# GEOPHYSICAL INVESTIGATIONS OF THE NICARAGUAN RISE

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ABSTRACT OF THE THESIS

Geophysical Investigations of the Nicaraguan Rise

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A crustal section across the Nicaraguan Rise is presented here. It is deduced from a combination of seismic refractions, gravity and magnetic data obtained from the rise. The two-dimensional geophysical models indicate that the rise is underlain by a layered crust whose thickness is intermediate between a continental and an oceanic crust. The velocity structure and the magnetic anomalies, however, are indicative of oceanic crust. Some magnetic anomalies that suggest the presence of normal and reversed magnetization have been identified.

It is postulated that the rise originated as a normal oceanic crust but has been modified during the episode of southward subduction of the North American plate beneath the Caribbean plate. This plate convergence resulted in the formation of the island-arc of the Greater Antilles. The subduction has since stopped, the Caribbean plate is now moving east and the subducting plate boundary is now replaced by the Cayman Trough. There is no evidence of unusually thick accumulation of carbonates as exists in the well known carbonate banks such as the Bahamas, the Yucatan and the Florida Platform.

# ACKNOWLEDGEMENT

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# 1. INTRODUCTION

It is generally agreed that a fundamental problem within the Caribben region today is the nature of the crust beneath the various tectonic provinces (Case, 1975; Nagle, 1971). This was clearly indicated in the report of a recent workshop organized to help identify important geological problems related to the evolution of the Caribbean (Burke et al., 1977). A report prepared for the National Science Foundation (Bell, 1979), has recommended that in the next decade efforts should be directed towards an understanding of the transition between ocean and continents - continental margins. This program has appropriately been named OMD, for Ocean Margin Drilling. Compared amongst the provinces, the Nicaraguan Rise is perhaps the least understood. Various interpretations of the available data made at different times by different investigators have led to many contradictory results. There is a paucity of studies conducted to date on the Nicaraguan Rise compared to the remainder of the Caribbean region. The study described herein was conducted to contribute to an understanding of the crustal structure and tectonics of the Nicaraguan Rise.

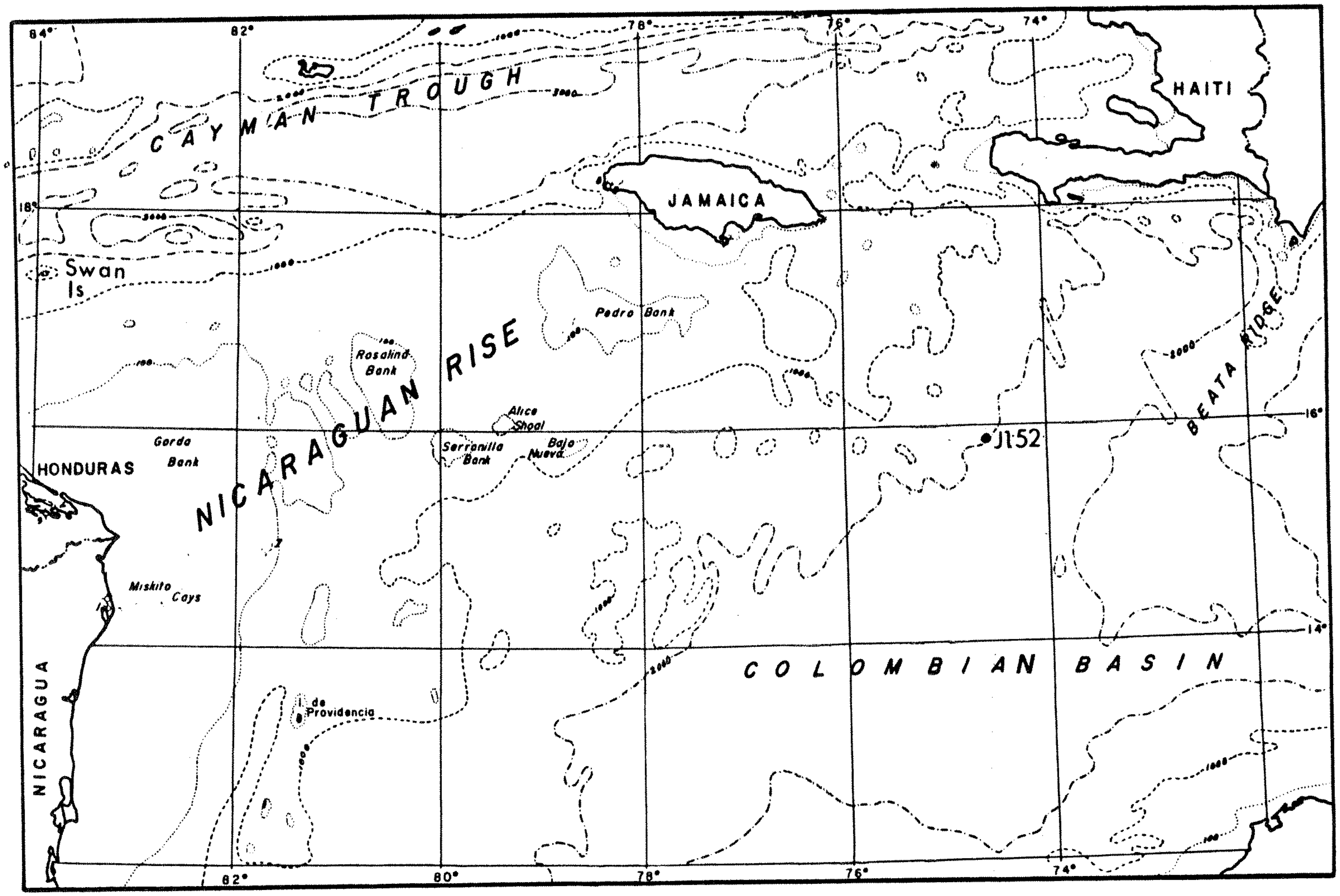



Fig. 1 Map of the Caribbean showing the Nicaraguan Rise. Water depth in fathoms.

## 2. GEOLOGIC SETTING OF THE STUDY AREA

The Nicaraguan Rise is a broad topographic high extending from Honduras and Nicaragua to the western tip of Hispaniola (Fig. 1). It includes Pedro Banks and the island of Jamaica and covers an area of approximately 500,000 $km^2$. The north-western end of the rise is linear and steep, dropping precipitously into the Cayman Trough. The southeastern flank descends into the abyssal plains of the Colombian Basin in a series of steps, terminating at the linear Hess Escarpment. Comparatively, the south-western segment of the rise is smooth and shallow whereas the northeastern section comprises highs and lows which appear to be structurally controlled (Uchupi, 1975). Some of these highs shoal to less than 50 m (Robinson and Cambray, 1971). To the north is a ridge paralleling the Cayman Trough. On this ridge are located several islands including Jamaica in the northeast and the Bay Islands to the west.

Alkaline basalts which erupted through Quaternary Coral reefs form the westernmost of the Bay Islands, Utila, (McBirney and Bass, 1966), while in Roatan, the central island, the Paleozoic metamorphic rocks forming the basement are gently folded and capped by pre-Tertiary limestones and conglomerates (Uchupi, 1975). (The Bay Islands, 16$^o$ N, 85$^o$ W are just off the western edge of Fig. 1.) A basement of metamorphosed graywacke, silty shale and cherts underlies the easternmost island, Guanaja.

The oldest rocks on the Swan Islands are predominantly calcareous siltstone highly deformed along a northwestward-trending structural axis. They were deposited in a deep-sea environment during Oligocene or early Miocene time (Todd and Low, 1967). Later units are bank limestones, reef limestones and beach deposits. There are other highs scattered over the smooth western section of the rise; some of them are volcanic islands while others are topped by reefs that appear to be structurally controlled (Stewart et al., 1961; Milliman, 1969).

In the complex northeastern section of the rise, the island of Jamaica can be divided into 3 physiographic provinces:

(a). the eastern mountainous region of mainly Mesozoic igneous and metamorphic rocks,

(b). the Wegwater belt - a trough filled with lower-middle Eocene shales, sandstones and conglomerates and

(c). the Cornwall - Middlesex block of Mesozoic - Cenozoic terrigenous and carbonate deposits (Zans et al., 1962).

In the vicinity of the island of Jamaica is a topographic high, the Pedro Bank. This has a Late Cretaceous granodiorite basement, capped by a few meters of granodiorite boulders and calcareous cemented sand-stones, and finally overlain by 2000 m of shallow-water Tertiary carbonates (Neff, 1971; Uchupi, 1975). There are other topographic highs trending nearly northeast. The shallowest ones are flat topped and have smooth steep slopes while the deeper ones have rugged crests and less steep slopes. In-between these structural highs are sediment ponds which consist of alternating turbidites and pelagic sediments (Uchupi, 1975).

## 3. THE PROBLEM

The core of the Nicaraguan Rise is not exposed anywhere. Deep drilling to sample the interior of the rise has been limited to a DSDP hole at site J152 (Fig. 1) located near the transition from the rise to the abyssal plains of Colombian Basin. A total of about 27 exploratory wells have been drilled in Jamaica, Pedro Bank and near Nicaragua (Arden, 1969, 1975). The well drilled on Pedro Bank bottomed at 1978 m, while the deepest in Jamaica and near Nicaragua are 2662 m and 4419 m deep respectively. Some dredges have been recovered from the northern scarps of the rise (Perfit and Heezen, 1978). With these few rock samples, recovered from isolated locations on the rise, the complete history of the Nicaraguan Rise cannot be interpreted from the record of the rocks alone. Indirect geophysical evidence therefore becomes very critical.

This investigation was conducted principally to:

1. establish the possible basement foundation of the Nicaraguan Rise, using bathymetric, gravity, magnetic and seismic data. Three models are proposed. The models are (Fig. 2):
   a. a sialic craton; in which the sedimentary cover is deposited on foundered continental craton.
   b. a volcanic foundation (plateau) or
   c. a more or less normal oceanic crust with thick sediment cover.

2. determine the possible thickness of the carbonates on the Rise, again using bathymetric, gravity, magnetic, seismic, and dredge data.
3. determine whether the linear magnetic anomalies characteristic of sea-floor spreading, which were identified in the eastern Colombian Basin, extend to parts of the southwestern Caribbean, or terminate against the Nicaraguan Rise.
4. determine if the eastern and western parts of the rise have the same history, or if the west is foundered continent and the east volcanic foundation.
5. present a possible evolution and tectonic history of the rise based on
    1. dredges recovered at various locations on and around the rise.
    11. magnetic lineations and other information from the geology of the surrounding provinces particularly Jamaica and the Cayman Trough.

Three models were proposed to explain the crustal structure of the rise. These are illustrated in Fig. 2.

MODEL 1. SIALIC CRATON

In this model, the sediments are assumed to be deposited on foundered sialic basement. The rise could be composed of continental crust with a fairly thick sedimentary cover of mainly shallow water carbonates and terrigenous sediments. Because cratons, by their bouyancy resist subsidence (Dietz et al., 1970) very little subsidence is expected. Gravity and magnetic anomalies over the area may reflect the continental crustal structure.

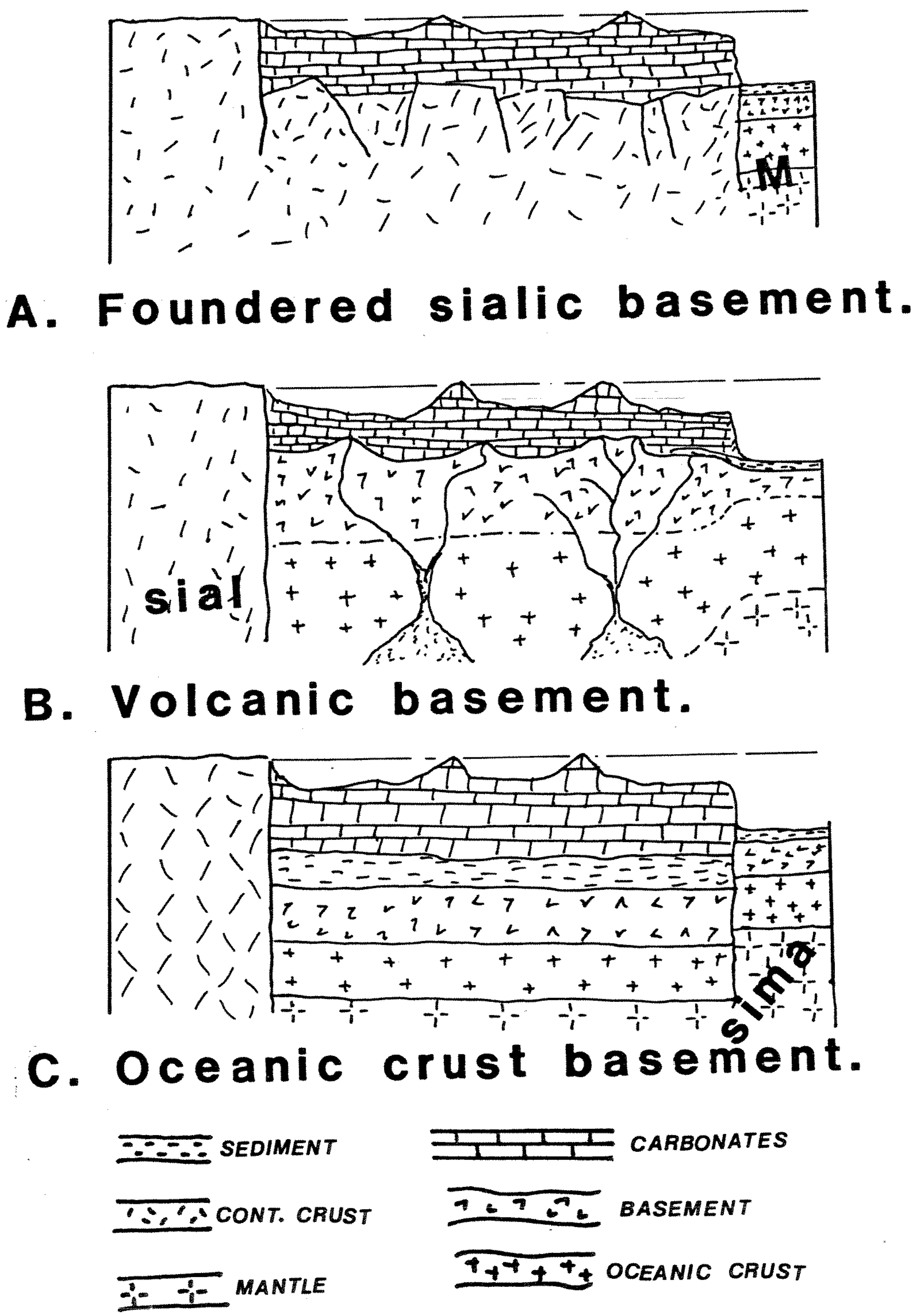



Fig. 2 Illustration of three possible models of the crust beneath the rise.

MODEL 2. VOLCANIC BASEMENT

A carbonate cap blankets a group of subsided volcanic islands or seamounts (Newell, 1955). This might be considered the drowned equivalent of the Azores, Canary Islands or of the Iceland - Faeroe or Walvis ridges, or perhaps a truncated and subsided island arc.

MODEL 3. OCEANIC CRUST BASEMENT

This model implies that the rise is only slightly thickened oceanic crust overlain by a large thickness of carbonate cover. The thicker than normal crustal section has resulted from some process of crustal thickening such as serpentinization. As is characteristic of oceanic crust, subsidence has taken place, with the accumulation of thick carbonate banks. The Moho beneath the Rise is depressed relative to the adjacent Colombian Basin and Cayman Trough in accordance with the principle of isostasy. It is estimated to be about 22 km deep.

## 4. PREVIOUS WORK

In their regional study of the Caribbean geology and geophysics, some investigators have made limited and often contradictory remarks with regard to the Nicaraguan Rise. Besides Arden's (1969, 1975) summary, there is no comprehensive work, known to this writer, devoted exclusively to the Rise as is the case with the other tectonic provinces of the Caribbean.

In what is generally regarded as a major contribution to the understanding of Caribbean crustal structure, Ewing et al., (1960) made 48 seismic refraction profiles in the western Caribbean Sea and in the Gulf of Mexico. Three of the profiles were shot on the Nicaraguan Rise. These are identified as V8-19, V8-20, V8-21 (Fig. 10).

They obtained a 4-layer crustal structure consisting of:

1. unconsolidated sediment layer (seismic velocity 1.7-2.2 km/sec).
2. Cretaceous to Tertiary sedimentary layer (vel. 3.9-4.8 km/sec).
3. upper crustal layer or low velocity crustal layer (vel. 5.2-5.4 km/sec.).
4. lower crustal layer or high velocity crustal layer (vel. 6.2-6.7 km/sec.).

The mantle was extrapolated to lie 20 to 25 km under the Rise. Ewing et al., (1960) are of the opinion that parts of the now submerged ridges (including the Nicaraguan Rise) were land areas with volcanic activities. These volcanic centers produced the large volumes of Cretaceous and Paleocene - Eocene pyroclastics found in the Caribbean islands. They cite the existence of magnetic anomalies as evidence that the ridges are volcanic and not foundered continental material.

Arden (1969) postulates that the rise originated as a mobile belt between crustal plates, in which a thickening root of oceanic crustal material develops along the boundary between plates with contrasting physical properties. In this model magma originates through partial melting of the hydrated upper mantle material along the axis of deformation and the thickened crustal zone grows into an island arc. He believes that most of the bulk of the Rise is composed of basic igneous rock, both intrusive and extrusive, overlain by 6-8 km of sediments in some places.

Freeland and Dietz (1971) have presented a possible model of the geological history of the Caribbean, beginning in the Paleozic, based primarily on plate tectonic theory. A consequence of their model is that the Yucatan and Nicaraguan blocks are old cratons which, by their movement, formed the Gulf of Mexico before mid-Jurassic time.

Edgar et al., (1971) examined 30 seismic refraction profiles located on areas of complex structure. They infer from these and other geophysical data that the rise has a four-layer crustal structure, as was earlier indicated by Ewing et al., (1960). Their velocity structure, they argued are comparable with those found in normal deep-ocean basins, but the layers are considerably thicker beneath the ridges. Concluding, Edgar et al., (1971) postulate that the Caribbean is a relict of Mesozoic

Pacific crust emplaced between North and South America during separation from Europe and Africa.

Reviewing the geology of the Caribbean, Nagle (1971) contends that the northwest Caribbean area (Cayman Trough) is one of thin crust of oceanic type bordered by Cayman Ridge and Nicaraguan Rise which have crusts of continental thickness. He believes that sialic or "granitic" basement is not present in the Greater Antilles, except perhaps in western Cuba and possibly under the Cuban shelf, Cayman Ridge and Nicaraguan Rise.

Arden (1975) states that the overall shape of the Nicaraguan Rise is that of a thick, elongated crustal prism sheared off along the northern and southern flanks. He presents a crustal model in which the mantle, (velocity 8.1 km/sec), underlies a crust of thickness 22 km. Overlying the mantle, he has a crustal zone with a maximum thickness of 19.5 km and averaging 13 km in thickness. This layer, which he refers to as "Layer 3" or "oceanic layer," has seismic velocities ranging from 6.2 to 7.2 km/sec with an average value of about 6.7 km/sec. While admitting that rocks representing a long Paleozoic history exist in Central America and that the western end of the Nicaraguan Rise connects with this segment of continental crust, Arden (1975) believes that the shape and thickness of the crust of the rise indicates that it is not a continuation of these old rocks, rather its axial thicknes of 22 km and the relative thickness of the major crustal zones is closer to subcontinental than to any type of continental crust. He postulated that the Nicaraguan Rise is a continuation of the Greater Antilles arc, which originated in Jurassic time as a belt of thickened crust along the boundary of two oceanic crustal plates. This is based on the fact that Jurassic clastics containing marine fossils in Honduras indicate the existence of marine conditions in the Caribbean before the end of Jurassic time. Evidence for a pre-Jurassic Caribbean Sea has not been demonstrated.

Perfit and Heezen (1978) analyzed rocks recovered from 80 dredge stations in the Cayman Trough. Some of these dredge stations lie on the northern flank of the Nicaraguan Rise. They found that the walls of the Cayman Trough (the southern wall being part of the Nicaraguan Rise) are composed of plutonic, volcanic, sedimentary and carbonate rocks "typically found in island arcs and continental margins such as the Greater Antilles and Central America." They present a model in which the Cayman Ridge and Nicaraguan Plateau developed as a single broad island arc during the Laramide Orogeny. By late Eocene, an east-west oriented fracture zone/spreading center zone had developed between the ridge and the plateau. This is perhaps the most important work to date on the Nicaraguan Rise because it is based on a large quantity of rocks dredged along the northern escarpment of the rise.

## 5. METHOD OF INVESTIGATION

The first phase of this study examined the differences and similarities between the Nicaraguan Rise and the well known carbonate platforms - the Bahama Platform, the Yucatan Platform and the Florida Platform. During this phase, the bathymetry, gravity field, magnetic field, seismic structure and tectonic style of the rise and the other platforms mentioned above were examined with the hope of applying the principle of analogy.

The Nicaraguan Rise has a well-defined linear characteristic feature. This makes it reasonable to apply 2-dimensional geophysical modeling on the rise. Several 2-D gravity models were made using the Talwani et al., (1959) computer program. Some prominent magnetic anomalies have also been modeled. The computations are based on Talwani and Hertzler's (1964) method. For these models physical properties of rocks such as density and magnetic susceptibility were obtained from the available data or reasonable values assumed where there are no data. These models were constructed subject to the numerous constraints imposed by the independent data. Several models with varying parameters were generated. Representative models are presented in another section of this report.

