45. Study on the Crust-mantle Structure in Japan.\(^*\)

Part I, Analysis of Gravity Data.

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Abstract

The Bouguer anomaly distribution in and around Japanese islands has been analyzed for the study of the crustal and upper mantle structures. Regional value of gravity anomalies has been adopted intending to remove unknown effects of various kinds which would obscure the regional structure. In the first stage of the treatment, the Bouguer anomalies \( \Delta g \) for 1° squares have been calculated from the map compiled by Tsuibo and then reduced by "influence coefficient method" to obtain the reduced Bouguer anomalies \( \Delta G \).

The reduced Bouguer anomaly could be regarded as the mean gravitational attraction over a square when the structure just below the square is assumed to extend to infinity. This enables one to estimate the depth of the Mohorovicic discontinuity \( D \) by the simple formula \( D = D_0 \frac{\Delta G}{2 \pi \Delta g} \), provided the normal depth of the Moho \( D_0 \) and the density difference \( \Delta \rho \) between the crust and mantle are given.

1. Data

Gravity values at every other bench mark along the line of precise levelling throughout Japan have been determined by Tsuibo, Jitsukawa and Tajima,\(^*\) by means of a Worden gravimeter.

In addition to these gravity determinations on land, we have obtained about twenty observations at sea which were made by Matsuyama and Kimmagi by means of a Venning Meineck pendulum.

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apparatus on board a submarine. These have been summarized by Tsuibo.\textsuperscript{2} Recently more gravity observations at sea were made by Tomoda, Kanamori, Sugiura and Tokuhiro.\textsuperscript{4,6} by means of a surface ship gravity meter developed by Tsuibo, Tomoda and Kanamori.\textsuperscript{1,2} This data covers the south-eastern area off the coast of Honshu, Shikoku and Kyushu Islands and consists of more than one thousand observation points of which more than five hundred values have been calculated with an accuracy of about 10 milligals. This data has been briefly included in the present analysis.

No gravity observations are available for the present study in the Japan Sea, but it is thought that the more gradual change of the Bouguer anomaly distribution in the Japan Sea coast side compared with the Pacific coast side of Japan and about 0 milligal Bouguer gravity anomaly at Seoul in Korea\textsuperscript{7} would imply the gradual change of gravity in the Japan Sea area. Therefore, we can reasonably extrapolate the values at land stations out in the Japan Sea. Although these extrapolated values are naturally uncertain within a range of about 20 milligals, they can be accepted so long as we only use them as supplementary to the values on land. In fact, these uncertainties have generally little effect on the study of the structure within the land area as will be shown in later discussions.

2. Method of analysis

2.1. Local and regional anomalies.

In order to study crustal structures from gravity anomalies, it is necessary to start with the Bouguer anomalies. However, before proceeding with the analysis, it should be remarked that ambiguous assumptions of various kinds have usually been made in the reduction of the observed gravity anomalies to the Bouguer anomalies.

First of all, the gravity values observed at height $h$ are reduced to the values at the mean sea level by the free air formula

$$\delta g_{\text{free air}} = \delta g_{\text{observed}} - \left(\frac{\delta g}{\partial h}\right)_h.$$

