Jour. Korean Inst. Mining Geol.
Vol. 18, No. 4, p. 309~320, 1985

A Study on the Crustal Structure of the Southern Korean Peninsula through Gravity Analysis

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Abstract: The crustal structure of the southern part of the Korean peninsula has been investigated based on the results of processing and anlaysis of gravity data. The processing techniques involve i) seperation of regional and residual anomalies by polynomial fittings, ii) power spectral analyses to determine the mean depth to the crustal base, iii) a filtering operation called "high-cut filtering and resampling," and iv) downward continuation to determine the undulation of the crustal base.

The Bouguer anomalies show a lineation in the NE-SW direction which is the same as that of most mountains and tectonic lines of this area. The mean crustal depth is found to be 34km. The depth of the crustal base is varying in the estimated range of 26km to 36km with a thinner crust below the east coast than that of the west coast. The relief of the crustal base is appeared to be correlated with the regional surface topography. The linear regression relations computed between elevations and gravity anomalies indicate that the crust of this area seems to be not in perfect isostatic equilibrium but a little undercompensated state.

INTRODUCTION

The Korean peninsula occupies the south-eastern part of the North China-Korean Platform which behaved as a stable craton subject to only epirogenic movements for over a thousand million years prior to the Mesozoic Era. During the latter part of its history, folding, metamorphism and igneous activity affected wide areas of the craton. In terms of plate tectonics, the peninsula is a part of the Eurasian plate and lies landward of the Japanese volcanic island arc. Precambrian basement occupying more than a half of the Korean peninsula is tectonically related to those of Manchuria and China (Lee, 1974).

The geophysical studies of the deep crustal structure of the peninsula have been attempted using both seismic data and gravity data. Lee (1979) analyzed the travel time data of the Ssanggye-sa earthquake, and concluded that the crustal thickness is about 35km. Kim (1983) investigated the earthquake data of Uljin and Pohang events and the auxiliary data of Hong-seong and Ssanggye-sa events, and suggested the crustal model which has the discontinuities of Conrad and Moho at the depth of 15km and 32km respectively. Kim (1979) analyzed the gravity data on the Korean peninsula and adjacent East (Japan) Sea by sin x/x method. He concluded that the thickness of the isostatic crust is about 26km, and the average isostatic gravity anomaly on this area is +24.8 mgal, of which result indicates that the surface features are underercompensated. On the other hand, Lee (1979) investigated the relations between elevations and gravity anomalies to test isostasy, and noted that the crust of the Korean peninsula is in isostatic equilibrium as a whole.

Gravity data can be processed and analyzed in both spatial and frequency domains. The spatial domain method deals directly with actual

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values, and the numerical computation scheme can be understood more easily. The frequency domain analysis, however, draws more attractions in many aspects of filtering operations in recent days with the aid of high speed digital computer.

In this study, gravity data of the southern part of the Korean peninsula have been analyzed in both spatial and frequency domains to investigate the gross crustal structure of this area. However, more emphasis has been placed on the frequency domain analysis during the course of this study. In the spatial domain, regional and residual anomalies are seperated from the Bouguer anomaly map using the method of polynomial fitting. The regional anomilies reflect the gross feature of the crust. In the frequency domain, power spectral analyses and downward continuation of the gravity anomalies are carried out to determine the mean depth and the undulation of the crustal base. In the course of downward continuation, a new filtering method called "high-cut filtering and resampling" has been developed and applied to retain the deep effects of gravity anomalies and to widen the sample interval at the same time. The status of isostasy of the peninsula is also tested by studying the relations between elevations and gravity anomalies.

GRAVITY DATA AND DATUM CONTROL

Gravity observations used in this study were originally accomplished by USAMSFE (U.S. Army Map Service Far East) at the request of APCS (Air Photographic and Charting Service) during September 1961 through October 1962 with two Worden gravimeters at 164 gravity stations. These statios are well distributed over the whole area extending from 126°02.4′ E to 129°25.8′ E, and from 34°6′N to 37°52.8′ N as shown in Fig. 1, and some of them are located at pretty high altitudes (Fig. 2).

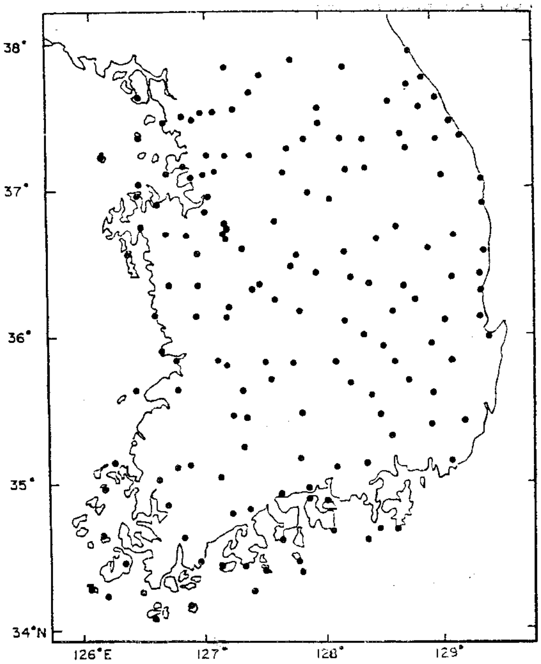

Fig. 1 Distribution of gravity stations.

