A REVIEW OF GEOPHYSICAL STUDIES OF ANTARCTICA

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Abstract: The feature of the Antarctic Continent beneath ice sheet has been clarified by applying geophysical methods since the International Geophysical Year which started in 1957. The crustal structure of the Antarctic Continent was studied by means of gravity data analysis, explosion seismology and surface wave dispersions. The seismicity in Antarctica was also studied with the data which were obtained through the world wide seismological network, especially at the seismological stations in Antarctica. Two active volcanoes are located in Antarctica.

1. Introduction

The Antarctic Continent is characteristic in that it is the one and only continent on the earth covered with the thick ice sheet. The feature of the continent beneath the ice sheet has been clarified by applying the geophysical methods since the International Geophysical Year (IGY) of 1957–1958. The crustal structure in the Antarctic was studied first by WOOLLARD (1962).

More than 8000 gravity measurements have been obtained in and around Antarctica since the IGY. These gravity data give information of the crust and upper mantle of the continent.

Structural features of the ice sheet and the upper crust have been gradually clarified by seismic explosion studies which were carried out mainly by the U. S. and Soviet expeditions. The thickness of the crust was measured using the group velocity of surface waves. Antarctica is one of the large aseismic areas on the earth, although small earthquakes were recorded there. Two active volcanoes are located in Antarctica and some eruptions have been observed.

This paper summarizes such geophysical results on the basis of data obtained since the IGY.

2. Gravity

The gravity measurement on the Antarctic Continent was commenced by many expeditions in the early part of the 20th century. The number of gravimetric measurements in the inland area increased remarkably since the IGY due to cooperative efforts of traverse parties from several nations. The details of the international cooperation for gravity measurements at the beginning of the IGY were summarized by GRUSHINSKY (1972). GRUSHINSKY and LAZAREV (1972) pointed out the importance of gravity measurements in Antarctica because the information on geoscience beneath the thick ice sheet could not be gained without applying geophysical methods such as the gravity measurements.

Antarctic gravity data were compiled by GRUSHINSKY *et al.* (1972) according to the resolution of the Working Group on Solid Earth Geophysics of Scientific Committee on Antarctic Research (SCAR). Some of these observations were carried out by the traverse parties in the inland. More than 1000 gravity data have been obtained in the ocean surrounding Antarctica; most of them were obtained by Japanese scientists (TOMODA *et al.*, 1968; TOMODA, 1974).

The free air and the Bouguer gravity anomalies are calculated by GRUSHINSKY and SAZHINA (1977) all over the Antarctic Continent and the surrounding ocean using all the gravimetric data which have been obtained since the IGY. Using the data of gravity and other geophysical methods, a general picture of the rock basement of Antarctica as well as the crustal thickness, the isostatic equilibrium and the feature of the geoid have been obtained (GRUSHINSKY *et al.*, 1975).

Many researchers have discussed regional structures of the Antarctic Continent based on the gravity data (*e. g.*, BENTLEY, 1964; DREWRY, 1975, 1976; ROBINSON, 1964).

The gravity surveys have been carried out also in the inland area around the Japanese Antarctic station, Syowa since the IGY by the Japanese Antarctic Research Expedition (JARE) (HARADA *et al.*, 1960, 1963; SUZUKI *et al.*, 1961; OURA, 1965). Some of these data are in the catalogue compiled by GRUSHINSKY *et al.* (1972). The Japanese party which traversed from Syowa Station to the South Pole in 1968–69 has succeeded in the gravity measurements every 4 km (YANAI and KAKINUMA, 1971). The gravimetric measurements on Mizuho Plateau have been made by the inland field parties of JARE in 1969–1971 (YOSHIDA and YOSHIMURA, 1972).

Gravity data thus accumulated up to the present are available for the studies of gravity anomaly distribution with reference to the crustal structure. However, in spite of the laborious task for gravity measurements at inland parts of Antarctica, neither the free air reduction nor the Bouguer reduction can provide exact gravity anomalies which permit direct interpretation of underground structures in such a region as Antarctica where the thickness of the ice sheet is not known with sufficient accuracy.