## 6. PRESENTATION OF DATA

Extensive archived data, both published and unpublished have been used in this study. They include primarily marine geophysical and geological data collected between 1960 and as late as the summer of 1978.

The topographic, gravity and magnetic data presented here are mainly from continuous measurements made aboard ships of the Lamont-Doherty Geological Observatory (magnetic tape provided by the National Geophysical and Solar Terrestrial Data Center) and the Marine Science Institute of the University of Texas (R/V Ida Green cruises IG15-6, IG24-1, and IG29-4). The measurements were conducted using the instruments and processing procedures described by Ewing et al., (1960) and Shipley et al., (1978). Continuous measurements made by the following organizations (and reported in the accompanying references) have been incorporated: Scripps Institution of Oceanography Lusiad expedition (Caputo et al., 1964), the Environmental Science Services Administration (ESSA; Peter, 1971; Lattimore et al., 1971; Grim, 1970) and the U.S. Naval Oceanographic Office (J.E. Matthews, 1976). In addition, the seismic refraction results of Ewing et al., (1960) and the continuous seismic profiler (CSP) records of Ewing et al., (1960) and those obtained aboard R/V Ida Green, are presented.

It is pertinent here to comment on the quality of these data. As would be expected, the quality of the data varies to some degree owing to the fact that their acquisition spanned over a period of about 18 years. It ranges from fair to very good. The very early data may have had large navigational errors. The recent data are the best because navigational control by satellite has helped greatly to locate precisely the position of a ship at any point in time. Furthermore, ship-borne geophysical instrumentation has become more reliable, accurate and sophisticated in the last decade.

A careful examination of the geophysical data revealed that while the bathymetric data agreed very well, there was a significant but consistent difference between the magnetic data collected on board the R/V Ida Green of the University of Texas on the one hand, and those of the R/V Vema and Conrad of Columbia University (see Table I). This is attributable, in part, to the scheme applied in deriving the residuals. A similar feature is observed in the composite magnetic map of the Caribbean prepared by Matthews (1976). There are sudden jumps of as much as 200 gammas in magentic contours as one moves from an area surveyed by one investigator to another.

The data presented here include topography, magnetics and gravity profiles. Sections of a recent continuous seismic profile record is also presented. Results of the seismic refraction surveys published so far on the rise are summarized in Table 2.

In Fig. 5-9 are plotted bathymetry (D, in fathoms), free air gravity (G, in mgals) and residual magnetic anomalies (M in gammas) all against distance (in nautical miles for Fig. 5, 6 and 7; kilometers for Fig. 8 and 9). The respective cruises are indicated in bold letters. Bathymetric profile is generally on top in the figures and is the lightest of the three curves. The gravity profile

TABLE 1

DIFFERENCES IN MAGNETIC MEASUREMENT AT INTERSECTIONS OF CRUISES

| Location | | Cruises | Magnetic anomalies in gammas | Difference |
|---|---|---|---|---|
| 16.74°N | 81.11°W | IG15-6/C1012 | 631/-145 | 776 |
| 16.55°N | 80.90°W | IG15-6/IG24-1 | 579/557 | 22 |
| 16.32°N | 80.90°W | IG24-1/C1012 | 521/-101 | 622 |
| 15.30°N | 80.81°W | IG24-1/C1012 | 654/-158 | 812 |
| 15.31°N | 77.94°W | IG29-4/V2402 | 695/-108 | 803 |
| 14.31°N | 77.55°W | IG15-6/V2402 | 811/-76 | 887 |

Table 2

SUMMARY OF SEISMIC REFRACTION RESULTS

| Profile | | Location | | Velocity (km/sec) | | | | | Thickness (km) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | U.S. | A | B | C | D | WATER | U.S. | A | B | C | D |
| 19 | S | 14°43'N | 78°14'W | (1.7) | 4.4 | 6.3 | | | 1.95 | 0.77 | 1.8 | | | |
| | N | 15°01'N | 78°29'W | | | | | | 2.22 | 0.69 | 3.2 | | | |
| 20 | S | 16°14'N | 79°15'W | 2.0 | 4.8 | 5.5 | 6.7 | | 1.39 | 1.0 | 3.2 | 4.5 | | |
| | N | 17°01'N | 79°36'W | | | | | | 1.39 | 1.0 | 0.93 | 2.6 | | |
| 21 | E | 17°33'N | 79°05'W | 1.8* | 3.9 | 5.2 | 6.2 | 7.6 | 0.86 | 0.59 | 2.3 | 3.3 | 12 | |
| | W | 17°31'N | 80°04'W | | | | | | 1.92 | 0.76 | 1.7 | 2.1 | 14 | |
| 35 | NW | 18°17'N | 75°14'W | 2.2* | 3.4 | (5.4) | 6.5 | 8.2 | .90 | 0.70 | 1.4 | 4.7 | 15 | |
| | SE | 17°16'N | 74°20'W | | | | | | 2.89 | 0.88 | 2.1 | 1.3 | 14 | |

Note: Assumed velocities indicated by asterisks, unreversed velocities by parenthesis.
Source: Ewing et al., (1960).

(thicker curve) runs generally in the middle while the magnetic profile (thickest curve) occupies the lower third of each figure. In Fig. 5 to Fig. 7 the vertical scales have been arranged such that magnetic scale is on the inside, gravity scale in the middle and the bathymetric scale on the outside. A more detailed description of this method of presentation is given by Talwani et al., (1974).

### a. Topographic Data

The profiles presented her show clearly the rough topography of the rise as compared to the Colombian Basin. The sudden drop in elevation from the rise into the Cayman Trough is well illustrated in Figs. 5-9 whereas the rise descends into the deep Colombian Basin in a series of steps. The rise is characterized by a principal crest to the north and a second local crest to the southeast with a saddle centered around the Pedro Bank Fracture zone between these crests. Many anomalous topographic features which appear to be intrusives exist on the rise. Notable depressions include the Pedro Trough southwest of Jamaica and the graben trending northsouth near longitude 81.6° west. The latter is about 2.4 km deep. There are some areas with fairly flat tops - a feature that is characteristic of carbonate banks. These flat-topped areas of the rise, however, are not as shallow as the other banks, for example the Yucatan platform.

### b. Gravity Data

The gravity field of the Nicaraguan Rise was discussed by Case (1975), Arden (1969, 1975), and Bowin (1968, 1976). A free-air anomaly map (Fig. 3) and a Bouger anomaly map

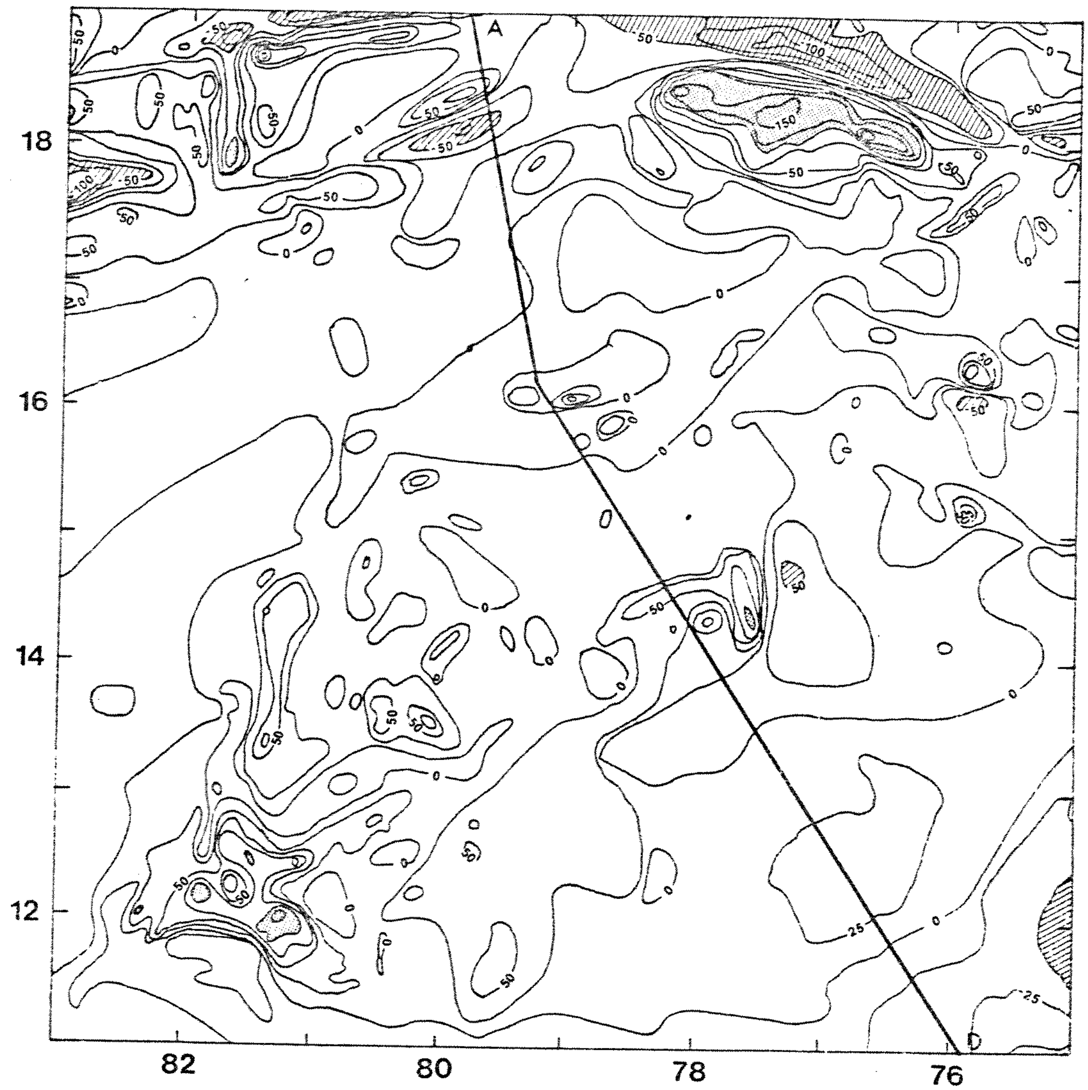



Fig. 3 Free-air gravity anomaly map of the Nicaraguan Rise (after Bowin, 1976). Contour interval 50 mgal. Areas of maximum and minimum gravities are dotted and striped respectively. A cross-section along A-D is modeled in Fig. 18.

(Fig. 4) were produced by Bowin (1976) from the available gravity data. The sources and methods of collection of these data are extensively discussed by Bowin in the text accompanying the map (1976). The high quality of the data gives one some measure of confidence despite the paucity of measurements.

Free-Air Anomaly:

The Free-air anomalies over the Nicaraguan Rise range from -50 to +50 mgal, with values rising to slightly over +100 mgal on the island of Jamaica. More than two-thirds of the area have free-air gravity values ranging from 0 to +50 mgal. The areas of 0 to +50 mgal include the entire coastal area of Honduras and Nicaragua and the crestal zone of the rise stretching from the northeast corner of Nicaragua towards the island of Jamaica. Another band of positive free-air anomaly closely parallels the southwest-northeast trending physiographic boundary between the Nicaraguan Rise and the deep Colombian Basin.

Negative free-air gravity anomalies varying from -50 to 0 mgal are concentrated in the northeast corner of the Rise. These include (i) a segment to the southwest of Jamaica trending parallel to the Cayman Trough, (ii) a segment to the south of Jamaica concentrated in the Pedro Trough, and (iii) a southwest-northeast trending band which appears to be centered over the Pedro Fracture Zone. Other isolated highs and lows are scattered ove the Rise especially to the southeast. These appear to be associated with the numerous seamounts and volcanic islands which have been mapped in this region (Case and Holcombe, 1977;

Christofferson and Hamil, 1978). The tongue of negative free-air anomaly trending north along longitude 80$^{o}$W is centered over a graben recently mapped (Christofferson, person. comm. 1980). The free-air anomalies measured in Jamaica appear very similar to those observed in both Hispaniola and southeast Cuba. The free-air anomaly pattern is fairly unusual in the northeast corner of the Rise where positive values have been observed over deeper waters. This may be the effect of shallower Moho, the lack of sediment cover, or a combination of all of the above.

The gravity profiles shown in Figs. 5 to 7 indicate that most of the prominent peaks and troughs are related to anomalous topographic features. For example, the +130 mgals free-air anomaly located near latitude 12.4$^{o}$N, longitude 81.1$^{o}$W (Fig. 5) is attributable to the corresponding anomalous topographic feature at the same location.

Bouguer gravity anomaly:

The Bouguer gravity field of the Nicaraguan Rise appears fairly simple. Low but positive values of 0 to +50 mgal cover the entire northeast section of Honduras and Nicaragua extending offshore to about 350 km in the northeast and 160 km to the east. From the west, the Bouguer anomaly values become more positive in all the other three direction, rising rapidly to cover +300 mgal in the Cayman Trough to the northwest. They increase more gradually to over +200 mgal in the Colombian Basin in the southeast. In the northeast, a broad region of +50 to +100 mgal extends beyond the island of Jamaica. This zone is punctuated by an almost circular patch of +0 to +50 mgal

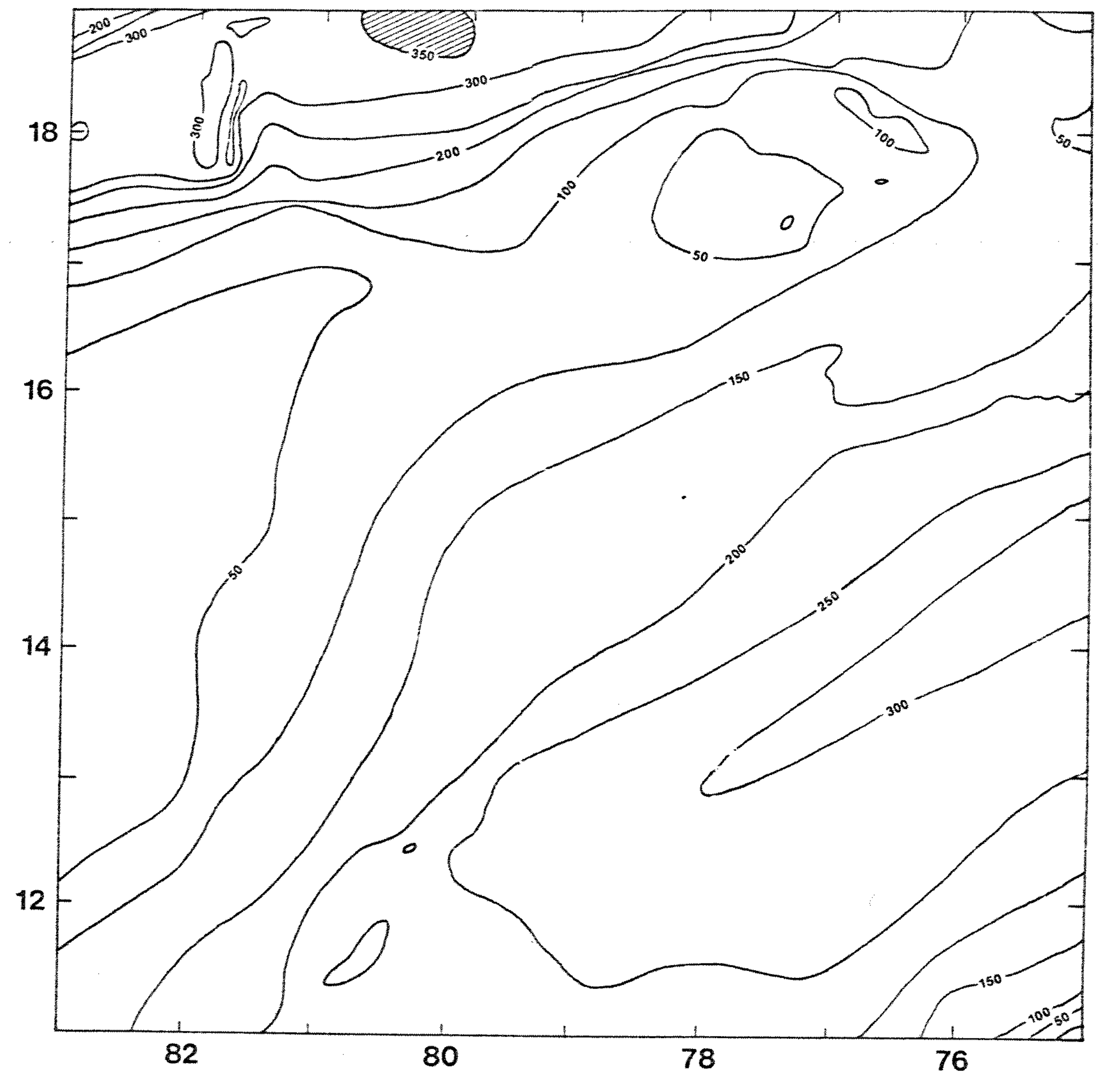



Fig. 4 Bouguer gravity anomaly map of the Nicaraguan Rise (after Bowin, 1976). Contour interval 50 mgal. Area of maximum Bouguer anomaly is striped.

centered over Pedro Trough to the south of Jamaica. Besides the northeast and northwest sections of Jamaica, the +50 to +100 mgal band encloses the island. The Bouguer anomalies over the rise are generally more negative than the surrounding Colombian Basin and Cayman Trough by about 200-300 mgal. Case (1975) has suggested that this may be the effect of differences in water depth. (The Bouguer effect of a 3.0 km slab is 207 mgal (density = 2.67 $gm/cm^3$) and the adjoining basins are about 3.0 km deeper than the Nicaraguan Rise). However, Bouguer anomalies are used to estimate depth to Moho, and a 200-300 mgal difference means the Moho is about 12-18 km deeper beneath the rise.

The free-air and Bouguer gravity anomalies suggest that (i) the Nicaraguan Rise is a piece of crust wedged in between the deep Cayman Trough and Colombian Basin; (ii) the structure more than anything else appears two-dimensional with its axis trending northeast, (iii) the continental crust beneath the coast of the northeast corner of Nicaragua and Honduras probably extends far into the Nicaraguan Rise in a more or less north-easterly direction and (iv) the island of Jamaica does not appear to be underlain by the same crust that underlies the rest of the Nicaraguan Rise, rather by a crust similar to that beneath Hispaniola and southeast Cuba.

### c. Magnetic Data

The Nicaraguan Rise is generally magnetically quiet and is characterized by apparently non-linear anomalies that appear to correlate with some irregular topographic

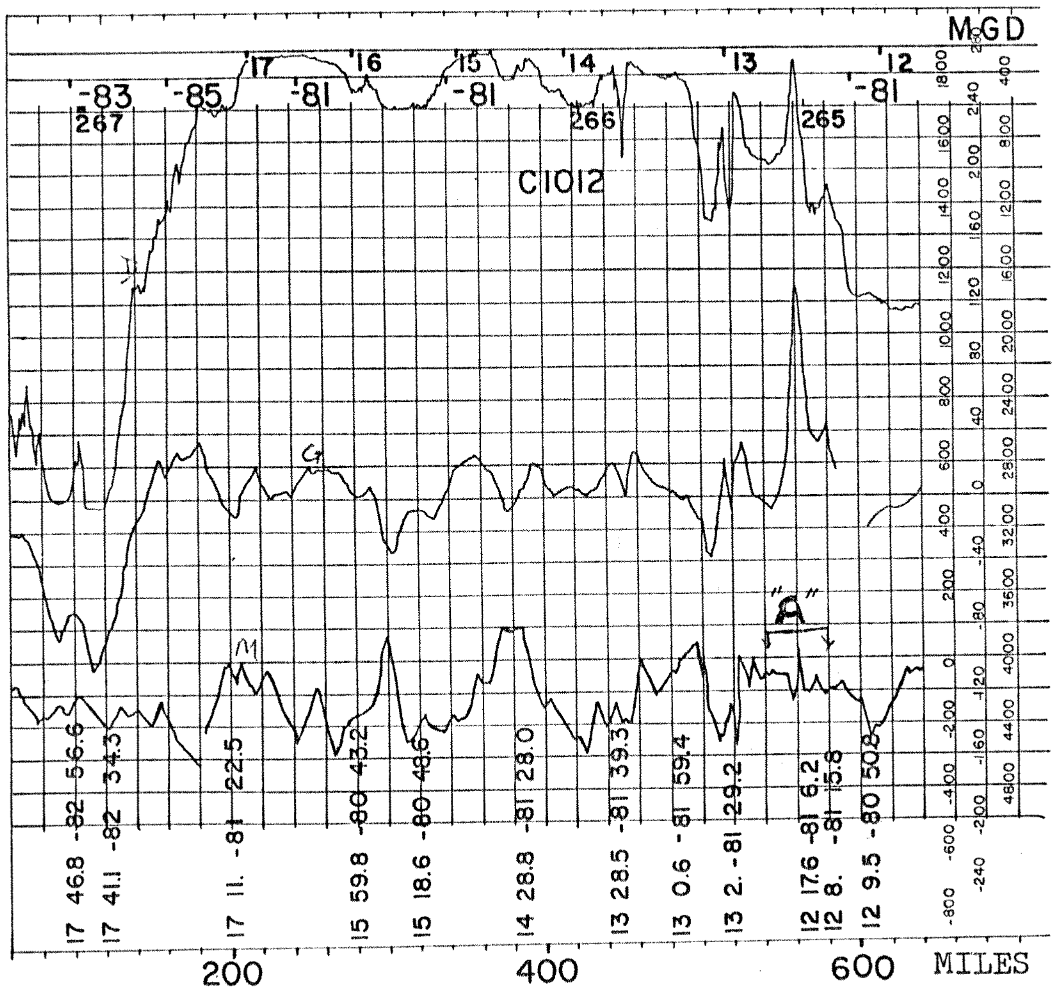



Fig. 5 Bathymetric, gravity and magnetic profiles along track C1012 across the Nicaraguan Rise. Magnetic anomaly "A" is shown.

highs and lows. The complexity of the magnetic field over this area certainly reflects the structural variability of the underlying crust. The magnetic map of the Caribbean (Matthews, 1976), based on data collected by several investigators, has been of limited use. There are sudden jumps in isochrons as one moves from an area surveyed by one investigator to that of another.

