Cenozoic

INTRODUCTION

Reconstruction of the geologic history and paleogeography of the Greater Antilles is simplest for the Cenozoic. The breakup of the orthogeosyncline that began during the middle Cretaceous "Subhercynian" orogenic pulses continued, and was completed by the end of the Eocene ("Laramide").

Campanian to Eocene time (*see* Figs. 26–28) was a transition period from tectonically unstable orthogeosynclinal conditions to relatively stable, post-orogenic, molasse-type conditions. The volcanic activity which characterized the Cretaceous changed gradually by the late Eocene or early Oligocene to predominantly carbonate and marl deposition. The only exception is Hispañola where volcanism (considerably diminished compared with the Cretaceous) continued until Pliocene and Pleistocene times.

The transition began at different times in different areas. Separate depositional regimes, ranging from carbonate shelves to subsiding fault-bounded grabens and half-grabens, were established throughout the Greater Antilles (*see* Fig. 29 for locations of basins). Jamaica and northern Puerto Rico generally were the sites of shelf deposition, whereas Cuba, Hispañola, and possibly the Virgin Islands and southern Puerto Rico were mainly sites of graben or half-graben formation.

Differentiation of the various Tertiary basins began in western and central Cuba during Campanian and Maestrichtian times; in eastern Jamaica, eastern Cuba, and Hispañola during Paleocene and Eocene times (although an earlier age is not excluded); and in the rest of Jamaica, parts of Cuba, Hispañola, Puerto Rico, and the Virgin Islands during late Eocene or Oligocene time.

Complete isolation of the various depositional shelves and basins was not attained, except locally. In general, shallow-marine conditions persisted in areas between the actively subsiding basins.

According to Khudoley, small landmasses persisted in the Caribbean Sea, but Meyerhoff does not agree with this.

Cuba

At least eight basins are known. The earliest to form were the Central basin (70 × 15 km) and, possibly, the Los Palacios basin (90 × 17 km) (Fig. 29).

These basins, by Campanian time, were the sites of rapid subsidence, in part along faults, and relatively thick sediment accumulation. However, significant thicknesses of Campanian and Maestrichtian are widespread on the island, and neither the Central nor the Los Palacios basin was formed fully during this time interval.

The Cauto basin also appears to have been subsiding rapidly by Campanian or Maestrichtian time but conclusive proof is lacking (G. Lewis and Straczek, 1955, p. 241–244; Bermúdez, 1961, p. 18–25).

By Paleocene time, the Cauto, Ana María, Central, Los Palacios, and (possibly) Cochinos basins were well developed. The Cauto basin, bounded approximately by the Cauto fault zone on the north and by the Bartlett fault system on the south, grew in two stages. The original or "old" Cauto basin (250 × 100 km) includes most of southern Oriente Province, and the offshore part of southeastern Camagüey Province. The "young" Cauto basin, the Ana María basin, the Nipe basin, and the Guantánamo basin are on the site of the old Cauto basin (Fig. 29).

The old Cauto basin is Paleocene-middle Eocene, and is underlain by 4000 to 6000 m of section (*see* M. T. Kozary's maps *in* Bowin, 1968, Fig. 5; Kozary showed as much as 4000 m of Paleocene-middle Eocene). The axis of the younger Cauto basin (160 × 50 km; Manzanillo or Guacanayabo basin of other authors) is north of the older axis, and contains 2300 to 2400 m of middle Eocene-Pliocene rocks in the axial part (1000 to 2400 m on M. T. Kozary's maps; *see* Bowin, 1968, Fig. 5). The Nipe basin (90 × 22 km; called Santa Isabel de Nipe basin by Keijzer, 1945) contains about 1700 m of latest Eocene and Oligo-Miocene (M. T. Kozary, *in* Bowin, 1968, Fig. 5); the Ana María basin (70 × 40 km) contains 2500 m of Paleocene-Miocene; and the Guantánamo basin (50 × 30 km; San Luis basin of Keijzer, 1945) contains 1000 to 4000 m of late Eocene-Oligocene, including evaporites (M. T. Kozary, *in* Bowin, 1968, Fig. 5). Except for the Cauto fault zone which controlled development of the Cauto basin, most of the other basins in this area seem to be structural downwarps having little or no relation to faulting. (The thickness data for Cuban basins are from G. Lewis and Straczek, 1955; Furrazola-Bermúdez and others, 1964, 1965; López and Ibarra, 1964; and M. T. Kozary, *in* Bowin, 1968).

Farther west, at least 4000 m of Paleocene through early Miocene sediment was deposited in the Los Palacios basin which is bounded on the north by the regional Pinar fault.

Possibly 3000 m or more of sediment was deposited in the Cochinos basin. The section in this basin has not been drilled, and the ages of the rocks are not known. Data from Iturralde-Vinent (1969) suggest that much of the section is Miocene. The Cochinos graben is anomalous in that its boundary faults strike approximately north-south, or 90° to the regional structural grain.

From 1350 to 3100 m of Paleocene-Oligocene accumulated in the Central basin (Furrazola-Bermúdez and others, 1964, 1965). On the north, 300 to 1520 m of late Eocene-early Miocene is in the Morón evaporite basin (50 × 25 km) (A. A. Meyerhoff and Hatten, 1968).

Jamaica

The history of Jamaica differed markedly from that of Cuba. After Maestrichtian time, all of Jamaica was uplifted except for the coast adjacent to the Blue Mountains zone, parts of the coast of the Cornwall-Middlesex zone (St. Ann Inlier), and a fault-bounded trough (Wagwater belt) between the modern Blue Mountains and Cornwall-Middlesex zones (Figs. 26, 28, 29). In this trough a minimum of 1150 to 3300 m of sediments accumulated (Zans, 1961; Zans and others, 1962; Chubb and Burke, 1963; Geol. Survey Dept. of Jamaica, 1966); this thickness includes only early and middle Eocene. Between 300 and 750 m of volcanic and intrusive rocks also are present. Paleocene may underlie the Eocene but has not been identified.

After middle Eocene time, Jamaica, except for the area of the present Blue Mountains, was a broad, slowly submerging area of carbonate-shelf deposition. Between 100 and 2000 m or more of middle Eocene-middle Miocene were deposited.

Hispañola

Northern and central Haiti and the Dominican Republic were the sites of deposition of at least 2000 m (locally 2500 m or more) of Paleocene through middle Eocene terrigenous clastic and volcanic, and some carbonate rocks. The equivalent section in the southwestern part of the island consists of 1000 to 4900 m or more of terrigenous clastic and carbonate rocks (thickness data for Hispañola are from Butterlin, 1960; H. Palmer, 1963; Bowin, 1966; and H. A. Meyerhoff, May 15, 1968, written commun.).

During late Eocene-early Oligocene time, the island was fragmented into several west-northwest-east-southeast-trending grabens (Guerra-Peña, 1956; *see* Fig. 29); latest Eocene(?) and younger rocks overlie the older strata unconformably. In the north is the Cibao graben (300 × 25 km), which contains at least 3650 m of Miocene alone (Spangler and Meyerhoff, 1959). Guerra-Peña (1956) estimated that 10 km of Tertiary (Paleocene-Eocene) is present but this is at best a guess. In the south-central part of the island, the San Juan (Matheux)-Azua basin is known to contain 2000 to more than 3000 m of late Eocene through Miocene (Harry Wassall and Assoc., 1962). The probable thickness is greater than 5000 m, though Guerra-Peña (1956) estimated 7 to 8 km of Tertiary in the Azua area alone. A notable feature of the Azua basin is the presence of thick Miocene salt deposits.

Cutting across the southwestern corner of the island is the Enriquillo graben in which Guerra-Peña (1956) estimated that 10 km of Tertiary is present. More than 5000 m of section has been measured, including a thick Miocene salt section.

In the central Dominican Republic, H. Palmer (1963) described a 3200-m-thick Oligocene section which is not in one of the fault grabens described. However, the Oligocene (and late Eocene) of Palmer's area is in a major graben system parallel with and just south of the Cibao graben, and evidently is closely related to the Cibao graben.

South of Hispañola, the Beata Ridge began to subside. Fox and others (P. J. Fox, October 9, 1968, written commun.) recovered a shallow-shelf middle Eocene fauna in limestone on the crest of the ridge (16°50'N., 72°20'W.; depth, 2410 m); a shallow, warm-water limestone of the same age, close to the first locality at 1730 m; and an outer neritic to bathyal, middle Eocene fauna nearby at 2000 m.

Puerto Rico

The Paleocene through middle Eocene is part of the eugeosyncline and is 4000 m or more thick (O. T. Tobisch, June 3, 1968, written commun.). Overlying the Eocene with angular unconformity are Oligocene and younger rocks.

Two carbonate shelves containing Oligocene and Miocene rocks are present—one on the north side of the island and one on the south (Fig. 29). The shelf along the south coast of Puerto Rico apparently is complicated by several large normal faults (Griscom, 1968). From 415 to 1685 m of section is known to be present along the north coast (Hubbard, 1920, 1923; H. A. Meyerhoff, 1933; Zapp and others, 1948; Gordon, 1960; Mitchell, 1960; Briggs, 1961; Berryhill, 1965; Nelson, 1966b), and from 655 to 1955 m along the south coast (Mitchell, 1960; Pessagno, 1963a). Gordon (1960, 1961a, 1961b) assigned the entire north and south coast sections to the Miocene.

