BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXIV, N. 136 - DECEMBER 1992

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A GENERALISED SCHEME FOR THREE-DIMENSIONAL GRAVITY MODELLING OF SEDIMENTARY BASINS WITH A CONSTANT, LINEARLY OR EXPONENTIALLY VARYING DENSITY CONTRAST

Abstract. A generalised scheme for modelling gravity anomalies of three-dimensional sedimentary basins is presented, and which covers the three cases of constant density contrast, the density contrast varying linearly with depth and the density contrast varying exponentially with depth. The initial depths to the floor of the sedimentary basin are calculated based on the gravity anomalies at the stations. The differences between the observed and calculated anomalies are then used to modify the depths at the stations. The gravity anomalies of sedimentary basins are calculated by considering parallel vertical cross-sections of the basin. Each vertical cross-section of the basin is replaced by a polygon. Equations are given for the gravity effect of the polygon for the case of constant density contrast and the density contrast varying linearly with depth, in terms of the coordinates of the vertices of the polygon and the density contrast d_0 and its rate of variation d_1. The gravity effects of these cross-sections are calculated and numerically integrated to get the anomaly of the entire body. For exponential variation in density contrast, each side of the polygon is subdivided into NS segments, along each of which the density contrast is assumed to vary linearly with depth. Gravity effects of all these segments are calculated and summed up for the gravity effect of the entire vertical cross-section. The scheme developed for an exponential variation works automatically for the case of linear variation by simply setting $NS=1$ and further reduces to the case of constant density contrast, if $d_1=0.0$.

INTRODUCTION

It is well known that the density contrast of sedimentary rocks filling sedimentary basins decreases exponentially with depth (Athy, 1930; Cordell, 1973). Gravity modelling of a sedimentary basin is a relatively simple affair following the ingenious method of Bott (1960), if the density contrast remains constant throughout the sediments. For linear and exponential variations of density contrasts, schemes for modelling gravity anomalies of three-dimensional sedimentary basins are only a few (for eg. Chai and Hinze, 1988).

In this paper, a scheme is suggested for three-dimensional modelling of sedimentary basins with an exponential density contrast. It is shown that the same scheme can be applied automatically for the cases of constant and linearly varying density contrasts also.

The method is similar to the one used by Bott (1960) in modelling 2-D sedimentary basins. The gravity anomalies are sampled at the corners of a square or rectangular grid. The initial depths to the floor of the sedimentary basin are obtained by the Bouguer slab formula. The depths to the floor of the sedimentary basin are improved based on the differences between the observed and calculated anomalies iteratively. The anomalies are calculated following the forward modelling scheme of Radhakrishna Murthy and Rama Rao (1985). In this, parallel vertical cross-sections of the three-dimensional body are sampled, and each is replaced by an N-sided polygon. Equations are derived for calculating the gravity effect of a vertical polygon with a density contrast varying linearly with depth. To accommodate exponential variation, each

Manuscript received October 1, 1990; accepted August 1, 1992.

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side of the polygon is subdivided into several segments, along each of which the density contrast is assumed to vary linearly. The gravity effects of all these segments are calculated with the help of the equation derived, and added to get the gravity effect of the side. The gravity effects of all the sides are calculated similarly and added to get the gravity effect of the polygon. The gravity contributions of the polygons considered are numerically integrated between the ends of the body to get the gravity anomaly of the entire body.

The modelling scheme was generalised to cover the three cases of constant density contrast, the density contrast varying linearly with depth and the density contrast varying exponentially with depth by suitably selecting NS, the number of segments into which each side of the polygon has to be divided. The scheme works for exponential variation if $NS \geq 2$. For linear variation or constant density contrast $NS=1$, so that each side of the polygon is divided into only one segment, thus automatically converting the program for exponential variation to the one dealing with linear variation. The program further reduces to the case of constant density contrast if the rate of variation of density contrast is zero in addition to $NS=1$.

GRAVITY ANOMALY OF THREE-DIMENSIONAL BODY WITH A DENSITY CONTRAST VARYING LINEARLY WITH DEPTH

Calculation of gravity anomalies of a three-dimensional sedimentary basin in particular, and any three-dimensional body in general, is done in the proposed modelling scheme by considering vertical cross-sections of the body (Fig. 1). The gravity effects of these vertical cross-sections are calculated in terms of the coordinates of the vertices and integrated between the ends of the body (Radhakrishna Murthy and Rama Rao, 1985). Equations are derived here for the gravity effect of a vertical polygon in terms of the coordinates of the vertices for the specific case of a linear variation in density.

The gravity anomaly $g\,(0,\,0)$ at any point $P\,(0,\,0,\,0)=P\,(0,\,0)$ (Fig. 1) of a three-dimensional body with the density contrast varying with depth is given by

$$g\,(0,\,0)=G\int_{v}\frac{d_c\,(z).z\;dv}{r^3}=\int_{Y-}^{Y+}dg.dy. \tag{1}$$

Eqn. (1) modified to

$$dg=d_o\,G\int_{s}\frac{z\;ds}{r^3}+d_1\,G\int_{s}\frac{z^2\;ds}{r^3} \tag{2}$$

represents the gravity effect of the X-Z cross-section of the body with unit thickness and at the shortest distance y from the point of calculation, and the density contrast $d_c\,(z)$ varies linearly with depth (z) according to the relation

$$d_c\,(z)=d_o+d_1 z. \tag{3}$$

d_o is the density contrast 'extrapolated' to the ground surface and d_1 is the rate of linear variation with depth; Y_- and Y_+ are the limits of the body along the y-axis as measured from the point of calculation.