In this formula the coefficient $\left(\frac{\delta g}{\partial h}\right)_h = -0.3088$ mgal/m is generally adopted, although it has been reported that the local value of $\delta g/h$ sharply varies from place to place ranging from $-0.27$ mgal/m to $-0.33$ mgal/m.\textsuperscript{4,7} Secondly, in the Bouguer reduction, the density $\rho_s = 2.61$ g/cm$^3$ is usually taken as the crustal density, but many laboratory measurements have shown that the density of materials forming topographical structures assumes various values ranging from about 1.7 g/cm$^3$ to 2.9 g/cm$^3$. Furthermore, since the neighboring topographical structures disturb the gravity anomaly distribution and obscure the anomalies of deeper origins, the Bouguer gravity anomaly should not readily be used in the interpretation of crustal structures. Although it is desirable to correct and exclude, prior to the analysis, all the above-mentioned errors involved in the reduction and due to the disturbing effects, it is not always possible for us to remove these effects because of absence of direct determination of density and $\delta g/h$ in various places. Furthermore, all these effects are usually rather local and if we use the gravity anomalies without removing those due to surface origin, the derived subterranean structures would hardly be plausible. As is well known, the disturbing gravity anomalies $\delta g$ of wave length $\lambda$ can be interpreted as due to the density distribution $\rho = (2\pi)^{-1} \rho_s \exp(2\pi D/\lambda)$ at the depth $D$. This shows that, because of the factor $\exp(2\pi D/\lambda)$, only a small disturbance in gravity might sometimes be interpreted as an unreasonably large anomalous structure. For instance, it happens quite often that the value of $\left(\frac{\delta g}{\partial h}\right)$ is larger than the normal value of 0.3088 mgal/m at any one place, whereas it is smaller at neighboring places only 10-50 kilometers away. Therefore, free air reduction assuming constant $\left(\frac{\delta g}{\partial h}\right)_h$ would result in false short-wave length anomalies. Considering these factors, we must not use the original gravity data which may contain much of shorter wave length components. However, taking the average of the gravity value over a region thousands of square kilometers in extent, those local effects would be cancelled out to a tolerable amount. Therefore, the larger the extent of the region, the smaller the disturbing effects stated above would be, at the expense of detailed knowledge of structures. In this study, the unit region has been taken to have an extent of 1 degree latitude x 1 degree longitude, which may be suitable for resolving

\textsuperscript{2} C. Tsuibo, Jigyo-kan (Japan, 1941), (in Japanese).
\textsuperscript{7} C. F. Woolard and W. E. Strange, Gravity Anomalies and the Crust of the Earth in the Pacific Basin, (American Geophysical Union, 1965).
\textsuperscript{8} N. Kemagai, D. Aki and Y. Yoshimura, Comitato di Giografia Terrestre ed Applicata, 2 (1960), 607.
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the problems when studying the general picture of the crust-mantle structure in Japan. With these 1° squares we can discuss the crustal structures of wavelength longer than 200 km, ambiguity originating from the effects of unknown local structures being lessened.

2.2. Mean gravity anomalies

In order to obtain the average value over every 1° square, we divided the whole area, into 115 1° squares. For the squares on land, we first divided the area, using the map of Bouguer anomaly distribution compiled by Tsuboi, into about 5000 10 km × 10 km sub-squares and read the corresponding mean gravity value in those sub-squares. The mean Bouguer anomaly for 1° square on land was obtained by taking the average of the values for these 10 km squares.

For the squares at sea, as we have not enough data to proceed with calculation in the same way as for the squares on land, we merely took the average of the values at observation points contained in every square. Accordingly, the resulting accuracy was reduced to 20~30 milligals. Accuracy of this order turned out to be sufficient for the present analysis, since this data at sea will be used only as supplementary data for the study on structures in the land area. The results are shown in Fig. 1 and Table 1. The computed mean Bouguer anomalies \( \delta g \) in milligals are written in the corresponding 1° squares (upper figures in Fig. 1). The figures in parenthesis at the left corner of every 1° square indicate the number of 1° squares. These values would be reliable to 10 mgal for land squares and 30 mgal for the squares at sea, or better.

In order to show clearly the regional features of the Bouguer anomaly distribution in Japan just obtained, the values at every grid point 1° apart are interpolated and contoured. The interpolation has been made by the following formula cutting off the anomalies of wavelengths shorter than 200 km,

\[
\delta g(x, y) = \sum_{i,j} \delta g_{i,j} \sin \frac{\pi}{L}(x-x_i) \sin \frac{\pi}{M}(y-y_j)
\]

where \( \delta g_{i,j} \) is the gravity anomaly at a grid point \((i, j)\) and \( L \) and \( M \) indicate the spatial intervals of the grid points in \( x \) and \( y \) direction respectively. The regional gravity distribution \( \delta g(x, y) \) contoured at the

interval of 10 mgal is shown in Fig. 2.

