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# EVALUATION OF CRUSTAL STRUCTURE AND BEDROCK TOPOGRAPHY AROUND MIZUHO PLATEAU, ANTARCTICA, BASED ON GRAVITY DATA

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***Abstract:*** For the last three decades, gravity surveys around Syowa Station have been conducted by the Japanese Antarctic Research Expedition (JARE). Especially, in the vicinity of Mizuho Plateau, gravity data made it possible to analyze three-dimensional subsurface structures. The data have revealed several contradictions between gravity anomaly and ice thickness measured by radio echo sounding. To explain ice thickness data and gravity anomaly-bedrock height relations without any contradiction, about 5 g/cm$^3$ of bedrock density is required. This high density is quite unnatural. In this study, the authors tried to construct the three-dimensional bedrock topography and shape of the Moho discontinuity by using gravity anomaly data. Through the analysis, we clarified the characteristics of the contradictions and found that ice thickness determined by radio echo soundings is always smaller than the actual thickness by a constant factor. Possible explanations are: 1) radio echo sounding detects an intra-ice discontinuity due to moraine and/or climatic change origin; 2) error of radio wave velocity due to variation of the estimated dielectric constant. This conclusion could explain theoretically the greatest part of the unnatural relationship between gravity anomaly and bedrock topography.

## 1. Introduction

Since the International Geophysical Year of 1957, gravity surveys have been conducted to obtain basic geophysical data on the crustal structure of the Antarctic continent.

Especially, in and around Syowa Station (Mizuho Plateau, Yamato Mountains, Belgica Mountains, and Sør Rondane Mountains), gravity surveys have been conducted not only for geophysical but also glaciological purposes (*e.g.*, ABE, 1975; ABE *et al.*, 1978; YANAI and KAKINUMA, 1971; YOSHIDA and YOSHIMURA, 1972; KAMINUMA and NAGAO, 1984; NAGAO and KAMINUMA, 1984, 1988). By using these data, several authors have presented models and maps of the subsurface structure. NAGAO and KAMINUMA (1984) suggested that the crustal thickness of the Yamato Mountains region is 4 km larger than that of the Syowa Station area, and that of the Mizuho Station area is 2 km larger than that of the Syowa Station area, from Bouguer anomaly analysis. If we assume a Moho depth of 40 km beneath Syowa Station, as has been determined by seismic refraction (IKAMI and ITO, 1984), the result of NAGAO and KAMINUMA (1984) implies that the crustal thickness of the Yamato Mountains region is about 44 km and that of the Mizuho Station area is 42 km. FUKUDA *et al.* (1990) combined gravity data obtained from satellite observation, sea surface gravity data and land gravity data around Syowa Station, and presented gravity anomaly and geoid maps. They also pointed out the possibility of tectonic zoning by using gravity anomaly data. NAGAO *et al.* (1991) showed three-dimensional gravity and topography maps in the vicinity of Mizuho Plateau from 68°S to 78°S, from 25°E to 55°E.

In applying gravity data to crustal structure analysis, bedrock topography data (*i.e.*, ice thickness data) are important to estimate deep crustal structure. It is also quite important in glaciological study conducted to evaluate the ice sheet mass balance deduced from climatic change, because the bedrock topography shape acts as a vessel for the ice sheet. The authors believe that the bedrock topography shape is a key to control of ice sheet flow.

To determine bedrock topography (*i.e.*, ice thickness), three methods are basically used : seismic reflection, radio-echo sounding, and gravity measurement. The seismic reflection method was used widely in inland traverse surveys in the 1960's, supplemented by gravity measurements. Radio echo sounding became the standard method in the late 1960's and has yielded fruitful results. Radio-echo soundings were conducted in and around the Yamato Mountains region (NARUSE and YOKOYAMA, 1975 ; OMOTO, 1976 ; WADA and MAE, 1981 ; NISHIO and OHMAE, 1989 ; WATANABE *et al.*, 1992). This method, however, also has some problems in determining ice thicknesses. It is sometimes difficult to identify a real echo from a subglacial rock surface from multiple radar echoes (MAE, 1978). Furthermore, an error in the dielectric constant of ice produces radio wave velocity error (in other words, ice thickness error). NAGAO (1984) pointed out that the accuracy of ice thicknesses obtained from radio echo soundings on the Syowa-Mizuho route is still debatable in comparison with gravity data.

