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Crust-mantle structure under South Pole and Ross Sea Beach in Antarctica

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Abstract A comparison of theoretical seismograms under discussion with four teleseismograms recorded by WWSSN of SBA (New Zealand) and SPA (U. S. A.), shows that the crustal thickness beneath South Pole is a double-layered structure, about 45 km; crustal thickness below the Ross Sea Beach, a single structure, is about 24 km; and at the depth of 350～450 km there exists a low velocity layer. The above results indicate the different tectonic characteristics on both sides of Antarctic Transantarctic Mountains.
Key words Antarctica, South Pole Station, Scott Base, crust-mantle structure.

1 Introduction

Because of the difficult natural conditions in the Antarctic area, researches on its deep crust and mantle structures started later. In 1959 some people, by using the surface wave data, determined the crustal thickness of East Antarctica to be 35 km, Marie Byrd Land of west Antarctica 25 km, Ross Sea 30～35 km and South Pole 48 km (Wei, 1986). In 1967, based on seismic and gravity data, former Russian scientists computed the crust thicknesses of East Antarctic center and the Transantarctic Mountains at 50 km and the edge of the continent at 20～25 km. In 1968 they carried on seismic profile tests (Wei, 1986) and in 1972, by using reflective method, they studied the crustal thickness in Queen Moud Land (Kogan, 1972). In 1982 they also made seismic tests across the Runber ice river on Enderby Land (Kurinin and Grikurov, 1982). From 1979 to 1981 a Japanese team made seismic profile tests in a section of 300 km between Syowa Station and Mizuho Station (Akira and Kiyoshi, 1986). In this paper we simulate antarctic crust-mantle structures by comparison of theoretical and observed deep teleseismic ($\Delta > 30°, h > 140$ km) earthquake waveforms. In this way, we may use records of single stations and don't consider time service system. In 1957 American Amundsen-Scott Station, or SPA, was built on Antarctic Pole. New Zealanders built on Ross Island a station named Scott Base, or SBA. They are part of WWSSN. In this paper we study the crust-mantle structure beneath the two stations according to waveforms's simulation and obtain the structure of nearly 1000 km below the two stations.

2 Data and method

The deep-teleseismograms used in this paper are earthquake films of WWSSN exchange which were later digitized. Earthquake parameters and station locations were listed in Table 1 and Fig. 1.

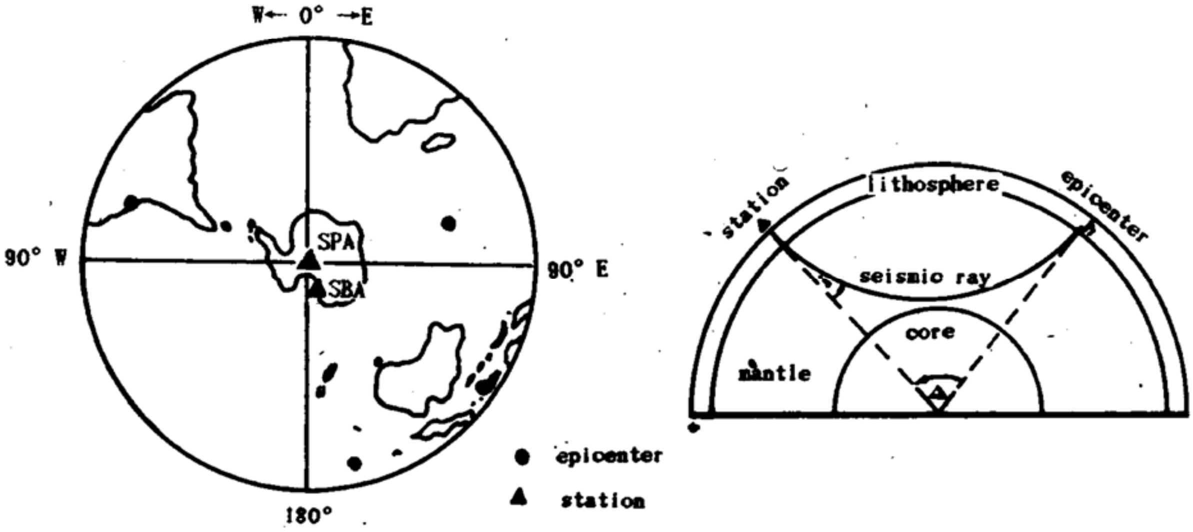


Fig. 1. Antarctic stations, epicenter and seismic ray. i — incident angle; Δ — epicenter distance; h — source depth.

