UPPER CRUSTAL STRUCTURE BENEATH THE ONGUL ISLANDS, EAST ANTARCTICA

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***Abstract*:** Two explosion seismic experiments were conducted in 1980 by the 21st Japanese Antarctic Research Expedition (JARE-21) to reveal the velocity structure beneath the Ongul Islands, East Antarctica. In one experiment eleven stations were established along a line of 5.2 km long at intervals of about 0.5 km on the outcrops on East and West Ongul Islands and two explosions of 100 and 80 kg were fired at the bottom of the sea. The other smaller-scale experiment was made on East Ongul Island to reveal the structure shallower than that obtained by the above-mentioned experiment. Five shots were fired and the seismic waves were observed at eight stations along two lines of 0.7 and 0.9 km long respectively. In both experiments direct waves were clearly recorded at all the stations as first arrivals. The mean apparent velocity and the mean average velocity of *P*-waves are 6.19 ± 0.11 and 5.74 ± 0.88 km/s, respectively. The obtained velocity in the ice-free area of the Ongul Islands is nearly the same as the velocities under the ice sheet in East Antarctica hitherto obtained by the research expeditions of the United States, USSR and Japan. The sedimentary layer with a velocity less than 5.5 km/s does not exist. Clear later arrivals with large amplitude were also detected at all the stations that ranged from 0.1 to 5.2 km from the shot point. The mean apparent velocity and the mean average velocity were 2.84 ± 0.03 and 2.94 ± 0.37 km/s, respectively. These later arrivals are presumably Rayleigh waves.

1. Introduction

In the upper crust of continents or island arcs, there exists generally a layer with a *P*-wave velocity of about 6 km/s, a granitic layer, which is overlaid by some layers of velocities less than 5.5 km/s. BENTLEY and CLOUGH (1972) compiled explosion seismic data in Antarctica and concluded that the sedimentary layers in East Antarctica are no more than 0.5 km thick. IKAMI *et al.* (1980, 1981), however, suggested a layer of about 4.0–5.0 km/s under the ice sheet from the first explosion seismic experiment carried out by the 20th Japanese Antarctic Research Expedition (JARE-20). Thus the velocity of the surface layer under the ice sheet is not clear.

Subglacial seismic wave velocities were derived from several tens of seismic experiments at many points in Antarctica (BENTLEY, 1973). The velocity structure under the ice sheet, however, has some uncertainties, when a complete reverse shot is not available or when the velocity structure of the ice sheet is not known. Experiments on ice-free areas were very few in Antarctica, though the direct identification of the rock velocity is possible *in situ* in such an area. The wintering party of JARE-21 conducted several explosion seismic experiments to study crustal structures in the vicinity of Syowa Station and in the Mizuho Plateau, East Antarctica. Two of them were made in the ice-free area. Although the two explosions were experiments for the large shots, observations and their operation in the following large-scale experiment, obtained records were clear enough to derive the velocity structure beneath the ice-free area. In the present paper the obtained velocity structures of the shallow crust in the ice-free area from the above experiments are presented and compared with those of other areas in Antarctica.

2. Description of Experiments

Two seismic experiments were carried out in the ice-free area in the vicinity of Syowa Station, one of the two Japanese Antarctic stations. One was made along a line of 5.2 km long in the vicinity of the Ongul Islands (hereafter refer to as experiment-II because this is the second explosion seismic experiment by JARE as listed in Table A-1 of Appendix). Another, though it was very small scale, was made on East Ongul Island (hereafter refer to as experiment-III). The detailed description of the field operations of the experiments was given by ITO *et al.* (1983).

Shot and observation points of experiment-II are shown in Fig. 1. Shots 3 and 4 were fired at the bottom of the sea under the shore sea ice at a depth of about 50 m. Shot 3, 100 kg in charge size was fired at the northeast end of the profile on May 20,