2.3. Reduction of the mean Bouguer anomaly

In the preceding section we obtained the mean Bouguer anomaly in 1° squares distributed over the Japanese islands and the surrounding seas.

As stated earlier, the advantage of taking the mean value over an area extending about 10 km² is to reduce the influence of the surrounding regions preserving the knowledge for the structure of about 200 km in wavelength which might be the upper-most wavelength necessary for a discussion of the structures of Japanese Islands. However, even when the extent of the region is taken as of the order of 10 km², the neighboring region still has appreciable effects on the region studied, and the mean Bouguer anomaly \( \delta g \) cannot directly be used for a discussion of the structures therein. The mean Bouguer anomaly should be reduced to a quantity which characteristically represents the structures of the corresponding region.

For illustration, a two-dimensional case is presented in the following.

a) Two-dimensional case

For the first stage of the treatment, we take the average value over the extent of 100 km along a two-dimensional gravity profile (Fig. 3). Let \( \delta g \) be the mean gravity anomaly over Region \( i \) and \( H_i \) the mean ordinate of the base of the crust (Moho) measured from the normal depth with which the Bouguer gravity anomaly is assumed to be zero. If we denote the influence on the mean gravity anomaly over Region \( i \) from the structures in Region \( i+k \) by \( \partial g_{i,k} \), \( \delta g_{i,k} \) can approximately be written, with a nondimensional coefficient \( \kappa_i \), as

\[
\delta g_{i,k} = 2\kappa_i \delta g_{i,k} (H_i - H_{i+k}) = -\delta g_{i,k}
\]

(1)

With \( \delta g_{i,k} \) defined above, \( H_i \) can be estimated from \( \delta g_i \) by the following formula,

\[
H_i = \frac{\delta G_i}{2\kappa_i \delta g_i}
\]

(2)

\[
\delta G_i = \delta g_i - \sum_{k \neq 0} \delta g_{i,k}
\]

(3)

where \( \sum_{k \neq 0} \) denotes the summation for all values of \( k \) except zero. \( \delta G \),

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\[ \Delta p(x, y) = \sum_{i,j} \frac{\sin \pi (x-x_i) \cdot \sin \pi (y-y_j)}{L \cdot M}, \]

where \( \Delta p_{i,j} \) is the gravity anomaly at a grid point \((i, j)\) and \(L\) and \(M\) indicate the spatial intervals of the grid points in \(x\) and \(y\) direction respectively. The regional gravity distribution \(\Delta p(x, y)\) contoured at the interval of 10 mgal is shown in Fig. 2.

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\[ \Delta p_{i,k} = 2 \pi k_{i,k} \Delta p_{i,k} (H_i - 1) - \Delta p_{i,k}, \]  \hspace{1cm} (1)

With \(\Delta p_{i,k}\) defined above, \(H_i\) can be estimated from \(\Delta p\) by the following formula,

\[ H_i = \frac{\Delta G_i}{2 \pi k_{i,k} \Delta p}, \]  \hspace{1cm} (2)

\[ \Delta G_i = \Delta p - \sum_{k} \Delta p_{i,k}, \]  \hspace{1cm} (3)

where \(\sum\) denotes the summation for all values of \(k\) except zero. \(\Delta G_i\)
Fig. 1. Mean Bouguer anomalies in milligals for 1° squares (upper figures) and in parentheses at the left corner indicate the square number.

Reduced Bouguer anomalies in milligals for 1° squares on land (lower figures). Numbers
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Table 1. Mean and reduced Bouguer anomalies in milligals for 1° squares in and around Japanese Islands.