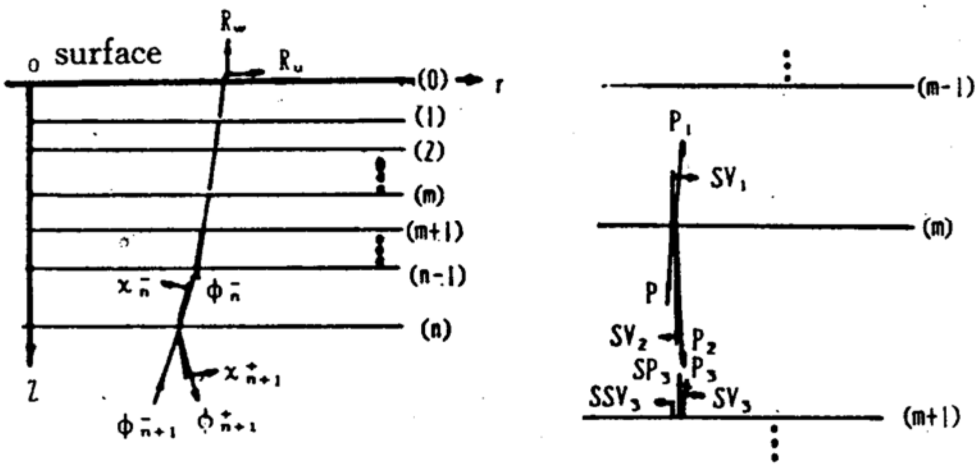
Table 1. Deep-teleseismic parameters observed by Antarctic SBA(77°51′S, 166°46′E, New Zealand) and SPA (90°S, U. S. A.) stations

Events	Year	Date	Time (h min s)	Longitude	Latitude	Depth (km)	Ms	Epicenter distance	Azimuth
SBA1	1988	Aug. 10	13-11-20. 2	167. 57°E	14. 86°S	144	6. 3	62. 99°	0. 88°NE
SBA2	1983	Nov. 24	05-30-37. 7	128. 60°E	7. 20°S	223	7. 2	73. 34°	320. 22°NE
SPA1	1987	Apr. 1	01-48-08. 3	66. 50°W	22. 40°S	223	6. 3	67. 60°	
SPA2	1988	Oct. 26	02-15-12. 4	70. 81°E	36. 99°S	223	6. 0	53. 01°	

Table 1 shows that the earthquakes under discussion in this paper are all of middle depth with the epicenter distance being above 5000 km. From the seismic ray in Fig. 1 we can find that the angle is so small that it nearly can be seen like the vertical incidence across medium below a station. If we regard the medium as a filter, the seismic waves, overlapping with the wavelets of multi-reflection and multi-conversion on the interface will show whole seismogram. The seismic ray brings us information of deep structure. A waveform recorded by seismic station may considered as three convolusion of source function, medium Green function and seismograph response (Li and Shu, 1982; Li *et al.*, 1983; Zhu and Li, 1985). Since the incident angle is very small, it reflects only a deep part of small area. During 4. 6 billion years of the earth's evolution, gravity separation has formed the earth's stratified structure. The wavelength of long period seismograph record is longer and doesn't express a inhomogeneity in semi-wavelength area. Therefore, we may describe medium model below a station by using paralled, isotropic and elastic layer.

A simplification of medium model helps us describe mathematically response of layer medium (Li and Shu, 1982; Li *et al.*, 1983). All wavelets of reflection, refraction and conversion on medium interface will be comprised in the overlapping theoretical seismogram.