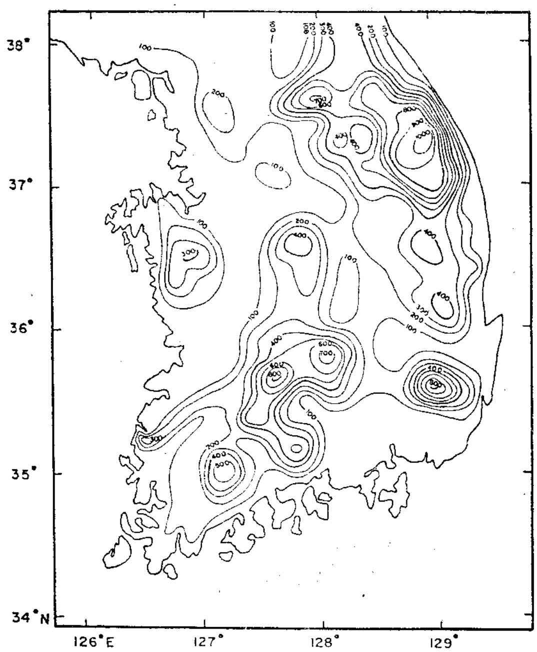

Fig. 2 Height contour map of gravity stations. Heights in meters.

Since the controls of these observations are 8 gravity reference stations (Table 1) established by the University of Wisconsin and APCS in 1961, the gravity data belong to the Potsdam

Table 1 Gravity base reference stations.

Station	Scaled Value		Elevation (m)	Gravity Value (mgal)
	Latitude	Longitude		
K-14 (Mats)	37°33.2°N	126°46.5°E	19.5	979,972.42
K-14 (Int'l)	37°33.1°	126°48.2°	19.5	979,972.18
K-16	37°30.9°	126°55.6°	9	979,970.28
K-5	36°20.6°	127°23.1°	40	979,848.38
A-1	35°07.6°	129°06.0°	10	979,787.94
A-3	35°50.4°	128°35.6°	31.4	979,822.77
K-46	37°26.26°	127°58.5°	135.6	979,915.74
K-7	35°08.6°	126°50.8°	13.1	979,758.43

system. Woollard (1979) showed that standardized gravity values on a global scale previously obtained by Woollard and Rose (1963) indicate a mean datum difference of 14.7 mgal relative to IGSN 71 (International Gravity Standardization Net, 1971) values at 776 sites having a worldwide distribution. We have some rationale to adopt the mean Woolard datum correction value, 14.7 mgal, to convert gravity values to IGSN 71 values (Kwon, 1982).

In order to analyze gravity data, it is prerequisite to correct the observed values for elevation. Elevation correction consists of free-air and Bouguer corrections. Free-air correction is the compensation for the vertical gradient of gravity from the sea surface. The free-air correction C_F at elevation h (in meters) is given as

$$C_F = 0.3086 \times h \text{ mgal} \quad (1)$$

Bouguer correction is the reduction of the effect of the infinite horizontal slab between the sea level and the observed station, and is expressed by

$$C_B = 2\pi G\rho h \text{ mgal} \quad (2)$$

where G is the universal costant of gravitation, ρ is the density of the Bouguer slab, and h is the elevation of the observed station. If the density is assumed to be 2.67 g/cm^3 as usual, the Bouguer correction becomes

$$C_B = 0.1119 \times h \text{ mgal} \quad (3)$$

Although terrain correction is necessary to obtain a complete Bouguer anomaly, the correction has not been attempted in this study. However, we feel that the effect of terrain will not seriously deteriorate the result of this study on the gross crustal structure unless the observed gravity stations are situated at very adverse locations.

Free-air and Bouguer anomalies can be defined as follows,

$$\Delta g_F = g_{obs} + C_F - \gamma_0 \quad (4)$$

$$\Delta g_B = g_{obs} + C_F - C_B - \gamma_0 \quad (5)$$

where Δg_F and Δg_B are respectively free-air and

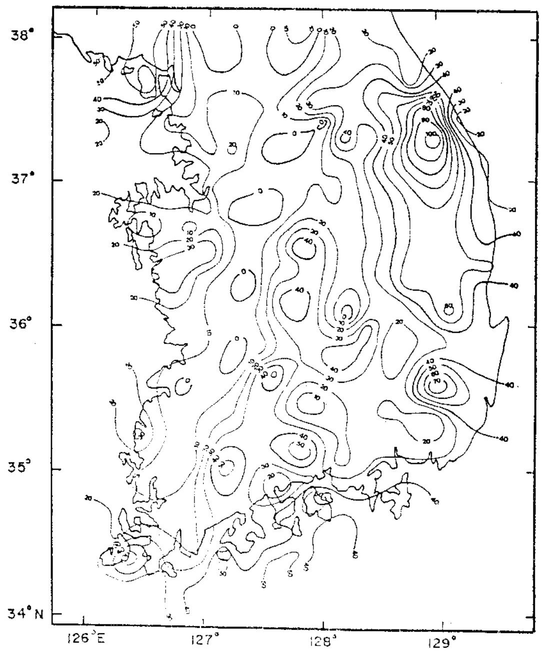

Fig. 3 Free-air anomaly map. Contour interval 10 mgals.

