

A PRELIMINARY STUDY OF THE ORIGIN OF THE
PHYSIOGRAPHIC BOUNDARY BETWEEN THE NICARAGUAN
RISE AND COLOMBIAN BASIN, CARIBBEAN SEA

By LOUIS FARRELL KLONSKY

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and approved by

Eric Christofferson
Walter M. ...
...

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ABSTRACT OF THE THESIS

A Preliminary Study of the Origin of the
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by LOUIS FARRELL KLONSKY, M.S.

Thesis director: Professor Eric Christofferson

The boundary between the Nicaraguan Rise and Colombian Basin is apparently linear for approximately 1000 km. Formation models include a rift, transform fault or subduction zone. Gravity, magnetic and geologic data, and gravity modeling weaken the idea that any of these plate tectonic settings is the cause for the boundary. Gravity modeling indicates faulting in the area of the boundary and may give evidence of tilting of the Nicaraguan Rise. More information is needed to develop a working hypothesis for the origin of the boundary.

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Introduction

The boundary between the Nicaraguan Rise and the Colombian Basin forms one of the most prominent crustal lineaments beneath the Caribbean Sea (Fig. 1). It trends N60°E for approximately 1000 km, and from bathymetric data, appears to be straight (Fig. 2). To the north of the boundary, lies the Nicaraguan Rise. Approximately one fourth of the Rise is shallower than 200 m. The crest of the Rise is the island of Jamaica (Arden, 1975). To the south of the boundary, lies the Colombian Basin, an abyssal plain with depths up to 4350 m (Moore and Fahlquest, 1976). Along most of its length, the boundary is approximately 15 km wide. Depths increase about 1000 m from the Nicaraguan Rise southeastward into the Colombian Basin.

The boundary is seismically inactive (Molnar and Sykes, 1969), implying that whatever process(es) formed it has since ceased, or that it is not fault controlled. The sea-floor adjacent to the boundary probably formed in the Late Cretaceous. This age of formation is shown by JOIDES drill site 152, which drilled to a Late Cretaceous sea-floor basalt (Edgar and Saunders, 1973). Additional evidence is a sea-floor spreading model for the Colombian Basin (Christofferson, 1976) that predicts, among other things, a Late Cretaceous age for the crust

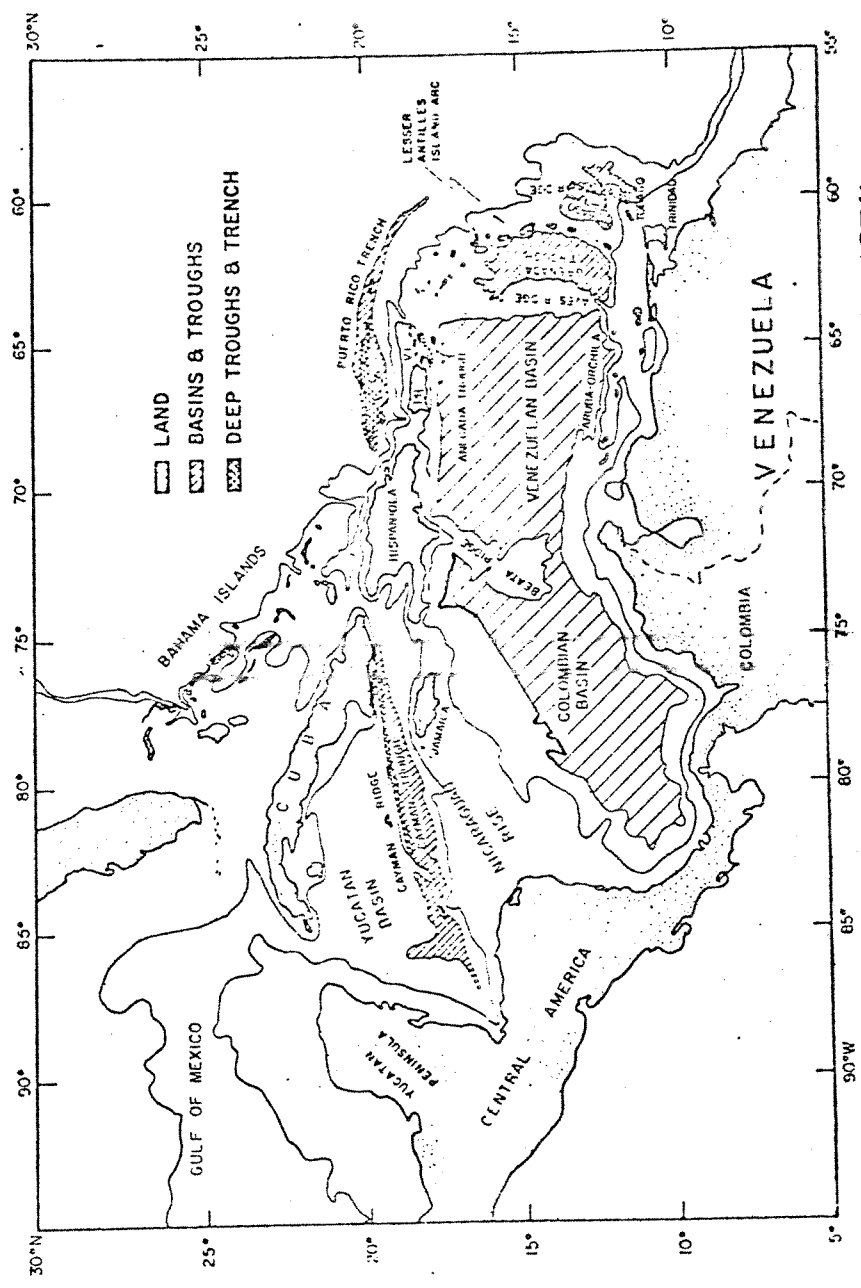


Fig.1: Physiographic features of the Caribbean (fromNagle, 1971).

