CRUSTAL STRUCTURE OF THE CONTINENTAL MARGIN OF THE EASTERN UNITED STATES

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ABSTRACT

Gravity data from the Cape May region of the eastern United States was employed to determine the behavior of the crust-mantle interface in the transition region of the continental margin. By using the Talwani method of approximating two-dimensional structures with polygons, it was determined that the depth to the Mohovoricic discontinuity may decrease linearly from 25 kilometers depth 160 kilometers landward of the shelf break to 10 kilometers depth at the shelf break. More realistic results using this approach would require better data control in the shelf break region and near shore continent.

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Introduction

Interest in the nature of the continental margins of the world has been increasing in recent years. The geologic significance of these areas has also become apparent as interest in the probable mineral and petroleum resources underlying the continental shelf has increased. This present day concern has resulted in extensive efforts in understanding the structure, geology, and origin of the world's continental margins. Examination of the continental margin of the eastern United States has been the objective of many of these endeavors. This paper will focus on interpretation of gravity data acquired near the continental margin of the eastern United States.

The emphasis of this investigation has been in constructing models of crustal layering and the determination of the depth to the crust-mantle interface (Mohovoricic discontinuity) in the transition region between continent and ocean basin. This transition region is geologically and structurally complex; these complexities make it difficult to establish the behavior of the crust-mantle interface through the use of seismic refraction data alone. In this study, unpublished gravity measurements supplemented by published gravity data and published seismic data were used in the attempts to model the structure of the transition region.

The specific area examined in this study is located seaward of Cape May, New Jersey. The unpublished gravity measurements were obtained from the Marine Geology and Geophysics Laboratory, AOML, National Oceanographic and Atmospheric Administration. The observations were obtained on cruises COMSED II and IV, 1974. The data was obtained from tracklines paralleling the margin of the continental shelf. Unfortunately, this provided only 10 isolated data points in the Cape May region instead of a continuous gravity profile running perpendicular to the margin. To supplement these sparse measurements, I have used a published free air anomaly profile from Rabinowitz, 1973, which was located in the preferred orientation.

The method of examination of this area required the use of the Talwani method of calculating gravity contributions due to two-dimensional structures (Talwani, et. al., 1959). This technique can be effectively implemented in a computer which facilitates fairly rapid results. This method is particularly convenient since continental margins on a regional scale can be considered to be two-dimensional geologic structures.

Models of the crustal structure and the Mohovoricic discontinuity can be approximated using constraints from seismic refraction data. The Talwani method can then be used to calculate gravity due to the assumed model. The gravity profile obtained from the model can then be compared with the observed profile.

Theory

Hubbert, in 1948, showed that the vertical component of the gravitational acceleration due to a two-dimensional body was equal to

$$2\,G\rho \oint Z\,d\theta$$

or

$$2\,G\rho \oint \theta\,dz$$

where G is the universal constant of gravitation and ρ is the volume density of the body. Talwani, et. al. (1959, p. 50) demonstrated that in the general case of an n-sided polygonal body, the vertical component could be evaluated from

$$V = 2\,G\rho \sum_{i=1}^{n} Z_i$$

where

$$Z_i = a_i \sin \Phi_i \cos \Phi_i \left\{ \theta_i - \theta_{i+1} + \tan \Phi_i \ln \frac{\cos \theta_i \left(\tan \theta_i - \tan \Phi_i \right)}{\cos \theta_{i+1} \left(\tan \theta_{i+1} - \tan \Phi_i \right)} \right\}$$

where

$$\theta_i = \tan^{-1} \frac{Z_i}{X_i}, \quad \Phi_i = \tan^{-1} \frac{Z_{i+1} - Z_i}{X_{i+1} - X_i}$$

$$\theta_{i+1} = \tan^{-1} \frac{Z_{i+1}}{X_{i+1}}$$

and

$$a_i = X_{i+1} + Z_{i+1} \frac{X_{i+1} - X_i}{Z_i - Z_{i+1}} \quad \text{(SEE FIGURE 1).}$$

These calculations are easily performed by computer for n-sided polygonal bodies with reasonable n. The requirements for the calculation are the locations of the vertices of the polygon and a chosen density contrast.

The advantage of the Talwani method is its adaptability to the case of two-dimensional structures which are not polygonal. A given two-dimensional structure can be approximated by an n-sided polygon of specified density. To calculate the gravitational attraction of the model to within any degree of accuracy, we merely increase the number of sides of the polygon to improve the fit between the polygon and the model.

The use of the Talwani method in modelling a geologic structure given a specific gravity profile is an example of an indirect method of interpretation: A model is assumed, the gravity profile computed, and the results compared with the observed profile. Modifications are then performed on the model to increase the correlation between the calculated and actual observed profiles. Once a suitable correspondence is achieved, the model represents one possible structure causing the observed anomaly. Unfortunately, the model is not unique in that there are an infinite number of models which will produce the observed anomaly.

