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Improved Technique for Rapid Interpretation of Gravity Anomalies Caused by Two-Dimensional Sedimentary Basins

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Abstract. An empirical interpretation technique is discussed which allows to compute the cross-section of a two-dimensional sedimentary basin from the measured residual Bouguer anomaly profile, if the density contrast is known. Initial depths to basement thus obtained may be taken to be the input for a further iterative interpretation programme. The proposed interpretation technique is tested on some few hypothetical models and results are compared to those obtained from other interpretation techniques.

Key words: Two-dimensional sedimentary basins – Semiempirical iterative interpretation technique – Principle of equivalence.

1. Introduction

The calculation of gravity anomalies for any geological body of arbitrary shape results in a unique solution (Grant and West, 1965). A rapid computer method is based on the line-integral method and is described by Talwani et al. (1959).

The inverse problem has no unique solution (Grant and West, 1965). However empirical and/or automatic iterative interpretation methods may result in satisfactory solution(s) if the density contrast is sufficiently well known and if further data from other geophysical exploration methods or drillings become available.

Empirical interpretation methods relate certain characteristics of the gravity anomaly (such as "half-width", maximum of anomaly, derivatives, etc.) to characteristic geometrical features of the geological body (such as maximum depth, body-width etc.) (Skeels, 1963; Jacoby, 1970).

Fournier and Krupicka (1975) propose an approximate method for direct interpretation of gravity profiles. They derive empirical relations of anomaly-shape to body-shape for hypthetical "bell-shaped" sedimentary basins.

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Bott (1960) describes an iterative computing method whereby the initial-depths as well as the iterative depth adjustments are calculated from the "flat-plate" formula and depth adjustments are applied after each cycle of computations.

Qureshi and Mula (1971) studied single and double iterative adjustment and come to the conclusion that the number of iterations can be cut by half if double adjustment is applied.

In a later paper, Qureshi and Idries (1972) conclude that the iteration process converges most rapidly if double adjustment is applied after each computation rather than after each cycle of computations.

Fournier and Krupicka (1973) modified Bott's interpretation technique empirically after ten iterations have proceeded and thus speed the convergence of the iterative modeling process. However computer time is saved only apparently.

The present paper describes an interpretation technique which is partly based on empirically derived anomaly-depth relations and partly on automatic iterative data processing.

2. Basic Principle

The "flat-plate" formula is given as

$$z_i' = 23.866\, \Delta g_i / \sigma \quad \text{(m)} \tag{1}$$

where σ is the assumed or known density contrast in gcm^{-3}, z_i' is the depth to basement in meters and Δg_i is the residual Bouguer anomaly in mgals, as measured at the i-th field station, respectively. The above formula is a rather unfavorable approach to estimate initial depths to basement. It overestimates depths towards the margins of a sedimentary basin and underestimates depths towards its center.

A triangular model is selected to derive empirical relations between body-shape and gravity anomaly. Although the triangular model represents a rather unrealistic sedimentary basin, it was selected for two reasons: firstly, it's gravity effect is rapidly computed applying the technique proposed by Talwani et al. (1959), and secondly, the triangular body represents a model, where present iterative interpretation techniques are unsatisfactory because of slow convergence towards the center of the basin.

The geometry of a symmetrical triangular body may be defined by its width W_b and its maximum depth z_0 (see Fig. 1). Accordingly, the gravity anomaly caused by a triangular body may be characterized by its "half-width" W_a and its maximum amplitude Δg_0 (see Fig. 1). Body-width W_b and anomaly half-width W_a are measured in kilometers and depths z_i', z_i and z_0 are measured in meters throughout this paper.