The aim of this paper is to present a basic concept of how to analyze the gravity data observed in Antarctica from the geophysical point of view. Furthermore, the authors reevaluated the accuracy of gravity anomalies and ice thickness data. Finally, we would like to point out the existence of fatal errors in the reported ice thickness data.

## 2. Data and Discussed Area

It is noted that the gravity anomaly data in Antarctica contain some problems such as the method of determining geographical coordinates and elevations (*e.g.*, NAGAO and KAMINUMA, 1988 ; NAGAO *et al.*, 1991). When a gravity station is set up on an ice sheet, the observation point itself moves together with the ice sheet flow ; therefore, the date of the measurement is important. Furthermore, different altitudes are obtained depending on the determination method : these discrepancies are significant sources of gravity anomaly errors. For example, an altitude value determined by GPS is not a height from the geoid but from the theoretical ellipsoid. To overcome this difficulty, NAGAO and KAMINUMA (1988) unified these altitudes by using the geoid model (GEM-10b) to adjust the altitude difference between the geoid and the theoretical ellipsoid. This study is based on their compilation.

The target area of this study is a part of the Mizuho Plateau, where we have relatively dense coverage of gravity data (Fig. 1). The area is roughly 600 km by 600 km and contains 1940 gravity stations. To calculate the Bouguer anomaly, we need to know the ice thickness beneath each gravity station. We employ the ice thickness data determined by radio echo soundings. Of 1940 gravity stations (NAGAO and KAMINUMA, 1988), 944

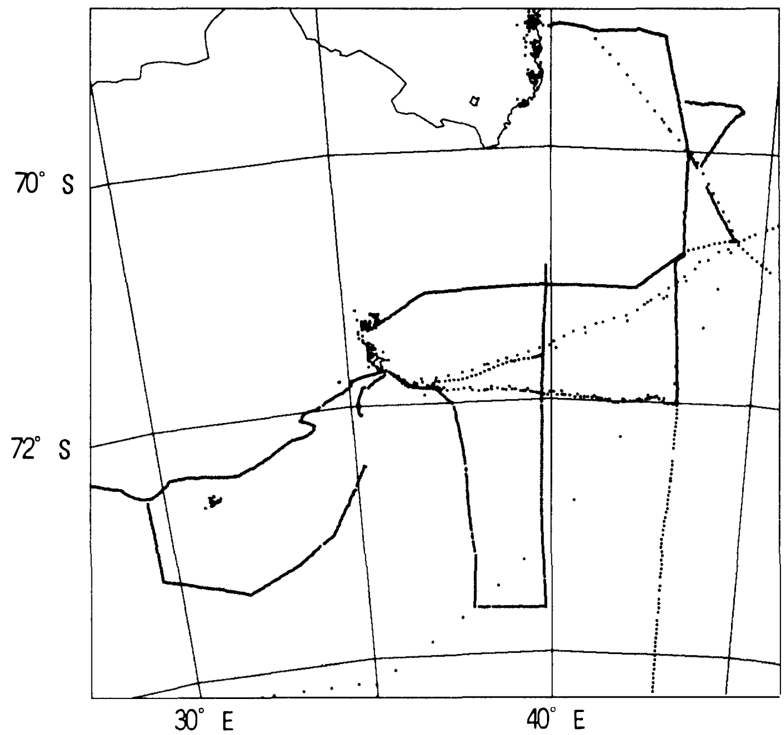


*Fig. 1. Study area and gravity stations. The total number of stations is 1940.*

have ice thickness data. Therefore, 944 Bouguer anomaly data were calculated.

## 3. Key Idea of This Work

This study supposes that gravity anomalies of the target area are largely controlled by two boundary shapes of different subsurface density. One is the ice sheet-bedrock boundary; the other is the crust-mantle boundary (Moho discontinuity). The basic concept of this analysis is as follows (Fig. 2).

