Gravity interpretation of the Laguna Salada Basin, Baja California, México.

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RESUMEN

Se llevó a cabo una interpretación gravimétrica de la cuenca de Laguna Salada, B. C., México, en donde se aplicaron dos técnicas de inversión para un modelo bidimensional. Se empleó la teoría del cuerpo ideal en combinación con programación lineal para calcular cotas en el contraste de densidad y el grosor del relleno sedimentario en la Laguna Salada. Si se asigna un contraste de densidad de -0.3 g/cm^3 al modelo (basado en evidencias geológicas), se encuentra que la mínima cota superior sobre el grosor mínimo de los sedimentos es de 3.7 km. Este resultado se emplea para restringir la geometría de la cuenca.

Se utiliza la aproximación de la hoja delgada para calcular la forma de la cuenca y la solución inicial obtenida a partir de ese método se restringe dentro de las cotas obtenidas. El modelo final calculado muestra que el relleno sedimentario se extiende hasta una profundidad de 5.3 km. Este resultado es congruente con la geología del área.

PALABRAS CLAVE: Inversión lineal, Cuenca de Laguna Salada, optimización, expansión espectral.

ABSTRACT

A gravity interpretation of the Laguna Salada Basin, B. C., Mexico, is carried out applying two inversion techniques for a two-dimensional model. The ideal body theory is applied in combination with linear programming to compute bounds on the density contrast and thickness of the sedimentary fill under Laguna Salada. If a maximum density contrast of -0.3 g/cm^3 is assigned to the model, the lower bound of the thickness of the sedimentary fill is 3.7 km. This result is employed to constrain the two-dimensional geometrical model of the basin.

The thin sheet approximation method is then used to compute the shape of the basin and the inverted initial solution can be constrained within the bounds obtained. The final model shows that the sedimentary fill is up to 5.3 km thick at its deepest point. The interpretation is consistent with the geological setting of the area.

KEY WORDS: Lineal inversion, Laguna Salada Basin, optimization, spectral expansion.

INTRODUCTION

Several methods of analysis of potential field data have been used to interpret and produce physically reasonable models that fit the observations in the least squares sense. Unfortunately, such an approach is often unreliable and non-unique. Another approach is to find properties that are common to all models fitting the data (Parker, 1974). For gravity data the greatest lower bound of the maximum density contrast is sought. Then, for a given data set and region of confinement there exists a unique solution with the smallest possible uniform norm. This means that for lower density contrasts no solution can be found within the constraints of the problem. Such a model is defined as the "ideal body". Any solution, including the "true" solution must equal or exceed this bound on the density contrast (Parker, 1974, 1975).

The mathematical process to compute the bounds for the ideal body uses the FORTRAN code developed by Huestis and Ander (1983) for inverting two-dimensional gravity data. Ander and Huestis (1987) have pointed out that firm bounds of the solution set can be achieved without assuming a previous knowledge of the geometry of the source. On the other hand, some simple models can be selected to satisfy the gravity observations under the restrictions imposed by such bounds in the solution set.

Physical parameters characterizing the body can be computed and combined with the calculation of the geometry of the source. In this investigation, the ideal body trade-off diagrams are obtained (Huestis and Ander, 1983), and physical and geological constraints are applied. Finally, the geometry of the anomalous body is computed by a thin sheet approximation (Chávez and Garland, 1985), selecting a given trade-off point within the solution field.

The gravity data set was compiled by Kelm (1972), from a gravity survey carried out as a part of a joint geophysical program between the University of San Diego and the University of Baja California in the Laguna Salada area, in northwestern Mexico (Fig. 1).