All magnetic data collected on several research cruises in the Caribbean indicate that generally the anomalies average about 300 gammas, peak to trough, except some scattered unusually large anomalies, few of which appear related to anomalous topographic features. Five magnetic profiles, (Figs. 5, 6, 7, 8 & 9), widely spaced across the Nicaraguan Rise, are representative of the magnetic field. In Fig. 5 (C1012) the smooth simple magnetic field over the Colombian Basin becomes disturbed as one moves across to the Nicaraguan Rise. Though most of the magnetic highs and lows appear to be related to some topographic anomalies, the magnitudes of some of these magnetic anomalies are not proportional to the corresponding anomalous topographic feature. For example, a pronounced topographic feature centered near $12^{\circ}20'$N, $81^{\circ}6'$W, ("A" in Fig. 5) with a relatively large gravity anomaly (+130 mgal) appears to correlate with a smaller magnetic anomaly than does a less pronounced feature at $12^{\circ}58'$N, $81^{\circ}20'$W (just next to "A"). Similar cases exist on the other profiles. In fact, some positive anomalous topographic features do correlate with very large negative magnetic anomalies (anomaly B, Fig. 7). Some of these anomalies will be re-examined later. In Figs. 8 and 9, taken from recent

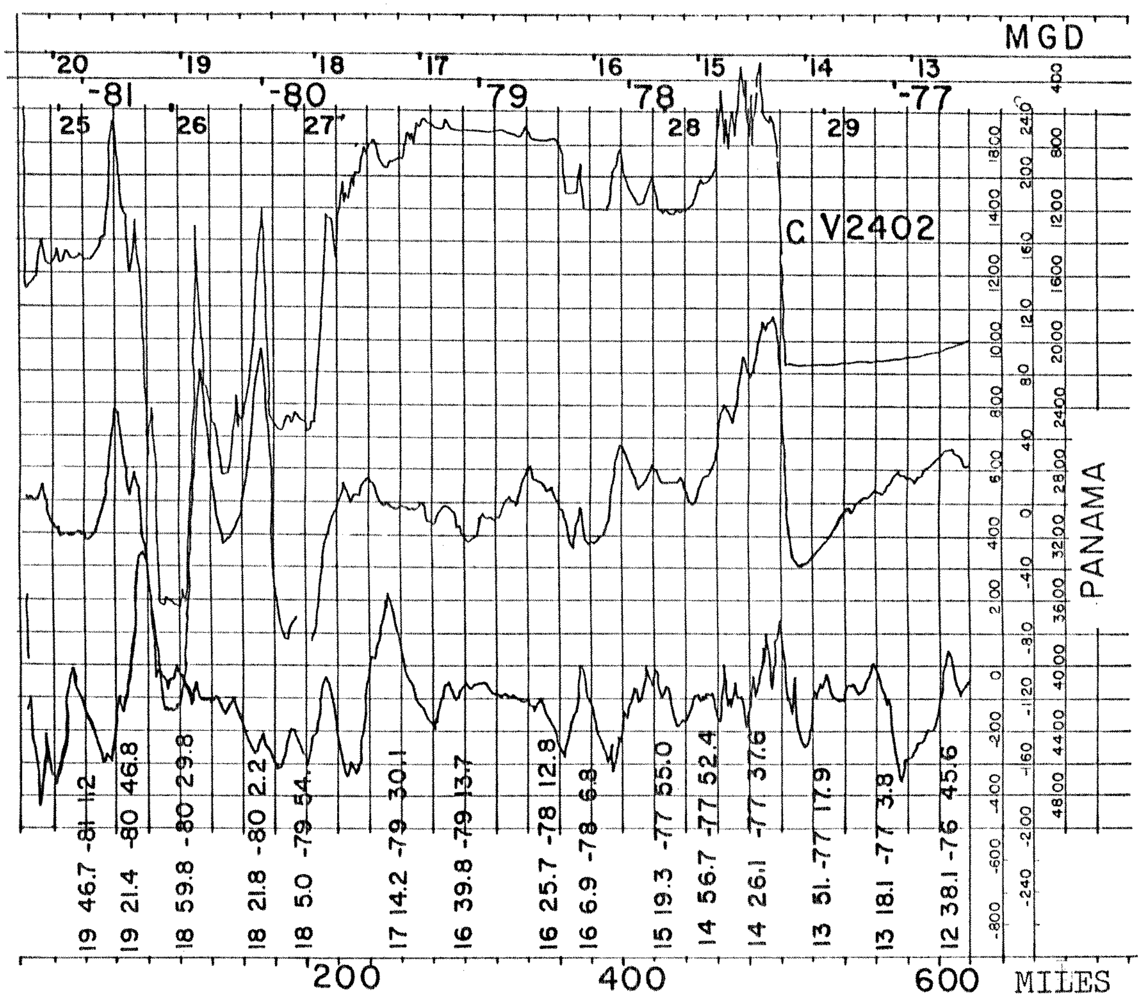



Fig. 6 Bathymetric, gravity and magnetic profiles along track V2402 across the Nicaraguan Rise.

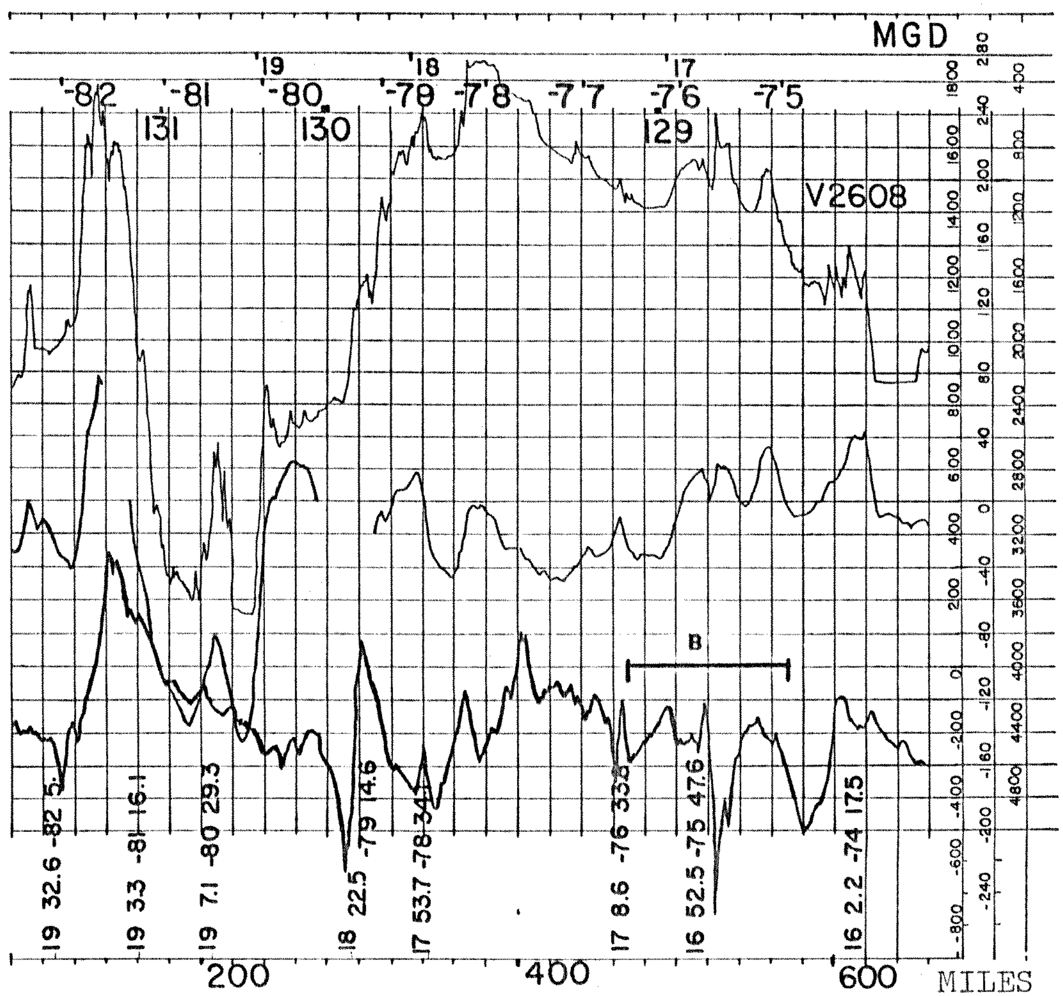



Fig. 7 Bathymetric, gravity and magnetic profiles along track V2608 across the Nicaraguan Rise. Magnetic anomaly "B" is shown.

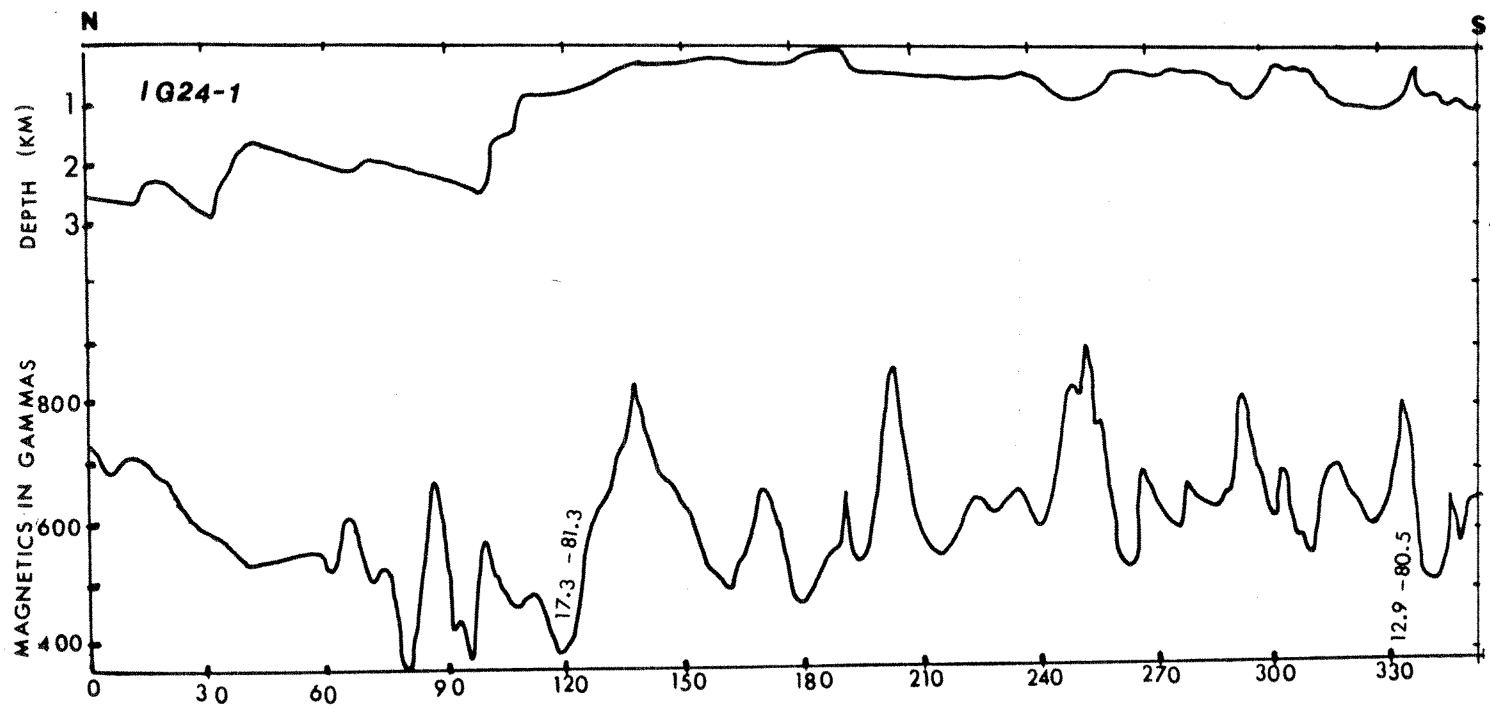



Fig. 8 Bathymetric and magnetic profiles along track IG24-1 across the Nicaraguan Rise.

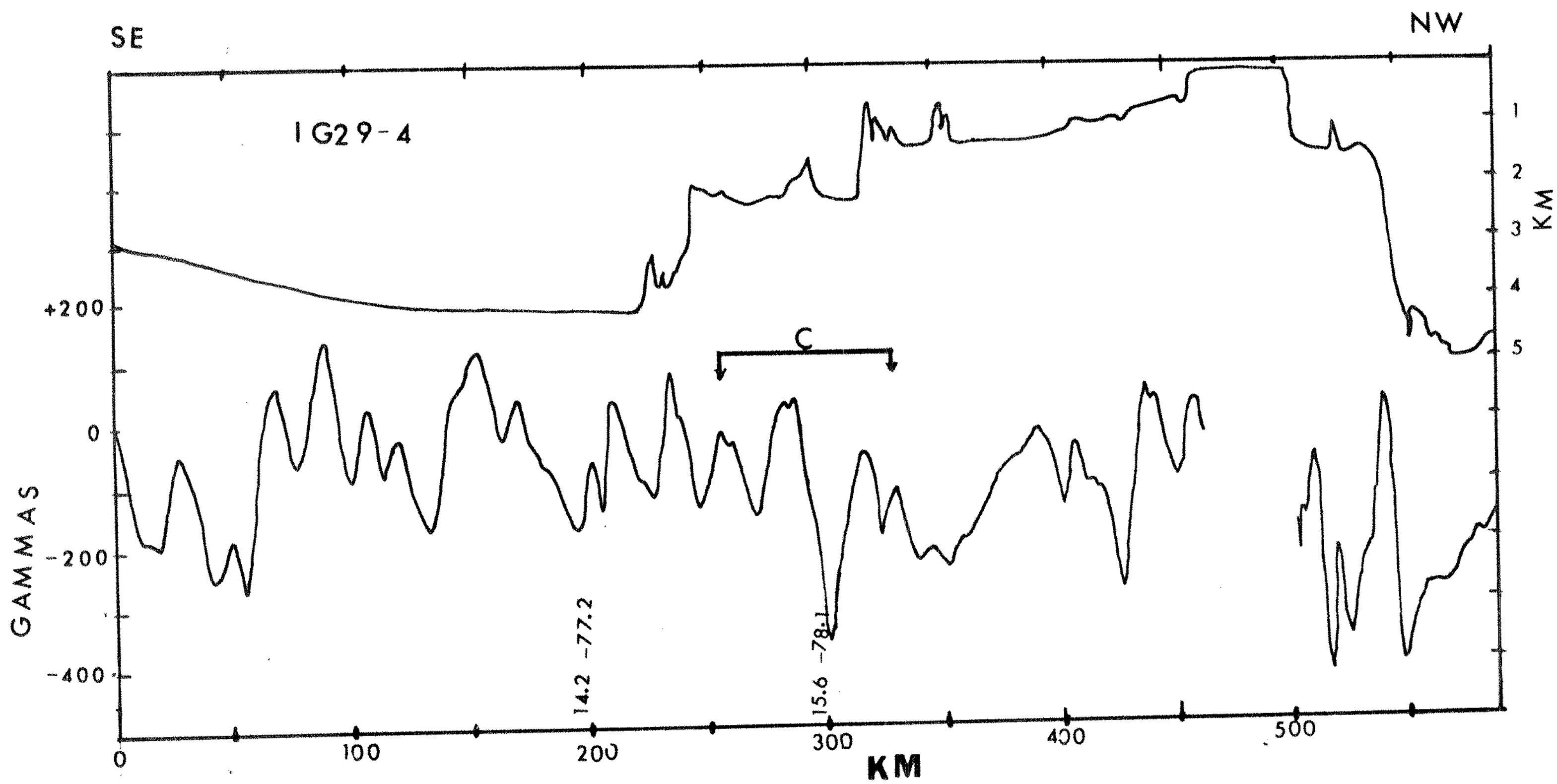



Fig. 9 Bathymetric and magnetic profiles along track IG29-4 across the Nicaraguan Rise. Magnetic anomaly "C" is shown.

Ida Green cruises, the general characteristics of the magnetic anomalies are still the same as those in Figs. 5, 6 and 7, even though absolute values of the anomalies differ as explained earlier. The extremely rough nature of the magnetic field over the rise coupled with the paucity of the data available to date can only permit a generalized interpretation. A more detailed and definitive interpretation must await further detailed survey.

### d. Seismic Data

Ewing et al., (1960) made several seismic refraction profiles in the Caribbean Sea. Three of their profiles (19, 20 and 21, Fig. 10) are situated on the Rise. Other profiles, such as (23, 32, 35, 36 & 85), shot during the same survey, are located somewhat on the periphery of the rise. This second group of profiles has not been used in this study because they are shot in a highly disturbed marginal zone which may not be typical of the rise.

The result of these seismic surveys are summarized in Table 2. They all support a four-layer crustal model with a maximum thickness of 22-25 km. The mantle is overlain by a 6.2-6.8 km/sec main crustal layer. Thickness of this is variable but does not exceed a maximum of 19.5 km (Arden, 1975). Above this is the upper crustal layer with seismic velocity of 5.1-5.8 km/sec. Its maximum thickness of 4.5 km is reached beneath the region between the two crestal zones. Above this there are two layers with a high variability of velocity and thickness. Velocity in the lower zone varies from 3.4 km/sec to 4.8 km/sec while the top layer has velocity ranging from 1.7 km/sec to 2.2 km/sec.

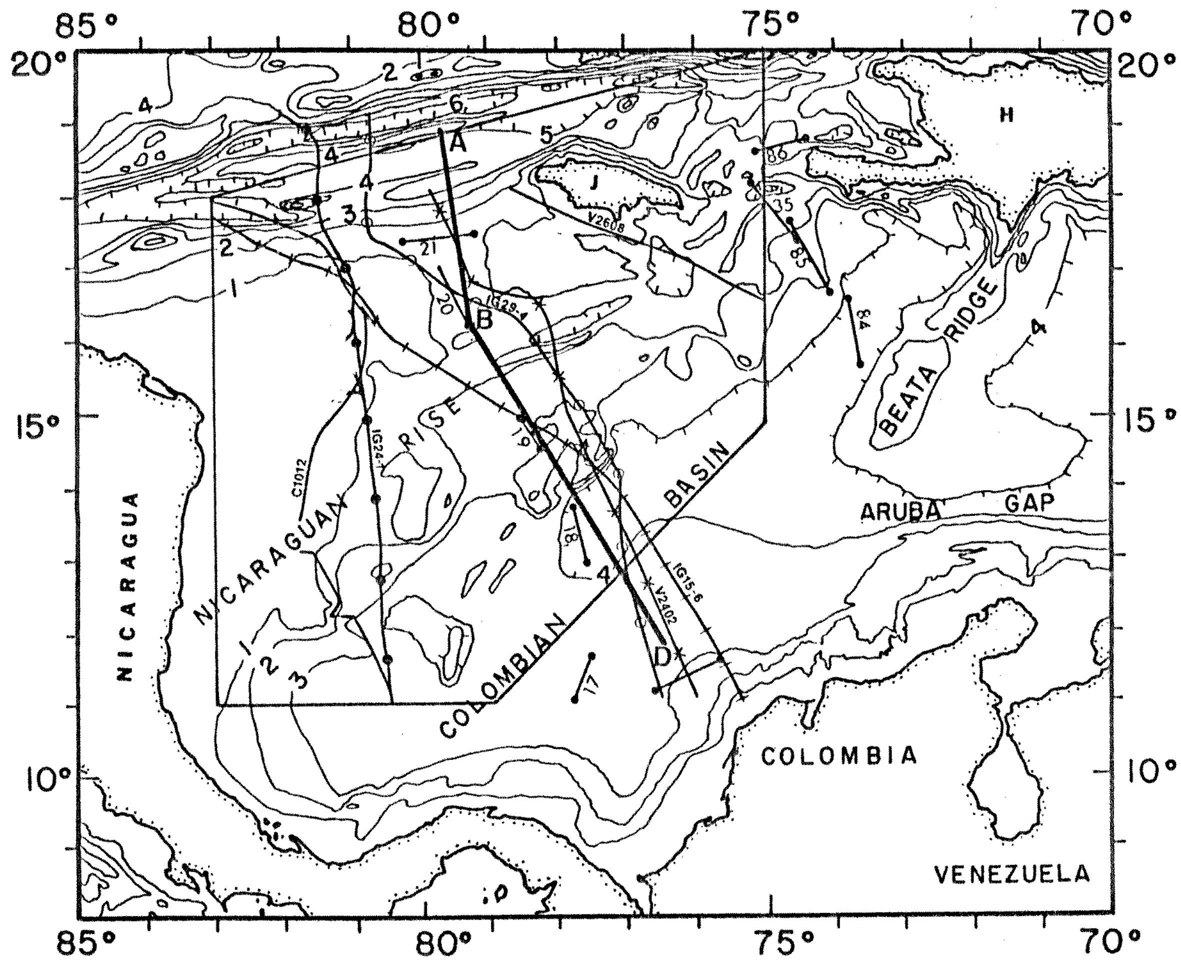



Fig. 10 Map of the Caribbean showing the seismic refraction profiles. Six important ship tracks are shown and the section (A-D) modeled in Fig. 18 is indicated.

