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45. *Study on the Crust-mantle Structure in Japan.**
Part 1, 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 Δg for 1° squares have been calculated from the map compiled by Tsuboi and then reduced by "influence coefficient method" to obtain the reduced Bouguer anomalies ΔG. 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 Mohorovičić discontinuity D by the simple formula $D=D_0-\Delta G/2\pi k^2\Delta\rho$, 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 Tsuboi, Jitsukawa and Tajima,[1] 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 Kumagai by means of a Venning Meinesz pendulum

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* Communicated by T. HAGIWARA.

1) C. TSUBOI, A. JITSUKAWA and H. TAJIMA, *Bull. Earthq. Res. Inst., Suppl.* **4** (1953) (1954) (1955) (1956), 1-551.

apparatus on board a submarine. These have been summarized by Tsuboi.[2] Recently more gravity observations at sea were made by Tomoda, Kanamori, Sugiura and Tokuhiro[3),4)] by means of a surface ship gravity meter developed by Tsuboi, Tomoda and Kanamori.[5),6)] 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[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

2) C. TSUBOI, *Zyuryoku*, (Iwanami Shoten, 1944), (in Japanese).

3) C. TSUBOI, Y. TOMODA, H. KANAMORI, K. SUGIURA and A. TOKUHIRO, *Annual Conference of Geodetic Soc. of Japan* (Oct. 1961).

4) Y. TOMODA, H. KANAMORI and A. TOKUHIRO, *ibid.*, (Oct. 1963).

5) C. TSUBOI, Y. TOMODA and H. KANAMORI, *Proc. Japan Acad.*, **37** (1961), 571.

6) Y. TOMODA and H. KANAMORI, *Jour. Geod. Soc. Japan*, **6** (1962), 116.

7) G. P. WOOLLARD and W. E. STRANGE, *Gravity Anomalies and the Crust of the Earth in the Pacific Basin*, (American Geophysical Union, 1962).

$$\Delta g_{\text{sea level}} = \Delta g_{\text{observed}} - \left(\frac{\partial g}{\partial h}\right)_0 h.$$

In this formula the coefficient $(\partial g/\partial h)_0 = -0.3086$ mgal/m is generally adopted, although it has been reported that the local value of $\partial g/\partial h$ sharply varies from place to place ranging from -0.27 mgal/m to -0.33 mgal/m.[8] Secondly, in the Bouguer reduction, the density $\rho_B = 2.67$ 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 neighbouring 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 $\partial g/\partial h$ in various places. Furthermore, all those 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 Δg of wave length λ can be interpreted as due to the density distribution $\rho = (2\pi k^2)^{-1} \Delta g \exp(2\pi D/\lambda)$ 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 $|\partial g/\partial h|$ is larger than the normal value of 0.3086 mgal/m at any one place, whereas it is smaller at neighbouring places only $10 \sim 50$ kilometers away. Therefore, free air reduction assuming constant $\partial g/\partial h$ 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° latitude $\times$ 1° longitude, which may be suitable for resolving

8) N. KUMAGAI, D. ABE and Y. YOSHIMURA, *Bolletino di Geofisica Teorica ed Applicata*, **2** (1960), 607.

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 wave length 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 complied by Tsuboi,[9] into about 5000 10 km × 10 km sub-squares and read the corresponding mean gravity value in these 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 Δg 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,

$$\Delta g(x,y)=\sum_{i,j}\Delta g_{i,j}\,\frac{\sin\frac{\pi}{L}(x-x_i)}{\frac{\pi}{L}(x-x_i)}\;\frac{\sin\frac{\pi}{M}(y-y_j)}{\frac{\pi}{M}(y-y_j)}\ ,$$

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

9) C. TSUBOI, *Bull. Earthq. Res. Inst. Suppl.*, 4 (1954), 124.

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 10^4 km^2 is to reduce the influence of the surrounding regions preserving the knowledge for the structure of about 200 km in wave length which might be the upper-most wave length 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 10^4km^2, the neighbouring region still has appreciable effects on the region studied, and the mean Bouguer anomaly Δg 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 Δg_i 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 $\delta g_{i,k}$, $\delta g_{i,k}$ can approximately be written, with a nondimensional coefficient κ_k, as

$$\delta g_{i,\kappa}=2\pi k^2 \Delta\rho\kappa_k (H_{i+\kappa}-H_i)=-\delta g_{\kappa,i}. \qquad (1)$$

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

$$H_i=\frac{\Delta G_i}{2\pi k^2 \Delta\rho}\quad , \qquad (2)$$

$$\Delta G_i=\Delta g_i-\sum_{k=-\infty}^{+\infty}{}' \delta g_{i,k}, \qquad (3)$$