The ratio (W_b/W_a) can be related empirically to the ratio

$$A = \Delta g_0 / \sigma W_a \quad (\text{mgals/km gcm}^{-3}) \tag{2}$$

and this relation appears to be linear in the range $0 \leqq A \leqq 13$ (see Fig. 2). A least squares regression fit results in

$$W_b / W_a = -0.056\text{A} + 1.827. \tag{3}$$

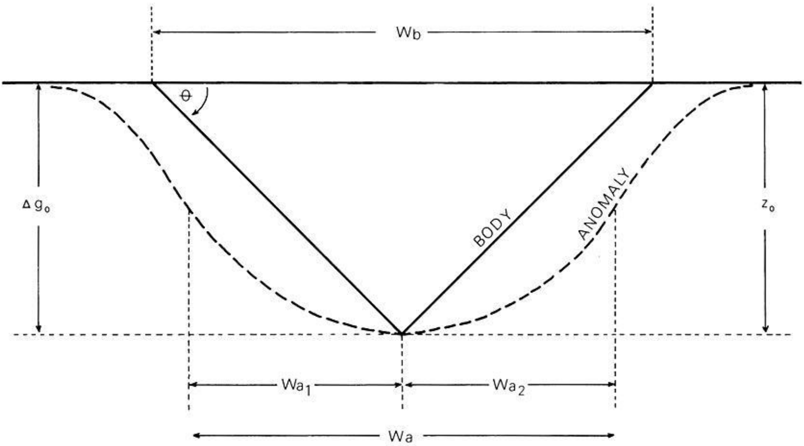

Fig. 1. Associated body- and anomaly parameters

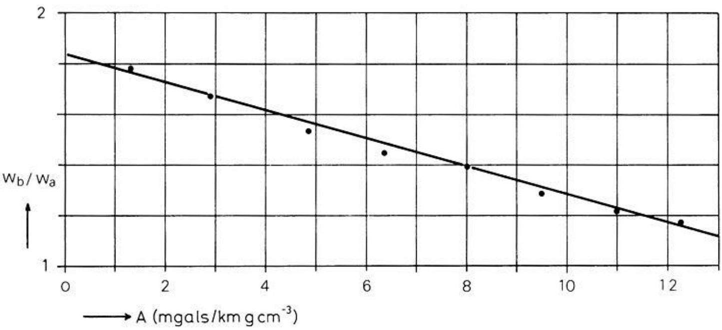

Fig. 2. Empirical relation between anomaly half-width W_a and body width W_b

Thus W_b may be estimated from formula (3) in cases where the body width cannot be inferred from surface geology.

The maximum depth of the basin may be extimated from the relations shown in Figure 3. This curve cannot be approximated reasonably by one single analytical function. Therefore two linear relations are derived:

$$z_0/z'_0 = 0.27A + 1.00 \qquad (\text{for } 0 \leqq A \leqq 9) \tag{4}$$

and

$$z_0/z'_0 = 0.12A + 0.57 \qquad (\text{for } 9 \leqq A \leqq 13) \tag{5}$$

The normalized residual Bouguer anomaly

$$G_i = \Delta g_i / \Delta g_0 \tag{6}$$

may be related to the normalized depth to basement

$$Z_i = z_i / z_0 \tag{7}$$

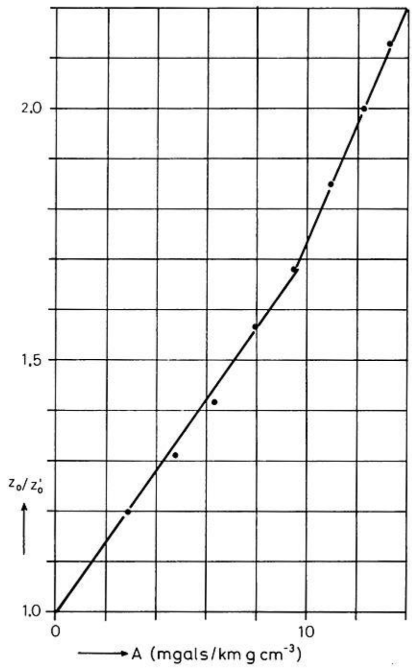

Fig. 3. Empirical relation to estimate the maximum depth z_0 of a two-dimensional sedimentary basin