West of Puerto Rico, between that island and the Dominican Republic, is Mona Island (Fig. 1) on which exceptionally pure limestone and dolomite of Miocene(?) and Pliocene to Pleistocene(?) ages have been mapped (Kaye, 1959b).

Virgin Islands

The Paleocene-middle Eocene is part of the eugeosynclinal sequence. The younger Tertiary strata overlie the eugeosynclinal section with angular unconformity.

Whetten (1966) postulated that an east-northeast-west-southwest-striking Tertiary graben (Fig. 29) crosses the island of St. Croix. H. A. Meyerhoff doubts this (May 15, 1968, written commun.), but the existence of a downwarp or half-graben is probable. About 600 m of late Oligocene-early Miocene crops out or lies just beneath the surface. Geophysical data suggest that at least 2 km of sedimentary, Tertiary, post-Campanian rocks may underlie the downwarp, graben, or half-graben (Whetten, 1966). The age of the oldest rocks in the graben (or half-graben) is unknown.

PALEOCENE

Stratigraphy

Carbonate-bank deposition continued in the Bahamas and northern Cuba (Fig. 27). Approximately 850 m was penetrated in the Andros well and 300 m in the Cay Sal well. The section is shallow-water bank limestone and the

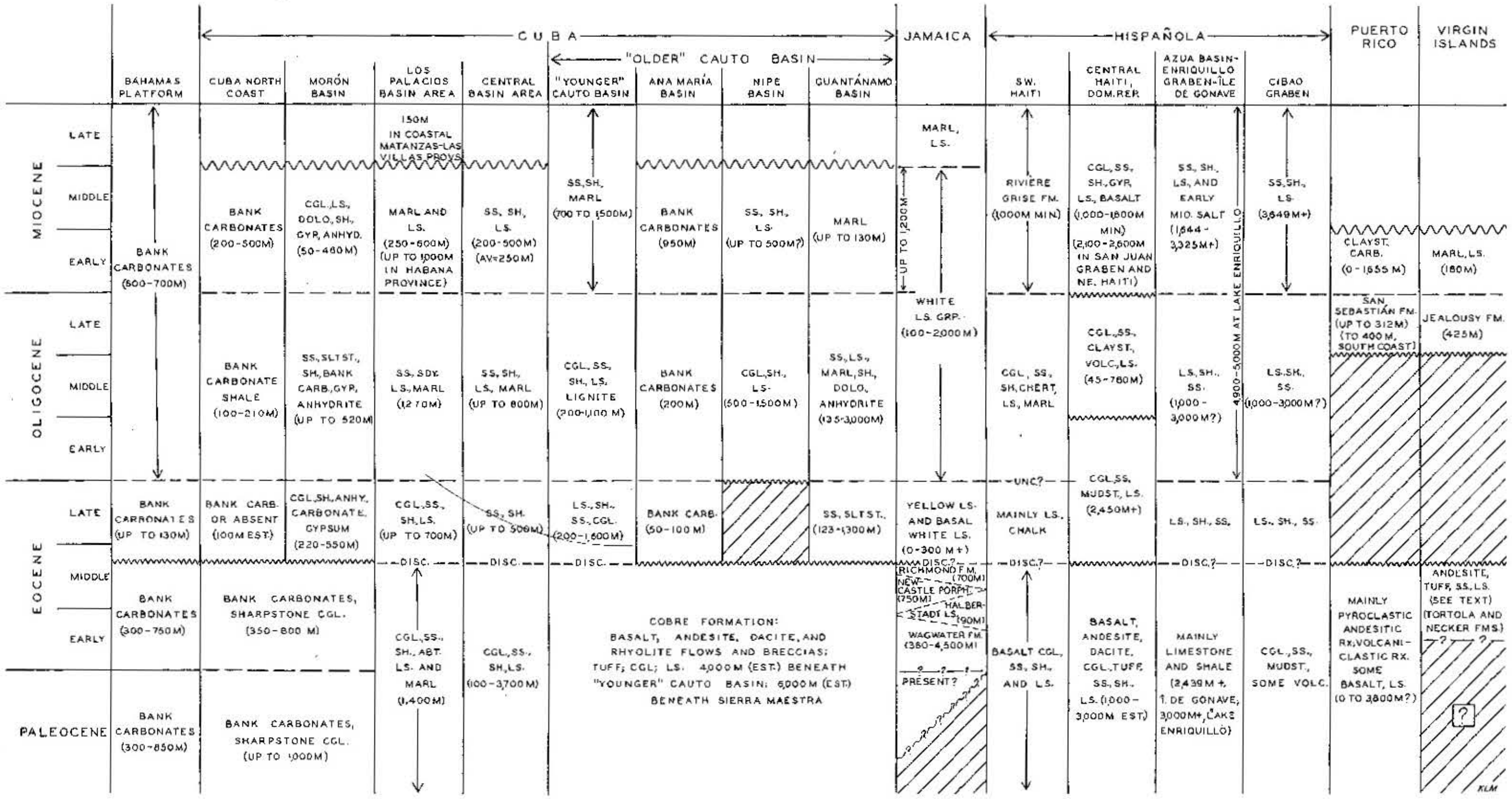

Figure 27. Generalized correlations of Tertiary rocks, Greater Antilles.

anhydrite of the Cedar Keys Formation of Florida was not found. The Paleocene bank limestone extends into north Cuba. Locally up to 300 m of limestone sharpstone conglomerate was deposited in depressions formed in northern Cuba during the "Laramide" orogeny.

In the median welt and eugeosynclinal areas of western and central Cuba, Paleocene terrigenous clastic sediments up to 1000 m thick were deposited. Outside of the newly forming basins, folding and faulting created many narrow, linear depressions which parallel the trend of the island. In these linear depressions, Paleocene syntectonic flysch-type sediments formed.

In eastern Cuba, rhyolite, dacite, andesite, and basalt flows, and tuff and tuff breccia were deposited in the Paleocene-middle Eocene "old Cauto basin" (Fig. 29). Tuffaceous rocks predominate. Thicknesses up to 1500 m accumulated locally (Furrazola-Bermúdez and others, 1964, their Fig. 49). A similar thickness (1400 m) is reported from the Los Palacios basin of western Cuba (Furrazola-Bermúdez and others, 1964, their Fig. 47). In southernmost Oriente Province, on the site of the Sierra Maestra, possibly 2500 to 3500 m of Paleocene is present. This thickness figure, however, is unproved, and its lower age limit is unknown (G. Lewis and Straczek, 1955, p. 141–144; Bermúdez, 1961, p. 18–25, p. 27). M. T. Kozary (*in* Bowin, 1968, Fig. 5) reported a thickness ranging from 300 to 2200 m.

Paleocene rocks are widespread on Hispañola, and in most places are unconformable on the Cretaceous (Butterlin, 1960). In the north, center, and east, at least 600 m of conglomerate, basalt, andesite, dacite, tuff, basaltic breccia, sandstone, shale, and limestone occurs. The basal conglomerate commonly contains cobbles of basalt. In southern Hispañola, a thickness of several hundred meters (possibly more than 1000 m) is present. This includes a local basalt conglomerate, sandstone, and shale, with some limestone. The basal conglomerate contains clasts of crystalline schist, quartz diorite, and Cretaceous rocks. Weyl (1966, p. 115–116) wrote that during Paleocene and early Eocene times, the zone south of the Cordillera Central (Fig. 7) was a deep basin in which thick sequences of sediments and volcanic-derived materials accumulated.

On Puerto Rico, the Paleocene is missing in some areas (Pessagno, 1962; Mattson, 1962, 1966a, 1967; U.S. Geol. Survey, 1967a). Where present, it is composed of dacite vitrophyre, spilitic andesite, spilitic pyroclastics, some basalt, siltstone, mudstone, and limestone. The thickness is unknown but is on the order of several hundred meters—possibly as much as 1800 m. In many areas, Paleocene is unconformable on the Cretaceous.

The presence of Paleocene is not proved in the Virgin Islands or Jamaica. If present in Jamaica, it probably underlies the Wagwater belt and parts of the coastal areas.

Geologic History and Paleogeography

Great tectonic instability characterized Paleocene time. Folding and vertical movements took place throughout the Greater Antilles area. Small land-

masses may have been present in the area of the modern Caribbean Sea (Khudoley) but the area of the present Caribbean could have been oceanic (Meyerhoff). West of the Ana María-Cauto basins, volcanic activity ceased, but east of the fault, volcanism continued. Jamaica was entirely emergent except possibly for the Wagwater belt and the coastal area along the north side of the Cornwall-Middlesex zone. Small islands were abundant in much of the Greater Antilles area, and the faunas show that warm water with normal salinity predominated. Granitic rocks were intruded, as proved by the radiogenic dates given on Table 4 (eastern Cuba, Jamaica, Hispañola, and Puerto Rico).