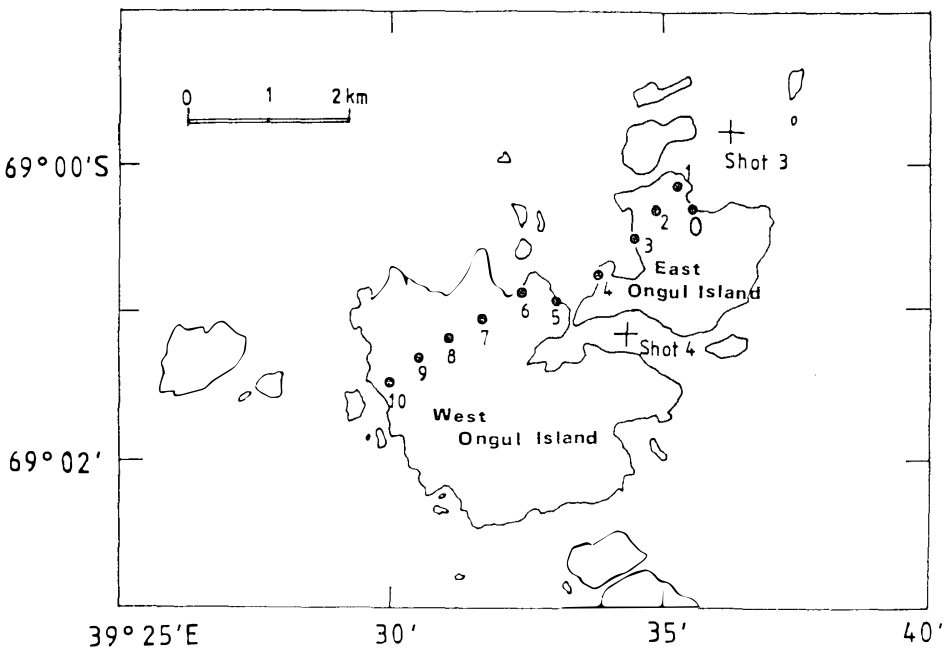

Fig. 1. Shot and observation points for Shots 3 and 4 in the Ongul Islands.

1980. Shot 4, 80 kg in charge size was fired at the bottom of the sea under the shore sea ice at a depth of about 50 m near the middle point of the line on May 22. The profile became shorter than previously planned and was only partially reversed, because of the breakup of the sea ice and the rough weather condition.

Eleven stations were provided on outcrops on East and West Ongul Islands at intervals of about 0.5 km. A vertical seismometer with a natural frequency of 2 Hz was set up at each station except at No. 0 station and signals from the seismometer were recorded by a direct analogue data-recorder with four channels. The output from the seismometer was recorded on three channels with different amplification to cover a wide dynamic range of 70 to 80 db. The time-code from a crystal oscillator equipped in the recorder was fed to the fourth channel. The electric power for the recording apparatus was supplied with a battery of 12 V. The recorder and the battery were kept warm with an electric panel-heater attached to the recorder in an insulated box. The electric power for the heater was also supplied from the same battery. At No. 0 station four seismometers of the same type were used. Three of the four were set in drill holes in shore sea ice at depths of 1, 2 and 3 m and one on the rock for a comparison of observation conditions. The signals were led to four recorders of the same type, and microtremors of blizzard as well as explosion seismic waves recorded at various depths were compared with each other to examine the S/N ratio in the drill hole. The crystal time-code generator at each station was calibrated