An analytical method was introduced to interpret gravity data for the study of the Antarctic crustal structure by using a reduced gravity anomaly where the thickness of the ice sheet is unknown (KAMINUMA and MIZOUE, 1978). The reduced gravity anomaly, designated as Δg_h(mgal), is defined by the equation $\Delta g_h = \Delta g_0 - 2\pi G\rho(H-h)$, where Δg_0(mgal) is the free air anomaly and H(m) is the elevation of the mea-

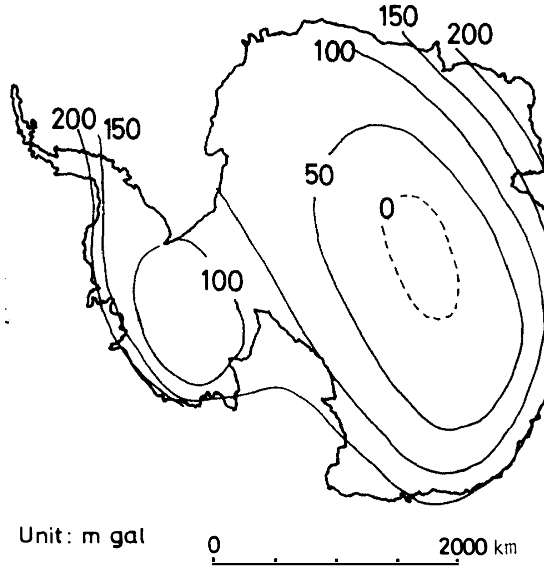

Fig. 1. An contour map of the reduced gravity anomaly.

surement point. H(m) is the elevation of the point for which the reduced gravity anomaly Δg_h is calculated. The results of the reduced gravity anomaly analysis reach the conclusion that the crust of the Antarctic Continent is possibly in a regional isostatic equilibrium, similar to other continents (Fig. 1). The thickness of the crust in West Antarctica, however is significantly less than that in East Antarctica by about 3 km. This difference corresponds to a gravity anomaly difference as large as 80 mgal when a mean density contrast $\Delta\rho=0.6$ g/cm^3 is assumed between the crust and the upper mantle.

3. Explosion Seismology

Most of seismic refraction profiles in Antarctica have been carried out during the reconnaissance exploration of the Antarctic inland area as a part of the U. S. Antarctic Research Programs for ten years since the IGY. Upper crustal structures obtained from about 40 seismic refraction profiles have been studied and the results are summarized by BENTLEY and CLOUGH (1972). The top of the basement complex generally lies near sea level in East Antarctica but typically 2 or 3 km below sea level in West Antarctica. The average thicknesses of ice sheet is 1980 m in East Antarctica and 1440 m in West Antarctica (BENTLEY, 1964).

Deep seismic soundings were carried out in 1969 by the Soviet Antarctic Expedition around Novolazarevskaya Station on the coast of the Queen Maud Land (KOGAN, 1972). The depth of the Moho-discontinuity is found to be 40 km below sea level.

Table 1 shows the number of P wave velocity layers which were compiled by BENTLEY and CLOUGH (1972) and KOGAN (1972). Three distinct layers of different velocities are shown in Table 1. The P wave velocities of the first layer are in a range

Table 1. The number of occurrence of P wave velocities estimated from explosion seismology.

1st layer		2nd layer		3rd layer		Bottom layer of crust	
Velocity (km/s)	N	Velocity (km/s)	N	Velocity (km/s)	N	Velocity (km/s)	N
4.1	2	5.2	2	5.7	3	6.7	3
4.3	3	5.3	4	5.8	2	7.0	2
4.4	3	5.4	1	5.9	2		
4.5	1	5.5	2	6.0	2		
4.6	1			6.1	3		
				6.2	2		
				6.4	2		

from 4.1 to 4.6 km/s, those of the second one 5.2–5.5 km/s and the third in 5.7–6.4 km/s. The first and the second layers are found mainly in West Antarctica. The *P* wave velocity of the top layer in East Antarctica is greater than 5.7 km/s. The velocities of the first and the second layers in West Antarctica were not found in East Antarctica except in the Queen Maud Land. The measured *P* wave velocity below the Moho-discontinuity is 7.9 km/s, which is unique as the *P* wave velocity measurement in the upper mantle of Antarctica (KOGAN, 1972).

4. Surface Wave Dispersion

Studies of the dispersion of Love and Rayleigh waves in Antarctica gave the first information of the crustal thickness in Antarctica at the beginning of the IGY, and the details of several studies were summarized by ADAMS (1972a, b). Group-velocity dispersions of Love and/or Rayleigh waves across Antarctica were given by EVISON *et al.* (1959) and PRESS and DEWART (1959). EVISON *et al.* (1960) determined a crustal thickness using the group-velocity dispersions of surface waves and proposed a crust and upper mantle model of the Antarctic Continent. KOGAN *et al.* (1961) also got the crustal thickness beneath the edge of the Antarctic Continent. KOVACH and PRESS (1961) criticized the earlier studies and proposed a new crust and upper mantle model with low-velocity channels of *S* waves.

A model of the Antarctic Continent with the ice sheet was proposed by DEWART and TOKSÖZ (1965). It was the one and only model that took the ice sheet into account.

