DEEP CRUSTAL STRUCTURE ALONG THE PROFILE BETWEEN SYOWA AND MIZUHO STATIONS, EAST ANTARCTICA

Akira IKAMI,

Regional Center for Earthquake Prediction Observation, School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464

Kiyoshi ITO,

Regional Observation Center for Earthquake Prediction, Faculty of Science, Kyoto University, 944, Nasahara, Takatsuki 569

Kazuo SHIBUYA and Katsutada KAMINUMA

National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173

***Abstract*:** Three big seismic explosion experiments were carried out by the 21st and 22nd Japanese Antarctic Research Expeditions in the vicinity of Syowa Station and in the northern Mizuho Plateau in East Antarctica. Twenty-seven temporal seismic observation stations were set up along a 300-km long profile from Syowa to Mizuho Stations. Explosives were fired near Syowa Station, near Mizuho Station and at the middle point of the profile.

The apparent *P*-wave velocity in the upper crust varies from 6.0 to 6.4 km/s, suggesting a gradual increase of the *P*-wave velocity with depth. Apparent velocities of 6.9 km/s for P^* and 7.9 km/s for P_n were observed from the biggest shot near Syowa Station. From the analyses of travel times and an amplitude study by synthetic seismograms, the crustal structure of the northern Mizuho Plateau was determined. The depth of the Conrad and the Moho discontinuities was determined as about 30 km and 40 km, respectively. The *P*-wave velocity increases from 6.0 km/s on the surface to 6.4 km/s at a depth of 13 km. At the Conrad, there is no sharp velocity discontinuity. The thickness of the transition zone is 2.4 km. Comparing our results with those in Dronning Maud Land (in the vicinity of Novolazarevskaya Station of USSR), East Antarctica, velocity values are nearly the same, but the thickness of lower crust in the northern Mizuho Plateau is about a half of that in Dronning Maud Land.

1. Introduction

In the past thirty years, the crustal and the upper mantle structures in Antarctica have been studied by many researchers. BENTLEY and CLOUGH (1972) compiled many seismic refraction profiles, which provided information about seismic velocities beneath the ice sheet.

In East Antarctica, a few data on the seismic wave velocity distribution in the crust have been available. The Soviet Antarctic Research Expeditions carried out three deep seismic sounding experiments in 1969, 1973 and 1979. In these experiments, P_n waves and several intracrustal reflection waves were successfully recorded and the crustal structures to the Moho could be determined (KOGAN, 1972; KURININ and GRIKUROV, 1982). In 1980, the 21st Japanese Antarctic Research Expedition

(JARE-21) conducted explosion seismic experiments for the investigation on the velocity structure of the ice-free area of East Antarctica and the resultant structure of the upper crust was discussed by ITO *et al.* (1984).

After the several small scale experiments, JARE-21 conducted two big explosion experiments on the Mizuho Plateau in late 1980, and the biggest explosive in the sea near Syowa Station was fired in cooperation with JARE-22 in January 1981. In this experiment, head waves were clearly recorded at all stations and reflected waves were also detected at several stations. Analyzing these travel-time data and comparing the observed seismograms with the synthetic ones, seismic velocity distribution in the crust along the profile between Mizuho and Syowa Stations, East Antarctica, was determined.

2. Description of Experiments

The circumstantial account of the experiments was reported by IKAMI *et al.* (1983), so its outline is given in this paper. The observations were made at 27 points along a 300-km long profile from Syowa to Mizuho Stations. Explosives were fired in ice holes near Mizuho Station (Shot 17) and at the middle point of the profile (Shot 18), and at the sea bottom near Syowa Station (Shot 19). Figure 1 shows the locations of shot and observation points in these experiments. An NNSS (Navy Navigation Satellite System) receiver was employed to determine the locations and to calibrate the clock at each observation station. The accuracies of determination of locations and of a time-correction using an NNSS receiver were tested at the astronomical control point in Syowa Station, East Antarctica (SHIBUYA *et al.*, 1982; SHIBUYA and KAMINUMA, 1982).