Generally, the Bouguer anomaly represents the effect of density structure of materials below sea level. In Antarctica, especially on the ice sheet, the effect of the ice sheet is corrected by what we call a Bouguer correction, like the gravity calculation in a sea area. In this correction, the ice sheet mass is replaced by ordinary crustal rock, which has a density of 2.67 g/cm$^3$. If this Bouguer correction is accurate, the effect of bedrock should basically disappear. Therefore, long wave length components of Bouguer anomaly should express the shape of the Moho discontinuity because we assumed a two-layer structure. On the other hand, expecting to obtain a gravity anomaly which is equivalent to the free-air anomaly on the sea, KAMINUMA and MIZOUE (1987) introduced the high level gravity anomaly (hereafter called HLGA). HLGA is the gravity anomaly at 4000 m height calculated by filling the free space with ice from the 4000 m height to the ice surface. The HLGA is expressed by the following equation,

$$g_{HL} = \Delta g_0 - 2\pi G \rho_i (H - h),$$

where $g_{HL}$ is the HLGA, $\Delta g_0$ the free air anomaly, $G$ the universal gravity constant, $\rho_i$ the

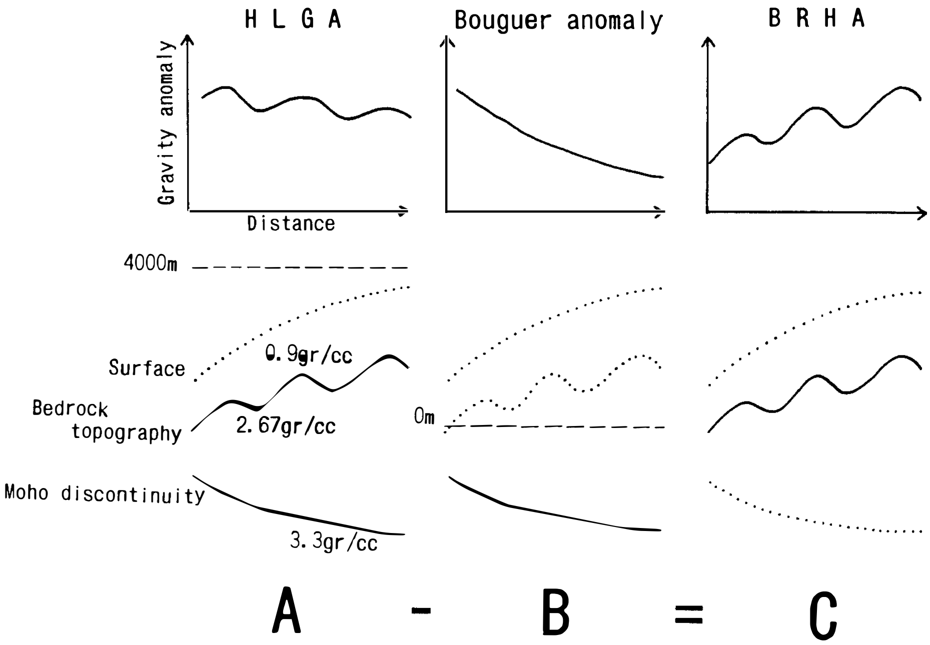


*Fig. 2. Basic concept of this analysis. A : High level gravity anomaly (HLGA) shows the gravity effect at 4000 m height by filling the space below that height with ice. B : The Bouguer anomaly represents the effect of density of materials below sea level. C : Bedrock height anomaly (BRHA) is gravity anomaly which subtracted long-wavelength components of Bouguer anomaly from HLGA.*

density of ice, $H$ the elevation of the gravity station, and $h$ the reduced height (in this study, $h=4000$ m), respectively. Therefore, the variation of HLGA contains effects of the shape of the Moho discontinuity and the bed rock topography. Furthermore, we expect that gravity anomaly which subtracted long-wavelength component of Bouguer anomaly from HLGA (hereafter Bed Rock Height Anomaly or BRHA) is presumably due to bedrock topography (see Fig. 2).

If the above assumptions are correct, the bedrock topography shape and Moho discontinuity from gravity data should be estimated. For normal gravity correction, a terrain correction should be used. However, we do not have sufficient topographic data. Therefore, a terrain correction is not used. How we accounted for the effect of terrain we will be discussed in the following section.

## 4. Algorithm for Crustal Structure Estimation

This study employs HLGA (KAMINUMA and MIZOUE, 1978) and Bouguer anomaly data to estimate the crustal structure of this region. To obtain Bouguer anomaly values in the polar region, we need both altitude and ice thickness data at each gravity station. However, only about 20% of the existing ice thickness data are accompanied by gravity data (KAMINUMA and NAGAO, 1984 ; NAGAO and KAMINUMA, 1988) (about 50% of the data in the studied area). Therefore, fewer points have Bouguer anomaly data than have HLGA data.

