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CARIBBEAN GEOLOGY, 1970[1]

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ABSTRACT

Portions of Caribbean land and marine geology, based on data available through 1970 and early 1971, are summarized in an effort to present the known tectonic framework as well as to stimulate further attempts to integrate the geology of the Caribbean area into the new global tectonics.

Other than in Cuba, the oldest known rocks in the Greater Antilles are Cretaceous. Pre-Mesozoic rocks may be present in parts of Cuba, Hispaniola, and southwestern Puerto Rico, but metamorphism has complicated interpretations of age.

The Lesser Antilles are generally assumed to be younger than the Greater Antilles, but radiometric dates from Desirade suggest some continuity of igneous activity between the two regions. Recent work suggests that the Lesser Antilles are presently cross-faulted into individual blocks, with each one developing its own stress pattern during sea-floor spreading. However, basement structures of the Lesser Antilles may continue to at least as far as 65°W; both geological and geophysical evidence indicate that a south Caribbean fault does not exist.

Paleozoic rocks are known to underlie part of the Yucatan and central Florida, but the nature of the basement under the Bahamas and Blake Plateau is unknown. However, striking similarities in the Cretaceous to Recent geology of these areas and that of northern Cuba suggest that this entire region has behaved as a unit since the Cretaceous.

The Yucatan Basin and Cayman Trough contain the thinnest crust (9 km and 6 km) in the Caribbean area. These two features are separated from one another, and from the Gulf of Mexico to the north, and the Colombian Basin to the south, by parallel ridges or welts of continental crustal thickness. One or more of these positive features may contain pre-Mesozoic rocks.

The Cayman Trough is not a westward continuation of the Puerto Rico Trench, and may be a much younger feature.

Vertical tectonics dominate the Late Cretaceous to Recent geologic history all around the Caribbean, through the Greater and Lesser Antilles, as well as along northern Colombia and Venezuela. Land and marine evidence

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for extensive wrench faulting after the Late Cretaceous is slim. Prior to that time, fault motion in most areas is unknown or nonexistent.

Earthquake first motion studies indicate *active* wrench faulting on both the northern and southern Caribbean margins, as well as underthrusting in the Lesser Antilles and in the northeast Hispaniola region. Such studies indicate nothing concerning past motions.

Although several radically different tectonic models have been proposed to explain the origin of Caribbean geologic features, no one model has captured the enthusiasm of the majority of investigators.

Foreword

Interest in Caribbean-Antillean geology has been steadily increasing since the exciting pioneer work of Hess, Ewing, and Vening-Meinesz some 35 years ago. More recently Hess's 1962 Presidential Address before the Geological Society of America suggested a framework for the evolution of ocean basins which focused on the dynamic nature and interrelations of ocean ridges and island-arc trench systems. Since that time, his model, much of which was based upon years of sea and land observations in the Caribbean, has been the center of growing support from earth scientists from all areas and specialties.

It seems appropriate to review the known marine and land geology as well as to point out major unsolved problems within the Caribbean and adjacent regions, an area which truly might be termed the birthplace of the current revolution in the earth sciences.

Introduction

Within the rather small area of the earth's surface represented by the Caribbean-Antillean region, one can find active volcanos, earthquake belts, fracture zones, deep-sea trenches, several varieties and thicknesses of continental and oceanic crusts, as well as all categories of rock types and tectonic styles. In this area there are events occurring daily which are indicative of the pattern of the earth's tectonic activities. Here then is truly a place where processes operate at a rate fast enough to study within the working years of a scientist's lifetime. The prospects for the unraveling of the past two hundred million years of planetary history from the study of such an active area seem exceptionally good.

This is due in large part to the fact that a model exists to be tested, the outlines of which were suggested by Hess (1960, 1962) and Dietz (1961, 1962). One of their major contributions was to focus attention on the evolution of ocean basins as the areas of primary importance in planetary history of the last several hundred million years, rather than on the continents, which they suggested should be considered passive plates being acted upon.

During the past ten years geophysicists, led by Vine, Sykes, Oliver, Isacks, Morgan, LePichon, Menard, J. T. Wilson and many others, have offered compelling evidence to support the ideas of Hess and Dietz. Traditionally trained, continental-oriented geologists have been somewhat slower to re-think their tremendously greater amount of detailed data into a form which could be integrated within the new suggested framework. In their defense one might mention that, at least in the initial stages of what has been termed the "revolution in the earth sciences" (Wilson, 1968), many models suggested by marine geophysical data either ignored or violated entirely the known continental geological data.

More recently, exchange of data between the two groups and joint participation in such worldwide efforts as the Deep Sea Drilling Project has led to increasing cooperation and excitement.

McBirney (1970) has synthesized the borderland geology in the Circum-Pacific region and has emphasized that a fundamental discordance exists between the smoothly continuous sea-floor spreading process in ocean basins and the episodic nature of events at plate borders. This first-order type of discrepancy, which is not restricted to the Circum-Pacific, might be resolved if the earth sciences had acceptable, rigorous models of the driving mechanism of sea-floor spreading. There is no such widely accepted model to date, although Hess, Vening-Meinesz, Orowan and others have made a strong initial case for thermal convection models.

Most earth scientists would now agree that new material is being added to the earth's crust along active oceanic rises. An equivalent volume of older material is presumed to be recycled back into the mantle at the sites of island arcs and active continental margins. If this is not so, then the earth is expanding. This is a fundamental matter to settle, whether one's interest be global tectonics, the discovery of new mineral deposits, or the imminence and association of earthquakes and volcanism.

Geophysicists have done much to show that island-arc areas such as the Caribbean are sites of recycling. Narrow belts of negative isostatic gravity anomalies, a characteristic inclined zone of earthquake hypocenters, and a relatively narrow zone of volcanic activity support the idea that these are areas of the downturning of oceanic crust. Further support comes from regional seismic data in the Caribbean (Molnar & Sykes, 1969), the Tonga-Kermadec (Oliver & Isacks, 1967), the Aleutians (Stauder, 1968), and the Indonesia-Philippine region (Fitch & Molnar, 1970), which has led to the conclusion that the lithosphere dips beneath the island arcs.

The burden of decision for the correctness of this model now rests upon the geologist and geochemist who are the natural candidates to sample and examine carefully the areas where rock relationships can be seen directly, i.e., the islands and continental borderlands adjacent to the proposed sinks. It is they who must work out the time sequence of igneous, metamorphic,

sedimentary, and tectonic histories to serve as the basis for integration with continuing marine geological (direct sea-floor and subbottom sampling) and indirect geophysical (reflection, refraction, gravity, magnetics, etc.) studies.

The time is appropriate for a major effort to synthesize Caribbean earth-science data past, present, and future into the framework of the "new global tectonics." The amount of data produced to date by literally hundreds of organizations and individuals has far outstripped the rate at which it has been digested. And yet, since the Caribbean contains a model island arc, there is every reason to be optimistic that, by careful selection of research problems and with good organization, several of the problems listed below, many having worldwide significance, will be answered within the decade. Almost all involve a linking together of geological, geophysical, and geochemical data. The following pages list the known problems and review the current land and marine geologic data which reflect upon these problems.

The geophysical data used in this report are mainly from studies of reflection and refraction. There has been no attempt in this paper to summarize the existing scattered data which group under the categories of gravity, magnetics, and heat flow. None of these geophysical parameters have yet been published in compiled form for the Caribbean region. Gravity data are being compiled by C. O. Bowin at Woods Hole and M. Talwani at Lamont-Doherty, among others. Some Caribbean gravity data has appeared in various reports, e.g., Ewing (1937), Hess (1938), Talwani *et al.* (1959). Talwani (1966), Sutton *et al.* (1960), Worzel (1965), Bunce *et al.* (in press), Bowin (1968), Peter (1970), Folinsbee *et al.* (1969), Bowin & Folinsbee (1970), Officer *et al.* (1959), Masson-Smith & Andrews (1965), Ball *et al.* (in press), Lagaay (1969), Hospers (1958), Lyons (*in* Eardly, 1962), Bush & Bush (1969), Bromery & Griscom (1964), and Valencio (1964).

Caribbean magnetic data is presented in the reports by the U. S. Navy (1970), Griscom & Geddes (1966), Starr & Bassinger (1968), Fink (1968), Renard (1967), Bunce *et al.* (in press), Krause (1968), Lagaay (1969), Ball *et al.* (in press), Dennis & Gunn (1964), Ewing & Heezen (1955), Stewart & Raff (1961), Van Voorhis & Davis (1964), Gough & Heirtzler (1969), Drake *et al.* (1963), Gough (1967), Miller & Ewing (1956), Ewing *et al.* (1960), Bracey (1968), and Valencio (1964).

Paleomagnetic and rock magnetic property data is virtually nonexistent in the Caribbean although studies are now in progress by Harrison (University of Miami) and Fink (University of Maine) in Puerto Rico and the Lesser Antilles, and Briden (Leeds) in the Lesser Antilles. Griscom (1964) did some initial paleomagnetic work in Puerto Rico, and Guja & Vincenz (1970) and Watkins *et al.* (1970) have reported on the first work done in Jamaica. McDonald & Opdyke (1970) have reported a few measurements on a probable Cretaceous pole for northern South America.

There are between 100-150 heat flow measurements for the Caribbean area including the Gulf of Mexico and the nearby Atlantic. These are summarized and discussed by Nason & Lee (1964), Von Herzen *et al.* (1970), and Epp *et al.* (1970).

ACKNOWLEDGMENTS

Any review paper depends heavily upon the work of previous investigators. Liberal use has been made of earlier papers by MacDonald (1967), Fink (1968), Martin-Kaye (1959, 1960), Dengo (1967, 1969a), Edgar (1968), Officer *et al.* (1959), and Bunce *et al.* (in press). Weyl's book (1966) contains a great deal of information up to the mid-1960's and is particularly useful for references and maps produced prior to that time. Fink (1964) compiled an extensive bibliography of Caribbean geology to that date, and Beinroth (1969) and Hooker (1969) have compiled geologic references to Puerto Rico. Weaver's (1969) annual publication "Status of Geological Research in the Caribbean" is probably the best source for short reports on current research in the region.

I thank the following for granting permission to use previously published, copyrighted illustrations: The American Geophysical Union and the respective senior authors, for the use of Figures 4, 6, 10, 11, 12, and 14; Dr. L. K. Fink, Jr., for Figures 1 and 3; Dr. N. T. Edgar, for Figure 7; Dr. Lynn Glover, III, for Figure 13; the Gulf Coast Association of Geological Societies, for Figure 2; Interscience Publishers and the senior author, for Figure 9; and MacMillan (Journals) Limited, for Figure 16, originally published in *Nature,* London.

Following completion of the first draft of this manuscript (April, 1970), important contributions by E. J. MacGillavry (1970) and Dietz & Holden (1970) have come to my attention. Both of these stimulating papers offer fresh approaches to Caribbean tectonics, and both are briefly commented upon herein, under the section entitled Regional Tectonics.

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Samples from six additional, relatively inaccessible islands and dredge hauls from the Aves Ridge were collected in the summer of 1970 during R/V PILLSBURY cruise No. P-7007 (Univ. of Miami) supported by O.N.R. Grant No. 00014-67-A-0201-0013. The writer acknowledges with great pleasure the cooperation and efforts of Dr. C. G. A. Harrison, Chief Scientist, as well as the help and good spirits of both the marine and scientific crews during that cruise.

Problems of Caribbean Geology

Listed below (not necessarily in order of importance) are several major, unsolved problems of Caribbean geology. The list is undoubtedly incomplete, but serves as a framework for the summarized data of this report.

1. Geologic history in relation to the sea-floor-spreading–arc-underthrusting hypothesis.
2. Age and interpretation of the oldest rocks in the Caribbean region.
3. Nature of the crust (rock types) under the Gulf of Mexico, the Colombian, Venezuelan, and Yucatan basins, and under the Cayman Trough.
4. Nature of major faulting through time along the northern and southern Caribbean borders and relationships to cross-arc fracturing throughout the arc.
5. Relationships (if any) between the Puerto Rico Trench and the Cayman Trough.
6. Relationship of the Puerto Rico Trench to the geosynclinal concept.
7. Ages of the Lesser Antilles arcs, as compared to each other, the Greater Antilles, the Aves Ridge and the Beata Ridge.
8. Explanation of the decrease of volcanism in the Greater Antilles after mid-Eocene and decrease of volcanism in the Lesser Antilles during the Oligocene.
9. Relationship of eastern Lesser Antilles to: Greater Antilles, southern Antilles, northern South America, Central America, and Trinidad and Tobago (implied in problems 1 and 7).
10. Tectonic and age relationships between the Caribbean Island Arc province and the Bahamas.
11. Explanation of the petrogenesis of igneous rock types through time.
12. Explanation of gravity, magnetic and heat flow data in light of marine and land geology.
13. Determination of the significance of an apparent major hiatus in the Venezuelan Basin sedimentary record between upper Eocene and lower Miocene, as discovered during Leg IV of the GLOMAR CHALLENGER cruises (Bader *et al.*, 1970).
14. Interaction of the western Caribbean crust with the proposed eastward-moving Pacific crust.
15. Relative interplay of underthrusting, volcanism, earthquake generation, and fault zones with time, leading to an evaluation of potential earthquake and/or volcanic eruption hazards.

Geologic Summary

The Greater Antilles.—Studies by Officer *et al.* (1959), Talwani *et al.* (1959) and Worzel (1965) indicate that crustal masses 30 km thick underlie Puerto Rico. Probably this is representative for the rest of the Greater Antilles.

Metamorphic rocks (mainly metamorphosed marine sedimentary rocks and volcanic rocks), presumably the oldest rocks in the Greater Antilles, underlie areas of Cuba (Isle of Pines, Sierra de Trinidad, Las Villas Province, and eastern Oriente Province), Jamaica (Blue Mountains), Dominican Republic (Cordillera Central, Samana Peninsula), and the Sierra Bermeja area in southwest Puerto Rico.

Meyerhoff *et al.* (1969) reviewed the radiometric dates (nine) from Cuba and concluded that they represent two thermal events, one at 121-103 m.y. (Neocomian-Cenomanian) and another at 78-61 m.y. (Campanian–early Paleocene). The ages of the rocks involved in these thermal events are unknown. They reported one date of 180 m.y. (Early Jurassic) on a granodiorite from Las Vilas Province (K-Ar, whole rock) and remarked that its significance is not understood in terms of the known history of Cuba. The oldest rocks dated paleontologically in the entire Greater Antilles are Early through Middle Jurassic. These dates are from marine fossils within the San Cayento Formation in Pinar del Rio Province, western Cuba.

There are four radiometric ages known to the author from the Dominican Republic, all from the Cordillera Central (MacDonald, 1968c; personal communication from C. O. Bowin). These range from 127 ± 6 m.y. to 68 m.y. The only published radiometric date from Haiti known to the writer is reported by Kesler (1968b). This date 66.7 ± 1.3 m.y.) is from a quartz monzonite intrusive in Upper Cretaceous rocks.

In Puerto Rico the oldest known radiometric date is 110 ± 3 from an amphibolite in the Sierra Bermeja (Mattson, 1964, 1966), while the oldest published radiometric date from Jamaica is 65 ± 5 m.y. from a granodiorite intrusive in metamorphic rocks of unknown age (Chubb & Burke, 1963). In the Virgin Islands the oldest rocks are considered to be Cretaceous (Donnelly, 1966; Whetton, 1966; Helsley, 1960). The oldest radiometric date reported (108 m.y. by K-Ar) is for a small keratophyric intrusion which, according to Donnelly (1968), dates one of the latest events in these oldest rocks.

There is no positive evidence indicating the presence of Paleozoic or Precambrian rocks in the Greater Antilles. However, metamorphism has complicated the picture so that the possibility of pre-Mesozoic rocks cannot be ruled out, particularly for areas of Cuba (Meyerhoff *et al.*, 1969) and possibly the Samana Peninsula of Hispaniola (Nagle, 1970).