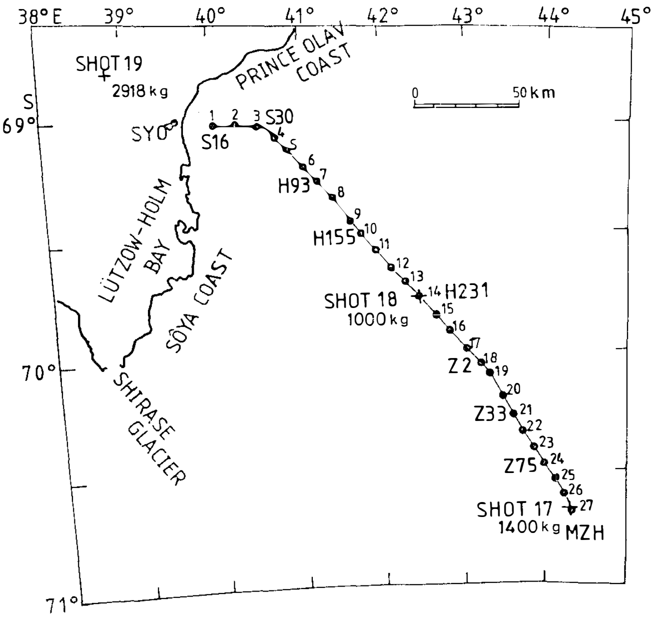

Fig. 1. Locations of shot points and observation stations. SYO and MZH indicate the positions of Syowa and Mizuho Stations, respectively. Solid circles are observation stations. All stations are set along the traveling route between Syowa and Mizuho Stations. Some of the guide-point's names, such as S16, S30, H93 and so on, are shown.

In the field operations, we adopted direct analogue data recorders, which were designed to work continuously for 26 days with a tape-driving speed of 0.2375 mm/s. The frequency response is flat from 0.1 to 20 Hz. The signal from a seismometer was fed to three amplifiers with different magnifications to improve a dynamic range and recorded on three channels on magnetic tape. Time signal from a quartz oscillator was recorded on the fourth channel. Reproduction of the signals was carried out with a tape-speed of 200 or 400 times faster than that of recording. Each seismic explosion signal was stored on a mini-floppy diskette (less than 0.01 s sampling interval) and then the onset time and amplitude of each phase were read on the display of digital oscilloscope. A hard copy of the signal was made at the same time for preparing a record section.

3. Results

3.1. Record section

In experimemts for Shots 17 and 18, clear seismograms could be recorded only at a few observation stations because of unlooked-for troubles. In Shot 19, however, high-quality seismograms could be obtained at all stations as shown in Fig. 2. The time axis of each seismogram is shifted by $\Delta/6$, where Δ is the shot distance in km. The amplitude scale in each seismogram in Fig. 2 is arbitrary.

3.2. Travel-time analysis

In Fig. 3, the travel-time plots for Shots 17, 18 and 19 are shown. In order to determine the crustal structure, we must estimate the travel times within the ice sheet. The thickness of the ice sheet along the profile from Syowa to Mizuho Stations was not fully determined (WADA *et al.*, 1981). Therefore, referring to the results by SHIMIZU *et al.* (1972), BENTLEY (1973) and WADA *et al.* (1981), it was assumed that the altitude of the basement was equal to the sea level. A *P*-wave velocity structure in the ice sheet was assumed to be increasing with depth (from 1.4 km/s at the surface to 4.0 km/s at the bottom). With these assumptions, we calculated time terms and offset distances due to the ice sheet, and then the travel-time curves. The results by JARE-20 (IKAMI *et al.*, 1980) and small explosion experiments by JARE-21 (ITO *et al.*, 1984; ITO and IKAMI, 1984) show the apparent velocity of initial arrivals with about 6.0 km/s near the shot point, and the intercept time to be nearly equal to zero. This means that the sedimentary layer is very thin if it exists.