As the first step, we assume that all data are highly accurate. The following is the analysis procedure :

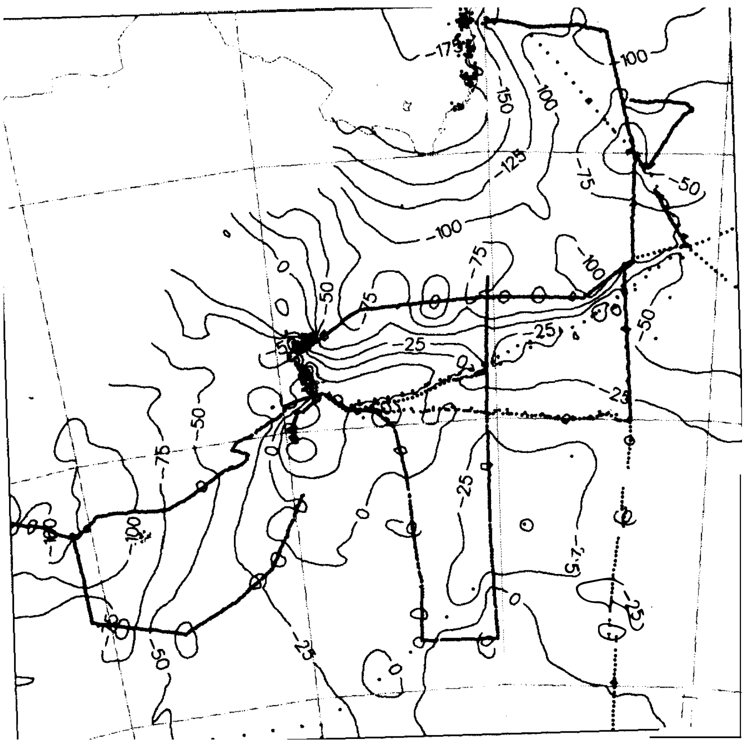


*Fig. 3. High level gravity anomaly (HLGA) map around Mizuho Plateau. Contour interval is 25 mgal.*

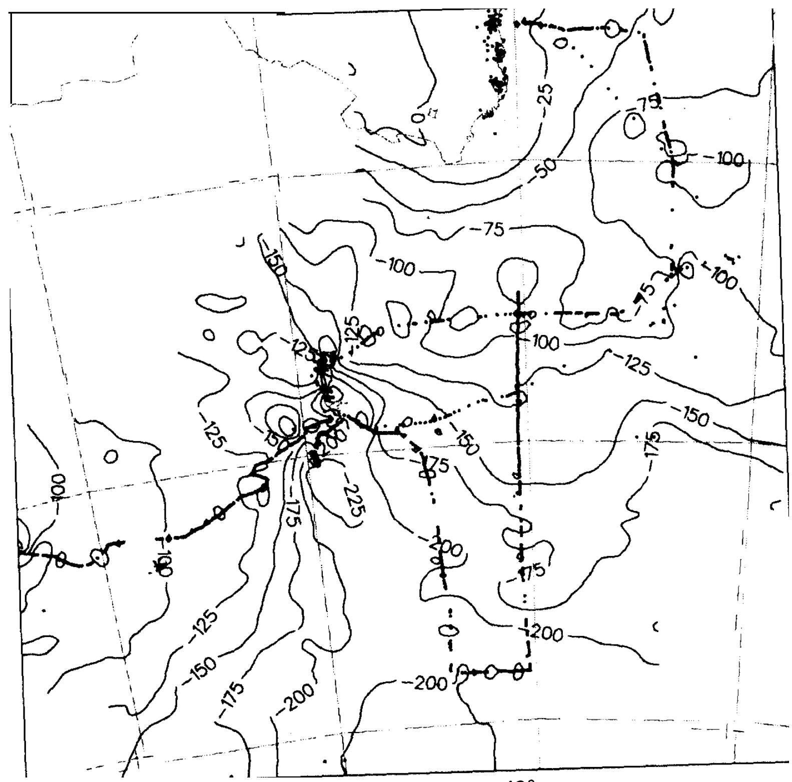


*Fig. 4. Bouguer anomaly map around Mizuho Plateau. Contour interval is 25 mgal.*

(1) Create grid data sets from HLGA and Bouguer anomaly data.
(2) Separate Bouguer anomaly data into short- and long-wavelength data. In this study, we applied a two-dimensional fast Fourier transform filtering technique.
(3) Estimate the shape of the Moho discontinuity from long wavelength components of the Bouguer anomaly. In this procedure, we applied an iteration method (HAGIWARA, 1987). This technique can calculate distance between the actual density discontinuity and given average boundary depth.
(4) The gravity anomaly which is calculated by subtracting the long-wavelength component of Bouguer anomaly from the high level anomaly (BRHA) is presumably due to bedrock topography. Therefore, we can estimate the bedrock topography by iteration (HAGIWARA, 1987).