where $\sum'$ denotes the summation for all values of k except zero. ΔG_i

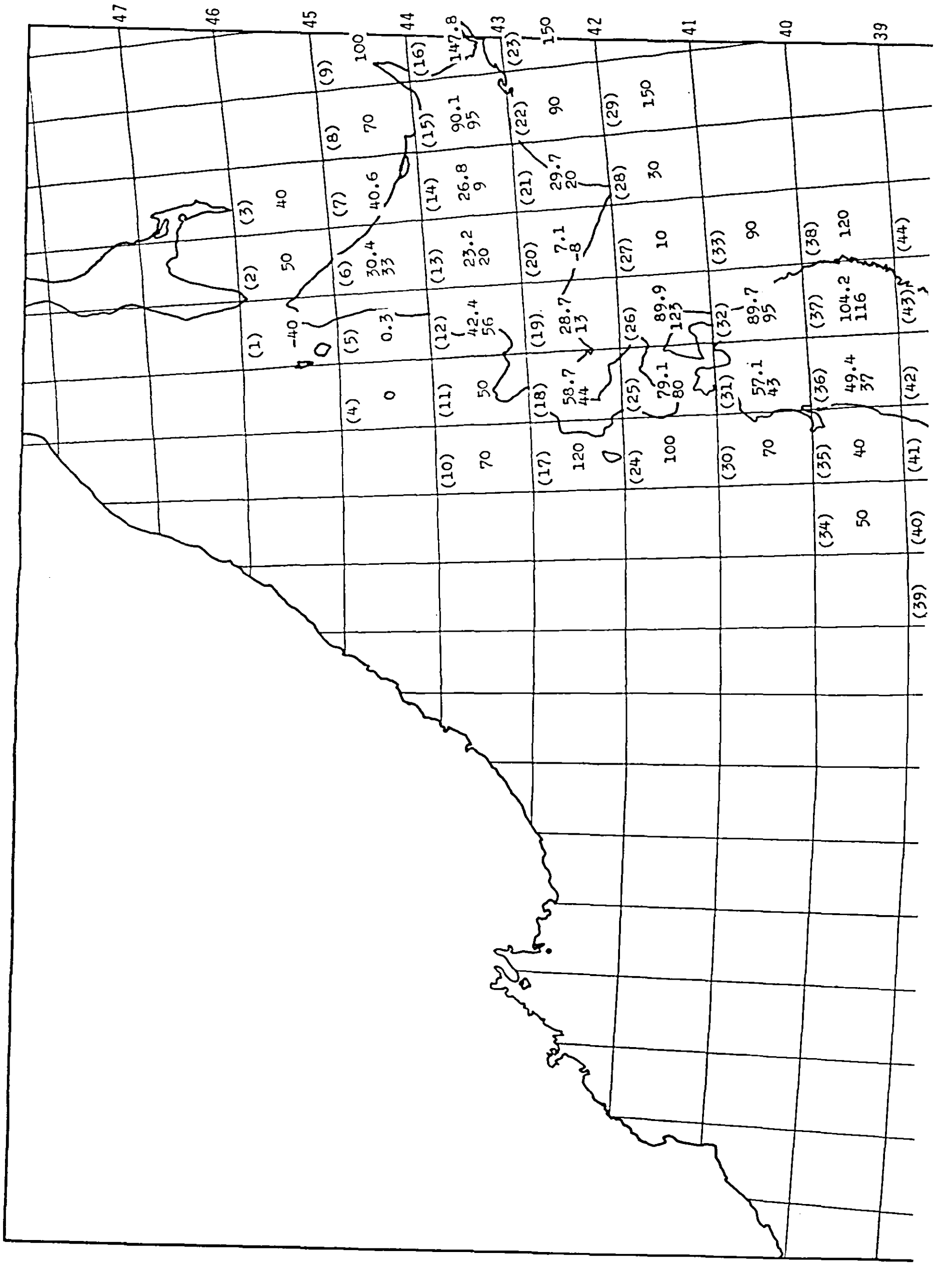
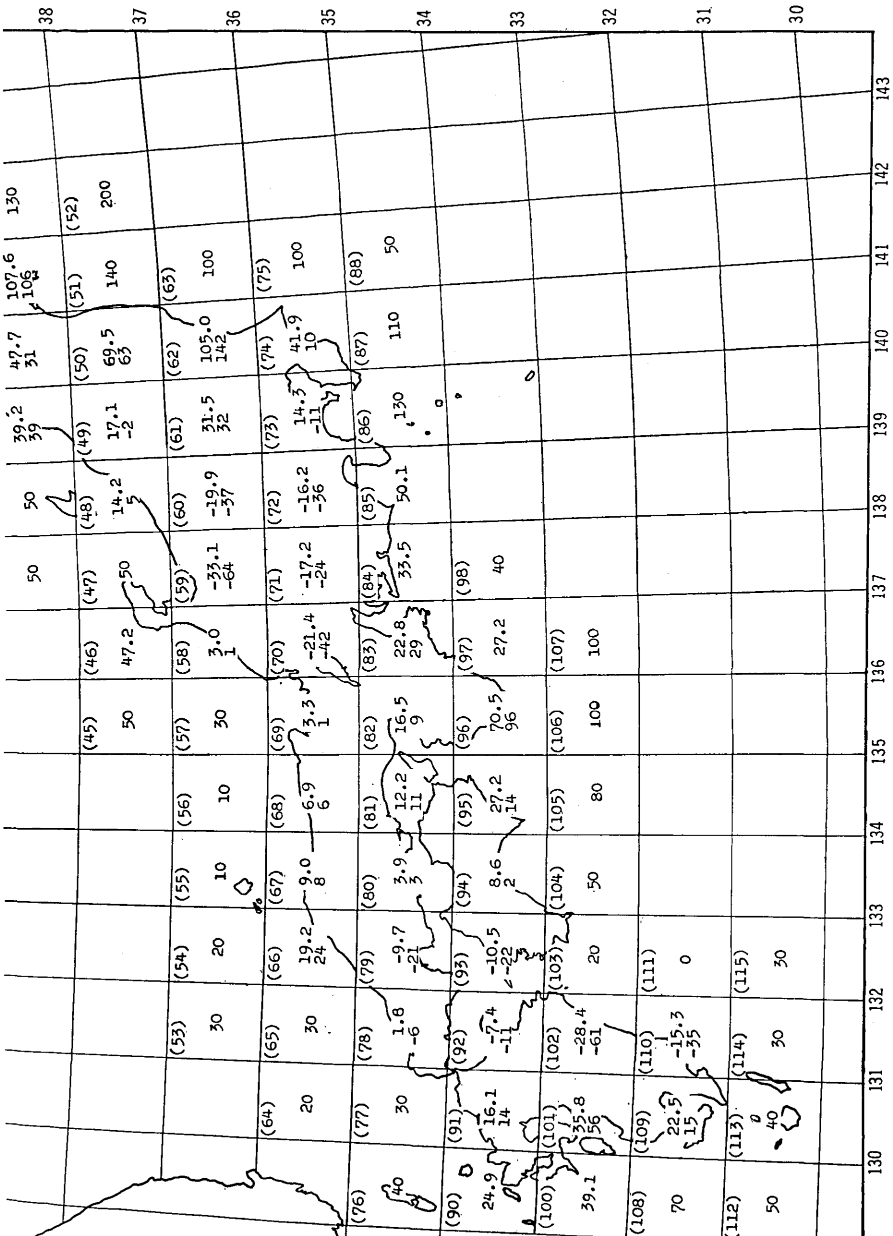


