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Crust and upper mantle structure in East Antarctica from phase velocity of Rayleigh wave

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Abstract: Phase velocities of Rayleigh waves in East Antarctica are accurately measured by using the two-station method in this study Rayleigh waves from the 16 May 1995 Loyalty Islands earthquake (23 05°S, 170 00°E, M_w 7 7) recorded at Dumont d'Urville (66 665°S, 140 010°E) and Syowa (69 009°S, 39 592°E) stations, Antarctica, are used The path runs through the central part of East Antarctica The measured phase velocities at periods shorter than 40 s are higher than those shown by a previous study in which the paths run through the western part of East Antarctica It is suggested that the seismic velocity in the crust beneath the central part of East Antarctica is faster or the crustal thickness is thinner than that beneath the western part A preliminary 1-D seismic structure model of the crust and uppermost mantle beneath East Antarctica is inferred from the measured phase velocities The velocity in the crust and the uppermost mantle is higher than the A-1 model and PREM, respectively

key words East Antarctica, crust, upper mantle, Rayleigh wave, phase velocity

1. Introduction

The Antarctic continent is divided by the Transantarctic Mountains into East and West Antarctica East Antarctica has a Precambrian shield that is stable, while the West Antarctic segment consists of several young geological or tectonic units that are rather mobile on a geological time-scale Antarctica is considered to play an important role in the tectonic history of Gondowanaland

The structure of Antarctica cannot be directly investigated because of the thick ice sheet (up to 4000 m) covering the continent, except for the coasts Seismological research is a useful way to investigate the Antarctic structure

Studies on the group and phase velocities of surface waves propagating in Antarctica have been carried out since the International Geophysical Year (IGY, 1957-1958) However, few long-period seismological stations had been established at an early stage of seismic observation in Antarctica Thus studies on seismic structure in Antarctica progressed less than those in other continents Recently, digital broadband seismic stations have increased, and we can readily measure the surface-wave velocities Previous studies on surface-wave velocities in Antarctica are reviewed in detail by Bentley (1991) and Roult and

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Rouland (1994).

Measurement techniques for surface-wave velocities can be classified into two groups, called the single- and two-station methods (*e.g.*, Lay and Wallace, 1995). The single-station method measures velocities between an epicenter and a station, and the two-station method measures those between two stations. While the single-station method requires a focal mechanism, uncertainties of which can cause errors in measurement, the two-station method does not. In addition, since few large earthquakes occur in and around the Antarctic continent (Kaminuma, 1994), the velocities measured by the single-station method, using earthquakes not located in and around Antarctica, are affected by the structures of the surrounding oceans. The two-station method presents more accurate surface-wave velocities in Antarctica when both stations are located there. Evison *et al.* (1960), Dewart and Toksöz (1965), and Singh (1994) measured group velocities in East Antarctica, the latter two papers presented the crust and upper mantle structure model. However, they adopted the single-station method.

In this study, we measure Rayleigh-wave phase velocities in East Antarctica by using the two-station method, and attempt to infer the crust and upper mantle structure from the measured velocities. Knopoff and Vane (1978) have already measured the phase velocities by the same method. However, the paths that they used run through the western part of East Antarctica and partly through the Transantarctic Mountains. We select the path connecting between Syowa and Dumont d'Urville stations, which runs through the central part of East Antarctica. The velocities that we measure are purely affected by the structure beneath East Antarctica.

2. Measurement of phase velocity

The phase velocity c at an angular frequency ω between stations 1 and 2 on a great-circle path of a surface wave are represented by

$$c(\omega)=\frac{x_1-x_2}{(t_1-t_2)+T[M-(1/2\pi)(\psi_1(\omega)-\psi_2(\omega))]},$$

where x is the epicentral distance, t is the start time of the time series, T is the period corresponding to ω, and ψ is the phase of the instrument-corrected seismogram (*e.g.*, Lay and Wallace, 1995). M is an integer, which arises from the periodicity of the harmonic function. M can be selected by the phase velocity at long periods consistent with globally averaged values, because less lateral heterogeneity in the deep structure causes less variation of phase velocities at long periods. M for short periods can be selected by smoothly connecting from phase velocities at longer periods to those at shorter periods.

The stations and earthquake that we used are shown in Fig. 1. The Rayleigh-wave data are recorded at Syowa (SYO, 69.009°S, 39.592°E) and Dumont d'Urville (DRV, 66.665°S, 140.010°E) stations, which have three-component broadband seismometers (STS-1). The great-circle path connecting these stations runs through the central part of East Antarctica and its length is 3766.4 km. The 16 May 1995 Loyalty Islands earthquake is used, because it is a large one located on this great circle. The earthquake parameters are taken from Dziewonski *et al.* (1996) (Table 1). The difference of azimuths from the earthquake to the stations is 0.4 degree.