In Fig. 3, the gradual increase of the apparent velocity of the upper crust with shot distance can be recognized. Data obtained by Shots 17 and 18 provide reversed recordings on the southern half of the profile and show an averaged apparent velocity of 6.3 km/s. To determine the crustal structure from the travel-time data, the velocities of P^* and P_n were assumed to be from 6.8 to 6.9 km/s and from 7.9 to 8.0 km/s. In Fig. 4, the resultant crustal structure is shown. There remains ambiguities of the Conrad and the Moho discontinuities as shown in hatched area. In this figure, topography of ice sheet (YOSHIDA and YOSHIMURA, 1972), free-air gravity anomaly (SHIMIZU *et al.*, 1972) and geomagnetic anomaly (SHIBUYA *et al.*, 1984) are also shown. Considering apparent velocities of 6.0 km/s near the shot points determined by IKAMI *et al.* (1980), ITO and IKAMI (1984) and ITO *et al.* (1984), we had better presume a gradual

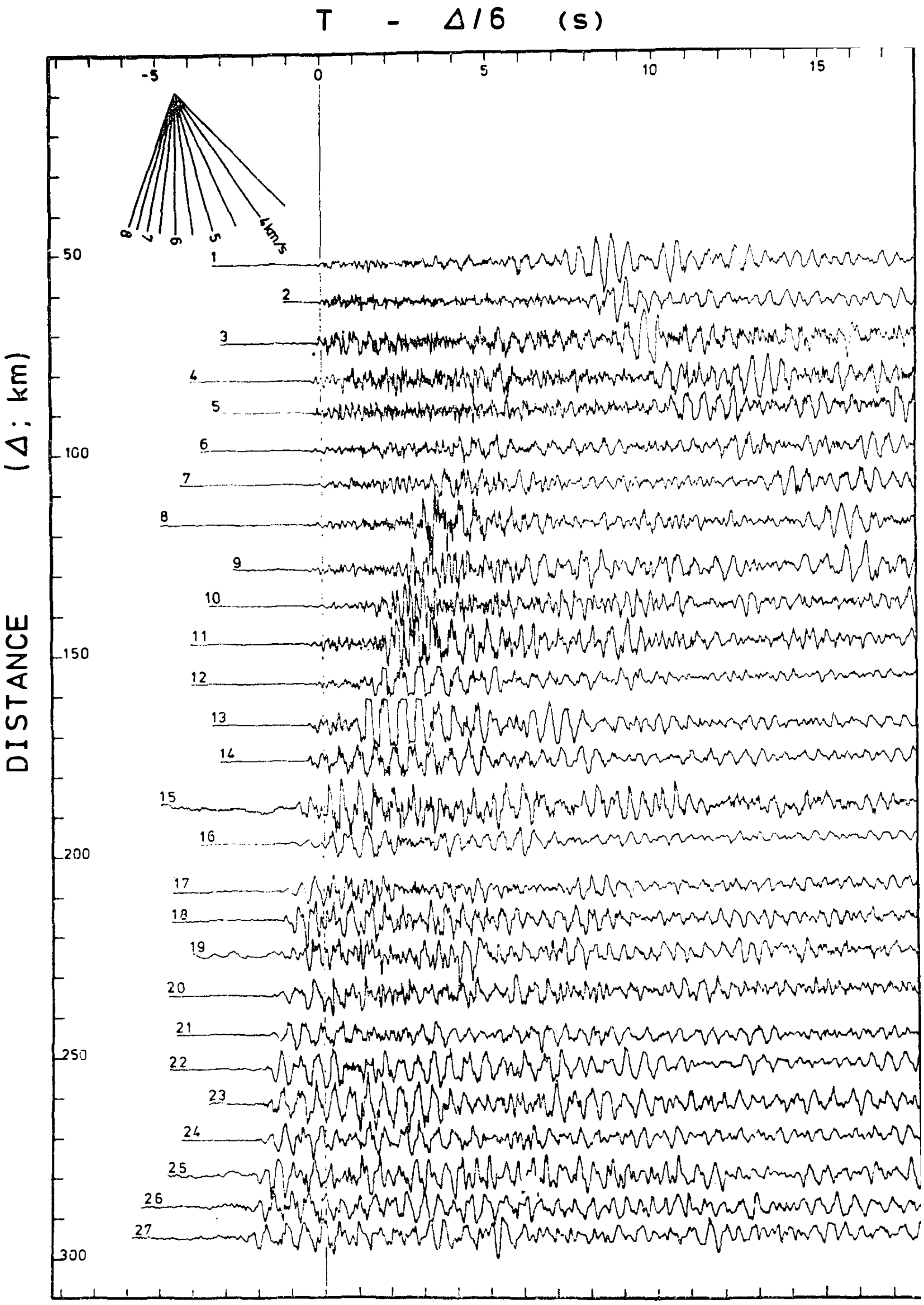

Fig. 2. Record section of Shot 19. Clear later phases can be traced from a station to adjoining stations. Time axis is reduced by a velocity of 6 km/s. Normalization by the maximum amplitude in each trace causes the difficulty in identifying P_n-phase in this record section.

increase of P-wave velocity with depth in the upper crustal layer. The existence of a downward velocity gradient in the upper layer was already pointed out by KOGAN (1972), who found that in the upper 15 km of the crust there was a gradual downward increase in P-wave velocity from 6.0 to 6.3 km/s.

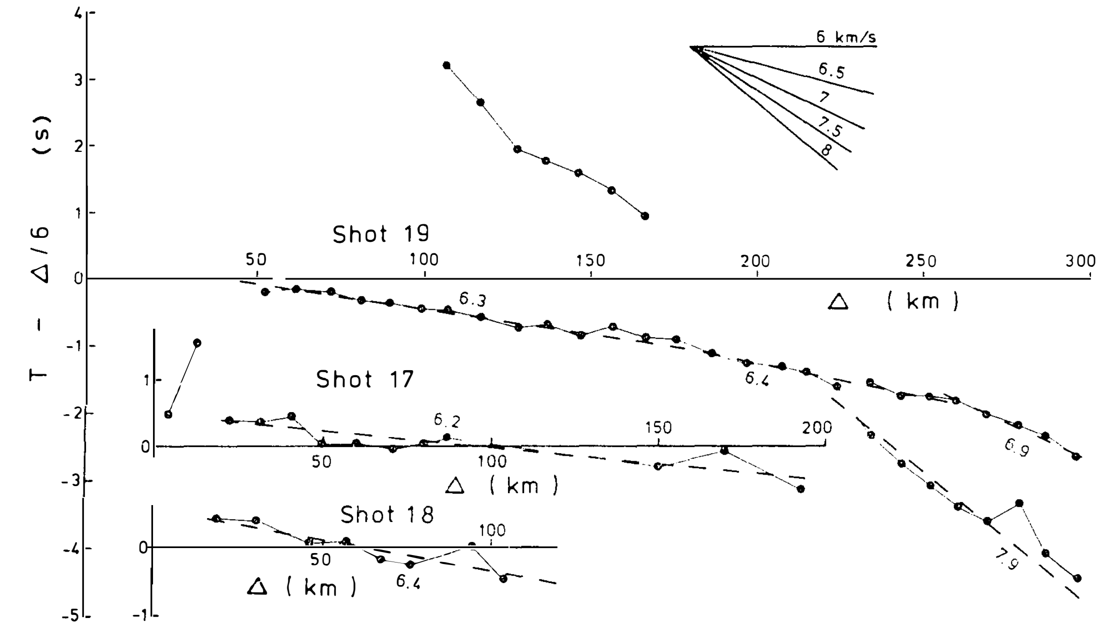

Fig. 3. Travel-time plots of Shots 17, 18 and 19. Travel-time in ice sheet and its offset distance are corrected. Numerals attached to the travel-time curves indicate apparent velocities (km/s).