The problem of non-uniqueness can be reduced by imposing constraints on the model which are derived from other data sources.

These constraints may include particular density contrasts, flooring depth, extent of structure, or simply geologic feasibility.

Data

The specific area of interest examined in this paper is the continental margin in the vicinity of Cape May, New Jersey. Gravity data from NOAA cruise COMSED IV was reduced to provide the profile for interpretation. The integrated gravity measurements obtained from the Lacoste & Romberg sea gravimeter were made in meter units and required conversion to milligals. To determine the free air gravity anomaly, an Eötvös correction for the ship's velocity was made and the deviation from the theoretical gravity at each corresponding latitude was calculated.

Since the COMSED IV cruise consisted of five tracklines that paralleled the continental margin, a profile across the margin consisted of only five points. Two of these sparse profiles from the Cape May region were considered. These values were compared to published data from Rabinowitz (1973) by projecting the values to equivalent positions on a line where seismic information was available (Figure 2). The comparison of the COMSED data to the profile presented by Rabinowitz (1973) was not especially favorable. There is good correlation for the data beyond the shelf break. Yet, the anomalous high preceding the break is significantly lower in the Rabinowitz free air anomaly (Figure 3).

It is difficult to explain this lack of correspondence between the two profiles, particularly in the region landward of the shelf break. The anomalous high in the COMSED data might be explained as due to an anomalous mass that violates the initial assumption that the structure is two-dimensional. The fact that the anomalous highs of the two profiles from the COMSED data correlate well with each other tends to dispute this possibility of isolated anomalous masses lying below the shelf. The discrepancy between the COMSED data and Rabinowitz data will be discussed further in the explanation of modelling results.

Analysis

In order to realistically model the structure causing the observed free air anomaly, some constraints on the model were required. The constraints used in this case were derived primarily from interpretation of seismic refraction data from the area of interest.

Drake, et. al. (1959), established the existence of two sedimentary troughs in the continental margin region. One trough with about a 5 kilometer thickness of sediments is located about 60 kilometers inside the continental shelf break. Another trough with an 8 kilometer thickness of sediments is located immediately under the shelf break. The resulting high in the basement rock which lies between the two troughs is interpreted as the source of the anomalous free air gravity high preceding the shelf break.

The crustal structure consists of two major rock units, sediment and basement rock. Drake, et. al. (1959, p. 173), determined the density of the sediments to be 2.3 g/cm^3 and the density of the basement to be 2.84 g/cm^3. He concurred with Worzel and Shurbet (1955, p. 92) that the density difference between crust and mantle was .43 g/cm^3. In this study, the sediment density was taken as 2.3 g/cm^3, the basement density as 2.7 g/cm^3, and the mantle density as 3.1 g/cm^3. These estimates are in agreement with seismic refraction data.

Limiting the extent of the anomalous mass is another type of constraint which was used in this study to relieve the non-uniqueness problem. This was achieved by forcing the model to adhere to seismic information concerning the depth of the crust-mantle interface. The depth to the mantle seaward of the shelf break was taken to be 10 kilometers (Drake, 1968, p. 1006). For the Cape May region, the depth to the interface under the continent was assumed to be 25 kilometers. This restricts the anomalous two-dimensional body to a vertical extent of 15 kilometers.

In order to determine the behavior of the crust-mantle interface in this transition region, the effect due to the anomalous mass created by the behavior of the Mohovoricic discontinuity must be isolated. This was accomplished through a simple referencing scheme.

Using the Talwani method, the gravity contribution for the polygonal approximation of the sediment with a density of .4 g/cm^3 was calculated. Similarly, the contribution for the polygonal approximation of the water layer of density 1.67 g/cm^3 was calculated (Figures 4 and 5). These values were added to the observed free air anomaly to effectively create the profile due to a uniform crust and mantle with an unknown boundary separating them. The gravity (g_d)

at a station located well beyond the shelf break was assumed to be equal to

$$(1)\quad 2\,\pi\rho_1\,G(10\text{ km}) + 2\,\pi\rho_2\,G(15\text{ km}) + g_m$$

where

ρ_1 = density of the crust,

ρ_2 = density of the mantle,

G = universal constant of gravitation,

and

g_m = gravity contribution due to the earth below 25 km.

At a station within reasonable proximity of the shelf break, the gravity value (g) will be equal to

$$(2)\quad 2\,\pi\rho_1\,G(25\text{ km}) + g_m + g_{an}$$

where

g_{an} = contribution due to the anomalous structure created by the behavior of the crust-mantle interface with a density $\rho_2 - \rho_1$.

