Modes of Gravity Anomaly Distributions in Relation to the Crustal Structure of the Antarctic Continent

Katsutada KAMINUMA* and Megumi MIZOUE**

重力からみた南極の地下構造

神沼克伊*・溝上　恵**

要旨： 南極大陸の地下構造について，その概略でも良いから全体像を把握する目的で，重力を用いた解析を行った．重力を用いて地下構造を求める場合，ブーゲ異常値を使う方法が一般的である．しかし，南極大陸は平均 1900 m の厚い氷床に覆われており，重力測定点の氷床の厚さは不明の場合が多く，ブーゲ異常値は得られないことが多い．

そこで，$\varDelta g_h=\varDelta g_0-2\pi G\rho(H-h)$ の式により $\varDelta g_h$ を求めた．$\varDelta g_0$ はフリーエア異常値，H は重力測定点の標高，h は $\varDelta g_h$ を求める基準面の高さで，取扱いを簡単にするため，便宜上 $h\geqq H_{\max}$ とした．$\varDelta g_h$ は $h-H$ の空間を密度 ρ の氷床で埋めた時の，標高 h の点でのフリーエア異常値である．

南極大陸で測定された重力値を用いて，$\varDelta g_{4000}$ を求めた．その値の変動には大陸の地殻の厚さの反映が見られる．これに着目すると，東南極と西南極では異なったパターンの地下構造であることが分かる．

Abstract: An analytical method is introduced in applying the gravity data to the study of crustal structure by using a reduced gravity anomaly when the thickness of ice sheet is unknown. The reduced gravity anomaly designated as $\varDelta g_h$(mgal) is defined by the equation of $\varDelta g_h=\varDelta g_0-2\pi G\rho(H-h)$, where $\varDelta g_0$(mgal) is the free air anomaly, H(m) is the elevation of measurement point and h(m) is the elevation of the point to which gravity anomaly $\varDelta g_h$ should be reduced. The density of ice sheet and the universal constant of gravitation are designated as ρ(g/cm^3) and G respectively. For the practical convenience, the value of h should be taken as constant and larger than or equal to the maximum value of H. The space bounded by the two levels of h and H is assumed to be filled up with ice sheet with density ρ in the reduction procedure. The reduced gravity anomaly $\varDelta g_h$ thus introduced is physically equivalent to the free air anomaly reduced to the points on the surface of ice sheet extending with the constant elevation h.

Predominant modes of the spatial distribution of reduced gravity anomalies $\varDelta g_{4000}$ are found in two ranges of wave length, *i. e.*, the shorter wave-length range of 100–200 km and the longer wave-length range of more than 1,000 km. The

* 国立極地研究所. National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173.

** 東京大学地震研究所. Earthquake Research Institute, the University of Tokyo, 1–1, Yayoi 1-chome, Bunkyo-ku, Tokyo 113.

mode of the shorter wave-length range is possibly correlated with topographical features of the rock and ice sheet interface, while the mode of the longer wave-length range is characterized by a decrease of Δg_{4000} toward the inland part of the continent. The result of the gravity data analysis leads to a conclusion that the crust of the Antarctic Continent is in a regional isostatic equilibrium common to the other continental regions on the earth, though the thickness of the crust in West Antarctica is relatively thinner than that in East Antarctica.

1. Introduction

The scientific surveys in Antarctica have been extensively carried out since the third International Geophysical Year (IGY) starting from 1957. As one of the main subjects, the crustal structure of the continent (EVISON *et al.*, 1960; WOOLLARD, 1962) have been studied with various geophysical means by overcoming all difficulties caused by the unavoidable severe field conditions.

Structural features of ice sheet and upper crust have been gradually clarified by seismic explosion studies in some limited parts of the continent despite the fact that most of the seismic explosion experiments ever operated in Antarctica were comparatively small in the explosive power and consequently were limited in the length of survey lines (BENTLEY, 1964 and 1965), except the deep seismic sounding operated by Russian scientists in the vicinity of Novolazarevskaya Station (KOGAN, 1972).