Fig. 1. Mean Bouguer anomalies in milligals for 1° squares (upper figures) and in parenthesis at the left corner indicate the square number.



reduced Bouguer anomalies in milligals for 1° squares on land (lower figures). Numbers

Table 1. Mean and reduced Bouguer anomalies in milligals for 1° squares in and around Japanese Islands.

1° square No.	Locality °E	°N	Mean Bouguer Anomaly Δg	Reduced Bouguer Anomaly ΔG
1	141-142,	45-46	−40 mgal	mgal
2	142-143,	45-46	50	
3	143-144,	45-46	40	
4	140-141,	44-45	0	
5	141-142,	44-45	0.3	
6	142-143,	44-45	30.4	33
7	143-144,	44-45	40.6	
8	144-145,	44-45	70	
9	145-146,	44-45	100	
10	139-140,	43-44	70	
11	140-141,	43-44	50	
12	141-142,	43-44	42.4	56
13	142-143,	43-44	23.2	20
14	143-144,	43-44	26.8	9
15	144-145,	43-44	90.1	95
16	145-146,	43-44	147.8	
17	139-140,	42-43	120	
18	140-141,	42-43	58.7	44
19	141-142,	42-43	28.7	13
20	142-143,	42-43	7.1	−8
21	143-144,	42-43	29.7	20
22	144-145,	42-43	90	
23	145-146,	42-43	150	
24	139-140,	41-42	100	
25	140-141,	41-42	79.1	80
26	141-142,	41-42	89.9	123
27	142-143,	41-42	10	
28	143-144,	41-42	30	
29	144-145,	41-42	150	
30	139-140,	40-41	70	
31	140-141,	40-41	57.1	43
32	141-142,	40-41	89.7	95
33	142-143,	40-41	90	
34	138-139,	39-40	50	
35	139-140,	39-40	40	
36	140-141,	39-40	49.4	37
37	141-142,	39-40	104.2	116
38	142-143,	39-40	120	
39	137-138,	38-39	50	
40	138-139,	38-39	50	
41	139-140,	38-39	39.2	39
42	140-141,	38-39	47.7	31
43	141-142,	38-39	107.6	106
44	142-143,	38-39	130	
45	135-136,	37-38	50	
46	136-137,	37-38	47.2	
47	137-138,	37-38	50	5
48	138-139,	37-38	14.2	−2
49	139-140,	37-38	17.1	63
50	140-141,	37-38	69.5	
51	141-142,	37-38	140	
52	142-143,	37-38	200	
53	131-132,	36-37	30	
54	132-133,	36-37	20	
55	133-134,	36-37	10	

(to be continued)

Table 1. (continued)