Using equations (1) and (2), g_{an} can be shown to be

$$g - g_d + 2\pi G(15 \text{ km})(\rho_2 - \rho_1),$$

or

$$\Delta g_{zc} - \Delta g_{zd} + 2\pi G(15 \text{ km})(\rho_2 - \rho_1)$$

where

Δ gzc = free air anomaly that has been corrected for water and sediment effects

and

g_{zd} = free air anomaly from a station well beyond the transition region that has been corrected for water and sediment effects.

The resulting gravity profile is the anomaly due only to the variation of the depth of the Mohovoricic discontinuity between the 10 kilometer and 25 kilometer depths (Figure 6).

Once this profile was established, the boundaries of the anomalous mass could be approximated as polygons. The depth to the discontinuity was restricted to 10 kilometers for locations well beyond the shelf break and was restricted to 25 kilometers for locations near the continent in order to be consistent with the referencing scheme used to determine the anomalous profile.

The simplest model developed to approximate the structure consisted of a linear decrease of the depth of the interface from the 25 kilometer depth to the 10 kilometer depth over the 20 kilometer to 180 kilometer portion of the profile (Figure 7). The resulting calculated gravity describes the general trend of the profile observed by Rabinowitz (1973). Yet, there is poor correspondence in the 20 kilometer to 80 kilometer portion and the region near the shelf break. The relative highs in the data in these areas may be caused by a local shallowing of the Mohovoricic discontinuity. Figure 8 is an illustration of an attempt to model the relative high in the near shore portion of the profile.

It is difficult to insure that any efforts to model the structure that produces the exact profile will not result in a totally incorrect result. Oscillations in the gravity profile could easily result from excess masses that are not two-dimensional, variations in topography that are not two-dimensional, or two-dimensional excess masses that have gone undetected in seismic interpretation.

The modelling attempts were tailored to approximate the Rabinowitz data. Efforts to model the COMSED data would have required shifting the linear decrease in depth of the crust-mantle interface approximately 50 kilometers closer to the continent. This seemed geologically unsound. It is still doubtful geologically that the Mohovoricic discontinuity maintains a 10 kilometer depth from the ocean basin up to the shelf break region as is indicated by the modelling attempts. The gentle decrease in depth of the interface, approximately 1 kilometer of depth per 10 kilometers horizontally, may be reasonable when the possibility of the ocean plate having been thrust under the continental plate is considered.

The major problem in developing any reliable interpretations from this method of approach is the limitation created by the scarcity of data. In order to realistically model the transition region, better control is required in the shelf break region and in the subsurface of the near shore region of the continent.

Assuming that better control can be achieved readily, the results of this study have indicated that the method of approach used here can be pursued to produce results that may be reasonable. The success of such a process would imply that gravity data in areas that are seismically complex can be used to determine regional behavior of major structures.

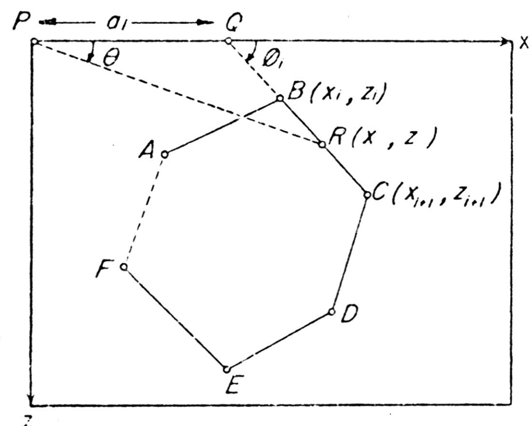

Figure 1 Geometrical elements involved in the gravitational attraction of an n-sided polygon (after Talwani, 1959)