In our simulation of long period waveform, we still select deep-teleseismograms because waveform of a deep source earthquake is relatively simple and can avoid the complexity of a source function caused by strong reflections of free surface above a source. Changes of model first effects horizontal component of P wave. From reference (Zhu and Li, 1985), matrix equation of a ground displacement for n-layer medium is:



$$\begin{bmatrix}\varphi^- \\ \varphi^+ \\ 0 \\ \chi^+\end{bmatrix}_{n+1} = \mathbf{M}_{n+1}^{-1}\mathbf{K}_{n,1}\begin{bmatrix}\boldsymbol{R}_u/k \\ 0 \\ \boldsymbol{R}_w/k \\ 0\end{bmatrix} \tag{1}$$

Where $\mathbf{M}_{n+1}$ is a transferred matrix of $(n+1)$th from layer displacement-stress vector $(\boldsymbol{R}_u/k,\ \tau_p/k^2c^2,\ \boldsymbol{R}_w/k,\ \tau_b/k^2c^2)^{\mathrm{T}}$ to a displacement potential $(\varphi^-, \varphi^+, \chi^-, \chi^+)^{\mathrm{T}}$, $\mathbf{K}_{n,1}$ is a transmission matrix from $(n+1)$th layer to free surface. Boundary condition is: (1) stress of free surface equal to zero; (2) there is only incidence (i.e. P wave) below $(n+1)$th layer. Therefore $\chi_{n+1}^-=0$, a reflection of φ_{n+1}^- lead to φ_{n+1}^- and χ_{n+1}^+. Defining a new matrix $\mathbf{H}=\mathbf{M}_{n+1}^{-1}\cdot\mathbf{K}_{n,1}$ from first and third rows of eq. (1) we find:

$$\begin{cases}\varphi_{n+1}^- = \mathbf{H}_{11}\cdot\boldsymbol{R}_u/k + \mathbf{H}_{13}\cdot\boldsymbol{R}_w/k \\ 0 = \mathbf{H}_{31}\cdot\boldsymbol{R}_u/k + \mathbf{H}_{33}\cdot\boldsymbol{R}_w/k\end{cases} \tag{2}$$

From eq. (2) we obtain:

$$\begin{cases} R_u = k \cdot H_{33}/(H_{11}H_{33} - H_{31}H_{13}) \cdot \varphi^-_{n+1} \\ R_w = k \cdot H_{31}/(H_{11}H_{33} - H_{31}H_{13}) \cdot \varphi^-_{n+1} \end{cases} \quad (3)$$

From eq. (3) we can see that the ground displacement is only decided by φ^-_{n+1} of incident P wave, i. e. source function besides medium model. When incident angle is very small, the vertical displacement components mainly reflect the initial wave field of incident wave. By crossing mth layer, P wave produced refracted wave P_1 and converted wave SV_1. The energy of P_1 plays the dominant role while reflective wave P_2 is weak. Reflective wave P_3 of $(m+1)$th layer is weaker. It is the same case with reflective converted wave SP_3 of converted wave SV_2 which is weak because multi-reflective and multi-converted waves become weaker and weaker and they can't be seen in vertical component and become insensible to model. If there is no conversion on a boundary, the horizontal component is zero. Therefore, a horizontal component is consisted to be a multi-convert-