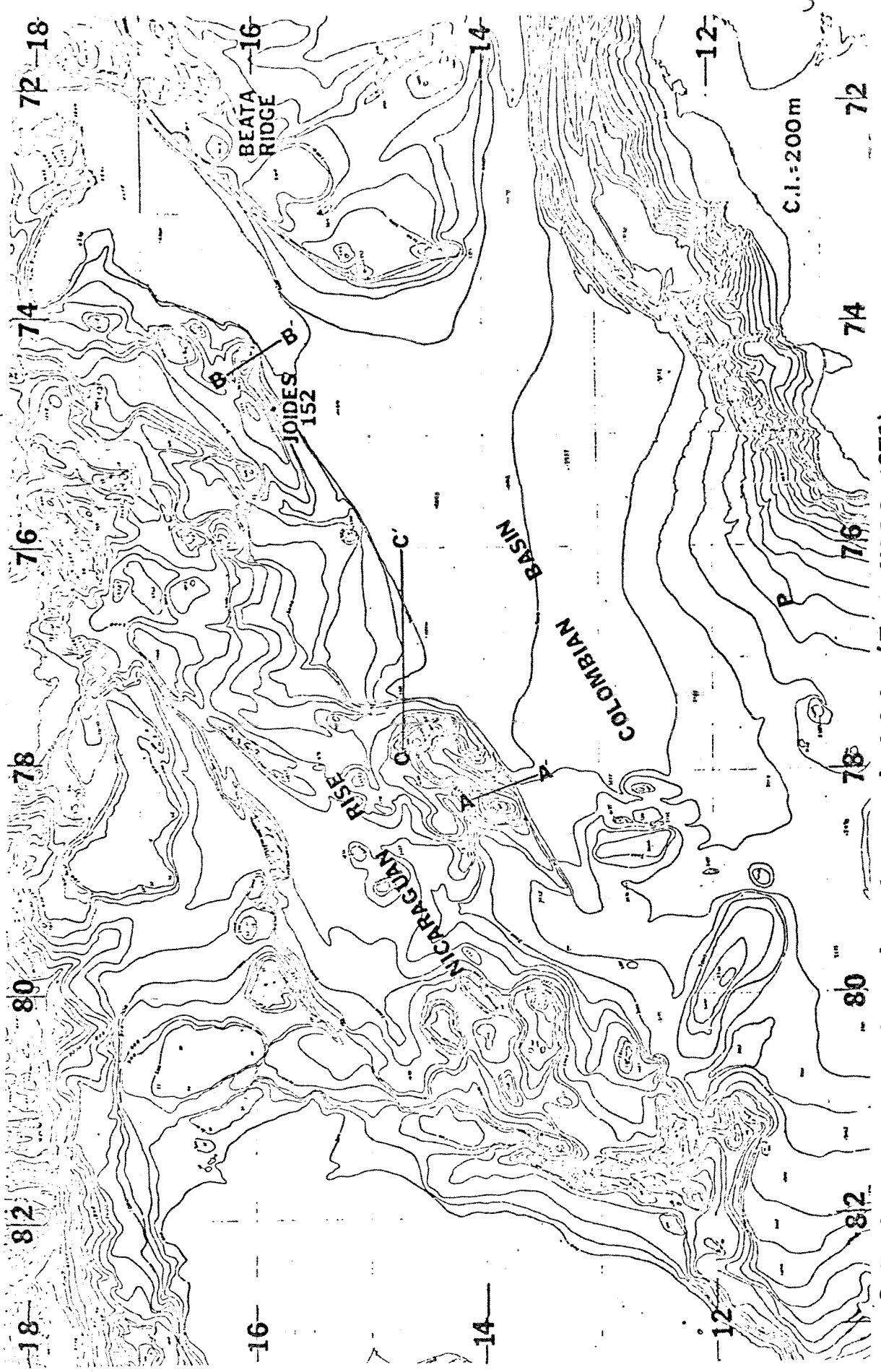


Fig.2: Bathymetric map of the boundary and vicinity (From USGS, 1976)

adjacent to the boundary.

As mentioned, the boundary appears to be straight, as shown on the most recent bathymetric chart published by the U.S.G.S. (Case and Holcombe, 1976; Fig. 2). A simple check of the accuracy of the bathymetric map was made using ship-track data from Conrad and Vema North Atlantic data (Talwani, 1974). The result showed that the map has some minor inaccuracies but the boundary was indeed quite straight for the areas shown.

Closer examination of the boundary reveals a number of irregularities. In the southwestern section at 82° to $80^{\circ}30'$ longitude, and 12° to 13° latitude, the topography and the boundary become indefinite. At 79° to $80^{\circ}W$ and 13° to $14^{\circ}N$ and 77° to $78^{\circ}W$ and 14° to $15^{\circ}N$, there are major embayments of the Colombian Basin into the area of the Nicaraguan Rise. Near the northeastern end, the physiographic boundary changes direction from $N60^{\circ}E$ to approximately $N30^{\circ}E$. Thus, from afar, the boundary appears straight, but in detail there are a number of irregularities. The imperfections of the boundary suggest that the concept of a continuous, straight boundary is incorrect. However, there may be simple explanations for each of these anomalous areas. Only one is apparent, however. The mountainous topography in the southwestern section may have been produced after the formation of the boundary and hence mask its

true appearance there. Since very little published data exist for this area (Edgar and Ewing, 1971), the linearity of the boundary cannot be easily discounted because of the flaws mentioned. In addition, a lineament of such length would imply some sort of plate-tectonic genesis (Morgan, 1968). We are left with the question: Can the Nicaraguan Rise - Colombian Basin boundary be identified as an ancient rift, a transform fault, or a trench? My work attempts to answer this question.

Nicaraguan Rise - Colombian Basin

Boundary as a Rift

Arden (1975) argues from mostly unpublished data that the Beata Ridge and the Nicaraguan Rise were once attached, with the Beata Ridge forming the southeastern flank of the Nicaraguan Rise. A rift separated the Beata Ridge from the Rise during the Laramide orogeny at the end of the Cretaceous. Evidence includes similar crustal structures for the Nicaraguan Rise and Beata Ridge, steep scarps along the southeastern side of the Rise and northwestern side of the Beata Ridge, and the thinner crust of the Colombian Basin, which lies between these two elevated areas.

Christofferson (1973, 1976) has found that the magnetic anomalies in the Colombian Basin generally trend east-west. This east-west trend, which exists in the area separating the Nicaraguan Rise from the Beata Ridge greatly weakens, if not eliminates, the concept that the two were rifted apart. That is, the remanent magnetization should show trends parallel to the rifted margins of the Nicaraguan Rise and the Beata Ridge (Vine, 1966). In the proposed rifted section, the magnetization is not parallel to the boundaries of the Nicaraguan Rise and the Beata Ridge, but is distinctly oblique to the proposed direction of rifting, making an angle of about 60° with it (Christofferson, 1976; Fig. 2). Adding to this fact the observation that there is no topographic evidence of a fossil rift in the Colombian Basin leads to the conclusion that the Beata Ridge was never part of the Nicaraguan Rise.

Nicaraguan Rise - Colombian Basin Boundary
as a Transform Fault

Considering the boundary as an inactive transform fault leads to some major problems. In general, major changes in the direction of a plate boundary are accompanied by a change of boundary type (Morgan, 1968). The division between the Nicaraguan Rise and Colombian

Basin is straight for nearly 1000 km from Central America, east-northeastward to 74°W , 16°N , where it either abruptly dies out, or changes direction from $\text{N}60^{\circ}\text{E}$ to $\text{N}30^{\circ}\text{E}$. If the boundary has changed direction, it should change its character to a rift or a trench along the $\text{N}30^{\circ}\text{E}$ segment. Until further study reveals evidence to the contrary, the direction change does not eliminate the idea that the boundary was a transform fault, but it requires the additional complexity of a rift or trench to join the transform fault at 74°W , 16°N .

It might be argued that the physiographic boundary does not change direction but actually continues along a $\text{N}60^{\circ}\text{E}$ direction and reappears at $71^{\circ}30'\text{W}$, 17°N , as part of the Beata Ridge. However, the orientation of magnetization in the Colombian Basin is east-west, crossing this trend at $16^{\circ}30'\text{N}$, which weakens the idea. A rift north of 16°N in the Colombian Basin is also weakened by the east-west magnetic trend. Magnetic trends striking $\text{N}30^{\circ}\text{E}$ should be found here.

It is possible that dextral movement of about 100 km occurred between the Nicaraguan Rise and Colombian Basin along their common boundary to the southwest of 74°W , 16°N . This concept is derived from the age determinations made from JOIDES drill-site 152 on the southeastern flank of the Nicaraguan Rise and age determinations for the adjacent crust of the Colombian

Basin by Christofferson (1973, 1976). Apparently there are differences in age across the boundary which can be eliminated if a dextral movement of about 100 km is assumed (Christofferson, personal communication, 1977). Although this hypothesis may prove to be correct, it is presently based on little data. To summarize, the concept of a transform fault cannot be ruled out. However, the boundary appears to be discontinuous, which tends to weaken rather than support this idea.

Nicaraguan Rise - Colombian Basin

Boundary as a Trench

The possibility of the boundary being a relict trench cannot be approached using the same techniques as those applied to the concepts of a rift or transform fault. Magnetic anomalies are known to be oblique to trenches (Fisher and Hess, 1963). Furthermore, a change in the direction of a trench is not an unusual feature since many are arcuate (Fisher and Hess, 1963). Whether or not a subduction zone existed in this area can be determined through analysis of gravity data taken across the boundary. Analysis of gravity data does not provide a unique solution to a geological problem. It is theoretically possible to produce the same gravity potentials and anomalies by any number of geologic

structures. However, when different data point towards a particular solution, then conclusions can be made with greater assurance.

Published gravity data across the Nicaraguan Rise are scanty, but the general gravity field is well established (Case, 1975). The collected data has been used to construct a free-air anomaly map of the Caribbean (Fig. 3). The data and map show that, in general, over the Nicaraguan Rise free-air anomalies range from -50 to +50 mgal. The Colombian Basin registers free-air anomalies of 0 to +35 mgal in most of the central part of the Basin, with values as low as -125 mgal along the foot of the continental margin of Panama and the Colombian coast, near the Guajira Peninsula. These low values have been interpreted as deep sediment-filled troughs, like trenches (Case, 1975).

Data in greater detail, but more limited in range is provided by Lamont-Doherty's Conrad and Vema cruises (Talwani, 1974). These data show that the physiographic boundary is characterized by a positive free-air anomaly, on the order of 40 to 70 mgal for the Nicaraguan Rise side, and a negative anomaly, on the order of -20 to -60 mgal on the Colombian Basin side (Fig. 4).