EOCENE

Stratigraphy

On the Bahamas platform, 750 m of shallow-water limestone and dolomite was penetrated in the Andros well (Spencer, 1967: *Coskinolina* cf. *C. elongata: Lockhartia* cf. *L. cushmani; Lituonella* cf. *L. floridana; Dictyoconus cookei*), and at least 300 m in the Cay Sal well (Furrazola-Bermúdez and others, 1964). Approximately 450 m of bank limestone and dolomite is in the north Cuba area. In addition, thick (± 800 m) limestone-sharpstone conglomerate accumulated in depressions formed during the "Laramide" orogeny. The clasts in the conglomerate are of Maestrichtian, Paleocene, and Eocene shallow-water limestone (A. A. Meyerhoff and Hatten, 1968) (*see* Fig. 27).

South of the median welt in central and western Cuba, thick Eocene terrigenous conglomerate, sandstone, and shale sections, interbedded locally with massive reefs, were deposited in the subsiding basin areas. Outside of the basins, faulting and folding caused the formation of deep-marine depressions between uplifted blocks and welts. In the basins, or furrows, thick sequences (up to 3700 m) of synorogenic Wildflysch and flysch (Tercier, 1947) were deposited (for example, Río Tuinicú section, southern Las Villas Province, A. A. Meyerhoff and Hatten, 1968).

On the welts, shallow-water deposits, including reefs, accumulated. Some exceptionally clean offshore bar or beach sands were formed in the Central basin area.

The synorogenic Wildflysch and flysch deposits consist largely of terrigenous debris on and south of the median welt, and of limestone-sharpstone conglomerate beds north of the median welt. Particularly in the eugeosynclinal area and the Sierra de los Órganos, the Wildflysch—"chaos breccia"—includes reworked eugeosynclinal rocks, together with great exotic blocks of igneous and metamorphic rocks. Sorting and bedding commonly are totally absent, and the flysch deposits in many areas are overridden, contorted, and crushed beneath synsedimentary thrust plates.

By late middle or early late Eocene time, faulting and subsidence were so intense that great "chaos breccias" formed locally in northern Pinar del Río, northern Las Villas Province, and northern Camagüey Province (Kozary, 1953, 1956, 1968; Hatten and others, 1958; Furrazola-Bermúdez and others, 1964,

1965; Knipper and Puig, 1967; A. A. Meyerhoff and Hatten, 1968). Serpentinites were crushed and mangled in these "chaos breccias"; the outcrop areas of some "fragments" (olistoliths and olistostromes of Flores, 1959) are as much as 50 to 100 sq km. Some of the "chaos breccias" or Wildflysch deposits described here are *mélanges*, as used by Hsü (1968), but others clearly are sedimentary deposits.

In western and central Cuba, the late Eocene overlies the early and middle Eocene with a prominent angular unconformity. The late Eocene includes 100 to 700 m of sandstone, shale, marl, and limestone. A Russian dredge haul (no. 91, 1430 m of water, Fig. 13) off western Cuba recovered a "lithoclastic tuff" in which angular clasts of Cenomanian through Eocene limestones are present. The age of the tuffaceous matrix is unknown (Mel'nik and Zernetskiy, 1966). Another haul (no. 68, 700 m of water) contained mafic lavas(?) of unknown age.

In the Central basin and in other basins, the late Eocene was deposited in water as much as several hundred meters deep. Late Eocene in the Morón basin consists of 220 to 550 m of conglomerate, reddish shale, shallow-water limestone, dolomite, anhydrite, and gypsum (Meyerhoff and Hatten, 1968).

In southeastern Cuba, the early and early middle Eocene consists of 600 to 3600 m (600 to 2800 m in Sierra Maestra; Kozary, *in* Bowin, 1968, his Fig. 5) of sedimentary and volcanic rocks (G. Lewis and Straczek, 1955; Furrazola-Bermúdez and others, 1964). The section is composed of andesite, dacite, basalt, tuff, and tuff-breccia with interbedded chert, limestone, sandstone, and shale. The overlying late middle to late Eocene, 200 to 1600 m thick (average 500 m), consists primarily of calcarenite, shallow-water limestone, shale, sandstone, and conglomerate. There is very little evidence of an angular unconformity in the Eocene section here, and the folding which was so intense from the Gibara area of northwestern Oriente Province to westernmost Cuba was very mild in southern Oriente.

Along the southern coast of Cuba, the Guantánamo basin began to form and 123 m of late Eocene marine sandstone and siltstone was penetrated in one well (Furrazola-Bermúdez and others, 1964). M. T. Kozary (*in* Bowin, 1968, Fig. 5) reported up to 1300 m in this basin.

The Jamaican section also contains two groups of strata: (1) the early to early middle Eocene section of the Wagwater belt (Figs. 7, 13, 29), between the Blue Mountains zone and the Cornwall-Middlesex zone (some early to middle Eocene rocks almost ring the Blue Mountains); and (2) the middle (late early Eocene according to Wright, 1968) to late Eocene carbonate-shelf section (Yellow Limestone Group and lower part of the White Limestone Group), which covered most of the area around the Blue Mountains, including the Wagwater belt, and the Cornwall-Middlesex zone. Some islands in the latter zone were large until almost complete submergence occurred during deposition of the White Limestone Group.

The Wagwater belt section (Zans, 1960, 1961; Zans and others, 1962; Chubb and Burke, 1963; Geol. Survey Dept. of Jamaica, 1966; Reed, 1966;

Craig, 1968) is 1150 to 3300 m thick in most areas where it has been measured, but the base generally is not exposed. Possibly 5000 m or more is exposed along the north side of the Blue Mountains and in the northern part of the Wagwater belt (Geol. Survey Dept. of Jamaica, 1966, p. 9). Its age range is early Eocene to early middle Eocene. Paleocene faunas have not been reported but ultimately may be found.

At the base of the section is the Wagwater Formation (Wagwater Conglomerate), which ranges in thickness from at least 450 to 4500 m. This formation and the overlying Richmond Formation were deposited mainly in a rapidly subsiding fault trough (Fig. 7) along the west, southwest, and south flanks of the rising Blue Mountains. Rapid subsidence also took place around the northern and eastern sides of the Blue Mountains, and some equivalent deposits may be present locally along the north coast of the Cornwall-Middlesex zone on the west.

In the Wagwater belt, or fault trough, the exposed section includes 450 m or more of Wagwater Formation at the base. This unit consists of conglomerate (with pebbles of granodiorite, and large amounts of andesite and rhyolite debris), sandstone, shale, and, near the top, beds of shaly limestone. In one area, a thick gypsum was deposited, and served as a lubricant for thrust faulting during late Eocene deformation. Locally, above the Wagwater, there is a reef limestone called the Halberstadt Limestone. This unit ranges in thickness from zero to 90 m. The Wagwater-Halberstadt is overlain by as much as 700 m of the Richmond Formation, which consists of graywacke, siltstone, shale, slide conglomerate, and a few submarine flows of basalt and spilite.

Within the northwestern part of the Wagwater belt is a 32-km-long and 5-8-km-wide igneous complex called the Newcastle Porphyry. According to Reed (1966) and Craig (1968), the Newcastle is a complex of intrusive and extrusive rocks. Craig (p. 15) described it as ". . . subaerial lava and pyroclastic flows." The thickness ranges from 300 to 750 m (Craig, 1968). According to Craig, dacite predominates and andesite is subordinate, but Reed (p. 32) wrote that the Newcastle is mainly hornblende rhyolite; conclusions similar to those of Reed were made by the Geological Survey Department of Jamaica (1964).

Along the north side of the Blue Mountains, the Wagwater Formation is at least 4500 m thick (est. by Geol. Survey Dept. of Jamaica, 1964). The lower 3200 m consists of conglomerate which contains no pebbles of granodiorite rocks. Above the basal conglomerate is 650 m of greenish-gray to gray arkose, coarse arkosic sandstone, and siltstone. The upper 650 m is similar to the Wagwater exposed in the Wagwater trough: conglomerate which contains abundant granodioritic boulders. A few spilite and basalt flows, greenish tuff beds, and calcareous mudstone strata are present. The overlying Richmond could not be measured because of the great structural distortion of the beds. It is composed of incompetent, thin-bedded, gray graywacke, arkosic wacke, siltstone, and mudstone. Many beds have the characteristics of turbidites.

Until very recently, early to middle Eocene strata equivalent to those of the

Wagwater belt were known only from that belt and from the coastal area around the Blue Mountains. Esker (1968, 1969) reported the presence of early to middle Eocene strata at the top of a Campanian sequence in the St. Ann Inlier (Fig. 7), along the north coast of the Cornwall-Middlesex zone. These strata may be partly equivalent to the Wagwater-belt sequence. The contained fauna includes *Globorotalia aragonensis, Glr. prolata, Turborotalia soldadoensis,* and *Pseudohastigerina wilcoxensis.* Careful study of other parts of the Cornwall-Middlesex zone may reveal the presence of additional areas of sedimentary rocks equivalent in part to the Wagwater sequence.