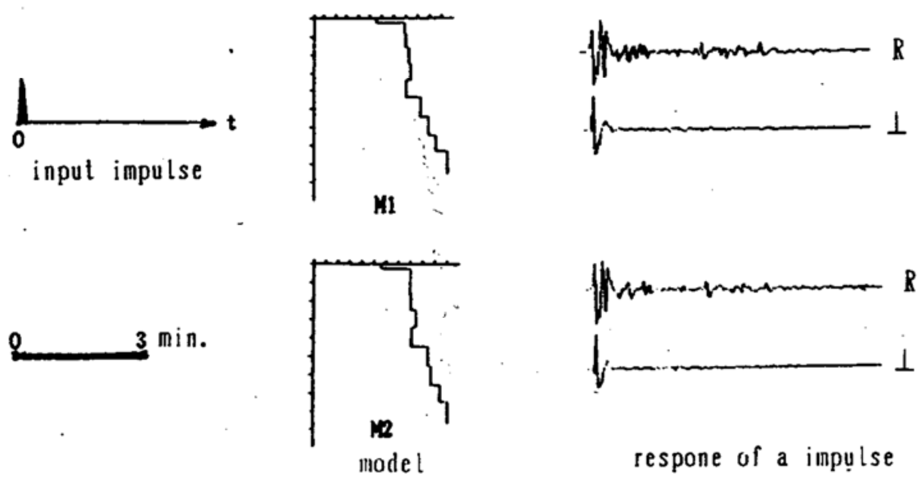


Fig. 2. A different respone of impulse for different models in a horizontal(R) and a vertical(⊥) direction.

ed and multi-reflective waves of layers. We have made vertical component tests of pure impulse input and found that different model vertical components nearly don't change and horizontal components have more varities (Fig. 2). Therefore, we can take vertical components as a base of a source function and obtain an exact theoretical seismogram convoluted by adding the response of seismograph's impulse. Five minutes on the onset of P wave is enough to reflect the influence of the medium changes on the waveform. Furthermore, the disturbance of PcP, PP, PPP and ScP phases toward the source functions must be avoided. Because they come from different channels and their incident angles vary, their energy is hard to be estimated and compared with that of P wave. By using error and test method of Monte Calo, we make, based on Bullen's global model, the first group of models and simulate observed seismograms. In comparison with theoretical seismograms we selected better models. According to the experience of waveform simulation, we changed the thickness and velocity of each layer and, thus, obtained the second group of models. We have done nearly 100 times of tests this way ,selected optimal models for automatic disturbed inversion (Li, 1988) and finally obtained the last group of models. In order to increase the stability and creditablity, we adopted several seismogram simulation of a definite station and selected more satisfied results. Because the structure below one station is unique, while earthquakes from different directions are relatively independent events, several seismograms simulation may compress inverse characteristics of multiple solutions.

It is obvious that the more the seismograms are, the better the effect will be. Unfortunately, they are very limited in amount and we selected only four pieces. Thanks to the accumulation of data at Great Wall Station and Zhongshan Station in Antarctica, we can carry on our researches and the method we used is very convenient and economical. Someone used receiver function obtained from teleseismic P waveforms (Thomas *et al.*, 1984). We used the method of waveform's comparison, which offered us an apparent sense.

3 Results and discussion

In this paper we selected M_3 and M_6 from many models as receivable models of structure SBA and SPA. In Fig. 3, M_3 is the last model. M_4 shows the model after the crust thickness was increased. In M_4 great differences and drifts between theoretical and observed seismograms can be seen. M_5 was produced by M_3 through deleting low velocity layer at 400 km deep. On SBA_1 column of Fig. 3 we didn't find big differences, but a tail on SBA_2 column was drifted rightward. Since waveform's simulation is a comprehensive effect of several seismograms' comparison, we didn't chose M_5.

In Fig. 4 M_6 is the last model and M_7 was produced by M_6 through removing double layers' crust. SPA_1 and SPA_2 columns on Fig. 4 show a drift of an onset. M_8 was produced by M_6 through adding low velocity layer and, thus, the comparison with observed seismograms are worse and SPA_2 is the worst. The wave heads of SPA_1 and SPA_2 are drifted and broadened.

An apparent comparison of Fig. 3 and Fig. 4 shows changes of different models on horizontal directions. This is the base of error and test method. Because the relation between a waveform and a large number of independant medium parameters is a strong nonlinear, the more the parameters are, the more difficult it will be. So in computation we have adopted controls of Moho's interface below a crust.