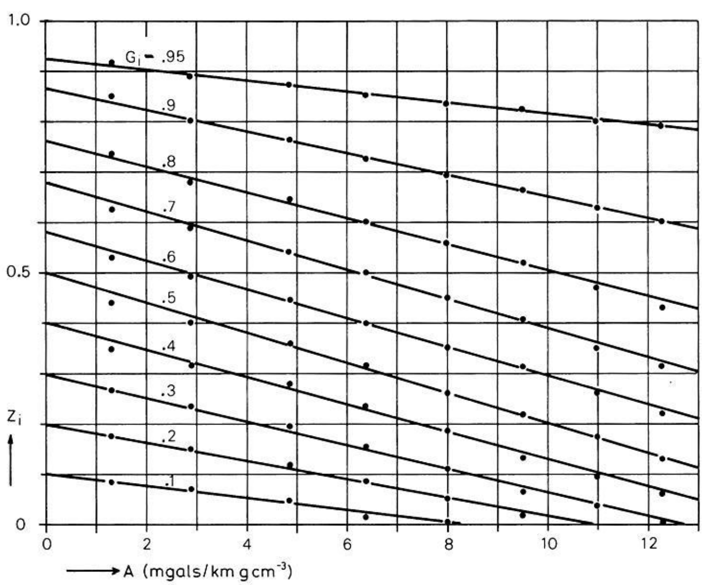

Fig. 4. Empiricla relation to estimate depths to basement underneath each individual field station

at each individual field station. Figure 4 shows z_i as function of A with G_1 being curve parameters. These relations appear to be approximately linear in the range $1 \leqq A \leqq 13$. However no single analytical function could be derived to represent Z_i as function of G_i. The best approximations is found to be

Table 1. Interpretation results for two-dimensional sedimentary basins with triangular cross-sections. (Deviations between calculated and true maximum depths in %. Number of iterations is given in brackets)

A	θ	Direct and empirical methods		Automatic iterative methods (iteration limit: 2% from Δg_0)	
		"Flat-Plate" Approach	Fournier and Krupicka (1975)	Bott (1960)	Qureshi and Mula (1971)
1.30	2.3°	− 14%	−11%	− 8 (2)	− 3% (4)
2.88	5.7	− 20%	−11%	− 7% (3)	− 3% (4)
4.86	11.3	− 32%	−14%	− 8% (4)	− 3% (4)
6.37	16.3	− 42%	−15%	− 1% (7)	+ 1% (4)
9.48	31.0	− 69%	−15%	−17% (7)	−16% (4)
10.98	38.7	− 85%	−11%	−24% (8)	−23% (5)
12.27	45.0	−100%	− 5%	−22% (8)	−21% (6)

$$Z_i = 0.081\ G_i[A\,(G_i^a - 1) + 12.27] \tag{8}$$

where

$$a = \begin{matrix} 2 \text{ for } 0 \leqq G_i \leqq 0.6 \\ (5G_i - 1) \text{ for } 0.6 \leqq G_i \leqq 1) \end{matrix} \tag{9}$$

Although Equations (3), (4), (5), (8) and (9) are valid strictly only for two-dimensional basins of triangular cross-sections, they may also approximately hold in general (see chapter 3).

Thus the general procedure to estimate initial depths to basement from a residual Bouguer anomaly profile as measured over a two-dimensional sedimentary basin of arbitrary shape can be summarized as follows:

a) determine the parameter A using formula (2),

b) estimate W_b from formula (3) or Figure 2 (if W_b cannot be inferred from surface geology),

c) determine Z_0 from formula (4) or formula (5) or Figure 3,

d) compute G_i and determine Z_i from formula (8) or Figure 4.

Computations are easily done by hand or may be programmed for a pocket calculator. Initial depths to basement, as estimated from the above procedure, may be sufficiently accurate for many reconnaissence surveys. Depths to basement may be improved if these initial depth estimates are taken to be the input for a further iterative interpretation programme.

3. Tests on Hypothetical Two-dimensional Models

The proposed method has been tested on some one hundred hypothetical models and has been proved to be superior to empirical or iterative interpretation techniques presently in use. All computations were done on a Compucorp deskcomputer, model 425/44.