Also there is no evidence for a "granitic" basement in most of the Greater Antilles. On the other hand, there is some evidence from Cuba, Puerto Rico, and northern Hispaniola that serpentinites occur in cores of major anticlinal folds. Several workers have suggested that these rocks represent the original oceanic crust (Hess, 1960, 1964; Kozary, 1968; Mattson, 1960; Tobisch, 1968; Nagle, 1966). If this is so, then these rocks are amongst the oldest exposed rocks in the Greater Antilles. Some support to the idea of a serpentinized peridotite basement for the Greater Antilles comes from the work of Bowin *et al.* (1966) who dredged the north wall of the Puerto Rico trench and tentatively concluded that the stratigraphy there is "serpentinized peridotite with altered basalt overlain by Upper Cretaceous sedimentary rocks which are in turn overlain by Lower Tertiary sedimentary rocks with minor vitric basalt."

In contrast to this, Hess (1964: 170) points out: "On the south side of the Caribbean, in the Cordillera de la Costa of Venezuela, the cores of major anticlines have a granitic gneiss basement underlying metamorphosed sedimentary rocks of Cretaceous age (Aquerrevere and Zuloaga, 1937; Dengo, 1953; Smith, 1953; Seiders, 1962; Menendez, 1962). The conclusion might be drawn that the coast range of Venezuela rests upon the thin edge of a continent and has 'granitic' crust beneath it, whereas the Greater Antilles rest directly upon oceanic crust."

MacGillavry (1970) takes a different point of view, at least for western Cuba, and points out that there are sialic metamorphic rocks on Isle of Pines, in the Trinidad Mountains, and in evaporite diapirs (Meyerhoff & Hatten, 1968) and that sialic detritus is present in the San Cayento formation. MacGillavry favors the view that a spur of old metamorphics from Guatemala and Honduras continued into the Caribbean area. Later this spur was broken into separate masses (e.g., Isle of Pines) during island-arc tectonism. Some recent support for this view is offered by Baie (1970) who reports two basement ridges paralleling the eastern Yucatan coast, one of which changes strike to the northeast across the Cuban shelf so that it is on strike with the Isle of Pines.

There is the possibility that other "spurs" containing a basement of sialic (quartzitic) possibly pre-Mesozoic metamorphic rocks extend into the Caribbean under the Cayman Ridge and Nicaraguan Rise.

The Cretaceous to middle Eocene Greater Antillean volcanic rocks are predominantly andesitic flows and pyroclastics preceded by spilites and keratophyres or basalt flows (Donnelly, 1964, 1966; Mattson, 1966; Lidiak, 1965; Bowin, 1966; Nagle, 1966; Palmer, 1963).

Tertiary rocks in the Greater Antilles are mainly marine clastic rocks and limestones; volcanism virtually ceased, following the middle Eocene, with the exception of minor activity during the Miocene in Jamaica and Pleistocene (?) in southwestern Hispaniola (MacDonald & Melson, 1969). The latter occurrence is noteworthy in that the rocks are undersaturated alkaline mafic types (nepheline basalt, limburgite). MacDonald & Melson suggest a relationship between the volcanic province, the Bartlett Trough, the Cul-de-Sac graben, and other east-west tectonic features to a major shear system in the upper mantle. These rock types are unique to the Caribbean islands, except for rocks of similar type and age on the island of Utila (McBirney & Bass, 1969b) on the southern border of the Bartlett Trough and possibly on Providence Island (Mitchell, 1955) 240 km east of Nicaragua on the Nicaraguan Rise.

The Lesser Antilles.—The Lesser Antilles will be discussed as two major geographic groups of islands. First, the eastern Lesser Antilles, or *Eastern Antilles,* which is composed of a N-S geographic arc of islands extending

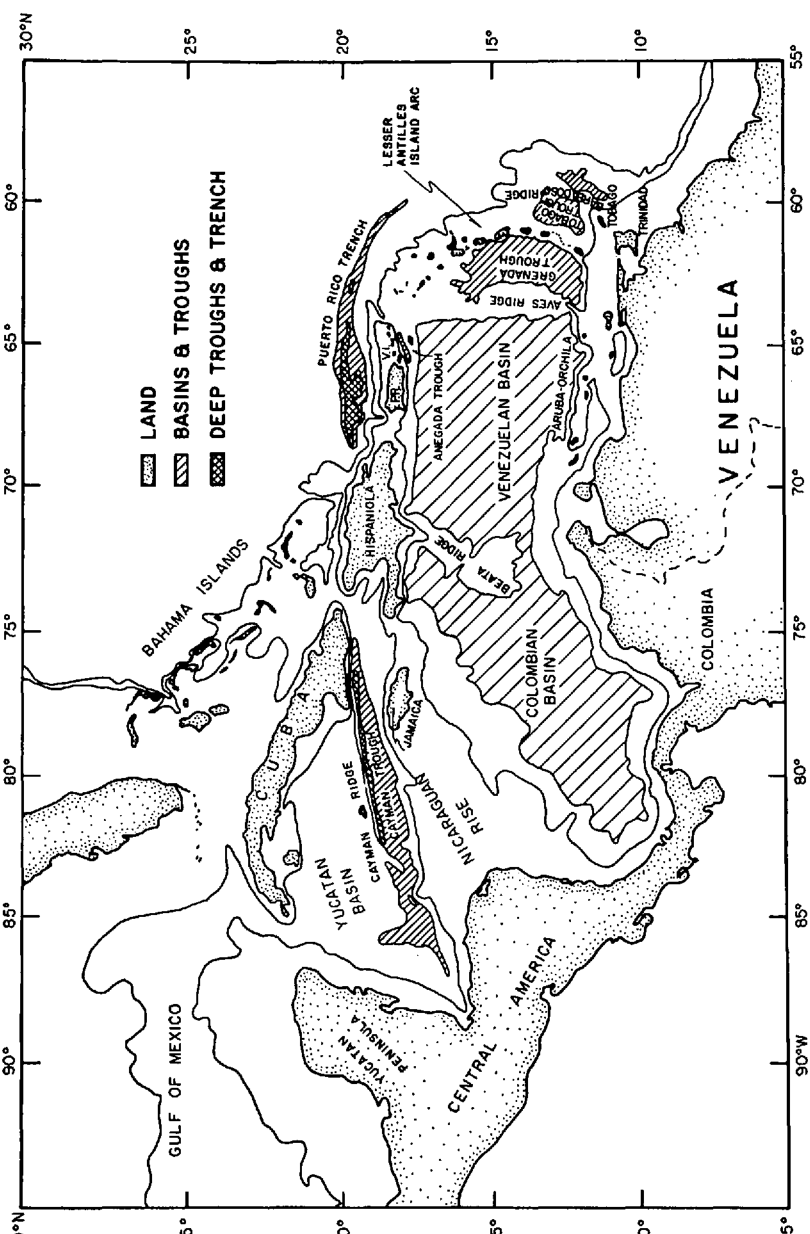

FIGURE 1. Physiographic features of the Caribbean. (From Fink, 1968.)

almost 450 miles from Anguilla in the north to Grenada in the south. Second, the southern Lesser Antilles, or *Southern Antilles,* which form an E-W geographic line of islands off the Venezuelan coast extending almost 450 miles from the Venezuelan Testigos group in the east to the Dutch island of Aruba in the west.

1. EASTERN ANTILLES: The rocks are calc-alkaline in the basalt-andesite-dacite-rhyolite association, with andesite predominating, typical of this association in orogenic belts. The island arc forms the eastern boundary between the Caribbean Sea and the Atlantic Ocean (Figs. 1, 2). Based on paleontologic determinations, the oldest rocks of the island chain are represented by the lower to middle Eocene volcaniclastics of St. Bartholomew (Christman, 1953) and Mayreau (Martin-Kaye, 1960) and the upper Eocene ones in Grenada and Carriacou (Martin-Kaye, *ibid.*). There are no published radiometric dates, with the exception of one reported by Fink (1970) and those discussed below. The only interruption in volcanic activity from lower Tertiary to the present was during the Miocene when widespread submergence occurred throughout the Caribbean, as marked by the deposition of shallow-water marine limestones (Martin-Kaye, *ibid.*).

The islands of the Eastern Antilles have been divided into the Limestone Caribbees (including Marie Galante, La Desirade, Grand Terre, Antigua, St. Bartholomew, St. Martin, Anguilla, Dog, and Sombrero islands) and the Volcanic Caribbees which include Grenada, the Grenadines, St. Vincent, St. Lucia, Martinique, Dominica, the Isles des Saintes, Basse Terre, Montserrat, Nevis, St. Kitts, St. Eustatius, and Saba. This division is based on the predominant rock type cropping out on the two rows of islands north of Dominica.

The geologic history of the Limestone Caribbees is presently interpreted as middle Eocene to late Oligocene volcanism followed by erosion, partial truncation, minor intrusions and faulting, then a late Oligocene–early Miocene cap of shallow-water marine limestones, followed by late Miocene uplift.

The geologic history of the Volcanic Caribbees is different north and south of the island of Dominica. The islands north of Dominica (Isles des Saintes, Basse Terre, Montserrat, Nevis, St. Kitts, St. Eustatius and Saba) are composed of volcanic rocks of latest Miocene or early Pliocene to Recent age. There are no intrusions, deformation is minor and the few sedimentary deposits are thin, ranging in age from Pleistocene to Recent. The islands south of Dominica (Martinique, St. Lucia, St. Vincent, the Grenadines, and Grenada) also have late Miocene to Recent volcanic rocks, but in addition may have older volcanic rocks, similar to those of the Limestone Caribbees, suggested by workers to range in age from middle Eocene to lower Miocene. It is not known whether the older volcanics underlie the younger series on Dominica.

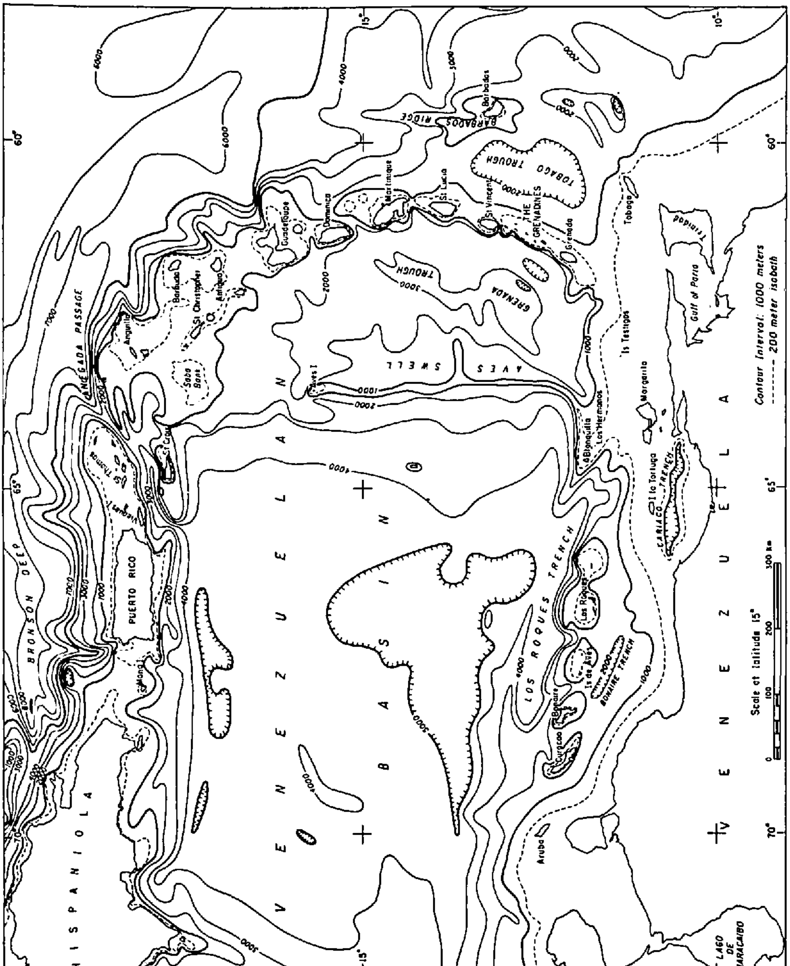

FIGURE 2. Location and generalized bathymetric map of the Antilles islands and Venezuelan Basin. (From Bush & Bush, 1969.)

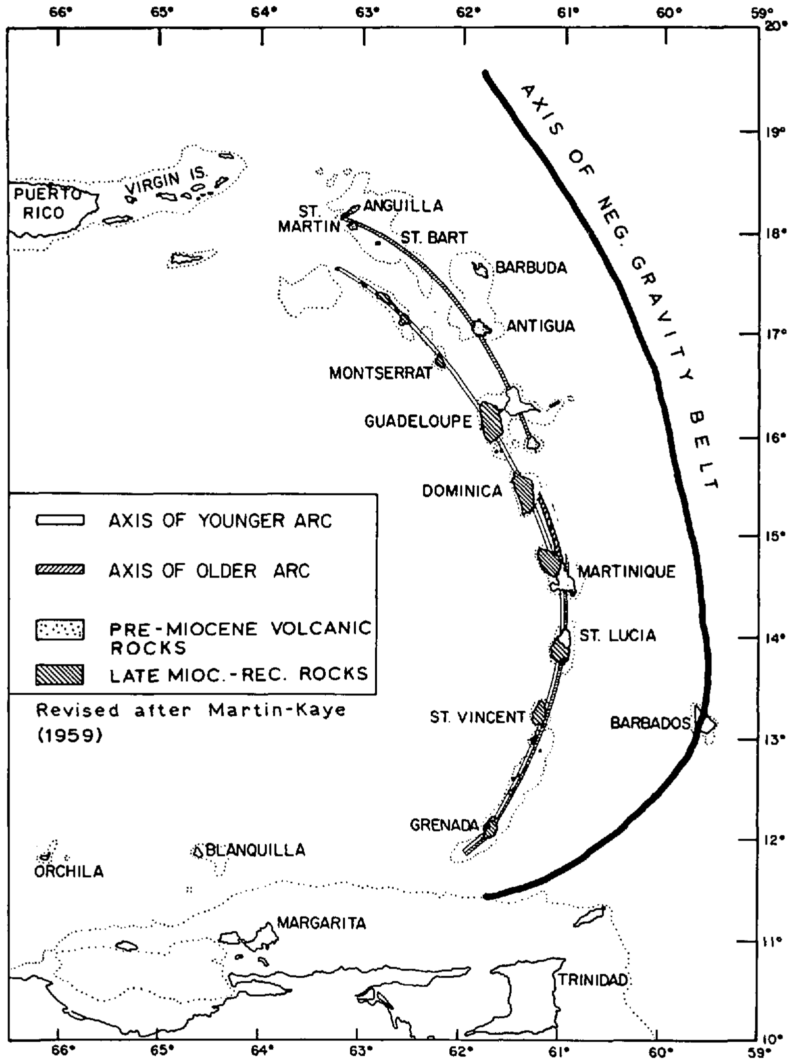

FIGURE 3. Lesser Antilles island arc, with axes of older and younger arcs and axis of negative gravity anomaly belt indicated. (From Fink, 1968.)

Thus there are two age zones of volcanism in the Eastern Antilles arc. These zones are superimposed south of Dominica, but to the north of this island the older zone is offset to the east (Fig. 3).

Martin-Kaye (1960) suggested that the double arc north of Dominica was due to differential eastward movement of the older arc by the tectogene

mechanism, and that the processes controlling the locus of the volcanics were lower crust or upper mantle processes unaffected by upper crustal movement.

Christman (1953) suggested a similar eastward movement of the older features in the St. Bartholomew–St. Martin region based on consistently increasing distances from the gravity anomaly axis of three early Tertiary volcanic centers. He assumed that crustal rolling to the east into a deep-sea trench moved the older centers eastward.

Fink (1968, 1970) discovered a spilite-keratophyre sequence on La Desirade, apparently Jurassic in age, indicating the Eastern Antilles may be a much older feature than heretofore thought. He suggested that the Greater and Lesser Antilles may be one continuous feature with similar pre-Miocene histories.