Above the Wagwater-belt sequence and overlying most areas of the Cornwall-Middlesex zone is the early middle Eocene Yellow Limestone Group (Matley, 1951; Zans, 1960, 1961; Versey, 1960; Versey, *in* Zans and others, 1962; Geol. Survey Dept. of Jamaica, 1964, 1965, 1966; Reed, 1966; Robinson, 1966, 1967; Wright, 1968). Wherever the Wagwater-belt section is present, the Richmond appears to grade upward into the Yellow Limestone. However, in the Cornwall-Middlesex zone, the Yellow Limestone Group transgresses the folded Cretaceous and fills a fairly rugged relief which was developed during Paleocene-early Eocene time. As a consequence, the Yellow Limestone Group is characterized in many areas, particularly near topographic highs, by marked and abrupt lateral facies changes.

Where relief was present on the eroded Cretaceous rocks of the Cornwall-Middlesex zone, the Yellow Limestone Group may consist of 150 to 200 m of conglomerate and sandstone in the depressions, and 3 m or less of bluish-gray claystone and shale on the highs. In places, the Yellow Limestone Group did not cover the highs and the younger White Limestone Group is directly on the Cretaceous.

Along the north side of the Blue Mountains, the Yellow Limestone Group consists of a basal, thick, massive, argillaceous reef limestone and abundant limestone conglomerate; a middle unit of calcareous arkosic sandstone, calcareous mudstone, and gypsum; and an upper unit of well-bedded marly limestone with a few turbidite-calcarenite beds (Geol. Survey Dept. of Jamaica, 1966). This three-fold division is widespread in parts of the Cornwall-Middlesex zone where the upper and lower limestone units are separated by 20 to 270 m of claystone and water-laid tuff (Versey, *in* Zans and others, 1962). Robinson (1967) described the Yellow Limestone Group of the Wagwater belt and the north coast of Jamaica as a sequence of planktonic, foraminiferal marl, bioclastic limestone, and slide conglomerate composed of noncarbonate debris. In the areas described by Robinson, deep-water conditions prevailed locally, in contrast to the shallow-water conditions in the central and southern parts of the Cornwall-Middlesex zone.

Although Zans (1961, p. 4) wrote that the maximum thickness of the Yellow Limestone Group is in the order of 170 m, the thickness range reported by other authors is from zero to 270 m (Versey, *in* Zans and others, 1962; Greiner, 1965); the section correlated with the Yellow Limestone Group in the West Negril well in western Jamaica (Fig. 7) is reported by Greiner (p. 17) to

be about 2700 m thick (Fig. 7). This last thickness requires verification, as do many of Greiner's statements. For example, he may be the only geologist who has written (p. 10), "The Yellow Limestone is of approximately equivalent age to the Wagwater-Richmond . . ."!

Conformably above the Yellow Limestone Group or, where the Yellow Limestone did not bury the Cretaceous topography completely, unconformably on the Cretaceous is the White Limestone Group of middle Eocene to middle Miocene age (Robinson, 1967). This unit consists of approximately 98 percent limestone and some dolomite. The Eocene part of the White Limestone Group consists of hard, compact, fine-grained limestone with interbedded bioclastic limestone layers and some slide conglomerate. The group as a whole represents deeper water (but mainly neritic) conditions. Locally water depths ranging from 300 to 3000 m may have prevailed (Robinson, 1967, p. 575). The total thickness of the White Limestone Group ranges from less than 100 m (probably an eroded thickness) to more than 1000 m, although Wright's (1968) 1200 m of Miocene alone indicates that a thickness of 2000 m may be present locally in the area which he studied. Greiner (1965, p. 18) reported 1950 m in the Santa Cruz well in the southwestern part of the island (Fig. 7). A thickness of 700 to 1000 m, where the unit is not deeply eroded, probably is common in many parts of the island. The Eocene part of this is at least 130 m in some areas (Versey, *in* Zans and others, 1962), although Greiner assigned the entire 1950 m in the Santa Cruz well to the middle Eocene.

The early to middle Eocene rocks of Hispañola are mixed terrigenous clastic, volcanogenic, and carbonate rocks in all but the southwestern part of the island where carbonates predominate. Middle to late Eocene strata along the south flank of the Massif du Nord have a geosynclinal character (Weyl, 1966, p. 116). Here, more than 3000 m of andesitic tuff and breccia, dacite, and basalt accumulated. This section resembles that of Oriente Province, Cuba. This geosyncline-like suite has not been traced into the Dominican Republic. Late Eocene rocks, except adjacent to the south flank of the Massif du Nord, are mainly carbonates (Butterlin, 1960), but even in that area, carbonates are abundant in the upper Eocene. Facies distribution generally parallels the northwest-southwest structural grain of the island.

Around the Gonaïve Plain, just southeast of the Terre Neuve Mountains (Fig. 7), the late Eocene strata consist of hard, thin-bedded, cherty limestone and, locally, massive, white, chalky limestone (Taylor and Lemoine, 1950). Similar lithologic types crop out adjacent to the Cul-de-Sac Plain east of Port-au-Prince (Taylor and Lemoine, 1949). Here the strata range from dense, thin-bedded, white limestone with chert bands to massive, gray limestone.

On the Massif de la Selle of southwestern Haiti, possibly several hundred meters are present. Taylor and Lemoine (1949) reported a minimum exposed thickness of 150 m (*see also* Woodring and others, 1924). In contrast, on the Île de Gonave, on strike with the Enriquillo graben, one well penetrated about 2439 m of Eocene and, possibly, latest Paleocene carbonate and shale (A. A.

Meyerhoff and Spangler, 1958). This great thickness difference suggests that the Enriquillo graben was well developed by early Eocene or late Paleocene time. (The well thickness is not corrected for dip, and Eocene thicknesses reported by Butterlin [1960] are only estimates. Nevertheless, there does appear to be a significant thickness difference between the section on the uplifted massif and that in the graben. Khudoley believes that the Eocene of Hispañola may attain a maximum thickness of 3000 m; H. A. Meyerhoff [May 15, 1968, written commun.] believes that 3000 m is a minimum figure in some areas of the graben, particularly near Lago Enriquillo.)

Eocene granodiorite, quartz diorite, and doleritic intrusions appear to be numerous in Haiti (Butterlin, 1960; Weyl, 1966).

The late Eocene of the San Juan and Cibao graben areas consists principally of carbonates (Butterlin, 1960; Harry Wassall and Assoc., 1962). These two grabens, if not older than the late Eocene, were in existence by late Eocene time.

South of the island on the Beata Ridge, Fox and others (P. J. Fox, October 9, 1968, written commun.) collected middle Eocene carbonates at depths ranging from 1730 to 2410 m (16°50′ N., 72°20′ W.). The carbonates contained faunas which lived at depths ranging from bank or shallow-neritic to outer neritic or bathyal. Bathyal early Eocene and younger sediments are present farther south along the ridge (Edgar, 1968). The northern part of the ridge appears to have been at or close to sea level before middle Eocene time, and subsequently has subsided.

The Eocene of Puerto Rico is mainly early to middle Eocene of the eugeosyncline sequence (Mattson, 1960a, 1960b, 1962, 1966a, 1966b; Pessagno, 1960a, 1960b, 1962, 1966; Berryhill and others, 1960; Briggs, 1961; Berryhill, 1965, 1966; Lidiak, 1965; Nelson, 1966c; U.S. Geol. Survey, 1967a). Late Eocene deposits have not been found. The Eocene rocks are the same types as those reported for the Paleocene, and were intruded by granodioritic stocks and batholiths (Berryhill and others, 1960; Pessagno, 1960b). The exact thickness is unknown but is on the order of 3000 to 4000 m or more in some areas (Nelson and Tobisch, *in* Cohee and others, 1967; Tobisch and Turner, in press), most of the rock consists of massive to thin-bedded volcaniclastic deposits with minor amounts of lava (O. T. Tobisch, June 3, 1968, written commun.).

Similarly, in the Virgin Islands, only early to middle Eocene is reported (Helsley, 1960, 1968; Donnelly, 1966a; Whetten, 1966). Late Eocene, if present, has not been described. Late Eocene could be preserved in the St. Croix graben (Whetten, 1966), if this graben exists. The early to middle Eocene consists of andesite breccia, tuff, volcanic-derived sandstone, and a few limestone lentils. Donnelly (1966a) reported a minimum thickness of 3400 m; Helsley (1960) reported that minimum and maximum estimated composite thicknesses range from 3000 to 6000 m (Tortola Formation) and 1400 to 2000 m (Necker Formation). Together this would be 4400 to 8000 m for the early and middle Eocene! Helsley also wrote that the middle Eocene Tor-

tola overlies Cenomanian conformably. The probability that several thousand meters of unfossiliferous rocks separate the beds with middle Eocene fauna from the strata with a Cenomanian fauna (which Donnelly, 1966a, called Albian) seems slight; this leaves the Eocene thickness problem unsolved, because both Paleocene and Late Cretaceous may well be present in the lower part of Helsley's middle Eocene. In a written communication to the writers (May 10, 1968), Helsley stated that the fossil control in the area is wholly inadequate, and that his 1960 conclusions are tentative.