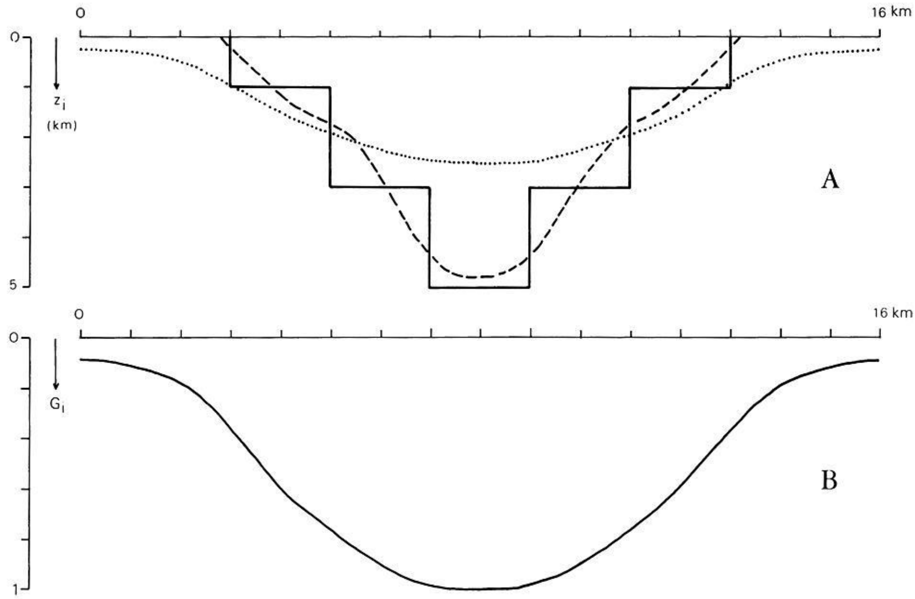

Fig. 5 A and B. Hypothetical symmetrical step-model. **A** Cross-sections of model; —— true cross-section, ... "flat-plate" approximation, ----- cross-section as derived from proposed method. **B** Normalized residual Bouguer anomaly profile

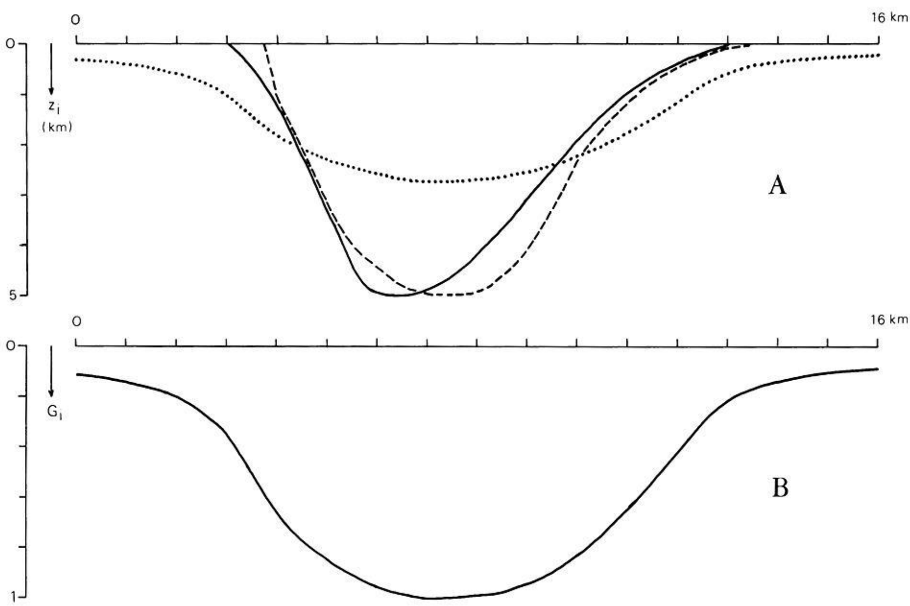

Fig. 6 A and B. Hypothetical asymmetrical step-model. **A** Cross-sections of model; —— true cross-section, ... "flat-plate" approximation, ----- cross-section as derived from proposed method. **B** Normalized residual Bouguer anomaly profile