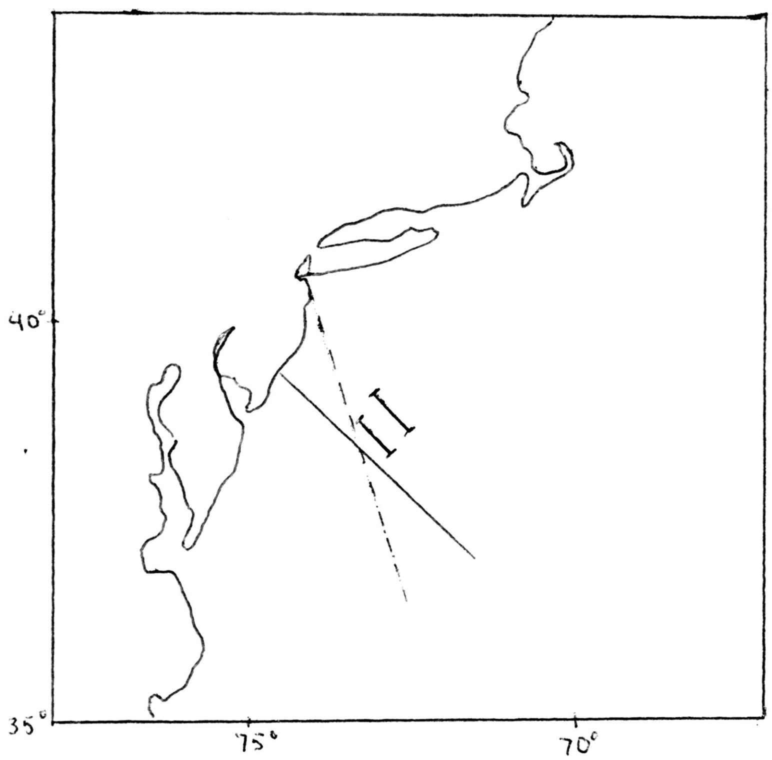

Figure 2 Location of profiles.