Soon after the installation of long-period seismographs in Antarctica in the early stage of the IGY, the preliminary estimation of the thickness of the crust of East and West Antarctica was given by EVISON *et al.* (1960), and KOVACH and PRESS (1961) using the group velocity of surface waves. The crustal thickness was estimated as 35–40 km beneath East Antarctica, 30–35 km beneath West Antarctica and 5–10 km in the oceanic regions surrounding the continent. No other reliable estimates from surface wave group and/or phase velocity have ever been provided mainly due to insufficient number of long-period seismographs operated in Antarctica.

The gravimetric survey in Antarctica was started at the early stage of the expedition in the 20th century. The number of gravity stations in the inland part of the Antarctic Continent has increased remarkably since the IGY in 1957–1958 owing to cooperative efforts of traverse parties from various nations.

Gravity data thus accumulated up to the present are available for the study of regional modes of gravity anomaly distributions with special reference to the crustal structure. Neither the free air nor the Bouguer reduction can provide gravity anomalies which permit direct interpretation in terms of underground structures in such a region as Antarctica where the thickness of ice sheet is scarcely known with sufficient accuracy.

A simple gravity reduction system is proposed in this connection to get standardized gravity anomalies considering the existence of a thick ice sheet layer and the undulatory ice sheet-bedrock interface. The gravity reduction introduced consists of the following two procedures, *i. e.*, reduction of gravity value to the surface at the level higher than or equal to the maximum height of ice sheet surface, and addition of the gravity effect produced by filling up the space between the two surfaces with material having ice sheet density.

2. Analytical Method

The area and the mean elevation of the Antarctic Continent are 12.5×10^6 km^2 and 2,300 m respectively. The ice sheet with the mean thickness of 1,880 m (BENTLEY, 1964) covers the vast continent, only 2% of which is free from snow or ice. Therefore, information on the thickness of ice sheet is essential for the reduction of gravity data to study the internal structure of the earth.

When the gravity data are used in the study of crustal structure, however, a great difficulty arises from the fact that an accurate knowledge of the thickness of ice sheet under the gravimetric observation points has scarcely been obtained. To avoid this troublesome situation for the gravity data analysis, a reduced gravity anomaly is introduced in this report.

The reduced gravity anomaly designated as Δg_h (mgal) is defined by the following equation,

$$\begin{aligned}\Delta g_h &= \Delta g_0 - 2\pi G\rho(H-h)\\ &= \Delta g_0 - 0.0419(H-h)\end{aligned}$$

where Δg_0 (mgal): the free air anomaly,
H (m): the elevation of measurement point,
h (m): the elevation of the point to which gravity anomaly Δg_h should be reduced,

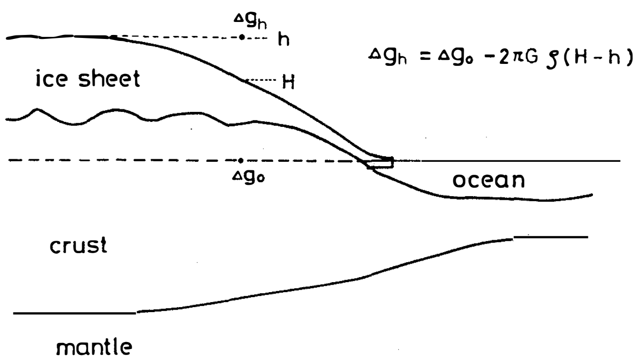

Fig. 1. A concept of reduced gravity anomaly Δg_h is illustrated. Δg_0 is a free air anomaly observed at the point of elevation H.

ρ (g/cm³): the density of ice sheet,

G (cm³/g·s²): the universal constant of gravitation.

The relation of h and H in the above equation is shown in Fig. 1. The value of h should be taken as constant and larger than or equal to the maximum value of H for the practical conveniences. The space bounded by the two levels of h and H is assumed to be filled up with ice sheet with density ρ in the reduction procedure. The reduced gravity anomaly Δg_h thus introduced is physically equivalent to the free air anomaly reduced to the points on the surface of ice sheet horizontally extending with constant elevation h.