Geologic History

The tectonic instability of the Greater Antilles was great during early and middle Eocene times, and in some areas continued into late Eocene time. Folding took place during all of these times in some parts of the Greater Antilles. The most notable angular unconformity is of middle Eocene age. However, a middle Eocene unconformity is not well developed in the Sierra Maestra of eastern Cuba (G. Lewis and Straczek, 1955), in the Wagwater belt of Jamaica (Zans and others, 1962), or in the basin areas of Hispañola (Butterlin, 1960). Butterlin wrote that the principal unconformity in the Eocene of Haiti is at the top of the upper Eocene, but H. Palmer (1963) and Bowin (1966) provided strong evidence for a middle Eocene angular unconformity in the central Dominican Republic.

This contradiction between the unconformity positions chosen by Butterlin and Palmer/Bowin might be explained if Butterlin's conclusions were based largely on studies of sequences along the flanks of subsiding basins, whereas Palmer and Bowin concentrated their studies in the mountain massifs between the basins. Moreover, the faunal control used by Butterlin is sparse for such a large area. Within the grabens of Haiti and the Dominican Republic, very little evidence for a middle Eocene angular unconformity has been reported. In contrast, studies of the uplifted blocks or massifs of Hispañola do provide evidence for a major unconformity near the top of middle Eocene sediments.

This explanation is supported by the fact that a middle Eocene angular unconformity is not well developed in the rapidly subsiding Paleocene-Eocene Cauto basin of Cuba, whereas in the positive areas north and west of the Cauto basin, a middle Eocene angular unconformity is pronounced. Similarly, in the rapidly subsiding Central and Los Palacios basins of central and western Cuba, respectively, the middle and upper Eocene apparently are conformable. The principal middle Eocene phenomenon observed in each of these subsiding basins is a change from clastic deposition to mainly carbonate deposition.

A similar situation is observed in Jamaica. A marked pre-late middle Eocene unconformity is widespread in the Cornwall-Middlesex zone, but is not evident in the Wagwater belt which was a rapidly subsiding basin where nearly continuous deposition may have taken place.

Therefore, the writers conclude that, of the various Eocene unconformities

in the Greater Antilles, those in the upper part of or at the top of the middle Eocene rocks are the most important and most widespread.

Important gabbroic to granitic (average, quartz dioritic to granodioritic) intrusions took place in Eocene time, from the Sierra Maestra of Cuba to the Virgin Islands (Table 4; *see* also G. Lewis and Straczek, 1955; Berryhill and others, 1960; Butterlin, 1960; Helsley, 1960; Pessagno, 1960b; H. Palmer, 1963; Donnelly, 1964; Bowin, 1966).

Paleogeography

Marine basins occupied the present site of the Greater Antilles, although many small and some large areas were exposed, forming archipelagos (Figs. 26, 28). Landmasses, in Khudoley's opinion, were present in the Caribbean, but were considerably reduced in size.

A carbonate platform continued to develop on the north side of Cuba and in the Bahamas. Terrigenous clastic deposition predominated in western and central Cuba. In fact, western and central Cuba constituted a moderately stable platform area from late Eocene time onward (*Cuban platform* of H. A. Meyerhoff, 1954, p. 152). Volcanogenic rocks formed in the remainder of the Greater Antilles until the end of middle Eocene time, when carbonate deposition became dominant in the Cuban basins, Jamaica, and Hispañola. Puerto Rico and the Virgin Islands (with the possible exception of the St. Croix "graben") were uplifted. Only in Hispañola did volcanic activity continue after Eocene time.

Faunal studies reveal that the early Eocene sea was warm and of normal salinity. Marine life was abundant—fish, echinoderms, mollusks, brachiopods, Foraminifera, and so on. During middle Eocene time, coral and algal reefs were numerous. Radiolaria and some microfaunal assemblages indicate that, locally, middle Eocene cold- or deep-water conditions prevailed. Late Eocene faunas, in contrast, suggest warm, normal-saline, tropical conditions in all of the Greater Antilles.

OLIGOCENE

Stratigraphy

Oligocene sediments are widespread in the Greater Antilles, but their extent is much more restricted than that of Eocene rocks (Fig. 27). With the exception of parts of Hispañola, all Oligocene rocks are carbonates and terrigenous clastics; some evaporites occur locally. The writers generally tried to follow Iturralde-Vinent's (1969) usage of "Oligocene" in Cuba, and included the Aquitanian Stage within the Miocene. However, many workers in the Greater Antilles did not specify in their publications whether strata which they assigned to the late Oligocene are Aquitanian and, for this reason, it was impossible for the writers to be consistent.

Possibly 100 to 500 m of Oligocene limestone and dolomite is present on the Bahamas platform and along northern Cuba. Echevarría and Veliev

(1967) reported 210 m from the Cayo Francés and Cayo Fragoso wells. In the Morón basin, up to 520 m of red shale, siltstone, sandstone, limestone, dolomite, anhydrite, and gypsum is known (A. A. Meyerhoff and Hatten, 1968, p. 342).

A Russian sample (no. 222, 1410 m of water, Fig. 13) from the Old Bahama Channel recovered Oligocene bathyal limestone (Mel'nik and Zernetskiy, 1966).

In western and central Cuba, Oligocene deposits range in thickness from zero to more than 1270 m. Thicknesses of 800 to 1270 m occur in the Central and Los Palacios basins, respectively (Furrazola-Bermúdez and others, 1964, 1965). In the interbasinal areas, the thickness reaches 500 m locally, but the 360 m reported by Bermúdez (1961) is more typical. The Los Palacios basin section consists of limestone, sandy limestone, deep-water marl, and minor amounts of sandstone. The Central basin section includes limestone and deep-water marl with lesser amounts of conglomerate, sandstone, and shale. Elsewhere, the Oligocene locally is reef or bank limestone, which grades basinward into pelagic, deep-water marl. Deep-water facies are common in the Cuban Oligocene (Bermúdez, 1961; Iturralde-Vinent, 1967, 1968).

In eastern Cuba, in the post-middle Eocene ("young") Cauto basin, 200 to 1100 m of Oligocene conglomerate, sandstone, shale, lignite, and limestone is present (Furrazola-Bermúdez and others, 1964; M. T. Kozary, *in* Bowin, 1968, Fig. 5). In the Guantánamo basin, 135 to 3000 m is reported (Furrazola-Bermúdez and others, 1964, 1965; M. T. Kozary, *in* Bowin, 1968, Fig. 5). Along the basin margins are sandstone and reefal limestone which grade toward the basin center into marl, marly limestone, limestone, dolomite, sandy dolomite, calcareous shale, shale, and anhydrite. In the Nipe basin 500 to 1500 m of lava-pebble conglomerate, wacke, shale, and limestone occurs (Furrazola-Bermúdez and others, 1964; M. T. Kozary, *in* Bowin, 1968, Fig. 5). In the Ana María basin, 200 m of limestone and shale has been penetrated in wells.

In the Sierra Maestra, Taber (1934) described 1520 m of Oligocene volcanic breccia (*see also* Bermúdez, 1961, p. 46), but the age of this sequence is more likely to be Eocene.

In the Cayman Islands, Oligocene bank limestone of unknown thickness is present (Matley, 1926).

The Oligocene of Jamaica (part of White Limestone Group; possibly 300 m thick) consists almost wholly of limestone of various facies (Zans and others, 1962; Robinson, 1967), ranging from shallow-water limestone banks to deep-neritic and even bathyal marl and slide conglomerate (Robinson, 1967). Some chert is present (Zans, 1961, p. 4). Southwest of Jamaica, significant thicknesses of Oligocene accumulated on the Nicaragua Rise (Hoylman and Chilingar, 1965; U.S. Geol. Survey, 1967b). Edgar (1968), using reflection-seismic data from the Signal Oil and Gas Company, reported the presence of more than 1500 m of Tertiary along the crest of the rise. At the western end of the rise are two Cretaceous-Tertiary basins, delineated by the reflection seismo-