During February 1970, Fink, J. J. Stipp, and the writer collected samples of a variety of igneous rock units on La Desirade. Preliminary K/Ar dating by Stipp and Chris Harper (Florida State University) yielded several dates ranging in age from 50-140 m.y.; all but a few, Cretaceous or older. These initial results suggest igneous activity in the Lesser Antilles contemporaneous with some of the earliest known episodes of igneous activity in the Greater Antilles. The results are in accord with Fink's earlier suggestion of ancient continuity between the two areas.

Fink (1968) also suggested, from a study of the marine geology of the Guadeloupe region, a major offset of the arc along a line immediately north of Dominica caused by eastward crustal translation of the arc ridge segment north of this line, during the late Eocene to middle Miocene. He attributed this movement to contrasting crustal response due to an interruption in intracrustal tectonic processes rather than large-scale eastward movement of a Caribbean plate via the tectogene mechanism. Such contrasting responses, he suggested, might have resulted from the presence of the thick accumulation of sediment filling the southern part of a pre-Miocene deep-sea trench. This caused a slower rate of isostatic adjustment in the southern part of the arc as compared to the northern part during cessation of crustal underriding from the east. Also produced was a major crustal fracture, along which relative offset resulted in an eastward crustal translation for the northern segment of the older arc. When volcanic activity was renewed it produced the younger volcanic arc continuous from Grenada to Saba.

The above contrasting views suggest that the source rocks and evolutionary history of the volcanic rocks in the West Indian arc remain very controversial. The generalities agreed upon by most workers are that basaltic rocks are more abundant among older rocks, that andesitic rocks are more common in younger volcanic rock series, and that in most islands andesitic volcanic products are more abundantly exposed. However, suggestions as to the genetic relations between these two major rock types as well as the

source regions for each seem nearly as varied as the number of problems studied. Apparently, no one individual or group has examined rocks of either type from more than a few of the islands within the arc.

The most important recent papers relating chemistry of igneous rocks to tectonics are papers by Tomblin (1968, 1969) and Donnelly *et al.* (in press). Particularly noteworthy in the light of Fink's work (1968) and earlier work of Donnelly (1967a) is the conclusion of Tomblin (1969), based on earthquake data, that the Eastern Antilles arc is cross faulted into blocks, with each developing its own stress pattern during sea-floor spreading. This in turn, he suggests, would affect earthquake distribution, depth of magma genesis and timing of volcanism within each block. This individual blocklike behavior is in addition to a major structural control—a westward dipping Benioff zone which has produced volcanic centers in a general north-south arcuate line.

2. SOUTHERN ANTILLES: It is very uncertain as to what happens to the Lesser Antilles structural trend south of Grenada. Weeks *et al.* (1969) and Lattimore *et al.* (1970) suggest that this structural trend is traceable into the Paria Shelf. However, the rock types on Grenada (unmetamorphosed sediments, basalts, and andesites) do not correlate with the older, highly metamorphosed rocks and complex structures in northern Margarita. What is known about the rocks in Margarita (W. Maresch, personal communication, 1970; Taylor, 1960; Hess & Maxwell, 1949) suggests similarities to basement rocks in the Venezuelan coastal ranges.

In the summer of 1970, the writer participated in R/V PILLSBURY cruise P-7007, during which landings were made on Testigo Grande and Frailes Grande, located between Grenada and Margarita, on the continuation of the Eastern Lesser Antilles trend. The rocks from these islands proved to be essentially unmetamorphosed, in contrast to those in northeast Margarita less than 20 km from Frailes Grande. One might be tempted to look for a fault separating these rock types trending approximately N45°W between the Frailes Group and Margarita. A shallow-level fault with approximately that trend has been suggested by Lattimore *et al.* (1970) between the Testigo Islands and Grenada.

Peter (1971) presents evidence that the structural trends of the Aves Ridge, Lesser Antilles arc, and Grenada Trough extend to 65°W, where they are either interrupted or truncated by a major NW-SE fault system bordering the Los Roques Canyon, continuing along the Urica fault onshore. He suggests that this fault zone has been in existence since Cretaceous, which would then allow little east-west displacement along the northeast Venezuelan margin during the Cenozoic.

The basement of rocks of Aruba, Bonaire, Curaçao (Lagaay, 1969; Beets, 1968; MacDonald, 1968d), although similar to one another (basic lavas, tuffs, dikes, and sills and larger diorite to granite intrusions) seem

not to be related to the Eastern Antilles (Fig. 2). The offshore islands of Blanquilla, Orchila, and the Hermanos group also have quartz diorite intrusions. Amphibolite also occurs in the Los Hermanos island group (Maloney, 1968) and on Orchila (Schubert, 1970). Thus, neither does this entire group of islands have a geology similar to Margarita.

One might presently postulate that Margarita, Tobago, and Trinidad (also anomalous islands in the Lesser Antilles) have formed on the South American continental shelf independently of the Lesser Antilles. Aruba, Bonaire, Curaçao, Blanquilla and the Hermanos group perhaps belong together as another independent group. The few radiometric dates reported on diorite intrusions (Lagaay, 1969) within the basal complex of both Aruba and Curaçao fall within a 65-80 m.y. range. Similar dates have been reported from intrusive rocks dredged from offshore of Blanquilla (Peter, 1971) and the western flank of the southern Aves Ridge (geological hearsay; see also Fox & Heezen, 1969), suggesting a connection between these islands and the Aves Ridge. The two could very well be an older arcuate structure inside the Lesser Antillean arc. MacDonald (1968d) suggested that there are similarities in metamorphic facies between Aruba and the Guajira Peninsula, indicating a westward extension of this older arc to at least the Guajira.

Several writers, amongst them Barr & Saunders (1968), Barr (1958), and MacDonald (1967) have postulated a major fault separating the structure of the Eastern Antilles from northern South America. This fault has not yet been found, and extensive seismic profiling work (L. Austin Weeks, personal communication; Hurley, 1966) indicates that this fault does not exist (see also Weeks, 1971; and Bassinger *et al.*, in press).

Central America.—In contrast to the Greater and Lesser Antilles, the Central American region has a basement of Paleozoic and perhaps older continental crust. Dengo (1962, 1967, 1969a) and Dengo & Bohnenberger (1969) have presented the latest and most complete summaries of that region. Central America is defined by Dengo (1967) as "the land and continental shelf area which extends from the Isthmus of Tehauntepec in Mexico east- and southeastwards to the Atrato lowland in Colombia." It is divided into two main geological units which had different tectonic histories and present different crustal structure.

North of central Nicaragua, the basement is Paleozoic or older rock overlain by upper Paleozoic, Mesozoic, and Cenozoic sedimentary rocks. The basement in this region presents two areas of metamorphic grade: metamorphic rock of the amphibolite facies in the northern part of the province, and phyllites and schists of the greenschist facies in the southern part. These areas are essentially separated along the Motagua fault zone in central Guatemala, a NE-SW zone of complex structures and faulting.

The oldest rocks in all Central America are in the northern province and

are either Precambrian or early Paleozoic. The closest dated Precambrian terrain is in southern Mexico (Fries *et al.*, 1966), but the relationship of these ages to the northern Central American province is unknown. Gomberg *et al.* (1968) suggested a Devonian age for some of these rocks which are carrying Precambrian zircons. Recent determinations from a core in the Yucatan indicates a probable age of 420 m.y. and a possible metamorphic event at 330 m.y. (written communication by M. N. Bass, reported by Dengo, 1969a).

Pre-Mesozoic rocks are not known south of central Nicaragua. Basement rocks here are Mesozoic basic volcanic and hypabyssal igneous rocks, with subordinate sedimentary rocks.

Both provinces share an active volcanic province on the Pacific side parallel to the Middle American Trench, as well as having late Tertiary volcanism in common. The tectonics and volcanism of this late-Tertiary-to-present-day volcanic province have recently been reviewed by Dengo *et al.* (1970).

Dengo (1969a) reviewed several past papers in which authors have attempted to correlate the Paleozoic belt of Central America to the southern Appalachians; he pointed out that all of these correlations depend upon rotation of northern Central America in one way or another, if such a continuation is upheld. Dengo (*ibid.*) supports the view that the Paleozoic history of northern Central America can be linked more easily with that of Mexico and that this does not rule out the possibility of drift at the end of the Paleozoic. Kesler & Heath (1970), on the basis of a structural study of Precambrian metasediments in Southern Mexico, support the idea of a Precambrian structural belt from Texas into Mexico.

Special mention should be made of the wide zone of serpentinites and serpentinized peridotites that crops out from Chiapos, Mexico, through Guatemala to the Bay Islands off the coast of Honduras (Dengo, 1969b; McBirney & Bass, 1969a, 1969b; Kesler *et al.*, 1970; Donnelly *et al.*, 1968). Major fold axes turn from NW-SE to generally NE-SW along this trend. Also, several major faults, perhaps related to the Bartlett Trough, are present in this area with roughly NE-SW trends. McBirney (1963) and McBirney & Bass (1969a) suggested that the ultramafic rocks represent mantle material emplaced along the fault zones. Some support for this idea comes from the presence of such rocks as amphibolite and eclogite (Dengo, 1967; McBirney *et al.*, 1967), along the same zone.

Dengo (1969b) points out that these serpentinites occur in an area where the crust is continental in character, pre-Carboniferous in age, and that they have been remobilized several times after having first been exposed to the surface during the Maastrichtian (Bonis, 1966).

Detailed geologic studies on the landward extension of the Bartlett fault system through Guatemala and northern Honduras (Donnelly *et al.*, 1968;

McBirney & Bass, 1969a; Meyerhoff, 1966) show no evidence here for major left lateral post-Cretaceous offset of the system suggested by Hess & Maxwell (1953).

Dengo (1969a) has suggested that if the serpentinites in Cuba and Guatemala are eventually proven to have had continuity in some past time, their separation now indicates relative northward motion of Cuba which in turn would imply that the Yucatan Basin is younger than the Colombian and Venezuelan basins. The relationship of the geology of Cuba to the geology of Central America and to the history of the Yucatan Basin is unknown.

Southern North America and the Bahamas.—In evaluating evolutionary geological processes concerning the Caribbean and the Americas, the most important structural trend in southern North America is that of the Appalachians. Southwest-trending magnetic anomalies described by Heirtzler *et al.* (1966) in the west Florida shelf strike along with the southwest trend of the Paleozoic Appalachian structures, which disappear under younger cover in central Alabama, suggesting a westward subsurface continuation. However, Paleozoic, igneous, and metavolcanic rocks have been found in wells as far south as central Florida (Milton & Grasty, 1969) and Gough (1967) describes southwestward trending magnetic structures in this area. It would be difficult to reconcile the southwestward trends in both these areas to an Appalachian projection through the Ouachita Mountains toward the west as proposed by many workers without either a large left lateral fault in northern Florida or "pull apart" between the western edge of the Florida shelf and the Ouachitas (Muehlberger, 1965; Tanner, 1965; Bass, 1969).

Equally tenuous are extrapolations of the Florida Paleozoic basement south toward Cuba or to the east toward the Bahamian platform. The age of the "basement" rocks in Cuba is obscured by metamorphism (see section on Greater Antilles), the geologic history across the Florida Straits toward Cuba is complex (Bryant *et al.*, 1969), and the nature of the rocks underlying the carbonate rocks of the Bahamian platform is unknown.

Recent models of the geologic history of the Bahamian platform (Lynts, 1970; Dietz *et al.*, 1970), a region of 40,000 square miles, present interesting speculative models which attempt to tie together the Bahamas, the Caribbean, and sea-floor spreading. The facts that these and other hypotheses must account for are: (1) the Bahamas are presently seismically inactive; (2) the regional topography is characterized by deep troughs, shallow banks, and low-lying islands; (3) evidence from two wells, one on Andros Island (Spencer, 1967), the other on Cay Sal (Furrazola-Bermudez *et al.*, 1964), indicates that the Bahamian platform since the Lower Cretaceous has subsided on the order of 5000 m; both wells penetrated essentially continuous shallow-water carbonates (minor anhydrite in the Cay Sal well); (4) there is no room for the Bahamas in the current prerifting reconstruction

models such as suggested by Bullard *et al.* (1965); (5) the nature of the platform basement is unknown and its depth, although probably irregular is a controversial topic (Emiliani, 1965; Furrazola-Bermudez *et al.*, 1964; Talwani *et al.*, 1959; Sheridan *et al.*, 1966; Ball, unpublished data); (6) JOIDES Site No. 4, drilled east of San Salvador, bottomed in Upper Jurassic sediments at 279 m, and seismic reflection results showed approximately 400 m of sediments below that to acoustic basement; while at Site No. 100 in approximately the same area, basalt was encountered at 315 m overlain by limestones of latest Middle Jurassic age (Deep Sea Drilling Project, 1970b); and (7) the timing and relative importance of faulting, folding, subaerial erosion, submarine erosion, and carbonate upbuilding in controlling the Bahamian topography and history is unclear (Andrews *et al.*, 1970; Ball, 1967; Lynts, 1970; Hess, 1933, 1960), although it seems generally agreed that submarine erosion and carbonate upbuilding have controlled the bank configuration at least since the Early Cretaceous. Recent results from JOIDES Site No. 98 support such a carbonate upbuilding upon a subsiding platform since at least the Middle Cretaceous (Deep Sea Drilling Project, 1970b).

Sheridan *et al.* (1970) have pointed out that the oldest sediments found in JOIDES Sites No. 4 and No. 100 are deep-water facies implying little or no vertical movement east of the Blake escarpment since Late Jurassic, while, to the west, vertical subsidence has been extensive. They have presented evidence for tilting along a subsurface fault 8 km east of the escarpment bordering Great Abaco Island and striking parallel to it (approximately N20°E), as well as evidence for right lateral movement on another fault (Great Abaco fault) striking at right angles to the first fault.

A major unsolved problem is the relationship of the Bahama platform to adjacent regions. Southern Florida to the northwest and the Blake Plateau to the north as well as the Yucatan to the southwest apparently have had histories similar to that of the Bahamas since the Early Cretaceous (Heezen & Sheridan, 1966; Sheridan, 1968; Deep Sea Drilling Project, 1970b; Sheridan *et al.*, 1969; Malloy & Hurley, 1970; Paine & Meyerhoff, 1970), while immediately to the south a volcanic island arc was developing during the same time.

Northern South America.—Recent summaries of the geologic history of all or part of northern South America are included in the reports of Mencher (1963), Oxburgh (1966), Menendez (1967), Morgan (1967), Bell (1967, 1968), MacDonald (1968b, 1969), Schubert (1969), and Gonzalez & Munoz (1968). Some 18 Ph.D. studies and other papers directed by H. H. Hess have been completed in selected areas along an approximately east-west line from the Guajira Peninsula in northern Colombia, through the Venezuela Coast Range and the Araya Peninsula to Margarita and Tobago.

These are indexed and several have been published in three publications of the Geological Society of America dedicated entirely to Caribbean geology (Bull. Geol. Soc. Am., Jan. 1953, March 1960; and Mem. Geol. Soc. Am., No. 98, 1966). Several others were published in the Transactions of the five Caribbean Geological Conferences held to date, as well as in foreign publications.

The presence of pre-Mesozoic rocks in the Caribbean Mountains of Northern Venezuela has never been demonstrated, although long suspected. Presently it is believed that the metamorphic rocks of coastal northern South America from Trinidad to the Guajira were metamorphosed during the Cretaceous–early Tertiary interval during a series of several episodes (Hess, 1960b). As in the Greater Antilles, metamorphism has complicated the radiometric age determinations and interpretations of suspected pre-Mesozoic rocks in these areas.