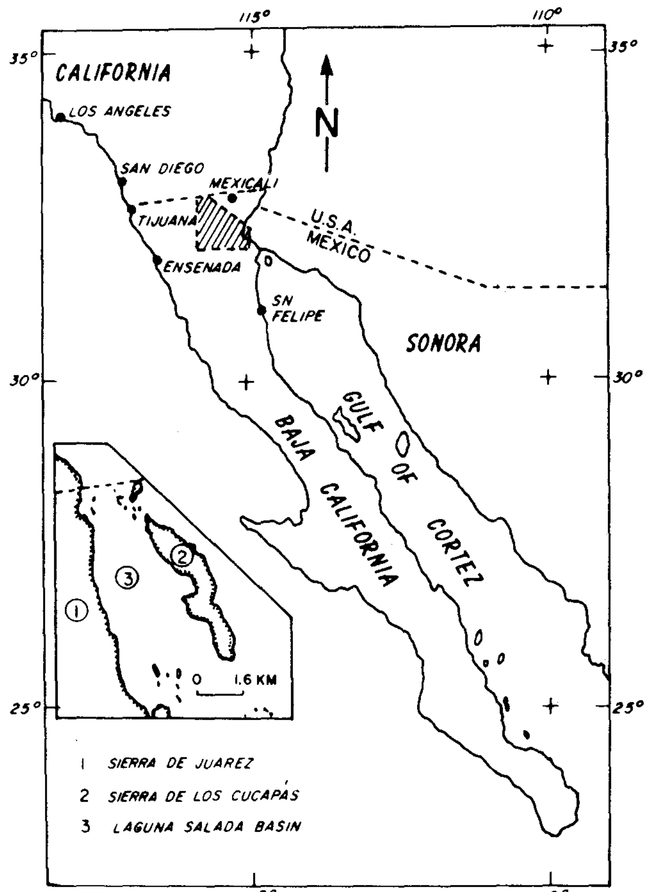

Fig. 1. The Laguna Salada area: Location of the main geological sites are shown.

GEOLOGICAL SETTING

The area under study is adjacent to the Salton Trough-Gulf of California depression (Fig. 1). It can be divided into three major geological areas (Kelm, 1972). These areas are:

(1) The granitic and metamorphic Sierra de Juárez, which comprises the entire west side of the area, along the volcanics overlying granitic rocks in the Sierra de la Tinaja.

(2) The granitic and metamorphic terrane of the Sierra de los Cucapás and Sierra del Mayor, which bounds the east side of the area.

(3) The Laguna Salada basin, formed by alluvial and lacustrine sediments deposited by the Colorado River. This area is quite flat and extends from the northwest to the southeast.

Figure 2 shows a simplified geological map of the area compiled by Kelm (1972) and Gastil *et al.* (1975). Structurally the Laguna Salada basin is a hinged graben, downfaulted to the east, bounded by the horst of the Sierra de los Cucapás and the Sierra del Mayor, and to the west by the Sierra de Juárez. This section consists of stepfaulted blocks thrown down to the east (Kelm, 1972). The whole area, from the Sierra de Juárez to the Gulf of California, is formed of basement blocks alternatively faulted up and down across the strike (Gastil *et al.*, 1975).

Two Tertiary sedimentary rock formations are found in the area. The Imperial formation is formed by marine claystones with some lenses of sandstone and limestone, and the Palm Spring formation contains bedded sandstones, siltstones, and mudstones deposited in a deltaic environment (Gastil *et al.*, 1975).

GRAVITY STUDY

The gravity survey was carried out as part of an unpublished Master thesis in the early seventies (Kelm, 1972). The gravity data reflect the existence of a very deep sediment-filled graben (Gastil *et al.*, 1975), between the Sierra de Juárez and the Sierra Cucapás (Fig. 3). A couple of gravity minima observed on the anomaly map at the center of the basin marks the deepest portion of the graben.

Biehler *et al.* (1964) predicted a depth to the basement of 5.8 km based on the gradient of the eastern side of the gravity anomaly. Kelm (1972) analysed gravity profiles A-A' and B-B' (Fig. 3), using a graticule method. He subtracted a regional gradient of approximately 1 mGal/km in the W-E direction to obtain a residual anomaly. Then, a two-dimensional topographic correction was computed. The topographic effects were found to be 4 mGals at the eastern side of the graben to 12 mGals near the Sierra de Juárez scarps. At the center of the basin the terrain correction was about 1 mGal. These corrections steepen the gravity gradient, enhancing the positive gravity highs, which are mainly associated with the Sierra de los Cucapás. Unfortunately, the model could not account reasonably well for the eastern faulting system associated with the Sierra de los Cucapás.

Gastil *et al.* (1975) suggested that the basin could be filled with up to 3 km of Palm Spring formation and 1.5 km of Imperial formation according to geologicl evidence. A reasonable average density would be 2.4 g/cm^3 for these formations, and 2.7 g/cm^3 for the basement rocks. A density contrast of -0.3 g/cm^3 could thus be estimated for the basement interface in the area.

Kelm's (1975) data for profile B-B' is used in this investigation to obtain the physical parameters of the basin, as well as its geometry. Two-dimensional methods are applied, 10 data points are used in the optimization process and 12 more to define the geometry of the source by the thin sheet approach. The maximum error assumed for the gravity observations was 1 mGal throughout the inversion process.