1° square No.	Locality °E	°N	Mean Bouguer Anomaly Δg	Reduced Bouguer Anomaly ΔG
56	134-135,	36-37	10 mgal	mgal
57	135-136,	36-37	30	
58	136-137,	36-37	3.0	1
59	137-138,	36-37	−33.1	−64
60	138-139,	36-37	−19.9	−37
61	139-140,	36-37	31.5	32
62	140-141,	36-37	105.0	142
63	141-142,	36-37	100	
64	130-131,	35-36	20	
65	131-132,	35-36	30	
66	132-133,	35-36	19.2	24
67	133-134,	35-36	9.0	8
68	134-135,	35-36	6.9	6
69	135-136,	35-36	3.3	1
70	136-137,	35-36	−21.4	−42
71	137-138,	35-36	−17.2	−24
72	138-139,	35-36	−16.2	−36
73	139-140,	35-36	14.3	−11
74	140-141,	35-36	41.9	10
75	141-142,	35-36	100	
76	129-130,	34-35	40	
77	130-131,	34-35	30	
78	131-132,	34-35	1.8	−6
79	132-133,	34-35	−9.7	−21
80	133-134,	34-35	3.9	3
81	134-135,	34-35	12.2	11
82	135-136,	34-35	16.5	9
83	136-137,	34-35	22.8	29
84	137-138,	34-35	33.5	
85	138-139,	34-35	50.1	
86	139-140,	34-35	130	
87	140-141,	34-35	110	
88	141-142,	34-35	50	
89	128-129,	33-34	70	
90	129-130,	33-34	24.9	
91	130-131,	33-34	16.1	14
92	131-132,	33-34	−7.4	−11
93	132-133,	33-34	−10.5	−22
94	133-134,	33-34	8.6	2
95	134-135,	33-34	27.2	14
96	135-136,	33-34	70.5	96
97	136-137,	33-34	27.2	
98	137-138,	33-34	40	
99	128-129,	32-33	70	
100	129-130,	32-33	39.1	
101	130-131,	32-33	35.8	56
102	131-132,	32-33	−28.4	−61
103	132-133,	32-33	20	
104	133-134,	32-33	50	
105	134-135,	32-33	80	
106	135-136,	32-33	100	
107	136-137,	32-33	100	
108	129-130,	31-32	70	
109	130-131,	31-32	22.5	15
110	131-132,	31-32	−15.3	−35
111	132-133,	31-32	0	
112	129-130,	30-31	50	
113	130-131,	30-31	40	
114	131-132,	30-31	30	
115	132-133,	30-31	30	