3. Reduced Gravity Anomaly along the Traverse Route

The reduced gravity anomaly is calculated from gravity data which were measured by the Japanese traverse party from Syowa Station to the South Pole in 1968–1969. The measurements were carried out with a LaCoste and Romberg gravimeter at the observation points of every four kilometers along the traverse route (YANAI and KAKINUMA, 1971). More than six hundred gravimetric observation points are estab-

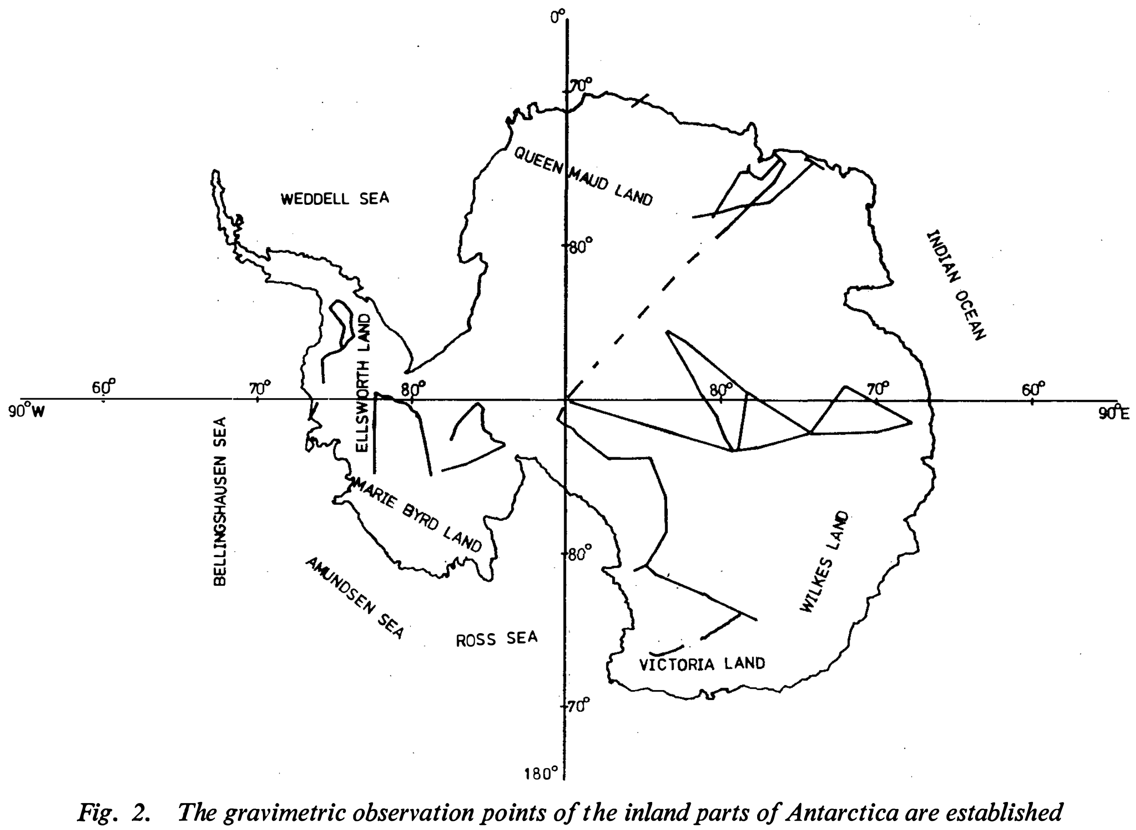

Fig. 2. The gravimetric observation points of the inland parts of Antarctica are established along the traverse which are shown by solid and dotted lines. The dotted line is the traverse route of Japanese party from Syowa Station to the South Pole in 1968–69.

lished along the traverse route which is shown by a dotted line in Fig. 2. The position (latitude and longitude), elevation and gravity value including free air anomalies are given for all points. On the other hand, the thickness of ice sheet is not available for most of the points.

The elevation of the highest observation point through the traverse route is over 3,700 m. Then 4,000 m is taken as the value of h in the equation introduced in the previous section and ρ is taken as 0.9 g/cm^3.