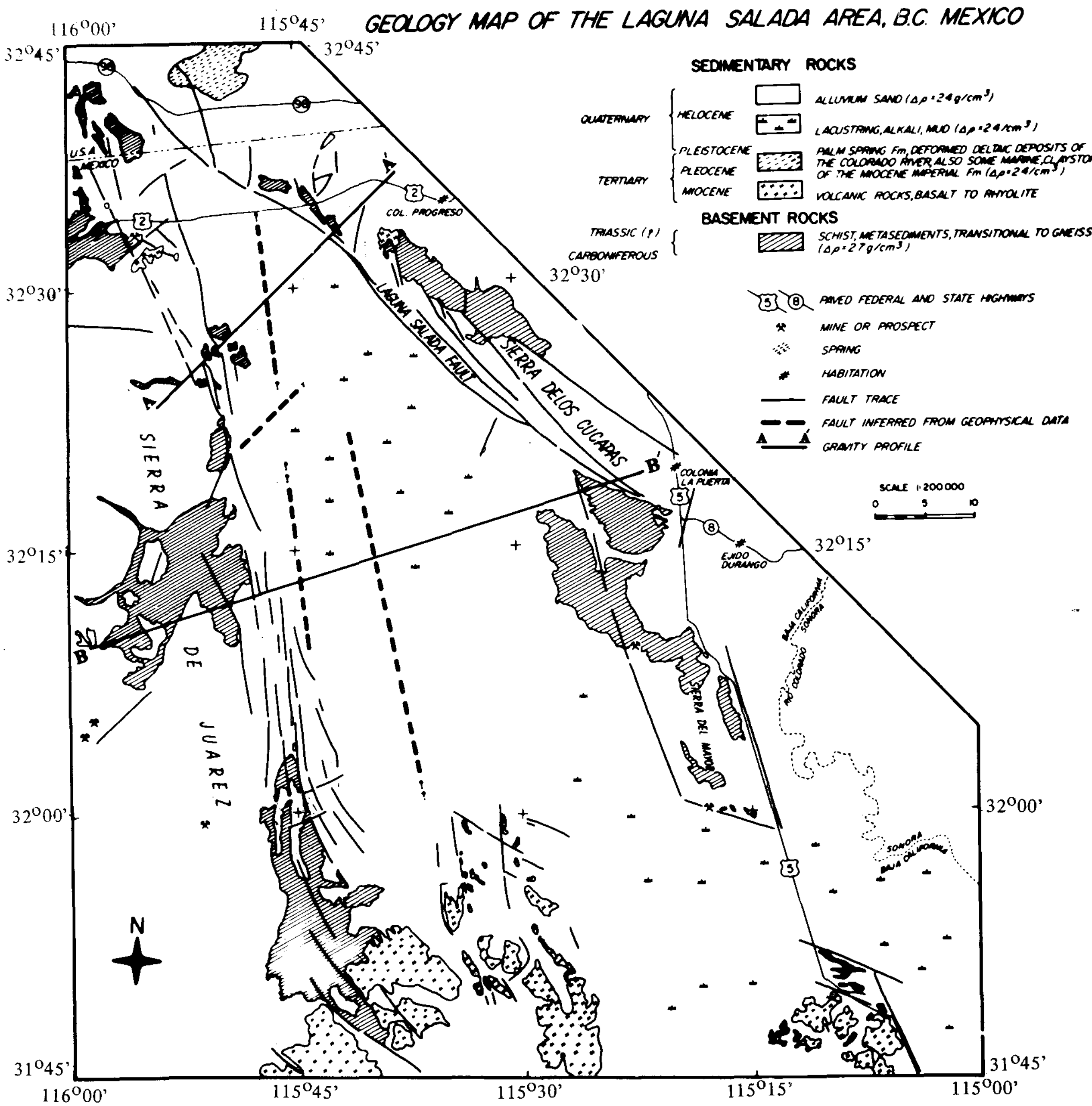

Fig. 2. Geological setting of the Laguna Salada basin (modified from Kelm, 1972).

OPTIMIZATION OF THE GRAVITY DATA

The gravity profile can be inverted to compute bounds on physical parameters that characterize the subsurface structure. This can be achieved by the Huestis and Ander's (1983) algorithm. It is based on linear programming algorithms, where an extremal solution ($\Delta\rho_o$) has to be encountered.