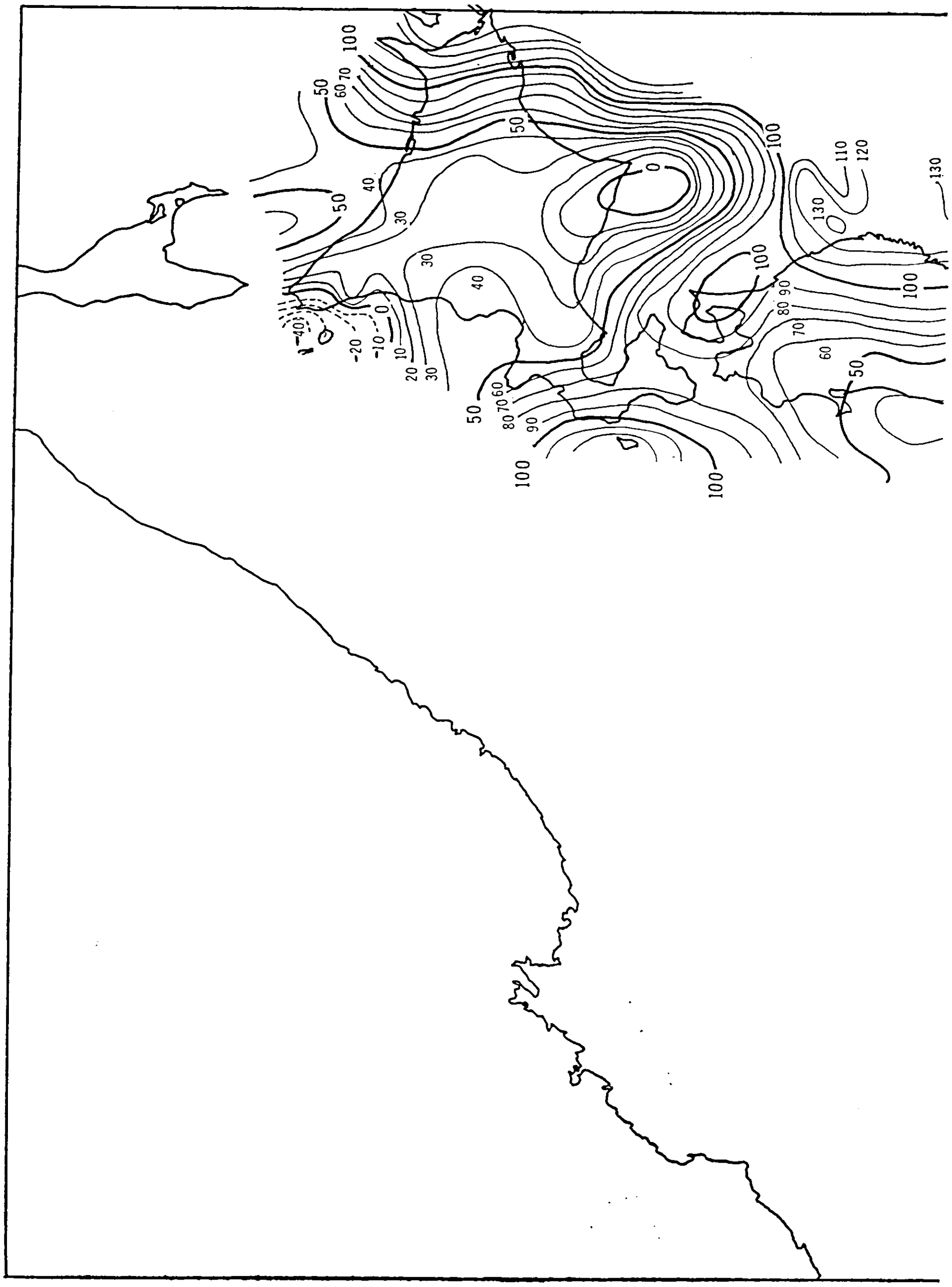
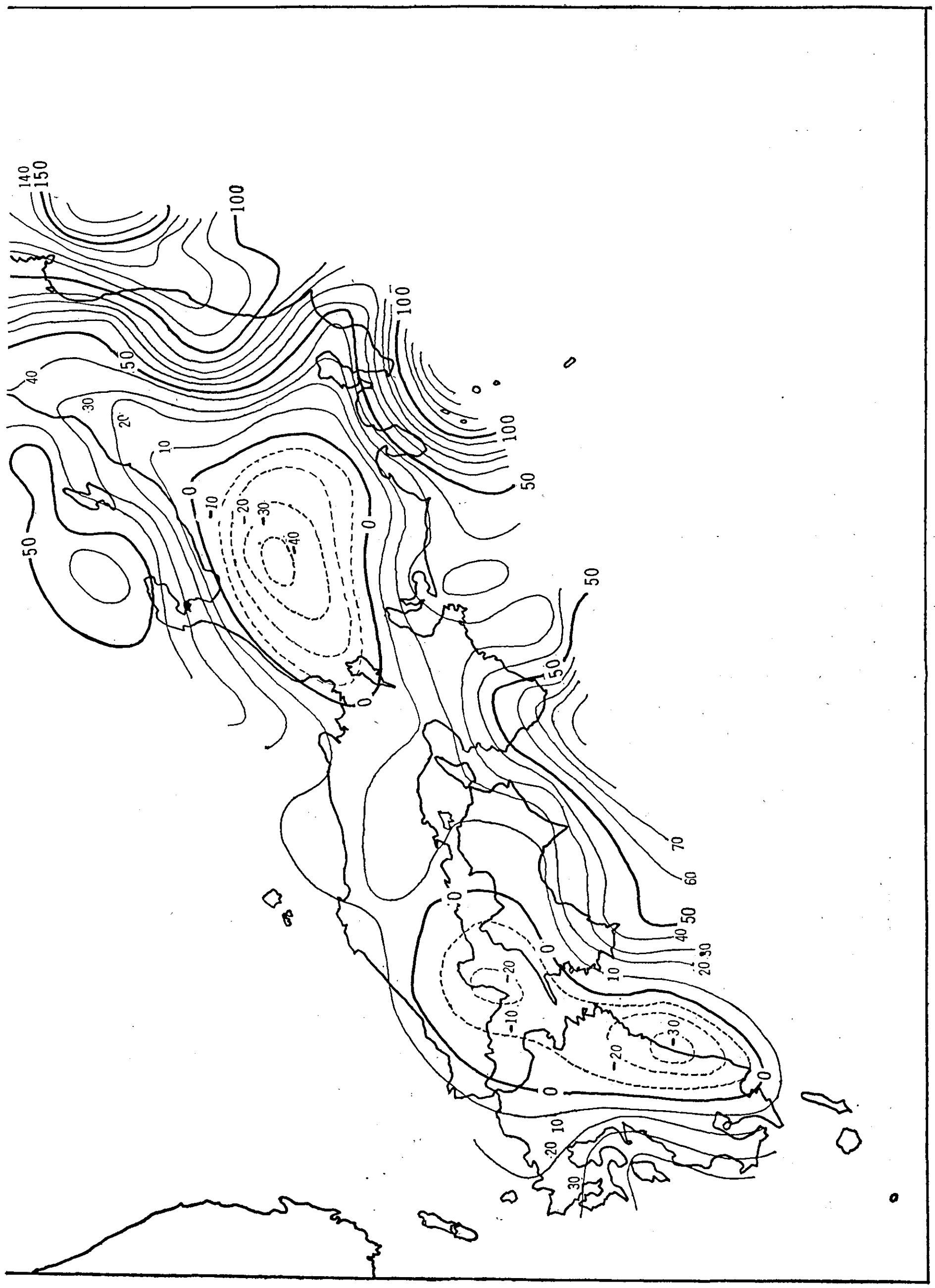


Fig. 2. Map of mean Bouguer anomaly distribution in



milligals in Japan. The contour interval is 10 mgal.

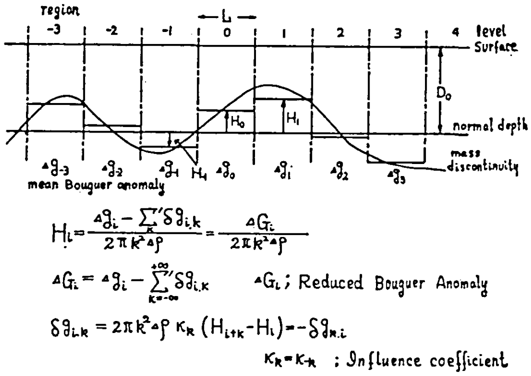


Fig. 3. Schematic figure illustrating the influence coefficient method in a two-dimensional case.

will be called the reduced Bouguer anomaly in the later discussions. From Formulas (1), (2) and (3)

$$\begin{aligned} \Delta G_i &= \Delta g_i - \textstyle\sum' \kappa_k (\Delta G_{i+k} - \Delta G_i) \\ &= \Delta g_i - \textstyle\sum' \kappa_k \Delta G_{i+k} \\ &\quad + \Delta G_i \textstyle\sum' \kappa_k, \end{aligned} \tag{4}$$

whereupon,

$$\Delta G_i = \frac{\Delta g_i - \sum' \kappa_k \Delta G_{i+k}}{1 - \sum' \kappa_k}. \tag{5}$$