From the collected data, it appears that for most of the area under study, free-air anomalies range from +50 to -50 mgal. Compared to the rest of the Caribbean

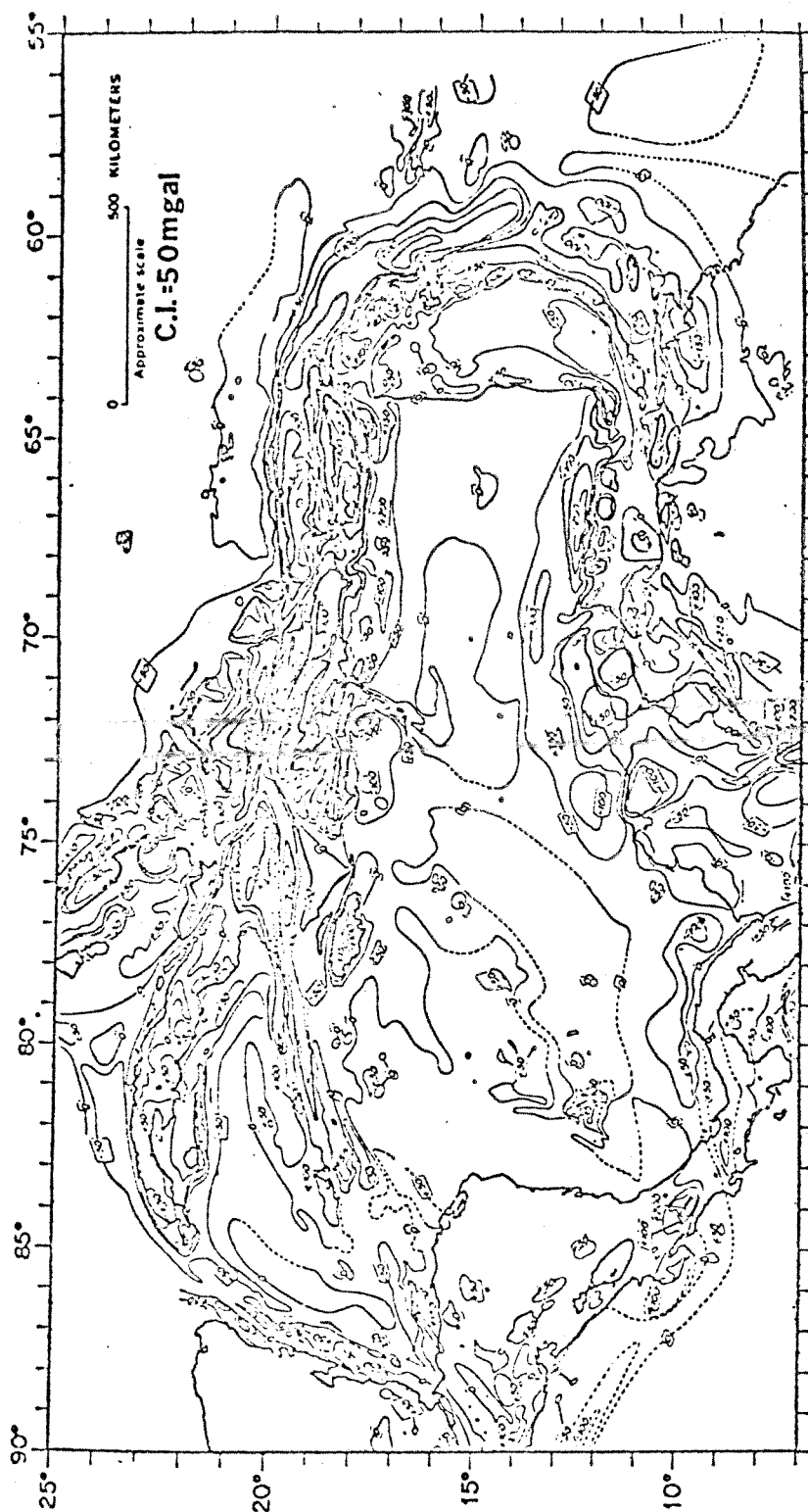


Fig.3: Free-air anomaly map of the Caribbean (From Case, 1975).

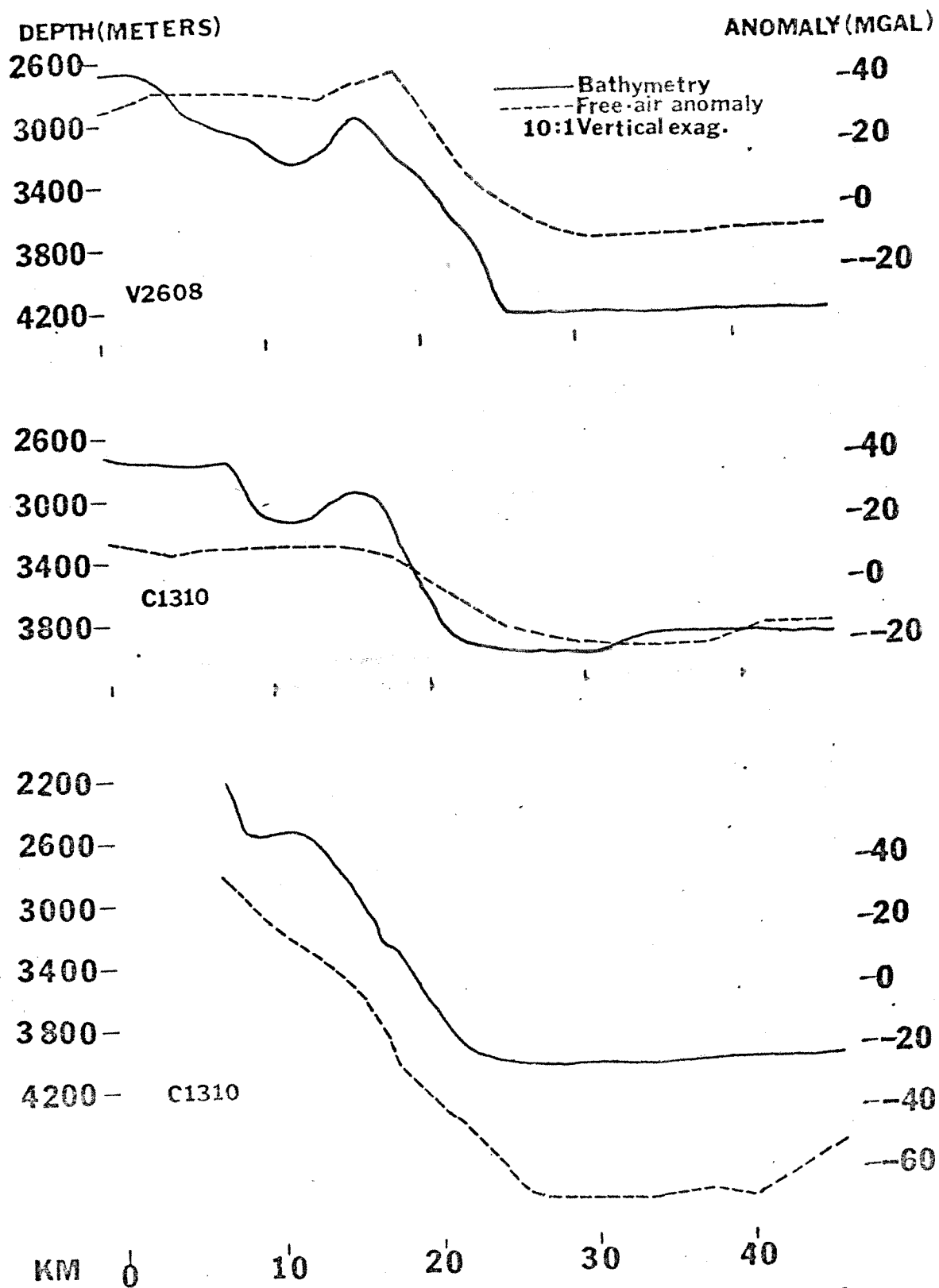


Fig 4. Bathymetry and free-air anomaly data for crossings of the boundary corresponding to portions of B-B, A-A, and C-C respectively, of Fig.2.

the section has little variation in gravity. Case (1975) has interpreted this to mean a general isostatic equilibrium for the central Caribbean.

Additional evidence against the trench hypothesis involves crustal models of three geophysical crossings, A-A', B-B', and C-C' (Fig. 2). The first two cross the boundary perpendicularly, whereas C-C' is an oblique traverse. These transects were made by the Lamont-Doherty Research Vessels Conrad and Vema. Data from Conrad cruise C1310, in 1970, are shown in crossings A-A' and C-C'; data from Vema 1969 cruise, V2608, is the source for B-B'.