—— Line of projection
- - - - Rabinowitz profile
⊢⊣ COMSED IV profiles

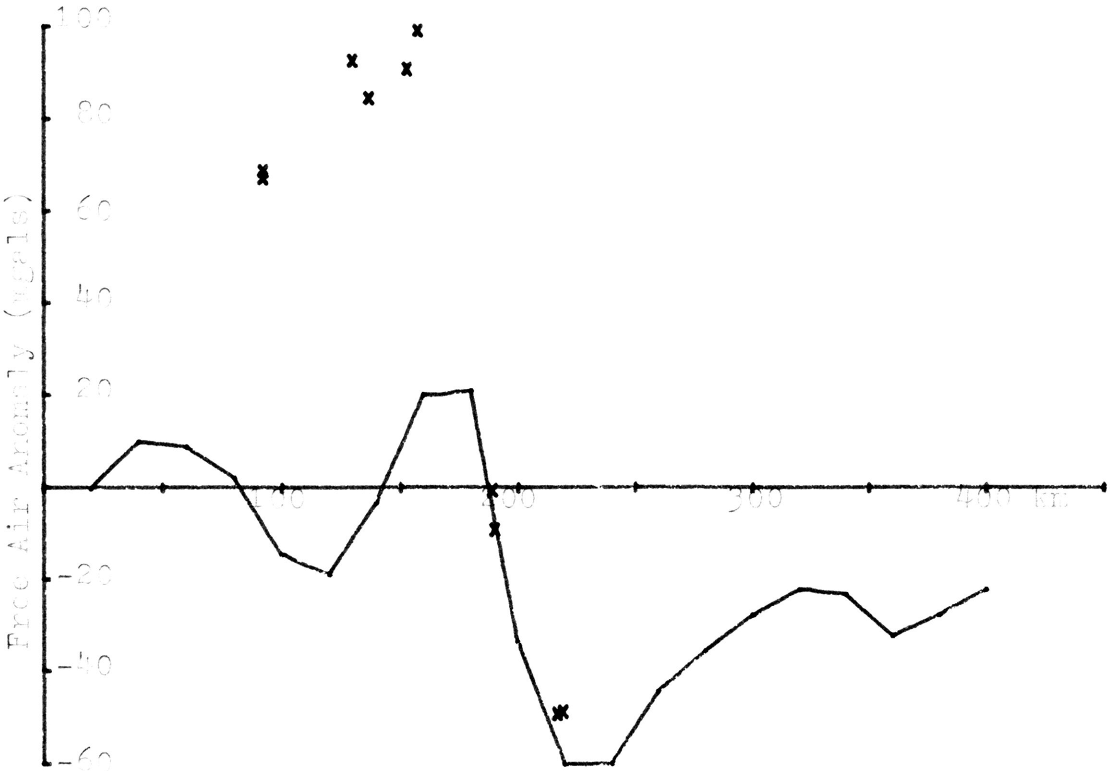

Figure 3 Free Air Anomaly
— Rabinowitz (1979)
x CONSED IV

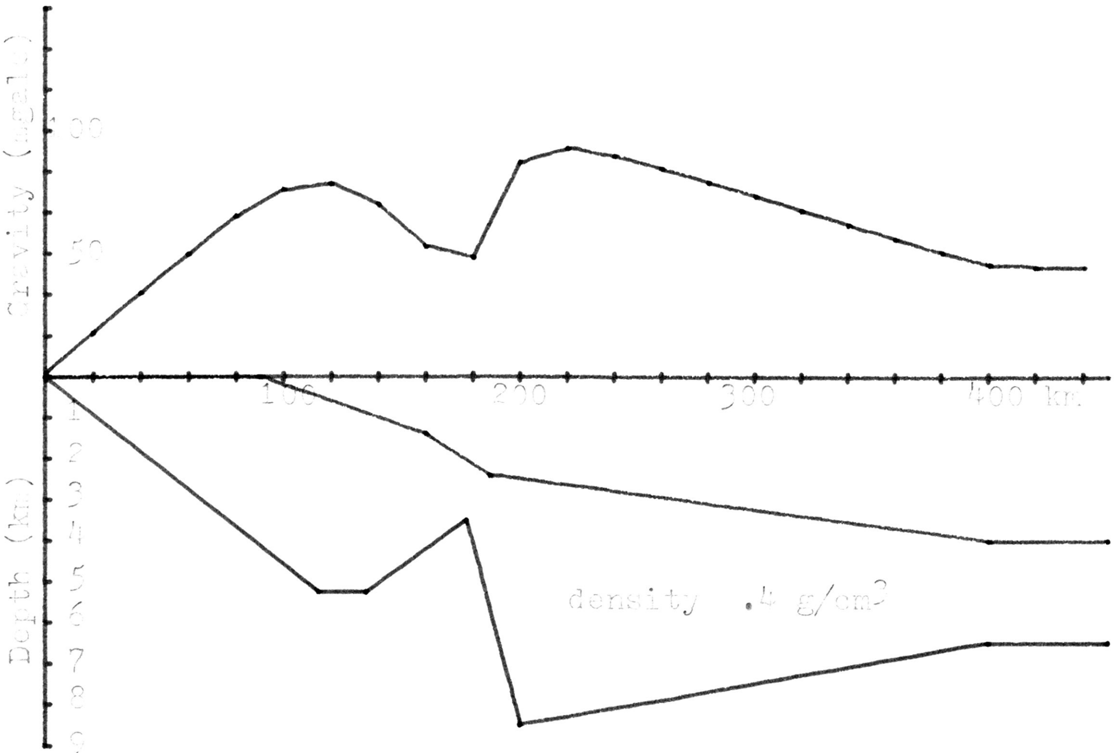

Figure 4 Gravity correction for sediment.

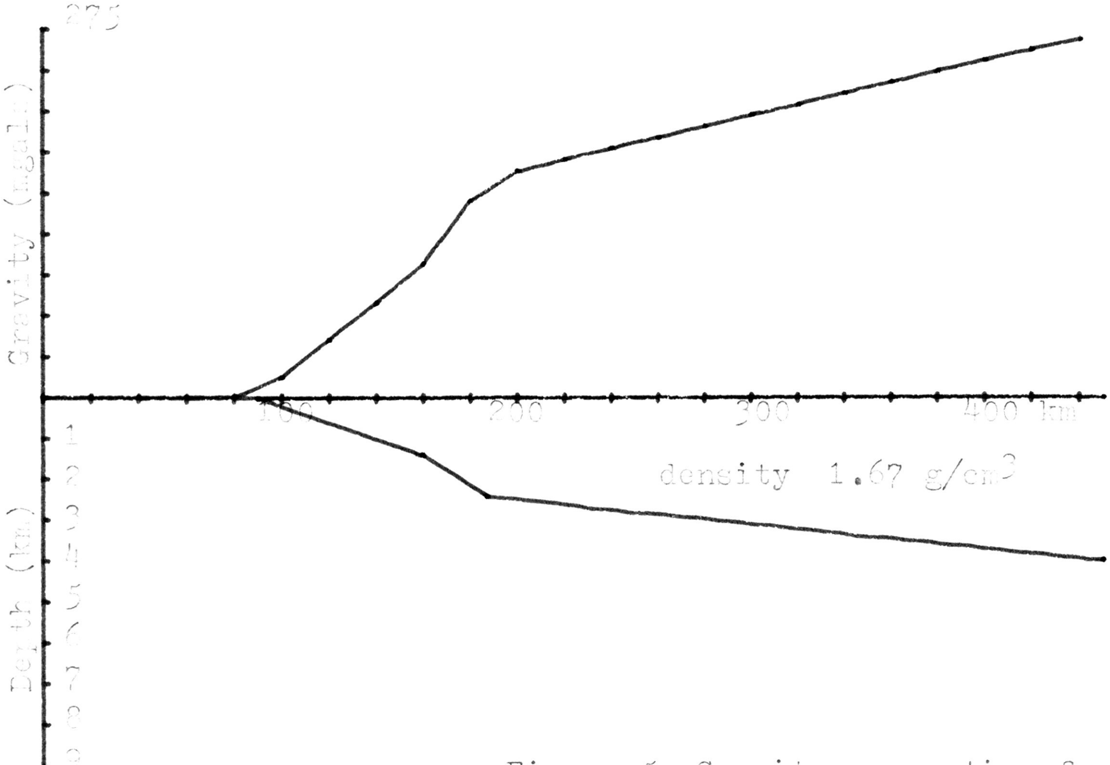

Figure 5 Gravity correction for water layer.