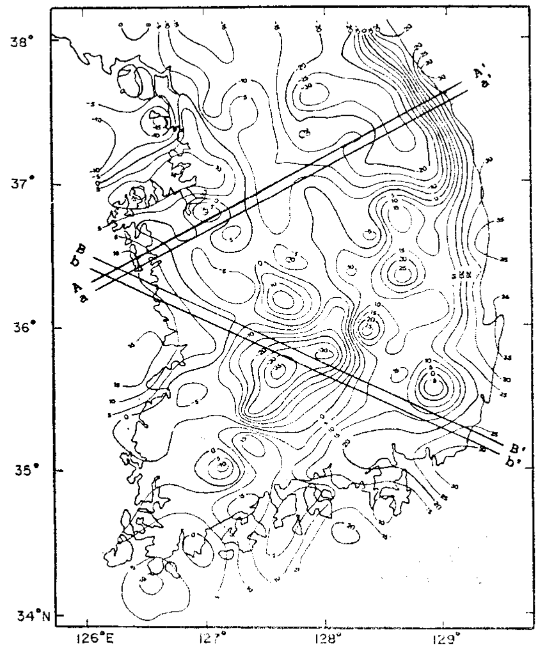

Fig. 4 Bouguer anomaly map. Contour interval 5 mgals.

simple Bouguer anomalies, g_{obs} is the observed gravity value and γ_0 is the theoretical sea level gravity value determined from GRS 67 (Geodetic Reference System, 1967) gravity formula.

In the course of digital processings, several routines such as FFT (Fast Fourier Transform) require the gravity data to be sampled at eqally spaced grid points. Therefore, irregularly observed gravity data are rearranged to the grid of 75×112 points by utilizing interpolation scheme based on the harmonic equation method included in the automatic plotting and contouring program (Briggs, 1974, Suh, 1982). Through automatic contouring, we may obtain more accurate map and can reduce time and personal bias which may be involved in manual method. Free-air and Bouguer anomaly maps which have been contoured automatically are shown in Fig. 3 and Fig. 4.

FILTERING IN THE SPACE DOMAIN

Since Bougure anomalies in general are produced by composite anomalous masses, it is desirable to seperate the residual anomaly from the regional anomaly which has a more smooth appearance with low curvature representing the deep effects of mass distributions.

Polynomial fitting method (Agocs, 1951) is one of the most widely used approach to determine the regional field. The suface giving the best fit to the gravity field can be obtained by least square method, and this surface can be considered as the regional field. The residual anomaly is defined as

$$\Delta g_{res}=\Delta g_{obs}-\overline{\Delta g} \qquad (6)$$

where Δg_{res} is the residual anomaly, Δg_{obs} is the total observed anomaly, and $\overline{\Delta g}$ is the regional anomaly.

In the first-order polynomial fitting, the regional field is approximated to be a simple inclined plane which is mathematically described as

$$\overline{\Delta g}=Ax+By+C \qquad (7)$$

Here, A, B and C are constants to be determined by the least square method, and x and y are the coordinates of gravity stations.

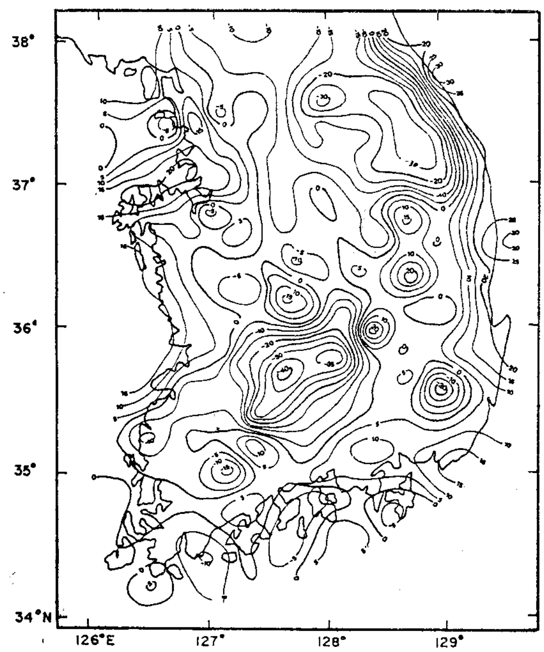

Fig. 5 Residual map of 1st order polynomial.