Antarctic continent, covered by ice and snow, has an awful weather condition. So far people have made seismic profiles only around north area of Antarctic Peninsula, south and east areas of the Weddell Sea ,Queen Maud Land, west area of the Enderby-Land, Kemari ice shelf and McMurdo gulf, ect. Because source energy on sea's profile is small ,exporation depth and resolution are limited (Fifield, 1987). In the inner part of the continent the ice averages 2450 meters deep and the reflection on the interface between ice and rock is strong. This restricts the depth of seismic profile. However, to a

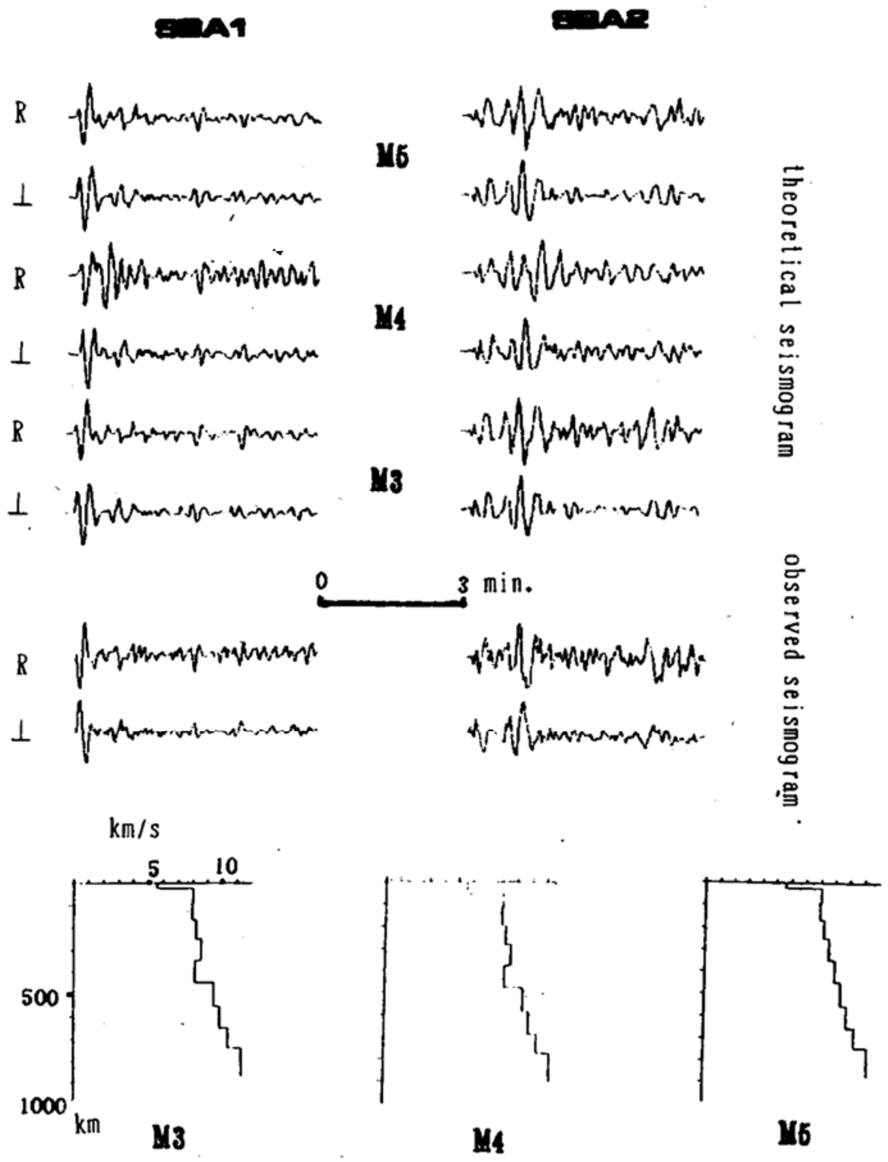


Fig. 3. A structure below the New Zealand's Scott Base (M_3).

Table 2. M_3 model parameters

Thickness(km)	24.10	63.00	76.20	85.70	95.80	100.20	107.80	99.99	88.80	129.80
Velocity(km/s)	5.61	8.01	7.94	8.23	8.55	8.17	9.40	9.80	10.40	11.26

Moho interface: crust thickness about 24 km

natural earthquake's transmission, there are no above mentioned restricted conditions. A simulation of long period body wave can obtain a structure almost 1000 km deep.