This technique computes a set of solutions in terms of trade-off diagrams, where the greatest lower bound on the maximum density contrast and the corresponding minimum thickness of the sedimentary fill are plotted. Figure 4 displays the bounds for regions extending from the surface of the Earth to a specified depth. There is no fixed rule for selecting the dimensions of the prisms or their number. Some tests were previously run to select the cell dimensions, until the results did not vary by more than 2%. A cell size of 2.2 x 0.5 km^2 was used, decreasing the thickness of the cell 0.1 km, subsequently. In all the

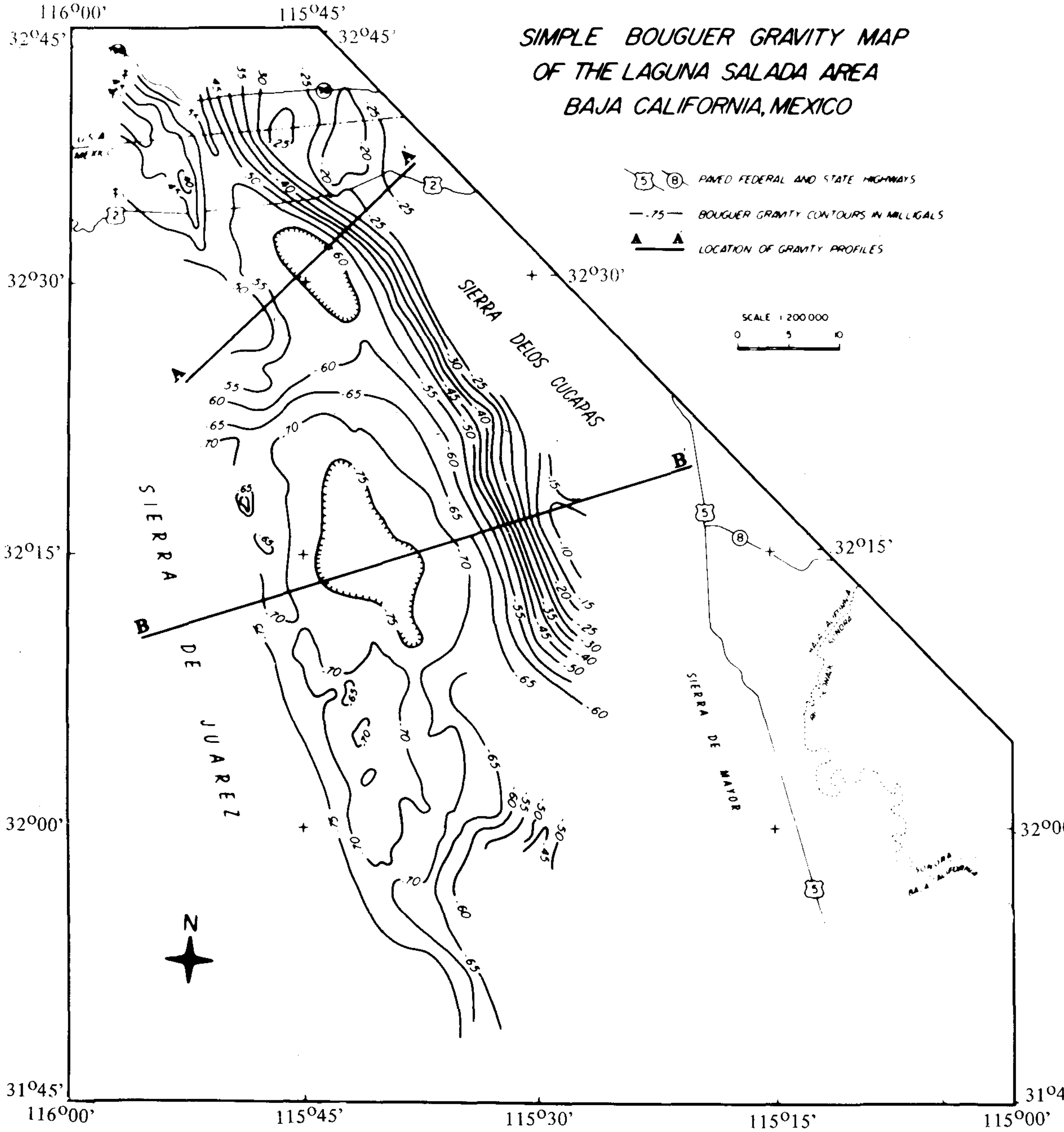

Fig. 3. Simple Bouguer gravity map of the Laguna Salada basin (modified from Kelm, 1972).

calculations 200 cells were used. Some of the cells reach the bound of the density contrast, while others will be empty.