Gravity modeling is a way of determining the general underlying structure of an area. It is, however, particularly difficult to produce an accurate picture of the area under study since so few seismic data are available to refine the gravity models. There have been some refraction surveys reported by Edgar and others (1971), and it is these data and crustal sections derived by Arden (1975), which were used to model the deeper layers of the crust. Although Ludwig, Houtz and Ewing (1975) presented results of sonobuoy measurements for part of C-C', they penetrated only to the base of the sediments overlying the crust. The approximate average velocities were incorporated however. For the sedimentary layers of the models, bathymetry data and

seismic reflection profiles collected by Conrad and Vema were used.

The Nicaraguan Rise consists of a thickened crust which appears to be oceanic in character (Barr, 1974). Edgar (1971) determined that the crust is about 23 km thick; Nagle (1971) states that the thickness is uncertain, but is about 26 km. The layer above the mantle has a maximum thickness of approximately 20 km, with a seismic velocity in the range of 6.2 to 7.0 km/sec (Arden, 1975). Seismic velocities through crustal layers can be converted directly to rock densities through the use of empirically derived curves (Grant and West, 1965). A seismic velocity of 6.2 km/sec represents a density of 2.75 gm/cc, which was used in the models. This layer is considered to be the oceanic layer or "Layer 3" and is thought to consist of serpentinite, metagabbro and other basic rocks of the oceanic crust (Arden, 1975). Above this layer is Layer 2 or the "volcanic layer" with a maximum thickness of about 5 km and a velocity of 5.2 to 5.8 km/sec (Arden, 1975). A seismic velocity of 5.8 km/sec is equivalent to 2.68 gm/cc which was used for the models. This layer is suggested to consist of Lower Cretaceous volcanic and metamorphic rocks (Arden, 1975). On top of Layer 2 is a Cretaceous and Tertiary sedimentary and volcanic sequence with a maximum

thickness of 5.0 km and velocities ranging from 3.9 to 4.8 km/sec. An average density of 2.45 gm/cc was derived from these velocities (Arden, 1975). An uppermost layer with a maximum thickness of 1.0 km consists of late Tertiary and younger sediments with a seismic velocity of 1.7 to 2.0 km/sec. These velocities indicate a density of 1.80 gm/cc, which was used in the gravity models (Arden, 1975). There is, of course, greater detail possible for each section, but these values of thickness and velocity were found to be adequate to build the models of the Nicaraguan Rise.

The Colombian Basin is fairly similar in structure to the Nicaraguan Rise, but is less thick, approximately 19 to 20 km. Case (1975) describes each layer in detail. The oceanic layer is found to have velocities of 6.7 to 7.5 km/sec (7.0 km/sec average velocity, equivalent to 2.85 gm/cc, was used in the models) and a thickness ranging up to 12 km. This is overlain by Layer 2, with a velocity of 5.8 to 6.5 km/sec (5.8 km/sec = 2.68 gm/cc was used in the models) and a thickness of up to 3 km. The Cretaceous and Tertiary sequence is characterized by velocities of 4.0 to 5.5 km/sec (4.6 km/sec = 2.50 gm/cc proved satisfactory in the models) and a maximum thickness of 4 km. The top layer is characterized by velocities of about 2 km/sec (equivalent to a density of 1.94 gm/cc) and a thickness ranging from 1.1 to 2.1

km.

Two different models for each crossing have been constructed (Figs. 5-10). One shows the boundary as a large vertical fault between the Nicaraguan Rise and Colombian Basin. The other shows a continuation of the upper crustal structure between the two areas, with a large vertical fault cutting the lower crustal structure only. In general, they are compatible with the seismic results concerning the thicknesses of the sections, with a few minor exceptions. However, both models fit the data fairly well and a conclusion as to which model, if either, is correct cannot be made.

My best-fit models differ greatly from a model of a trench and subduction zone as developed by Westbrook, Bott and Peacock (1973) for the Lesser Antilles to the east (Fig. 11). They are different in that the lower crustal layers of the Colombian Basin cannot dip into the mantle beneath the Nicaraguan Rise. A model of these layers dipping down to about 50 km or so, would generate very large negative gravity anomalies, which are not observed. It therefore seems unlikely that such underthrusting of crustal layers exists here. Gravity studies in areas of known subduction zones show the free-air anomalies to be very negative on the subducted side, with values on the order of -200 to -350 mgal, and positive on the obducted side, with values of 100

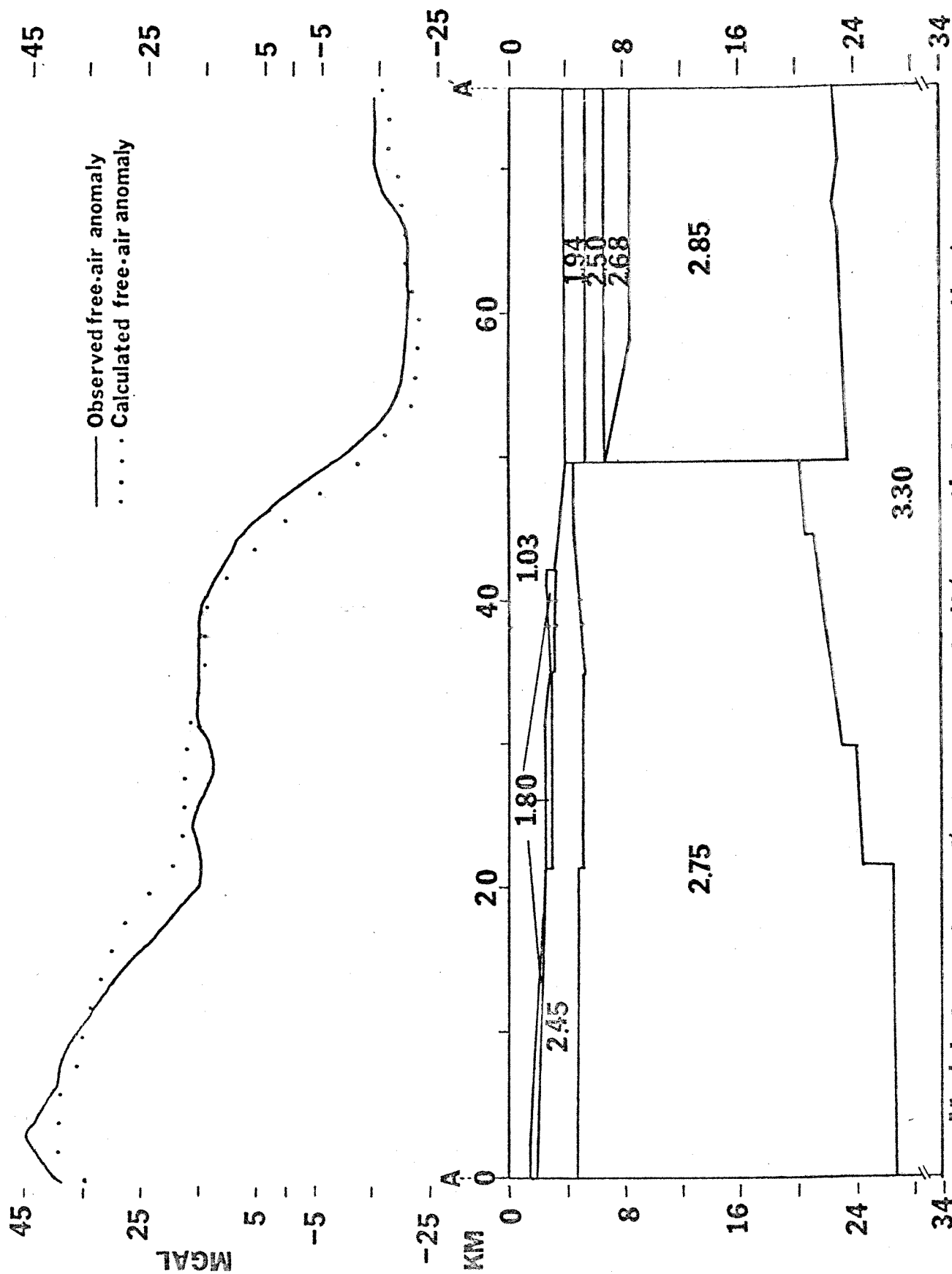
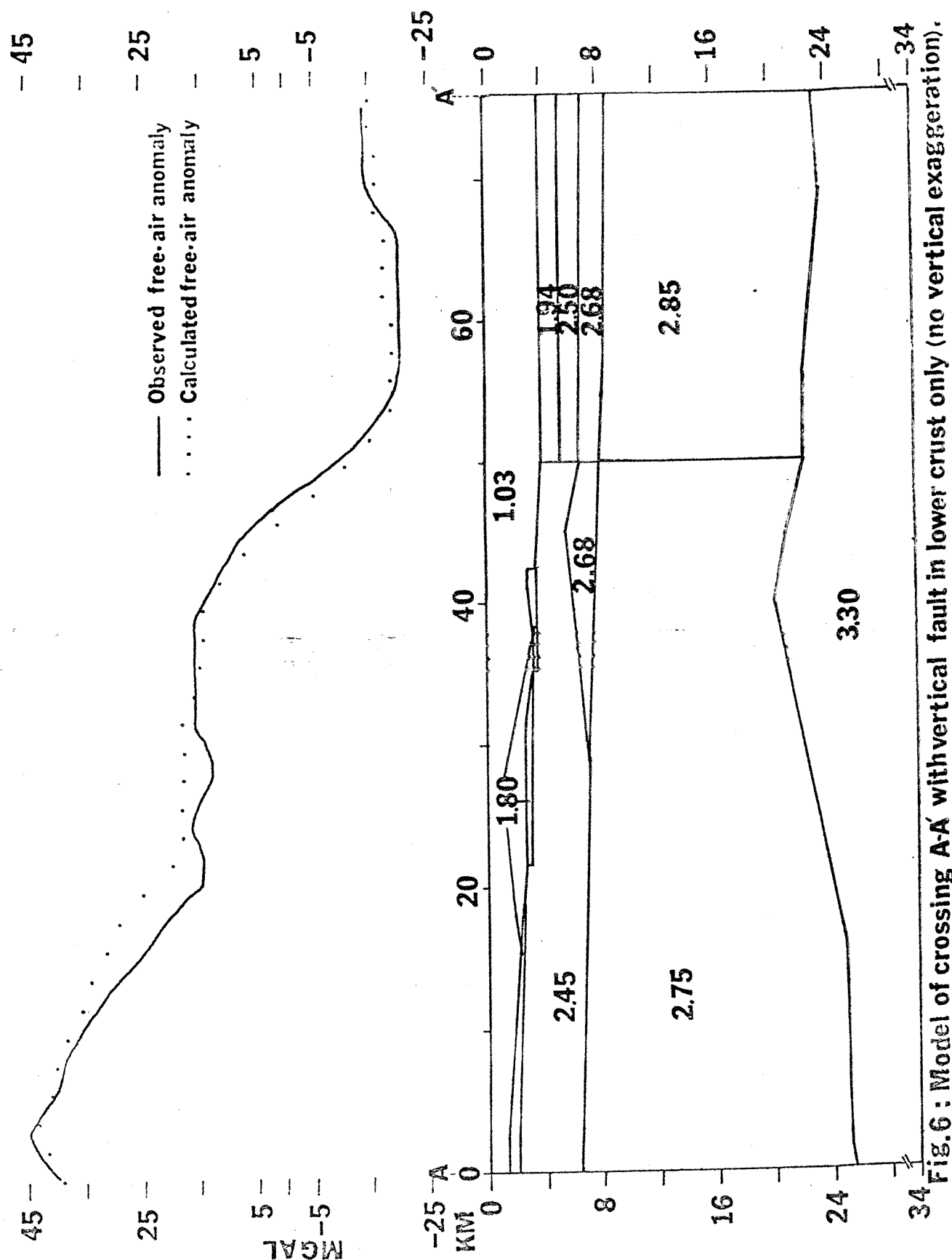