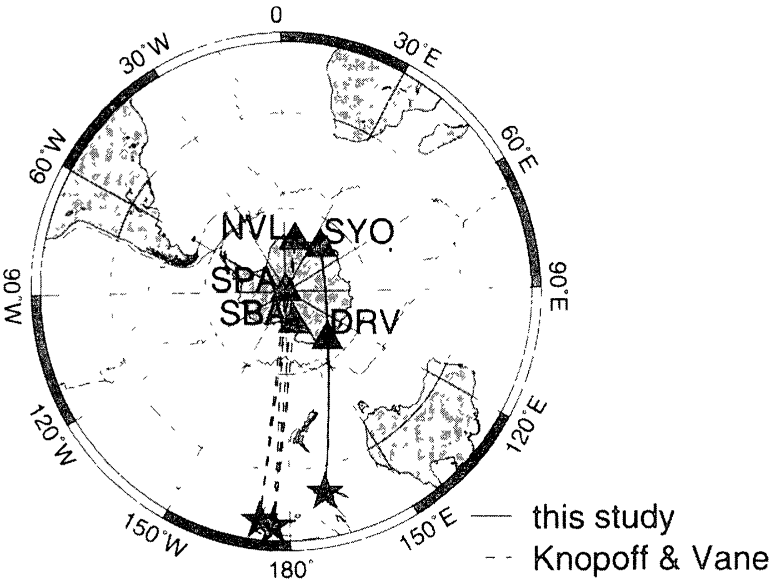

Fig 1 Stereo projection showing stations (triangles) and epicenters (stars) Solid and dashed thick lines represent the paths used in this study and by Knopoff and Vane (1978), respectively Plate boundaries are also plotted by thin lines

Table 1 Parameters of the 16 May 1995 Loyalty Islands earthquake

Date	1995/05/16
Origin Time	20 13 2 1
Location	23 05°S, 170 00°E
Depth	24 7 km
Magnitude	M_W 7 7
Azimuth	195 64° (DRV) 196 07° (SYO)

The sampling rates of the SYO and DRV data are 0 05 and 1 s, respectively Decimation of the SYO data with an anti-alias filter is done so that the sampling rate is 1 s

Figure 2 shows the dispersion curve of the phase velocities of the Rayleigh wave measured at periods 20 5–170 7 s The vertical components are used, because the radial components are possibly contaminated by the laterally refracted Love wave due to lateral heterogeneity along the path

The theoretical dispersion curve for the spherically symmetric Earth model PREM (Dziewonski and Anderson, 1981) shows that the measured velocities are lower than the theoretical one for PREM at periods shorter than 30 s, and are slightly higher at periods longer than 40 s This suggests that East Antarctica has a typical continental lithosphere

The phase velocities in the western part of East Antarctica obtained by Knopoff and Vane (1978) are also plotted in Fig 2 At periods shorter than 40 s, the velocities measured in this study are higher than those measured by Knopoff and Vane It is inferred that beneath the central part of East Antarctica the seismic velocity in the crust is

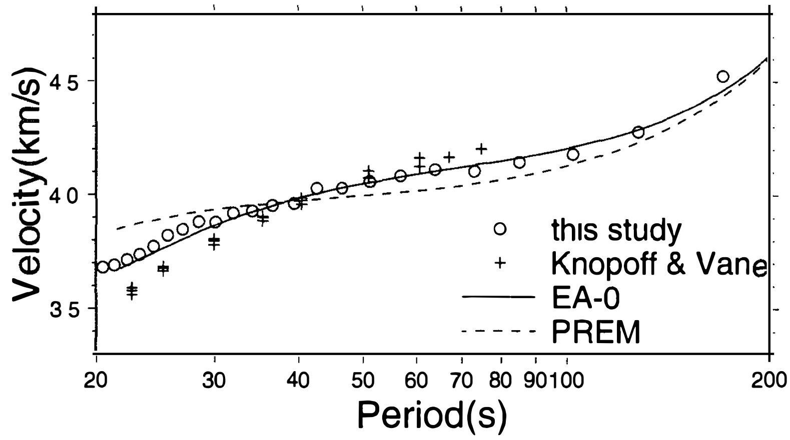

Fig 2 Rayleigh-wave phase velocities as a function of period Circles and crosses are the phase velocities measured in this study and by Knopoff and Vane (1978), respectively Solid and dashed lines are the dispersion curves calculated for the EA-0 and PREM models, respectively

higher or the crust thickness is thinner than those beneath the western part The ice sheet on the crust can also affect the surface-wave phase velocity at shorter periods However, the ice sheet in the central part is thicker than that in the western part which is near the Transantarctic Mountains, and thus the phase velocity in the central part should be slower than that in the western part This is inconsistent with our result