In the first run, the greatest lower bound on the maximum density contrast reached -0.23 g/cm^3 assuming error-free data and -0.17 g/cm^3 with errors. I assumed a region of confinement 10 km thick. The next run restricted the ideal body to a thickness of 8 km, increasing the density bound (Fig. 4). This process is continued until the trade-off plot is defined.

The trade-off curve can be interpreted as yielding the least upper bound on the minimum thickness of the ideal body (about 1 km), given the maximum allowable density contrast. The plot also gives the bounds on the infinite solution set, below which no solution exists under the conditions imposed to the problem (Parker, 1975). The least possible maximum density contrast permitted by the gravity data is thus -0.17 g/cm^3.

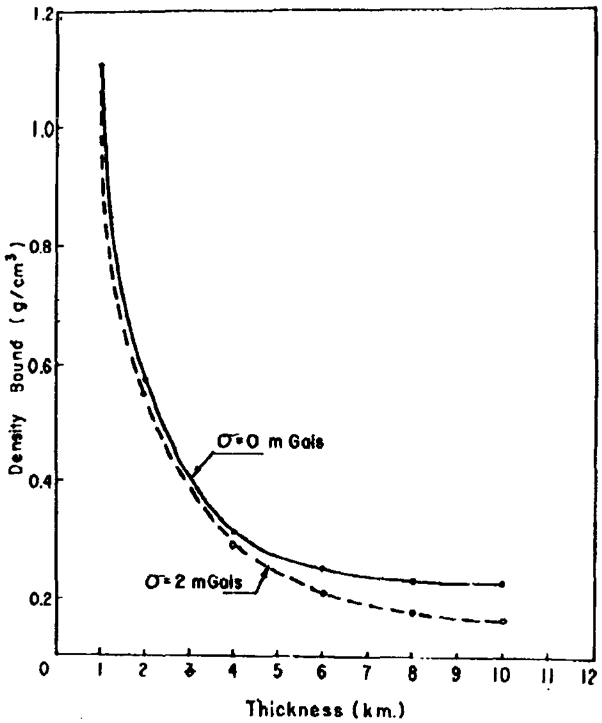

Fig. 4. Trade-off diasgrams between the greatest lower bound on the density contrast and minimum thickness of the ideal body, when its top is at the surface.

If a density contrast of -0.3 g/cm^3 between the sediments and the basement is assumed (Kelm, 1972, Gastil *et al.*, 1975), then the minimum thickness of the body will be 4.4 km for the error-free data curve, or 3.7 km for the 2mGal error data curve (Fig. 4). Stratigraphic or well data may further restrict the physical parameters in the future. Some drilling projects are currently in progress; unfortunately no data have been published.

Once the density contrast and the thickness of the anomalous body have been bounded by means of the ideal body method, the shape of the gravity source must be computed. Ander and Huestis (1987) suggested that one or several trade-off points could be selected to model the observed gravity anomaly. In this example, a single solution point has been selected from the trade-off plot, namely (3.7 km, -0.3 g/cm^3).

GRAVITY INVERSION PROCEDURE

The thin sheet approximation method can be applied to compute the subsurface geometry of the Laguna Salada basin, taking into account the above solutions. The procedure is simple. The anomalous mass is represented by a thin sheet located at a depth of reference z_o (here $z_o = 0$ km). It is divided into M strips (Chávez and Garland, 1985). The spectral expansion method (Parker, 1977) is used to invert the gravity profile B-B' to produce the surface density distribution ($\beta(r)$) in each segment.

The surface density distribution is transformed into a set of two-dimensional adjacent prisms of variable depth (z_j^o) to represent the basement topography, given by (Chávez and Garland, 1985)

$$\beta_j(r) = \Delta\rho \; (z_j^o - z_o) \quad , \qquad (1)$$

where $\Delta\rho$ is the constant density contrast between both interfaces. In order to avoid an oscillatory solution, the width of the strips must be larger than the depth of reference (Tanner, 1967).

An iterative approach is now applied to adjust the shape of the basin until a reasonable fit is obtained. The newly computed value of z_j in each iteration is given by:

$$z_j = z_j^o + \Delta z_j \quad , \qquad (2)$$

under the constraint that the maximum depth of the body must be at least equal to 3.7 km. z_j^o is the depth for the initial model computed by (1), and Δz_j is calculated for each iteration.