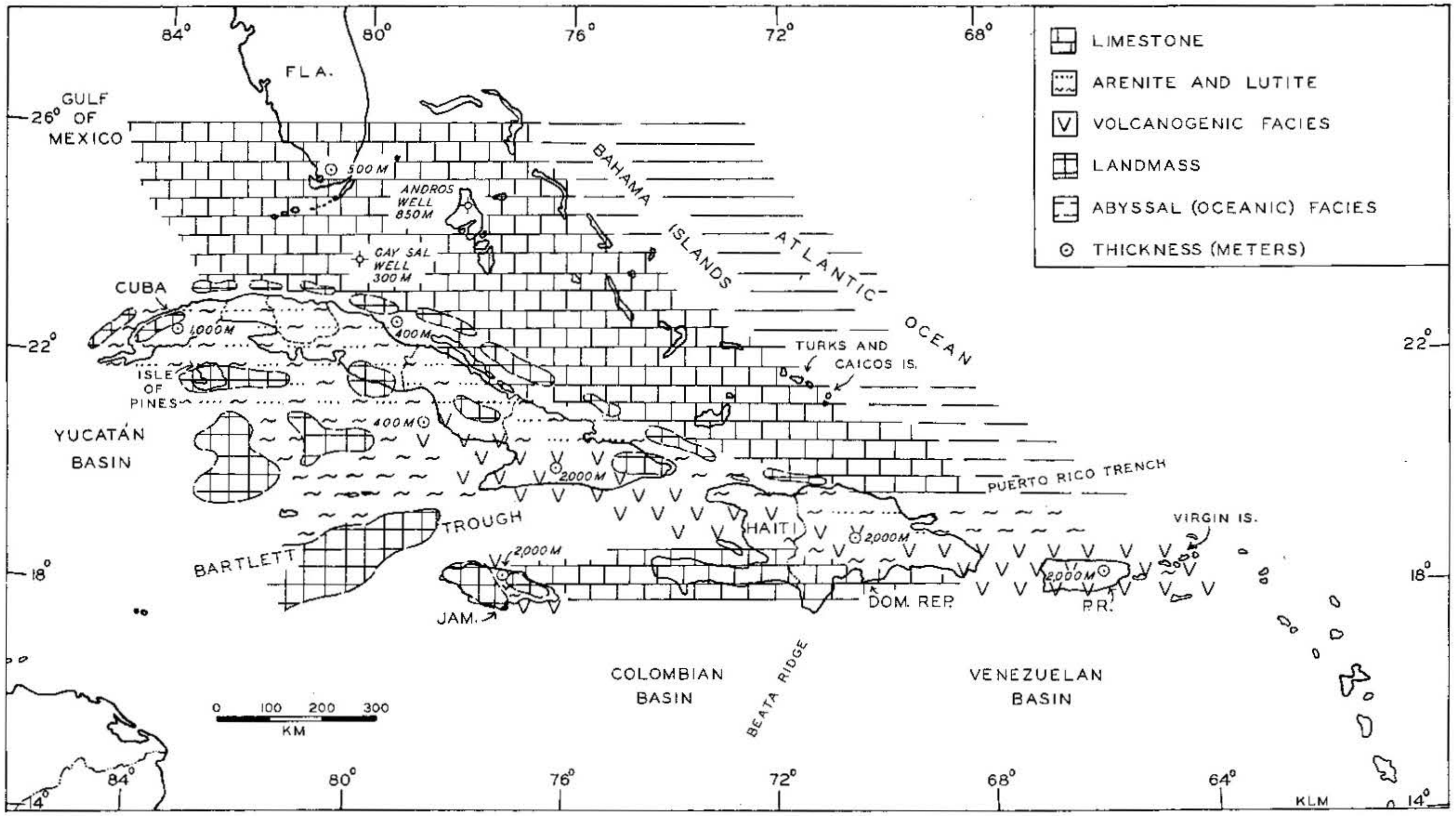

Figure 28. Paleogeography of Greater Antilles during early Eocene time, according to Khudoley.

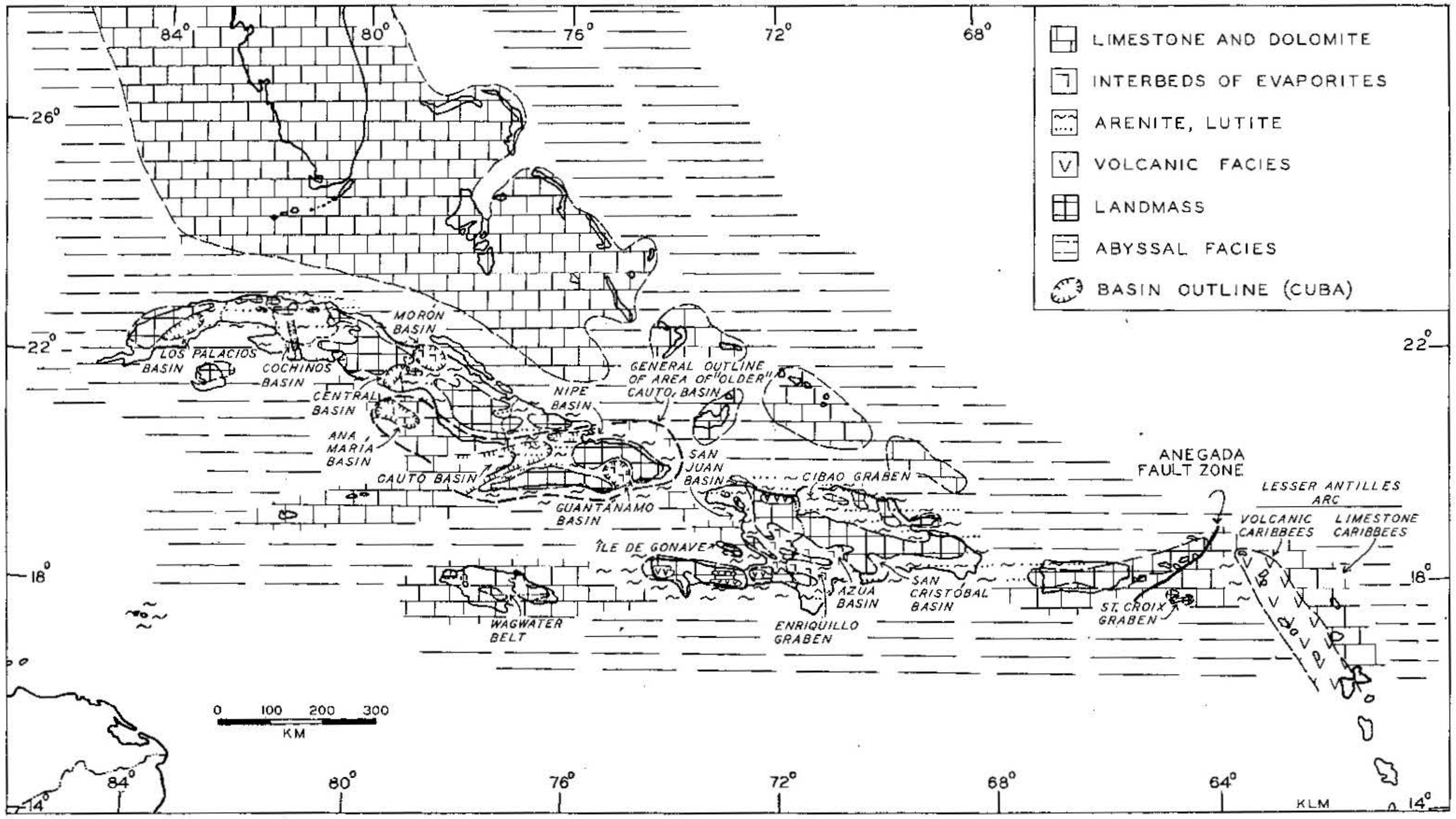

Figure 29. Paleogeography of Greater Antilles during late Eocene to Pliocene time, according to Meyerhoff.

graph, that have more than 8000 m of sedimentary rocks. About 1500 m of this amount may be Oligocene, a conclusion based on age determinations of samples collected from a deep offshore well drilled on the Nicaragua Rise (Hoylman and Chilingar, 1965).

In Hispañola, in the Massifs de la Hotte and de la Selle (Fig. 7), the Oligocene is absent locally, but where present, several hundred meters of reef limestone, chalky limestone, calcarenite, and chert may be present (Butterlin, 1960; Weyl, 1966). Just north and east of Port-au-Prince, Taylor and Lemoine (1949) reported the existence of several hundred meters of sharply folded, massive, white and tan limestone. Farther east, on the north side of the Enriquillo graben, late Oligocene limestone overlies Oligocene nepheline basalt flows. On the south side of the graben, folded, thin-bedded, hard, white to gray limestone and some massive white limestone are exposed. Chert beds are present locally, but are not as common as in the underlying late Eocene limestone.

Although limestone characterizes the early and middle Oligocene along the north slope of the Massif de la Selle, the late Oligocene of that area consists of argillaceous limestone, claystone, and siltstone. Some conglomerate and sandstone are present.

The section in central and part of northern Haiti consists of 500 to 1220 m of massive reef limestone; thin-bedded, chalky limestone; hard, platy limestone; chert; shale; sandstone; conglomerate; and nepheline basalt flows (Taylor and Lemoine, 1949; Butterlin, 1960). Terrigenous clastic material is particularly abundant in the upper part of the section. In the Northwest Peninsula and in the Massif du Nord of north-central Haiti, limestone predominates.

In the central Dominican Republic, H. Palmer (1963) reported up to 3200 m of conglomerate, sandstone, mudstone, shale and small amounts of limestone of latest Eocene and Oligocene ages. The Oligocene is folded intensely, and is preserved in a graben system. This graben is parallel with and just south of the main part of the Cibao graben (Fig. 29, p. 143). In the Azua-San Juan graben system of the Dominican Republic (Fig. 29), Bermúdez (1949) described a thick sequence of early to middle Oligocene limestone, limestone breccia, and marl, overlain by late Oligocene shale, marl, sandstone, and conglomerate. Some conglomerate is present locally in the middle Oligocene.

The thickness of the Oligocene in the main grabens which cross the island is unknown. Information from wells reported by Weeks (1948) and Harry Wassall and Associates (1962) suggests that 1000 to 3000 m of Oligocene may underlie parts of the grabens. H. A. Meyerhoff (May 15, 1968, written commun.) reported that at least 4900 m of Oligocene, Miocene, and Pliocene has been measured in the Enriquillo graben. In these grabens, much limestone occurs with some conglomerate, sandstone, and shale. Reefs also are present, and are a principal objective of petroleum exploration in the Azua and Enriquillo grabens (Martyn, 1962). The late Oligocene consists mainly of carbonates in the Enriquillo graben (Bermúdez, 1949).