<table>
<thead>
<tr>
<th>1° square No.</th>
<th>Locality</th>
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(to be continued)
Fig. 2. Map of mean Bouguer anomaly distribution in milligals in Japan. The contour interval is 10 mgal.
Fig. 2. Map of mean Bouger anomaly distribution in milligals in Japan. The contour interval is 10 mgal.
will be called the reduced Bouguer anomaly in the later discussions. From Formulas (1), (2) and (3)

\[ \mathcal{G}_j = \Delta g - \sum \epsilon_i (\mathcal{G}_{j+i} + \mathcal{G}_{j-i}) \]

\[ = \Delta g - \sum \epsilon_i \mathcal{G}_{j+i} \]

\[ + \mathcal{G}_j \sum \epsilon_i, \tag{4} \]

whereupon,

\[ \mathcal{G}_j = \Delta g - \sum \epsilon_i \mathcal{G}_{j+i} \sum \epsilon_i, \tag{5} \]

which gives the reduced Bouguer anomaly \( \mathcal{G}_j \) in a region from the mean Bouguer anomaly \( \Delta g \) of the same region and \( \mathcal{G}_j \) of the neighboring regions.

From the expression (6), it can easily be seen that if the structure is flat \( (\Delta g_y = \Delta g = \Delta g) \), \( \mathcal{G}_j \) is reduced to \( \Delta g \) and if the neighboring regions have no influence on the region studied, \( \epsilon_i \) should be taken as 0, and \( \mathcal{G}_j \) would naturally become \( \Delta g \). Putting \( s = 0.154 \) in Formula (6), we obtain the final formula for the two-dimensional case in the form,

\[ \mathcal{G}_j = 1.57 \Delta g - 0.296 (\Delta g_1 + \Delta g_2). \tag{7} \]

b) Three-dimensional case

The three-dimensional treatment of the present problem is essentially similar to that of the two-dimensional problem.

The expression which is comparable to (6) is written as,

\[ \mathcal{G}_{j,i} = \Delta g - \sum \epsilon_i \mathcal{G}_{j+i} \sum \epsilon_i, \tag{8} \]

(See Fig. 4)

If we neglect the coefficients other than \( \epsilon_i = \epsilon_{i=1} = \epsilon_{i=2} = \epsilon_{i=3} \) and \( \epsilon_i = \epsilon_{i=4} \) and extrapolate the data in the manner

\[ \mathcal{G}_{j=1} = \mathcal{G}_{j=1-i}, \]

\[ \mathcal{G}_{j=2} = \mathcal{G}_{j=2-i}, \]

\[ \mathcal{G}_{j=3} = \mathcal{G}_{j=3-i}, \]

\[ \mathcal{G}_{j=4} = \mathcal{G}_{j=4-i}, \]
will be called the reduced Bouguer anomaly in the later discussions. From Formulas (1), (2) and (3)

$$G_1 = \frac{\beta}{2\pi} \sum \epsilon_k (G_{k+1} - G_k)$$

$$= \frac{\beta}{2\pi} \sum \epsilon_k G_k$$

$$+ \frac{\beta}{2\pi} \sum \epsilon_k L_k$$

whereupon,

$$G_k = \frac{\beta}{2\pi} \sum \epsilon_k G_k$$

Fig. 3. Schematic figure illustrating the influence coefficient method in a two-dimensional case.

If we condense the anomalous mass on a plane placed at the normal depth $D_k$ as in the Fourier series method, it is clear from Formula (1) that $\epsilon_k$ can be calculated as the mean gravity anomaly over a region due to a mass block of unit thickness and of density $(2\pi k^2)$ placed at the depth $D_k$ beneath another region which is away from the former by the distance $k$ times the length of a unit region (the $k$-th nearest neighbour). In the present case, $\epsilon_k$ has been calculated, assuming the depth $D_k$ to be 33 km, by the following formula:

$$\epsilon_k = \frac{1}{100} \left[ \tan \left( \frac{x-x_0}{\pi v} \right) - \tan \left( \frac{x-x_0}{\pi v} \right) \right] dx.$$

The results are $\epsilon_k = 0.154$ and $\epsilon_k = 0.026$.