The boundary of each X-Z cross-section can, in turn, be replaced by an N-sided polygon, and the coordinates $(X_K\,,\,y,\,Z_K)$ of their vertices defined. By converting the surface integration to line integration, the gravity effect is evaluated along all the sides and summed for the gravity effect of the polygon. The equation for the gravity effect of the entire cross section in the final form for computer programming can be written as

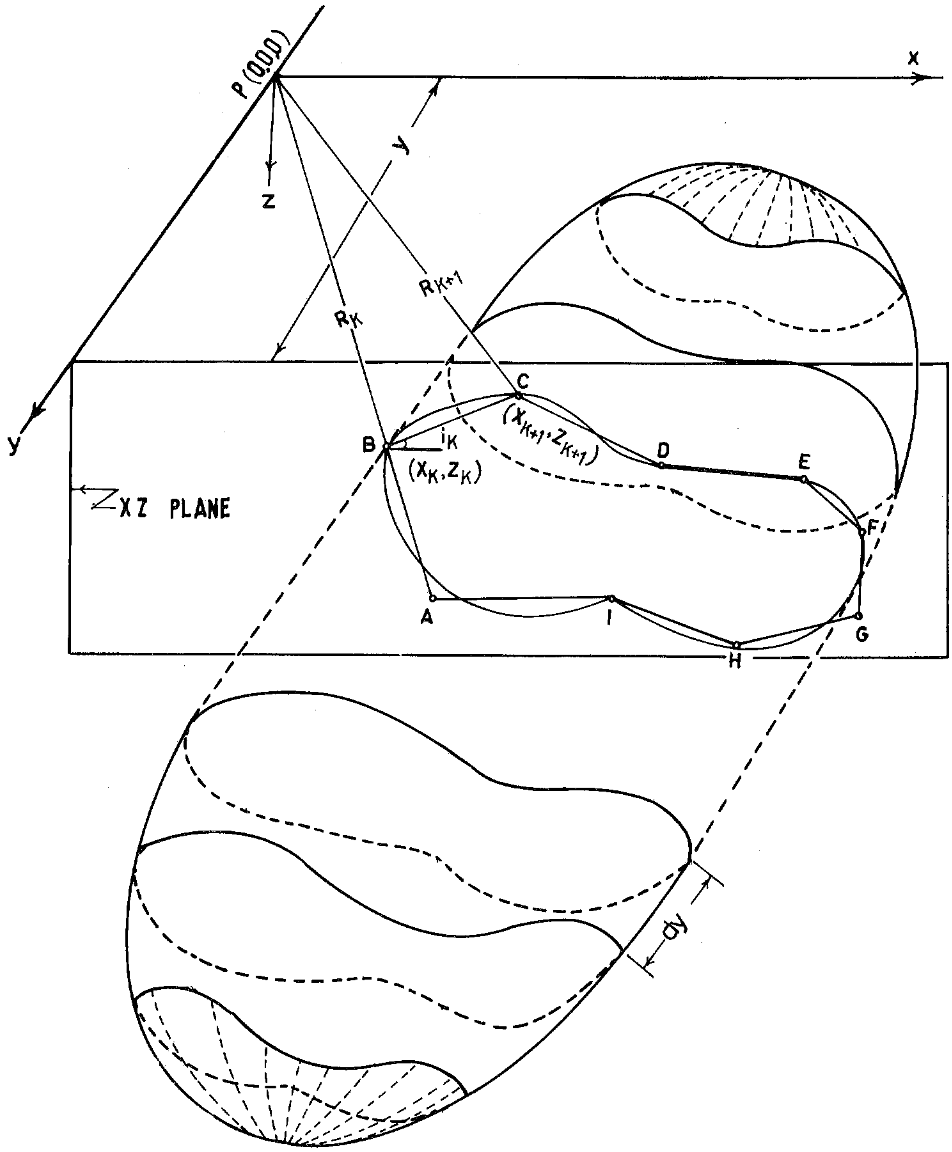

Fig. 1 — Three-dimensional body and the representation of its vertical cross-sections by N-sided polygonal models.

$$dg = G \sum_{k=1}^{N} dg_k \ ,$$

where

$$dg_k = d_o \ F_1 + d_1 \ [-\tan i_k \sin i_k \cos i_k \ P_k \ F_1$$
$$+ 0.5 \sin 2i_k \ F_2 + y \ (F_3 - F_4) + F_5$$
$$+ F_6 - y \ F_7] \ , \qquad (4)$$

with

$$F_1 = \cos i_k \ln [(R_{k+1}+Q_{k+1}) / (R_k+Q_k)] ,$$
$$\text{for } R_{k+1} + Q_{k+1} \neq 0 \text{ and } R_k+Q_k \neq 0,$$
$$= \cos i_k \ln (R_k / R_{k+1}),$$
$$\text{for } R_k+Q_k=0 \text{ and } R_{k+1}+Q_{k+1}=0,$$
$$F_2 = R_{k+1}-R_k ,$$
$$F_3 = \arctan [(R_k^2 \sin i_k-Z_k Q_k) / (y \cos i_k R_k)] ,$$
$$F_4 = \arctan [(R_{k+1}^2 \sin i_k-Z_{k+1} Q_{k+1}) / (y \cos i_k R_{k+1})] ,$$
$$F_5 = X_{k+1}-X_k ,$$
$$F_6 = X_k \ln (Z_k+R_k)-X_{k+1} \ln (Z_{k+1}+R_{k+1}),$$
$$F_7 = \arctan (X_{k+1} /y)-\arctan (X_k /y),$$

$$R_{k+1}^2=X_{k+1}^2+y^2+Z_{k+1}^2 ,$$
$$R_k^2 =X_k^2+y^2+Z_k^2 ,$$
$$Q_{k+1}=X_{k+1} \cos i_k + Z_{k+1} \sin i_k ,$$
$$Q_k =X_k \cos i_k + Z_k \sin i_k ,$$
$$P_k =Z_k \cos i_k-X_k \sin i_k ,$$
$$\sin i_k=(Z_{k+1}-Z_k) / \sqrt{(X_{k+1}-X_k)^2 + (Z_{k+1}-Z_k)^2} ,$$
$$\cos i_k=(X_{k+1}-X_k) / \sqrt{(X_{k+1}-X_k)^2 + (Z_{k+1}-Z_k)^2} ,$$
$$\text{and } X_{N+1}=X_1 \text{ and } Z_{N+1}=Z_1 .$$