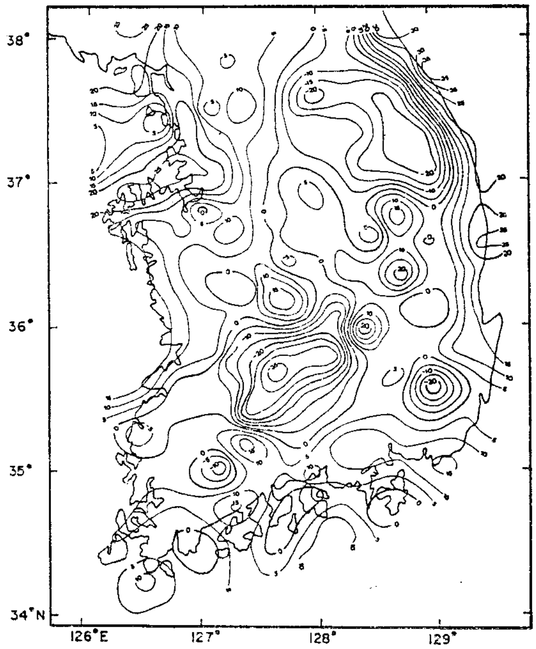

Fig. 6 Residual map of 2nd order polynomial.

The second-order polynomials can be obtained by a similar method, but the surface is assumed to be a bowel shaped surface in this case. The equation for this surface is

$$\overline{\Delta g}=Ax^2+By^2+Cxy+Dx+Ey+F \quad (8)$$

where $A, B, C, D, E,$ and F are constants to be determined.

By the numerical computation, the following equations were obtained for the first-order and second-order polynomials over this region of interests.

$$\overline{\Delta g}=1.2781x-0.9666y+5.4668 \quad (9)$$

$$\overline{\Delta g}=0.1042x^2-0.0618y^2+0.0119xy-0.0235x+0.1613y+0.0610 \quad (10)$$

The coefficients of these polynomial equations suggest that the overall regional field is inclined to the NW direction. The correspondent residual anomaly maps are shown respectively in Fig. 5 and Fig. 6, and do not show a significant difference to each other.

DATA PROCESSING IN THE FREQUENCY DOMAIN

Power Spectral Analysis

Power spectral analysis of potential field data (Tomoda, 1965) is a useful method to determine the crustal thickness neither assuming the density value nor the hypothesis of isostasy. The surface gravity anomaly data of M points sampled along a traverse can be expressed by Fourier series

$$\Delta g(x)=\sum_{n=0}^{M-1}(A_n\cos\frac{2n\pi}{L}x+B_n\sin\frac{2n\pi}{L}x) \quad (11)$$

where A_n and B_n are Fourier coefficients, n is the degree of the freqyency, and L is the length of the traverse. If it is assumed that the gravity anomaly is due to the undulation of the subsurface interface which has a two-dimensional structure, the surface gravity anomaly can also be expressed by different Fourier series

$$\Delta g(x)=2\pi G\Delta\rho\sum_{n=0}^{M-1}e^{-2n\pi d/L}(C_n\cos\frac{2n\pi}{L}x+D_n\sin\frac{2n\pi}{L}x) \quad (12)$$

where $\Delta\rho$ is the density contrast of two layers, d is the mean depth to the interface, and C_n and D_n are the Fourier coefficients of the function representing the topographic relief of the interface. From equation (11) and (12), power spectrum P_n of this surface gravity anomaly $\Delta g(x)$ can be obtained as follows,

$$P_n=A_n^2+B_n^2=(2\pi G\Delta\rho)^2e^{-4\pi nd/L}(C_n^2+D_n^2)$$
$$=(2\pi G\Delta\rho)^2e^{-4n\pi d/L}C_0, \quad (13)$$

if the topographic relief $h(x)$ is assumed to be random function whose power spectrum is white. Hence, the logarithm of power spectrum becomes

$$\log_e P_n=C-4\pi d/L\cdot n \quad (14)$$

where $C=\log_e(2\pi G\Delta\rho)^2C_0$. The equation (14) represents a straight line of slope $-4\pi d/L$ on the $\log_e P_n$ vs. n plot. The determination of the interface depth is thus reduced to the measure-