The results of this paper indicate that the deep structures on the both sides of the Transantarctic Mountains differ greatly. Crust thickness below SBA on the Ross Sea

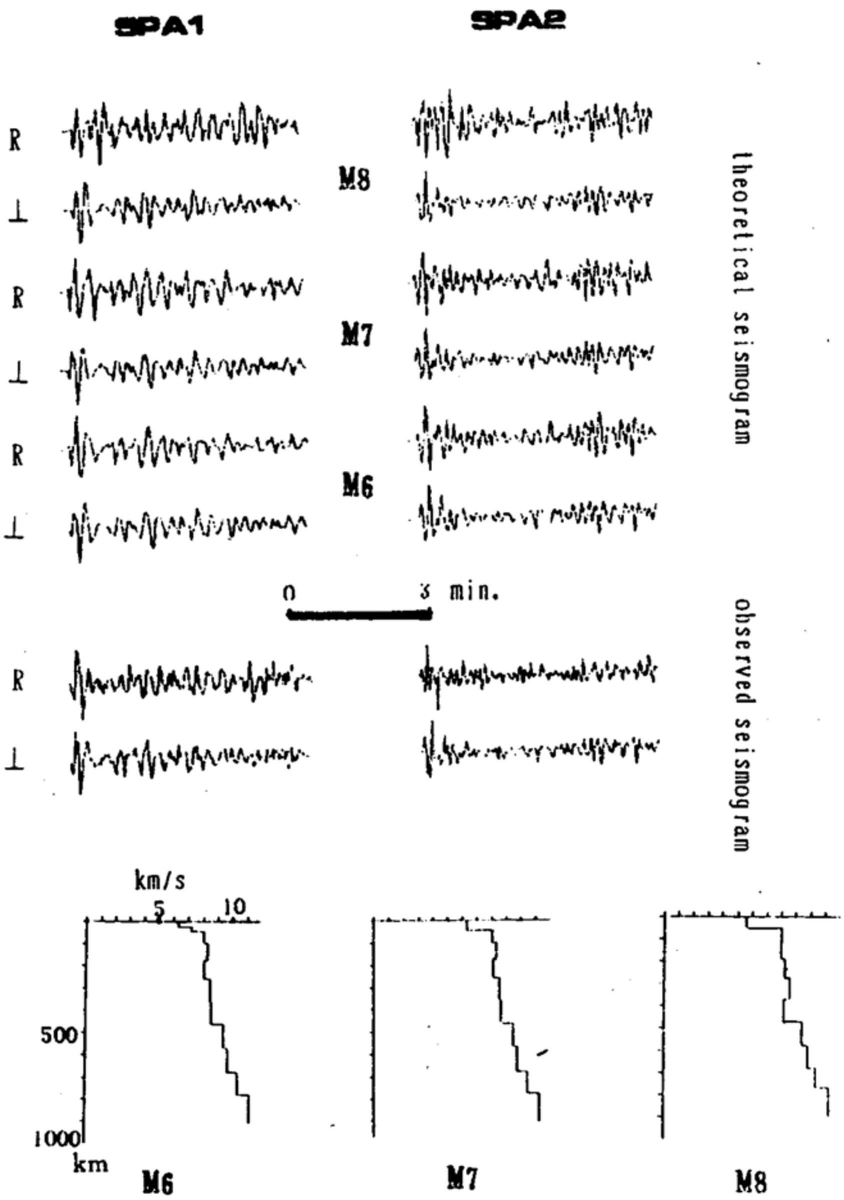


Fig. 4. A structure below the South Pole Station (M_6).

Table 3. M_3 model parameters

Thickness(km)	25.00	20.00	53.00	78.00	85.00	100.20	102.00	105.00	110.00	98.00	130.00
Velocity(km/s)	6.30	7.20	8.03	8.30	8.10	8.50	8.60	9.40	9.70	10.40	11.20

Moho interface: crust thickness about 45 km

beach is only about 24 km, and distinct low velocity layer does exist at the depth of 400 km. Beneath the south pole the depth of crust can reach to about 45 km and be divided into two layers. Under the crust the velocity increases gradually following the increase of depth and low velocity layer doesn't exist.