Fig. 5: Model of crossing A-A' with vertical fault (no vertical exaggeration).



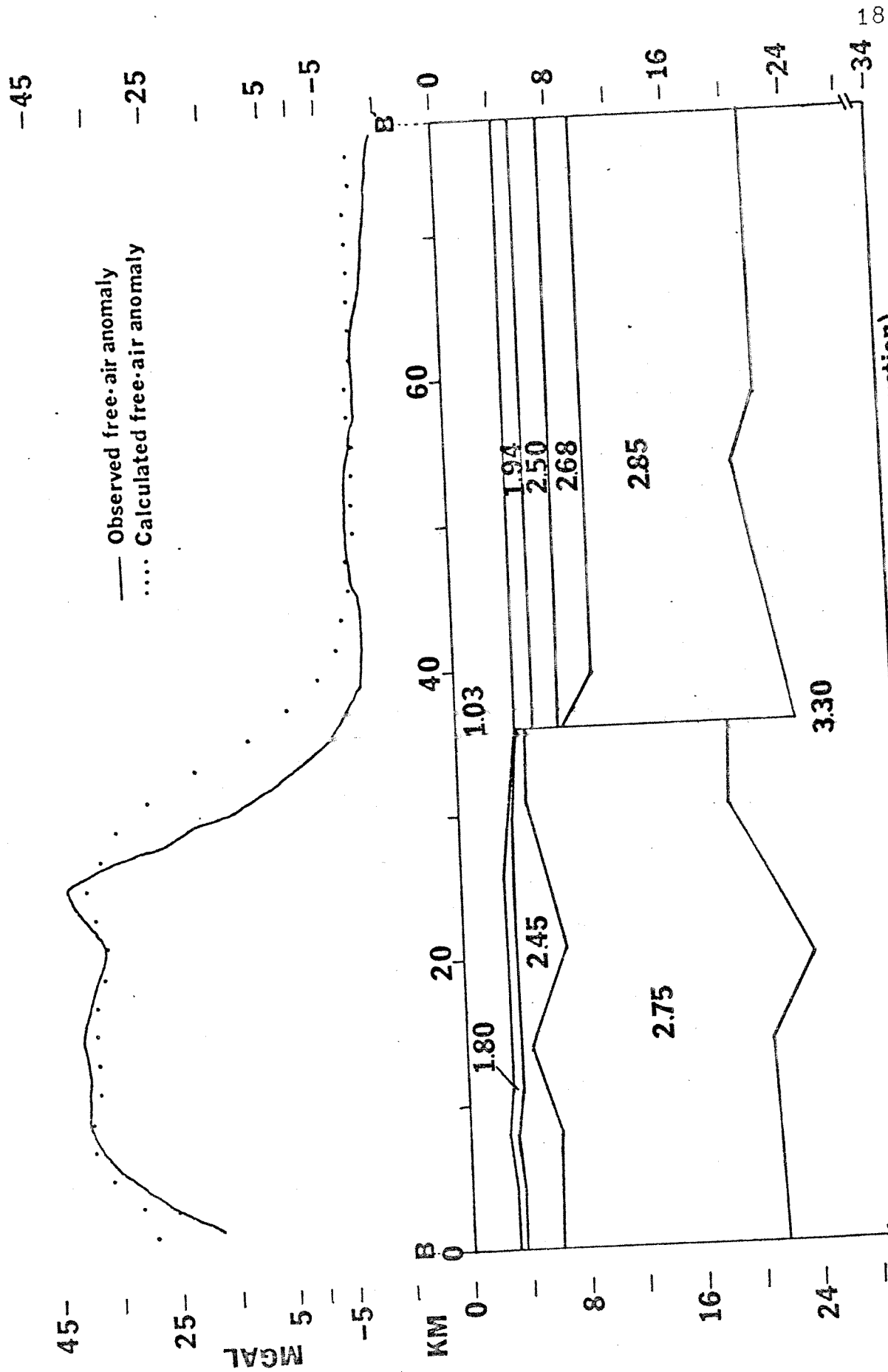


Fig. 7 : Model of crossing B-B with vertical fault (no vertical exaggeration).