As $|G_{k+1} - G_k|$ would not exceed 300 mgal, it can be inferred from Formula (4) that $\epsilon_k$ can reasonably be neglected so long as an accuracy of 10 mgal in $G_k$ is required. Consequently, we can neglect, in the later treatment, the influence from all regions except the neighbouring ones. Accordingly, if $G_k$ is required, we can arbitrarily assume $G_{k+1}$ and $G_{k-1}$. In the present study, we simply extrapolate the data in such a way as $G_{k+1} = G_{k+1}$, $G_{k-1} = G_{k-1}$ and obtain the following expressions from Formula (6),

$$G_{k+1} = -\epsilon_k (G_{k+1} + G_{k-1})$$

$$G_{k-1} = -\epsilon_k (G_{k+1} - G_{k-1})$$

Eliminating $G_1$ and $G_{k+1}$ leads to

$$G_k = \frac{1}{1-\epsilon_k} \frac{D_k}{1-\epsilon_k} (1-\epsilon_k) D_k$$

which gives the reduced Bouguer anomaly $G_k$ in a region from the mean Bouguer anomaly $D_k$ of the same region and $D_k$ and $D_{k-1}$ of the neighbouring regions.

From the expression (6), it can easily be seen that if the structure is flat $(D_{k+1} = D_{k} = D_{k})$, $G_k$ is reduced to $D_k$ and if the neighbouring regions have no influence on the region studied, $\epsilon_k$ should be taken as 0, and $G_k$ would naturally become $D_k$. Putting $\epsilon_k = 0.154$ in Formula (6), we obtain the final formula for the two-dimensional case in the form,

$$G_k = 1.57 D_k - 0.296 (D_k + D_{k-1}).$$

b) Three-dimensional case

The three-dimensional treatment of the present problem is essentially similar to that of the two-dimensional problem.

The expression which is comparable to (6) can be written as,

$$G_k = \frac{D_k}{1-\epsilon_k} \frac{1}{1-\epsilon_k} \frac{1}{1-\epsilon_k}$$

(8)

(See Fig. 4)

If we neglect the coefficients other than $\epsilon_k$, $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, and $\epsilon_k = \epsilon_k$, and extrapolate the data in the manner $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, $\epsilon_k = \epsilon_k$, and $\epsilon_k = \epsilon_k$, the formula (8) can be reduced to a 9-th degree simultaneous
algebraic equation for $\mathcal{G}_{1,1}$, $\mathcal{G}_{1,2}$, $\mathcal{G}_{2,1}$, $\mathcal{G}_{2,2}$, $\mathcal{G}_{3,1}$, $\mathcal{G}_{3,2}$, $\mathcal{G}_{3,3}$, $\mathcal{G}_{3,4}$, $\mathcal{G}_{4,1}$, $\mathcal{G}_{4,2}$, $\mathcal{G}_{4,3}$, $\mathcal{G}_{4,4}$, which can be given by the following.

\[
\begin{pmatrix}
1-2e_x & -2e_y & e_x & e_y & e_x & e_y & e_z & e_x & e_y & e_z \\
-2e_x & 1-2e_y & e_x & e_y & e_x & e_y & e_z & e_x & e_y & e_z \\
e_x & e_y & e_x & e_y & e_x & e_y & e_y & e_x & e_y & e_x \\
e_y & e_x & e_y & e_x & e_y & e_x & e_y & e_x & e_y & e_x \\
e_z & e_x & e_z & e_x & e_z & e_x & e_z & e_x & e_z & e_x \\
e_z & e_y & e_z & e_y & e_z & e_y & e_z & e_y & e_z & e_y \\
e_z & e_z & e_z & e_z & e_z & e_z & e_z & e_z & e_z & e_z
\end{pmatrix}
\]