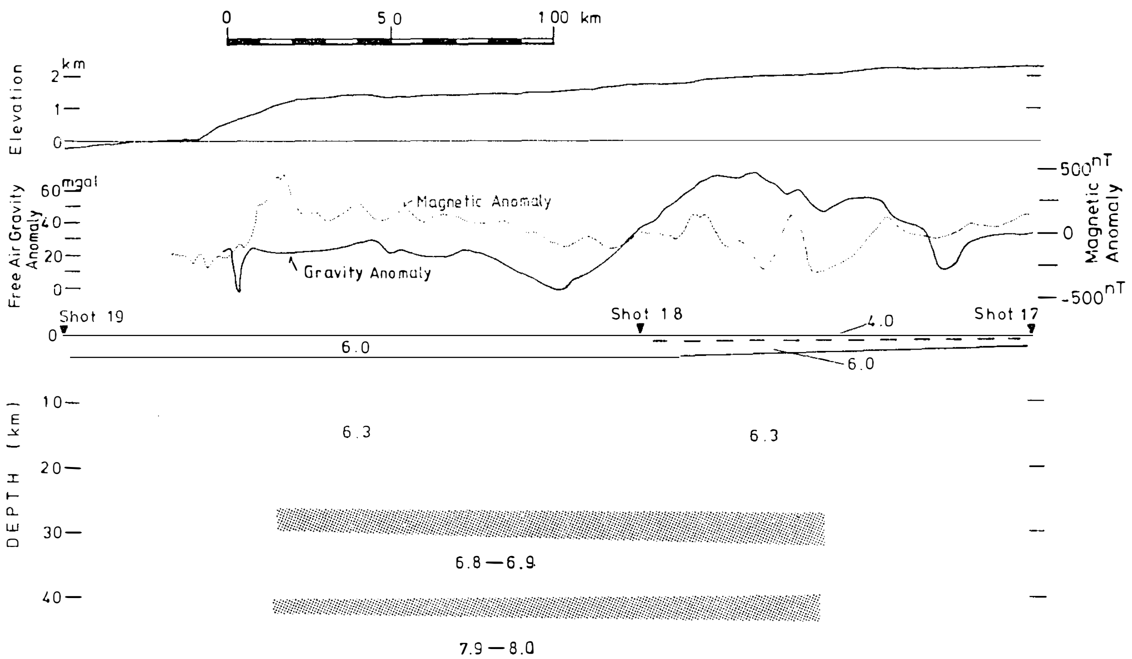

Fig. 4. The crustal structure along the traverse route determined from travel-time data. Numerals in layers are P-wave velocities in km/s. Topography of ice sheet, free air gravity anomaly and geomagnetic anomaly are after SHIMIZU et al. (1972), YOSHIDA and YOSHIMURA (1972) and SHIBUYA et al. (1984), respectively.

There are no arrival time data from the Conrad and the Moho discontinuities except for those from Shot 19, so true velocities beneath these discontinuities must be assumed. Supposing a flat layering model, the true velocities of P^* and P_n were set to be equal to the apparent velocities of 6.95 and 7.93 km/s, respectively. The derived depth of the Conrad is about 30 km and the Moho depth about 40 km. KOGAN (1972) showed 6.7 km/s for the averaged velocity beneath the Conrad and a 30-km thick upper crustal layer, and the Moho depth is about 40 km and 7.9 km/s for P_n. KURININ and GRIKUROV (1982) determined 7.1 km/s for P^* and 7.7 km/s for P_n and the Conrad and the Moho depths were 10 and 30 to 33 km, respectively.

3.3. *Synthetic seismograms*

The crustal structure discussed in the above paragraph was derived from travel-time data, but no information on amplitude was taken into consideration. The inversion of travel-time data into a depth-velocity model is no longer valid to discuss the complicated crustal structure with transition zones. An observed seismogram has information on its source effect and the medium through which the wave propagates. The source effect on seismic waves generated by an explosion is common to the seismograms recorded at all stations, so dissimilar wave form at each station is conceivable to reflect the features of the medium along the ray path. In the past 20 years or more, many papers on the mathematical treatment of wave form have been presented and discussed the inhomogeneous crustal and upper mantle structures. The comparison of observed and synthesized seismograms can provide more detailed structures than those determined only by the inversion of travel-time data. In this paper, the numerical computation of synthetic seismograms by FUCHS (1968) is applied to the derivation of a detailed crustal structure.

Antarctica is a shield continent, and consequently the crustal structure may be simple, so it is adequate to assume a horizontally layered crustal structure. In Fig. 2, special attention can be paid to the later phases, which are reflected and refracted waves from the Conrad and the Moho discontinuities. In addition to this, the gradual increase of the apparent velocity from 6.0 to 6.4 km/s is also taken into consideration to calculate synthetic seismograms. Amplitude scale in Fig. 2 is normalized by the maximum amplitude of each trace to make a clear record section. Therefore, discussion on wave forms was focused only on the relative amplitude of each phase in a seismogram but not on the absolute one.