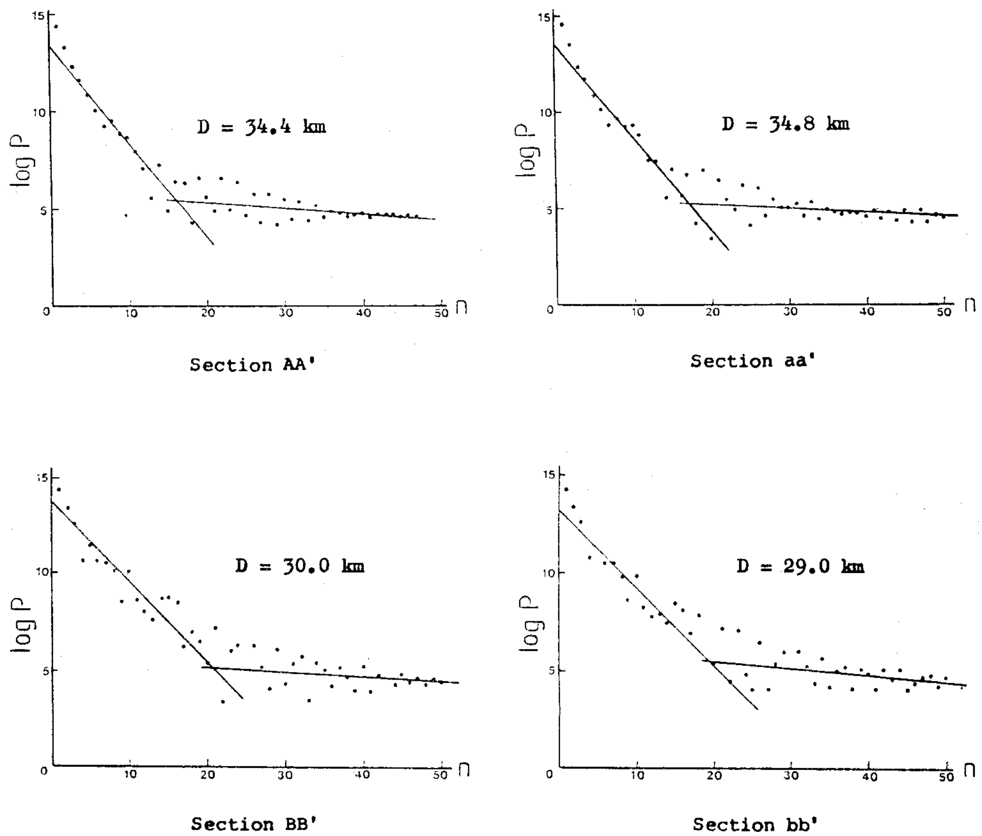

Fig. 7 The results of power spectral analysis.

ment of the slope of logarithmic power spectrum which is appeared as a straight line.

In this study, two regions which approximately reveal two-dimensional structure are selected as shown in Fig. 4. The power spectral analyses are carried out along the two near-by traverses in each region to reduce the errors. The result for each traverse is shown in Fig. 7. The depths to the crustal base determined from traverse AA' and aa', which are along NW-SE direction below 36N, are 34.4km, 34.8km, while those determined from the traverse BB' and bb' along NE-SW direction over 36N are 30.0km and 29.0km. Therefore, it can be concluded that the mean depth of the crustal base of this area is approximately 32km.

Downward Continuation

The downward continuation of potential field data is a powerful technique to determine the shapes of the interface between two layers having different formation densities or different magnetized media.

The downward continued field can be obtained with the use of Fast Fourier Transform (Kwon, 1981). If the gravity data are sampled from an equally speced square map which contains M grid values along x and y axes, the gravity anomaly at any depth d can be replaced by a double Fourier series

$$\Delta g(x, y, d) = \sum_{m=0}^{M-1} \sum_{n=0}^{M-1} F_{mn} e^{(2\pi d/L)\sqrt{m^2+n^2}} \begin{matrix}\cos\\ \sin\end{matrix} m\frac{2\pi x}{L} \begin{matrix}\cos\\ \sin\end{matrix} n\frac{2\pi y}{L} \qquad (15)$$

where F_{mn} is the Fourier coefficients of surface gravity map, and L is the fundamental wavelength.