This formula will be used in the present study to reduce the mean Bouguer anomalies to the reduced Bouguer anomalies. As in the two-dimensional problem, if we put $\mathcal{G}_{1,1} = \mathcal{G}_{1,2} = \mathcal{G}_{2,1} = \mathcal{G}_{2,2} = \mathcal{G}_{3,1} = \mathcal{G}_{3,2} = \mathcal{G}_{3,3} = \mathcal{G}_{3,4} = \mathcal{G}_{4,1} = \mathcal{G}_{4,2} = \mathcal{G}_{4,3} = \mathcal{G}_{4,4}$ (i.e. the structure is assumed to be flat), Formula (10) gives $\mathcal{G}_{1,1} = \mathcal{G}_{1,2}$ satisfying the physical requirement. It is also clear from this formula that the coefficient for $\mathcal{G}_{1,1}$, $\mathcal{G}_{1,2}$, $\mathcal{G}_{1,3}$ and $\mathcal{G}_{1,4}$ is very small compared with others. This implies that no accuracy better than 100 mgal in $\mathcal{G}_{1}$ is required for the diagonally located regions. For the same reason, an accuracy of about 20 mgal for $\mathcal{G}_{2,1}$, $\mathcal{G}_{2,2}$, $\mathcal{G}_{2,3}$ and $\mathcal{G}_{2,4}$ would be sufficient to obtain the value of $\mathcal{G}_{2}$, with an accuracy greater than 5 milligals. In this study, all the sea observations and the extrapolated values which may be uncertain within the range 20 to 30 mgal have been adopted only for $\mathcal{G}_{4}$ $(0,0) = 0(0,0)$, and $\mathcal{G}_{3}$, which has been obtained only for the 1st squares on land for which an accuracy of $\mathcal{G}_{4}$ higher than 10 mgal was attained. This guarantees the reliability of the value of $\mathcal{G}$ obtained by the present method.

It will be of some interest to note here that Tschoe, Oldham and Waitzman coefficients' $\Phi(x,y)$ in the sin $x/z$ method, which have recently been calculated and tabulated by Saito et al.," give $\Phi(0,0) = 2.136$, $\Phi(1,0) = 0.397$, and $\Phi(0,1) = 0.015$ for $D = 0.3$ (e.g. the depth of the compensation 30 km for 100 km horizontal spacing) which are comparable to the coefficients in Formula (10). Although, since the squares adopted in this study are not taken equilaterally, the coefficients given by the sin $x/z$ method cannot readily be used here, they are in good agreement with the coefficients obtained by Formula (10). Similar coefficients can be obtained by the sin $x/z$ method modified by Kanamori.2) They are $\Phi(0,0) = 2.098$, $\Phi(1,0) = 0.397$, $\Phi(0,1) = 0.012$ and also in fairly good agreement with those obtained by the other two methods.

Thus, the reduced Bouguer anomaly was computed by Formula (10) for all 1st squares on land and the results are given in Fig. 1 (lower figures) and Table 1.

algebraic equation for \( \mathcal{G}_{\xi,-1} = \mathcal{G}_{\xi,-1,0} = \mathcal{G}_{\xi,-1,0,0} = \mathcal{G}_{\xi,-1,0,1} = \mathcal{G}_{\xi,-1,1} \) and \( \mathcal{G}_{\xi,-1} \) which can be given by the following.