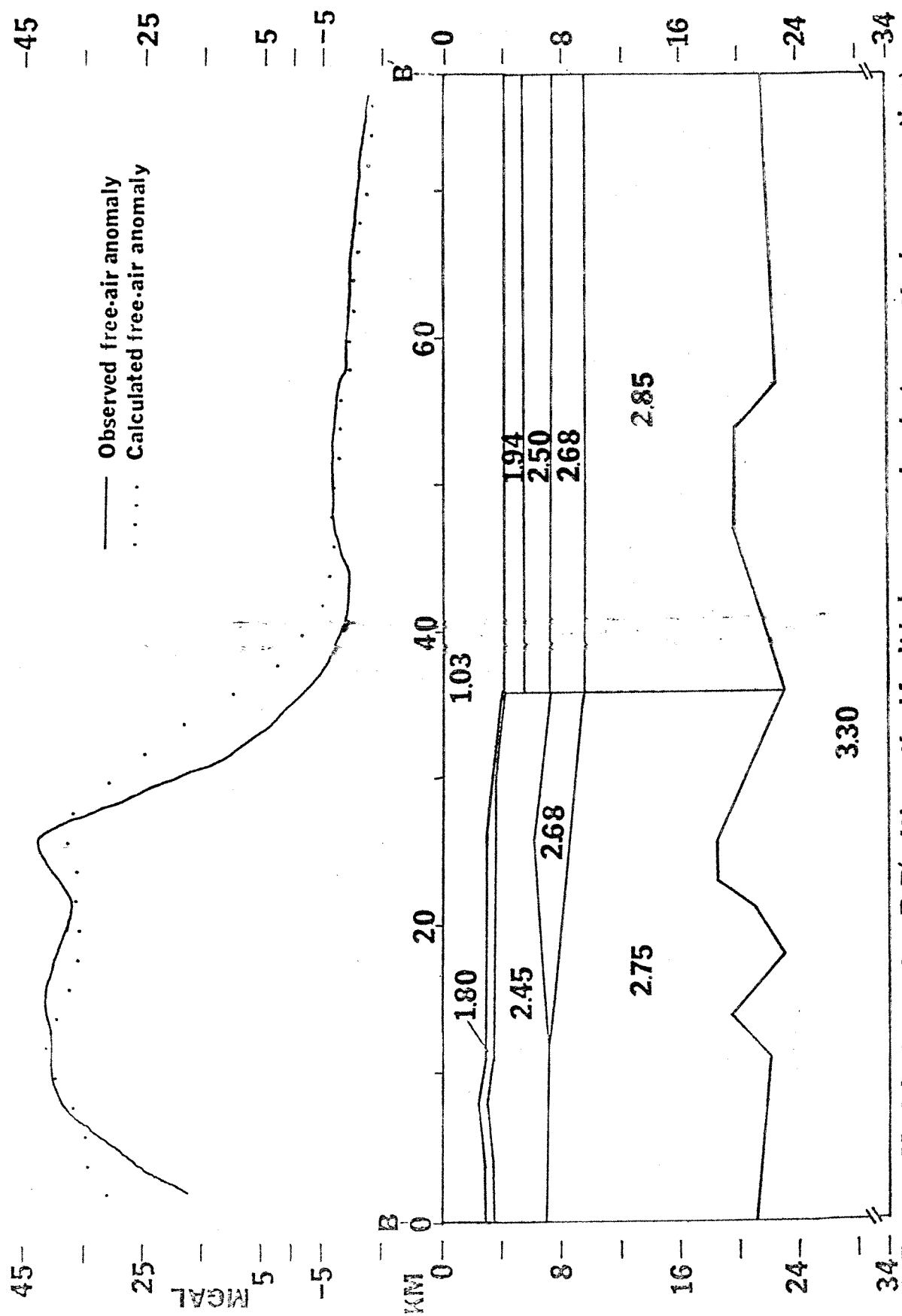


Fig. 8 : Model of crossing B-B' with vertical fault in lower crust only (no vertical exaggeration).

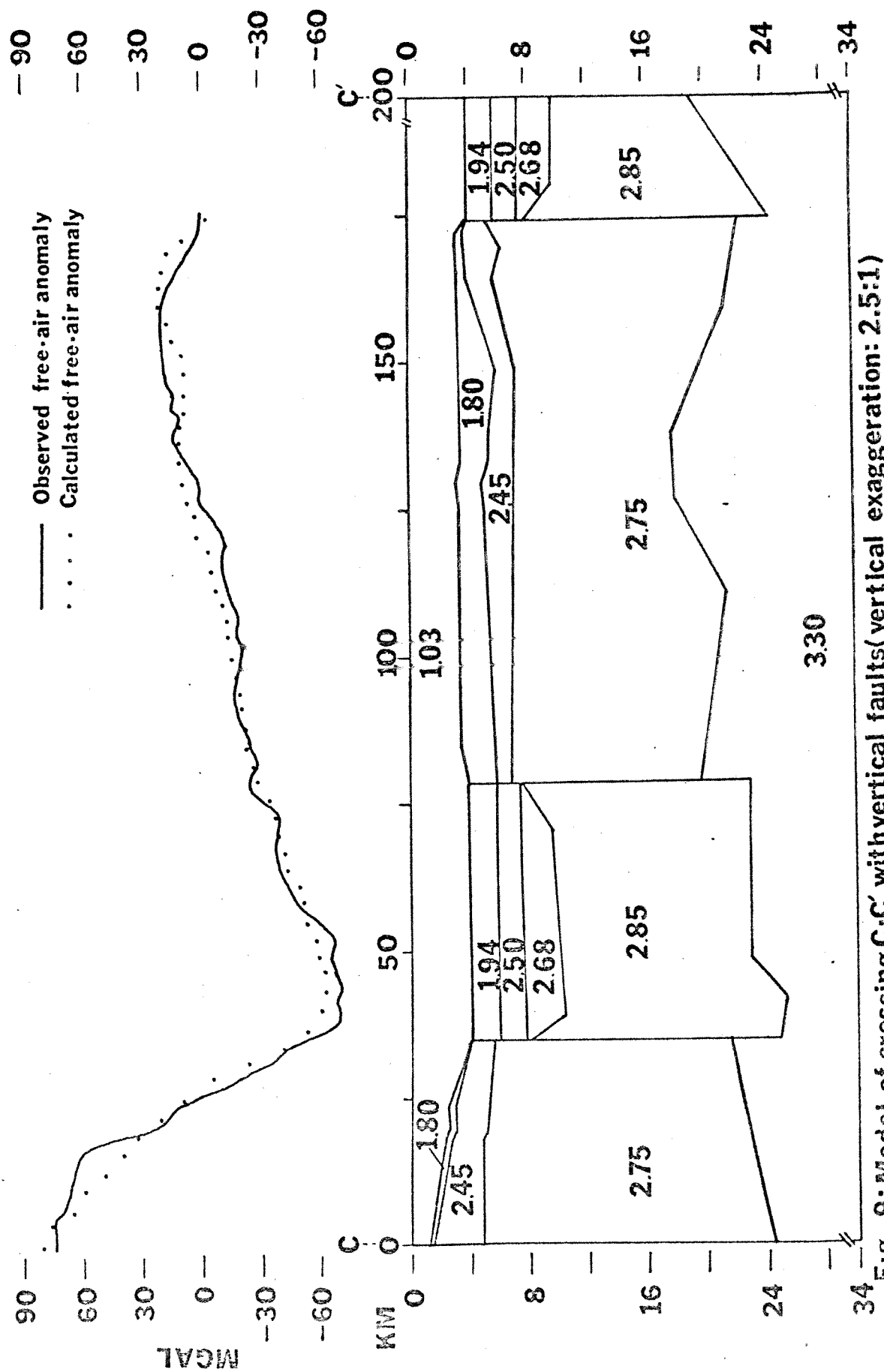


Fig. 9: Model of crossing C-C' with vertical faults (vertical exaggeration: 2.5:1)