If we condense the anomalous mass on a plane placed at the normal depth D_0 as in the Fourier series method, it is clear from Formula (1) that κ_k can be calculated as the mean gravity anomaly over a region due to a mass block of unit thickness and of density $(2\pi k^2)^{-1}$ placed at the depth D_0 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, κ_k has been calculated, assuming the depth D_0 to be 33 km, by the following formula.

$$\kappa_k = \frac{1}{100\pi}\left[\int_{-100}^{0} \tan^{-1}\left\{\frac{x-100(k-1)}{33}\right\} dx - \int_{-100}^{0} \tan^{-1}\left\{\frac{x-100k}{33}\right\} dx\right].$$

The results are $\kappa_1 = 0.154$ and $\kappa_2 = 0.026$.

As $|\Delta G_{i,2} - \Delta G_i|$ would not exceed 300 mgal, it can be inferred from Formula (4) that κ_2 can reasonably be neglected so long as an accuracy of 10 mgal in ΔG_i is required. Consequently, we can neglect, in the later treatment, the influence from all regions except the neighbouring ones. Accordingly, if ΔG_0 is required, we can arbitrarily assume ΔG_2 and ΔG_{-2}. In the present study, we simply extrapolate the data in such a way as $\Delta G_{-2} = \Delta G_{-1}$, $\Delta G_2 = \Delta G_1$ and obtain the following expressions from Formula (5),

$$\Delta G_0 = \frac{\Delta g_0 - \kappa_1 (\Delta G_{-1} + \Delta G_1)}{1 - 2\kappa_1},$$

$$\Delta G_1 = \frac{\Delta g_1 - \kappa_1 (\Delta G_0 + \Delta G_{-1})}{1 - 2\kappa_1},$$

$$\Delta G_{-1} = \frac{\Delta g_{-1} - \kappa_1 (\Delta G_0 + \Delta G_1)}{1 - 2\kappa_1} \ .$$

Eliminating ΔG_1 and ΔG_{-1} leads to

$$\Delta G_0 = \frac{(1-\kappa_1)\,\Delta g_0 - \kappa_1 (\Delta g_1 + \Delta g_{-1})}{1 - 3\kappa_1} \ , \qquad (6)$$

which gives the reduced Bouguer anomaly ΔG_0 in a region from the mean Bouguer anomaly Δg_0 of the same region and Δg_1 and Δg_{-1} of the neighbouring regions.

From the expression (6), it can easily be seen that if the structure is flat ($\Delta g_{-1} = \Delta g_0 = \Delta g_1$), ΔG_0 is reduced to Δg_0, and if the neighbouring regions have no influence on the region studied, κ_1 should be taken as 0, and ΔG_0 would naturally become Δg_0. Putting $\kappa_1 = 0.154$ in Formula (6), we obtain the final formula for the two-dimensional case in the form,

$$\Delta G_0 = 1.57\,\Delta g_0 - 0.286\,(\Delta g_1 + \Delta g_{-1}). \qquad (7)$$

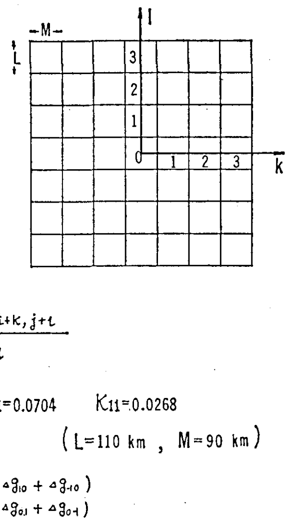
b) *Three-dimensional case*

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

The expression which is comparable to (5) can be written as,

$$\Delta G_{i,j} = \frac{\Delta g_{i,j} - \sum_{k,l}' \Delta G_{i+k,j+l}}{1 - \sum_{k,l}' \kappa_{k,l}} \ . \qquad (8)$$

(See Fig. 4)



$$\Delta G_{ij} = \frac{\Delta g_{ij} - \sum_{k,l}'' \Delta G_{i+k,j+l}}{1 - \sum_{k,l}'' K_{k,l}}$$

$K_{10} = 0.0883$ $K_{01} = 0.0704$ $K_{11} = 0.0268$

($L = 110$ km , $M = 90$ km)

$$\Delta G_{00} = 1.854\,\Delta g_{00} - 0.230\,(\Delta g_{10} + \Delta g_{-10}) - 0.180\,(\Delta g_{01} + \Delta g_{0-1}) - 0.009\,(\Delta g_{-1,1} + \Delta g_{1,1} + \Delta g_{-11} + \Delta g_{1-1})$$

Fig. 4. Illustrative figure of the influence coefficient method in a three-dimensional case.