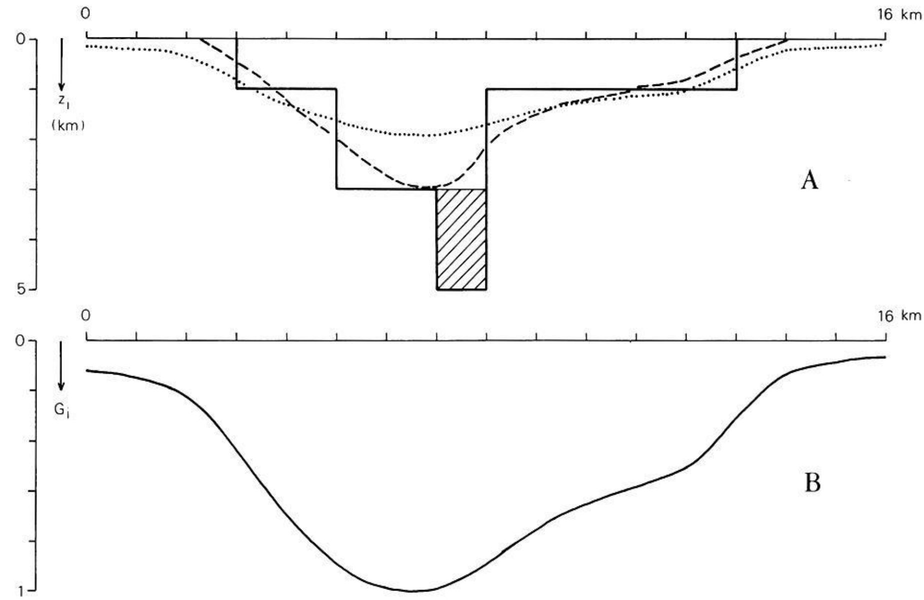

Fig. 7A and B. Hypothetical symmetrical bell-shaped model. **A** Cross-sections of model; —— true cross-section, ..."flat-plate" approximation, ----- cross-section as derived from proposed method. **B** Normalized residual Bouguer anomaly profile

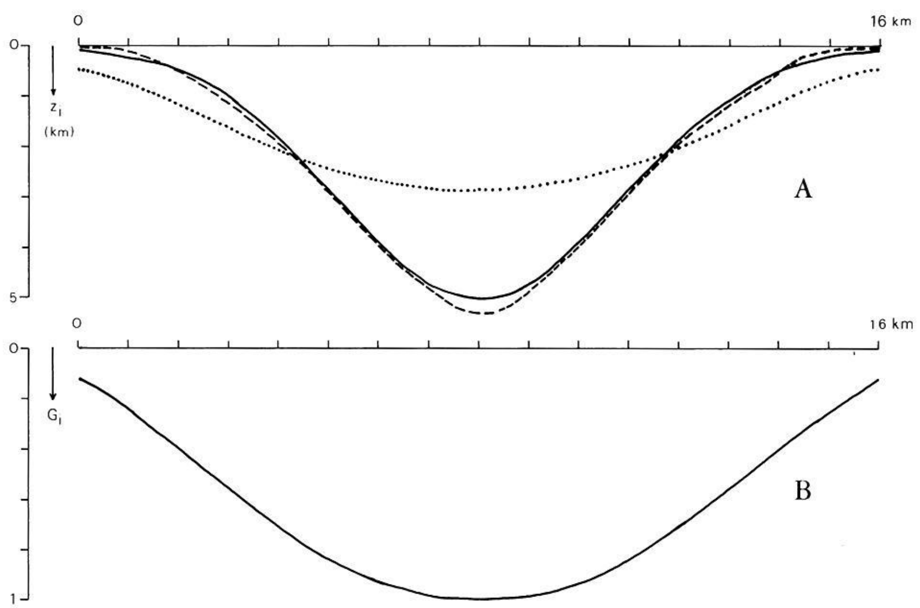

Fig. 8A and B. Hypothetical asymmetrical bell-shaped model. **A** Cross-sections of model; —— true cross-section, ..."flat-plate" approximation, ----- cross-section as derived from proposed method. **B** Normalized residual Bouguer anomaly profile

Interpretative results of a set of hypothetical triangular models, as shown in Table 1, may illustrate the weakness of most present methods. The body width was assumed to be known for the iterative interpretation programs.

The "flat-plate" approach undoubtfully gives very unsatisfactory results which in turn leads to a relatively large number of iterations.

The number of iterations needed to meet the specified iteration limit (2% from Δg_0) is generally smaller for the method proposed by Qureshi and Mula (1971) than for the method proposed by Bott (1960).