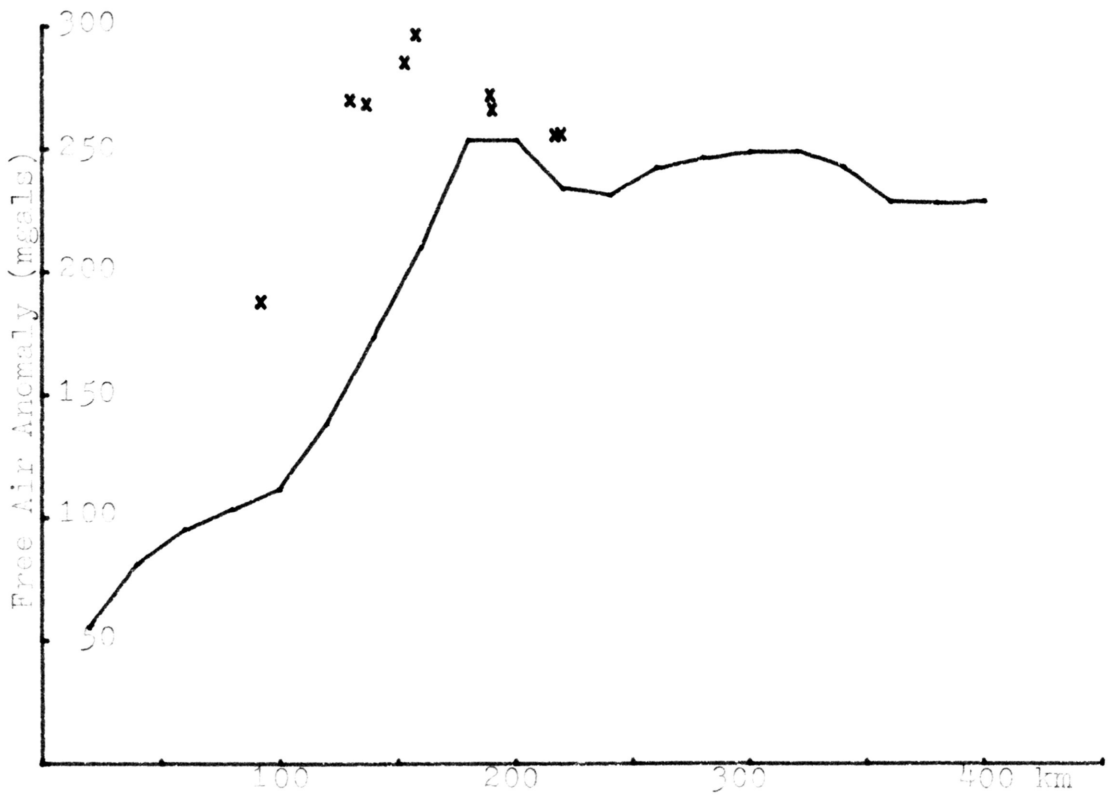

Figure 6 Gravity due to the anomalous mass.