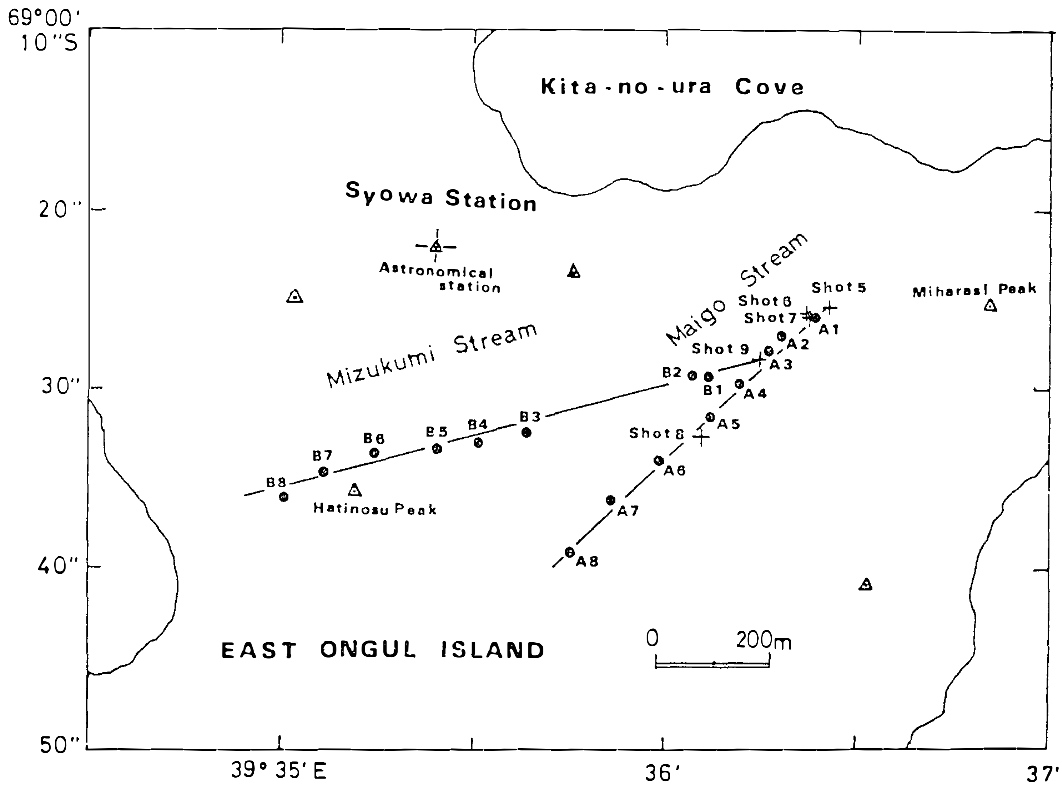

Fig. 2. Shot and observation points on East Ongul Island. A1 to A8 are observation points for Shots 5 to 8 and B1 to B8 for Shot 9. Triangles with a dot indicate triangulation stations. Cross mark at the astronomical station is taken as the origin of the coordinates.

with a master clock before and after the two explosions and the time accuracy was eventually kept within 0.01 s. The observation points were positioned on a map with a scale of 1:5000 and shot points at the sea were surveyed with a transit and the map. Ten to fifteen members of the wintering party were engaged in the experiment and it took 25 days from May 5 to June 8, 1980.

Experiment-III was made at the Maigo and the Mizukumi Streams on East Ongul Island. Shot and observation points are given in Fig. 2. Explosions were made to examine the effects of dynamite in outcrops on the island for the construction of an aircraft runway. The amount of explosives was 0.1 to 0.7 kg, much smaller than that for Shots 3 and 4. Observation sites were set up on the rocks within 1 km from the shot points along two lines which were much shorter than that of experiment-II. This is useful to reveal the very shallow structure of the island. By the combination of experiments-II and -III, therefore, we can derive a structure of the ice-free area from shallow to very shallow parts of the crust. Shots 5 to 8 were observed at eight sites, A1–A8 (A-profile), and Shot 9 at B1–B8 (B-profile). The direction of the B-profile differed from the A-profile by 30° and was a little longer than the A-profile. As shown in Fig. 2 reverse shots were partially made on the A-profile but not on the B-profile. The same seismometers in experiment-II were used again in the experiment, their outputs were connected to FM data recorders on snow-vehicles in order to keep time signals as accurate as 0.002 s. Signals from the seismometer were so amplified that clear onsets of the explosion signal could be recorded. Therefore, most of later signals had been clipped off on recording.

The experiments were carried out by ten to twelve persons for two days. Shot and observation points were located by a plane-table surveying on a map of 1:2000 with an accuracy of 10 m. It took two more days.

3. Data Analyses and Results

The recorded signals of Shots 3 and 4 from the direct analogue recorders were reproduced with a speed of 400 times the recording one. The reproduced signal was sought and displayed on a digital-oscillograph, then stored on a mini-floppy disk attached to it, and finally plotted on an X-Y recorder with a low speed. Then seismograms were arranged in the form of record sections at a reduction velocity of 6 km/s, which were shown in Figs. 3 and 4. The first arrivals were as clear as the later ones. The arrival times were picked up with the digital-oscillograph. The resultant travel-time graphs are shown in Fig. 5 for Shots 3 and 4.

The magnetic tapes recorded for Shots 5 to 9 with FM-recorders were reproduced with the same speed as that of recording. The procedure of data analyses was the same as mentioned above. Later arrivals if any were picked by finding frequency changes in wave forms, because most of seismograms were clipped off for Shots 5 to 9 on recording. The obtained travel-time graphs for experiment-III are shown in Fig. 6.