MacDonald & Hurley (1969) reported a Rb-Sr age in the west of 1400 m.y. (the oldest known rocks in Colombia) from a high-grade metamorphic rock (horneblende-plagioclase gneiss) on the northern flank of the Sierra Nevada de Santa Marta in northern Colombia, confirming the geological deductions of Gansser (1955) concerning their Precambrian age. MacDonald & Hurley (1969) suggested that this area represents an uplifted remnant of the Guayana Shield, which extends northwestward beneath younger sedimentary rocks into the Andes of Venezuela and Colombia. To the south, some 800 km, Precambrian ages of about 1200 m.y. have been reported from localities near the Macarena Mountains east of the Andes in eastern Colombia (Pinson *et al.*, 1962; Hurley *et al.*, 1968). Bass & Shagam (1960) reported Paleozoic Rb-Sr ages of some metamorphic rocks of the Venezuela (Merida) Andes.

However, in most of northern Colombia and Venezuela, thick Mesozoic and Tertiary deposits obscure the pre-Mesozoic (?) rocks. In the Guajira peninsula MacDonald (1968b) described metamorphic rocks of possible pre-Mesozoic age intruded by granodiorite. Pegmatites associated with the granodiorite yield a minimum age of 195 m.y. ± 4 per cent. MacDonald (*ibid.*) believes that there are two periods of pre-Mesozoic as well as a period of late-Cretaceous-to-early-Tertiary metamorphism. The rocks in this area are mostly sediments and metasediments. Volcanic activity was minor in the Mesozoic and absent in the Tertiary.

To the east, in the coastal range of Venezuela, there are two major series of metamorphics: one metasedimentary sequence to the north (Caracas Group) and one essentially metavolcanic sequence to the south (Villa de Cura Group). These belts extend for several hundred kilometers in an east-west direction and for most of this distance are separated by a fault zone (the Paracotos graben) within which are very lightly metamorphosed sedi-

ments of Late Cretaceous age and serpentinites. The age of these belts relative to each other is unknown, although the Caracas Group is considered by many to be older, originally overlain by the Villa de Cura Group. The Caracas Group rests uncomformably on the Sebastopol granitic gneiss complex, also of unknown age but presumably of pre-Mesozoic (?) age. One other possible pre-Mesozoic basement outcrop is the Tinaco Complex, a metamorphosed sedimentary sequence of arkoses and impure quartzites (Oxburgh, 1966), occurring between Tinaco, El Pao, and Tinaquillo. The oldest dated rocks to rest upon it are unmetamorphosed Albian limestones (Renz & Short, 1960). The rocks are metamorphosed to the almandite-amphibolite facies, a higher grade than the Villa de Cura Group. Menendez (1967) correlated some of the units of the Caracas Group with units found in the El Tinaco complex, reinterpreting them as basement exposures. Further, Menendez pointed out that the presence of dated Late Jurassic beds along strike in the metamorphosed phyllites, quartzites, and recrystallized limestones in the Northern Range of Trinidad (Barr & Saunders, 1968; Potter, 1968; Furrer, 1968) and of possible Jurassic fossils from the Las Brises formation (Wolcott, 1943; Dusenbury & Wolcott, 1949; Bucher, 1952) favor a Late Jurassic age for the base of the Caracas Group.

In general, metamorphic grade in the coastal ranges increases to the north, over most of the range. Cretaceous (Albian?) metamorphism was most intense (Hess, 1960b), and other periods of metamorphism may have ranged into the Eocene (Von der Osten & Zozaya, 1957). Much interest has centered about the problem of the relation of the Caracas and Villa de Cura Groups. Presently they are nowhere in contact. Based on structural, paleogeographic, and metamorphic grade interpretations, the majority opinion suggests extensive gravity sliding and/or thrusting of the Villa de Cura Group south to its present position (Menendez, 1962; Seiders, 1962; Bell, 1967; Hess, 1966). Bell (1967) summed up much of the earlier evidence for the movement of this massive unit (approximately 100 miles long, 12 miles wide, and 15,000 feet thick) and suggested, on the basis of his work, that the Villa de Cura Group moved 45 km south during Maestrichtian through Miocene time, although Menendez (1967) favors a late Maestrichtian time of Villa de Cura sliding.

MacDonald (1969) noted similar southward thrusting of metamorphosed Mesozoic rocks during Latest Cretaceous to late Eocene in the Guajira Peninsula. He made the important observation that the direction and timing of this thrusting–gravity sliding appears to be regional (Santa Marta, Colombia; Guajira; Paraguana Peninsula; Caribbean Mountains, Venezuela) and suggested a regional uplift in the South Caribbean at, or north of, the present coastline during the Late Cretaceous and early Tertiary. Bell (1970) and MacGillavry (1970) have suggested Caribbean plate motions other than

right lateral with respect to the American plates, in order to explain overthrusting episodes.

Mencher (1963) pointed out that genetic and structural continuity of the Venezuelan Andes and the Venezuelan coastal ranges is questionable since these two ranges differ from each other in the following ways: "(a) The Coast Range had its origin in a trough of geosynclinal character, the Venezuelan Andes did not. (b) Many of the Coast Range rocks were metamorphosed during deformation; no metamorphism took place during the Andean orogeny. (c) Volcanism was common in the Coast Range both before and during deformation; no post–lower Miocene volcanism is known in the Venezuelan Andes. (d) The Coast Range has a belt of sepentinites; the Andes do not. (e) The major deformation of the Coast Range was Middle to Late Cretaceous; that of the Andes was latest Eocene to Miocene."[2]

On the other hand, Hess (1960b) suggested that there may be a close connection between island arcs, alpine mountain ridges (specifically, the Venezuelan coastal ranges), and germano-type mountains such as the Venezuelan Andes. He suggested that "the mechanics of deformation in these cases are similar but the thickness and character of the crust are different, hence the structural results are different." He agreed that the Venezuelan Andes are somewhat younger than the coastal ranges and the Greater Antilles but suggested that the area is an example of transitions in structure along a continuous belt from oceanic crust (the Antilles) to marginal continental crust (coastal ranges) to continental crustal conditions (Venezuelan Andes). That the crust under the Greater Antilles is different from that under the coastal ranges is suggested from the fact that serpentinite and basic volcanic rocks occur in the cores of major anticlinal structures in southwestern Puerto Rico, northern Dominican Republic, and eastern Cuba, while granitic rocks are in the cores of major anticlinal folds in the Venezuelan coastal ranges.

Marine Features.—1. GULF OF MEXICO: A wealth of data concerning the nature and origin of the basin of the Gulf of Mexico can be found in the following papers: Antoine & Bryant (1969); Ewing, Worzel & Burk (1969); Ewing, Edgar & Antoine (in press); Worzel, Leyden & Ewing (1968); Antoine (1968); Gough (1967); Talwani & Ewing (1966); Heirtzler, Burckle & Peter (1966); Ewing, Worzel & Ewing (1962); Antoine & Ewing (1963); and Ewing *et al.* (1955). The most recent, comprehensive, regional review, including an extensive reference list, is that of Paine & Meyerhoff (1970).

In 1955, Ewing *et al.* suggested from seismic refraction data that the crust underlying the Gulf of Mexico is thin and of oceanic character. Later work (Ewing *et al.*, 1960; Ewing *et al.*, 1962) showed that although the Gulf basin has a much thicker sedimentary section than that in a typical ocean

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[2] Permission to quote was granted by the American Association of Petroleum Geologists, Tulsa, Oklahoma.

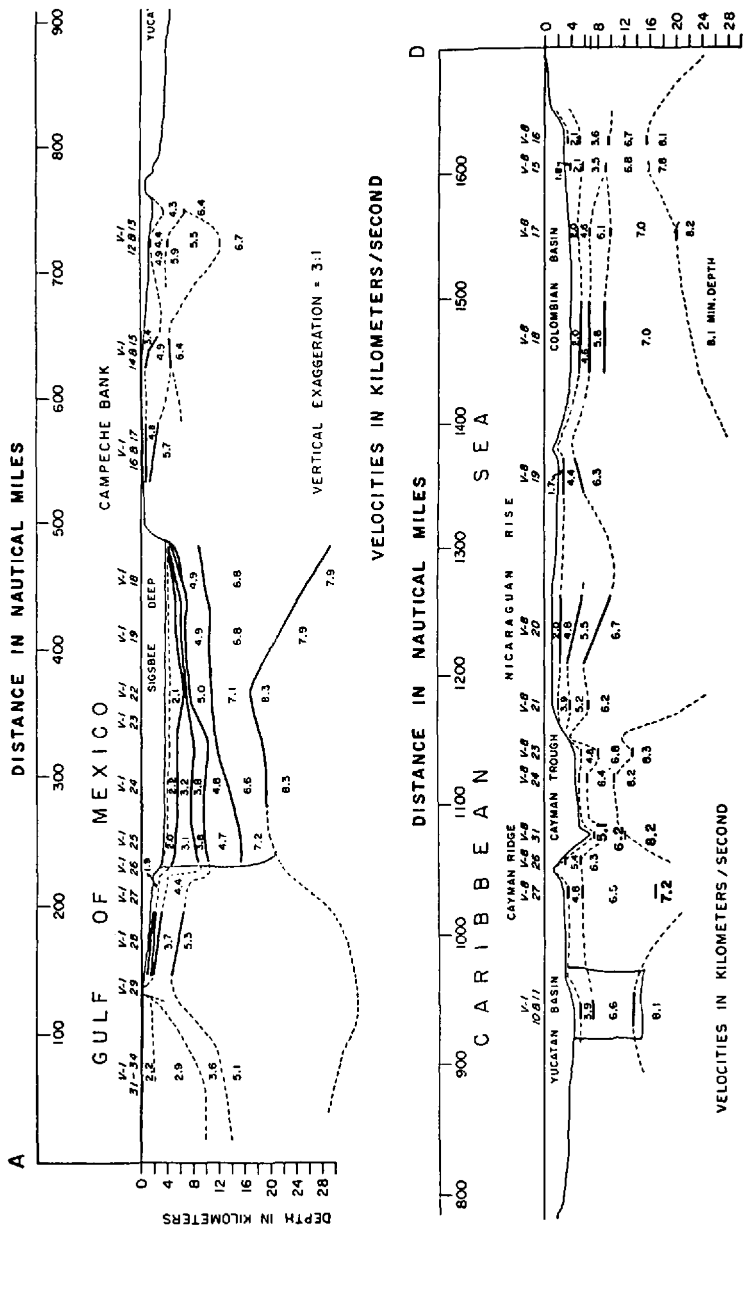

FIGURE 4. Structural section A-D from Galveston, Texas (A) to Cartagena, Colombia (D). (Modified from Ewing, Antoine & Ewing, 1960.)

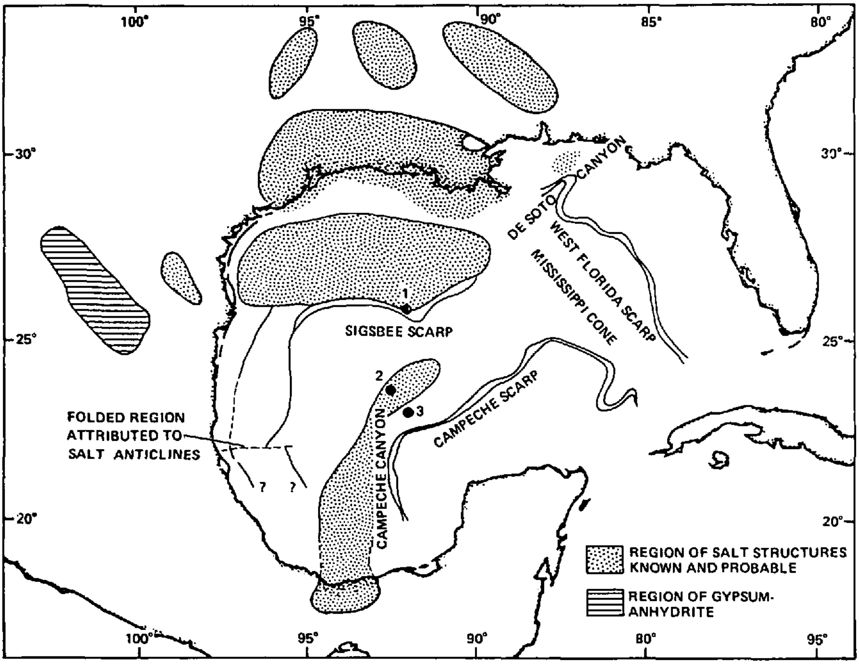

FIGURE 5. Physiographic diagram of Gulf of Mexico, showing locations of Sites 1, 2, and 3, from Deep Sea Drilling Project, Leg I. (From Ewing, Worzel, Beall *et al.*, 1969.)

basin, the crust underneath is oceanic (Fig. 4). In the Gulf basin an oceanic crustal layer (V_p = 6.6-7.2 km/sec) about 6 km thick is overlain by layered rocks of 6 to 12 km thickness. An average value of crustal thickness above mantle velocities (V_p = 8.0+) might be 16 km as compared to average oceanic basin crustal thicknesses of 7 km and continental crustal thicknesses of 30 km.

Most fascinating has been the discovery over the past 16 years of extensive areas of knolls around the rim of the gulf basin and extending into the Sigsbee Deep. Many of these knolls are suspected and known salt domes (Fig. 5). The basic problem is that the deposition of salt in an ocean basin this deep is unlikely (although possible [Schmalz, 1969]) at the temperatures and pressures prevalent. Ewing *et al.* (1962), Antoine (1968), and Antoine & Bryant (1969) suggested that the salt has migrated into the basin from the known occurrences around the basin's rim. Alternatively, the basin was once shallow sea or land, an unlikely possibility in light of its subsediment oceanic crustal structure.

Paine & Meyerhoff (1970) favor the view that the Gulf is an ancient ocean basin of Precambrian age. Moores (1970) also suggests this possibility. Leg 10 of the Deep Sea Drilling Project has established that the Gulf has been a deep-water basin since at least Late Cretaceous and in the southeastern part since Cenomanian time.

A feature of some interest is that the available geologic and geophysical information indicate that Campeche Bank and the south Florida platform are much alike (Antoine, 1968). Antoine (*ibid.*) suggested that at one time these two areas were connected. Magnetic studies by Heirtzler *et al.* (1966) indicate closed conformed NE-SW positive anomalies in both the west Florida shelf and north of the Campeche Bank which trend toward each other but are separated by a zone of NW-SE anomalies. Gough (1967) showed the same trends and inferred that a belt of volcanic-type rocks at a depth of approximately 9 km is following the NE-SW "Appalachian" structural trend and that "Appalachian trends dominate the eastern Gulf of Mexico." That there are Paleozoic rocks underlying the Yucatan at least as old as Silurian has been mentioned previously. Ewing *et al.* (1960) implied crustal thickness greater than 30 km (continental?) under the Campeche Bank, but they did not find mantle velocities under the bank.

Drake *et al.* (1963) showed positive magnetic anomalies off the east coast from Nova Scotia to Florida, which are aligned with the anomalies in northwest Florida. Gough (1967) pointed out southeast of these a parallel set of anomalies, which he calls "volcanic type" trending from the east coast of Florida to the Campeche Bank. This set of anomalies trends toward the Blake Plateau, perhaps indicating volcanic rocks in the subsurface there.

2. THE CARIBBEAN: Most of the marine geophysical data wihin the general Caribbean region is reviewed in papers by Officer *et al.* (1959); Edgar (1968); Bunce *et al.* (in press); Hurley (1966); Fink (1968); Ewing, Antoine & Ewing (1960); MacDonald (1967); Donnelly (1964, 1967a); Ewing *et al.* (1967); Ewing, Talwani & Ewing (1968). Recent papers which have focused attention on the Cayman Trench include those of Meyerhoff (1966); Bowin (1968); Gough & Heirtzler (1969); Ewing, Antoine & Ewing (1960); Banks & Richards (1969); Fox & Schreiber (1970) and Pinet (1970). Beginning with Vening-Meinesz *et al.* (1934), Ewing (1937), and Hess (1933, 1938), papers on some portion of the Puerto Rico Trench or its vicinity have been appearing with surprising frequency. Some of the more recent studies in this area of the Caribbean include those of Ewing & Heezen (1955); Ewing & Ewing (1962); Hersey (1962, 1966); Bunce & Fahlquist (1962); Talwani (1964); Bowin, Nalwalk & Hersey (1966); Monroe (1968); Savit *et al.* (1964); Bunce & Hersey (1966); Griscom & Geddes (1966); Bunce, Fahlquist & Clough (1969); Glover (1967); Chase & Bunce (1969); Bunce (1966); Ewing, Leonardi & Ewing (1968); and Bracey & Vogt (1970).