In Puerto Rico, the Oligocene (part of San Sebastián Formation) of the northern coastal plain reaches a maximum thickness of 300 to 312 m (Briggs, 1961), and consists of poorly consolidated conglomerate, sandstone, siltstone, claystone, calcareous claystone, sandy chalk, and some coal (Hubbard, 1920, 1923; Briggs, 1961; Monroe, 1966; Habib, 1968b; Tobisch and Turner, in press). Shallow-water and coastal-lagoon strata are common in outcrop, but samples from a test well closer to the present coast were studied by Briggs (1961) and Gordon (1961a) and contain numerous beds of pelagic facies.

Whether part of the San Sebastián really is Oligocene is not known. The U.S. Geological Survey regards some of the overlying units as Oligocene (Lares Limestone and possibly the lower part of the Cibao Formation). Part of the section is Aquitanian and, on the basis of this, Gordon (1960, 1961a, 1961b) assigned the entire unit to the Miocene. Gordon's opinions, however, are not shared by all paleontologists. Moreover, the age of the base of the San Sebastían cannot be determined accurately with the data presently available. More work is necessary on this problem.

Equivalent strata along the south coast of Puerto Rico may be 400 m thick. Seiglie and Bermúdez (1968, 1969) have demonstrated the presence there of at least two Oligocene pelagic foraminiferal zones, thus confirming Miss Todd's identification of Oligocene in the same area (*in* Butterlin, 1969, p. 187). A recent gravimetric and aeromagnetic survey reported by Griscom (1968) revealed that the middle Tertiary of the southern coastal plain occupies depressions which are downdropped along several large normal faults. Consequently, thickness estimates based on projections from surface measurements may be substantially in error, and a considerable thickness of Oligocene sedimentary rocks could be present in the deeper parts of the downfaulted blocks.

The Oligocene Jealousy Formation of the Virgin Islands (St. Croix) is reported by Whetten (1966) to consist of 425 m of montmorillonitic mudstone. The upper part of this unit is Miocene (van den Bold, 1970).

Geologic History and Paleogeography

The Oligocene is characterized by well-differentiated deep-water and shallow-water basins which subsided steadily, and by shallow-water positive areas between (Fig. 29). Except for parts of Cuba (Tinguaro Formation), Jamaica (parts of White Limestone Group), and central Hispañola, most deposition was in shallow water. The Tinguaro, various facies of the White Limestone Group, and some strata in Hispañola accumulated in water depths of 200 to 500 m or more. Some Oligocene units in southern Puerto Rico may have been deposited at depths of up to 500 m (Seiglie and Bermúdez, 1969).

The Oligocene sample recovered from the Old Bahama Channel (no. 222 on Fig. 13) was deposited at bathyal depths (Mel'nik and Zernetskiy, 1966). The fauna includes *Globigerina bulloides*, *G.* spp., *Braazudosphaera bigelowi*, *B. disula*, *Discoaster bedlaini*, and *D. accus*.

Intense folding and minor volcanism took place during the late Oligocene in Hispañola; in fact, Hispañola is the only Greater Antillean island where

post-Eocene orogeny was intense. Elsewhere, the Oligocene is either almost flat-lying (Puerto Rico, Virgin Islands), or only gently arched (Cuba, Jamaica). Deformation *within* the graben or basin areas of Hispañola appears to be less than that within the intergraben areas, but data to prove this statement are lacking. Volcanism took place only in central and northern Hispañola.

In many parts of the Greater Antilles, outside of basinal areas, folding in late Eocene or earliest Oligocene time led to uplift and some erosion of older strata. Within the intervening subsiding areas, deposition was essentially continuous. Minor discordances occur locally within the Oligocene.

In general, the sea was shallow and warm. Marine life was abundant. Locally islands were present.

Khudoley believes that landmasses in the Caribbean Sea area were completely basified by the end of Oligocene time.

Oligocene in Caribbean Region?

Gordon (1960, 1961a, 1961b) wrote that none of the Oligocene strata of northern Puerto Rico are Oligocene, but that all are Miocene. From the fossil evidence available along the north coast, Gordon's conclusion is reasonable if assignment of the Aquitanian Stage to the early Miocene is accepted. Gordon's conclusion does not apply to the south coast. The writers, like Monroe (1966), have accepted for Puerto Rico the "traditional," view and have treated the oldest units of the Puerto Rican middle Tertiary as Oligocene, even though this approach is inconsistent with the fact that, in Cuba, the writers followed Iturralde-Vinent (1967, 1969), who placed the Aquitanian Stage in the Miocene. The writers justify this approach on the grounds that the arguments advanced by Gordon (1960, 1961a, 1961b) in favor of an Aquitanian age for the basal part of the middle Tertiary of Puerto Rico are not well supported by facts. To quote Gordon himself (1960, p. 88), "The lower San Sebastián Formation is poorly fossiliferous . . ."; (p. 89): "The lower part of the San Sebastián Formation could possibly be pre-Aquitanian, but there is no significant fossil evidence available"; and (p. 89): "The evidence of the forementioned in determining the age of the later middle Tertiary of northwestern Puerto Rico is inconclusive." Later, Gordon (1961a, p. 31) wrote of the entire middle Tertiary section of Puerto Rico: "The question of the age of these beds is not yet finally resolved."

Habib's (1968b) study of the palynological materials in a coal seam in the San Sebastián led him to conclude that the San Sebastián coal is Oligocene. However, Habib failed to define what stages he considered to be Oligocene. From the preceding, it is evident that the problem of correlating the middle Tertiary of Puerto Rico "needs work," and that paleontologists themselves must agree on some definition of the Miocene and the Oligocene.

In southern Puerto Rico, the presence of Oligocene has been demonstrated by Todd (*in* Butterlin, 1969), Seiglie and Bermúdez (1968, 1969), and by Van den Bold (1968).

North of Puerto Rico, strata of possible Oligocene age have been sampled along the north wall of the Puerto Rico Trench, and it is reasonable to assume that definite pre-Aquitanian Oligocene faunas will be found in the subsurface of, or offshore from, northern Puerto Rico, if not on the surface itself.

However, the age of the oldest middle Tertiary sedimentary rocks of Puerto Rico is only a "tempest in a teapot" compared with assertions by Eames and others (1962). These authors maintained that, except for two localities—one in Mexico and the other in the Dominican Republic—Oligocene is not present either in the Greater Antilles or in the Gulf of Mexico region. Iturralde-Vinent (1967) has disproved the assertions of Eames and his colleagues in Cuba. Butterlin (1969; *see* also Weyl, 1966, p. 118) has refuted Eames and others' conclusions as they apply to Hispañola and Jamaica. Robinson (1969) has disproved Eames and other's assertions in Jamaica. Todd (*in* Butterlin, 1969) and Seiglie and Bermúdez's (1968, 1969) work in southern Puerto Rico further refutes Eames and others' conclusions. A recent paper by Van den Bold (1968) also negates Eames and his co-authors. Eames and others also are wrong about the Gulf Coast region of the United States, for reasons summarized by A. A. Meyerhoff (1968, p. 466). Regardless, Eames and others have demonstrated the need for better mid-Tertiary trans-Atlantic correlations, and clearly many studies on this problem remain to be made.

MIOCENE

Stratigraphy

The Miocene Epoch was a time of active vertical uplift and considerable basinal or coastal subsidence (*see* Fig. 27). In addition, this was the last time during which important thicknesses of sediments accumulated on the existing Greater Antilles islands, with the exceptions of parts of west-central Cuba, possibly the younger Cauto basin of southeastern Cuba, and locally within the grabens of Hispañola. After Miocene time, most deposition was confined to present coastal and offshore areas—reefs, estuaries, and river mouths.

Several hundred meters of Miocene bank dolomite and limestone are present on the Bahamas platform and in north Cuba. Similar shallow-water limestone and some deep-water sedimentary rocks cover the remainder of Cuba. Iturralde-Vinent (1969) recently completed a regional study of the Miocene deposits which overlie the eugeosynclinal part of Cuba. He divided the Cuban Miocene (including Aquitanian) into five facies complexes, each of which is in a different part of Cuba (Fig. 30). Iturralde-Vinent's study is the most careful regional study yet made of the Cuban Miocene and is reviewed briefly.