Two phases were plotted on Figs. 5 and 6. One is a first arrival with an apparent velocity of approximately 6 km/s and another is a later arrival with an apparent velocity of approximately 3 km/s. As the intercept times of the travel times of the first arrivals are nearly zero as shown in Figs. 5 and 6, the phases are considered to be direct waves. Therefore, the apparent velocity and the average velocity, D/T, can be

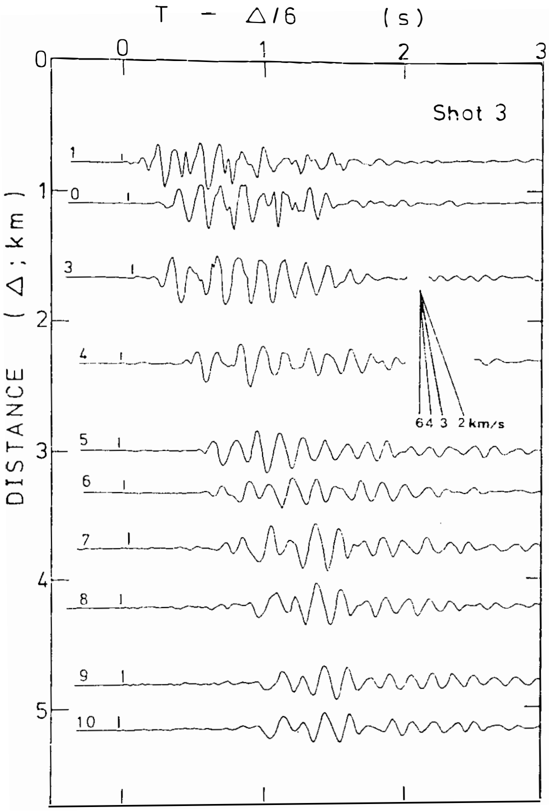

Fig. 3. Record section for Shot 3.

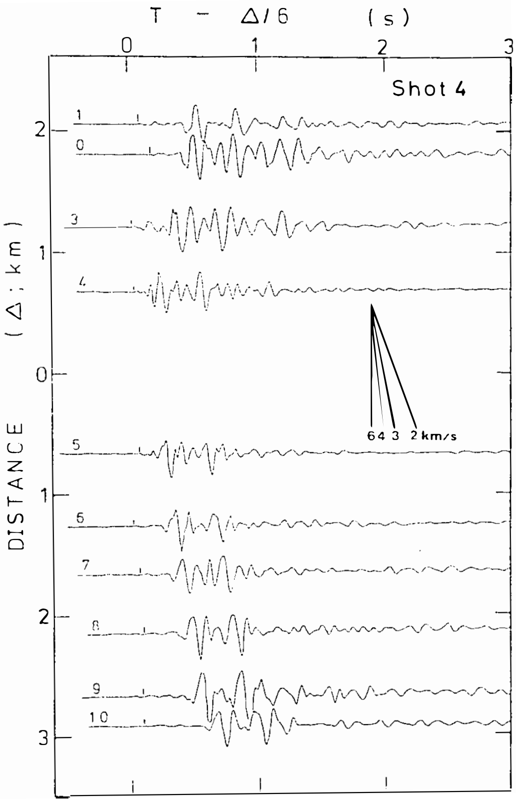

Fig. 4. Record section for Shot 4.

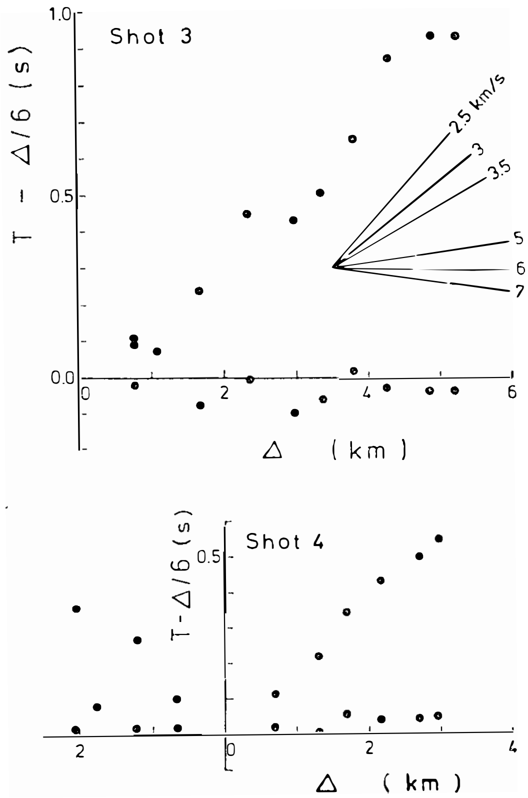

Fig. 5. Travel-time graphs for Shots 3 and 4.