Edgar et al., (1971, Fig. 9, p. 844) tried to compare various provinces of the Caribbean with standard ocean basin. Their figure (Fig. 11a) gives the impression that the "average" Nicaraguan Rise is more than 3.0 km deep and that the Rise and Beata Ridge have identical velocity structure. Fig. 11b shows what we consider an "average" velocity structure of the Nicaraguan Rise based on the available seismic data. The rise is much shallower, average velocities slightly different, and depths to interface significantly different than normal ocean. Figure 11b also shows clearly the differences between the structure beneath the rise proper and the region east of the island of Jamaica.

Sections across the rise show that the underlying crust is arched upwards in two zones - in the northwest and southeast - with a great depression between these bulges (Ewing et al., 1960; Edgar et al., 1971; Arden, 1969, 1975). Figures 12 and 13 show segments of a continuous profiler record obtained on a recent cruise (R/V Ida Green, IG 29-4) across the rise. The profile extends in a southeast-northwest direction across a portion of the Colombian Basin, the Nicaraguan Rise and the Cayman Trough. The abyssal plain surface in the southeast is fiarly flat with a slight slope towards the rise. An irregular reflecting surface, a major unconformity in the section, dips southeast beneath the abyssal plain. This interface can be traced to a short distance from the southeast end of the section where it disappears beneath thick sediment cover. This same reflecting horizon continues as the surface of the south flank of the Nicaraguan Rise. The slope of the rise here is devoid of sediments. But

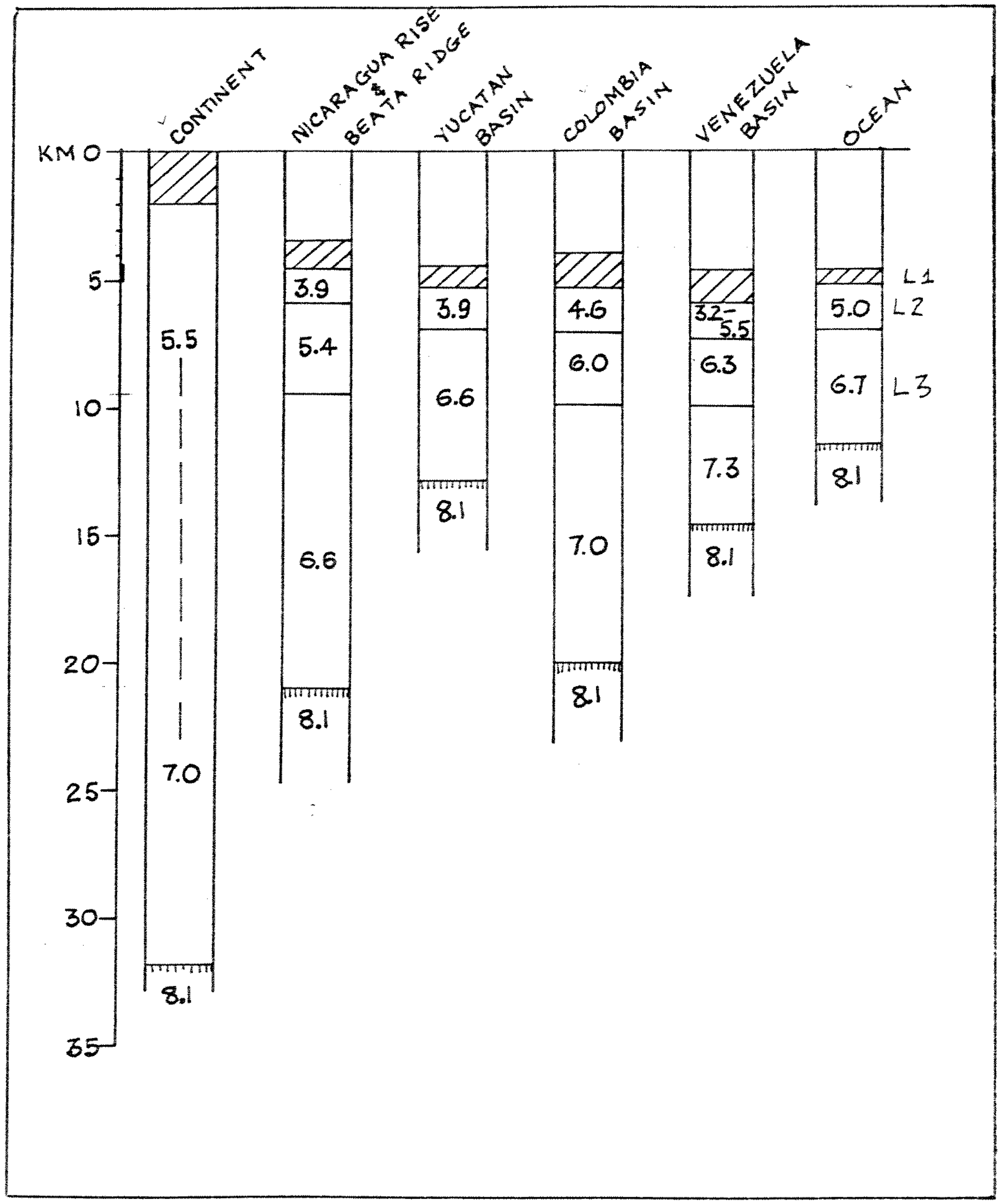



Fig. 11a Comparison of velocity structure in the Caribbean by Edgar et al. (1971).

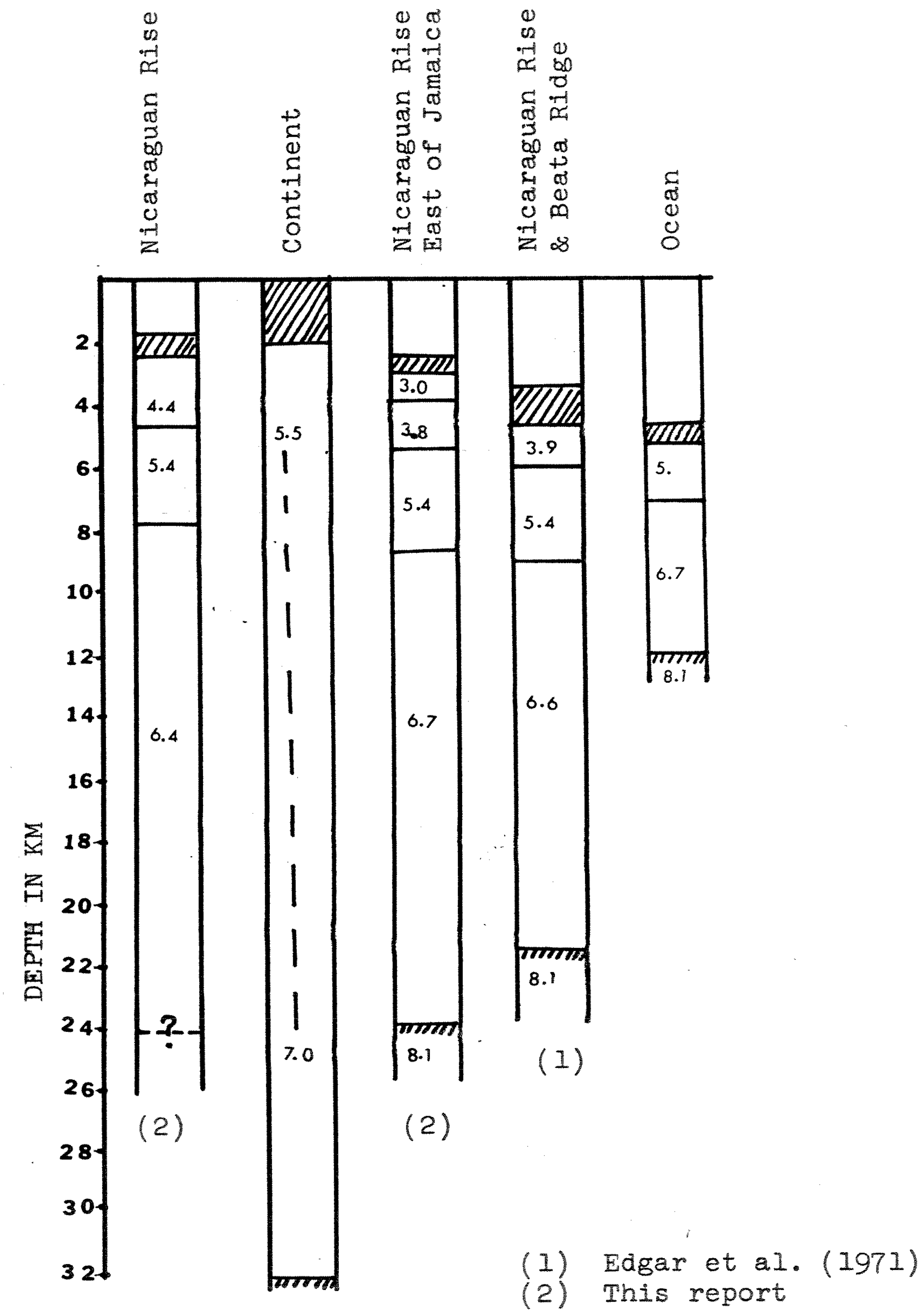



Fig. 11b Comparison of Edgar's result and my interpretation based on Ewing et al. (1960) data.

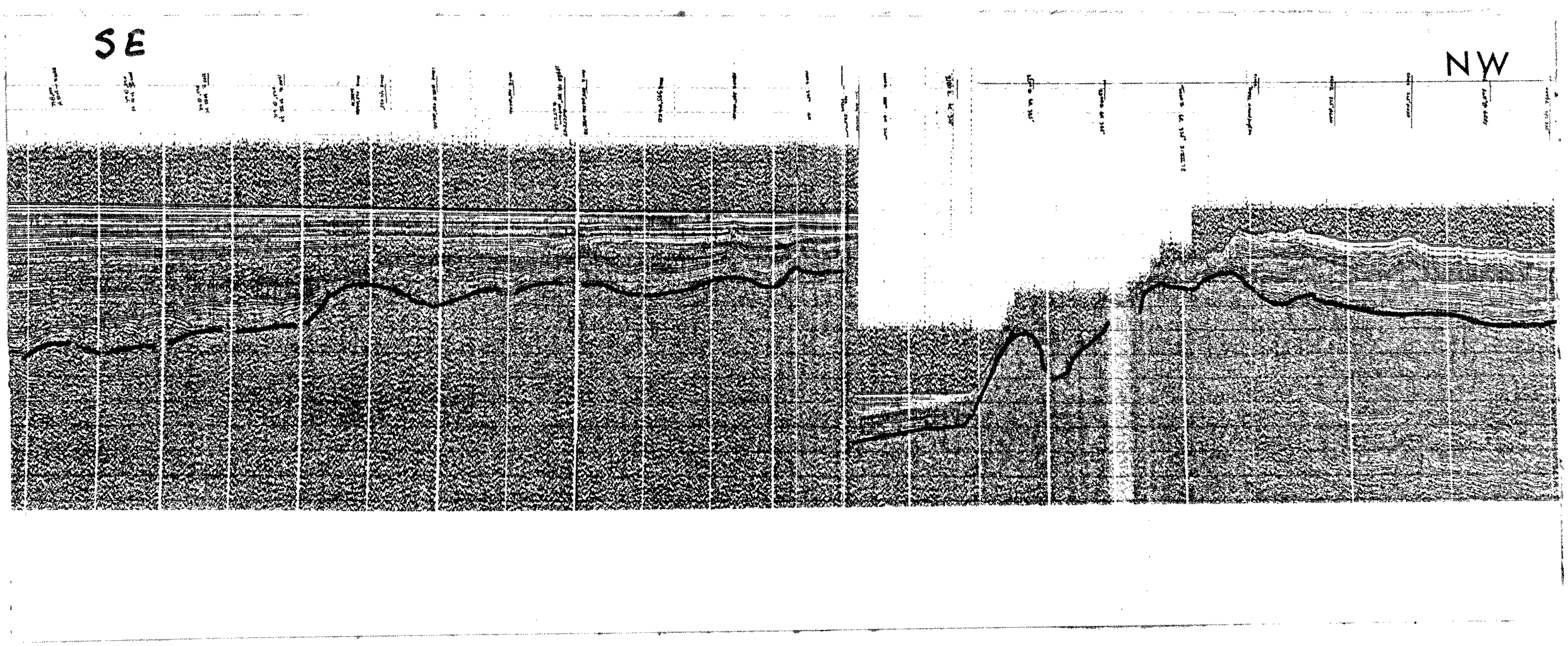



Fig. 12 Seismic profiler record across the southeast of Nicaraguan Rise along track IG 29-4. The prominent interface believed to be top of basement is marked.

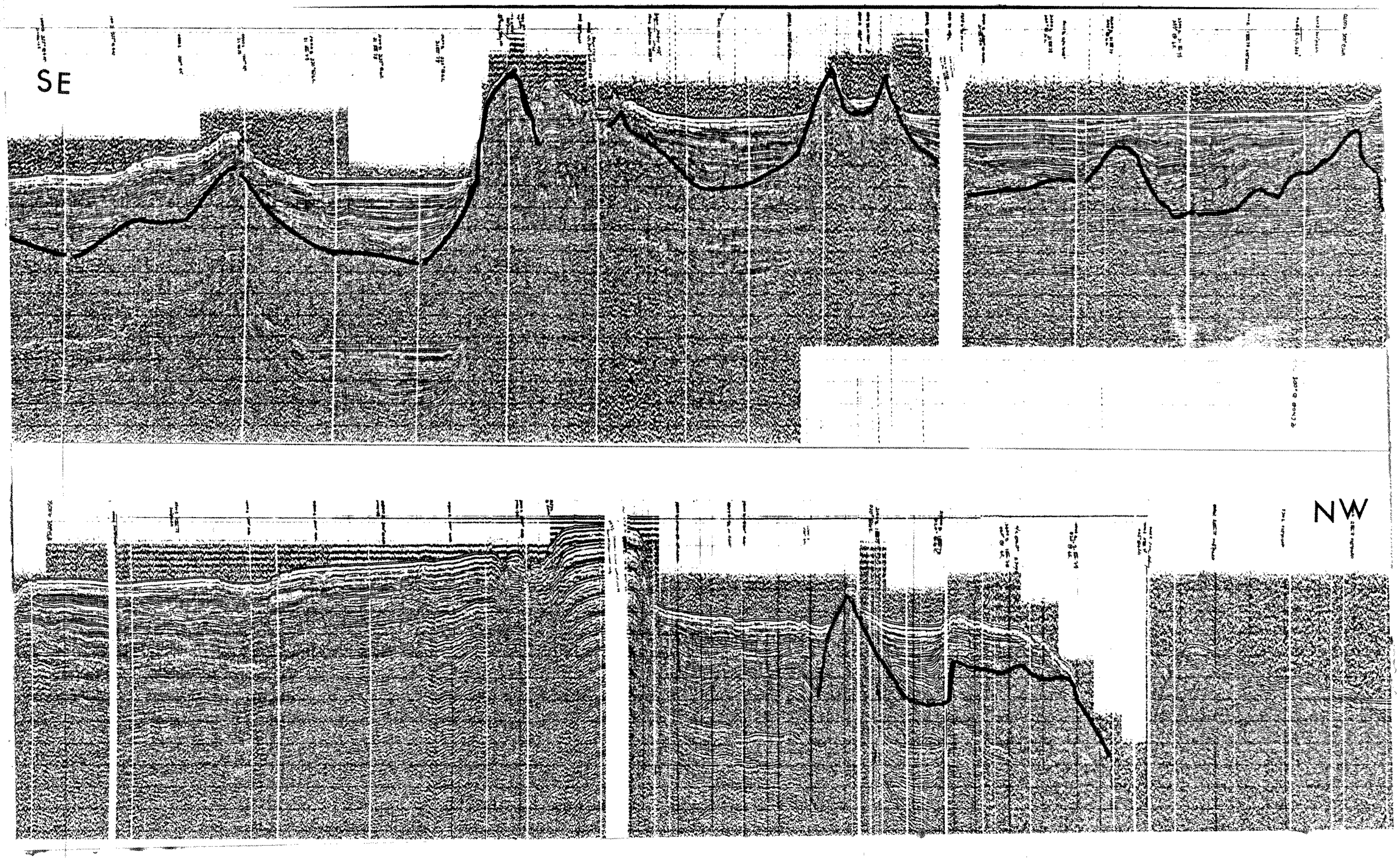



Fig. 13 Seismic reflection record across the northwest section of the Nicaraguan Rise along track IG 29-4. Interface marked is believed to be basement.

for a few sections, the reflecting surface appears to be traceable all through this section of the Nicaraguan Rise. At some locations, thick sedimentary layers can be observed above this interface, but at other locations it forms a rugged surface of the rise with no apparent sediments beneath it. The sediments trapped between the highs of this unconformity tend to form perched plains. This same interface has been observed by other investigators (Rezak et al., 1972; Case, 1975). The nature of this reflector is not known but its surface is rough, and compares well with a similar interface identified as basement in the adjacent Colombian Basin by Houtz et al., (1977). The prominent reflectors A" and B" do not appear in these sections nor those of Rezak et al., (1972). The seismic reflection record in Fig. 14 is taken across the southwest section of the rise along track C1012. The sedimentary layer with varying thickness is clearly delineated in this figure. The zone of the magnetic anomaly, "A" discussed above and modeled in another section of this report is shown. The irregular reflecting surface again manifests itself here.

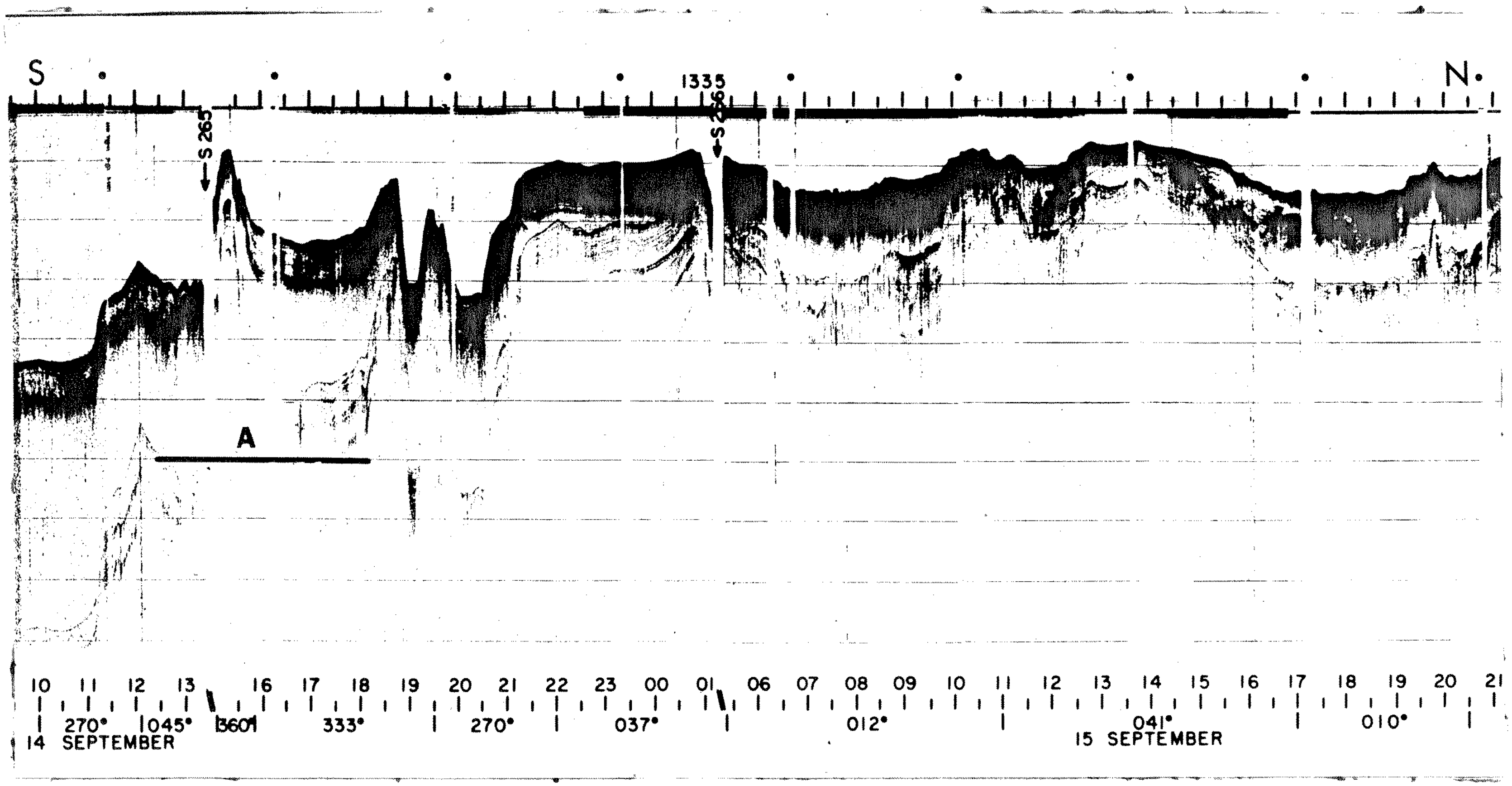



Fig. 14 Seismic reflection record across southwest of Nicaraguan Rise along track C1012. Zone of magnetic anomaly "A" is shown.