Eqn. (4), however, has a singularity point at $y=X_k=Z_k=0.0$. The gravity effect on profiles over shallow or out-cropping cross-sections can be calculated with the help of the gravity anomaly equation for two-and-a-half dimensional bodies derived by Rama Rao and Radhakrishna Murthy (1989), assuming a strike length of one unit $(Y=1.0)$. The necessary equation for ready reference is given in the Appendix.

It can be seen that eqns. (4) and (5) can also be used to calculate the gravity effects of polygons with a constant density contrast. Then d_1 in eqn. (3) is zero, so that calculation of the terms in the second square brackets of eqns. (4) and (5) can be avoided.

The gravity anomaly $g\ (0,\ 0)$ of the entire body is obtained from the gravity effects $dg\ (y)$ of different cross-sections with different values of y as

$$g\ (0,\ 0)= \int_Y dg\ (y)\ dy.$$

The above integral can be evaluated numerically by any standard method, such as Simson's rule in the case of non-outcropping bodies. For outcropping bodies, the anomaly is dominated by the contribution from the outcropping strip immediately below the point of calculation. This

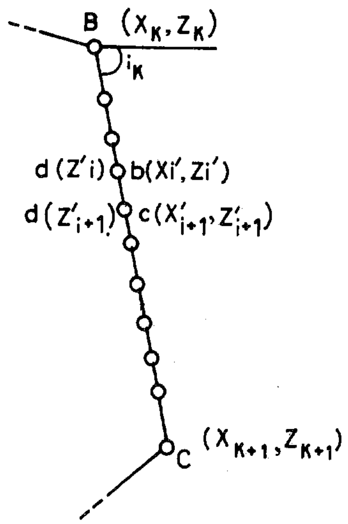

Fig. 2 — Division of the side of a polygon into a number of segments.

results in an exponential variation of dg between two successive cross-sections and the normal methods of numerical integration were found ineffective. Based on exponential variation, the integral value between two values of dg is evaluated as

$$\int_{y_k}^{y_{k+1}} dg\ (y)\ dy = \frac{dg\ (y_{k+1})-dg\ (y_k)}{ln\ [dg\ (y_{k+1})\ /\ dg\ (y_k)]}\ dy.$$

If $dg\ (y_k)$ and $dg\ (y_{k+1})$ are of opposite sign, the point of zero contribution is found by linear interpolation and the integral is evaluated separately between the two intervals. Then,

$$g\ (O,\ O) = \sum_{k=1}^{N_y-1} \int_{y_k}^{y_{k+1}} \frac{dg\ (y_{k+1})-dg\ (y_k)}{ln\ [dg\ (y_{k+1})\ /\ dg\ (y_k)]}\ dy,$$

where N_y is the number of cross-sections considered.

EXPONENTIAL VARIATION IN DENSITY CONTRAST

For the exponential variation, the equation for the gravity effect of the side of a polygon cannot be obtained in a closed form. What will be obtained is an infinite series of terms. Such a series, which may not necessarily converge, is of no practical use. For the gravity anomalies of three-dimensional bodies with the density contrast varying exponentially with depth, the following procedure based on the method of Radhakrishna Murthy and Bhaskara Rao (1979) is recommended. The outline of the vertical cross-section is fitted with a polygon of a reasonable number of sides, and the coordinates of the vertices are obtained. Each side of the polygon is subdivided into NS segments (Fig. 2), along each of which the density contrast can be approximated to vary linearly with depth. The gravity effects $(dg_k)_i$ $(i=1, \ldots, NS)$ of each of these segments are calculated and summed. Thus,