2a. The Yucatan Basin, Cayman Ridge, Cayman Trough: The Yucatan Basin has a relatively thin crust (approximately 9 km) consisting of a V_p 6.6 layer of about 6 km overlain by layers of lower velocity totaling 3 km (Fig. 4). These layers presently cannot be correlated with the structure under the Campeche Bank, where the top of the mantle (V_p= 8.0 or greater) has not been found. Across the Cayman Ridge the 6.6 crustal layer thickens to about 10 km and, while mantle velocities have not been found, the total crustal thickness is postulated to be in excess of 20 km (Ewing *et al.*, 1960).

Seismic, gravity, and magnetic studies (Ewing & Worzel, 1954; Ewing, Antoine & Ewing, 1960; Bowin, 1968; Gough & Heirtzler, 1969) indicate that the thinnest crust in the Caribbean area (approx. 6 km) is found under the Cayman Trough (Figs. 4 and 6). Here approximately 2 km of "sedimentary" layers (V_p = 2.1-4.6) overlie 4 km of oceanic crust (V_p = 6.4). This crustal structure is in distinct contrast to that under the Puerto Rico Trench, where the oceanic crust is of normal thickness (4 km) or thicker (8 km), and where mantle depth is estimated to be 12 to 15 km from the sea bottom on the basis of seismic data combined with gravity data (Talwani *et al.*, 1959; Bunce & Fahlquist, 1962; Bunce, 1966). These results contradict and supersede earlier models which predicted thinner than normal oceanic crust under the Puerto Rico Trench on the basis of gravity and limited seismic information (Worzel & Shurbet, 1955; Ewing & Heezen, 1955).

Bowin (1968) showed a positive Bouguer gravity anomaly axis along the Cayman Trough which does not cross the Windward Passage between Cuba and Hispaniola and does not connect up with the negative anomaly trends associated with the extension of the Puerto Rico Trench. Bowin concluded that the Cayman Trough structure is not a westward continuation of the structure producing the Puerto Rico Trench negative free-air anomaly belt, and that, instead, the Cayman curves into the Enriquillo Basin–Cul de Sac Trough through Hispaniola. Bowin believes the trough to be a tensional feature associated with crustal failure under conditions of an eastward drift of the Caribbean region and distinguishes it from the type of structure produced along the world rift system. Gough & Heirtzler (1969) stated that their magnetic data suggest larger and more irregular displacements than would be expected from an orderly pattern of normal faults. They also suggested that horizontal movement or strike-slip faulting parallel to trough axis is the most likely way to produce the observed pattern. On the other hand, Banks & Richards (1969), working with bathymetric, magnetic, and seismic data in the western end of the trough, found that their data are difficult to reconcile with strike-slip movement, but resemble features associated with block faulting and minor vertical and lateral movement of individual blocks.

In any case, contrast in crustal thickness, gravity and magnetic patterns,

and perhaps isostatic balance (Ewing *et al.*, 1960) indicates that the trough and Puerto Rico Trench have different tectonic origins, different ages, or both. This observation does not rule out the possibility that both features may *now* be influenced by similar tectonic motions.

Fox & Schreiber (1970) have reported the discovery of granodiorite as well as metagranodiorite and metabasalt from three deep (3400m-6000m) dredge hauls in the Cayman Trough. Tentatively, they have correlated the metabasalts with the V_p 4.8-5.5 km/sec layer and the granodiorite with the V_p 6.2-6.4 km/sec layer known to underlie the trough (Figs. 4 and 6).

Refraction results over the Nicaraguan Rise (Ewing *et al.*, 1960; Arden, 1969) show a thick crust consisting of 6 to 8 km of "sediments" (V_p = 1.7-5.5) overlying a V_p 6.3-6.7 layer whose thickness is unknown, but by extrapolation is another 18 km thick under the rise (Fig. 4).

The picture, then, in this region seems to be an area of thin crust of oceanic type (Cayman Trough) bordered on the north and south by ridges of continental crustal thickness (Cayman Ridge and Nicaraguan Rise).

To the north the Yucatan Basin similarly has a relatively thin crust of oceanic type and is also bordered on the north (Campeche Bank) and south (Cayman Ridge) by ridges with continental crustal thicknesses.

2b. Colombian Basin, Venezuelan Basin, Beata Ridge, Aves Swell, Grenada Trough, Lesser Antilles, and Tobago Trough: Representative sections of oceanic crust from both the Atlantic and Pacific basins show crustal thicknesses of about 6.5 to 7 km (Ewing, 1969; Shor & Raitt, 1969; Officer *et al.*, 1959; Raitt, 1963). Immediately above mantle (V_p = 8.0-8.4 km/sec) there is about a 5-km-thick oceanic layer (V_p = 6.6-7.1 km/sec), topped by two layers: a lower layer (V_p = 5.5-6.0 km/sec) about 1.5 km thick and the upper (V_p = 2 km/sec) about 0.5 km thick. Maynard (1970) has recently suggested that wide areas of the Pacific may have a two-layered oceanic layer structure: a deeper layer of V_p = 6.9-7.6 km/sec underlying the normal layer of V_p = 6.8 km/sec. Presently this deeper layer is not accepted as a general feature of deep ocean basins but this two-layered structure does have similarities to ocean crustal sections under such small basins as the Caribbean (see below). The question as to why this deeper layer has been seen in basins such as the Caribbean but never before in the deep ocean basins is unanswered.

Ewing *et al.* (1960), Officer *et al.* (1959), Edgar (1968), Fink (1968), and Bunce *et al.* (in press) have summarized in detail parts, or all, of the geophysical data in the areas listed under heading *2b* of this report. The crustal sections under the Colombian and Venezuelan basins are similar to each other; both have irregular thickness (about 8-15 km thick) and both are structured differently than either standard oceanic crust or the sections under the Cayman Trough and Yucatan Basin, which have strong similarities to each other and to oceanic crust. By comparison, the normal oceanic layer

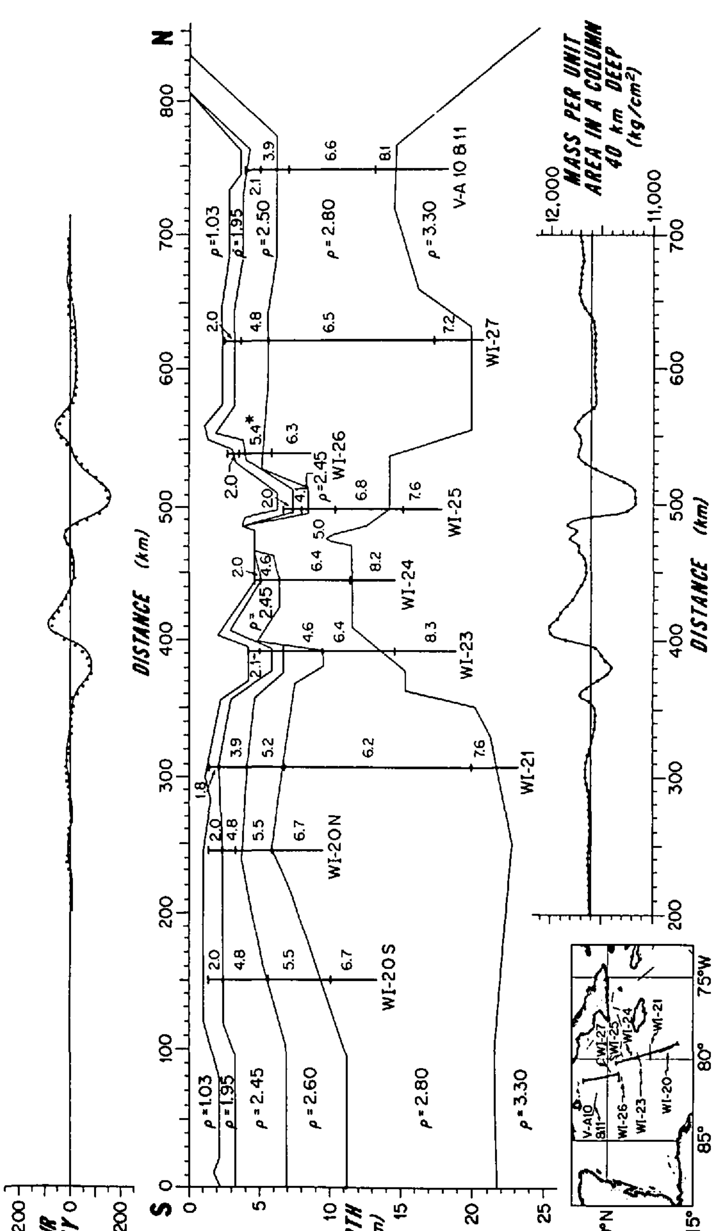

FIGURE 6. Structural model across the Cayman Trough. Observed free-air anomaly (continuous line; calculated values are dots) and bathymetric profiles. Seismic refraction measurements from Ewing *et al.* (1960); their locations are indicated in the inset. Values for compressional velocities given beside lines indicated on refraction profiles are in km/sec. Asterisk indicates an assumed velocity. Values for density are in gm/cm³. (From Bowin, 1968.)

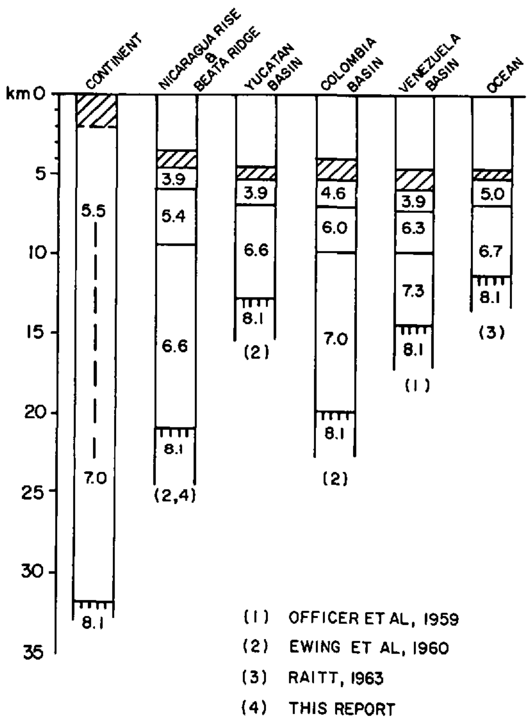

FIGURE 7. Crustal sections. (From Edgar, 1968.)

(V_p = 6.0 km/sec or greater) in the two major Caribbean basins is a *two*-layered structure: an upper layer about 4 km thick (V_p = 6.0-6.3) and a lower layer varying between 5 and 10 km thick (V_p = 7.0-7.3; Fig. 7). The composition of these crustal layers remains unknown, so that debate over whether they represent either altered primitive oceanic crust or altered and foundered continental crust are interesting but presently unresolvable. Donnelly (1964) makes the point that more than half of the Caribbean crust consists of material "whose seismic velocity (about 7.2 km/sec) exceeds that of any possible sialic material and even that of basalt!"

Perhaps the most important conclusion so far derived from the profiler work (Edgar, 1968; Ewing, Talwani & Ewing, 1968; Ewing *et al.*, 1967) in the Caribbean is that the interior basins of the Caribbean Sea have been stable, deep-water areas since middle Mesozoic, possibly earlier. This work has shown two continuous, comformable, reflecting horizons called the "Carib" beds, with strong reflecting horizons at the base of each called A″

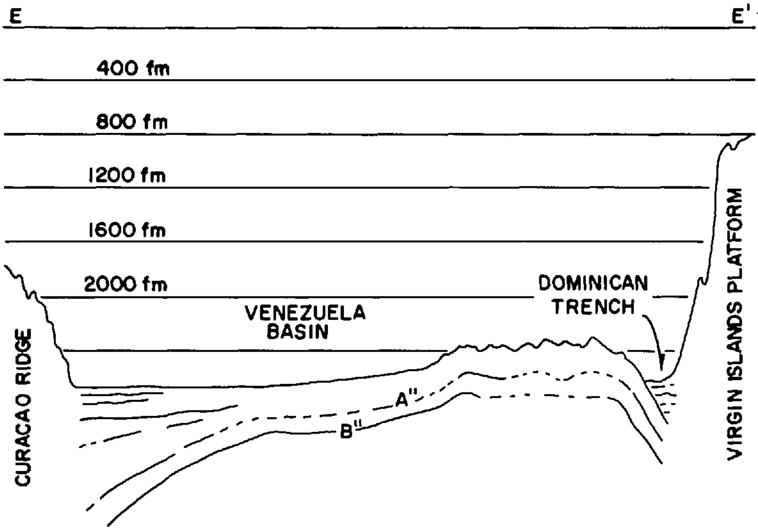

FIGURE 8. Tracing of seismic profiler record from the Curaçao ridge to the Virgin Islands platform. Turbidites cover the Carib beds in the lower marginal areas. Vertical exaggeration is × 25. (Adapted from Ewing, Talwani, Ewing & Edgar, 1967.)

and B″, respectively (Fig. 8). According to Ewing & Ewing (1962), seismic velocities in the beds above, between, and below horizons A″ and B″ are 1.8, 2.2, and 3.6 km/sec, respectively. These beds are in the uppermost crustal layers of the Caribbean basins and are buried only by younger turbidites near the South American continent and by small turbidite wedges near the Greater Antilles. The Carib beds arch up in the central part of each basin, bend down under the marginal trenches (Los Roques on the south, Dominican [or Muertos] Trench on the north) and rise conformably with the topography of the Aves and Beata ridges. The age of these horizons has been determined by dredgings near A″ on a fault scarp (Edgar, 1968; Ewing, Talwani & Ewing, 1968), from which it has been deduced that this horizon is the Mesozoic-Cenozoic boundary. By extrapolation of sedimentation rate, horizon B″ would be near the Paleozoic-Mesozoic boundary (J. Ewing *et al.*, 1968). It is apparent that results from the Deep Sea Drilling Program Leg IV (Bader *et al.*, 1970) may call for a reconsideration of the ages of horizons A″ and B″ in the Caribbean area. In the Venezuelan Basin, at site 29, horizon A″ was determined to be Eocene, presumably Lower-Middle Eocene, or about the same age as horizon A in the North Atlantic basin, as determined on previous Deep Sea Drilling legs (Gartner,

1970; Ewing *et al.*, 1970). The significance of the age of this horizon within the Caribbean basins and its possible correlation to horizon A north of Puerto Rico is great, since the units of sediment above these horizons dip under (apparently with constant thickness) turbidite sequences in the Puerto Rico Trench, the Muertos Trench to the south of Hispaniola, and the Roques Trench. This would seem to establish that these features cannot be older than lower Eocene. Hersey (1966) apparently dredged the layer above horizon A on the north wall of the Puerto Rico Trench and concluded that its age could be as young as Oligocene or at least as old as Late Cretaceous and further that the Puerto Rico Trench in its present form must be younger than Oligocene. Horizon A at site 28, Leg IV (north wall of the Puerto Rico Trench) is apparently middle Eocene as determined by the Deep Sea Drilling Program (Bader *et al.*, 1970: 665). The age of horizon B″ is unknown, but older than Eocene.