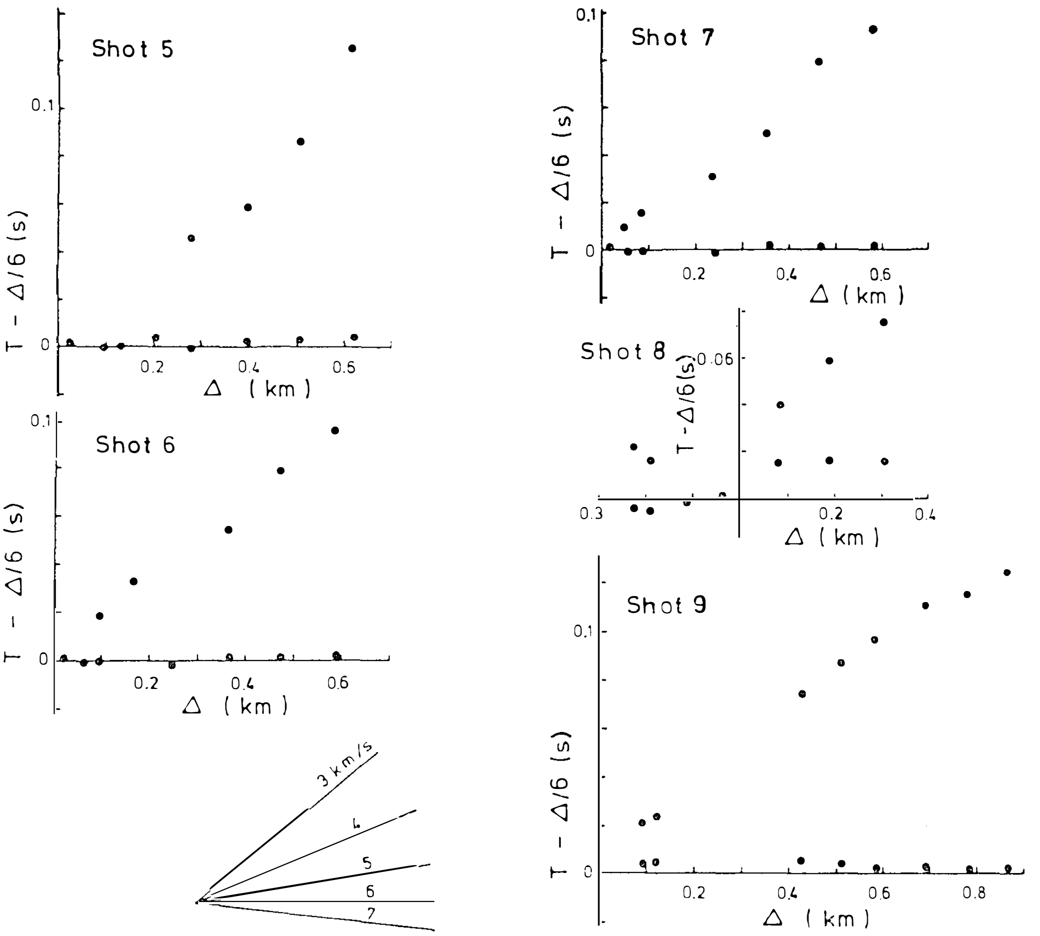

Fig. 6. Travel-time graphs for Shots 5 to 9.

Table 1. Apparent velocity, average velocity and velocity ratio for the first and the later arrivals for Shots 3 to 9. AV_1 and V_1 indicate the apparent velocity and the average velocity for the first arrivals, respectively, and AV_2 and V_2, for the later arrivals. Lower three lines shows the results for combined data, for example 3 to 9 indicate that all data for Shots 3 to 9 are used for the velocity determination.