Figure 3 shows an HLGA map of the study area. Figure 4 shows the Bouguer anomaly map. The distribution of Moho depth calculated by the technique of HAGIWARA (1987) is shown in Fig. 5. IKAMI and ITO (1984) estimated the Moho depth as 40 km beneath Syowa Station by using explosion seismic data of JARE-21 and -22. Therefore, in this study, we employed the point directly below Syowa Station, with Moho depth of 40 km, as a control point. Figure 5 shows that Moho depth generally increases with latitude. This gives a Moho depth below the Yamato Mountains of about 45 km, compatible with the result of NAGAO and KAMINUMA (1984) in the same area. Figure 6 shows the BRHA map of the same area. Although we tried to estimate the bedrock

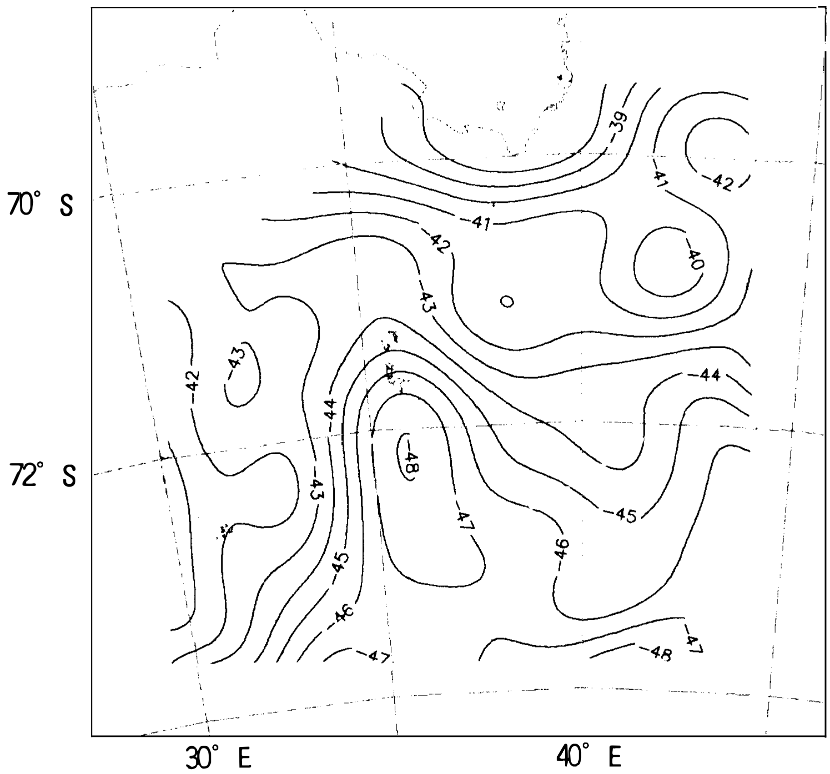


*Fig. 5. Distribution of Moho depth calculated by the iteration method (HAGIWARA, 1987) by using the long-wavelength component of the Bouguer anomaly data. Contour interval is 1 km.*