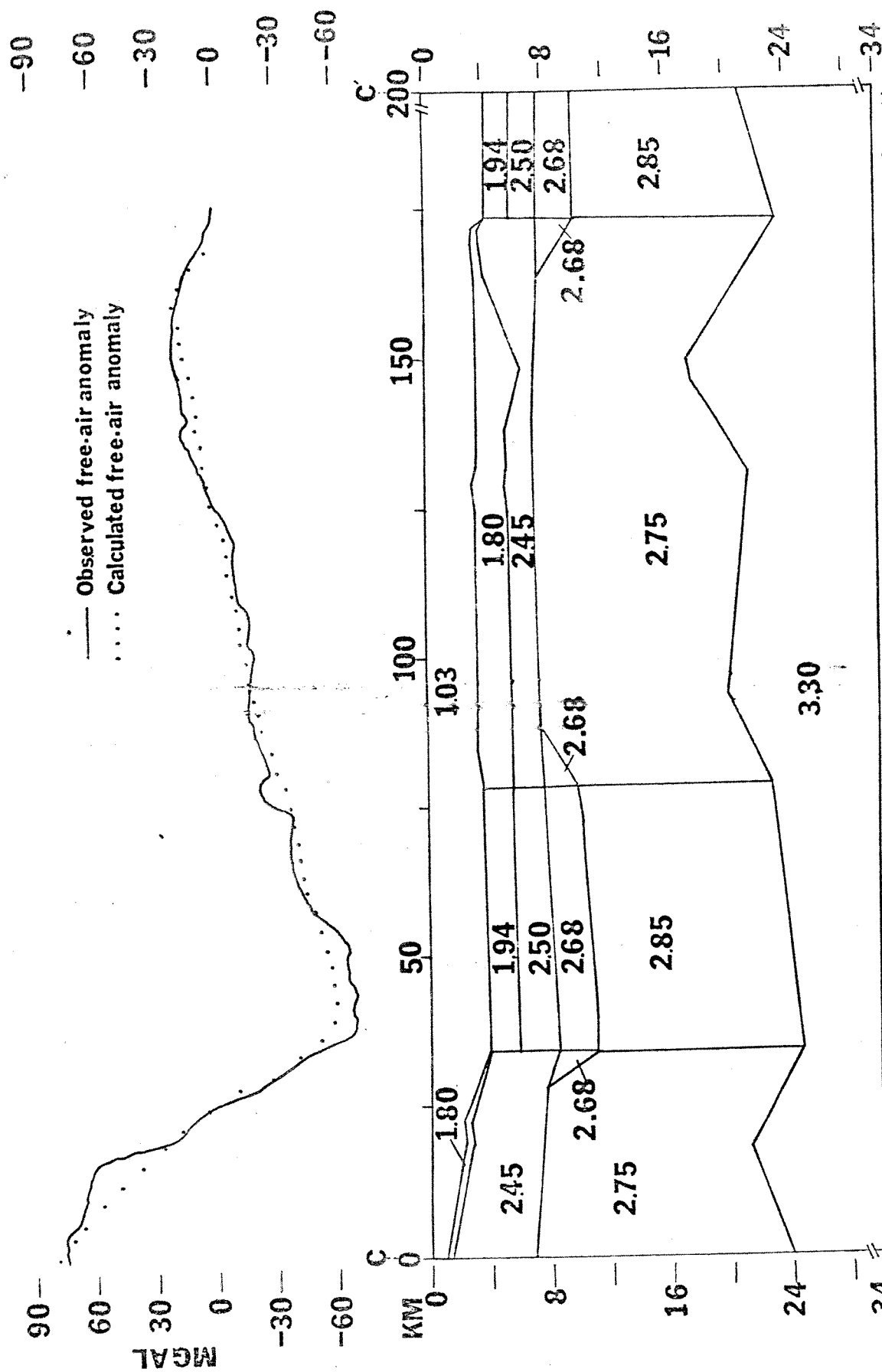


Fig.10: Model of crossing C-C' with vertical faults in lower crust only (vertical exag.: 2.5:1).

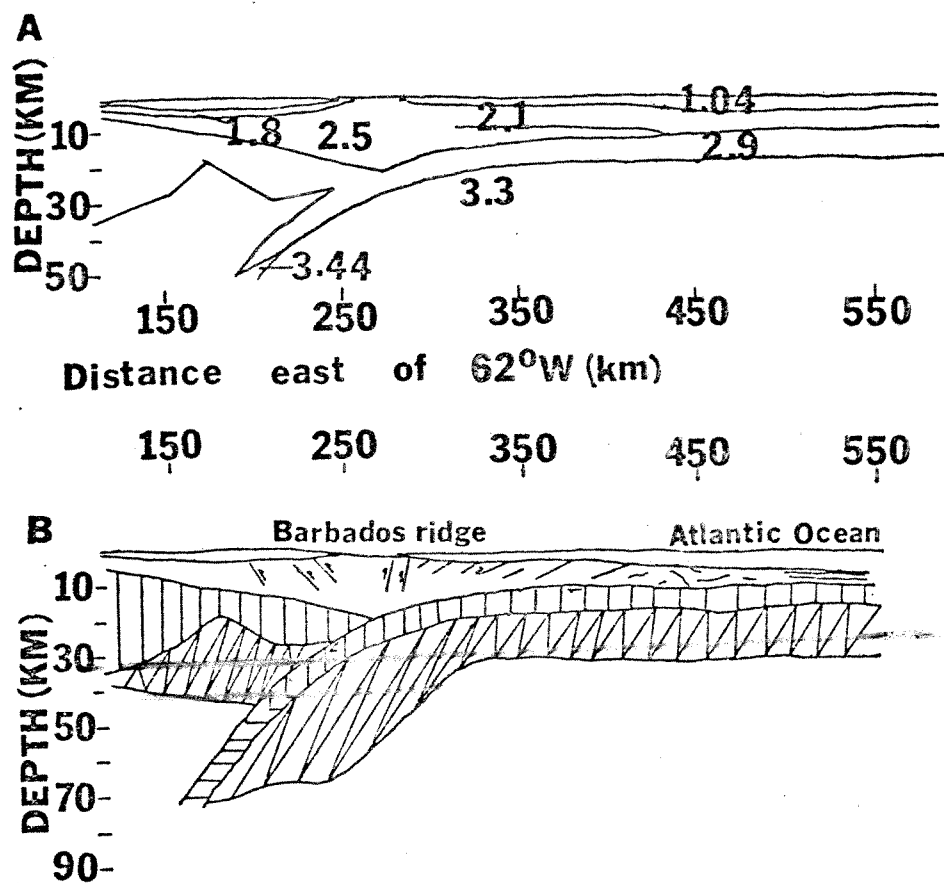


Fig.11: Model (A) and diagram (B) of Lesser Antilles subduction zone (From Westbrook, Bott and Peacock, 1973).

to 200 mgal common (Fig. 12). Although the anomalies at the Nicaraguan Rise and Colombian Basin boundary differ by about 100 mgal, the difference is much smaller than that observed at the known trenches. The possibility that the boundary is a sediment-filled trench like the one east of the Lesser Antilles seems to be unlikely when the free-air anomalies for the two areas are compared (Figs. 4 and 12).

There is another line of evidence against the subduction zone that has recently emerged. That is, the Colombian Basin is covered with a thick sequence of turbidites which are derived from the Magdalena River Delta (Case, 1975). Below these turbidites are sometimes found the Carib beds (Edgar and Ewing, 1971), labelled A" and B". Layer A" is a chert of early Eocene age and B" is an Upper Cretaceous basalt, diorite or diabase (Case, 1975). These reflectors have also been located on some areas of the Nicaraguan Rise (Edgar and Ewing, 1971).

An important aspect of those Carib beds near the boundary is that although seismic reflection profiles reveal some evidence of faulting (Talwani, 1974), there is no evidence of the large-scale deformation of sediments that characterizes the subduction zone of the Lesser Antilles (Fig. 11).