No. of Shot	Apparent velocity			Average velocity			Total of T_1	Total of T_2
	AV_1 (km/s)	AV_2 (km/s)	AV_1/AV_2	V_1 (km/s)	V_2 (km/s)	V_1/V_2		
3	6.28	2.64	2.38	6.44	2.94	2.19	10	8
4	5.55	2.80	1.99	5.34	2.87	1.86	10	9
5	5.81	2.94	1.98	5.60	3.03	1.85	8	4
6	5.85	3.02	1.94	5.92	3.01	1.96	7	5
7	5.85	2.98	1.97	5.89	3.04	1.94	7	6
8	5.28	3.40	1.55	5.33	2.76	1.93	7	5
9	6.10	3.26	1.87	5.55	2.95	1.88	8	8
3 to 4	6.53	2.81	2.32	5.89	2.90	2.03	20	17
5 to 9	5.93	3.18	1.86	5.65	2.96	1.91	37	28
3 to 9	6.17	2.84	2.17	5.74	2.94	1.95	57	45

regarded as the true velocity in the area, where D is a shot-detector distance and T is a travel time. In order to determine the velocity, the apparent velocity was calculated by a method of least squares for each shot and for some combinations of shots and listed in Table 1. The average velocity was also calculated and listed in Table 1. The agreement is not good with each other even if the error is taken into consideration. This indicates that the velocity varies from place to place or with depth. To see the velocity variation with depth, the average velocity for each station is plotted against a distance from shot for the first and later arrivals in the lower two figures of Fig. 7. In the upper two figures of Fig. 7, the reduced travel times with reduction velocities of 6.0 and 3.0 km/s are also indicated. As shown in Fig. 7 the scatter of average velocities is large at short distances less than 0.5 km, though the scatter of the travel time is small. Most of data at short distances are from Shots 5 to 9 and the large error of the average velocity is caused by the error of the travel time at short distances. Therefore, the apparent velocity is more reliable than the average velocity for Shots 5 to 9.

The apparent velocity of the first arrivals averaged for all travel time data (V_1) is 6.17 ± 0.11 km/s and that of the later arrivals (V_2), 2.84 ± 0.03 km/s, though the former varies from 5.55 to 6.28 km/s and the latter from 2.64 to 3.26 km/s, except for Shot 8. The travel times of Shot 8 to the southwest show 0.015 s delay compared with those to the northeast direction (Fig. 6), and the averaged apparent velocity for P-wave is very small. The averaged ratio V_1/V_2 is obtained as 2.32 for Shots 3 and 4, 1.86 for Shots 5 to 9, and 2.17 for all data.