\[
\begin{pmatrix}
1 - 2e_1 - 2e_2 & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 \\
e_1 - e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_8 \\
e_1 & e_2 + e_3 & e_4 & e_5 & e_6 & e_7 & e_8 \\
e_1 - e_2 - e_3 & -e_4 & e_5 & e_6 & e_7 & e_8 & e_9 \\
e_1 - e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_8 \\
e_1 & e_2 + e_3 & e_4 & e_5 & e_6 & e_7 & e_8 \\
e_1 - e_2 - e_3 & -e_4 & e_5 & e_6 & e_7 & e_8 & e_9 \\
e_1 & e_2 + e_3 & e_4 & e_5 & e_6 & e_7 & e_8
\end{pmatrix}
\]

This formula will be used in the present study to reduce the mean Bouguer anomalies to the reduced Bouguer anomalies. As in the two-dimensional problem, if we put \( \delta_{\alpha} = \delta_{\beta} = \delta_{\gamma} = \delta_{\delta} = \delta_{\varepsilon} \), (i.e. the structure is assumed to be flat), Formula (10) gives \( \mathcal{G}_{\xi,0} - \delta \) satisfying the physical requirement. It is also clear from this formula that the coefficient for \( \delta_{\alpha}, \delta_{\beta}, \delta_{\gamma}, \delta_{\delta}, \delta_{\varepsilon} \) is very small compared with others. This implies that no accuracy better than 100 m Gal in \( \delta \) is required for the diagonally located regions. For the same reason, an accuracy of about 20 m Gal for \( \delta_{\alpha}, \delta_{\beta}, \delta_{\gamma}, \delta_{\delta}, \delta_{\varepsilon} \) and \( \delta_{\varepsilon} \) would be sufficient to obtain the value of \( \mathcal{G}_{\xi,0} \) with an accuracy greater than 5 milligals. In this study, all the sea observations and the extrapolated values which may be uncertain within the range 20 to 30 m Gal have been adopted only for \( \delta_{\alpha}, \delta_{\beta}, \delta_{\gamma}, \delta_{\delta}, \delta_{\varepsilon} \), and \( \delta_{\varepsilon} \) has been obtained only for the 1st squares on land for which an accuracy of \( \delta_{\varepsilon} \) higher than 10 m Gal was attained. This guarantees the reliability of the value of \( \mathcal{G} \) obtained by the present method.

It will be of some interest to note here that Tsuehi, Oldham and Watschman coefficients\textsuperscript{10} \( \Phi(x,y) \) in the sin x/z method, which have recently been calculated and tabulated by Saito et al.,\textsuperscript{11} give \( \Phi(0,0) = 0.2190 \), \( \Phi(1,0) = 0.297 \), and \( \Phi(1,1) = 0.015 \) for \( D = 0.3 \) (e.g. the depth of the compensation 30 km for 100 km horizontal spacing) which are comparable to the coefficients in Formula (10). Although, since the squares adopted in this study are not taken equidistantly, the coefficients given by sin x/z method cannot readily be used here, they are in good agreement with the coefficients given by Formula (10). Similar coefficients can be obtained by the sin x/z method modified by Kanamori.\textsuperscript{12} They are \( \Phi(0,0) = -0.012 \), \( \Phi(1,0) = 0.202 \), and \( \Phi(1,1) = 0.012 \) and also in fairly good agreement with those obtained by the other two methods.

Thus, the reduced Bouguer anomaly was computed by Formula (10) for all 1st squares on land and the results are given in Fig. 1 (lower figures) and Table 1.

\begin{align}
\mathcal{G}_{\xi,0} & = 1.854 \delta_{\alpha} - 0.239 (\delta_{\beta} + \delta_{\gamma}) \\
& - 0.180 (\delta_{\delta} + \delta_{\varepsilon}) \\
& - 0.099 (\delta_{\varepsilon} + \delta_{\delta} + \delta_{\varepsilon} + \delta_{\varepsilon}).
\end{align}

In Fig. 1 and Table 1, it can be seen that the mean Bouguer anomalies in the central mountain area are largely decreased reflecting the syncline structure in this area. Further, the anomalies in Chugoku district are changed only slightly, indicating the slowly varying structure there.