# 7. GEOPHYSICAL MODELING

## a. Magnetic Models.

One of the major questions yet unresolved on the Nicaraguan Rise is the origin of the magnetic anomalies. Are they due to geomagnetic field reversals, characteristic of the ocean floors or are they due to shallow-seated variations in magnetic susceptibility due to (1) volcanic or near-surface intrusive activity and/or (2) shallow structural irregularities in a material with relatively high susceptibility?

To investigate this, three interesting and prominent anomalies were selected from the profiles for detailed study and modeling. These are marked A, B and C in Fig. 5, 7 and 9 respectively. Anomaly A (Fig. 5) located near 12°20'N, 81°6'W, is rather small in relation to both the topographic and gravity anomalies to which it is related. The seismic profiler record and the gravity anomaly at the same location indicate that this anomalous topographic feature may be (1) an intrusion of a dense material, (2) a surfacing of basement or (3) a volcanic eruption. The magnetic anomaly here has a steep gradient of about 33 gammas/km (1 gamma = $10^{-5}$ oersteds).

Simple magnetic models of anomaly A were made (Figs. 15a and 15b. A basic assumption of the modeling exercise is that the body causing the magnetic anomaly in each case is uniformly magnetized. The body is also assumed to be two-dimensional. The computations are based on the method of Talwani and Heirtzler (1964). Both cases of induced and remanent magnetization (NRM) with both normal and

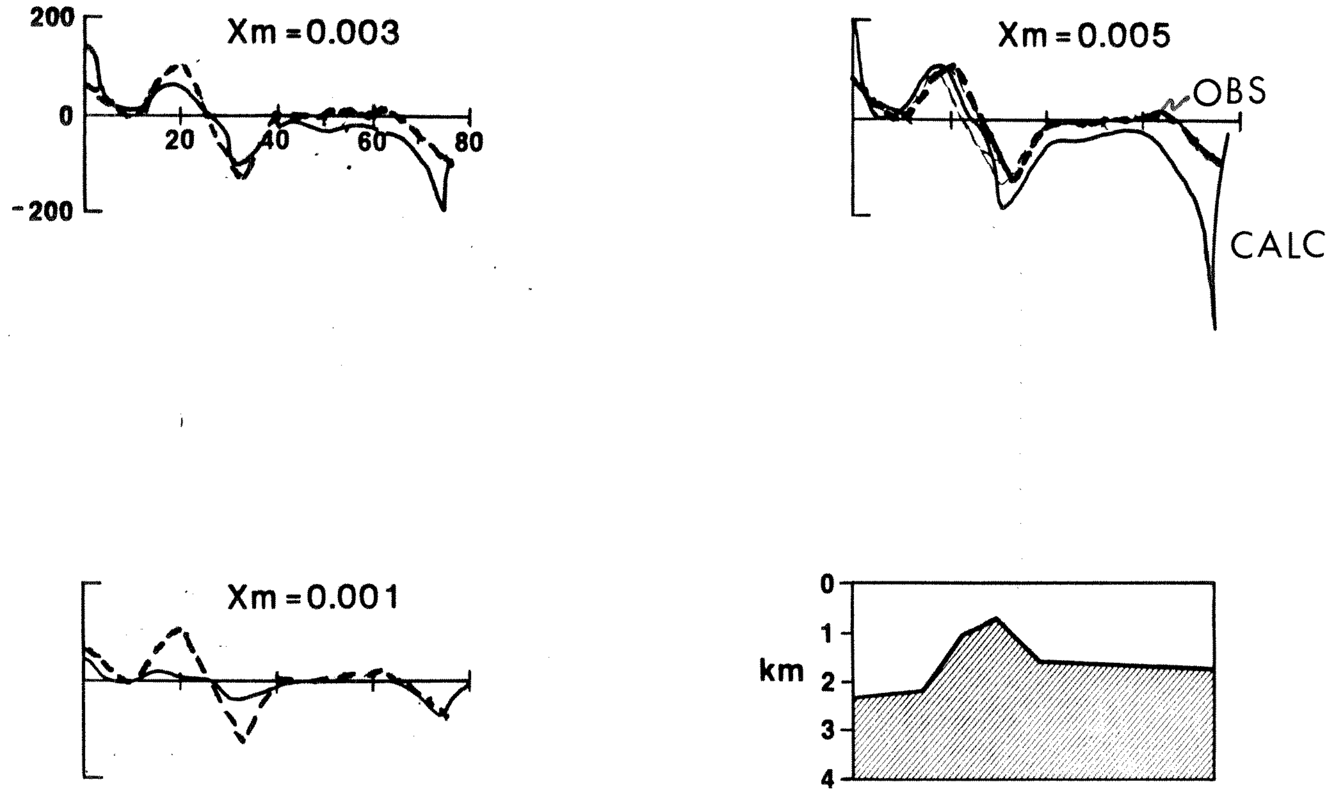



Fig. 15a Simple magnetic model of anomaly "A": induced magnetization case. Susceptibility (X m) is varied as shown while the geometry is assumed constant.

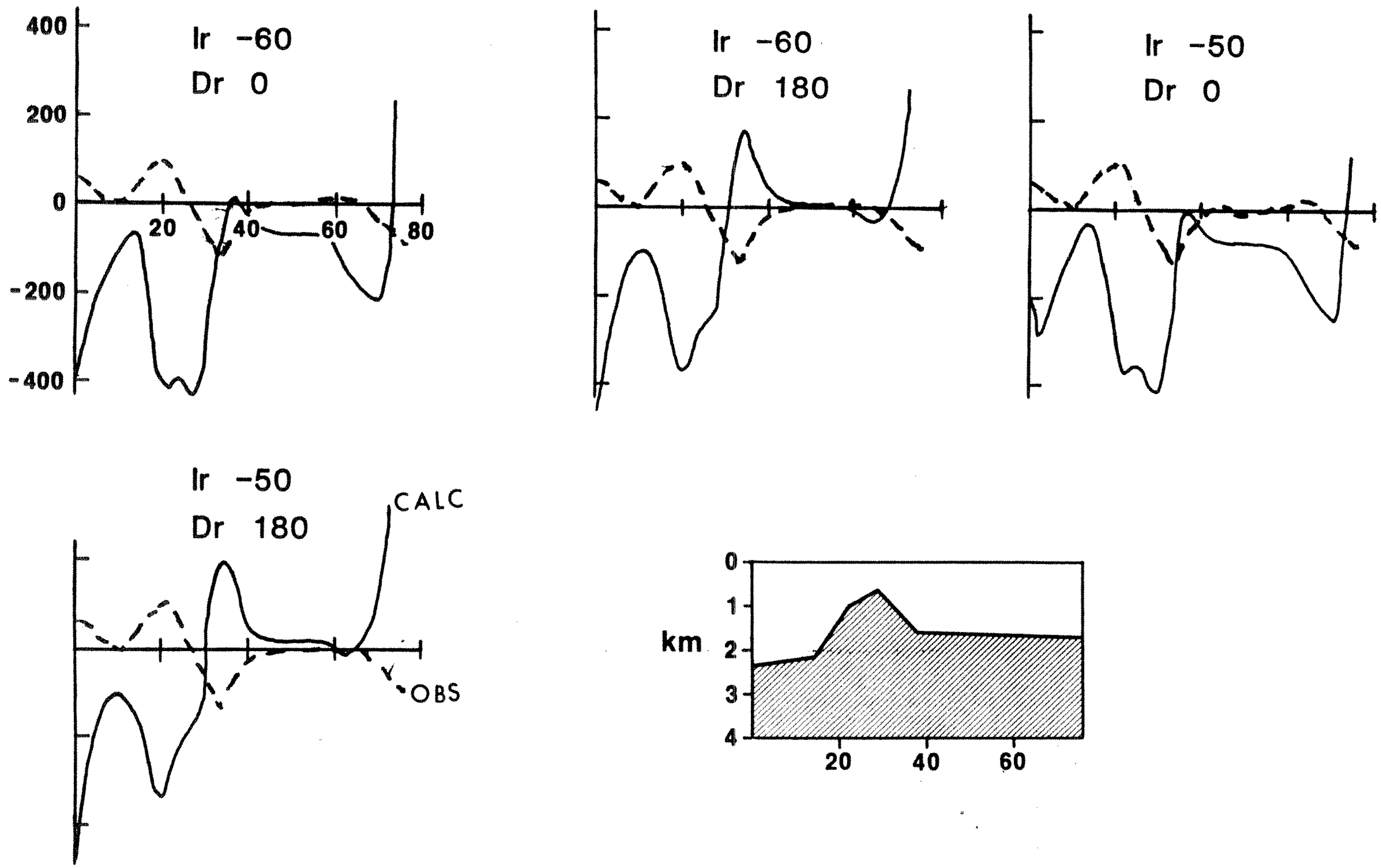



Fig. 15b Magnetic model of anomaly A: RNM. Declination ($D_r$) and Inclination ($I_r$) varying as shown.

reversed fields were examined. For each anomaly, the effect of varying parameters such as susceptibility, inclination, declination and thickness of the causative body, was examined. In Figs. 15a and 15b, we assumed that the anomaly is due principally to the magnetization of the top 2 km of the crust beneath the sediment layer as revealed by the seismic profiler record. The geometry of the anomalous body was kept very simple while its magnetic susceptibility was varied. In Fig. 15a, we assume the anomaly is induced, and show models for several values of susceptibility, $X_m$. The present geomagnetic field at this location was assumed to be 43,000 gammas and the dip $30^o$. Fig. 15b shows the case of remanent magnetization. Here again, the bulk of the anomaly is believed to be caused by the top 2 km of the crust beneath the sedimentary cover. The present geomagnetic field is the same as described above. The strength of magnetization of the body was set constant at 0.005 e.m.u./$cm^3$, while the other parameters, dip and declination, were varied as shown on the diagram.

We do not expect magnetic modeling to yield unique solution to the observed anomalies. However for any given causative body, it can be employed to eliminate a great number of solutions that are not compatible with the observed data. It is evident here that the simple model in Fig. 15a does reproduce the gross character of anomaly A especially when the susceptibility is about 0.005 e.m.u.

Anomaly B (Fig. 7) which has a range of about 750 gammas is the largest anomaly observed on any of the profiles presented here. The minimum value of -780 gammas is centered around 16.8$^{\circ}$N, 75.6$^{\circ}$W. The anomaly has steep gradient on both sides with one oscillation on the left shoulder. Figs. 16a and 16b show the simple two-dimensional magnetic model of this anomaly. Here again it was assumed that the magnetism resides in the top 2 km beneath the sedimentary cover of the crust. The geometry of the causative body presented was based on information obtained from the seismic profiler record.

Results of the computations here indicate that induced magnetism alone cannot produce anomalies of the same magnitude as observed here, given the magnetic properties of prevailing rocks in the area (Edgar et al., 1973). The remanent magnetization models (Fig. 16b) however, do reproduce the general character of the anomaly. The effect of varying the parameters of the magnetization vector is illustrated in Fig. 16b. The best fit is obtained for $I_r = -30^{\circ}$ and $D_r = 0^{\circ}$.

Anomaly C, centered around 15.6$^{\circ}$N, 78.1$^{\circ}$W, is one of the anomalies that appear very large in relation to the topographic anomaly to which they could be related. It has a steep gradient of about 30 gammas/km on both sides and dips to a low of less than 450 gammas in an area with an average magnetic anomaly of about 700 gammas.

Simple magnetic models of this anomaly are illustrated in Fig. 17a and 17b. Again, the geometry of the causative body is fixed in part by the results of the seismic profiler record which delineates an interface beneath a thin sedimentary cover. The effects of varying the susceptibility of the magnetic material is shown in Fig. 17a while in Fig. 17b the parameters of the magnetization vector are varied. It is obvious here that the anomaly is best

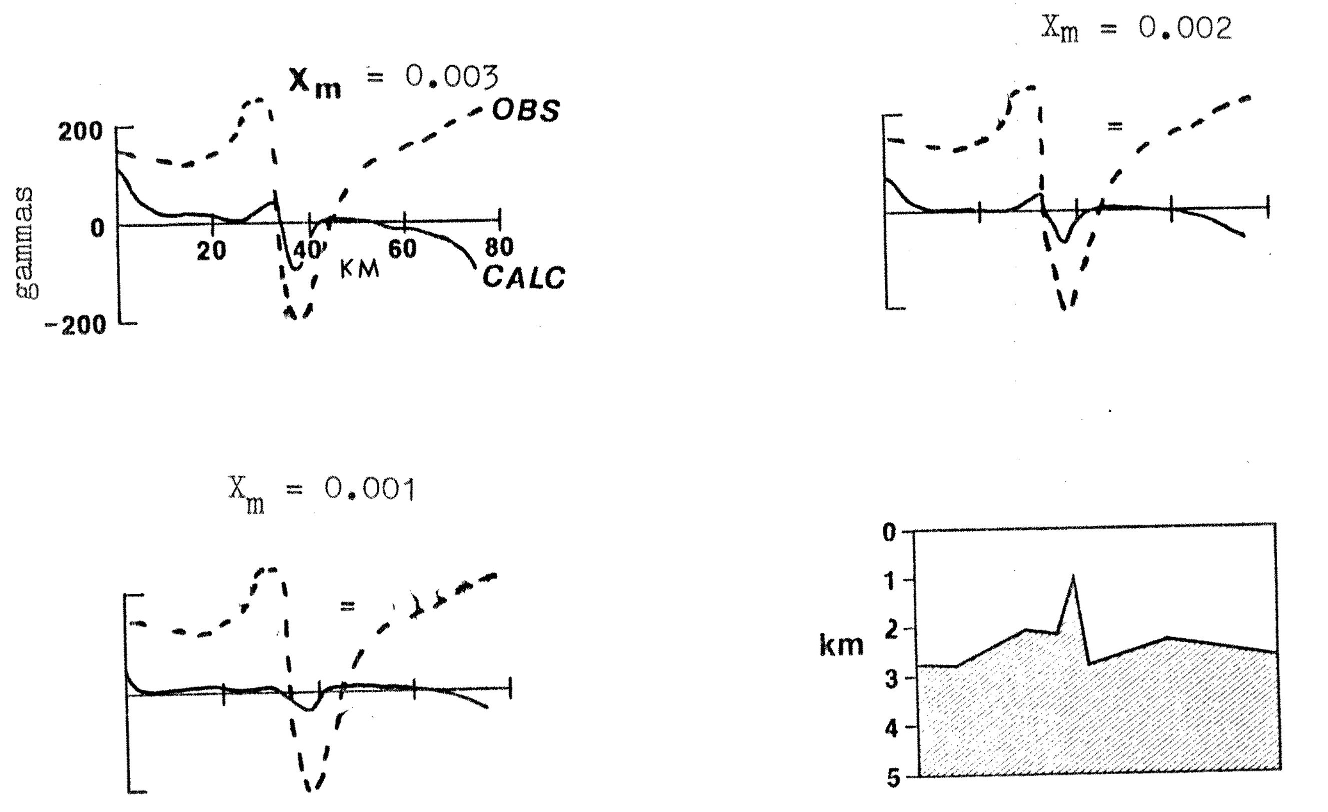



Fig. 16a Simple magnetic model of anomaly B: induced magnetization with $X_m$ varying as shown but geometry held constant.

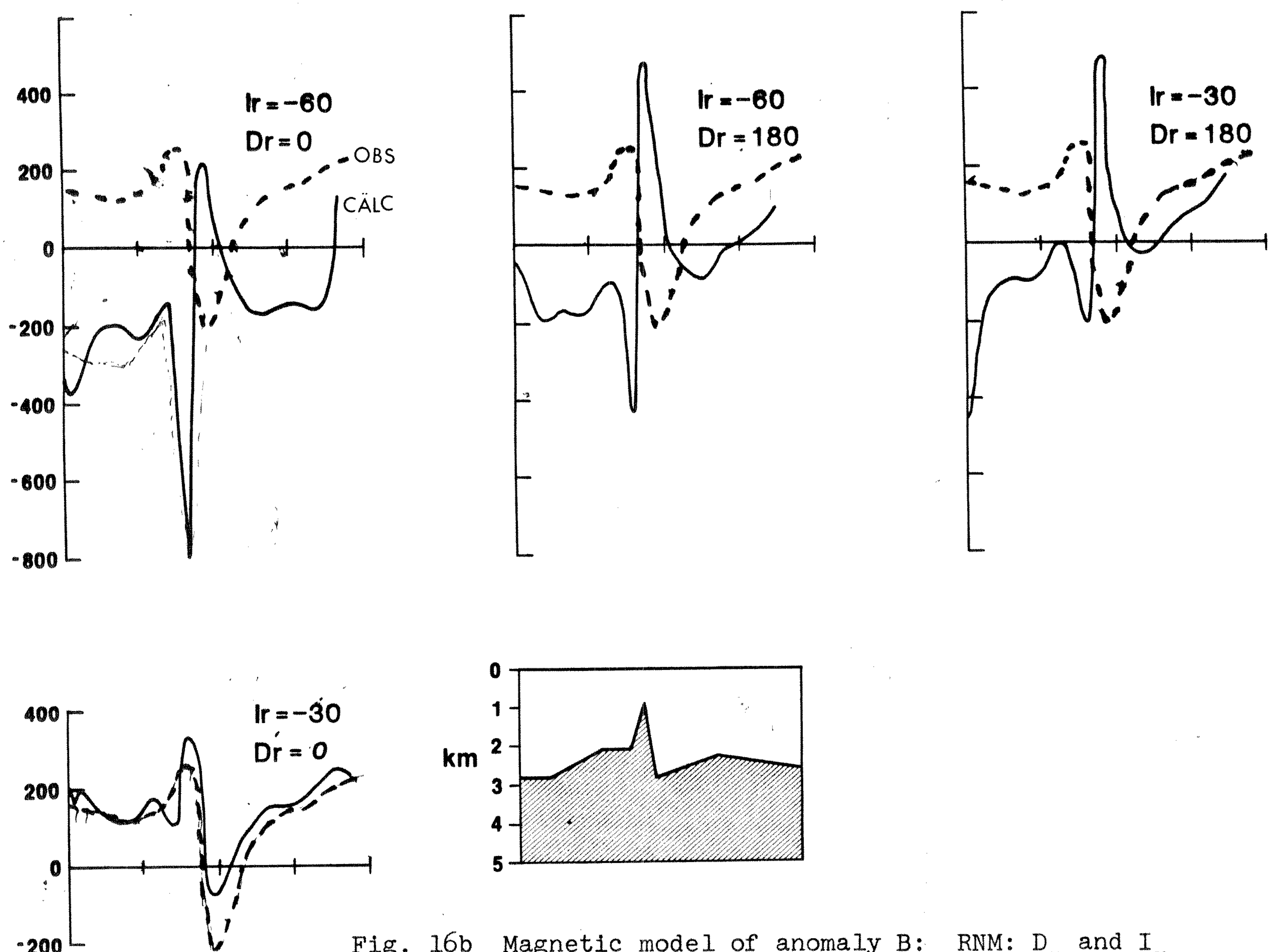



Fig. 16b Magnetic model of anomaly B: RNM: $D_r$ and $I_r$ varying as shown.