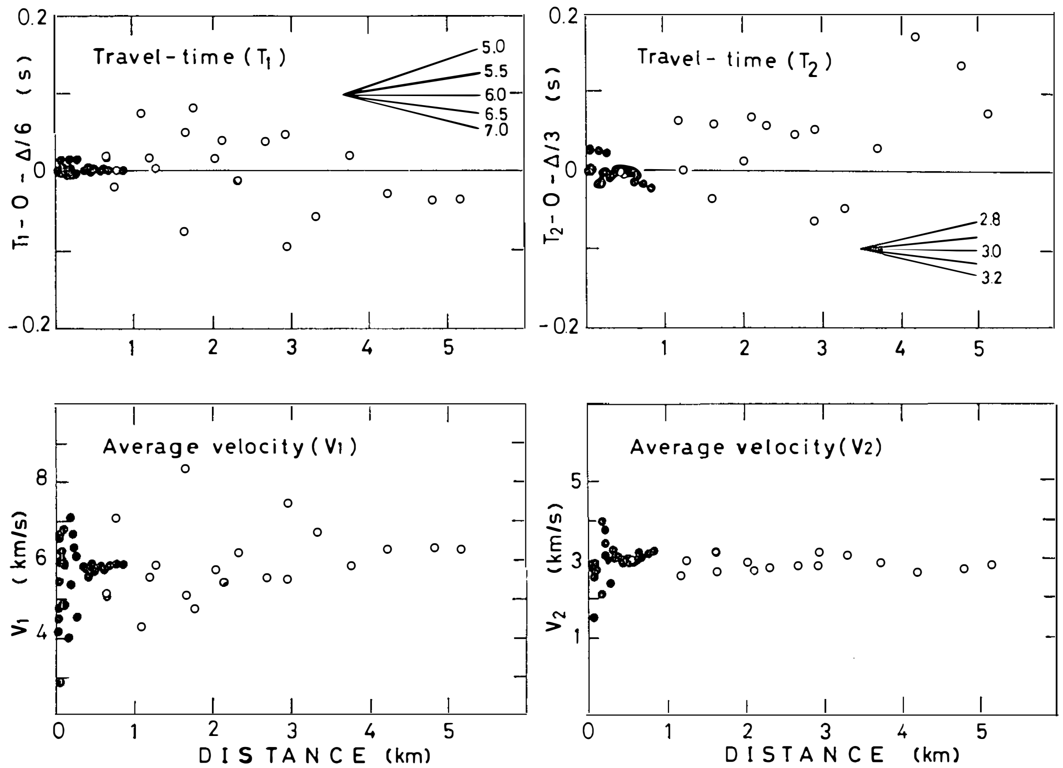

Fig. 7. Reduced travel-time graph of the first arrivals (T_1) and the later arrivals (T_2) (upper figure) and the average velocity (lower figure). Open circle indicates travel time for Shots 3 and 4 and solid circle indicates that for Shots 5 to 9.

4. Discussion

Figure 7 shows that the average velocity does not seem to increase with distance, though the scatter is large at short distances. That is, the velocity gradient with depth is not large enough to be detected in a shallow part of the surveyed area. The variation of velocity from 5.4 to 6.2 km/s, as indicated in Table 1, however, is not small. This is partly due to the observation error and partly due to heterogeneous velocity distribution from place to place or to anisotropic propagation of waves. BENTLEY (1973) suggested the velocity increases with depth in Antarctica and IKAMI *et al.* (1983) also presented a similar evidence supporting existence of a velocity gradient with depth in East Antarctica. So, the velocity increase may occur at deeper parts of the crust. Our measuring line is too short to detect the velocity gradient.

P-wave velocities in ice-free areas hitherto obtained in Antarctica are as follows: CRARY (1963) reported the results of the United States Traverse in Antarctica, in which he reported two explosion seismic profiles near the Skelton Glacier in Victoria Land, where the ice sheet is as thin as 10 m or less and the basement velocities are directly identified as 5.7 and 6.7 km/s. BENTLEY and CLOUGH (1972) summarized subglacial velocities from explosion seismic experiments in Antarctica. Their results and the up-to-date results by USSR and Japan (KOGAN, 1972; KURININ and GRIKUROV, 1982; IKAMI *et al.*, 1983) are illustrated in Fig. 8. Since most of the results were obtained from unreversed profiles, the velocity of the basement complex bears some inaccuracy. In East Antarctica the *P*-wave velocities of the underlying basement are 5.7 to 6.4 km/