If we neglect the coefficients other than $\kappa_{1,0} = \kappa_{-1,0}$, $\kappa_{11} = \kappa_{-1,1} = \kappa_{1,-1} = \kappa_{-1,-1}$ and $\kappa_{0,1} = \kappa_{0,-1}$ and extrapolate the data in the manner $\Delta G_{0,2} = \Delta G_{0,1}$, $\Delta G_{2,0} = \Delta G_{1,0}$, $\Delta G_{-2,0} = \Delta G_{-1,0}$, $\Delta G_{0,-2} = \Delta G_{0,-1}$, $\Delta G_{2,2} = \Delta G_{1,2} = \Delta G_{2,1} = \Delta G_{1,1}$, $\Delta G_{-2,2} = \Delta G_{-1,2} = \Delta G_{-2,1} = \Delta G_{-1,1}$, $\Delta G_{-1,-2} = \Delta G_{-2,-2} = \Delta G_{-2,-1} = \Delta G_{-1,-1}$ and $\Delta G_{2,-2} = \Delta G_{2,-1} = \Delta G_{1,-2} = \Delta G_{1,-1}$, Formula (8) can be reduced to a 9-th degree simultaneous algebraic equation for $\Delta G_{0,0}$, $\Delta G_{-1,1}$, $\Delta G_{0,1}$, $\Delta G_{1,1}$, $\Delta G_{-1,0}$, $\Delta G_{1,0}$, $\Delta G_{-1,-1}$, $\Delta G_{0,-1}$ and $\Delta G_{1,-1}$ which can be given by the following.

$$\begin{pmatrix}
1-2\kappa_1-2\kappa_2-4\kappa_3 & \kappa_3 & \kappa_2 & \kappa_3 & \kappa_1 & \kappa_1 & \kappa_3 & \kappa_2 & \kappa_3 \\
\kappa_3 & 1-\kappa_1-\kappa_2-3\kappa_3 & \kappa_1+\kappa_3 & 0 & \kappa_2+\kappa_3 & 0 & 0 & 0 & 0 \\
\kappa_2 & \kappa_1+\kappa_3 & 1-2\kappa_1-\kappa_2-4\kappa_3 & \kappa_1+\kappa_3 & \kappa_3 & \kappa_3 & 0 & 0 & 0 \\
\kappa_3 & 0 & \kappa_1+\kappa_3 & 1-\kappa_1-\kappa_2-3\kappa_3 & 0 & \kappa_2+\kappa_3 & 0 & 0 & 0 \\
\kappa_1 & \kappa_2+\kappa_3 & \kappa_3 & 0 & 1-\kappa_1-2\kappa_2-4\kappa_3 & 0 & \kappa_2+\kappa_3 & \kappa_3 & 0 \\
\kappa_1 & 0 & \kappa_3 & \kappa_2+\kappa_3 & 0 & 1-\kappa_1-2\kappa_2-4\kappa_3 & 0 & \kappa_3 & \kappa_2+\kappa_3 \\
\kappa_3 & 0 & 0 & 0 & \kappa_2+\kappa_3 & 0 & 1-\kappa_1-\kappa_2-3\kappa_3 & \kappa_2+\kappa_3 & 0 \\
\kappa_2 & 0 & 0 & 0 & \kappa_3 & k_3 & \kappa_1+\kappa_3 & 1-2\kappa_1-\kappa_2-4\kappa_3 & \kappa_1+\kappa_3 \\
\kappa_3 & 0 & 0 & 0 & 0 & \kappa_2+\kappa_3 & 0 & \kappa_1+\kappa_3 & 1-\kappa_1-k_2-4\kappa_3
\end{pmatrix}$$

$$\times \begin{pmatrix} \Delta G_{0,0} \\ \Delta G_{-1,1} \\ \Delta G_{0,1} \\ \Delta G_{1,1} \\ \Delta G_{-1,0} \\ \Delta G_{1,0} \\ \Delta G_{-1,-1} \\ \Delta G_{0,-1} \\ \Delta G_{1,-1} \end{pmatrix} = \begin{pmatrix} \Delta g_{0,0} \\ \Delta g_{-1,1} \\ \Delta g_{0,1} \\ \Delta g_{1,1} \\ \Delta g_{-1,0} \\ \Delta g_{1,0} \\ \Delta g_{-1,-1} \\ \Delta g_{0,-1} \\ \Delta g_{1,-1} \end{pmatrix} \tag{9}$$

where κ_1, κ_2 and κ_3 denote $\kappa_{1,0}$, $\kappa_{0,1}$ and $\kappa_{1,1}$ respectively. The three influence coefficients κ_1, κ_2 and κ_3 have been numerically computed for a region $1°$ lat.$\times 1°$ long. in extent (about $110\,\mathrm{km}\times 90\,\mathrm{km}$) and a normal depth $D_0=33\,\mathrm{km}$. The results are,

$$\kappa_1=0.0883, \quad \kappa_2=0.0704, \quad \kappa_3=0.0268.$$

Substituting these values in Equation (9) and inversing the matrix numerically, we obtain the final expression for $\Delta G_{0,0}$ as,

$$\begin{aligned}\Delta G_{0,0}=1.854\,\Delta g_{0,0}&-0.230\,(\Delta g_{1,0}+\Delta g_{-1,0})\\&-0.180\,(\Delta g_{0,1}+\Delta g_{0,-1})\\&-0.009\,(\Delta g_{-1,1}+\Delta g_{1,1}+\Delta g_{-1,-1}+\Delta g_{1,-1}).\end{aligned}\qquad(10)$$