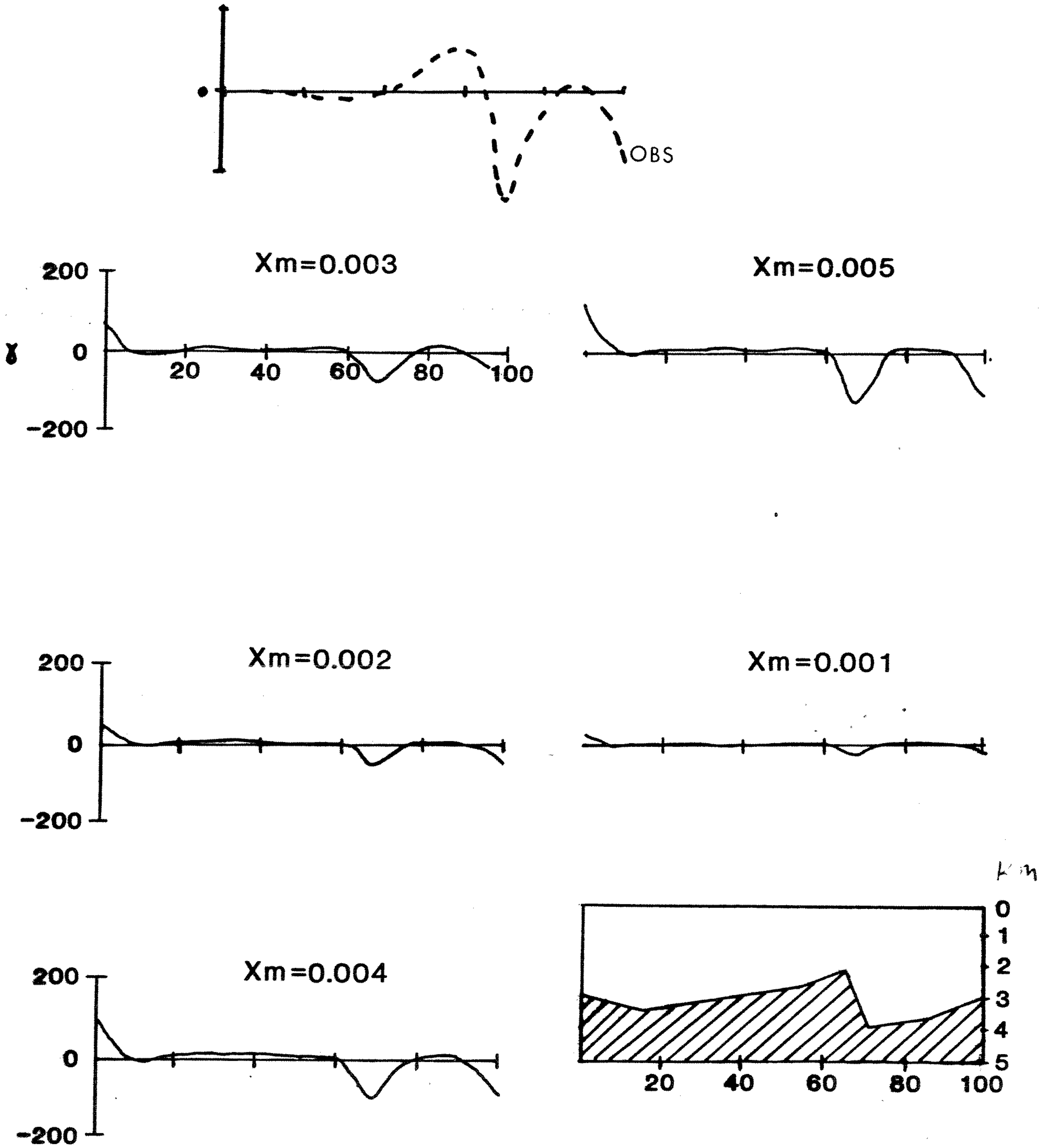



Fig. 17a Magnetic models of anomaly C: Induced magnetization. Xm varying as shown.

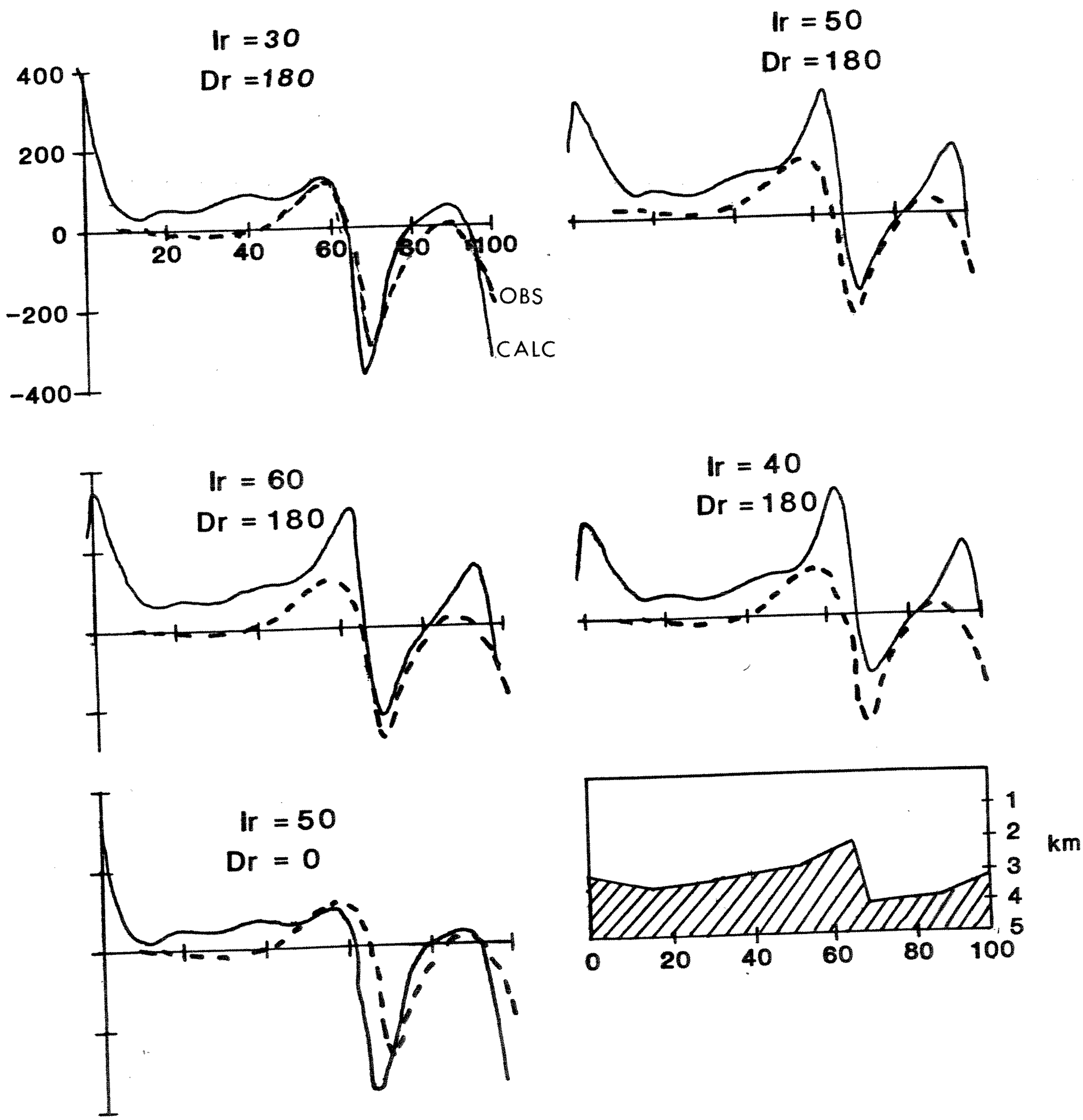



Fig. 17b Magnetic model of anomaly C: RNM case. $D_r$, $I_r$ varying as shown.

simulated by the case of remanent magnetization (Fig. 17b). To generate similar models from induced magnetization, unreasonably large values of magnetic susceptibility would be used. Such models would not be compatible with observed data, (Lowrie and Updyke, 1973).

In all we observe that anomaly A is best simulated by induced magnetization alone, while anomalies B and C are simulated by the case of remanent magnetization. Furthermore, anomaly B corresponds to a magnetization vector with parameters $I_r = -30^o$, $D_r = 0^o$ while anomaly C corresponds to a magnetization vector with $I_r = 30^o$, $D_r = 180^o$. The magnetic models presented here lead one to conclude that the magnetic anomalies in the Nicaraguan Rise are not entirely due to shallow-seated variations in magnetic susceptibility as proposed by Ewing et al., (1960). (Note, however, that in 1960 variations in susceptibility were being proposed as the reason for magnetic stripes in the ocean; "NRM effects" hadn't been "discovered" yet.) Instead, these fits indicate that some of the anomalies are attributable to remanent natural magnetization "frozen into" the crust as the newly generated material cooled through the Curie temperature. It will be interesting to carry out further detailed survey of these zones of geomagnetic field reversals.

### b. Gravity Models

In modeling the observed gravity anomalies here, two basic principles were adopted: (1) to present as simple a model as possible that is consistent with the observed data. No doubt, it is possible that a more complicated model can reproduce the general features of the observed data, but it is questionable whether the available data make such a body geologically more reasonable than the simple model. (2) to utilize as many independent data as possible. It is well known that potential field problems in geophysics do not have unique solutions. However, the more controls (by way of independent data) one has, the better the model.

A knowledge of the density distribution in a region is very critical for any gravity modeling. Actual rock samples recovered from the Nicaraguan Rise are very few. In such a situation, density values can only be obtained by an indirect method. Densities used here have been derived from the seismic refraction results utilizing the empirical relationship between compressional wave velocity and the rock density (Nafe and Drake, 1967; Hamilton, 1978). Fig. 10 shows the location of the three seismic profiles shot on the rise proper. A generalized section, (A-D) across the rise, was selected close to these seismic profiles. This enhances our confidence in the densities used in the models.

The seismic surveys (Ewing et al., 1960) have delineated several interfaces thus giving the thickness of most of the upper layers. Unfortunately the deepest crustal layer has not been well determined because the mantle has not been sampled anywhere on the rise. The depth to the mantle and the mantle velocity beneath the rise have only been estimated by various investigators (Ewing et al., 1960; Arden, 1969, 1975; Edgar et al., 1971). They all estimate the crust here to be 22-25 km thick.

Demenitskaya et al. (1969) derived empirical relationships between crustal thickness and Bouguer gravity anomaly and elevation. The equations are:

$$H = 35(1 - \tanh 0.0037\Delta g) \text{ ----------------- } (1)$$

$$H = 33 \tanh(0.38\Delta h - 0.18) + 38.0 \text{ -------- } (2)$$

Where

$H$ = total thickness of the crust, km

$\Delta g$ = Bouguer gravity anomaly, mgal

$\Delta h$ = height above the sea level, km

These equations have been known to give accurate results (Woolard, 1959, 1969). Table 3 shows representative values calculated for assumed gravity and elevation. Values similar to those found on most parts of the rise indicate that the crust beneath the rise can be anywhere from 18 km to 28.6 km thick.

In Fig. 18 to Fig. 20 are shown structural models compatible with the seismic, topographic and magnetic data. In model 1 (Fig. 18), the mantle is overlain by a main crustal layer (density = 2.80 g/cm$^3$). This layer has a variable thickness with a minimum of about 8.0 km between the two upward bulges. The overlying upper crustal layer (density = 2.60 g/cm$^3$) abutts against the southern upward bulge of the lower crustal layer. This upper crustal layer is in turn overlain by the basement (density = 2.45 g/cm$^3$). Sedimentary layers of various levels of consolidation complete the sequence. Densities here vary from 2.00 g/cm$^3$ to 2.02 g/cm$^3$. The Moho is assumed to be 20.0 km deep.

In model 2 (Fig. 19), two major differences are introduced: (a) the Moho is now deeper (25.0 km) and

TABLE 3

CRUSTAL THICKNESS CALCULATIONS

A. Based on Bouguer Anomaly

$$H = 35 \left[ 1 - \tanh (0.0037 \Delta g) \right]$$

| $\Delta g$ (mgal) | H (km) | |
|---|---|---|
| +300 | 6.9 | |
| +200 | 12.98 | |
| +100 | 22.6 | Nic. Rise |
| +50 | 28.6 | Nic. Rise |
| 0 | 35.0 | |
| -100 | 47.4 | |
| -200 | 57.0 | |
| -300 | 63.1 | |

B. Based on Elevation

$$H = 33 \tanh \left[ 0.38 \Delta h - 0.18 \right] + 38$$

| $\Delta h$ (km) | H (km) | |
|---|---|---|
| -5 | 6.01 | |
| -3 | 9.4 | |
| -2 | 13.7 | Nic. Rise |
| -1 | 21.2 | Nic. Rise |
| 0 | 32.1 | |
| +1 | 44.5 | |
| +2 | 55.2 | |
| +3 | 62.6 | |

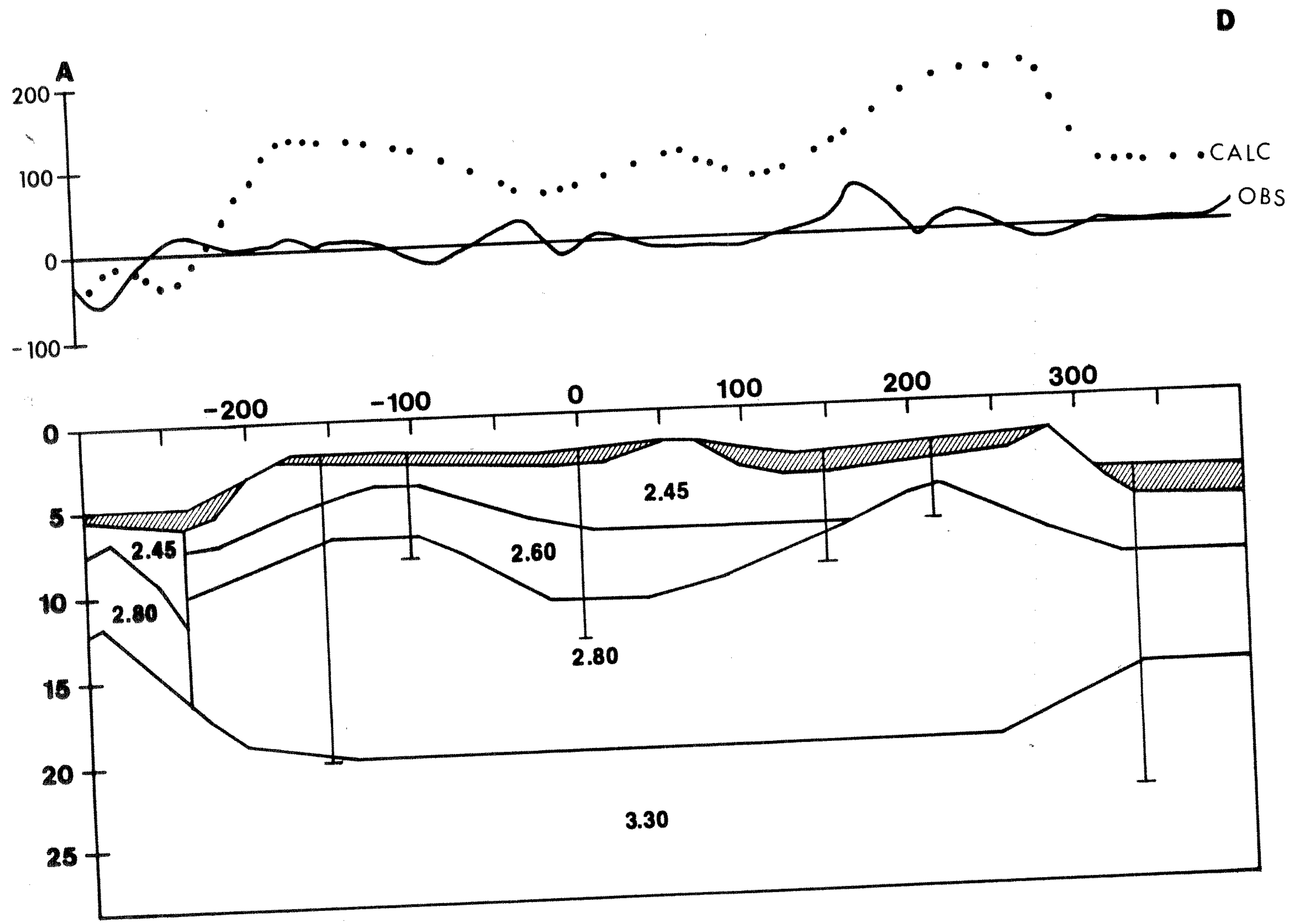



Fig. 18 Crustal model 1 across the Nicaraguan Rise (section A-D) based on gravity, seismic and magnetic data. Densities are given in $g/cm^3$. The vertical lines indicate the location and depth of penetration of seismic surveys.

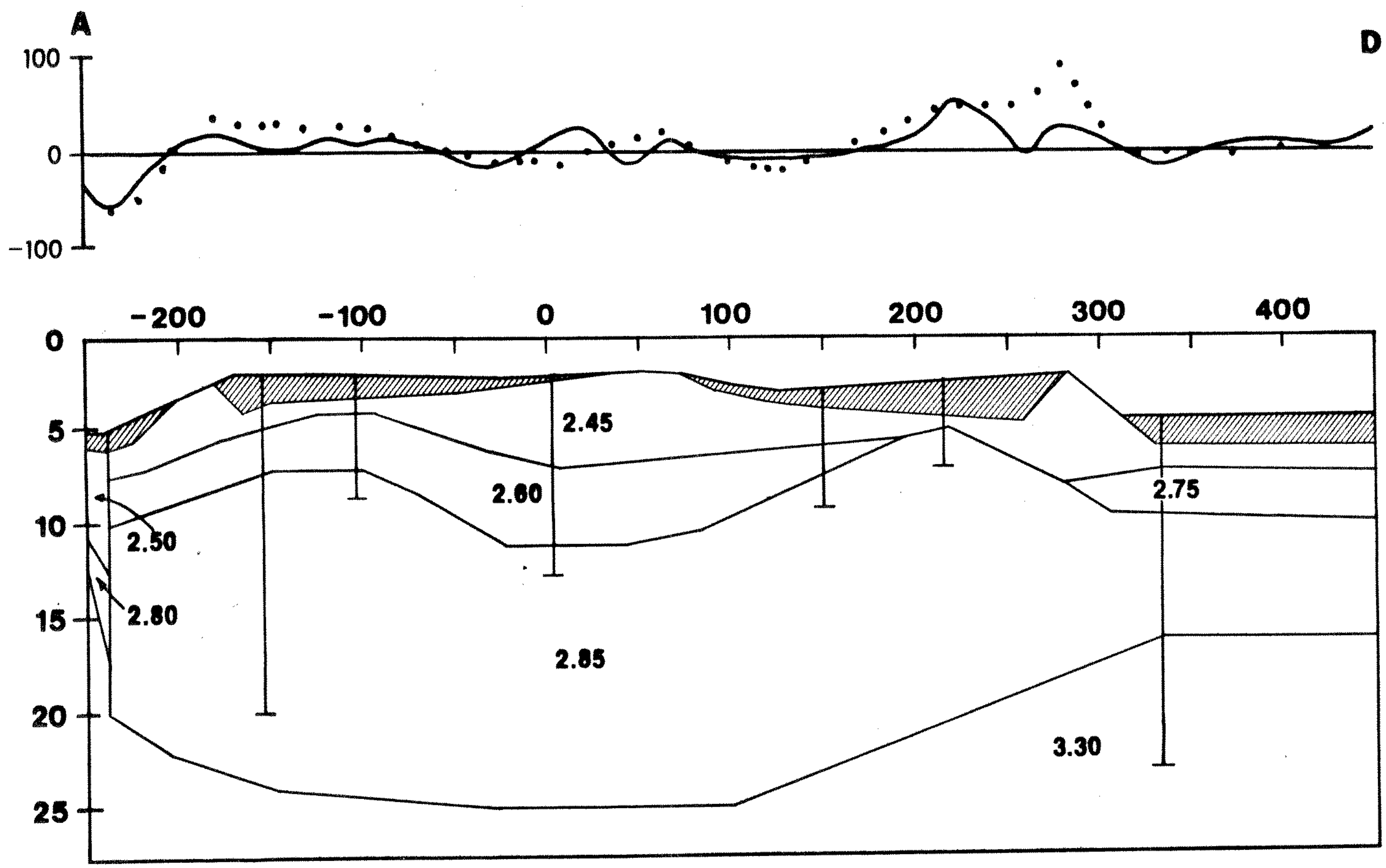



Fig. 19 Crustal model 2.

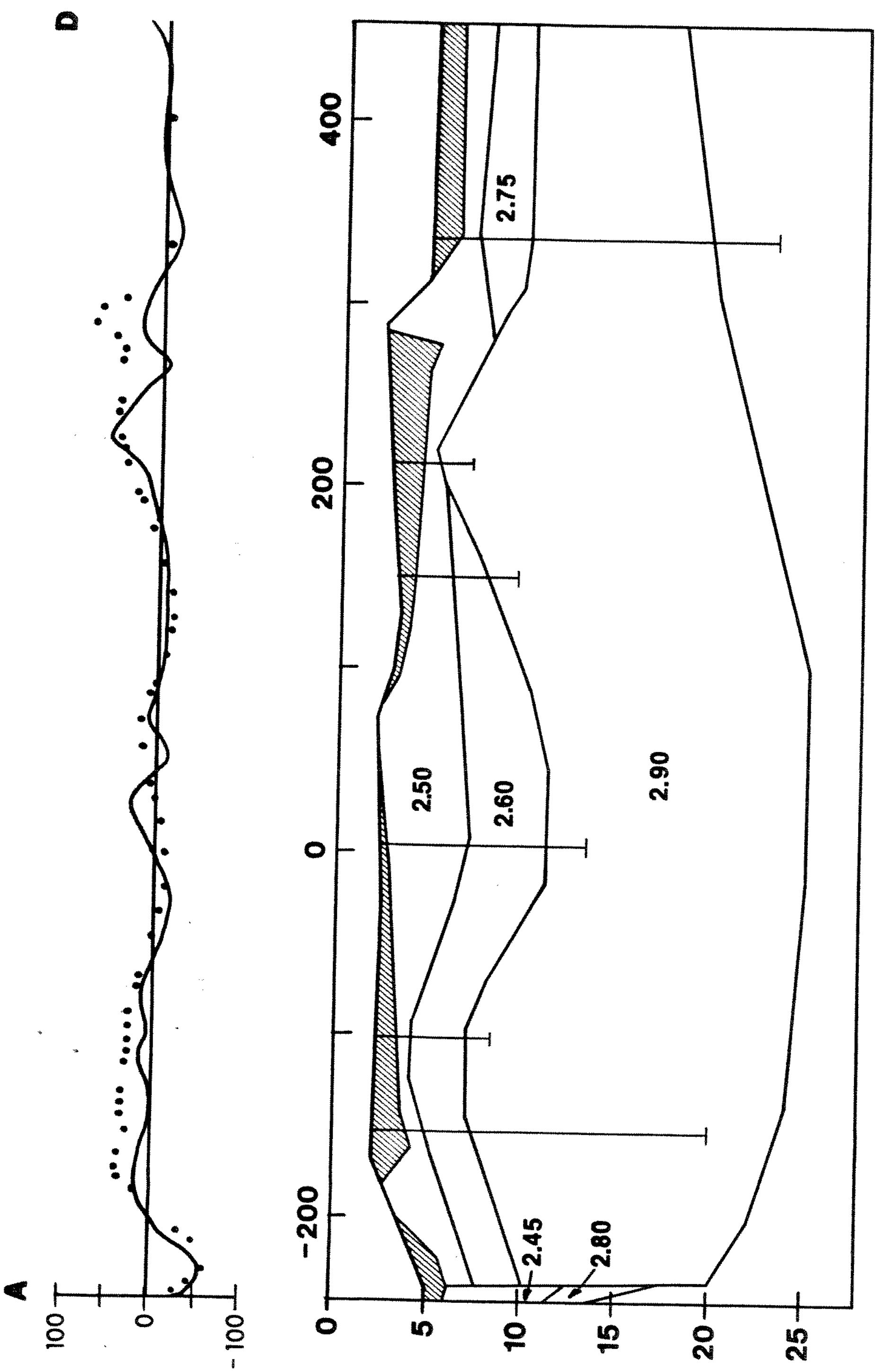



Fig. 20 Crustal model 3.