For the starting velocity model to compute synthesized seismograms, model A of the structure shown in Fig. 5 was constructed, which was derived from travel-time data. In this procedure, under the consideration of the gradual increase of the apparent velocity with a shot distance, a model with a downward increase of a P-wave velocity was constructed. In this model, the velocity discontinuities of the first order at the Conrad and the Moho were assumed. Synthetic seismograms for this model are shown in Fig. 6a. The phase from the Conrad is more distinctive than observed one. In the second model (model B in Fig. 5), a velocity increase without first-order discontinuity in the crust is considered. The resultant synthetic seismograms (Fig. 6b) show the clear initial phases and too fast initial phase arrivals. The third crustal model (model C in Fig. 5), has a 6.6 km/s layer with a thickness of 2 km above the Conrad. In this case, synthetic seismograms (Fig. 6c) are also clear phase from the Conrad. In the fourth model (model D in Fig. 5), the Conrad discontinuity is a narrow transitional zone with a steep velocity increase. In the fifth model (model E in Fig. 5), the rate

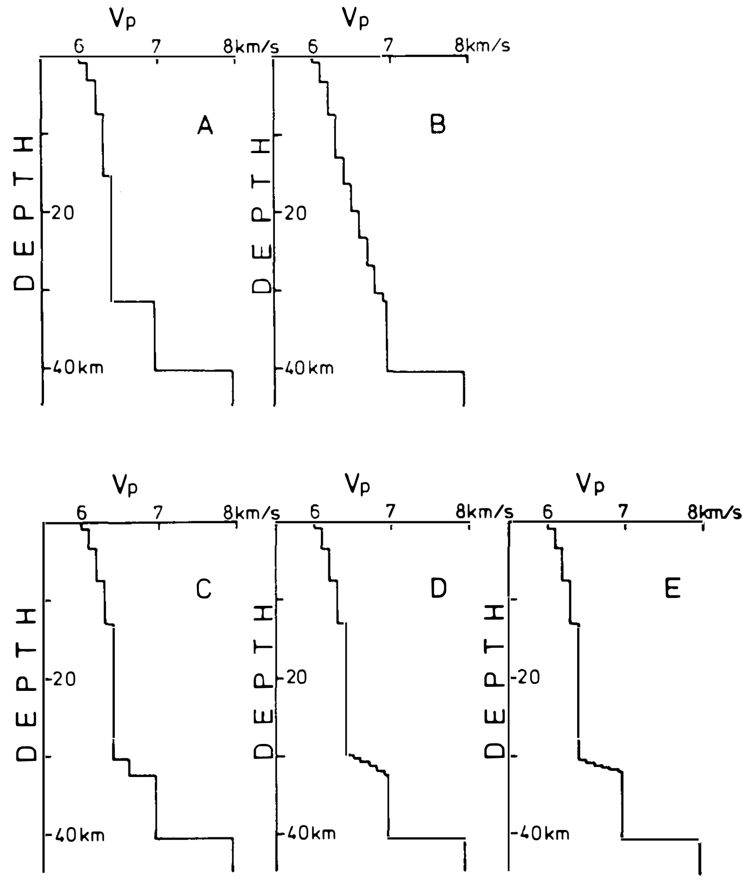

Fig. 5. Seismic velocity-depth relations, for which synthetic seismograms were calculated.