The crust under the Beata Ridge is thick (18 km approx.) and apparently similar to that under the Nicaraguan Rise (Edgar, 1968), although mantle velocities have not been recorded under either feature. Edgar (*ibid.*) suggested that both the 3.9 km/sec layer and the 5.9 km/sec layer thicken under the Beata Ridge. He also suggested that this thickening may be present because of igneous activity or because the ridge and the basement of the Nicaraguan Rise may represent relicts of former basin crust. Fox *et al.* (1968a, 1968b) reported on dredging and coring from a 2.5-km escarpment on the western side of the Beata Ridge where they found a "ferromagnesian rich igneous suite" grading vertically upward to a diabasic igneous rock and shallow-water Cretaceous algal rock on the crest of the ridge. They found no metamorphic or hydrated igneous rocks. They suggested that the ridge resulted from vertical uplift of the Caribbean crust and called upon Mesozoic subsidence of the ridge to account for the shallow-water Cretaceous limestone capping. Edgar (1968) described the relief on the Beata Ridge as variable from one coring to the next, although the western side is a steep scarp without sediments while the eastern side drops in a series of steps (faults?) and reflectors A″ and B″ are easily recognized and noticeably offset.

Bunce *et al.* (in press), Edgar (1968), and Officer *et al.* (1959) all have produced compilations of refraction and reflection cross sections from the Venezuelan Basin across the Aves Swell, the Grenada Trough, Lesser Antilles, Tobago Trough, and Barbados Ridge to the Guiana Basin (Fig. 9). Mantle velocities have not been found under any of the areas between the two major basins. The two-layered Caribbean oceanic crust dips eastward under the western flank of the Aves Swell, while the single-layered oceanic crustal layer dips westward under the Barbados Ridge (see also Chase & Bunce, 1969). By inference we can assume that mantle velocities ($V_p = 8.0$

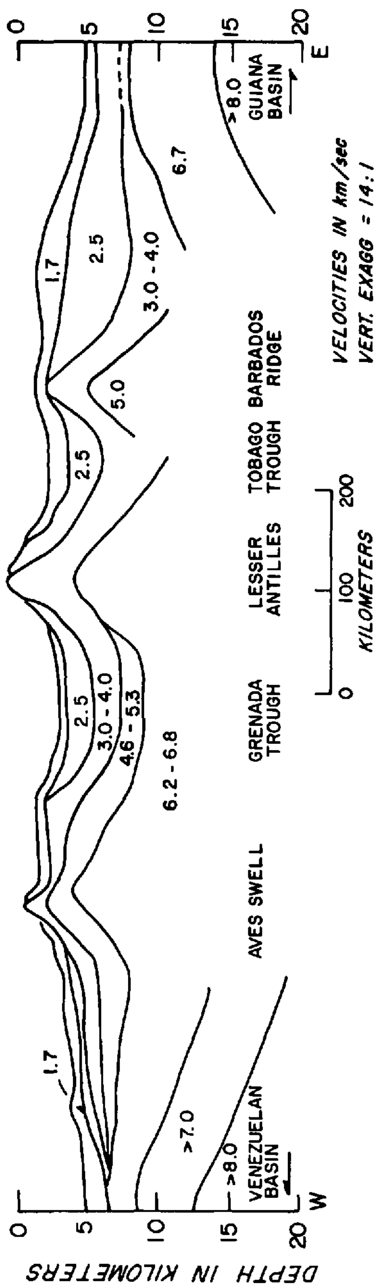

FIGURE 9. Crustal section, Venezuelan Basin to Guiana Basin. (From Bunce, Phillips, Chase & Bowin [in press], after J. Ewing *et al.* [1957] and Officer *et al.* [1959].)

km/sec or greater) are at depths in excess of 20 km below sea level under all features mentioned, or alternatively that there is a mass of material of uniformly lower velocity which makes up an altered mantle under the entire area. The detailed geophysical knowledge of all mentioned features in this area are covered in the papers by Bunce *et al.* (in press) and Edgar (1968). Of special interest is the increasing geologic knowledge of the Aves Swell which Bunce *et al.* show is made up of many topographic peaks of "basalt" material (V_p = 3.0-4.0 km/sec) aligned north-south along both the eastern and western flanks of the swell. These topographic highs are associated with short-wavelength–high-amplitude magnetic anomalies suggesting an igneous origin (Bunce *et al.*, *ibid.*; Ewing *et al.*, 1960). The resemblance of peaks along the western margin of the swell to submerged volcanoes was pointed out by Hess in 1938. Hurley (1966), Marlowe (1968), Marlowe *et al.* (1968), and Bunce *et al.* (*ibid.*) have reported dredging of volcanic rocks in the vicinity of these probable seamounts. Other deep (1000-2000 m) dredge hauls by Fox *et al.* (1969) from the southeastern slope of the Aves Ridge yielded rocks granodioritic in composition, which have been tentatively related by Fox *et al.* to the 6.0-6.3 upper oceanic crustal layer under the Caribbean. Alternatively, these rocks may represent a line of intrusions under the Aves Ridge. In any case the relation of the suspected volcanic peaks to the granodiorite on the ridge is unresolved.

During July and August 1970, the writer and C. G. A. Harrison dredged three seamounts on the Aves Swell between 15°-16°N and 63°-64°W. Initial examination indicates that these rocks are predominantly pyroclastic flow breccias, tuffs, and amygdaloidal basalts (?) similar to rocks of the Lesser Antilles. There are no hyaloclastic basaltic rocks typical of volcanic seamounts in the major oceans.

One dredge haul from the southeastern flank of the Aves Ridge, approximately 30 km southwest of Fox and Heezen's granodiorite site, taken from 800-m to 1700-m depths, recovered volcanic rocks (basalts?), gray, dense limestones and a green sheared breccia (fault breccia?), but no granodiorite. It is not certain which velocity layers of the Ridge we sampled at this locality, but tentatively the writer favors the interpretation that Fox *et al.* (1969) sampled a local granodiorite intrusion.

Bunce *et al.* (in press) point out that both the Aves Swell and the Antilles arc are similar, in that they are underlain by a broad rise of low velocity material (6.2-6.8 km/sec) and capped by material (basalts or volcanics?) with velocities of 3–5.3 km/sec. However, in contrast to the Lesser Antilles, the Aves Ridge is presently relatively inactive seismically (Fig. 14). Whether or not this feature is an old island arc, inside the present active Lesser Antilles, perhaps related to the Aruba-Orchila island platform, remains unknown.

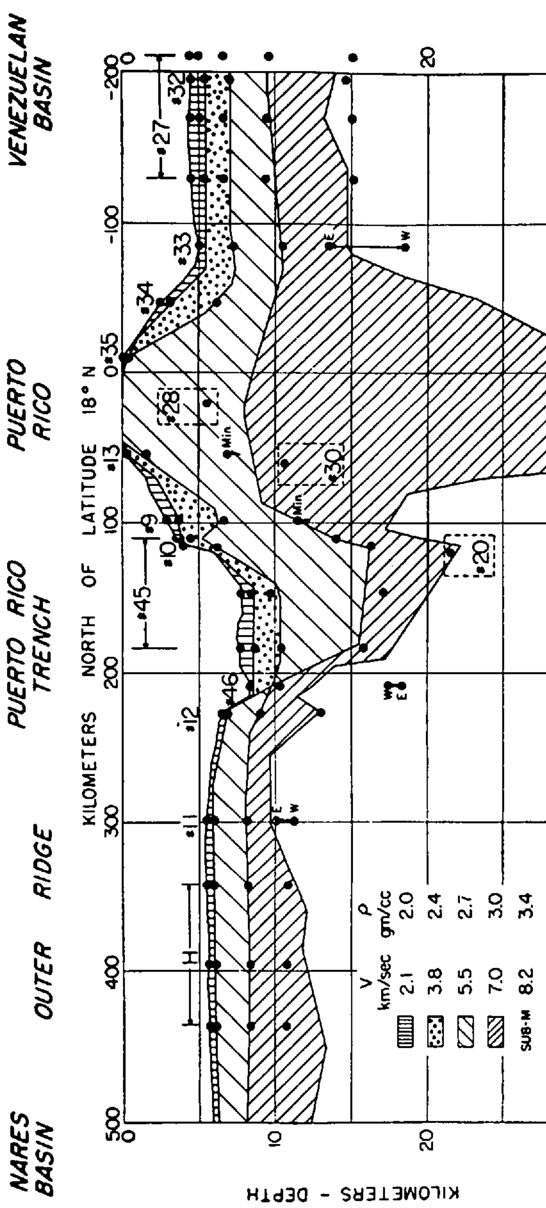

FIGURE 10. Crustal structural section from the Venezuelan Basin through Puerto Rico, the Puerto Rico Trench, and the outer ridge. (After Talwani, Sutton & Worzel, 1959.)

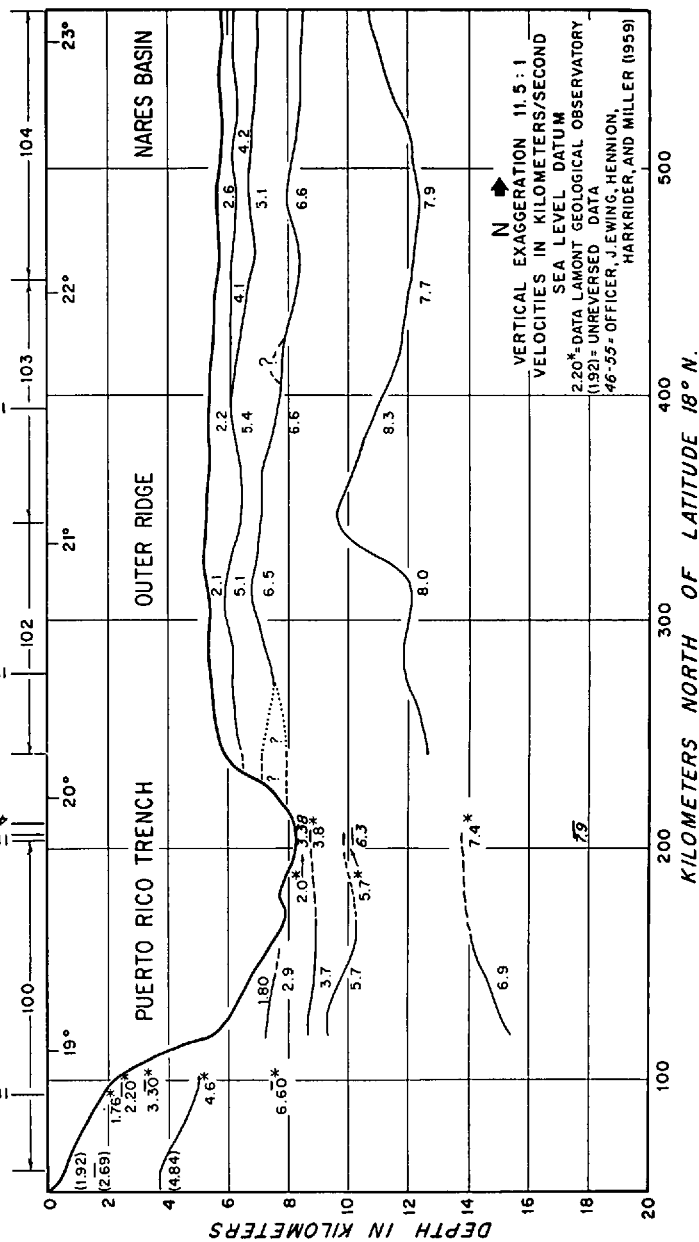

FIGURE 11. Structural section, Puerto Rico Trench to Nares Basin along longitude 66°33′W. (From Bunce & Fahlquist, 1962.)

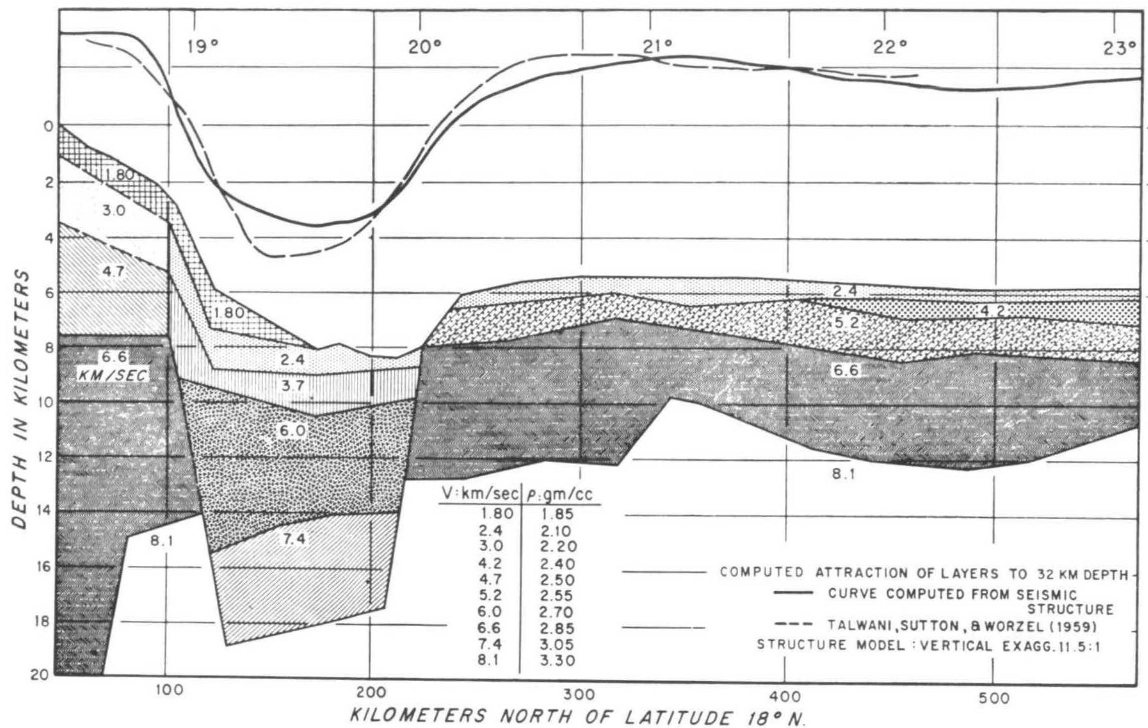

FIGURE 12. Upper, comparison of computed free-air anomaly (solid line) and measured anomaly (dashed line) for a cross section from Puerto Rico to Nares Basin (see Fig. 11). Lower, crustal layer model and assigned densities for computed total attraction (free-air anomaly). (From Bunce & Fahlquist, 1962.)

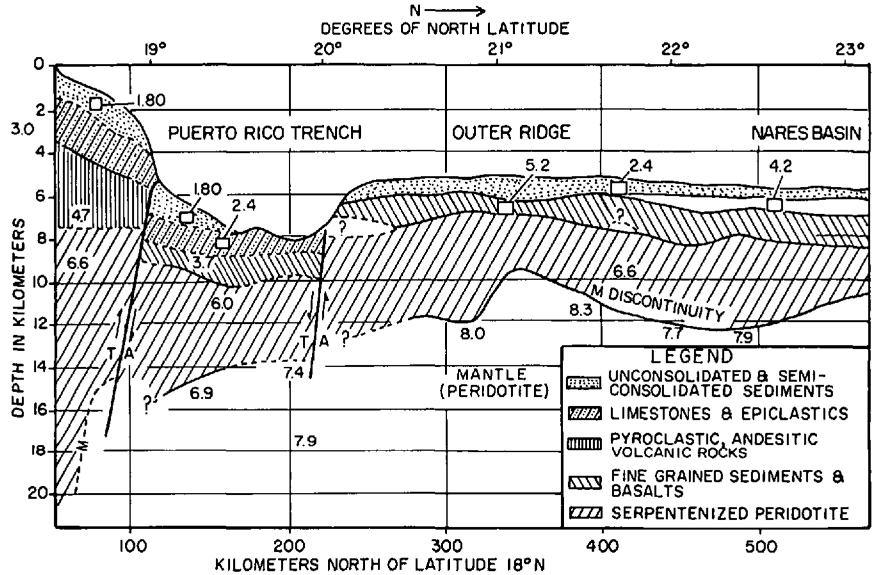

FIGURE 13. Structural section, Puerto Rico Trench to Nares Basin along longitude 66°33'W. Velocities are given in km/sec. Vertical exaggeration 11.5:1. (After Glover [1967], as adapted from Bunce & Fahlquist [1962], with modifications by Glover, based in large part upon observations and interpretations by Hersey [1962], Hess [1964], Bowin and others [1966].)