The reduced gravity anomalies along the survey routes are given in Fig. 3. The maximum value of the reduced gravity anomalies Δg_{4000} is 160 mgal at the points around 70°S and the minimum value is -15 mgal at 89°S.

Predominant modes of the spatial distribution of reduced gravity anomalies Δg_{4000} are found in the two wave-length ranges, as shown in Fig. 3, *i. e.*, the shorter wave-length range of 100–200 km and the longer wave-length range of more than 1,000 km. The mode of the shorter wave-length range is possibly correlated with topographical features of the Antarctic bedrock and ice sheet interface. On the other hand, the mode of the longer wave-length range is characterized by a decrease of Δg_{4000} values toward the inland part of the continent where the altitude of ice sheet surface is higher than that in the marginal parts.

A remarkable decrease of Δg_{4000} values around the 89°S is interpreted as an indication of the topographical variation of basement rocks beneath the thick ice sheet.

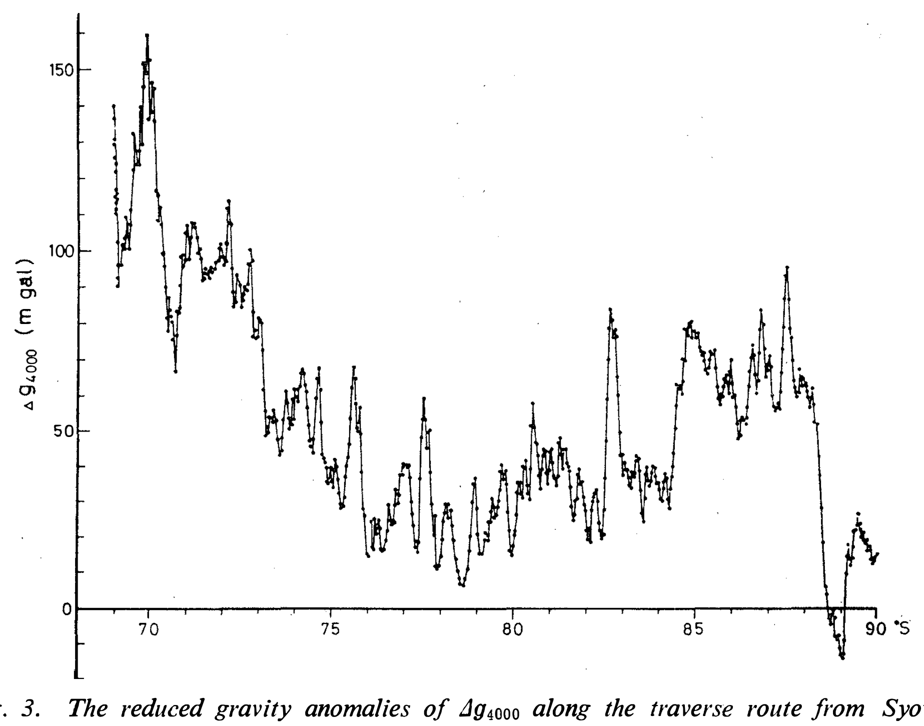

Fig. 3. The reduced gravity anomalies of Δg_{4000} along the traverse route from Syowa Station to the South Pole.