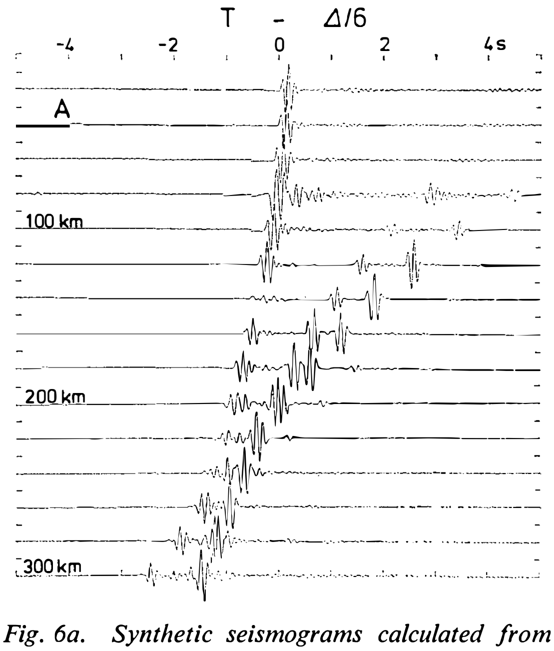

Fig. 6a. Synthetic seismograms calculated from model A in Fig. 5.

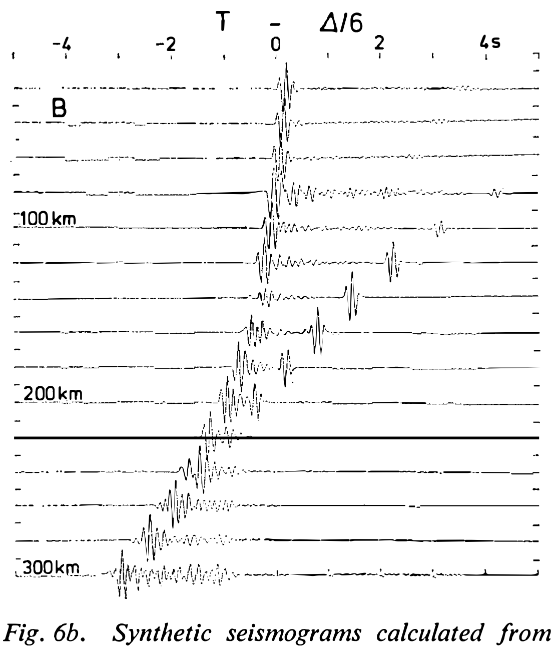

Fig. 6b. Synthetic seismograms calculated from model B in Fig. 5.

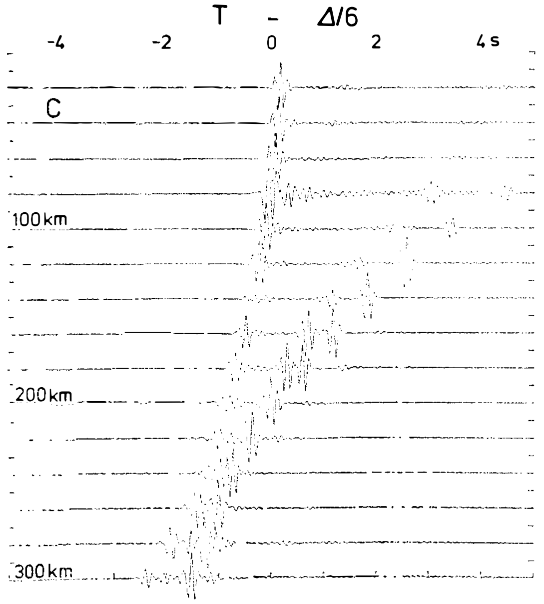

Fig. 6c. Synthetic seismograms calculated from model C in Fig. 5.

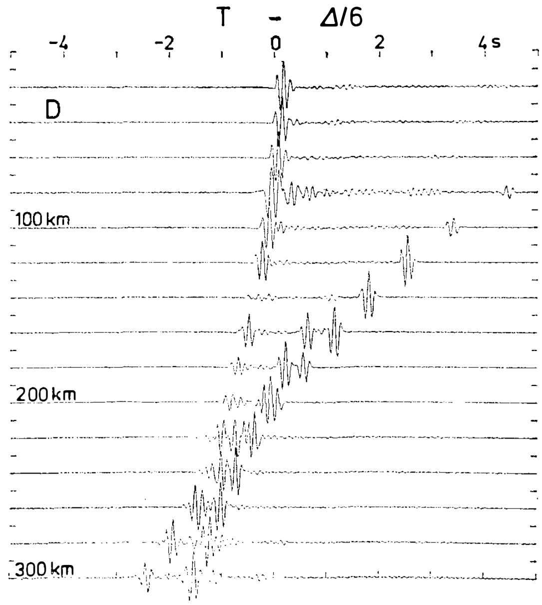

Fig. 6d. Synthetic seismograms calculated from model D in Fig. 5.