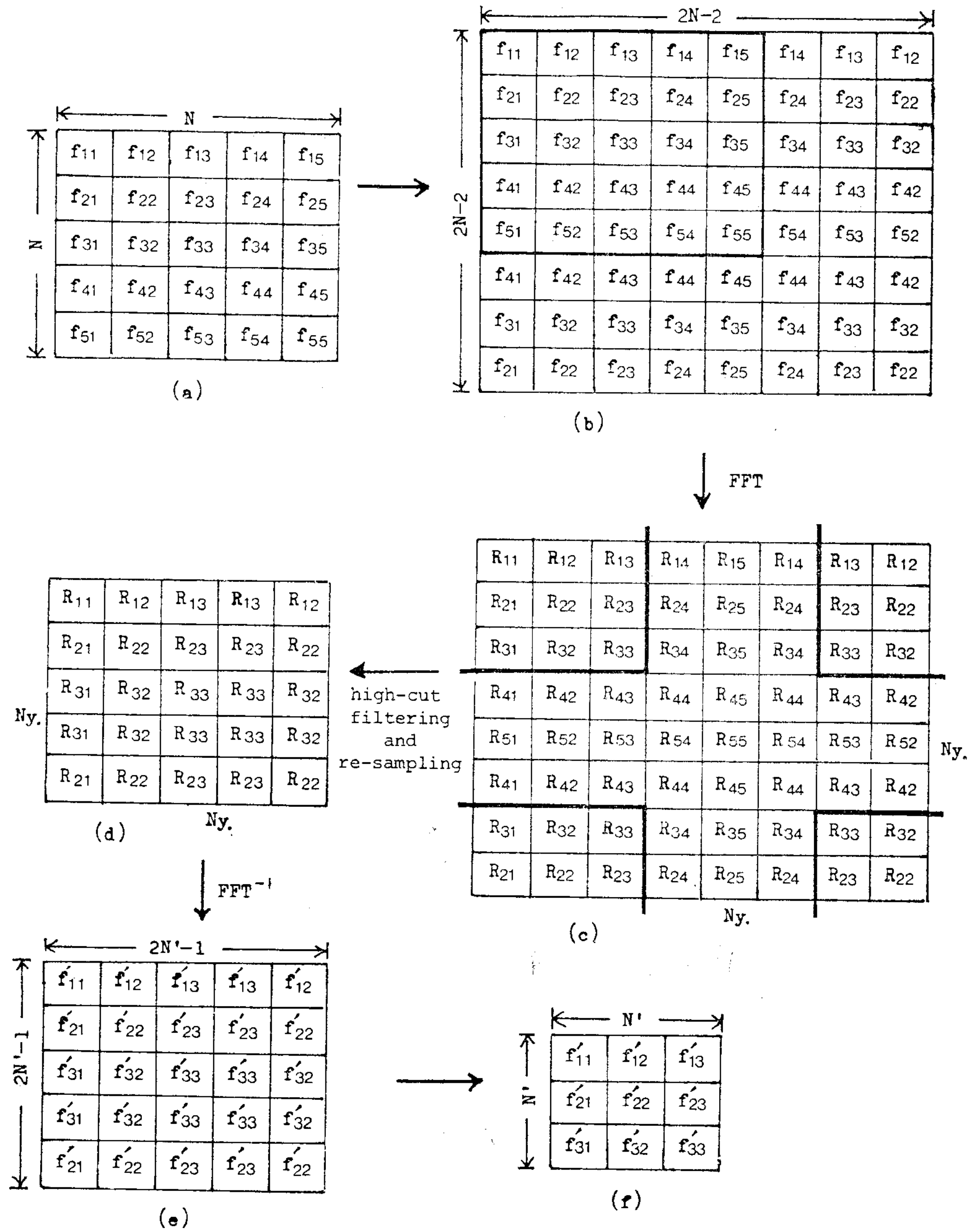

Fig. 8 Process of high-cut filtering and re-sampling in 2-dimensions.

The usual method to determine the relief of the interface involves calculation of the equivalent stratum at the mean depth to the interface, and then replacing it with the topographic surface $h(x, y)$, which is given by

$$\sigma(x, y) = \Delta\rho h(x, y), \quad (16)$$

Since the gravity anomaly at the mean depth d is related to the equivalent stratum

$$\Delta g(x, y, d) = 2\pi G\sigma(x, y), \quad (17)$$

the topographic height of the crustal base is determined from

$$h(x,y)=\frac{1}{2\pi G\Delta\rho}\cdot\Delta g(x,y,d), \qquad (18)$$

assuming that $\Delta\rho$ is the density contrast between the crust and the upper mantle.

High-Cut Filtering and Resampling

As can be seen from equation (15), the downward continuation involves multiplication of the factor $\exp(\sqrt{m^2+n^2}\cdot d)$ in the frequency domain. Therefore the high frequency components, which may be originated from the shallow sources, are significantly emphasized. In consequence, to obtain a reliable result of downward continuation, the surface gravity anomaly should be a smooth function whose Fourier spectrum attenuates with the shorter wavelengths more rapidly than, the exponential term rises.

The running average and conventional high-cut filtering methods have been usually used for smoothing the data. However, we have found that the sample interval also affects the result of downward continuation significantly. If the sample interval is much shorter than the downward continued depth d, the gravity function becomes fluctuated severely. In general, maximum tolerable depth for downward continuation is about one-half or two-thirds of the sample interval (Bhattacharyya, 1965, Kwon, 1981).

In this study, we have developed a new filtering technique which is called "high-cut filtering and resampling" method. This filtering operation accomplishes the function of high-cut filtering and widening the interval simultaneously. The process of high-cut filtering and resampling of two-dimensional gravity map is described in Fig. 8.

The original $N\times N$ map (Fig. 8-a) is first expanded into the symmetric matrix of $(2N-2)\times(2N-2)$ to avoid the edge effect (Fig. 8-b). Then, all spatial domain values are transformed into the frequency domain values using FFT (Fast Fourier Transform) algorithm. Since the input matrix is an even symmetric function, all imaginary parts of the Fourier spectrum vanish and there remain only real parts (Fig. 8-c). In conventional high-cut filtering, the high frequency values are replaced by zeros. But, in this high-cut filtering and resampling method, the high frequency values are all removed. After the high frequency values are removed symmetrically about the central maximum (Nyquist) frequency, the remained spectral values are recombined together to form a new matrix of reduced samples $(2N'-1)\times(2N'-1)$ as shown in Fig. 8-d. Through the inverse FFT, they are transformed into the spatial domain gravity values (Fig. 8-e). And then, the final high-cut filtered and resampled outputs of $N'\times N'$ can be obtained (Fig. 8-F).

This high-cut filtering and resampling method appeared to be an useful technique for smoothing, and widening the sample interval, that is, reducing the number of samples at the same time. The cut-off frequency can be represented by the ratio of the sample interval and the depth of downward continutaion.