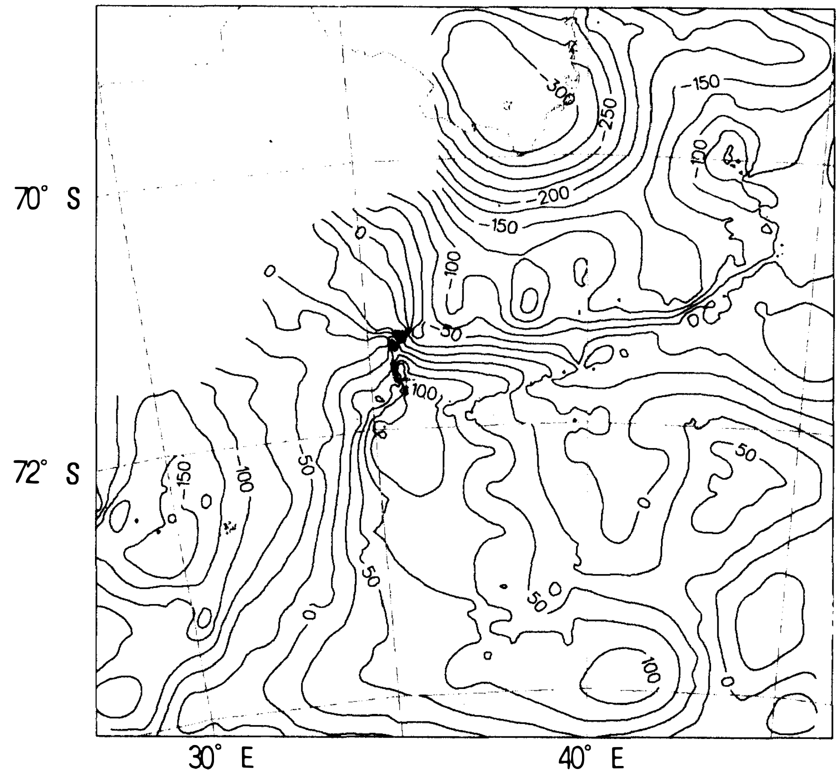


*Fig. 6. Bedrock height anomaly (BRHA) map around Mizuho Plateau. Contour interval is 25 mgal.*

topography by using the same iteration method (HAGIWARA, 1987), the solution (value of bedrock height) has not converged to a certain condition in a large part of the study area. This result indicates that some of the input data (BRHA) are unnatural.

On the other hand, we calculate the first order approximation of bedrock height by the following equation,

$$h=(g-g_{syo})/2\pi G(\rho_b-\rho_i),$$

where $h$ is the bedrock height, $g$ the BRHA, $g_{syo}$ the BRHA at Syowa Station, $G$ the universal constant of gravity, $\rho_b$ the density of the bedrock, and $\rho_i$ the density of the ice sheet. This approximation is based on the theoretical infinite horizontal plane model. The control point of this approximation is at Syowa Station, with 0 m bedrock height. Figure 7 shows the result by using the above formula. This result is quite unnatural because, in almost all of the target area, calculated bedrock heights are higher than the real topography of the ice surface. So we need to evaluate the accuracy of the whole data.

## 5. Evaluation of Data Accuracy

In the previous section, we obtained several unnatural results.

To evaluate data accuracy, we examined the relationship between gravity anomaly (BRHA) and bedrock height (Fig. 8). If the gravity contribution is caused only by bedrock topography (because BRHA has already removed the effect of the Moho disconti-

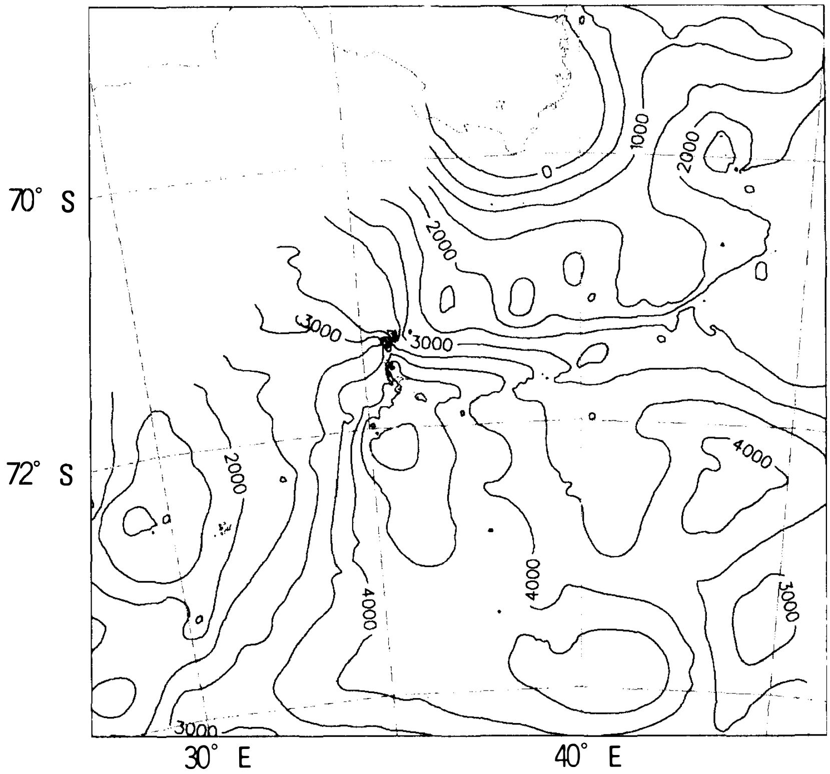


*Fig. 7. Bedrock topography calculated from first order approximation of the BRHA data. Contour interval is 500 m.*