2c. The Puerto Rico Trench: Recent papers dealing with the Puerto Rico Trench are listed on page 398 of this report. The most recent seismic sections north of Puerto Rico were published by Bunce & Fahlquist (1962), Hersey (1966), and Bunce (1966). It is uncertain as to how to correlate the known seismic sections from the Outer Ridge to that under the trench, and to that on the south flank of the trench (Figs. 10, 11, 12). Mantle velocities are not found under the south flank of the trench. One attempt to make a correlation across the trench, using the data of Bunce & Fahlquist as well as known geology, has been done by Glover (Fig. 13). The north wall of the Puerto Rico Trench has been dredged by the Woods Hole Oceanographic Institute (Bowin *et al.*, 1966; Hersey, 1966; Chase & Hersey, 1968) between 65°00'W and 66°30'W over the interval of 3200-3800 fm. They have established a tentative stratigraphy for that region: serpentinite overlain by altered basalts interbedded with Cenomanian sediments (chert, claystone, limestone) probably representing the V_p 5.1 km/sec layer, and this in turn overlain by Lower Tertiary sedimentary rocks with minor vitric basalts. The oceanic or V_p 6.1 km/sec layer apparently was not sampled (Bowin

et al., 1966) although Chase & Hersey (1968) suggested that the serpentinite might represent the upper part of this layer. If so, then the oceanic layer in the Cayman Trough region is granodiorite (Fox & Schreiber, 1970) while on the north wall of the Puerto Rico Trench it is at least partially serpentinite. One or both of these rock types may represent local intrusions rather than regional layers.

In all sections across the trench north of Puerto Rico it is debatable whether the oceanic crust bends under the trench in this area or whether the trough is a downfaulted block. It is presently undecided whether faults exist on one or both sides of the trench and how much vertical movement vs. how much horizontal motion has taken place on one or both sides (e.g., see Chase & Hersey, 1968). There is also the question as to whether the present motion on the hypothesized faults (such motion suggested to be parallel to the trench in the region north of the Greater Antilles by Molnar & Sykes, 1969) is at all like past motion. The reason for the abrupt termination of the Puerto Rico Trench to the west, north of Hispaniola, is unknown, but this termination is almost directly north of two converging seismic belts (Fig. 14). One reason that the nature of the western termination is unknown is that there are no published refraction lines and only one reflection line west of 68°W longitude.

Bracey & Vogt (1970), on the basis of information published by Molnar & Sykes (1969) and Sykes & Ewing (1965), have postulated an active miniature arc structure originating in the Tertiary for the region northeast of Hispaniola extending from Mona Canyon to about 70°W. They suggest that a small crustal slab is being thrust to the southwest under Hispaniola in this region, bounded by hinge faults, which transform into faults of left-lateral motion to the northwest and southeast following the southern flank of the Puerto Rico Trench.

Chase & Bunce (1969) showed three seismic profiles, two at the southeastern end of the Puerto Rico Trench and one across the eastern margin of the northern Barbados Ridge, all indicating oceanic crust and basement dipping beneath the Antilles arc. Further south, thicker sediments obscure such a feature, although the authors inferred a similar westward basement dip from unpublished data. Vogt *et al.* (1969) also showed one profile indicating basement and sedimentary layers dipping beneath the Barbados Ridge. Chase & Bunce (1969) interpreted dip and offset relations in the basement and sediments in terms of a series of westward-dipping thrust faults at the eastern margin of the Barbados Ridge. Officer *et al.* (1959), in their refraction sections, also showed mantle material and oceanic crust dipping beneath both the Puerto Rico Trench and the Barbados Ridge.

The bathymetric contours of the Puerto Rico Trench curve south and east uninterrupted until about the latitude 17°N, east of Antigua, where the trend of the trench is partially interrupted by a cross ridge of the Barra-

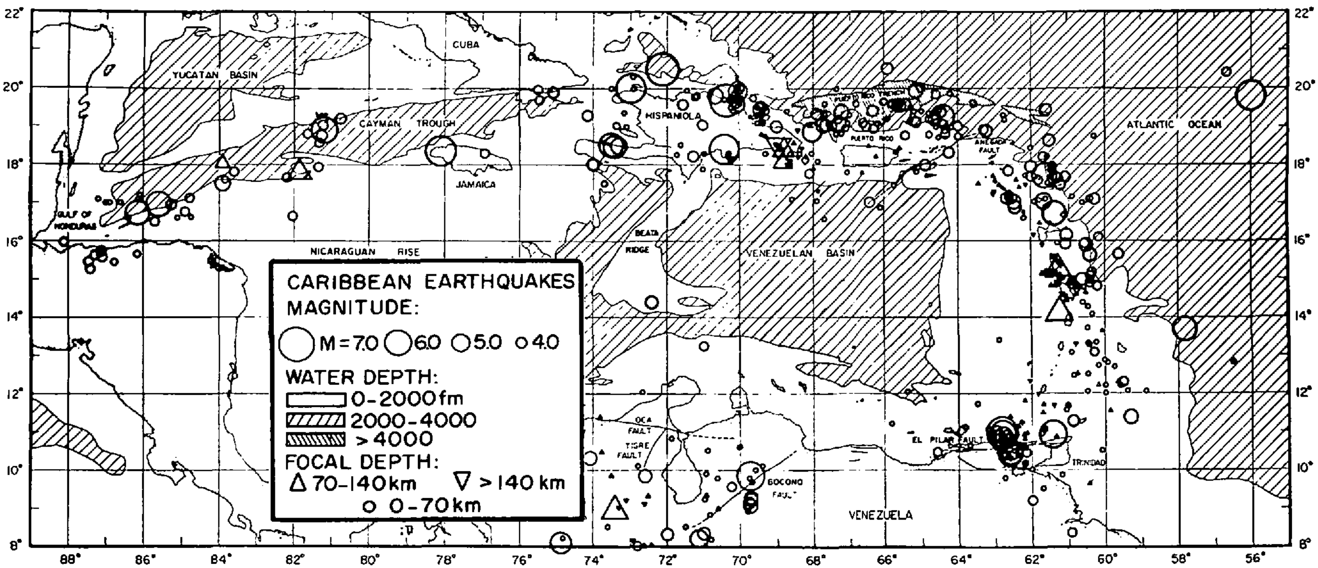

FIGURE 14. Epicentral map of Caribbean earthquakes for the period 1950 through 1964. Earthquakes in Central America not included. Water depths from H. O. Chart 5487. Major fault zones after Bucher (1950), Butterlin (1953), Rod (1956), and Alberding (1957). Events for which magnitudes could not be determined were assigned a magnitude of 3.5 for purposes of illustration. (Adapted from Sykes & Ewing, 1965.)

cuda Fracture Zone trending NW-SE across the eastern margin and the Desirade Fault Zone (Fink, 1968) trending NE-SW.

Recent U. S. Navy bathymetric charts indicate that neither the Desirade nor Barracuda Fault Zone completely crosses the Puerto Rico Trench. The relationship between the two fault zones is unknown. From that point on toward the south, the Puerto Rico Trench begins to shoal. This in spite of the fact that there is apparently no major subsurface change in basement rocks as shown by a featureless magnetic anomaly field across the ridge (Bunce *et al.*, in press) and the well-known southward continuation of the characteristic negative gravity anomalies of the trench. The shoaling is caused by an increase in total thickness of the sediment toward the south (Chase & Bunce, 1969; Bunce *et al.*, in press) and is probably due to increasing proximity to a South American source of sediment (Chase & Bunce, *ibid.*; Bunce *et al.*, *ibid.*; Pushkar, 1968) as originally suggested by Hess (1939). Hurley (1966) first made the interesting observation that the Barracuda Fault scarp may have acted as a partial dam to axial sedimentary fill from the south and suggested that a relationship exists between the trench-filling sedimentation and subsequent deformation process. Ewing & Ewing (1962) showed that the comparatively small amount of sediment in the Puerto Rico Trench north of Puerto Rico is essentially undeformed (tilted somewhat to the south), while on Barbados itself and on the Barbados Ridge the sediments are greatly contorted (Chase & Bunce, 1969; Vogt *et al.*, 1969). Perhaps this is related to the fact that underthrusting is nearly perpendicular to the Barbados Ridge, creating a tectogene situation here, as Hess (1933) originally described it, whereas north of Puerto Rico underthrusting is nearly parallel to the trench (Molnar & Sykes, 1969), leaving the sediments there virtually undisturbed.

Regional Tectonics

The number of attempts to synthesize the tectonic framework of the Carribbean are infinite, as are the number of different frameworks which have been suggested. Attempting to summarize them all would require a very large tome which would reach no firm conclusions at this time in the history of geology as the new framework of plate tectonics continues to develop. In the past, several schemes have been suggested, based on various hypotheses, sometimes by writers who had never been in the area.

Years of land work by Princeton students and many others around the Caribbean have indicated that the classical tectogene concept for the Greater Antilles is invalid. There has been no strong evidence for compressional tectonics in the Greater Antillean arc past Early Cretaceous; in fact vertical tectonics and gravity sliding seem to dominate. The Eocene seems to have been a particularly significant period of gravity tectonics. Also during this time, volcanism ceased in the Greater Antilles and began in the Lesser An-

tilles. The entire arc has been emerging since the Cretaceous, developing many cross fractures during the Tertiary which divided the arc into segments that have probably had nonuniform behavior and history from that time on.

Major long fracture zones have been discovered both on land and at sea on the northern and southern borders of the Caribbean. However, proving what kinds of movement have occurred through time has been difficult. Particularly difficult has been the interpretation of the magnitude of wrench faulting along east-west faults at the northern and southern Caribbean margins. Most recent studies limit wrench motion on any one fault to between 10 km and 40 km at both borders; detailed field studies favoring the lower limit (Metz, 1968; MacDonald, 1968e, 1969; Briggs & Pease, 1967; Peter, 1971; Campbell, 1968; Wilson, 1968). Ball *et al.* (in press) present arguments for large-scale normal faulting in the Gulf of Barcelona which in turn would trigger gravity slide-thrust sheets such as seen onshore. They find little evidence for wrench faulting in this area. Along the southern Caribbean margin, as in the north, vertical tectonics seem to be dominant from Late Cretaceous to the present. There is the possibility that several of the larger faults currently have different movements along different parts of the same fault line and/or that their present relative movement is different from past relative movement (e.g., see Schubert & Sifontes, 1970).

In terms of the plate tectonic "revolution" in earth sciences, it would be very much preferable if the Caribbean area and Bahamas did not exist. There are several general models afloat which can include these areas. Each of these has a variety of interesting offshoots, embellishments, and ardent supporters. One is Carey's (1958) model which involves great rotational and translational movements of the Greater and Lesser Antilles, Bahamas, and Central America (Fig. 15). The other comes as an outgrowth of a fit of the continent around the Atlantic produced by Funnell & Smith (1968), and suggests a zone of north-south extension and shear encompassing the Caribbean (Fig. 16). This suggestion has triggered a series of papers by Ball and co-workers (Ball & Harrison, 1969, 1970; Ball *et al.*, in press), who have modeled the Caribbean as a zone of north-south extension and left lateral shear between crustal areas spreading in different directions at different rates.

Their suggestions fit nicely the land and marine evidence in the Greater Antilles for left lateral motion and gravity tectonics as well as the suggestion by Glover (1967), among others, that the Greater Antilles is a *fracture* arc (a linear pile of submarine volcanics developed over a zone of wrench faulting) in contrast perhaps to the Lesser Antilles, which more nearly resemble an area of classic tectogene island-arc development oriented perpendicular to underthrusting. Birch (1970) proposes that the Barracuda Fault lies in a zone of crustal tension and shear, which also favors the Funnell & Smith (1968) hypothesis. The only apparent difficulty with this framework

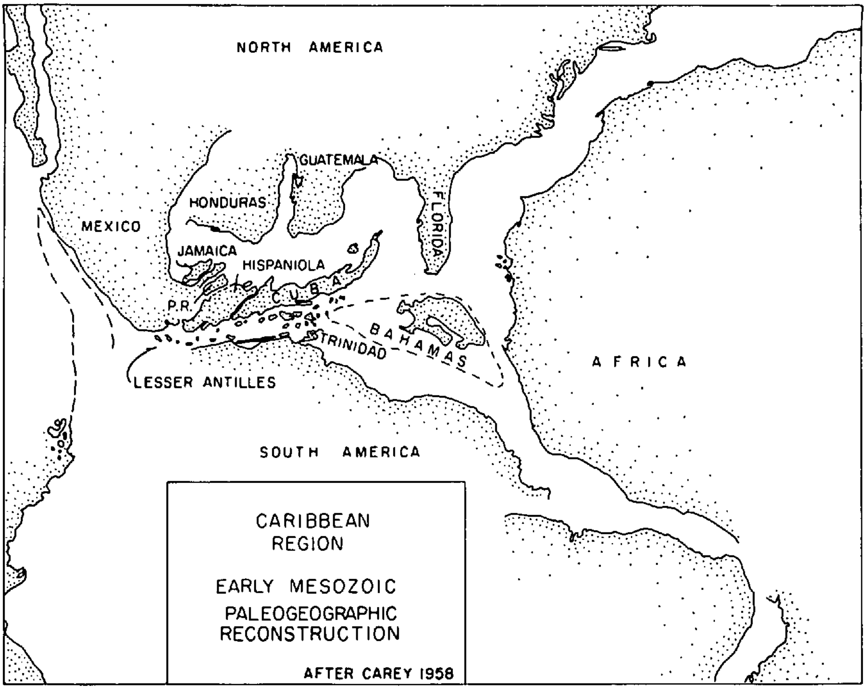

FIGURE 15. Early Mesozoic paleographic reconstruction of the Caribbean. (After Carey, 1958.)

appears to be on the southern margin where Molnar & Sykes (1969) have shown present right lateral motion, and at least minor motion of that nature (10 km) is known to have taken place on the El Pilar Fault. Perhaps this is a fault zone which shows a change in relative motion from one side of the island arc to the other.

Dietz & Holden (1970) suggest a zone of rifting and extension in the Caribbean from the end of the Triassic through Jurassic. There is little known geophysical or geological evidence for this suggestion; however, Krause (1967, 1968) has discovered east-west trending magnetic anomalies in the Colombian Basin. He explains these as a result of north-south spreading during the Cretaceous, but notes that the eastern Caribbean was unaffected.

MacGillavry (1970) suggests that the Caribbean is an old, stable oceanic plate at least as old as Upper Jurassic, which underwent tension in the Early Cretaceous, then rotated clockwise during the Late Cretaceous. He summarizes a great deal of geologic evidence to support this hypothesis.

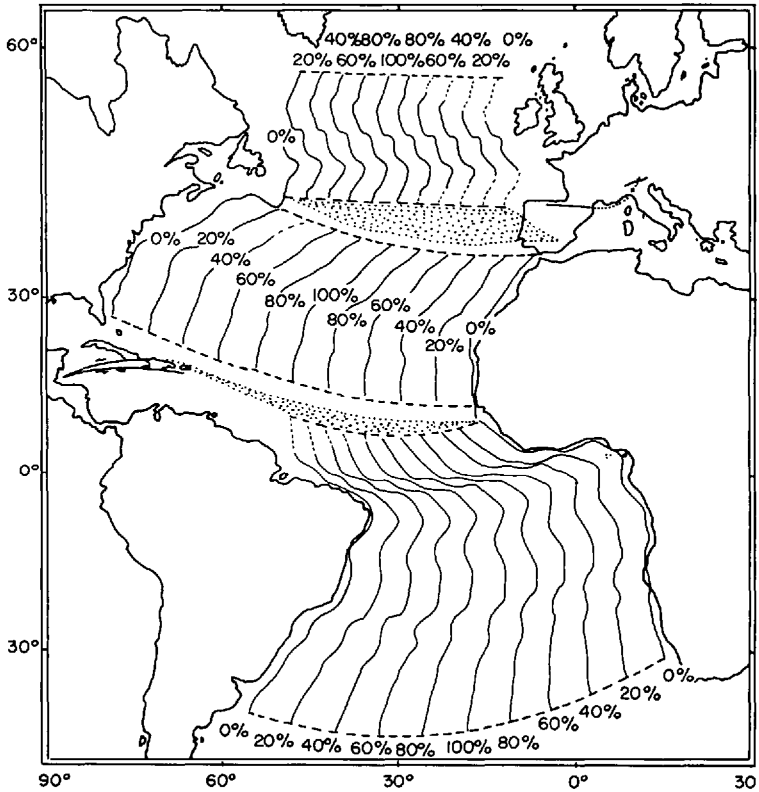

FIGURE 16. Successive positions of the three join-segments (from Figure 2 of Funnell & Smith, 1968) rotated by angular increments of 10 per cent between continents, representing limits of 20 per cent stages of opening. Limits of northern and southern transverse zones indicated by dashed lines, and amount of north-south extension by stipple. Principal fundamental and wrench faults indicated for Mediterranean and Caribbean orogenic belts. (Mercator projection.) (Adapted from Funnell & Smith, 1968.)