$$dg\ (0,\ 0) = \sum_{k=1}^{N} \sum_{i=1}^{NS} (dg_k)_i\ .$$

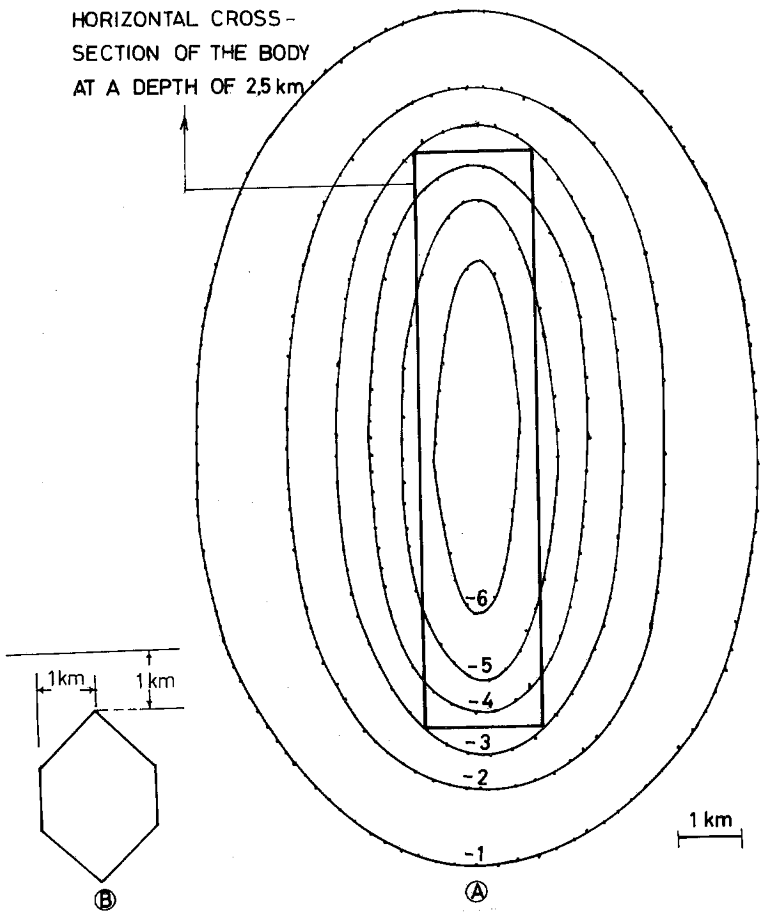

Fig. 3 — a) Gravity anomalies calculated by the present method (continuous lines) and by the method of Rao and Murthy, 1989 (dotted lines) over a hexagonal model of strike length = 10 km with an exponential variation in density contrast $d_c\ (z) = -0.54.\ exp\ (-0.2z)$. The anomalies are in milliGals.
b) Vertical cross-section of the body whose anomalies are shown in a).

If $(X_k\ ,\ Z_k\ )$ and $(X_{k+1}\ ,\ Z_{k+1}\ )$ are the coordinates of the vertices of the *kth* side of the vertical polygon, the coordinates $(X'_i\ ,\ Z'_i\ )$ of the various segments are given by

$$X'_i = X_k + [(X_{k+1} - X_k) \ / \ NS] \ [i-1] \ ,$$

and

$$Z'_i = Z_k + [(Z_{k+1} - Z_k) \ / \ NS] \ [i-1] \ ,$$

$$(i=1, \ ..., \ NS+1).$$

If $d_c\ (z) = d_o\ exp\ (d_1\ z)$ is the exponential variation in the density contrast, where d_o is the density contrast extrapolated to the ground surface and d_1 is the exponential constant, then the constants defining the linear variation in density between Z'_i and Z'_{i+1} are given by

$$d'_1 = [d_c\ (Z'_{i+1}\ ) - d_c\ (Z'_i)] \ / \ (Z'_{i+1} - Z'_i)$$

and

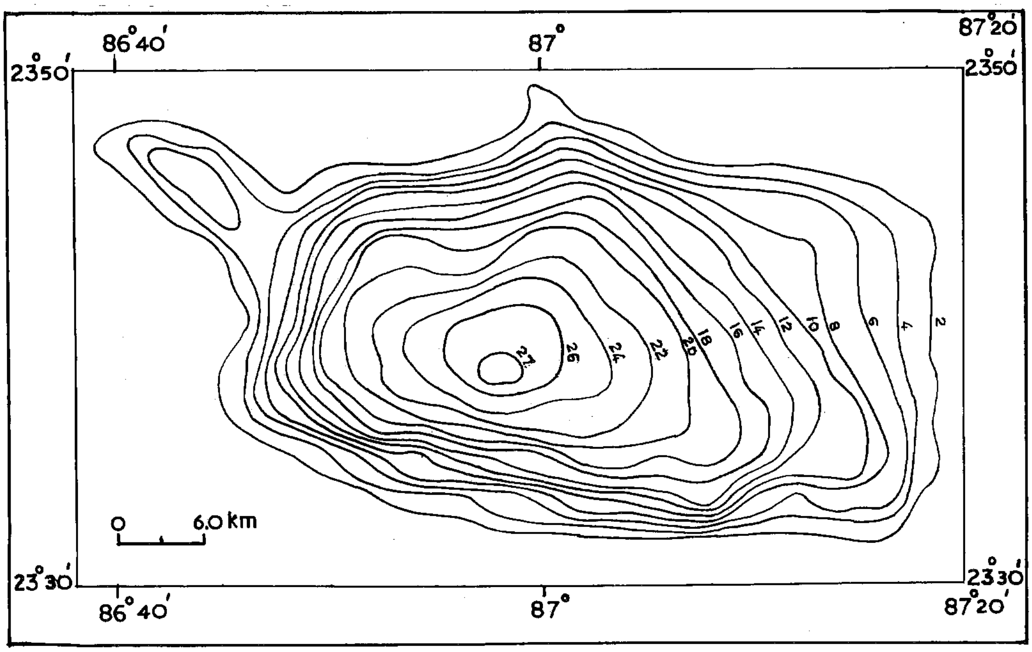

Fig. 4 — Residual gravity anomaly map of Raniganj coal field, India (Verma et al., 1980).

$$d'_o = d_c\,(Z'_i) - d'_1\,Z'_i\,.$$

These values of d'_0 , d'_1 , $(X'_i\,,\,Z'_i)$ and $(X'_{i+1}\,,\,Z'_{i+1})$ are substituted into the right hand side of eqn. (5) for the gravity effect $(dg_k)_i$ of a segment.

It is clear that the calculation time for the exponential variation is approximately NS times the time for a linear variation. Such a drastic increase in computer time has to be tolerated because there is no solution for the problem unless the body is replaced by a polygon of many sides of small length, so that the density contrast can be safely approximated to vary linearly along the vertical distance of each of these sides.