The differences of structures below SBA and SPA perhaps have something to do with the plate tectonics and geological evolution. Antarctic continent is situated in the center of the Gondwana Land. The history of plate motion shows that (Jin, 1984) in the geological period from J_3 to K_1, i. e. about 130 Ma ago, after Africa and South America drifted away from the Antarctica, Afterwards, India plate first drifted quickly northward and was separated from the Australia-Antarctica. In the E_1-E_3 geological period about 50 Ma ago the Australia drifted away from the Antarctica again, while the latter moved southward slowly. The Gondwana Land was then divided. These events took place around the Antarctic continent, which were caused mainly by the stretching deformation of rift valley type. So far inside it there are still a large quantity of rift valley systems from 100 to 1000 km long. Some deep and large faults can stretch up to mantle and cut crust into many pieces of massifs. It is of interest that so much vast rift valleys are concentrated on one continent. Geological surveys show that the East Antarctica is a stable shield and has never become active since the Middle Mesozoic (Wei, 1986). Due to the gravity separation, the high-density materials move downward, while low-density materials upward. These caused the gradual increase of series of velocity layer under SPA station. The long cooling in a stable environment make the action crust to become thicker in the East Antarctica. The SBA station is on the other side of the Transantarctic Mountains or in the West Antarctica. Between the East Antarctic ancient shield and the West Antarctic geosynclinals orogeny is a gradient zone of geophysical field (Fig. 5) (Zhang,

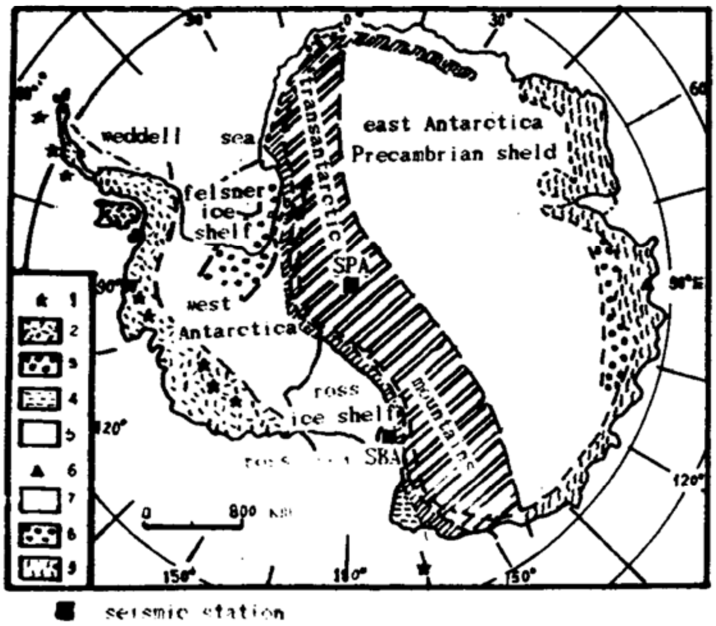


Fig. 5. Antarctic geological tectonic map (from Li *et al.*, 1989). 1. Cenozoic and recent volcano; 2. Andes fold zone; 3. Asyos fold zone; 4. Boheglivenk fold zone; 5. Ross fold zone; 6. Gossbeg quaternary volcano; 7. Early Silurian-Jurassic sedimentary zone; 8. Late proterozoic-early palaeozoic sedimentary zone; 9. Precambian complex rock.

1987). Again geological surveys show that the basement of West Antarctica consists of a series of Palaeozoic metamorphic rock and intrusive rock. Up to now the Precambrian sediment has't been discovered yet. The age of the most ancient rock in East Antarctica may reach to more than 3000 Ma. The Ross Island in West Antarctica consists of all basalt, and the age of which measured by Rb-Sr method is only 4.47~0.27 Ma. All these basalts are derived from eruption from deep rift valley belt of the mantle (Li *et al.*, 1989). These show why crust has become thin and that low velocity layer exists in mantle. Antarctic continent is still in the situation of stretching tectonic motion. East and West Antarctica are perhaps two different tectonic units and the continent is in the geological period of separation and collision.

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