nuity), the theoretical gradient of the gravity anomaly (BRHA)-bedrock height graph (G-H graph) is 74 mgal per 1 km of bedrock height difference, assuming that the density contrast between ice and bedrock is about 1.8 g/cm$^3$. The gradient of BRHA is too steep (more than 160 mgal/km) compared with the theoretical gradient of 74 mgal/km. This result means that the density contrast is more than 3.8 g/cm$^3$. It is impossible that the material beneath the ice sheet has a density of 4.7 g/cm$^3$ (0.9 g/cm$^3$ + 3.8 g/cm$^3$). Therefore, this fact indicates that some nonnegligible errors were present in our data sets.

As fundamental data, this study used gravity value, ice thickness, and measurement point height. If these errors are caused by gravity data errors, a correction of more than 100 mgal should be applied to fit the theoretical gradient (74 mgal/km) in a large part of the study area. However, the measurement error of gravity itself is usually at most 0.1 mgal. The error of height data may be lower than 20 m (influence of gravity anomaly data about 7 mgal). For the gravity anomaly data we used in this study, terrain correction is not considered because we do not have detailed bedrock topography data. However, if we consider terrain correction, we can expect theoretically that the gradient of BRHA-bedrock height should be steeper than that in Fig. 8. We have already evaluated the accuracy of the gravity and measurement point height. Therefore, ice thickness is suspected.

We suggest the following possible cause of the unsatisfactory results. To simplify the discussion, we present a simple model explaining the relationships between subsurface structures and gravity anomalies (see Fig. 9). In this model, the shape of the Moho discontinuity is a horizontal plane (D in Fig. 9). Ice thickness increases with distance

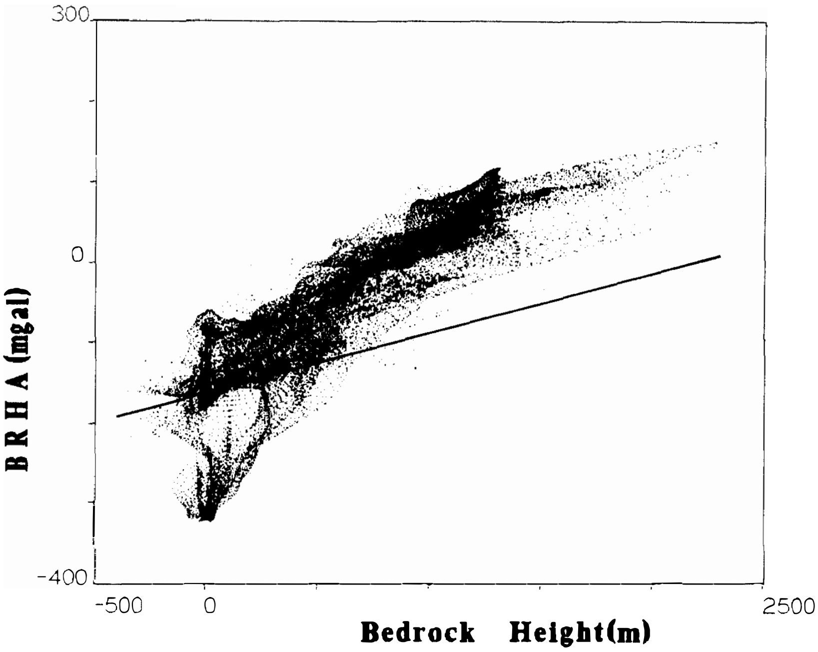


*Fig. 8.* *Correlation between BRHA and the bedrock height of the target area. The solid line indicates the theoretical gradient (74 mgal/km).*