Results of Depth Computation to the Crustal Base

The square grid of 66×66 samples is selected from original grid of 75×112 samples for the convenient computation. The grid spacing and the overall length are 4.11km and 271.3km respectively. The mean depth to the crustal base is assumed to be 32km from the power spectral analysis. The density contrast is chosen as 0.43g/cm^3, since the density of the crust and the upper mantle are assumed to be 2.84g/cm^3 and 3.27g/cm^3 respectively.

The relief of the crustal base has been computed repeatedly through downward continuation of the resampled gravity data set which has been reduced from original map to 15×15, 12×12, 10×10, 8×8, 6×6, and 5×5 square samples using high-cut filtering and resampling method. When the resampled data set reduced to 5×5

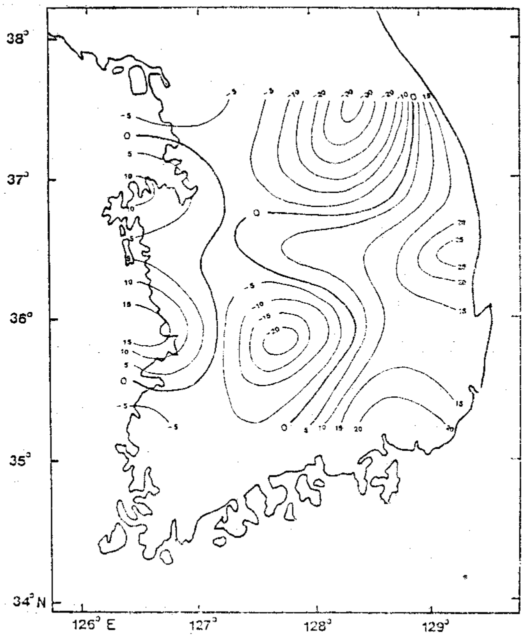

Fig. 9 Bouguer anomaly map of deep effect.

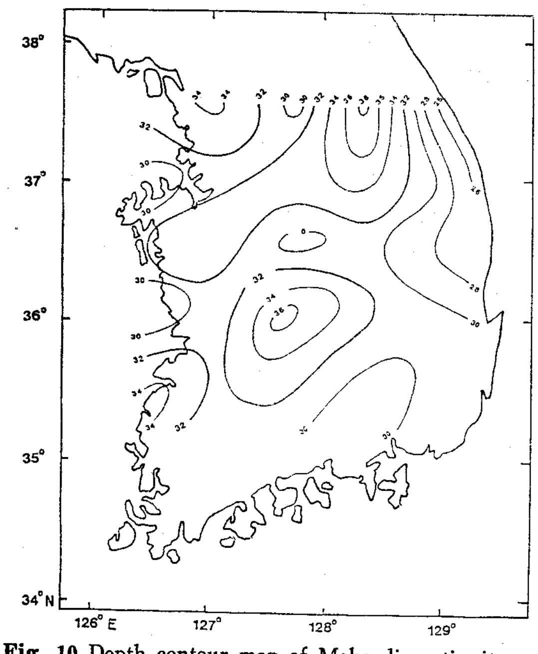

Fig. 10 Depth contour map of Moho discontinuity. Contour interval 2km.

matrix, no more considerable fluctuation has been observed. The ratio of the depth and the grid spacing at this point has a reasonable value of 32/54. 3. Therefore, the results obtained from

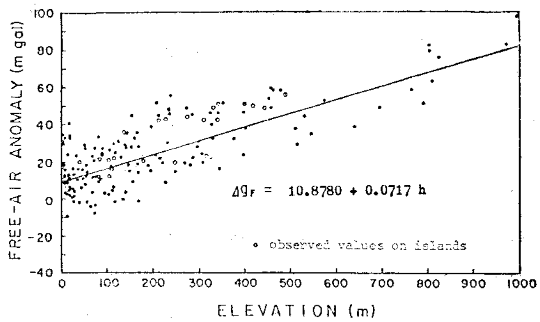

Fig. 11 Free-air anomaly versus elevation.

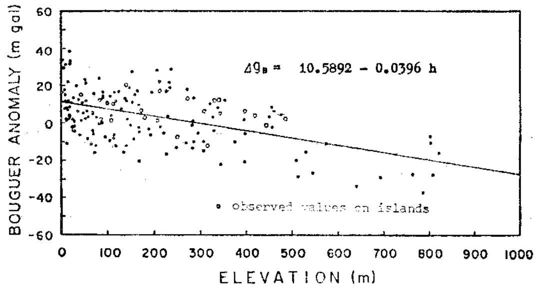

Fig. 12 Bouguer anomaly versus elevation.

this data set are accepted as the representative values of the relief of the crustal base. The deep effects of the gravity anomalies and the depth contour map of Moho discontinuity are shown in Fig. 9 and Fig. 10.