Moores (1970) postulates that the Caribbean arc is a remnant of a migrating arc system which began its journey in the Pacific and moved eastward. On the other hand, Hamilton (1966) proposed that the Caribbean arc is part of a Mesozoic engeosynclinal belt which lagged behind as North and South America drifted westward. In the opinion of this writer, the known evidence supports neither idea.

The unknowns in the framework which, if known, might limit further tectonic speculation seem to me to be the following: (1) the nature and age of the Caribbean crust, (2) the relative amounts of rotation of the Caribbean

islands, (3) the age relations of the Greater and Lesser Antilles, and (4) the relative importance of the interplay between the Cocos and Caribbean plates.

SUMMARY

Portions of Caribbean land and marine geology are summarized in an effort to present the known tectonic framework, as well as to emphasize remaining areas of controversy and ignorance. The object of this paper is to stimulate further attempts to integrate the geology of the Caribbean area into the new global tectonics and to serve as a brake to such attempts when conceived without accounting for the known geology.

Other than in Cuba, the oldest known rocks in the Greater Antilles are Cretaceous. Except for one 180 m.y. date in Cuba, the oldest known rocks there are Early-Middle Jurassic. Pre-Mesozoic rocks may be present in parts of Cuba, Hispaniola, and southwestern Puerto Rico, but metamorphism has complicated interpretations of age. 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. Volcanism in the Greater Antilles virtually ceased at the end of middle Eocene time.

The Lesser Antilles are generally assumed to be younger than the Greater Antilles, but recent radiometric dates from Desirade suggest some continuity of igneous activity between the two regions. The reasons for the double island arc north of Dominica remain controversial. Recent work suggests that the Lesser Antilles are cross-faulted into individual blocks, with each one developing its own stress pattern during sea-floor spreading. However, basement structures of the Lesser Antilles may continue to at least as far as 65°W; both geological and geophysical evidence indicate that a south Caribbean fault does not exist.

Paleozoic rocks are known to underlie part of the Yucatan and central Florida, but the nature of the basement under the Bahamas and Blake Plateau is unknown. However, striking similarities in the Cretaceous to Recent histories of these areas and that of the north coast of Cuba suggest that this entire region has behaved as a single unit since the Cretaceous.

Detailed geologic studies on the landward extension of the Bartlett fault system in Guatemala and Honduras show no evidence for major left-lateral post-Cretaceous offset.

The presence of pre-Mesozoic rocks in the Caribbean Mountains of northern Venezuela, though long suspected, has never been demonstrated. The oldest rocks known in the Caribbean Mountains are Late Jurassic. Southward thrusting or gravity sliding beginning in latest Cretaceous is reported to have occurred all along the southern Caribbean margin. Current

opinion seems divided as to the explanation of this thrusting, although vertical tectonic schemes are popular.

Vertical tectonics dominate the Late Cretaceous to Recent geologic history all around the Caribbean, through the Greater and Lesser Antilles, as well as along northern Colombia and Venezuela. Land and marine evidence for extensive wrench faulting is slim after Late Cretaceous. Prior to that time, fault motions in most areas are unknown or nonexistent. First motion studies, however, indicate active wrench faulting on both the northern and southern Caribbean margins, as well as underthrusting in the Lesser Antilles and possibly in the northeast Hispaniola region.

The Gulf of Mexico is underlain by ancient oceanic crust and has been a deep-water basin since at least Late Cretaceous. Some investigators suggest that the Gulf is a Precambrian ocean basin.

The Yucatan Basin and the Cayman Trough contain the thinnest crust (9 km and 6 km) in the Caribbean area. These two features are separated from one another, and from the Gulf of Mexico to the north, and the Colombian Basin to the south, by parallel ridges or welts of continental crustal thickness. One or more of these positive features may contain pre-Mesozoic rocks. The Cayman Trough is not a westward continuation of the Puerto Rico Trench, and may be a much younger feature, although current motion along both features is left lateral. The crustal sections under the Colombian and Venezuelan basins, which are similar, have an irregular thickness (8-15 km thick) and possess a two-layered oceanic layer: an upper layer about 4 km thick ($V_p = 6.0$-6.3) and a lower layer which varies between 5-10 km thick ($V_p = 7.0$-7.3). The composition of these crustal layers remains unknown, so that debate over whether they represent either altered primitive oceanic crust or altered and foundered continental crust is interesting but presently unresolvable.

Horizons A″ and B″, within the uppermost layers and above the oceanic layer of both Caribbean basins, bend under the marginal trenches (Los Roques on the south, Muertos on the north). Horizon A″ has been determined as lower-middle Eocene in age, which is approximately the same age as horizon A on the north wall of the Puerto Rico Trench. Horizon A dips under the Puerto Rico Trench. This would seem to establish that the Roques Trench, the Muertos Trench, and the Puerto Rico Trench are all no older than early Eocene.

Profiler work to date indicates that large areas of the interior basins of the Caribbean Sea have been stable, deep-water areas since middle Mesozoic time or possibly earlier. Preliminary magnetic surveys within these basins suggest, however, that the Colombian Basin has had a different older history than the Venezuelan Basin.

Sea mounts on the Aves Swell are composed predominantly of pyroclastic rocks with occasional flows. Marine fossils from several of the dredge hauls

from the sea mounts and other places on the swell indicate that this feature has been sinking since early Tertiary. Whether or not this feature is an old island arc, inside the present active Lesser Antilles, perhaps related to the Aruba-Orchila island platform remains unknown. Scanty heat-flow data do not favor the interpretation that the swell is a rifted portion of the Lesser Antilles as has been suggested for analogous features in recently published Pacific island-arc models.

The Beata Ridge is an upfaulted segment of Caribbean crust, which was at shallow depths in the Cretaceous and which has undergone subsidence since that time.

Granodiorite has been found in dredge hauls from both the Aves Swell and the Cayman Trough. It has been suggested that these rocks represent the upper oceanic crustal layer under the Caribbean, but they could also be interpreted to represent local intrusions.

New information concerning the age and nature of the crust under several Caribbean marine features will result from the current Deep Sea Drilling Leg XV.

The Puerto Rico Trench is best known in the area north of Puerto Rico. Even there, it is uncertain whether faults exist on one or both sides of the trench and how much vertical versus how much horizontal motion has taken place on one or both sides. Present left-lateral motion on the hypothesized faults, parallel to the Puerto Rico Trench in this region, may or may not be like past motion.

Seismic profiling, refraction profiles, and first motion studies of earthquakes indicate underthrusting of the Lesser Antilles along the arc between Saba and Grenada, in contrast to the general parallel east-west motion at the northern and southern margins of the Caribbean.

Although several radically different tectonic models have been proposed to explain the origin of Caribbean features, no one model has captured the enthusiasm of the majority of investigators.

Sumario

Geología del Caribe, 1970

Se sumarizan porciones de la geología terrestre y marina del Caribe, en un esfuerzo por presentar el marco tectónico conocido así como para enfatizar áreas restantes de controversia e ignorancia. El objeto de este trabajo es estimular a llevar adelante intentos para integrar la geología del área del Caribe dentro de la nueva tectónica global y servir como un freno a tales intentos cuando son concebidos sin contar con la geología conocida.

Exceptuando Cuba, las rocas más antiguas conocidas en las Grandes Antillas son del Cretáceo. Excepto por una fecha 180 m.a. en Cuba, las rocas más antiguas allí conocidas son de los inicios del Jurásico Medio.

Rocas pre-Mesozoicas pueden estar presentes en partes de Cuba, La Española y sudoeste de Puerto Rico pero el metamorfismo ha complicado las interpretaciones de la edad. No se encuentra basamento sialítico o granítico en las Grandes Antillas excepto quizás en la parte occidental de Cuba y posiblemente bajo la plataforma de Cuba, el camellón de Cayman y la elevación de Nicaragua. El volcanismo en las Grandes Antillas cesó virtualmente al final de la mitad del Eoceno.

Generalmente se asume que las Antillas Menores son más jóvenes que las Antillas Mayores, pero fechas radiométricas recientes de Desirade sugieren cierta continuidad de actividad ígnea entre las dos regiones. Las razones para el doble arco insular al norte de Dominica siguen siendo objeto de controversia. Estudios recientes sugieren que las Antillas Menores están contra falladas en bloques individuales, cada uno desarrollando su propio patrón de fuerza durante expansiones del fondo marino. Sin embargo, estructuras del basamento de las Antillas Menores pueden continuar hasta por lo menos tan lejos como 65° O; ambas evidencias, geológica y geofísica, indican que no existe una falla en el sur del Caribe.

Se sabe que rocas Paleozoicas están por debajo de parte de Yucatán y centro de la Florida pero la naturaleza del basamento debajo de las Bahamas y la meseta de Blake es desconocida. Sin embargo, sorprendentes similaridades en las historias de estas áreas del Cretáceo al Reciente, así como la de la costa norte de Cuba sugieren que toda esta región se ha comportado como una sola unidad desde el Cretáceo.

Estudios geológicos detallados del sistema de la falla de Bartlett en su extensión hacia la tierra en Guatemala y Honduras no muestran evidencia de grandes compensaciones laterales izquierdas en el post-Cretáceo.

La presencia de rocas pre-Mesozoicas en las montañas del Caribe del norte de Venezuela aunque por largo tiempo sospechada nunca ha sido demostrada. Las rocas más antiguas conocidas en las montañas del Caribe son de finales del Jurásico. El empuje hacia el sur o deslizamiento por gravedad, comenzando en los finales del Cretáceo, es reportado como que ha ocurrido a todo lo largo del margen sur del Caribe. La opinión actual parece dividida en cuanto a la explicación de este empuje aunque son populares los modelos tectónicos verticales.

Los tectónicos verticales dominan la historia geológica desde los finales del Cretáceo hasta el Reciente alrededor de todo el Caribe, a través de las Antillas Mayores y Menores, así como a lo largo del norte de Colombia y Venezuela. Son escasas las evidencias terrestres y marinas de extenso dislocamiento de fallas después de los finales del Cretáceo. Con anterioridad a ésto el tiempo del movimiento de las fallas en la mayoría de las áreas no se conoce o no existe. Los estudios de los primeros movimientos, sin embargo, indican otros dislocamientos de fallas en ambos bordes, norte y sur, del Caribe, así como compresión inferior en las Antillas Menores y posiblemente en la región noreste de La Española.

El Golfo de México está forrado por corteza oceánica antigua y ha sido una fosa de agua profunda al menos desde los finales del Cretáceo. Algunos investigadores sugieren que el Golfo es una fosa oceánica del Pre-Cámbrico.

La hoya de Yucatán y el camellón de Cayman tienen la corteza de menos espesor (9 Km y 6 Km) en el área del Caribe. Estos dos accidentes están separados uno del otro y del Golfo de México hacia el norte y de la hoya de Colombia al sur, por camellones paralelos o ribetes del grueso de la corteza continental. Uno o más de estos accidentes positivos pueden tener rocas pre-Mesozoicas. El camellón de Cayman no es una continuación hacia el oeste de la fosa de Puerto Rico y puede ser un elemento mucho más reciente, aunque el movimiento actual a lo largo de ambos accidentes es lateral izquierdo. Las secciones de la corteza bajo las fosas de Colombia y Venezuela, que son similares, tienen un espesor irregular (8-15 Km) y poseen un lecho oceánico de dos capas: una capa superior de alrededor de 4 Km de espesor ($V_p = 6.0$-6.3) y una capa inferior cuyo espesor varía entre 5-10 Km ($V_p = 7.0$-7.3). La composición de estas capas de la corteza permanece desconocida, de modo que un debate sobre si ellas representan bien corteza oceánica primitiva alterada o corteza continental alterada y fundida es interesante pero actualmente irresoluble.

Los horizontes A″ y B″ dentro de las capas más superiores y por debajo de la capa oceánica de ambas hoyas del Caribe, se doblan debajo de las fosas marginales (Los Roques al sur, Muertos al norte). La edad del horizonte A″ ha sido determinada como Eoceno medio-inferior, que es aproximadamente la misma edad del horizonte A en la pared norte de la fosa de Puerto Rico. El horizonte A se sumerge debajo de la fosa de Puerto Rico. Esto parecería establecer que la fosa de Los Roques, la de los Muertos y la de Puerto Rico son todas no más viejas que principios del Eoceno.

Estudios del perfil hasta la fecha indican que grandes áreas de las fosas interiores del Mar Caribe han permanecido estables, como áreas de aguas profundas, desde tiempos del Mesozoico Medio o posiblemente antes. Investigaciones magnéticas preliminares dentro de estas fosas sugieren, sin embargo, que la fosa de Colombia ha tenido una historia más antigua y diferente que la de Venezuela.

Las montañas marinas en el promontorio Aves están compuestas predominantemente de rocas piroclásticas con crecientes ocasionales. Los fósiles marinos de varios de los dragados de las montañas marinas y otros lugares en el promontorio indican que el mismo ha estado hundiéndose desde principios del Terciario. Si este accidente es o no un antiguo arco insular, dentro de las presentes activas Pequeñas Antillas, quizás relacionado con la plataforma insular de Aruba-Orchila, permanece desconocido. Los escasos datos del flujo calórico no favorecen la interpretación de que el promontorio sea una porción hendida de las Antillas Menores, como ha sido sugerido por

otros accidentes análogos en recientemente publicados modelos de arcos insulares del Pacífico.

El Beata Ridge es un segmento de falla ascendente de la corteza del Caribe que estuvo a poca profundidad en el Cretáceo y que ha estado sumergido desde entonces. Ha sido encontrada Granodiorita en dragados en el promontorio Aves y en la depresión de Cayman. Se ha sugerido que estas rocas representan la capa superior de la corteza oceánica bajo el Caribe, pero también pudieran ser interpretadas como representantes de intrusiones locales.

Del actual Deep Sea Drilling Leg XV se obtendrá nueva información concerniente a la edad y naturaleza de la corteza bajo varios accidentes marinos del Caribe.

La parte mejor conocida de la fosa de Puerto Rico es la del área norte de Puerto Rico. Aún allí es incierto si existen fallas en uno o en ambos lados de la fosa y cuánto movimiento vertical versus cuánto movimiento horizontal ha tenido lugar en uno o en ambos lados. El presente movimiento lateral-izquierdo en las fallas hipotéticas, paralelas a la fosa de Puerto Rico en esta región, puede ser o no como los pasados movimientos.

Perfilamiento sísmico, perfiles de refracción y estudios de los primeros movimientos de temblores de tierra indican compresión inferior en las Antillas Menores a lo largo del arco entre Saba y Granada en contraste con el movimiento general paralelo este-oeste en la parte norte y sur de las márgenes del Caribe.

Aunque varios radicalmente diferentes modelos tectónicos han sido propuestos para explicar el origen de los accidentes del Caribe, ningun modelo ha captado el entusiasmo de la mayoría de los investigadores.

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