The lack of evidence for a parallel line of volcanoes

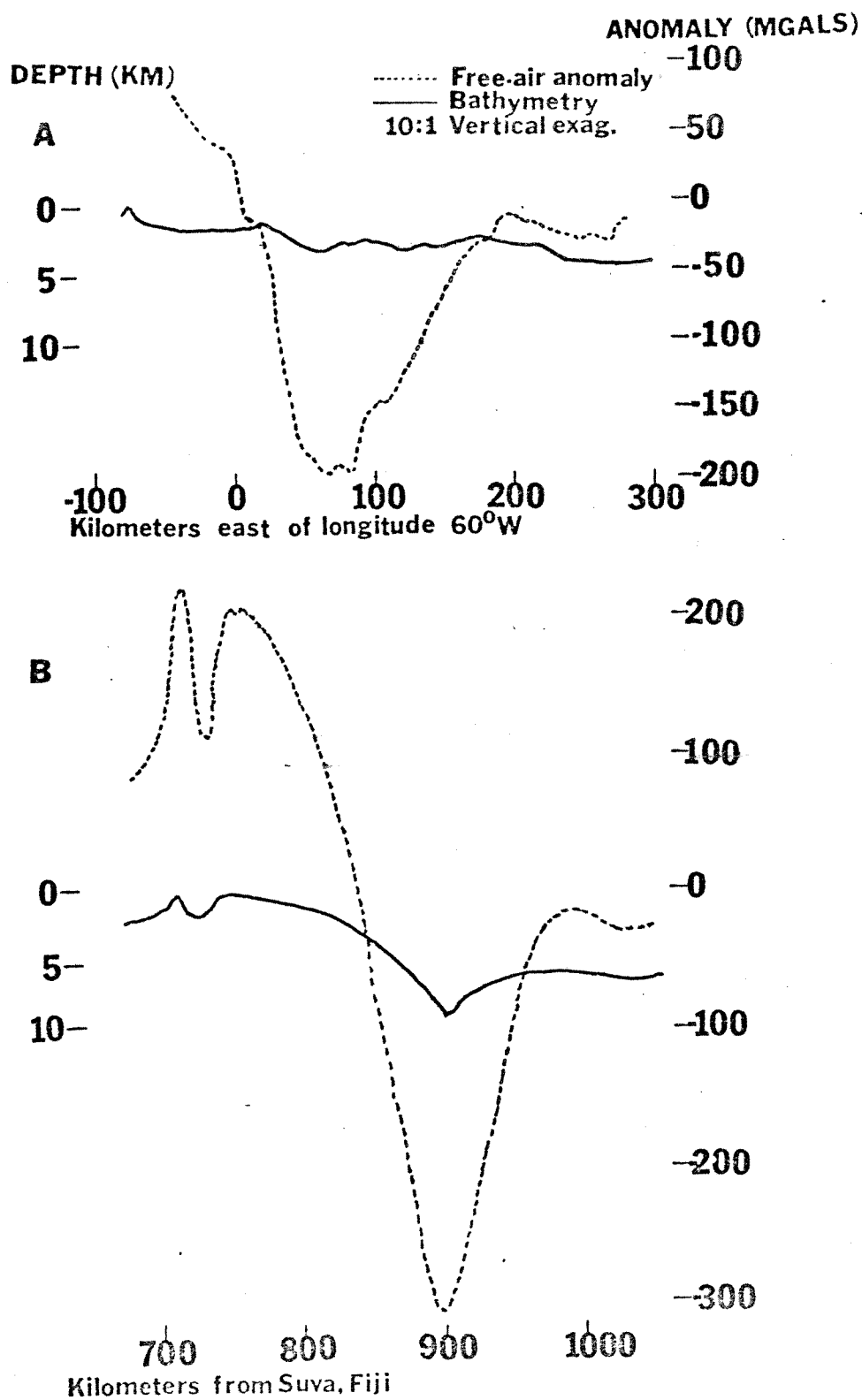


Fig.12: Bathymetry and free-air anomaly data for: A. The Lesser Antilles near Barbados, and, B. The Tonga Trench (From Worzel and Harrison).

on the Nicaraguan Rise can also be cited as negating the possibility of an active subduction zone here. Instead there seems to be a chaotic distribution of topography on the Rise.

It should be mentioned that along the boundary between the Nicaraguan Rise and the Colombian Basin particularly at 14°N , 77° to 79°W there are mountainous areas. The majority of the mountain slopes measured are less than 20° , and the topography is magnetized (Christofferson, 1973). A volcanic origin is implied. If these are volcanic, it is difficult to explain how they were formed so close to a trench located at the boundary.

In sum, the evidence against the interpretation of the boundary as a trench appears to be strong. Isostatic equilibrium, the absence of tectonic activity, the lack of a parallel volcanic lineament, the lack of a large negative gravity anomaly, the absence of extensive deformation of the sediments, and the results of modeling do not support the idea that the boundary represents a relict trench.

Discussion of the Gravity Models

It appears that existing evidence argues against the boundary having been either a site of a rift or a

subduction zone, but the evidence is not strong against the idea of the boundary being a transform fault. Although there are not enough facts to decide exactly what the boundary represents the gravity data and my derived models enable further information to be obtained. It is therefore worthwhile to examine these models in more detail.

Studying the sample gravity anomaly data and bathymetry (Fig. 4) leads to the conclusion that the change in bathymetry is generally responsible for the gravity anomaly. However, for the first two crossings on the side of the Nicaraguan Rise, there are large sections where the topography changes but gravity does not change. In addition, at equal depths the gravity anomalies on all three crossings differ. This could be due to the differences in the surrounding areas, e.g., C-C' traverses an area of comparatively higher elevation than crossings A-A' and B-B'. The difference could also be due to a difference in the thickness or density distribution of the crust underlying these areas.

Crossing B-B' (Figs. 7 and 8) is not the same as A-A' and C-C' which show some similarities. Whereas the A-A' and C-C' models show fairly good agreement with the observed gravity anomaly at the boundary, the models of B-B' have a too small anomaly slope at the boundary. The models would fit better if the boundary sloped at a slight

angle. Layer 3 of the Nicaraguan Rise would partially underlie the Colombian Basin. This is a simple adjustment to the model and may be a real feature of the boundary.

If such faulting were real it would add evidence to Arden's (1975) hypothesis that the Rise tilted southward during the late Miocene. Because the crest of the Rise is located north of the maximum thickness of the Rise, Arden concludes that the Rise must have tilted to the south. A test of this hypothesis could be made by studies of sediments cored on the Rise. Changes in the character of the general foraminifera population, e.g., if benthonic varieties overlie planktonic species, could indicate a change in depth for the tilted section. Unfortunately, the only cores that exist come from JOIDES Site 152 (Edgar and Saunders, 1973) which was drilled in an area where there was little sedimentary cover and the youngest sediments recovered were late Paleocene-early Eocene. Arden's hypothesis must therefore remain untested.

The models tend to reinforce the idea that there are some discontinuities in the crust. All the models show that large-scale faulting in the deeper layers is probable in addition to the faulting interpreted from the reflection profiles (Talwani, 1974). The models cannot predict which layer or layers are faulted, but

there is a need for such discontinuities if the models are to fit the data.

It may be questionable whether the difference between the densities of Layer 3 of the Rise and the Basin, as determined by seismic refraction studies at the boundary, really exists. Actually, only one study was made in this area (Edgar and Ewing, 1971) and the difference may not be widespread, but rather a local phenomenon peculiar to that singular measurement. If there were no difference, with a slight adjustment the models would still fit the structural controls placed on them by seismic studies. For example, if Layer 3 on the Rise and Layer 3 on the Basin had densities of 2.75 this would not affect the thickness of Layer 3 under the Rise, while Layer 3 under the Colombian Basin would become thinner by a kilometer or so.

The final question concerning the models involves subjective preference. The model without the vertical fault through the entire crust at the boundary seems closer to the observed data (Figs. 6, 8 and 10). This type of model incorporates the idea that the Cretaceous-Tertiary sequence of sedimentary rock thickens along the southern edge of the Rise (Arden, 1975). With the other type of model, the sedimentary sequence thins along the southern edge. In addition, the fact that the vertical fault models require the Colombian Basin crust to ex-

tend several kilometers deeper than the Nicaraguan Rise crust at their common boundary is at odds with the seismic data which show that the Nicaraguan Rise crust extends to a greater depth than does the Colombian Basin crust (Edgar and Ewing, 1971). The preferred gravity models (Figs. 6, 8 and 10) imply the absence of a large through-going vertical fault at the boundary between the Nicaraguan Rise and Colombian Basin.

Conclusions

Scant evidence suggests that the boundary between the Nicaraguan Rise and Colombian Basin is not related to a relict rift, a subduction zone, or a relict transform fault. Magnetic and gravity data tend to weaken these possibilities. Little evidence exists in favor of any of them. One is led to conclude that the various embayments, the changing direction, and other anomalous zones along the boundary could be related to some single event of formation or related to some sequence of events of formation.

Gravity data and modeling lead one to believe that there are a number of faults in the area of the boundary. The crustal models without the large through-going vertical fault at the boundary (Figs. 6, 8 and 10) are preferred.

A core study of the thick sedimentary layer on the Rise would tell much about its evolution and could provide an answer to Arden's (1975) hypothesis of southward tilting in the Miocene. The origin of the boundary between the Nicaraguan Rise and Colombian Basin represents a complex problem that cannot be solved with the present data. However, it is hoped that this paper has effectively eliminated some of the possible answers and helped point towards others.

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Louis Farrell Klonsky

- 1952 Born September 4 in New York City, New York.
- 1970 Graduated from Cardozo High School, Bayside, New York.
- 1970-74 Attended Columbia College, New York City, New York; majored in Physics.
- 1974 B.A., Columbia College.
- 1974-75 Graduate work in Physics, Rutgers University, New Brunswick, New Jersey.
- 1974-76 Teaching Assistantship, Department of Physics.
- 1975-77 Graduate work in Geology, Rutgers University, New Brunswick, New Jersey.
- 1976-77 Teaching Assistantship, Department of Geology.
- 1977 M.S. in Geology