Fig. 3 shows an example of gravity anomalies (dotted lines) using the present method over a hexagonal model of strike length 10 km, with an exponential variation in density contrast. The constants of the exponential variation were taken to be $d_c = -0.54$ and $d_{c1} = 0.2$. Gravity anomalies of the above model were calculated using the two-and-a-half equations of Rao and Murthy (1989). The two sets of anomalies are very close, proving the correctness of the derived equations.

GENERALISATION

Using the method described above, one can develop a program to calculate the gravity effect dg of a polygon with an exponential variation in density contrast, viz., $d_c\,(z) = d_o\,exp\,(d_1\,z)$, where d_o is the density contrast extrapolated to ground surface and d_1 is the exponential constant. The expression on the right hand side of eqn. (4) is worked out NS times for each side of the polygon. For exponential variation, NS can be any number greater than or equal to two, but a figure of 10 is recommended. The same program can be used to calculate the gravity effect of the polygon with a linearly varying density contrast by setting $NS = 1$, so that each side of the polygon is divided into only one segment along which the density contrast varies linearly with the values of d_o and d_1 as defined in the equation $d_c\,(z) = d_o + d_1\,z$.

Further, if d_1 is zero, such a program automatically reduces to the calculation of the gravity

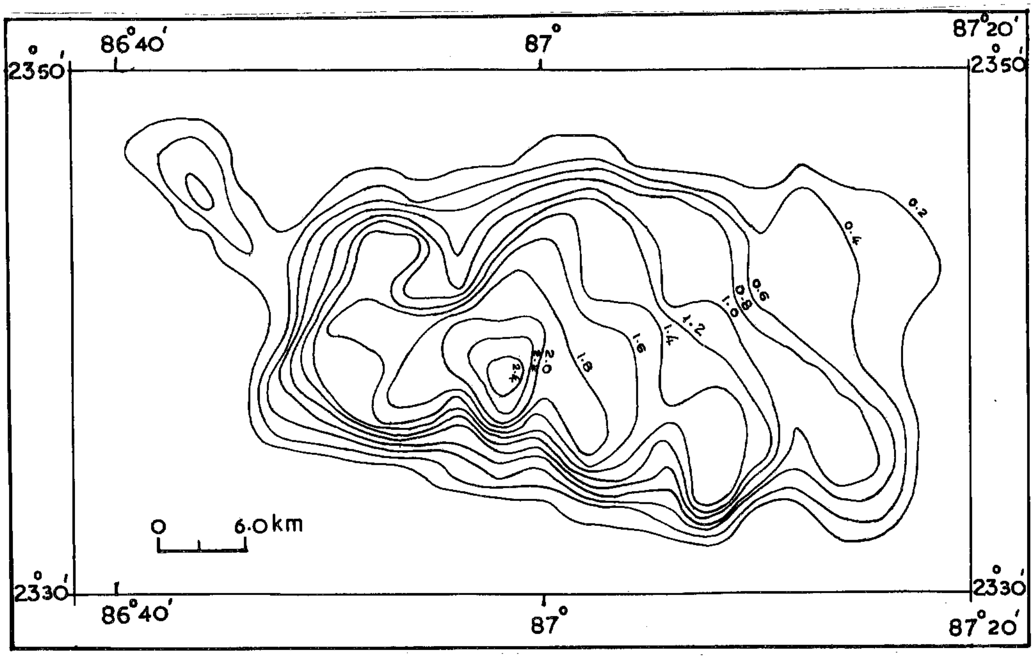

Fig. 5 — Depth to the basement deduced by modelling the anomalies shown in Fig. 4 assuming a uniform density contrast.

effect of a polygon with a constant density contrast. Thus, the same program can be used for the three types of density variations; namely the constant density contrast, the linearly varying density contrast and the density contrast varying exponentially with depth.

THREE-DIMENSIONAL MODELLING OF OUTCROPPING SEDIMENTARY BASINS

The scheme requires the gravity anomalies sampled at the corners of a square or rectangular grid. The values of NS, d_o and d_1 are also defined. NS is obviously 10 for exponential variation and 1 for linear variation and constant density contrast. Further, $d_1=0$ for the constant density contrast. The depth Z to the top of the basin is also defined. The scheme determines the initial depths to the floor of the sedimentary basin based on the Bouguer slab formula and improves them iteratively based on the differences between the observed and calculated anomalies. The scheme essentially depends on the method of Bott (1960) and consists of three steps viz., (i) initialisation, (ii) calculation of anomalies and (iii) improvement. The calculations involved in each of these steps are as follows:

(i) Initialisation. The formula for obtaining the initial values are different for the three types of density variations.

For constant density contrast (i.e., $NS=1$ and $d_1=0$) the initial depths Z_T to the floor of the sedimentary basin are obtained from

$$Z_T\ (j,\ k)=Z+g_{obs}\ (j,\ k)/2\pi G d_o\ ,$$

for all values of $j=2,\ N_y-1$ and $k=2,\ N_x-1$, where N_x is the number of points along each profile and N_y is the number of profiles.

