface wave reflects an average velocity of the structure, so it does not necessarily coincide with the results by refraction or reflection experiments. It is concluded that, though not in detail, we could estimate the velocity structure of ice sheet.

There are many phenomena that we cannot explain but must be explained in future: Comparing the result of Shot 12 with that of Shot 16, we observed strong surface waves from Shot 12 but not from Shot 16, and surface waves were limited within a shot distance range from 2 to 8 km. According to many seismic experiments in Japan, strong surface waves were observed in the case of the existence of a low-speed surface layer. Studies on surface waves have been extensively done by the JISHIN TANKÔ JIKKEN GURÛPU (1976). Therefore, establishment of a suitable observation system for surface waves will be useful to study a velocity structure of ice sheet through the analyses of dispersion of surface waves.

Numerical calculation was performed at the Computation Center of Nagaya University (Problem No. 4001KW2670).

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