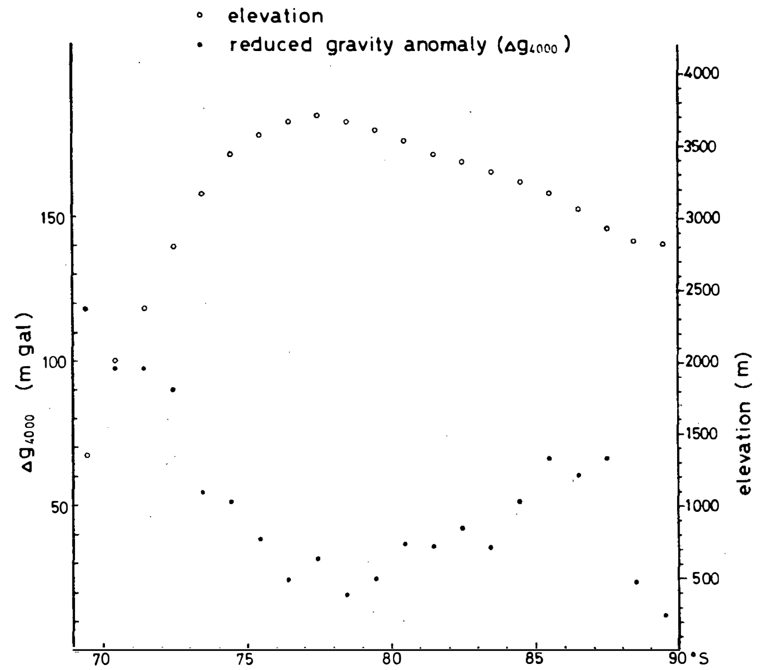

Fig. 4. The reduced gravity anomalies and elevations averaged over every one degree along the traverse route from Syowa Station to the South Pole.

The mean reduced gravity anomalies averaged over every one degree in the latitude are shown with solid circles in Fig. 4. The mean elevations corresponding to the gravity data are also given with open circles. The predominant mode of the longer wavelength range clearly represented in Fig. 4 is considered to reflect the regional variation of the crustal thickness of the continent. In this connection, the lower values of the mean reduced gravity anomaly found in the central part of East Antarctica of Precambrian shield can be correlated with the increase of the thickness of the crust.

4. Regional Variation of the Thickness of the Crust of the Antarctic Continent

Gravity data measured in and around Antarctica are compiled by GRUSHINSKY *et al.* (1972). More than 6,000 gravity stations have been established in the last ten years. Most of these observations have been carried out by the traverse parties of scientific expedition for the inland area of Antarctica. The Japanese party participated in the observation for the traverse route from Syowa Station to the South Pole as described in the previous section.

The traverse routes for which gravity survey was accomplished are given in Fig. 2.

The reduced gravity anomalies are calculated using the data hitherto presented in various publications (YANAI and KAKINUMA, 1971; GRUSHINSKY *et al.*, 1972). The value of h is also taken as 4,000 m. The mean reduced gravity anomalies in West and

East Antarctica, are obtained by averaging data in the areas of 76°–85°S and 80°–140°W, and 74°–85°S and 35°–135°E, are shown in Fig. 5. The mean value in West Antarctica is 92 mgal, whereas it is 30 mgal in East Antarctica. It is remarkable that the values of Δg_{4000} in West Antarctica are relatively larger than those in East Antarctica as shown in Fig. 5. In other words, it is highly probable that the crustal structure of East Antarctica is different from that of West Antarctica, which agrees with geographical and geological data (CRADDOCK, 1972). The thickness of the crust estimated from the surface wave study is 35–40 km in East Antarctica and 30–35 km in West Antarctica (EVISON *et al.*, 1960).

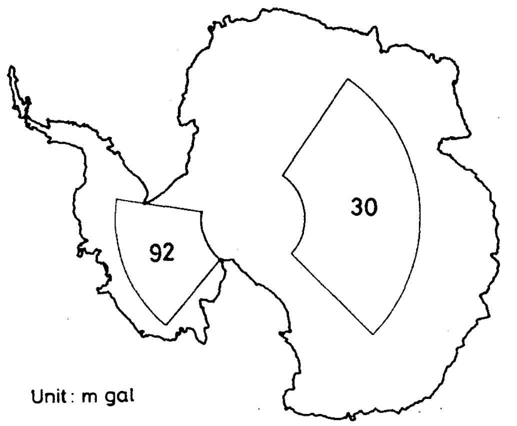

Fig. 5. Mean reduced gravity anomalies in West and East Antarctica, averaged data in the areas of 76°–85°S and 80°–140°W, and 74°–85°S and 35°–135°E.