— Rabinowitz (1973)
x COMSED IV

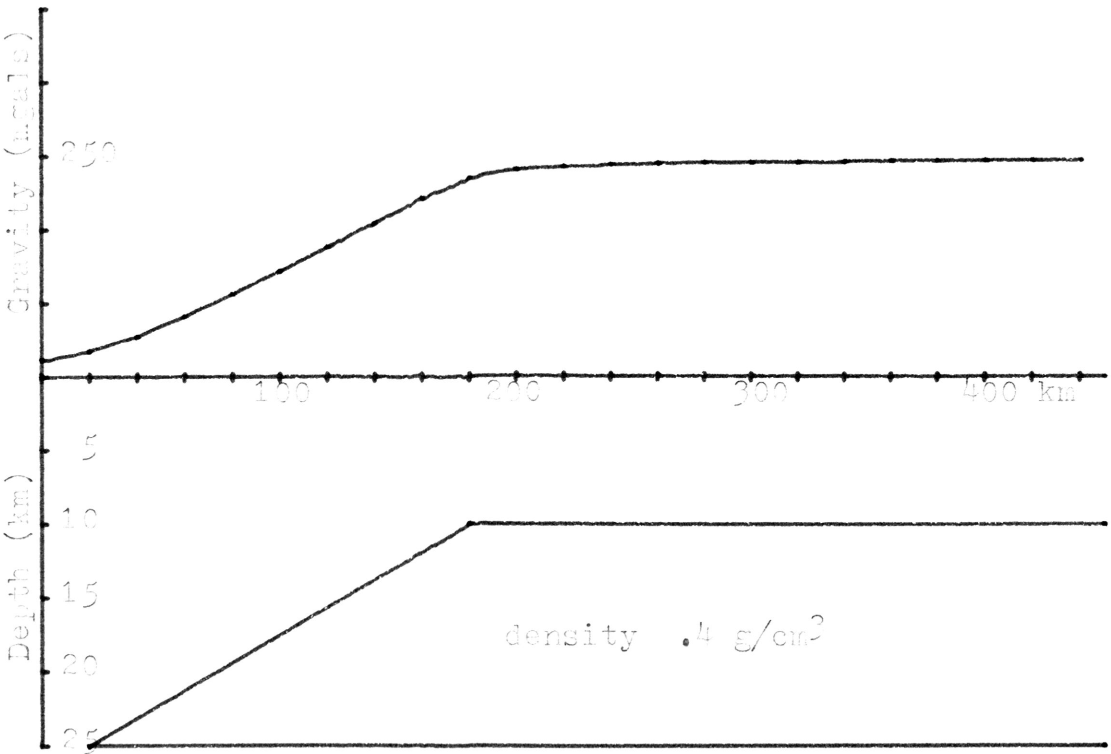

Figure 7a Model of structure

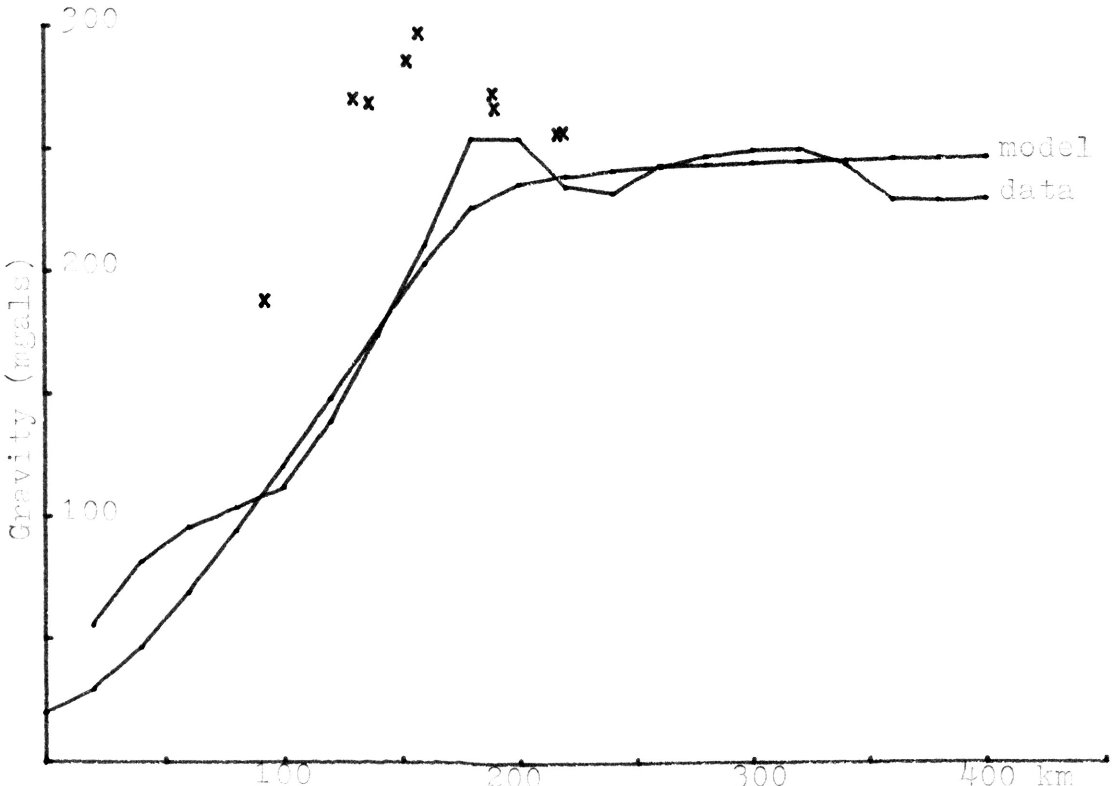

Figure 7b Comparison of gravity