From all studies of surface-wave dispersion across the Antarctic Continent mentioned above, the crustal thickness was estimated to be 35–40 km beneath East Antarctica which was a typical continental crust, 25–30 km beneath West Antarctica which was not so well determined due to the scarcity of data, and 5–10 km in the oceanic regions surrounding the continent. KNOPOFF and VANE (1978/79) have studied the Rayleigh wave dispersion measurements across East Antarctica. They found high phase velocities to periods as long as 75 s and concluded that the crust and upper mantle of East Antarctica is similar to other ancient Precambrian shield area of the world.

5. Seismicity

It is well known that no earthquakes were located in Antarctica (GUTENBERG and RICHTER, 1954). The Antarctic Continent and surrounding ocean, constituting the so-called Antarctic plate, although enclosed by marginal seismic belts, is one of the large aseismic areas in the world. More than ten seismological stations have been operating in Antarctica since the IGY. Nevertheless, with the exception of the volcanic eruptions of Deception Island, no earthquakes have been located in the Antarctic area by the World Wide Seismological Station Network (WWSSN) which can detect almost all the earthquakes of magnitude greater than five (U. S. NOAA, 1970).

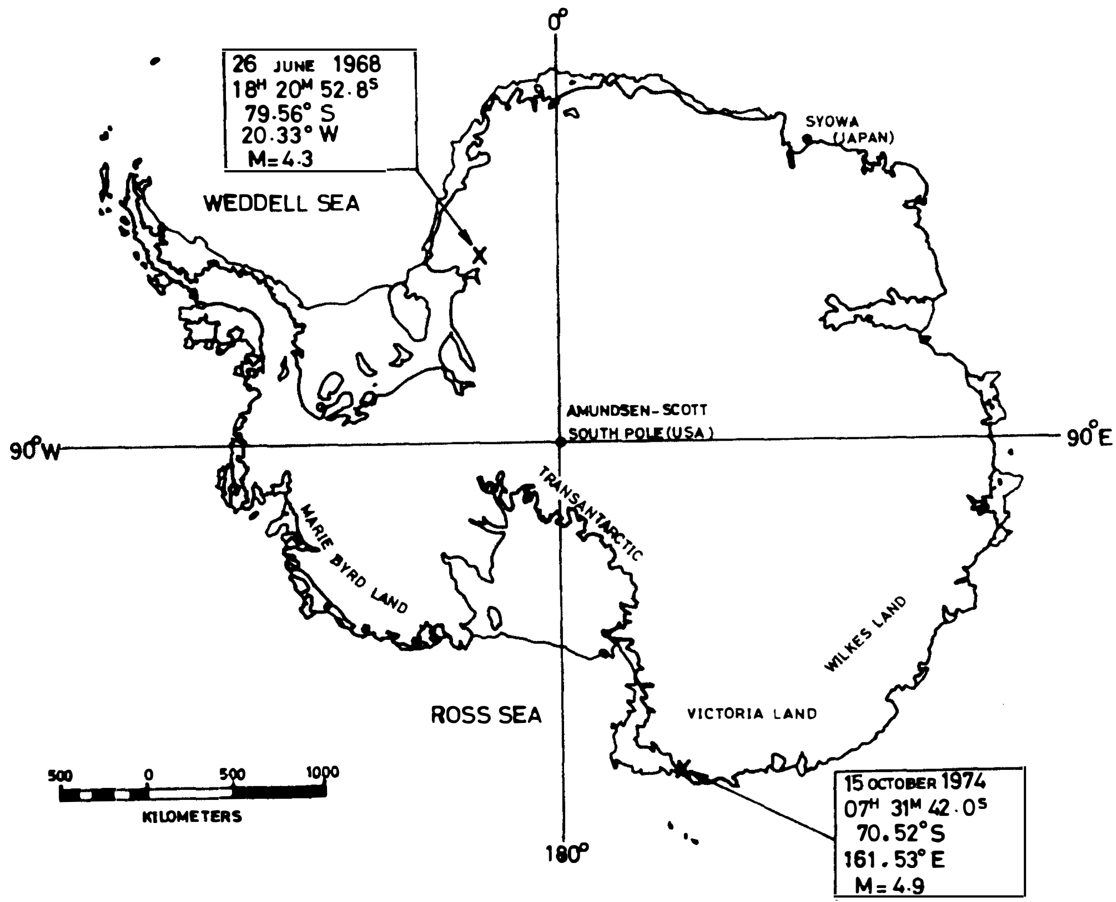

Fig. 2. Two earthquakes were located in the Antarctic Continent.