Figure 5 shows the initial model (dots), with a density contrast of -0.3 g/cm^3 and maximum thickness of 3.74 km. The gravity response of this model is displayed in Figure 6 (discontinuous line).

The model is adjusted until the fit is optimized. Seven iterations were needed to obtain the final model displayed in Figure 5 (squares). The misfit between the computed anomaly (continuous) and the observed data (squares) is shown in Figure 6. This result reflects the faulted system, characteristic of the western section of the area bounded by the Sierra de Juárez system, and the Sierra de los Cucapás to the east (Biehler *et al.*, 1964; Gastil *et al.*, 1975).

CONCLUSIONS

Two different methods have been successfully applied to model a sedimentary basin. First, the ideal body theory in connection with linear programming algorithms (Huestis and Ander, 1983) provided optimal bounds on the density contrast and thickness of the causative body. Second, the geometry of the basin could be evaluated using the thin sheet approach (Chávez and Garland, 1985).

Once the ideal body theory has provided bounds on the model, more traditional techniques can be used to define its shape. One or several bounds can be explored to produce different models. The thin sheet method is faster (in terms of computer time) and the interpreter does not need to guess an initial model. Therefore this approach was applied here.

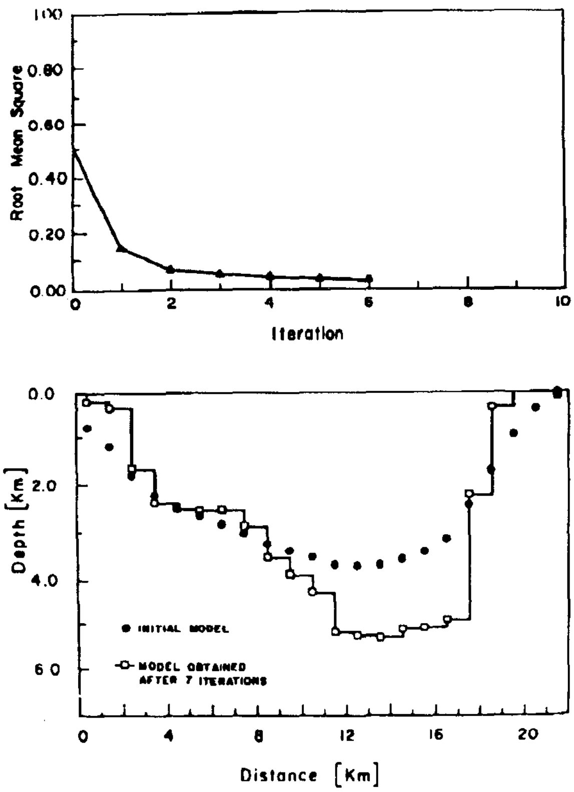

Fig. 5. Object function (top) plotted in terms of the number of iterations to obtain the final geometry of the sedimentary fill (bottom) that covers the Laguna Salada basin. Initial model computed by the thin sheet approach (dots) and final solution obtained through an iterative scheme (squares).

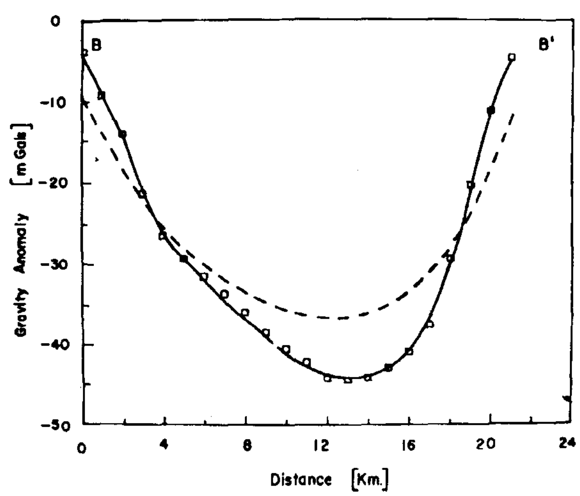

Fig. 6. The gravity response of the initial (discontinuous line) and final (continuous) models compared with the residual gravity data (squares) obtained by Kelm (1972).

Proper knowledge of the geological and stratigraphic data will help to select the appropriate body shapes. Drilling and well data will help to constrain the solutions and allow a more precise interpretation of the geological and geophysical situation.

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