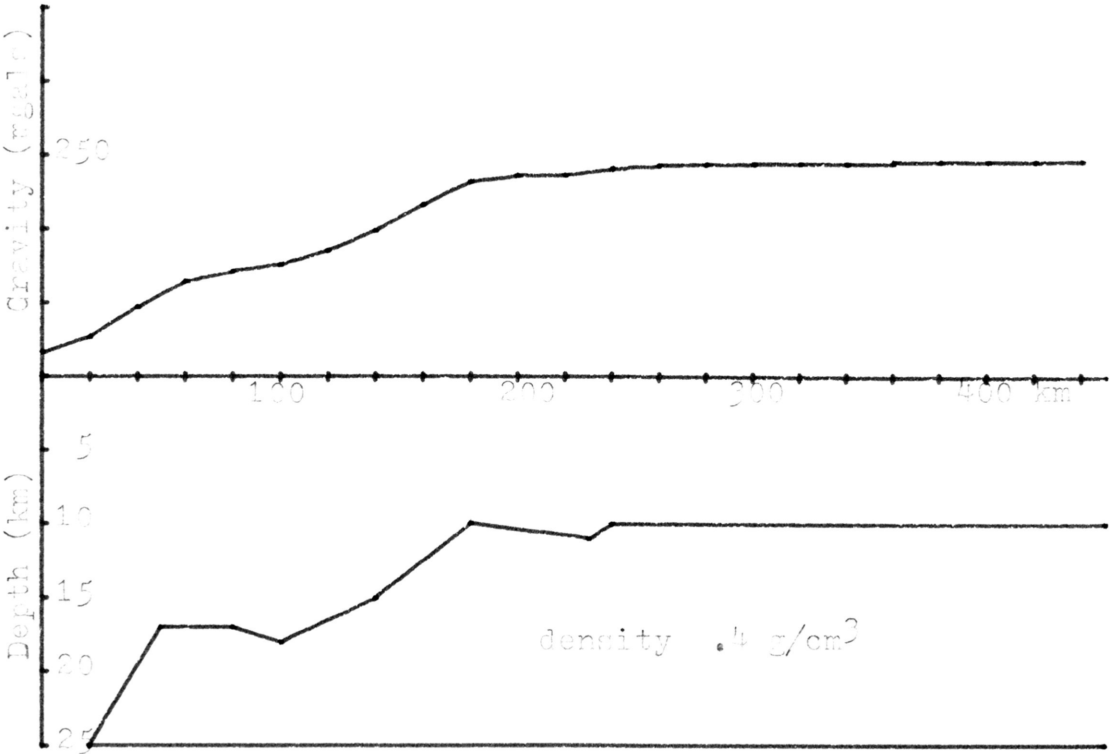

Figure 8a Model of structure

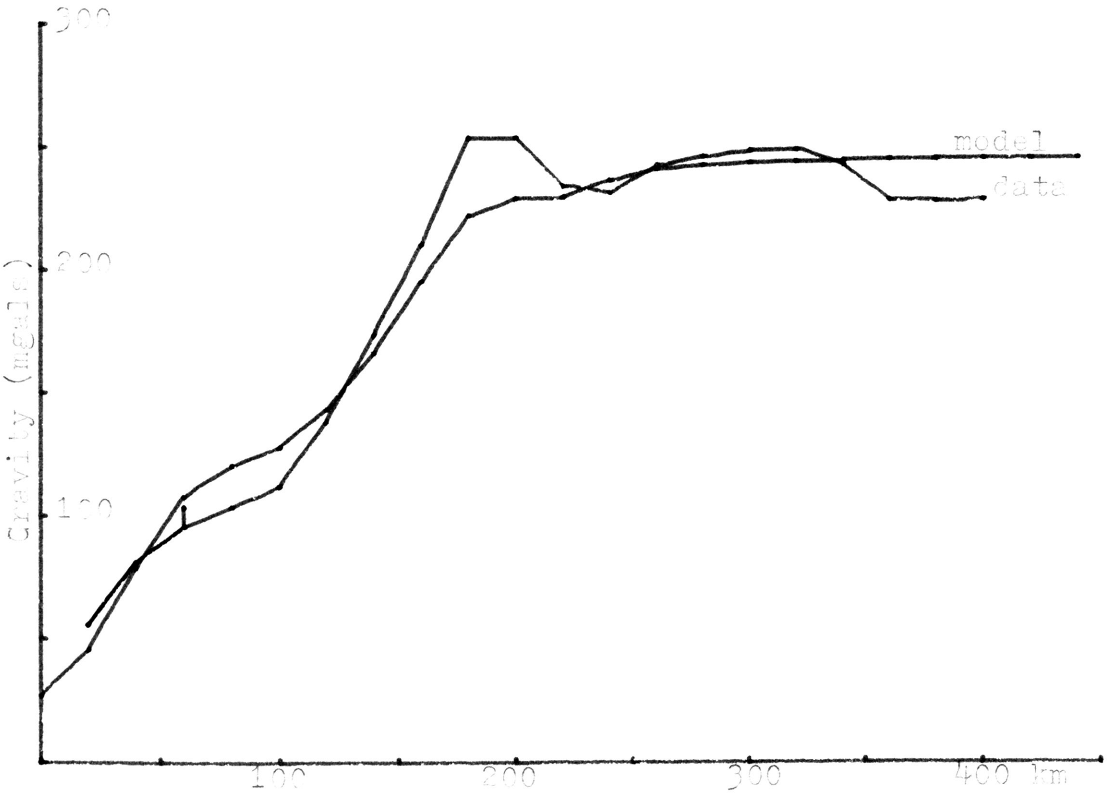

Figure 8b Comparison of gravity

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