No significant earthquakes have been located in Antarctica; however, the occurrence there of small-magnitude events has been recognized for some time. Since the IGY, the seismic activity of this region has been studied by many researchers (*e. g.*, HATHERTON, 1961; HATHERTON and EVISON, 1962; KOGAN *et al.*, 1965; LAZAREVA and SYTINSKIY, 1965; BROWNE-COOPER *et al.*, 1967; EVISON, 1967; KAMINUMA, 1971, 1976 b; ADAMS, 1972 a, b). Some of them found strong evidence that many shocks recorded at the Antarctic stations were originated from the calving of icebergs or cracking of the ice sheet. Although a few researchers have reported some shocks in the Antarctic regions, these shocks were not confirmed clearly by other investigators or were regarded as icequakes.

ADAMS (1972a, b) reported small earthquake activities in the Victoria Land area. Two small earthquake locations in the Coats Land and in the Adélie Land were found by KAMINUMA and ISHIDA (1971) and by the U. S. NOAA respectively as given in Fig. 2. The ordinary earthquake activities around Syowa Station and the McMurdo Sound area are summarized in Table 2 (KAMINUMA, 1971, 1976a, b), and KAMINUMA (1979) gave a summary account as follows:

Table 2. Seismicities of volcanic and non-volcanic areas in Antarctica.

Station	Magnification of seismograph	The number of earthquakes
McMurdo (1974–75) (Volcanic)	100,000	1.0 per day
(1975–76) (Volcanic)	120,000	0.9 per day
Lake Leon (Non-volcanic)	50,000	0.5 per day
Syowa (Non-volcanic)	50,000	7–10 per year

1) Small earthquakes occur at least in West Antarctica, though their activity is very weak. However, the earthquakes are generally difficult to be detected by the insufficient seismological network in Antarctica.

2) The seismicity around Syowa Station in East Antarctica is less than one micro-earthquake per month. However, earthquakes do occur in the marginal zone of the East Antarctic shield.

3) The seismicity around the Dry Valleys in the Victoria Land is one micro- or ultramicro-earthquake every two days, and that around McMurdo Station on Ross Island is one micro-/ultramicro-earthquake per day.

4) The seismic activity in the volcanic region in Antarctica is relatively stronger than that in the surrounding region.

5) The seismicity in West Antarctica is generally some ten times higher than that in East Antarctica.

6. Volcanic Activities

Two active volcanoes, Deception Island and Mount Erebus, are located respectively near the tip of the Antarctic Peninsula in West Antarctica and on Ross Island in the Ross Sea. Mount Erebus, the most active volcano in Antarctica, was discovered by Sir James Ross on January 27, 1841 (ROSS, 1847). It was recognized by the officers of the expedition ship that red lave streams spurted out from the summit crater. Since then, some volcanic activities such as steam eruptions, reflection of glow, volcanic flame, lava lake in crater, etc., have been observed on and off (SHACKLETON, 1909; PRIESTLEY, 1913; GIGGENBACH *et al.*, 1973; KAMINUMA, 1976a, b, c). Steam eruptions have been occurred frequently since the end of 1972 (GIGGENBACH *et al.*, 1973; KAMINUMA, 1978).

The eruption of Deception Island witnessed for the first time by man occurred on December 4, 1967. Eruption was repeated from 1969 to 1970 and an island appeared in the north western part of Foster Bay which was a caldera. The volcanic activity of Deception Island ceased at the end of 1971 (BAKER *et al.*, 1969; CLAPPERTON, 1969; HAUFF, 1969).

It was observed that steam blew up from Mount Melbourne in northern Victoria Land, but no eruption was recognized (NATHAN and SCHULTE, 1967).

Some other active or potentially active volcanoes are located at the tip of the Antarctic Peninsula, in the Marie Byrd Land, in the western part of the Ross Sea, and in the Victoria Land (KATSUI, 1971). Although active eruptions were not observed.

7. Conclusion

The geophysical feature of the Antarctic Continent is summarized briefly as follows:

1) The crust of the Antarctic Continent is possibly in a regional isostatic equilibrium, similar to other continents. The thickness of the crust in West Antarctica is significantly less than that in East Antarctica by 3 km which is estimated from gravity study.

2) The crustal thickness estimated from surface wave dispersions is 35–40 km beneath East Antarctica, 25–30 km beneath West Antarctica and 5–10 km in the oceanic region surrounding the continent.

3) The P wave velocity of the top layer of crust in West Antarctica is in a range of 4.1–4.6 km/s, but, in East Antarctica the values are greater than 5.7 km/s with a few exceptions.

4) Small earthquakes occur at least in West Antarctica, but the activity is very weak.

5) Antarctica is the world of ice and rock, but two active volcanoes are located.

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