The empirical interpretation technique, as proposed by Fournier and Krupicka (1975), results in deviations of about -13%.

The present method naturally results in extremely small deviations since it was derived from hypothetical triangular models.

Interpretative results for the hypothetical symmetrical and asymmetrical step model are shown in Figures 5 and 6, respectively. These models are taken from the paper presented by Fournier and Krupicka (1975) for reason of comparison. The steep part of the assymmetrical step model (shaded in Fig. 6) is not resolved by any of the tested interpretation techniques. However this is not surprising since the maximum contribution from the shaded section to the total anomaly only amounts to -3.38 mgals or 6.5%.

Figures 7 and 8 show interpretative results for hypothetical symmetrical and asymmetrical bell-shaped models, respectively.

4. Discussion of Results

Table 2 summarizes results obtained from six different interpretation techniques.

The "flat-plate" approximation results in large deviations, between -75% and -156%.

The empirical method proposed by Fournier and Krupicka (1975) indicates deviations between $+14\%$ and -79%, whereas the present method shows deviations between $+6\%$ and -69%. If the asymmetrical step model is excluded from this discussion, because of its extremely unrealistic shape to represent sedimentary basins, then it may be concluded that the present method is superior to the method proposed by Fournier and Krupicka (1975) by a factor of about two.

The automatic iterative interpretation method proposed by Bott (1960) results in deviations between -5% and -14% after 11 to 14 iterations, whereas the technique proposed by Qureshi and Mula (1971) requires 5 to 8 iterations to result in deviations between -2% and -15%. In general, maximum depths as obtained from both iterative interpretation techniques indicate larger deviations from the true maximum depths of the investigated two-dimensional models than those initial depth estimates as derived form the proposed empirical method.

The number of iterations is substantially decreased if initial depths, as estimated from the present method, are taken to be the input for automatic data processing (see column 6 of Table 2). However it is interesting to note that maximum depths of the investigated models were not further improved during the iteration process.

Table 2. Interpretative results for two-dimensional sedimentary basins of various cross-sections. (Deviations between calculated and true maximum depths in %. Number of iterations is given in brackets)

Model	see Figure	Direct and empirical methods			Automatic iterative methods (iteration limit: 2% from Δg_0)		
		"Flat-Plate" approximation	Fournier and Krupicka (1975)	Present method	Bott (1960)	Qureshi and Mula (1971)	Present method
sym. step	5	−100%	−11%	− 5%	−14% (14)	−15% (8)	− 5% (2)
asym. step	6	−156%	−79%	−69%	−32% (23)	−37% (10)	−24% (14)
sym. bell-shape	7	− 75%	− 7%	+ 6%	− 9% (11)	−14% (5)	+ 6% (2)
asym. bell-shape	8	− 82%	+14%	± 0%	− 5% (13)	− 2% (8)	+ 3% (2)

The presented interpretative results as obtained for the asymmetrical step- and bell-shape models may indicate a criterion whereby interpretation becomes non-unique (see Figures 6 and 8, respectively). It is observed that the anomaly maximum does not coincide with the depth maximum of the hypothetical model. Accordingly, the interpretative cross-sections of the asymmetrical models show maximum depths which are shifted from the true maximum depths of the original models. This phase-shift amounts to about 0.5 km for the asymmetric step body and 1.0 km for the asymmetric bell-shaped model (see Figs. 6 and 8, respectively).

One may thus postulate that any of the tested interpretation methods will result in an interpretative model which is different in shape but is equivalent in its gravity effect to the true structure, if the anomaly maximum does not coincide with the depth maximum of the structure. Only additional data from either drillings or seismic exploration techniques may solve this ambiguity.

5. Conclusions

The proposed empirical method gives better results than other tested empirical methods and than those iterative automatic interpretation techniques which apply the "flat-plate" formula to approximate initial depths to basement. The derived relations of residual Bouguer anomaly profiles to geometrical cross-sections of two-dimensional sedimentary basins are expressed analytically and may therefore be programmed to compute initial depth estimates within an automatic iterative interpretation process. Equivalent solutions seem to result if the anomaly maximum does not coincide with the maximum depth of the two-dimensional structure.

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