(b) the upper crustal layer of the Nicaraguan Rise is continued into the Columbian Basin. There is also a slight variation in the density of some layers as noted on the figure.

The model 3 (Fig. 20) presented here shows the effect of varying the densities of some of the layers while retaining the other parameters, particularly the depth to the Moho.

We note here that there is a more pronounced mismatch between the theoretical free air anomaly and the observed near the boundary between the Nicaraguan Rise and the Colombian Basin otherwise called the Hess Escarpment. This is explained by the fact that sharp edges such as the Hess Escarpment behave as points of singularity in gravity modeling.

Our results here indicate that models 2 and 3 fit the observed data best, while model 1 deviates most from the observed. The best models indicate that the crustal layer extends to a depth of about 25 km in the central region of the rise and shallows to less than 18 km beneath the adjoining basins. Since there is no significant difference between models 2 and 3 we shall consider model 3 (Fig. 20) as our best fit. The model is compatible with the idea that there are two upward bulges of the crust beneath the rise. The sedimentary layer is thickest just before the rise finally drops into greater depths in the southeast. The basement has its largest thickness in the central zone but thins rapidly above the upward bulges of the underlying crustal layer. The rise is devoid of any sedimentary cover in a number of locations. The upper crustal layer disappears over the southern bulge of the crust.

I should point out that my preferred model presented here is just one of several possible models. Further improvements on this model can be made as more data become available on the rise. It is also pertinent to note here that what I have presented is a generalized model. The actual picture beneath some of the anomalous topographic features may be different.

## 8 ORIGIN AND TECTONIC HISTORY OF THE CARIBBEAN

A number of theories have been proposed to explain the origin and tectonic history of the Caribbean. Ewing et al. (1967) concluded that the Caribbean is an ancient craton that has undergone vertical tectonic deformation. This is not consistent with the velocity structure and other geophysical data obtained from the area. Edgar et al. (1973) and Malfait and Dinkelman (1972) on the other hand, believe that the Caribbean is a relict of a Mesozoic Pacific crust that was emplaced between North and South America. This model does not account for the presence of the continental crust in the central Americas satisfactorily.

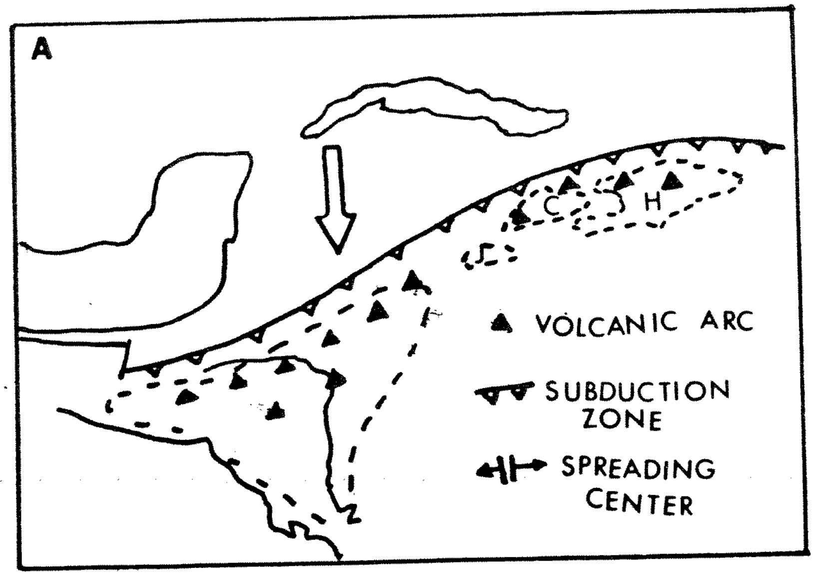
According to the hypothesis of sea-floor spreading (Dietz, 1961; Hess, 1962), new oceanic crustal material is generated in the mid-ocean ridge. This spread laterally into the ocean basins to be assimilated into the mantle or continental crust at plate margins. As a result of the fundamental differences amongst the prevailing geologic processes the crustal structure beneath the ocean basins is significantly different from that beneath the continents (Gaskell et al., 1958; Raiit, 1954, 1963; Shor, 1960).

Most of the ocean basins is underlain by a crust which has a seismic Layer 2 of variable velocity ranging from about 4.0 to 6.0 km/sec and a seismic Layer 3 or oceanic crust that has a velocity range of 6.6 to 6.9 km/sec. The upper layer has a fairly variable thickness but averages about 1.75 km. The underlying Layer 3 has a more uniform thickness of about 5 km. Major departures from the typical oceanic structures are usually associated with continental margins (Nafe and Drake, 1969; Houtz and Ewing, 1963), the mid-ocean ridge (Raiit, 1956; LePichon et al., 1965; Talwani et al., 1965), and other topographic features such as seamounts. Continental crustal structure, on the other hand, is characterized by a sedimentary layer of average thickness 2 km underlain by a continental crust which has a velocity range of 5.5 to 7.0 km/sec.

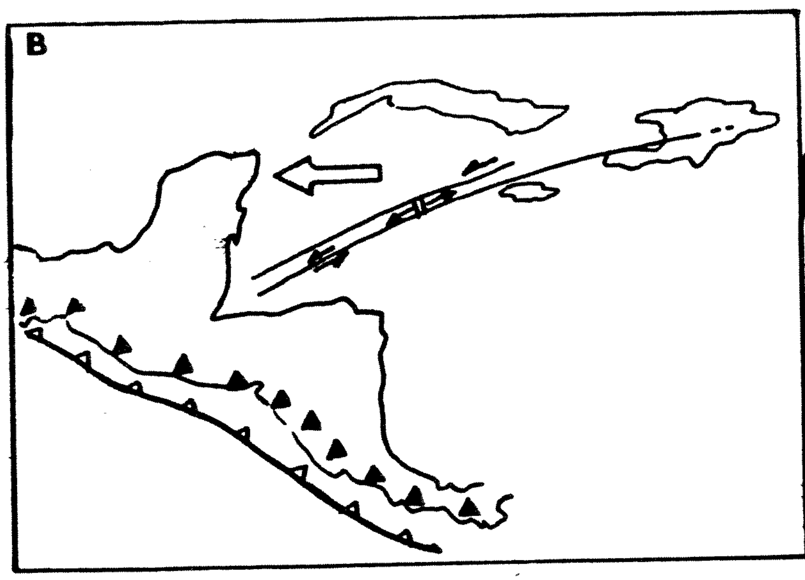
The results of this investigation and the works of others indicate that the Nicaraguan Rise is certainly not continental but has a layered crustal structure similar in many respects to oceanic structure. Abnormally thick crust is not unique to the rise. In a study of the Northwest Pacific Basin, Den et al., (1969) observed that the depth to mantle is at least 22 km near the crestal zone of the Shatsky Rise. This pronounced crustal thickening beneath the rise, they argued, is associated mainly with a 7.3 to 7.8 km/sec layer intermediate between the main crustal layer (Layer 3) and the upper mantle.

We note that (1) the crustal thickness of the Nicaraguan Rise is intermediate between that of a normal oceanic crust and a continental one (2) the velocity structure beneath the rise is closer to a normal oceanic crust than a continental one. (3) the magnetic pattern though apparently not symmetric or linear has magnitudes not markedly different from the 300 gammas range characteristic of ocean floors (4) typical rough oceanic basement surface has been observed on the reflection records presented here and elsewhere (Rezak et al., 1972) and (5) some magnetic anomalies modeled in this study are consistent with the idea that they originated as a result of sea-floor spreading.

I therefore postulate that the Nicaraguan Rise originated as a normal oceanic crust by a process of sea-floor spreading with the east-west spreading center located in the low northern or southern latitudes. This crust has subsequently been modified by tectonic and other processes resulting principally from plate boundary interactions. Interaction can explain some of the differences between the crustal structure of the Nicaraguan Rise and that of a "normal" ocean basin. It is my opinion that the Rise and the adjacent areas of the Caribbean now form an inactive back-arc basin entrapped by the inactive island arc that formed the northern boundary of the Caribbean plate. The island arc was formed by the southerly subduction of the North American plate (Perfit and Heezen, 1978; Mattson, 1974; Donnelly, 1968; Arden, 1969, 1975). This plate convergence during the Cretaceous led to the formation of a chain of volcanic islands (volcanic arc) to the south, along the North American - Caribbean plate boundary. Numerous ophiolite-like outcrops that fringe north Caribbean margin are believed to reflect a Late Cretaceous closure of this subduction zone (Perfit and Heezen, 1978). The onset of relative eastward movement of the Caribbean plate may have caused a reduction in volcanic activity in the Greater Antilles in Early Tertiary. On the whole, the relatively short episode of subduction was successful in modifying to a large extent the existing crustal structure of the area. The conversion of upper mantle material to lower crustal rocks thus leading to a thickening of the oceanic layer is believed to have




A. Cretaceous subduction of the North American plate beneath the oceanic Caribbean plate.




B. Left-lateral motion begins in the Cayman Trench fault in Early Tertiary. By Late Tertiary Cayman Spreading center is developed. Subduction and volcanism now intensified in the Middle Americas Trench.

Fig. 21 Origin and Tectonic history of the Nicaraguan Rise.

taken place during this event. Rock samples recovered from the southern scarps of the Cayman Trough include andesites, greenschist volcanics and some deep open-sea limestones (Perfit and Heezen, 1978). Greenschists and andesites are well known rocks associated with island arcs (Mitchell and Reading, 1971; Uyeda and Kanamori, 1979). Though the data is still scanty, the presence of deep-open-sea limestones is consistent with the idea that the rise has undergone an uplift thus resulting in its present shallow characteristic.

## 9. SUMMARY AND CONCLUSIONS

Within the limits of the data available, a number of conclusions can be made about the nature of the crust beneath the Nicaraguan Rise. The results of this investigation and the work of others indicate that even though the rise is underlain by a thick crust (22-25 km thick), it is certainly not continental in nature. Rather I believe it is thickened oceanic crust. In my view the original oceanic crust was modified and thickened as a result of plate convergence in which an oceanic part of the North American plate was subducted beneath the oceanic Caribbean plate. The magnetic field of the rise is very rough and data sparse, yet I have identified some magnetic anomalies that suggest the presence of normal and reversed magnetization. Thus the oceanic magnetic pattern identified in the Colombian Basin may have extended westward to the Nicaraguan Rise but has not been modified by subsequent tectonic events. The magnetic evidence here is fairly speculative and we hope this will stimulate further detailed work in the area. Our investigation has not revealed any unusually thick layers of carbonates, except in a few isolated locations. In this respect the Nicaraguan Rise is quite different from large carbonate banks such as the Bahamas, the Yucatan and the Florida Platform.

# BIBLIOGRAPHY

Anderson, C.N., Vogt, P.R., Bracy, D.R., and Kontis, A.I., 1969, A Magnetic Survey in the Eastern Gulf of Mexico and its relation to the east coast aeromagnetic survey, Trans. Am. Geophys. Union, 50, 207 (abstract).

Antoine, J., Bryand, W.R., and Jones, B.J., 1967, structural features of continental shelf, slope, and scarp, northeastern Gulf of Mexico, Am. Assoc. Petr. Geol. Bull., 51, 257-262.

Antoine, J.W., 1959, Seismic studies in the western Caribbean, Trans. Am. Geophys. Union, 40, 73-75.

Antoine, J.W., and Ewing, J., 1963, Seismic refraction measurements on the margins of the Gulf of Mexico, J. Geophys. Res., 68, 1975-1996.

Antoine, J.W., and Harding, J.L., 1965, Structure of the continental shelf, northeastern Gulf of Mexico, Texas A. & M. Techn. Rep., 63-13T, 18p.

Antoine, J.W., and Pyle, T.E., 1970, Crustal studies in the Gulf of Mexico, Tectonophysics, 10, 477-494.

Arden, D.D., 1969, Geologic history of the Nicaraguan Rise, Gulf Coast Assoc. Geol. Soc. Trans., 19, 296-309.

Arden, D.D., 1975, Geology of Jamaica and the Nicaraguan Rise in The Ocean Basins and Margins, vol. 3, The Gulf of Mexico and the Caribbean, Nairn, A.E.M., and Stehli, F.G., eds., Plenum Press, New York, pp. 617-662.

Ball, M.M., 1967, Tectonic control of the configuration of the Bahama Banks, Gulf Coast Assoc. Geol. Soc. Trans., 17, 265-267.

Ball, M.M., Supko, P., Gaudet, R., and Leist, C., 1968, Geophysical measurements in Exuma Sound, Bahamas, 5th Caribbean Geol. Congr. Trans. (abstract).

Bass, M.N., and Zartman, R.E., 1969, The basement of Yucatan Peninsula, EOS, Trans. Am. Geophys. Union, 50, 313 (abstract).

Bell, P.M., 1979, Post-IPOD Science, EOS, Trans. Am. Geophys. Union, 60, 777-778.

Ben-Avraham, Z., and Nur, A., 1980, The Elevation of Volcanoes and Their Edifice Heights at Subduction Zones, J. Geophys. Res. 85, 4325-4336.

Bence, A.E., Papike, J.J., and Ayuso, R.A., 1975, Petrology of Submarine Basalts from the Central Caribbean: DSDP Leg. 15, J. Geophys. Res. 80, 4775-4804.

Bowin, C.O., 1968, Geophysical study of the Cayman Trough, J. Geophys. Res. 73, 5159-5173.

Bowin, C.O., 1976, Caribbean Gravity Field and Plate Tectonics: Geol. Soc. Am. Spec. Paper 169, pp. 1-79.

Brooks, H.K., 1973, Geological oceanography, in A summary of knowledge of the eastern Gulf of Mexico, Jones, J.L. et al., eds. Florida State Univ. Inst. Oceanography, Tech. Report, p. IIE-1-IIE-50.

Bryant, W.R., 1968, Structure of Mexican continental shelf and slope, Gulf of Mexico, Am. Assoc. Pet. Geol. Bull., 52, 1204-1228.

Bullard, E.C., Everett, J., and Smith, A., 1965, The fit of the continents around the Atlantic, in symposium on continental drift: Roy. Soc. London Philos. Trans. 258A, 41-51.

Burgl, H., 1961, Contribucion a la Estratigrafia y Litogenesis de Isla de San Andres, Bol. Geol. 7, No. 1-3, p. 5-25, Bogota, Colombia.

Burke, K., and Fox, D.J., 1976, Caribbean ocean floor as hard-to-subduct remnant, Geol. Soc. Am. Abstr. with Programs, 8, No. 6, 795-796.

Burke, K., and Fox, P.J., 1977, Caribbean Problems: A report on workshop to held identify geological problems related to the evolution of the Caribbean, State University of New York, Albany, Tech. Rept., 65p.

Caputo, M., Masada, R., Helfer, M., and Hager, C.L., 1964, Gravity measurements in the Atlantic, Pacific and Indian Oceans: Interim Rept. No. 7, 19p., Inst. Geophys. Planet. Phys., Univ. Cal. Los Ang.

Carey, S.W., 1958, A tectonic approach to continental drift: A symposium: Hobart, Tasmania Univ., p. 177-358.

Carpenter, R.H., 1954, Geology and ore deposits of the Rosario Mining District and the San Juancito Mountains, Honduras, Central America: Bull. Geol. Soc. Am. 65, 23-38.

Case, J.E., 1975, Geophysical studies in the Caribbean Sea, in The Ocean Basins and Margins, Vol. 3, The Gulf of Mexico and the Caribbean, Nairn, A.E.M., and Stehli, F.G., eds. Plenum Press, New York, p. 107-173.

Case, J.E., and Holcombe, T.L., 1977, Preliminary bathymetric and geologic-tectonic maps of the Caribbean region, U.S. Geol. Survey, Open-File Map, 75-146.

Celal-Sengor, A.M., and Burke, K., 1978, Relative timing of rifting and volcanism on the Earth and its tectonic implications: Geophys. Res. Lett. 5, 419-421.

Christofferson, E., 1973, Linear magnetic anomalies in the Colombian Basin, central Caribbean Sea, Geol. Soc. Am. Bull., 84, 3217-3230.

Christofferson, E., 1976, Colombian Basin magnetism and Caribbean plate tectonics: Geol. Soc. Am. Bull., 87, 1255-1258.

Christofferson, E., and Hamil, M.M., 1978. A radial pattern of sea-floor deformation in the southwestern Caribbean sea: Geology, 6, p. 341-344.

Cook, E.E., 1967, Geophysical reconnaissance in the northwestern Caribbean: Soc. Expl. Geophys., 1967 Ann. Mtg., Preprint, 17p.

Demenitskaya, R.M., and Belyaevsky, N.A., 1969, The relation between the Earth's Crust, Surface Relief, and Gravity Field in the USSR, in the Earth's Crust and Upper Mantle, Hart, P.J., ed. Am. Geophys. Union Monograph, 13, 312-319.

Den, N., Ludwig, W.J., Murauchi, S., Ewing, J.L., Hotta, H., Edgar, N.T., Yoshii, T., Asanuma, T., Hagiwara, K., Sata, T., and Ando, S., 1969, Seismic-Refraction Measurements in the Northwest Pacific Basin, J. Geophys. Res. 74, 1421-1434.

Dengo, G., 1969, Problems of tectonic relations between Central America and the Caribbean, Gulf Coast Assoc. Geol. Soc. Trans., 19, 311-320.

De Paolo, D.J., and Wasserburg, G.J., 1977, The sources of island arcs as indicated by Nb and Sr isotopic studies, Geophys. Res. Lett., 4, 465-468.

Dewey, J.W., 1972, Seismicity and tectonics of Western Venezuela, Seis. Soc. Am. Bull., 62, 1711-1751.

Dewey, J.W., and Algernissen, S.T., 1974, Seismicity of the Middle America arc-trench system near Managua, Nicaragua: Seis. Soc. Am. Bull., 64, 1033-1048.

Dietz, R.S., 1952, Geomorphic evolution of continental terrace (continental shelf and slope), Am. Assoc. Pet. Geol. Bull., 36, 1802-1819.

Dietz, R.S., 1961, Continental and ocean basin evolution by spreading of the sea floor, Science, 190, 854-857.

Dietz, R.S., 1964, Origin of continental slopes, Am. Sci. 52, 50-69.

Dietz, R.S., Holden, J.C., and Sproll, W.P., 1970, Geotectonic evolution and subsidence of Bahama Platform, Geol. Soc. Am. Bull., 81, 1915-1928.

Dillion, W.P., Vedder, J.G., 1973, Structure and development of the continental margin of British Honduras, Geol. Soc. Am. Bull., 84, No. 8, 2713-2732.

Dillion, W.P., Vedder, J.G., and Graf, R.J., 1972, Structural profile of the northwestern Caribbean: Earth Planet. Sci. Lett. 17, 175-180.

Donnelly, T.W., 1968, Caribbean island-arcs in light of the sea-floor spreading hypothesis, Trans. New York Acad. Sci. 197, 745-750.

Donnelly, T.W., 1973, Late Cretaceous basalts from the Caribbean: A possible blood basalt of vast size, EOS, Trans. Am. Geophys. Union, 54, 1004-1006 (abstract).

Donnelly, T.W., Melson, W., Kay, R., and Rogers, J.J.W., 1973, Basalts and dolerites of Late Cretaceous age from the central Caribbean, in Initial Rep. Deep Sea Drilling Program Vol. 15, Edgar, N.T., Saunders, J.P., et al., eds., U.S. Govt Printing Office, Washington.

Drake, C., and Nafe, J.E., 1968, Transition from ocean to continent from seismic refraction data, in Crust and Upper Mantle of the Pacific Area, Am. Geophys. Union, Geophys. Mon., 12.