From $\Delta g$ calculated above, one can obtain the mean depth of the Mohoroviči discontinuity $D$ for each 1° square by the simple formula,

$$D = D_0 - \frac{\Delta g}{2g' \rho_f},$$

provided the mean density difference $\Delta \rho$ between the crust and mantle and the normal depth of the Moho $D_0$ with which the Bouguer anomaly is zero are given. For the values of $D_0$ and $\Delta \rho$, the values given by Worzel and Shurbet (i.e. $D_0 = 33$ km, $\rho_f = 4.3$ g/cm$^3$) may well be used for an analysis of this kind. However, since ignorance of $D_0$ and $\Delta \rho$ for Japan offers no unambiguous solutions, a determination of the depth of Moho will be made in Part 2 of this study with the supplementary data from explosion studies and seismic surface wave studies. Still, it should be noted here that the reduced Bouguer anomalies just obtained can be regarded as a proper measure showing the mean depth of Moho in every 1° square and will be of some use in the interpretation of seismic data.

I am greatly indebted to Prof. H. Takeuchi and Dr. S. Uyeda for their advice and encouragement on this work and their critical review of the manuscript. I am also grateful to Prof. C. Tsuibo for his critical advice at the early stage of this work.

45. 日本の地質とマントル上層部の構造

Part 1. 重力異常の解析

東京大学理学部地質学教室

重力異常によって地質構造を説明する場合に用いることが考えられる。これはどのようにすることである。

1) 許容の範囲内にあるもの Bouguer 異常であるが Bouguer 異常には、いろいろな不確定さが含まれている。第一は Free Air Reduction を行う際に、密度 $\Delta \rho = 0.3$ を用いるが、これの構造は様々であることを考慮に入れるべきである。しかし、かなりどの範囲内においては、密度は一定の値をもってよいと考えてよいであろう。

In Fig. 1 and Table 1, it can be seen that the mean Bouger anomalies in the central mountain area are largely decreased reflecting the syncline structure in this area. Further, the anomalies in Chugoku district are changed only slightly, indicating the slowly varying structure there.

From $d^2$ calculated above, one can obtain the mean depth of the Mohorovičić discontinuity $D$ for each 1° square by the simple formula,

$$D = D_0 - \frac{d^2}{2e^2 \rho_0},$$

provided the mean density differences $\rho_0$ between the crust and mantle and the normal depth of the Moho $D_0$ with which the Bouger anomaly is zero are given. For the values of $D_0$ and $\rho_0$, the values given by Worzel and Shurbet [i.e., $D_0 = 33$ km, $\rho_0 = 37$ g/cm$^3$] may well be used for an analysis of this kind. However, since ignorance of $D_0$ and $\rho_0$ for Japan offers no unambiguous solutions, a determination of the depth of Moho will be made in Part 2 of this study with the supplementary data from explosion studies and seismic surface wave studies. Still, it should be noted here that the reduced Bouger anomalies just obtained can be regarded as a proper measure showing the mean depth of Moho in every 1° square and will be of some use in the interpretation of seismic data.

I am greatly indebted to Prof. H. Takeuchi and Dr. S. Uyeda for their advice and encouragement on this work and their critical review of the manuscript. I am also grateful to Prof. C. Tsuboi for his critical advice at the early stage of this work.

45. 日本の地殻とマントル上層部の構造

Part 1. 重力異常の解析

東京大学理学部地球科学教室 金森博雄

重力異常を日本地殻構造を考察する場合には欠かすことのできないものである。1) 言語学に用いるものは Bouger 异常であるが、Bouger 异常には、いろいろな不確定さが含まれている。第一に、Free Air Reduction を行うと、異常は大気変化の影響を含めて、つまり、各観測点が大気変化の影響を含むのに少なくなる点がある。第二に、Bouger Reduction を行う場合、地殻構造の密度として、$p$ に不確定さは含まれている。