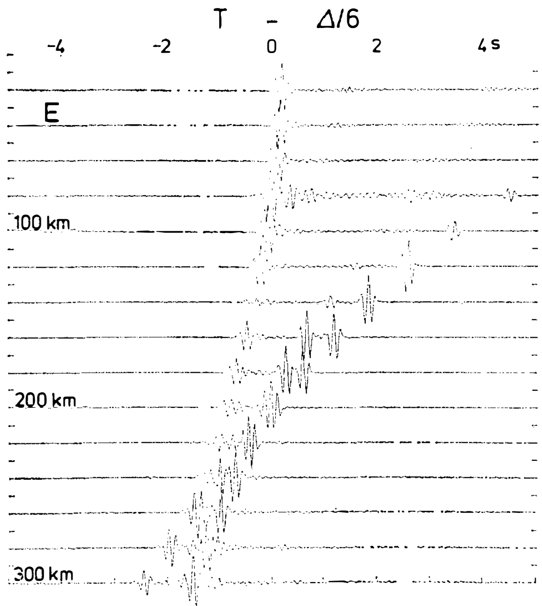

Fig. 6e. Synthetic seismograms calculated from model E in Fig. 5.

of the velocity increase is steeper than model D. Though synthesized and observed seismograms are not fully concordant with each other, model D might be the most likely model among the five models.

The resultant crustal structure has the following characteristics: (1) a gradually increasing velocity from 6.0 km/s on the surface to 6.4 km/s at the 13 km depth, (2) a constant velocity of 6.4 km/s from the 13 km depth to the Conrad, (3) a linear velocity increase of 0.55 km/s in the transitional zone of 2.4 km thick at the Conrad, (4) a constant velocity of 6.95 km/s in the lower crust, (5) a P_n-wave velocity of 7.93 km/s, and the Moho discontinuity at a depth of 40 km.

4. Discussion and Conclusion

Explosion seismic experiments carried out by JARE-21 and -22 could successfully reveal the crustal structure along the profile between Mizuho and Syowa Stations, East Antarctica. The investigated area, however, covers a very limited part of the huge Antarctic Continent. It is necessary to compare the result with those in other regions. More than 40 explosion seismic refraction profiles have been completed so far on the Antarctic ice sheet. Most of them have been carried out in West Antarctica, and the approximate upper crustal columns were determined. A summary of the profiles was presented by BENTLEY and CLOUGH (1972). The Soviet Antarctic Research Expeditions conducted three deep seismic soundings in 1969, 1973 and 1979 (KOGAN, 1972; KURININ and GRIKUROV, 1982; KADMINA *et al.*, 1983). Although no fundamental data such as record sections and travel-time curves were presented, the information on the crustal structure in the regions can be obtained only from their results.

Comparing our results with those by KOGAN (1972), the *P*-wave velocities in each layer are nearly the same. The depth to the Moho in the both models is also the same, 40 km deep, but the thickness of the lower crust is different from each other. The thickness of our derived model is a half of that of KOGAN's model. In the results by KURININ and GRIKUROV (1982), the more complicated structure was derived. In the area of their survey, there runs the big glacier (the Lambert Glacier) in the middle of the profile. So the results reflect the complicated structure and it may be meaningless to compare them with our results.

Synthetic seismograms were useful to refine the crustal structure in detail. In the present structure, there is a gradual downward increase of *P*-wave velocity from 6.0 km/s on the surface to 6.4 km/s at a depth of 13 km. Below this depth to the Conrad, the *P*-wave velocity may be constant. The Conrad discontinuity may be a transition zone with a thickness of 2.4 km. The thickness of the lower crust is about 10 km in our derived model. Seismic surface wave dispersion studies indicate a mean crustal thickness of about 30 km in West Antarctica and about 40 km in East Antarctica (EVISON *et al.*, 1960). Resultant crustal thickness is concordant with the results by surface wave studies.

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

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