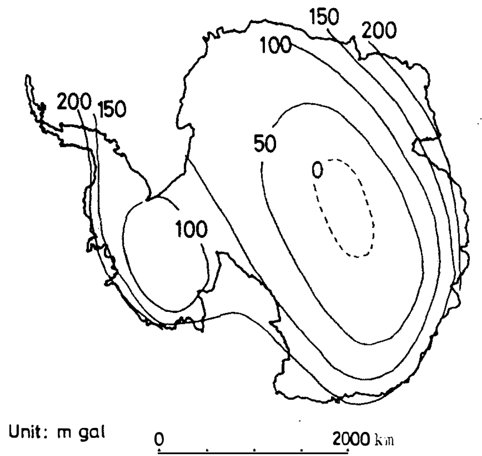

Fig. 6. A contour map of the reduced gravity anomaly Δg_{4000}.

The contour map of the reduced gravity anomalies is given in Fig. 6. The reduced gravity anomalies in West Antarctica and the marginal area of East Antarctica are relatively large compared with the inland part of East Antarctica. Some of Δg_{4000} values in East Antarctica are negative. This mode of gravity anomaly distributions characterizes one of the geophysical features of East Antarctica which is regarded as an old and stable Precambrian continent.

The result of the gravity data analysis leads to a conclusion that the crust of East Antarctic Continent is possibly in a regional isostatic equilibrium common to the other continental regions, though the thickness of the crust in West Antarctica is significantly less than that in East Antarctica by 2.5–4 km corresponding to gravity anomaly difference as large as 60–100 mgal when the mean density contrast $\Delta\rho=0.6$ g/cm^3 between the crust and the upper mantle is assumed.

5. Conclusion

An analytical method is introduced in applying the gravity data to the study of crustal structure of Antarctica by using a reduced gravity anomaly when the thickness of ice sheet is unknown. The reduced gravity anomalies Δg_h are calculated from the gravity data observed in Antarctica, taking h as 4,000 m to be defined as the elevation of the point to which free air anomaly Δg_0 should be reduced. Modes of the distribution of reduced gravity anomalies Δg_{4000} have two predominant wave-length ranges, *i. e.*, the shorter wave-length range of 100–200 km and the larger wave-length range of more than 1,000 km. The former mode seems to be correlated with topographical features of the Antarctic bedrock and ice sheet interface and the later mode seems to reflect the regional variation of the thickness of the crust in the continent.

The remarkable decrease in Δg_{4000} values toward the inland part of East Antarctica indicates that the regional isostatic equilibrium condition is satisfied in the continent.

References

BENTLEY, C. R. (1964) : The structure of Antarctica and its ice cover. Research in Geophysics, Vol. 2; Solid Earth and Interface Phenomena, ed. by H. ODISHAW. Cambridge, The MIT Press, 335–389.

BENTLEY, C. R. (1965) : The land beneath the ice. Antarctica, ed. by T. HATHERTON. London, Methnen, 259–277.

CRADDOCK, C. (1972) : Antarctic tectonics. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitetsforlaget, 449–455.

EVISON, F. F., INGHAM, C. E., ORR, R. H. and LEFORT, J. H. (1960): Thickness of earth's crust in Antarctica and the surrounding oceans. Geophys. J. R. Astron. Soc., **3**, 289–306.

GRUSHINSKY, N. P., KORJAKIN, E. D., STROEV, P. A., LASAREV, G. E., SIDOROV, D. V. and VIRSKAJA, N. F. (1972) : The catalogue of the gravity stations in Antarctica. Trudy Gosudarstvennogo Astronomicheskogo Instituta, **42**, 115–311.

KOGAN, A. L. (1972) : Results of deep seismic sounding of the earth's crust in East Antarctica. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitetsforlaget, 485–489.

KOVACH, R. L. and PRESS, F. (1961) : Surface wave dispersion and crustal structure in Antarctica and the surrounding oceans. Ann. Geofis., **14**, 211–224.

WOOLLARD, G. P. (1962) : Crustal structure in Antarctica. Antarctic Research: the Matthew Fontain Maury Memorial Symposium, ed. by H. WEXLER *et al.* Washington, Am. Geophys. Union, 53–73 (Geophys. Monogr. Ser., No. 7).

YANAI, K. and KAKINUMA, S. (1971) : Measurement of gravity along the traverse route Syowa-South Pole. JARE Sci. Rep., Spec. Issue, **2**, 131–150.

(Received October 12, 1977)