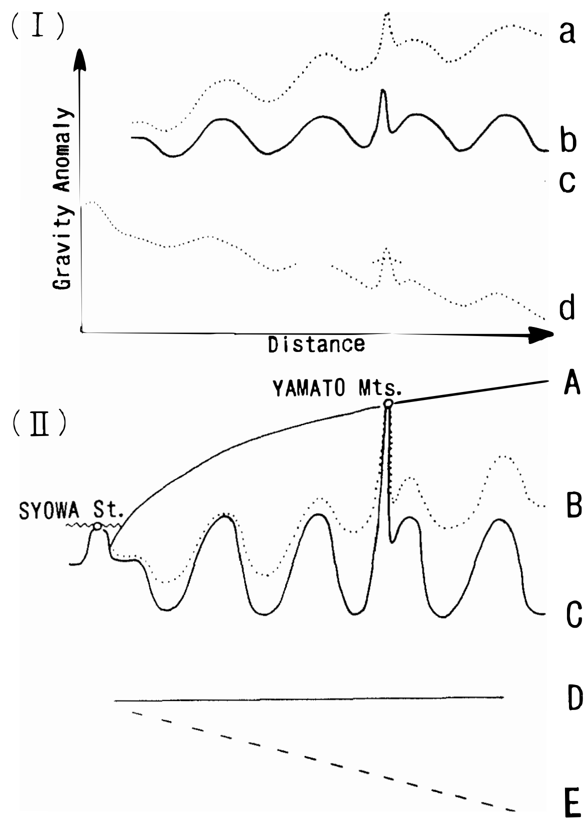


*Fig. 9.* *Schematic model of the relationship between gravity anomalies (I) and subsurface structures (II).*
*(I) : Gravity anomalies expected from the model of (II) ; a : BRHA ; b : HLGA ; c : Expected complete Bouguer anomaly (after terrain correction) ; d : Observed Bouguer anomaly ;*
*(II) : Model of subsurface structure ; A : Ice surface ; B : Observed bedrock topography by radio echo sounding ; C : Real bedrock topography ; D : Real Moho discontinuity ; E : Observe Moho discontinuity. Dotted and broken lines indicate data influenced by the assumed error in ice thickness.*

from the coast line, and the shape of the ice sheet-bedrock boundary is a horizontal plane on which is superimposed a simple wave form (C in Fig. 9). By using this model, we supposed one circumstance of arising the error of the ice thickness data.

In Antarctica, the Bouguer correction is calculated by the following equation,

$$C_B = 2\pi G(\rho_i(H-h_b)+\rho_b h_b),$$

where $C_B$ is the Bouguer correction, $G$ the universal gravity constant, $\rho_i$ the ice sheet density, $H$ the gravity station elevation, $h_b$ the bedrock height, and $\rho_b$ the bedrock density. If the ice thickness value is always smaller than the actual thickness by a constant factor (B in Fig. 9), the amount of the Bouguer correction error should be a constant factor of the actual thickness. As a general tendency, the ice thickness in this area increases with distance from the coast line. Therefore, the observed Bouguer anomaly, influenced by the error of ice thickness, decreases with distance from the coast line (d in Fig. 9). Therefore, the estimated gradient of the Moho discontinuity (E in Fig. 9) is steeper than the actual gradient. Moreover, the general trend of BRHA (a in Fig. 9) ascends with distance from the coast line. If the Moho is flat (horizontal plane), undulation of HLGA (b in Fig. 9) should express undulation of bedrock topography, and HLGA and BRHA should be parallel to each other. However, the distribution of BRHA is not parallel to HLGA. This means that the BRHA does not express the bedrock topography shape. This derived conclusion is not in accordance with our initial BRHA definition (assumption) in Section 3.

## 6. Concluding Remarks

The authors have reached the following three conclusions.

(1) Qualitatively, ice thickness determined by radio echo soundings is smaller than the actual thickness by a constant factor. Possible explanations are: a) radio echo sounding detects some intra-ice discontinuity due to moraine and/or climatic change; b) radio wave velocity error due to variation of the estimated dielectric constant.

(2) The gradient of the Moho discontinuity estimated by using ice thickness data is too steep in comparison with the actual gradient.

(3) This type of analysis based on gravity data is a very powerful tool to evaluate the accuracy of ice thickness data. In this analysis, we can evaluate ice thickness data using the density difference value (obtained gradient of the G-H graph as shown in Fig. 8). If the density difference is deduced by using the correct ice thickness, the density difference should be the actual density difference across the ice sheet-bedrock boundary. Suppose, if ice radar observed some intra-ice echoes, the density difference value is an indicator of discriminating a real echo from the bedrock. Ice thickness data giving the correct density contrast should be the most reliable data.

We will try to estimate more reliable ice thickness from a gravitational point of view. Thereafter, using the resulting data, we plan to reconstruct the crustal model in and around Mizuho Plateau.

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