When the density contrast varies linearly with depth (i.e., $NS=1$ and $d_1\neq 0$), the initial depths are calculated based on the formula (Radhakrishna Murthy et al., 1981)

$$Z_T\ (j,\ k)=Z+\left[\frac{-d_o}{d_1}\right]-\sqrt{\frac{d_o^2}{d_1^2}+\frac{2g_{obs}\ (j,\ k)}{41.9047\ d_1}}\ ,$$

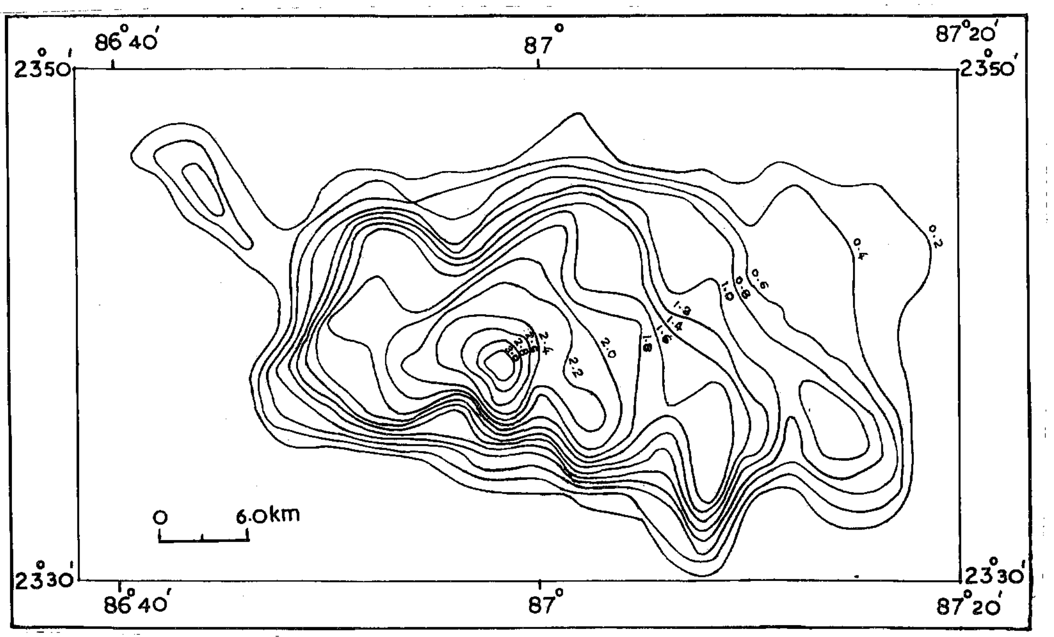

Fig. 6 — Depth to the basement deduced by modelling the anomalies shown in Fig. 4 assuming a linearly varying density contrast.

for all values of $j=2,\ N_y-1$ and $k=2,\ N_x-1$.

For exponential variation in density contrast (i.e., $NS=10$) the initial estimates of the depths are obtained as follows:

$$Z_T\ (j,\ k)=Z+(1/d_1)\ ln\ [1+d_1\ g_{obs}\ (j,\ k)/2\pi Gd_o]\ ,$$

for all values of $j=2,\ N_y-1$ and $k=2,\ N_x-1$.

The depth to the floor of the sedimentary basin along the boundary of the chosen area is equated to Z.

(ii) Calculation of anomalies. The gravity anomalies $g_{cal}\ (j,\ k)$ of the initial model thus obtained are calculated through the forward modelling scheme outlined in the foregoing pages, wherein, parallel vertical cross-sections of the sedimentary basin are considered. Each vertical cross-section of the basin is replaced by an N-sided polygon whose vertices $(x,\ z)$ are the distance coordinates along each profile and the corresponding initial depths Z_T obtained in step (i). For exponentially varying density contrast, each side of the polygon is subdivided into NS segments and d'_o and d'_1 are calculated as follows.

If $(X\ (j,\ k),\ Z\ (j,\ k))$ and $(X\ (j,\ k+1),\ Z\ (j,\ k+1))$ are the coordinates of the vertices of the kth side of the vertical polygon on the jth profile, the coordinates $(X'_i\ ,\ Z'_i)$ of the various segments are given by

$$X'_i = X\ (j,\ k)+[\,[(X\ (j,\ k+1)-X\ (j,\ k)]/NS]\ (i-1),\quad i=1,\ NS+1,$$

and

$$Z'_i = Z\ (j,\ k)+[Z\ (j,\ k+1)-Z\ (j,\ k)]\ (i-1),\quad i=1,\ NS+1.$$

The constants defining the linear variation in density contrast between Z'_i and Z_{i+1}' are given by

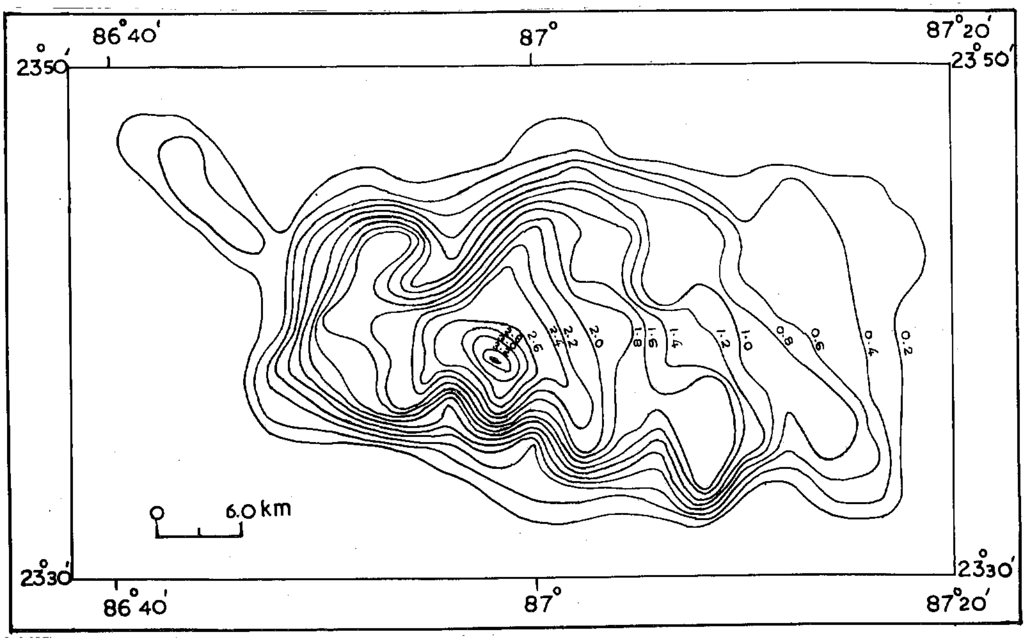

Fig. 7 — Depth to the basement deduced by modelling the anomalies shown in Fig. 4 assuming an exponential variation in density contrast.