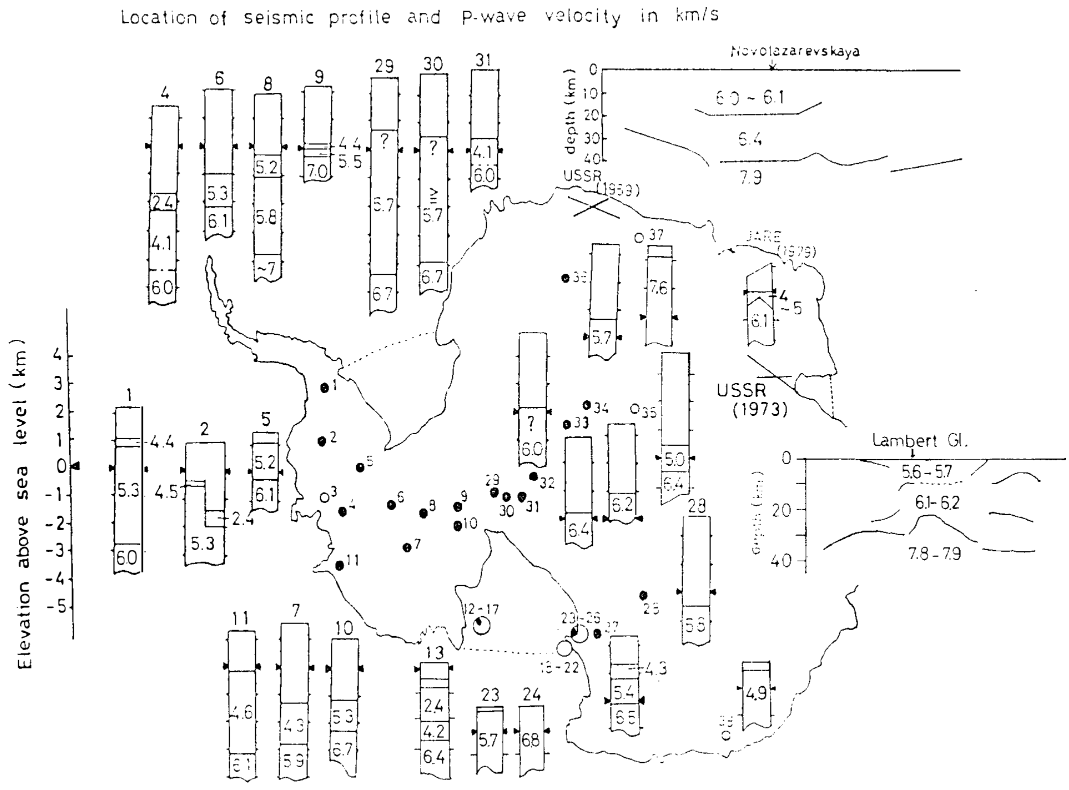

Fig. 8. Summary of the crustal structure derived for explosion seismic experiments in Antarctica.

s, which coincide with the result of this study. According to BENTLEY and CLOUGH (1972), in East Antarctica the surface layer is no more than 0.5 km, whereas sedimentary layers with velocities of 4.5 to 5.5 km/s overlie the basement complex at depths from 1 to 5 km in West Antarctica. As for the surveyed area in this study, intercept times are nearly zero as shown in Figs. 5 and 6, that is, no surface layer with a velocity less than 5.5 km/s is found.

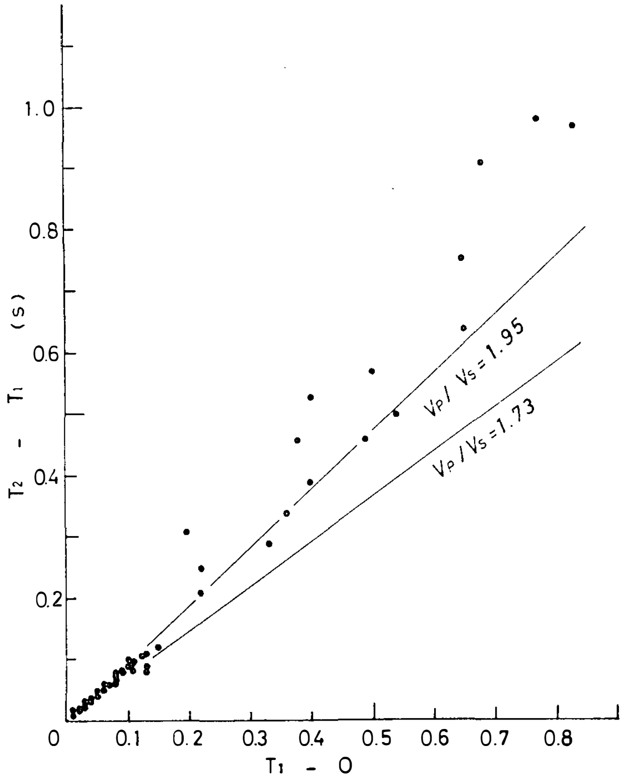

Fig. 9. T_2-T_1 vs. T_1-O, where T_1 and T_2 are travel times of the first and the later arrivals, respectively, and O is a shot time. If the later arrival is an S-wave and a Poisson's ratio of the medium is constant, a straight line passing through the origin can be fit to the plots. Two lines are illustrated for V_P/V_S=1.95 and 1.73.

It is not obvious whether the later arrival is an S-wave or not, because only the vertical seismometers were used. In Fig. 9 the travel-time difference between the first and later arrivals is plotted against its first arrival as it is usually used for the origin-time determination of earthquakes. If the later arrival is an S-wave and the Poisson's ratio is constant, the time difference is proportional to the travel time of the first arrival and the gradient of the line is easily converted into a V_1/V_2 ratio and to a Poisson's ratio. The average value of V_1/V_2 derived from apparent velocities is 2.17, which corresponds to a Poisson's ratio of 0.365. The value is markedly larger than those determined in other regions such as in Japan. As the P-wave velocity (V_1) is close to that obtained in Japan where V_p/V_s is around 1.73, V_2 seems to be 90% of the S-wave velocity. Therefore, the later arrival seems to be a Rayleigh wave.

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