ISOSTASY

Isostasy means that the crust is floating on the denser upper mantle in hydrostatic equilibrium. It has been known that the major parts of the Earth's crust are in isostatic equilibrium. Isostasy can be tested rather simply using the relations between the elevations and the gravity anomalies (Garland, 1971, Lee, 1979). The free-air anomaly Δg_F and Bouguer anomary Δg_B are defined as follows

$$\Delta g_F = g_{obs} + 0.3086\ h - \gamma_0 \tag{19}$$

$$\Delta g_B = g_{obs} + 0.3086h - 2\pi G\rho h - \gamma_0$$
$$= \Delta g_F - 2\pi G\rho h \tag{20}$$

If it is in isostatic equilibrium on a large scale, the topographic masses are compensated by the mass deficiencies below the sea level. Therefore, Bouguer anomaly will be related to the elevation, while the free-air anomaly is independent of the elevation. The coefficient of h in the equation (20) has the value of -0.1119mgal/m when the crust is in perfect isostasy and the topographic density is assumed to be 2.67g/cm.

To investigate the status of isostasy of the peninsula, the relations between elevations and gravity anomalies are obtained through linear regression computations (Fig. 11, Fig. 12)

$$\Delta g_F = 10.8780 + 0.0717h \qquad (21)$$

$$\Delta g_B = 10.5892 - 0.0396h \qquad (22)$$

The data observed on islands have been excluded because the small-scale islands could be supported by the rigid crust without isostatic compensation.

The linear regression equations show that the free-air anomalies are closely related to the elevations, and the coefficient of h in the Bouguer effect has a quite lower value than expected. These results indicate that the crust of this area is not in perfect equilibrium, but a little undercompensated.

CONCLUSIONS AND DISCUSSION

The results of the polynomial fitting show that the regional field of the gravity anomalies is declined to the NW direction, therefore it can be noted that the gravity anomalies have a lineation in the NE-SW direction. This pattern is also revealed in the deep effects of the gravity anomalies separated by high-cut filtering. It is the same as the direction of tectonic lines, and that of most mountains in this area except Taebaeck Mountains.

The mean crustal thickness of the southern part of Korean peninsula obtained by power spectral analyses is approximately 32km, which is a reasonable value compared with the results of the previous studies, 35km (Lee, 1979) and 32 km (Kim, 1983). Since we have no direct evidence of the existence of Conrad discontinuity in this study, the crustal thickness is obtained with an assumption of a homogeneous single layer structure. If this crust is considered to have a two-layer structure as suggested by Kim (1983), the crustal thickness may have a different value.

The deep effects of the gravity anomalies are separated using high-cut filtering and resampling technique, and the depth distribution of the crustal base is obtained through downward continuation. The depth of the crustal base is well correlated with the regional surface topography, and it is distributed between 26km below the east coast, and 36km below the central region of Sobaek Mountains. It is shown that the crustal thickness of the east coast facing to the oceanic crust is thinner than that of the west coast.

The investigation of the relations between elevations and gravity anomalies indicates that the crust of this area seems to be not in perfect isostatic equilibrium state but a little undercompensated, which is contrary to the former study by Lee (1979), though same technique has been applied. This means that there is room for argument about the suitability of gravity data set for this kind of test. We feel that the isostasy of the peninsula should be studied with various methods.

For the frequency domain analysis, the original data have been reduced to a square map and expanded to the two-dimensional symmetric matrix form before FFT to reduce the edge effects. For more exact interpretation, it is desirable to supplement the data observed on the surrounding sea instead of expanding the limited data. The range of the computed depth distribution is appeared to vary depending on the cut-off frequency, sample interval, and the assumed density contrast between the crust and the upper mantle. Therefore, it may be needed to verify the computed results using direct methods such as Talwani's method (1960).

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중력자료분석을 통한 한반도 지각구조에 관한 연구

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요약 : 한반도 남한 지역의 지각구조를 연구하기 위하여 USAMSFE(1961~1962) 중력자료를 분석하였다. 이들 중력측정치를 IGSN 71중력치로 환산하기 위하여 −14.7mgal 보정을 실시하였으며, 중력이상의 계산에서는 GRS 67식을 사용하였다. 자료처리과정에 있어서는 polynomial fitting을 이용하여 지역중력이상과 잔류중력이상을 분리하였고, 지각의 평균두께와 지각기저면의 깊이분포를 구하기 위해 FFT(Fast Fourier Transform)를 이용한 power spectrum분석과 하향연속을 실시하였다. 하향연속을 위한 필터링 과정에서 고주파수차단 필터링과 동시에 자료간의 간격을 넓히는 효과를 낼 수 있는 2차원에서의 high-cut filtering and resampling법을 개발적용하였다.

분석의 결과로는 (1) 부우게 이상이 대체로 이 지역의 지체구조선의 방향과 같은 NE-SW방향의 분포를 보이고 있으며, (2) 지각의 평균두께는 약 32km로 나타났고, (3) 지각기저면의 깊이분포는 26km~36km의 범위로서 지

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표면의 광역적인 지형고도를 반영하고 있으며, 동해안의 지각이 서해안보다 더 얇은 것으로 나타났다. (4) 지각평형정도를 지시해주는 측정점의 고도와 중력이상 사이의 선형회귀방정식을 계산해본 결과, 우리 나라의 지각은 다소 보상이 덜되어 있는 것으로 나타났다.