Eardley, A.J., 1954, Tectonic relations of North and South America, Am. Assoc. Pet. Geol. Bull., 38, 707-773.

Edgar, N.T., Ewing, J.I., and Hennion, J., 1971, Seismic refraction and reflection in Caribbean Sea, Am. Assoc. Pet. Geol. Bull. 55, 833-870.

Edgar, N.T., Saunders, J.B., et al., 1973, Initial Reports of the Deep Sea Drilling Project, v. 15, U.S. Govt. Printing Office, Washington.

Emery, K., 1965, Geology of the continental margin off eastern United States, in Submarine Geology and Geophysics. Proceedings of the 17th symposium of the Colston Research Society, held in the University of Bristol, Whittard, W.F. and Bradshaw, R. eds., Butterworths, London, p. 1-20.

Emery, K., 1973, Outline for a geophysical and geological study of the Caribbean Sea, Report by Woods Hole Ocean Inst., Woods Hole, Mass., 75 p.

Emery, K.O., and Karudzki, E.F.K., 1967, Seismic reflection profiles along the drill holes on the continental margins off Florida, U.S. Geol. Surv. Prof. Paper 581A, 1-8.

Erickson, A.J., Helsley, C.E., and Simmons, G., 1972, Heat flow and continuous seismic profiles in Cayman Trough and Yucatan Basin, Geol. Soc. Am. Bull., 83, 1241-1260.

Ewing, J., Antoine, J., and Ewing, M., 1960, Geophysical Measurements of the Western Caribbean Sea and in the Gulf of Mexico: J. Geophys. Res. 65, 4087-4126.

Ewing, J.R., Edgar, N.T., and Antoine, J.W., 1970, Structure of the Gulf of Mexico and Caribbean Sea in The Sea, vol. 4, Maxwell, A.E., ed., Wiley-Interscience, New York, p. 321-358.

Ewing, J., and Ewing, M., 1970, Seismic Reflection, in The Sea, vol. 4, Maxwell, A.E., ed., Wiley-Interscience, New York, p. 1-51.

Ewing, J., Talwani, M., Ewing, M., and Edgar, T., 1967, Sediments of the Caribbean, Studies in Tropical Oceanography, 5, 88-102.

Ewing, M., Worzel, J.L., Erickson, D.B., and Heezen, B., 1955, Geophysical and Geological investigations in the Gulf of Mexico, 1, Geophysics, 20, 1-18.

Fahlquist, D.A., and Davies, D.K., 1971, Fault-back origin of the western Cayman Ridge, Caribbean Sea, Deep-Sea Res. 18, 243-253.

Fox, P.J., Ruddiman, W.F., Bryan, W.B.F., and Heezen, B.C., 1970, The geology of the Caribbean crust, I: Beata Ridge: Tectonophysics 10, 495-513.

Fox, P.J., and Schreiber, E., 1970, Granodiorites from the Cayman Trench, Geol. Soc. Am. Abstr. with Programs 2, No. 7, p. 553.

Fox, P.J., and Schreiber, E., 1973, Compressional wave velocities in basalt and dolerite samples recovered during Leg XV. Initial reports of the Deep Sea Drilling

Project: U.S. Govt. Printing Office, Washington, 15, 1013-1016.

Fox, P.J., Schreiber, E.S., and Heezen, B.C., 1971, The geology of the Caribbean crust: Tertiary sediments, granitic and basic rocks from the Aves Ridge: Tectonophysics 12, 89-109.

Freeland, G.L., and Dietz, R.S., 1971, Plate tectonic evolution of Caribbean/Gulf of Mexico region, Nature 232, 20-23.

Garrison, L.E., and Buell, M.W., Jr., 1971, Sea-floor structure of the eastern Greater Antilles, in Symposium on investigations and resources of the Caribbean Sea and adjacent regions, Willemstad, Curacao, 1968, Unesco, Paris, p. 241-245.

Gaskell, T., Hill, M.N., and Swallow, J., 1958, Seismic measurements made by HMS Challenger in the Atlantic, Pacific and Indian Oceans and in the Mediterranean Sea, 1950-53, Roy. Soc. Lon. Philos. Trans., 251A, 23-83.

Gerasimov, I.P., 1978, The Caribbean basin as transitional intercontinental sutural geotexture: Okeonologiya, 18, 472-483.

Glockhoff, C., 1973, Geotectonic evolution and subsidence Of Bahama Platform: Discussion, Geol. Soc. Am. Bull., 84, 3473-3476.

Goodell, H., and Garman, R., 1969, Carbonate geochemistry of superior deep well test, Andros Island, Bahamas: Am. Assoc. Pet. Geol. Bull., 53, 3, 513-536.

Gough, D.I., 1967, Magnetic anomalies and crustal structure in eastern Gulf of Mexico, Am. Assoc. Pet. Geol. Bull., 51, 200-211.

Gough, D.V., and Heirtzler, J.R., 1969, Magnetic anomalies and tectonics in the Cayman Trough, Geophys. J. 10, Roy. Astron. Soc., 33-49.

Grim, P.J., 1970, Bathymetric and magnetic anomaly profiles from a survey south of Panama and Costa Rica: U.S. ESSA Tech. Memo. No. ERLTM-AOML9, 87p.

Hales, A.L., 1973, The crust of the Gulf of Mexico: A discussion, Tectonophysics, 20, 217-225.

Hales, A.L., Helsley, C.E., and Nation, J.B., 1970a, Crustal structure study on Gulf coast of Texas, Am. Assoc. Petr. Geol. Bull., 54, 2040-2057.

Hamilton, E.L., 1976, Variations of Density and Porosity with depth in deep-sea sediments, J. Sed. Petr. 46, 280-300.

Hamilton, E.L., 1978, Sound, Velocity-density relations in sea-floor sediments and rocks, J. Acoust. Soc. Am., 63, 366-377.

Heirtzler, J.R., Burckle, L.H., and Peter, G., 1966, Magnetic anomalies in the Gulf of Mexico, J. Geophys. Res., 71, 519-526.

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., III and Le Pichon, X., 1968, Marine Magnetic anomalies geomagnetic field reversals, and motions of the ocean floor and continents: J. Geophys. Res., 73, 2119-2136.

Henderson, G.C., 1963, Preliminary study of the crustal structure across the Campeche Escarpment from gravity data, Geophysics, 28, 736-744.

Hess, H.H., 1960, Caribbean Research Project, Progress report, Geol. Soc. Am. Bull., 71, 235-240.

Hess, H.H., 1962, History of ocean basins, in Petrologic Studies: A volume in honor of A.F. Buddington, Geol. Soc. Am., 660p.

Holcombe, T.L., Vogt, P.R., Matthews, J.E., and Murchison, 1973, Evidence for sea-floor spreading in the Cayman Trough, Earth Planet. Sci. Lett., 20, 357-371.

Horsfield, W.T., and Roobol, M.J., 1974, A tectonic model for the evolution of Jamaica, J. Geol. Soc. Jam., 14, 31-38.

Houtz, R.E., and Ewing, J.I., 1963, Detailed sedimentary velocities from seismic refraction profiles in the western North Atlantic, J. Geophys. Res., 68, 5233-5258.

Houtz, R.E., Ewing, J.I, and LePichon, X., 1968, Velocity of deep-sea sediments from sonobuoy data, J. Geophys. Res., 73, 2615-2641.

Houtz, R.E., and Ludwig, W.J., 1977, Structure of Colombia Basin, Caribbean Sea, from Profiler-Sonobuoy Measurements: J. Geophys. Res., 82, 4861-4867.

Hussong, D.M., Wipperman, L.K., and Kroenke, L.W., 1979, The Crustal Structure of the Ontong Java and Manihiki Oceanic Plateaus, J. Geophys. Res., 84, 6003-6010.

Jordan, T.H., The present-day motions of the Caribbean plate, J. Geophys. Res., 80, 4433-4439.

Karig, D.E., 1972, Remnant Arcs, Geol. Soc. Am. Bull., 83, 1057-1068.

Kerr, J.M., Jr., 1977, The volcanic and tectonic history of La Providencia Island, Colombia (M.S. thesis): Rutgers University (New Brunswick).

Khudoley, K.M., and Meyerhoff, A.A., 1971, Paleography and geological history of the Greater Antilles, Geol. Soc. Am. Mem., 129, 199.

King, E.R., 1959, Regional magnetic map of Florida, Am. Assoc. Pet. Geol. Bull., 43, 2844-2854.

Klonsky, L.F., 1977, Physiographic Boundary between the Nicaraguan Rise and Colombian Basin, Caribbean Sea (M.S. thesis): Rutgers Univ. (New Brunswick).

Konig, M. and Talwani, M., 1977, A geophysical study of the southern continental margin of Australia: Great Australian Bight and western sections, Geol. Soc. Am. Bull., 88, 1000-1014.

Krivoy, H.L., 1970, A magnetic lineament in the Bay of Campeche, Geol. Soc. Am. Abstr. with Programs, 2, 288 (abstract).

Krivoy, H.L., and Pyle, T.E., 1972, Anomalous crust beneath west Florida shelf, Am. Assoc. Pet. Geol. Bull., 56, 107-113.

Krivoy, H.L., Eppert, H.C., Jr., and Pyle, T.E., 1976, Simple Bouguer gravity anomaly map of the Gulf of Mexico and adjacent land areas, U.S. Geol. Surv. Geophys. Inv. Maps GP-912.

Lattimore, R.K., Weeks, L.A., and Mordock, L.W., 1971, Marine geophysical reconnaissance of continental margin north of Paria Peninsula, Venezuela: Am. Assoc. Petrol. Geol. Bull., 55, 1719-1729.

Leibov, M.B., Mirlin, E.G., 1978, Statistical Analysis of magnetic anomalies recorded in deep-sea magnetic surveys: Okeonologiya, 18, 484-488.

LePichon, X., 1968, Sea-floor spreading and continental drift, J. Geophys. Res., 73, 3661-3698.

Lowrie, W., and Updyke, N.D., 1973, Paleomagnetism of Igneous and sedimentary samples, in: Edgar et al., ed. Initial Rep. of the Deep Sea Drilling Project, v. 15, U.S. Govt. Printing Office, Washington, p. 1017-1022.

Malfait, B.T., and Dinkelman, M.G., 1972, Circum-Caribbean tectonic and igneous activity and evolution of the Caribbean plate, Geol. Soc. Am. Bull., 83, 251-272.

Matthews, J.E., 1974, The geomagnetic field of the Caribbean sea, Geol. Soc. Am. Abs. with Programs, 6, 859 (abstract).

Matthews, J.E., 1976, Geomagnetic Field of Caribbean Sea, U.S. Geol. Surv. Misc. Field Studies, Map MF-742.

Mattson, P.H., 1974, Mesozoic and Teritary lithospheric plate interactions in the northern Caribbean, 7th Caribb. Geol. Conf. (Guadeloupe).

McBirney, A.E., and Bass, M.M., 1969b, Geology of the Bay Islands, Gulf of Honduras, in Tectonic Relations of Northern Central American and the Western Caribbean, McBirney, A.R., ed., Am. Assoc. Pet. Geol. Mem. 11, 229-243.

McBirney, A.R., and Williams, H., 1965 Volcanic history of Nicaragua: Univ. California Publ. in Geol. Sci., 55, p. 1-73.

Meyerhoff, A.A., 1967, Future hydrocarbon provinces of Gulf of Mexico - Caribbean region, Gulf Coast Assoc. Geol. Soc. Trans., 17, 217-260.

Milliman, J.D., 1969, Carbonate sedimentation on four south western Caribbean atolls and its relation to the "oolitic problem," Gulf Coast Assoc. Geol. Soc. Trans., 19, 195-206.

Milliman, J.D., and Supko, P.R., 1968, On the geology of San Andres Island, western Caribbean: Geologic En Mijnbouw, N.W. Series, v. 47, No. 2, p. 102-105.

Mills, R.A., Hugh, K.E., Feray, D.E., and Swolfs, H.C., 1967, Mesozoic stratigraphy of Honduras: Bull. Am. Assoc. Petr. Geol., 51, 1711-1786.

Mitchell, R.C., 1955, Geologic and petrographic notes on the Colombian Islands of La Providencia and San Andres, West Indies: Geologic En Mijnbouw, N.W. Series, v. 17, p. 76-83.

Mitchell, A.H., and Reading, H.G., 1971. Evolution of island arcs, J. Geol., 79, 253-284.

Molnar, P., 1977, Gravity anomalies and the origin of the Puerto Rico Trench, Geophys. J. R. Astr. Soc., 51, 701-708.

Mullins, H.T., and Lynts, G.W., 1977, Origin of the northwestern Bahama Platform: Review and reinterpretation, Geol. Soc. Am. Bull., 88, 1447-1461.

Nafe, J.E., and Drake, 1969, Floor of the North Atlantic summary of geophysical data, in North Atlantic - geology and continental drift, M. Kay, ed., Am. Assoc. Petr. Geol. Mem., 12, 1082p.

Nagle, F., 1971, Caribbean Geology, 1970, Bull. Mar. Science, 21, No. 2, 375-439.

Neff, C.H., 1971, Review of the 1970 petroleum developments in South America, Central America, and Caribbean Sea: Am. Assoc. Petr. Geol. Bull., 55, 1418-1482.

Newell, N.D., 1955, Bahamian Platforms, Crust of the Earth, in Poldervaart, A., ed., Geol. Soc. Am. Spec. Paper, 62, 303-315.

Oxburgh, E.R., and Turcotte, D.L., 1970, Therman Structure of island arcs, Geol. Soc. Am. Bull., 81, 1665-1688.

Paine, W.R., and Meyerhoff, A.A., 1970, Gulf of Mexico basin: interactions among tectonics, sedimentation and hydrocarbon accumulations, Gulf Coast Assoc. Geol. Soc. Trans., 2, 139-175.

Perfit, M.R., and Heezen, B.C., 1978, The geology and evolution of the Cayman Trough, Geol. Soc. Am. Bull., 89, 1155-1174.

Peter, G., 1971, Geology and Geophysics of the Venezuelan continental margin between Blanquilla and Orchilla Islands (Ph.D. dissertation): George Washington Univ. (Washington, D.C.).

Pinet, P.R., 1975, Structural evolution of the Honduras continental margin and sea-floor south of western Cayman Trough, Geol. Soc. Am. Bull., 86, 830-838.

Pyle, T.E., and Antoine, J.W., 1973, Structure of the west Florida platform, Gulf of Mexico, Texas A. & M. Tech. Rep., 73-7-T, 168p.

Pyle, T.E., Antoine, J.W., Fahlquist, D.A., and Bryant, W.R., 1969, Magnetic anomalies in straits of Florida, Am. Assoc. Petro. Geol. Bull., 53, 2501-2505.

Rabinowitz, P.D., 1974, The boundary between oceanic and continental crust in the western Northern Atlantic, in The geology of continental margins, Springer-Verlag New York, p. 67-84.

Raiit, R.W., 1954, Seismic refraction studies of Bikini and Kwajalein atolls, U.S. Geol. Surv. Prof. Paper, 260-K, 507-527.

Raiit, R.W., 1956, Seismic refraction studies of the Pacific ocean basin; pt. 1, crustal thickness of the central equatorial Pacific, Geol. Soc. Am. Bull., 67, 1623-1640.

Raiit, R.W., 1963, The crustal rocks, in The Sea, vol. 3, p. 85-102, New York, M.N. Hill, ed., Interscience Pub.

Rezak, R., Antoine, J.W., Bryant, W.R., Fahlquist, D.A., and Bouma, A.H., 1972, Preliminary Results of cruise 71-A-4 of the R/V Alaminos in the Caribbean, Trans., 6th Caribbean Geol. Conf., Margarita, Venezuela, p. p. 441.

Sheridan, R.E., 1969, Subsidence of continental margins: Tectonophysics, 7, 219-229.

Sheridan, R.E., 1971, Geotectonic evolution and subsidence of Bahama platform: Discussion, Geol. Soc. Am. Bull., 82, 807-810.

Sheridan, R.E., Drake, C.L., Nafe, J.E., and Hennion, J., 1966, Seismic refraction study of continental margin east of Florida: Am. Assoc. Pet. Geol. Bull., 50, 1972-1991.

Shipley, T.H., Buffler, R.T., and Watkins, J.S., 1978, Seismic stratigraphy and geological history of Blake Plateau and adjacent western Atlantic continental margin, Am. Assoc. Pet. Geol. Bull., 62, 792-812.

Shor, G.G., 1960, Crustal structure of the Hawaiian Ridge near Gardner Pinnacles, Seis. Soc. Am. Bull., 50, 563-573.

Spencer, M., 1967, Bahamas deep test: Am. Assoc. Pet. Geol. Bull., 51, 263-268.

Spudich, P. and Orcutt, J., 1980, A New Look at the Seismic Velocity Structure of the Oceanic Crust, Rev. Geophys. Space Phys., 18, 627-645.

Stegen, G.R., 1974, Programs for Digital Time Series Analysis: Unpublished manuscript, Princeton University, Dept. of Geological and Geophysical Sciences.

Stewart, H.B., Jr., Raff, A.D., and Jones, F.L., 1961, Explorer Bank - A new discovery in the Caribbean: Geol. Soc. Am. Bull., 72, 1271-1274.

Talwani, M., 1960, Gravity anomalies in the Bahamas and their interpretation: Ph.D. thesis, Columbia Univ., New York, p. 1-89.

Talwani, M., 1965, Gravity anomaly belts in the Caribbean, in Continental Margins and Island Arcs, International Upper Mantle Project, W.H. Poole, ed., Canada Geol. Surv. Paper 66-15, p. 177 (abstract).

Talwani, M., and Heirtzler, J.R., 1964, Computation of magnetic anomalies caused by two-dimensional structures of arbitrary-shape, in Computers in the Mineral Industries, Parks, G.A., ed., Palo Alto, California, Stanford Univ., p. 464-480.

Talwani, M., Sutton, G.H., and Worzel, J.L., 1959, A crustal section across the Puerto Rico Trench, J. Geophys. Res., 64, 1545-1555.

Talwani, M., Worzel, J., and Ewing, M., 1959, Gravity anomalies and structure of the Bahamas: 2nd Carib. Geol. Congr. Trans., 156-160.

Talwani, M., Hayes, D., Pitman, W., and Aitken, T., 1974. Underway Marine Geophysical Data in the North Atlantic, June 1961-January 1971, Parts C and D: Lamont-Doherty Survey of the World Ocean, Talwani, M., ed.

Talwani, M., Worzel, J.L., and Landisman, M., 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino sunmarine fracture zone: J. Geophys. Res., 64, 49-59.

Todd, R., and Low, D., 1967, Oceanic Islands: geology of Swan Islands, U.S. Geol. Surv. Prof. Paper, 575, A127.

Uchupi, E., 1973, Eastern Yucatan continental margin and western Caribbean tectonics, Am. Assoc. Petr. Geol. Bull., 57, 1075-1085.

Uchupi, E., 1975, Physiography of the Gulf of Mexico and Caribbean Sea, in The Ocean Basins and Margins, vol. 3, The Gulf of Mexico and the Caribbean, Nairn, A.E.M., and Stehli, F.G., eds. Plenum Press, New York, p. 1-64.

Uchupi, E., Milliman, J.D., Luyendyle, B.P., Bowin, C.O., and Emery, K.O., 1971, Structure and Origin of southeastern Bahamas, Am. Assoc. Petr. Geol. Bull., 55, 687-704.

Uyeda, S., and Kanamori, H., 1979, Back arc opening and the mode of subduction, J. Geophys. Res., 84, 1049-1061.

Williams, H., and McBirney, A.R., 1969, Volcanic history of Honduras: Univ. Calif. Publ. Geol. Sci., 85, 1-101.

Wilson, J.T., 1959, Geophysical Institute of the U.S.S.R. and of the People's Republic of China, Trans. Am. Geophys. Union, 40, 3-24.

Winston, G.O., 1969, A deep glimpse of west Florida's platform, Oil and Gas J., 67, 128-129, 132-133.

Woollard, G.P., 1959, Crustal structure from gravity and seismic measurements, J. Geophys. Res., 64, 1521-1544.

Woollard, G.P., 1969, Regional Variations in Gravity, in The Earth's Crust and Upper Mantle, Hart, P.J., ed., Am. Geophys. Union Monograph, 13, 320-341.

Worzel, J.L., and Burk, C.A., 1978, Margins of Gulf of Mexico, Am. Assoc. Pet. Geol. Bull., 62, 2290-2307.

Yungul, S.H., 1971, Magnetic anomalies and the possibilities of continental drifting in the Gulf of Mexico, J. Geophys. Res., 76, 2639-2642.

Yungul, S.H., and Dehlinger, P., 1962, Preliminary free-air gravity anomaly map of the Gulf of Mexico from surface-ship measurements and its tectonic implications, J. Geophys. Res., 67, 4721-4728.

Zans, V.A., Chubb, L.J., Versey, H.R., Williams, J.B., Robinson, E., and Cooke, D.L., 1962, Synopsis of the geology of Jamaica. An explanation of the 1958 provincial geological map of Jamaica: Bull. Geol. Surv. Dept., Jam., 4, 72p.

Zoppis Bracci, L., 1957, Estudio geologico de la region de Palaguina y su deposito de antimonio: Bol. Serv. Geol. Nac. Nicaragua, v. 3, p. 29-34.

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