3. Forward modeling

We attempt to infer the isotropic 1-D seismic structure model of the crust and upper mantle beneath East Antarctica by using a trial and error method of comparison between the measured and theoretical phase velocities Our preliminary model EA-0 is based upon the East Antarctic model A-1 (Dewart and Toksöz, 1965) for the crust and upon the spherically symmetric Earth model PREM for the mantle (Table 2). The thicknesses of the ice sheet and crust are fixed as 3 and 39 km, respectively, which are considered to be average in East Antarctica (*e.g*, Dewart and Toksöz, 1965)

The velocities of the crust and uppermost mantle ($\leq$220 km) of EA-0 are estimated to be higher than those of the A-1 and PREM models, respectively (Fig 3). The structure below 220 km is the same as PREM The dispersion curve of the Rayleigh-wave phase velocities for EA-0 is shown in Fig 2 The dispersion curves for the 1-D models are calculated by using DISPER 80 (Saito, 1988) The curve for EA-0 can roughly explain the estimated phase velocities. However, some discrepancies exist in detail, especially at periods shorter than 30 s

4. Discussion

Some studies of seismic tomography focusing on Antarctica have presented the surface-wave phase velocity distribution beneath the Antarctic region (Rouland and Roult, 1992, Roult *et al*, 1994) Their studies shows the higher velocity anomaly in East Antarctica at periods longer than 70 s This is consistent with our result that the measured

Table 2 Parameters of the EA-0 model

Depth (km)	Density (g/cm³)	*Vp* (km/s)	*Vs* (km/s)
0 0	0 90	3 80	2 00
3 0	0 90	3 80	2 00
3 0	2 67	5 77	3 33
5 0	2 67	5 77	3 33
5 0	2 74	6 40	3 67
15 0	2 74	6 40	3 67
15 0	2 81	6 50	3 72
27 0	2 81	6 50	3 72
27 0	3 00	7 00	3 97
42 0	3 00	7 00	3 97
42 0	3 41	8 02	4 44
82 0	3 41	8 02	4 44
82 0	3 45	8 23	4 55
150 0	3 45	8 23	4 55
220 0	3 45	8 23	4 55

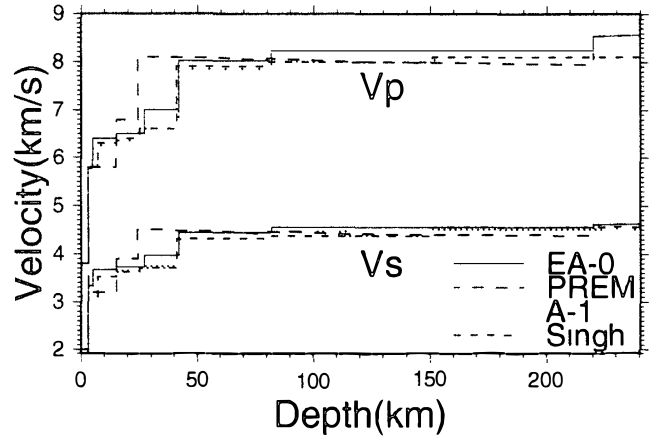

Fig 3 Comparison of four velocity-depth models

velocities at periods longer than 40 s are slightly higher than the theoretical one for the standard Earth model PREM

Ritzwoller *et al* (1999, unofficial report on WWW-site http //jspc-www colorado edu/geophysics/antarctica dir/antarctica_new html) presented the group velocity maps Their map for Rayleigh waves at the period of 20 s shows that the central part of East Antarctica has a higher velocity structure than the western part of East Antarctica and the Transantarctic Mountains This is consistent with our result that the phase velocities at shorter periods measured in this study are higher than those measured by Knopoff and Vane (1978) (Fig 1), although phase velocities cannot be directly compared with group velocities The crust beneath the western part of East Antarctica and the Transantarctic Mountains should be thicker or have slower phase velocities than those beneath the central part of East Antarctica

The velocities in the lower crust and uppermost mantle of our model are 0-7% higher than those of the previous studies (Dewart and Toksöz, 1965, Singh, 1994) which used group velocities and applied the single-station method. It is difficult to interpret the difference of the velocities in terms of geology and geophysics in East Antarctica, because the difference among the features in the areas focused on by the studies are less known The velocity difference is probably caused by the uncertainties of the velocity determination from the dispersion curve The structure inferred from group velocities is generally non-unique, because an unlimited number of structures can theoretically yield the same group velocity (Dewart and Toksöz, 1965) In addition, our preliminary model, which is not quantitatively inverted from the dispersion curve, is not robust, although phase velocities are used

In this study, the crust thickness of 39 km is fixed It is difficult to know at this stage whether the thickness or velocity of the crust causes higher surface-wave velocities at shorter periods In a second stage, more measurements of phase velocities from other large earthquakes and an inversion technique for modeling will provide us with a more reliable model

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