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 $\Delta g_{0,0}=\Delta g_{1,0}=\Delta g_{-1,0}=\Delta g_{0,1}=\Delta g_{0,-1}=\Delta g_{1,1}=\Delta g_{-1,-1}=\Delta g_{1,-1}$ (i.e. the structure is assumed to be flat), Formula (10) gives $\Delta G_{0,0}=\Delta g_{0,0}$ satisfying the physical requirement. It is also clear from this formula that the coefficient for $\Delta g_{-1,1}$, $\Delta g_{1,1}$, $\Delta g_{-1,-1}$ and $\Delta g_{1,-1}$ is very small compared with others. This implies that no accuracy better than 100 mgal in Δg is required for the diagonally located regions. For the same reason, an accuracy of about 20 mgal for $\Delta g_{1,0}$, $\Delta g_{-1,0}$, $\Delta g_{0,1}$ and $\Delta g_{0,-1}$ would be sufficient to obtain the value of $\Delta G_{0,0}$ 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 mgal have been adopted only for $\Delta g_{i,j}$ $((i,j)\neq(0,0))$, and $\Delta G_{0,0}$ has been obtained only for the 1° squares on land for which an accuracy of $\Delta g_{0,0}$ higher than 10 mgal was attained. This guarantees the reliability of the value of ΔG obtained by the present method.

It will be of some interest to note here that Tsuboi, Oldham and Waithman coefficients[10] $\Phi(x,y)$ in the $\sin x/x$ method, which have recently been calculated and tabulated by Saito et al.,[11] give $\Phi(0,0)=2.130$, $\Phi(1,0)=\Phi(0,1)=-0.267$, 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 equilaterally, the coefficients given by $\sin x/x$ 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 $\sin x/x$ method modified by Kanamori.[12] They are $\Phi(0,0)=2.036$, $\Phi(1,0)=\Phi(0,1)=-0.202$, $\Phi(1,1)=-0.012$ 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 1° squares on land and the results are given in Fig. 1 (lower figures) and Table 1.

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10) C. TSUBOI, C.H.G. OLDHAM and V.B. WAITHMAN, *J. Phys. Earth*, **6** (1958), 7.

11) M. SAITO and H. TAKEUCHI, *Monthly meeting of the Earthq. Res. Inst.*, (*June*, 1963).

12) H. KANAMORI, *Proc. Japan Acad.*, **39** (1963), 469-473.

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 synclinic structure in this area. Further, the anomalies in Chugoku district are changed only slightly, indicating the slowly varying structure there.

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

$$D = D_0 - \frac{\Delta G}{2\pi k^2 \Delta\rho},$$

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[13] (i.e. $D_0 = 33$ km, $\Delta\rho = 0.43$ 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.

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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

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重力異常によつて地殻構造を議論する場合に問題となることは次のようなことである.

1) 普通に解析に用いるのは 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 を行なう際には係数 $\partial g/\partial h = -0.3086$ mgal/m を用いるが, この値は場所々々によつてかなり異なる. しかし, かなり広い範囲にわたつての平均は本質的に上の値になる筈である. 第二は, Bouguer Reduction を行なう際, 地表構造の密度として, ρ_B

13) J. L. WORZEL and G. L. SHURBET, *Crust of the Earth*, (Geol. Soc. Amer. 1955).

$=2.67\,g/cm^3$ を用いるが，この値を用いる特別な物理的根拠はないと考えられる．実際に地表の構造を作る物質の密度を実験室で直接的に測定することは可能で，その結果は大体，$2\text{–}3\,g/cm^3$ である．したがつて $2.67\,g/cm^3$ を用いて得られた Bouguer 異常は海抜高度の高い観測点についてはかなりの誤差の原因となる．第三は，地表近くの複雑な地質構造の影響が Bouguer 異常には含まれているが，この影響を正しく見積つて，とり除くことは一般には不可能である．

2) 日本の場合，陸上においては質的にも量的にも十分な測点があるが，海における測点は質的にも量的にも未だ十分ではない．

3) 波長 λ の重力異常を深さ D における構造で説明する際には，一般に，倍率 $e^{2\pi D/\lambda}$ がかかる．したがつて 1) で述べたような不確定さが比較的短い波長の誤差として重力異常に含まれている場合，その解析の際に取り扱いに十分注意しないと，得られた構造はほとんど誤差だけを表わすことになる．

以上の三点を考慮して，ここでは，地表近くの構造の代表的な大きさより大きい地域についての平均の重力異常を考えて，解析を行なつた．この地域の大きさは，大きければ大きいほど，1) に述べた影響は小さくなるが，あまり大きくとることは日本列島の中で変化する構造をとらえにくくする．ここでは取り扱いの簡単さも考慮して，経緯度 1° についての平均値を用いた．これらの平均 Bouguer 異常からそこでの構造を議論するために "Influence coefficient method" を導入して reduced Bouguer 異常 ΔG を求めた．reduced Bouguer 異常はその地域での平均的な Moho の深さ D と $D=D_0-\Delta G/2\pi k^2\Delta\rho$ によつて結びつけられるものである．ここで D_0 は Bouguer 異常 0 のところでの Moho の深さ，$\Delta\rho$ はクラストとマントルの密度差である．

2) でのべたように，海での値は信頼度が陸上の値にくらべて低いので，ΔG は陸上の 1° square についてのみ求めた．また，Reduction の際に，海での値に含まれる不確定さが，陸での ΔG に与える影響は十分に小さいことが示される．