$$d'_1 = [d_c\,(Z_{i+1}') - d_c\,(Z'_i)]/(Z_{i+1}' - Z'_i)$$

and

$$d'_o = d\,(Z'_i) - d'_1\,Z'_i\ .$$

The gravity effect of each of these segments in a side of the cross-section and in turn the whole polygon is calculated by the equation

$$dg = \sum_{k=1}^{N} \sum_{i=1}^{NS} (dg_k)_i$$

where $(dg_k)_i$ is the gravity effect of the *ith* segment of the *kth* side of the polygon and dg_k is given by eqn. (4).

(iii) Improvement. As in step (i), the formulae for improving the depth values are different for the three cases. The equations are

$$Z_T\,(j,\,k) = Z_T\,(j,\,k) + \frac{[g_{obs}\,(j,\,k) - g_{cal}\,(j,\,k)]}{2\pi G d_o}\ ,$$

for constant density contrast (*i.e.* $NS=1$ *and* $d_1=0$);

$$Z_T\,(j,\,k) = Z_T\,(j,\,k) + \frac{[g_{obs}\,(j,\,k) - g_{cal}\,(j,\,k)]}{2\pi G\,[d_o + d_1\,Z_T\,(j,\,k)]}\ ,$$

for linearly varying density contrast (i.e. $NS=1$ and $d_1 \neq 0$), and

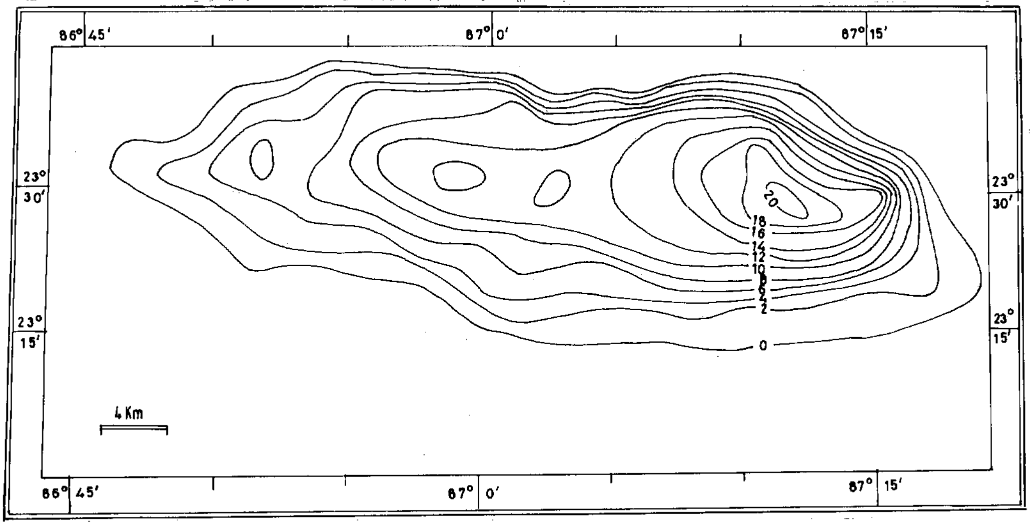

Fig. 8 — Observed Bouguer anomaly map over Bankura anorthosite complex, West Bengal, India. (Verma et al., 1975).

$$Z_T(j,\ k) = Z_T(j,\ k) + \frac{[g_{obs}(j,\ k) - g_{cal}(j,\ k)]}{2\pi G d_o \exp\ [d_1\ Z_T(j,\ k)]},$$

for exponentially varying density contrast (i.e. $NS=10$), for all values of $j=2,\ N_y-1$ and $k=2,\ N_x-1$. Depths becoming less than Z during this modification are equated to Z, which is zero for an outcropping sedimentary basin.

The iteration is terminated either when the objective function, defined as the sum of the squares of differences between observed and calculated anomalies, tends to increase or falls below an allowable error, or after a specified number of iterations is completed.

EXAMPLES OF INTERPRETATION

Two examples are presented showing the utility of the above generalised scheme. The example in Fig. 4 deals with the modelling of a sedimentary basin with a variable density contrast, while the second one in Fig. 8 deals with the modelling of a flat-topped gabbroic mass with a constant density contrast.

Example 1

Fig. 4 shows the residual Bouguer anomaly map of the Raniganj coal field, India (Verma et al., 1980). Twenty two profiles were constructed from these contours and thirteen stations sampled along each of them. The station interval is 3.0 km and profile spacing is 3.0 km. The density contrast between the Gondwana sediments and the underlying metamorphic rocks is —0.37 gm/c^3. These anomalies were modelled for the case of a constant density contrast of —0.37 gm/c^3 and also for hypothetical linear and exponential variations.

Fig. 5 shows the depth to the basement as deduced from the three-dimensional modelling of the anomalies shown is Fig. 4, assuming a constant density contrast of —0.37 gm/c^3. This shows the maximum thickness of sediments filling the basin to be 2.5 km in the central part of the basin. Verma et al. (1980) report a maximum thickness of 2.9 km in the central part of the basin.

Fig. 6 shows the basement with a maximum thickness of 3.1 km in the central part of the basin, when the anomalies shown in Fig. 4 are modelled assuming a density contrast varying linearly according to the relation $d_c\ (z) = -0.37 + 0.05\ z$.

Fig. 7 shows that the maximum depth of the basement is 3.4 km in the central part of

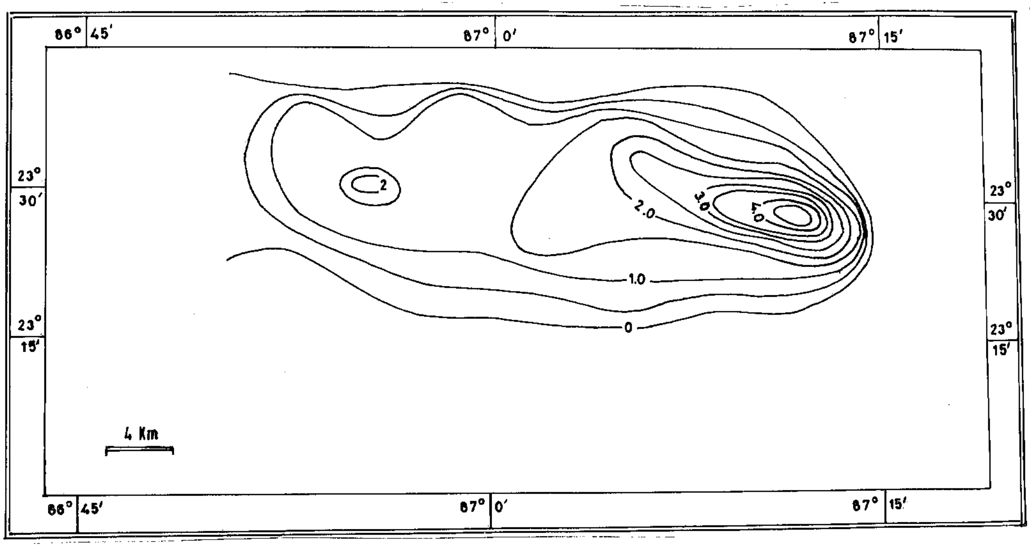

Fig. 9 — Outlines of the high density gabbroic mass deduced by modelling the anomalies shown in Fig. 8.

the basin when it is modelled assuming an exponential density contrast defined by the equation $d_c\ (z) = -0.37\ exp\ (-0.18\ z)$.

It is observed that the depth to the floor of the sedimentary basin expectedly increases in the case of linear and exponential variations.

Example 2

Fig. 8 shows the residual Bouguer anomaly map over a possible high density mass of gabbroic composition lying partly below a thin layer of anorthosite in the Bankura anorthosite complex, West Bengal, India (Verma et al., 1975). Thirteen parallel profiles were constructed from these contours and fourteen stations sampled along each of them. The station interval is 1.34 km and profile spacing is 4.7 km. The anomalies were modelled assuming a constant density contrast of 0.23 gm/c^3. The outline of the gabbro is shown in Fig. 9 in the form of depth contours giving a maximum depth of 4.6 km. Verma et al. (1975) report a maximum thickness of 5.0 km of this rock.

APPENDIX

Gravity anomaly equation for an out-cropping cross-section

$$dg = 2G \sum_{k=1}^{N} \left\{ d_o \left[0.5 \cos i_k \ln \left(\frac{R_{k+1} + Q_{k+1}}{R_k + Q_k} \right) \right. \right.$$

$$- P_k \left[0.5 \sin i_k \ln \left(\frac{(R_{k+1} - 0.5)(R_k + 0.5)}{(R_k - 0.5)(R_{k+1} + 0.5)} \right) \right.$$

$$- \cos i_k (\delta_k - \delta_{k+1}) + (Z_{x+1}\, \theta'_{k+1} - Z_k\, \theta'_k)$$

$$\left. + 0.25 \ln \left(\frac{(R_{k+1} - X_{k+1})^2 (Z_k^2 + 0.25)}{(R_k - X_k)^2 (Z_{k+1}{}^2 + 0.25)} \right) \right]$$

$$+0.5\, d_1 \Bigg[0.5 \cos i_k \sin i_k \,(R_{k+1} - R_k)$$

$$- P_k \sin^2 i_k \ln \left(\frac{(R_{k+1} + Q_{k+1})}{R_k + Q_k} \right)$$

$$+ P_k^2 \Bigg[0.5 \sin 2i_k \ln \left(\frac{(R_{k+1} - 0.5)(R_k + 0.5)}{(R_k - 0.5)(R_{k+1} + 0.5)} \right)$$

$$- \cos 2i_k \,(\delta_{k+1} - \delta_k) \Bigg]$$

$$+ 0.25\, (\delta'_{k+1} - \delta'_k) + (Z_{k+1}{}^2\, \theta'_{k+1} - Z_k^2\, \theta'_k) \Bigg] \Bigg\}, \qquad (5)$$

where

$$R_k^2 = X_k^2 + 0.25 + Z_k^2 ,$$

$$\delta_k = \arctan \,[0.5\, Q_k / P_k\, R_k] ,$$

$$\theta'_k = \arctan \,[0.5\, X_k / Z_k\, R_k] ,$$

$$\delta'_k = \arctan \left[\frac{R_k^2 \cos i_k - X_k\, Q_k}{0.5 \sin i_k\, R_k} \right]$$

and similar other formulae for R_{k+1} , δ_{k+1}, θ'_{k+1} and δ'_{k+1} .

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