From west to east, the five facies complexes recognized by Iturralde are: (1) Complex I: most of southern Pinar del Río Province; this is an area of conglomerate, sandstone, and bank limestone, 500 to 600 m thick. A north-south-trending fault zone bounds this complex on the east. (2) Complex II: easternmost Pinar del Río Province, Habana Province, western Matanzas Province, and the Zapata Peninsula of southwestern Las Villas Province; the eastern boundary, like the western, is a north-south-trending fault zone,

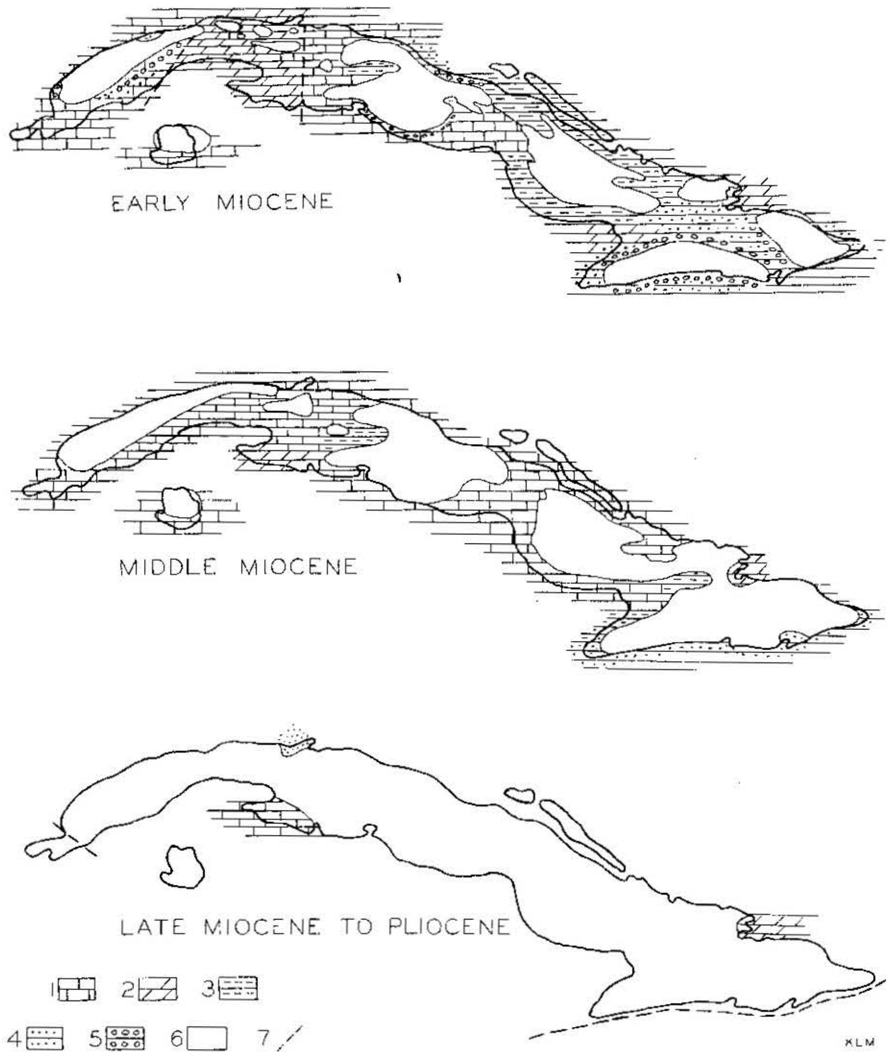

Figure 30. Miocene (including Aquitanian) and Pliocene facies complexes of Cuba (*from* Iturralde-Vinent, 1969). 1-carbonate rocks, neritic facies; 2-marly rocks, pelagic facies; 3-shale, shallow-water brackish facies; 4-shaly terrigenous rocks; 5-basal conglomerate; 6-land areas; 7-faults (published with permission).

probably the eastern boundary fault of the Cochinos graben (Fig. 29). The sediments consist mainly of deep-neritic marl and shale, which grade upward into shallow-neritic limestone. The thickness reaches 1000 m locally. (3) Complex III: southern Isle of Pines; this complex consists of as much as 400 m of shallow-neritic carbonate. (4) Complex IV: most of Las Villas and Camagüey Provinces, and western Oriente Province; the strata are mainly shallow-water carbonate and terrigenous clastic deposited in shallow water. The thickness reaches 400 to 500 m. (5) Complex V: Nipe, Guantánamo, and

younger Cauto basins, Oriente Province. This group of basins includes from 500 to 1500 m of limestone, shale, and marl. Some sandstone and conglomerate are present in the Guantánamo and younger Cauto basins. Deep-water facies are present in the lower part of the Nipe basin sequence.

On the offshore area of the Cauto basin (Gulf of Guacanayabo), the presence of 950 to 1254 m of Miocene was reported by Furrazola-Bermúdez and others (1964), versus 700 to 1100 m by Iturralde-Vinent (1969). M. T. Kozary (*in* Bowin, 1968, Fig. 5) showed as much as 1500 m of Miocene just west of the town of Manzanillo. These sequences consist of sandstone, shale, marl, and limestone. A 950-m section in the Ana María basin is principally shallow-water limestone.

In Jamaica, a maximum of 600 m of early to middle Miocene (White Limestone Group) was deposited in most areas. Noncarbonate deposits are scarce. Wright (1968) reported 1200 m of Miocene in one place on the island. Chert occurs in parts of the section (Robinson, 1967). An unconformity separates the Miocene from the Oligocene (Zans and others, 1962; Robinson, 1967). Late Miocene marl and limestone were deposited in some coastal areas.

Thick Miocene sections are present in the graben areas of Hispañola. Unlike Miocene sections elsewhere in the Greater Antilles, those of Hispañola are strongly to moderately deformed. Butterlin (1960) reported a minimum of 1000 m in the Massif de la Selle of southern Haiti. This section consists of sharply folded beds of conglomerate, sandstone, shale, marl, limestone, and basalt flows (Rivière Grise Formation). A similar section is present in the Massif de la Hotte area. However, limestone reefs characterize the Île de Gonave section.

The Miocene of the Haitian end of the Enriquillo graben consists of more than 500 m of folded and faulted, thin-bedded claystone, siltstone, sandstone, and conglomerate, with some marl and limestone (Taylor and Lemoine, 1949). Both marine and fluviatile facies are present. Commonly the beds are exposed in outcrops which show steep dips or even overturned strata.

In the area between the Enriquillo and San Juan grabens, a thick (1000 to 1600 m) folded conglomerate, sandstone, shale, and basalt section is present, together with massive reefal limestone (1000 m?) and gypsum (Butterlin, 1960). In the San Juan graben area of Haiti and in the mountains of northeastern Haiti, about 2100 to 2600 m of Miocene beds is exposed, including continental conglomerate, sandstone, and lignite, together with marine sandstone, shale, claystone, and gypsum. Abrupt lateral facies changes are characteristic.

In the Massif du Nord and Presqu'ile du Nord-Ouest (Northwest Peninsula) areas, there are thick (1000 m) sections of massive reefal limestone, conglomerate, sandstone, shale, and basalt.

In the central Dominican Republic, H. Palmer (1963) described 120 to 580 m of coarse conglomerate and medium- to thick-bedded calcareous sandstone. Some limestone was found in the area studied by Bowin (1966).

In the Azua basin, Cibao graben, and Enriquillo graben, the Miocene is very thick. Data from Harry Wassall and Associates (1962) suggest that 5000 m of Oligocene and Miocene may overlie the Eocene in the Enriquillo graben alone. H. A. Meyerhoff (May 15, 1968, written commun.) reported the presence in the Lake Enriquillo area (Fig. 7) of at least 4900 m of Oligocene, Miocene, and Pliocene. The Mella No. 2 well, just east of Lake Enriquillo (Fig. 7), penetrated 3325 m of Miocene sandstone, shale, limestone, and salt, reaching total depth in a thick section of early to middle Miocene salt. The section thins considerably toward the west, as shown by the Cabritos No. 1 well at the west end of Lake Enriquillo. This well reached a total depth of only 1644 m in limestone of probable late Eocene age. However, the thinning probably is a result of pre-Pliocene erosion (H. A. Meyerhoff, May 15, 1968, written commun.).

In the Azua-San Juan basins of the Dominican Republic, the lower Miocene consists of about 1750 m of deep-marine shale and claystone at the base, and conglomerate, sandstone, and reef limestone above. This sequence is overlain by several hundred meters of conglomerate, sandstone, and claystone.

The lower Miocene includes at least 500 m of limestone, sandy claystone, red sandy claystone, and red conglomerate. The upper part of the early Miocene strata comprises the base of a thick sequence which, according to Bermúdez (1949), ranges in age from late early Miocene into the Pliocene. The basal part contains red and dark-gray sandstone and black gypsum and salt interbedded with clay-shale. This basal part of the section is equivalent to the red conglomerate described above, and is early Miocene. It is overlain by several hundred meters of salt. Above the salt is up to 2000 m of light-colored, fossiliferous, calcareous clayshale, sandy clay-shale, and limestone conglomerate of late Miocene and Pliocene ages. An angular unconformity separates this sequence from younger Pliocene above.

In the Cibao graben, a very thick section is present. One well, drilled in 1958 in the Dominican Republic part of the graben, reached a total depth of 3649 m without having penetrated pre-Miocene strata (Spangler and Meyerhoff, 1959). This thickness, however, is uncorrected for possible dip, and includes rocks of Pliocene and Pleistocene ages. Bermúdez (1949) assigned up to 2600 m to the Miocene in the Cibao graben area. The lower Miocene consists of a basal conglomerate, sandstone, shale, calcarenite, and some limestone. The middle Miocene is mainly marl with some coralline limestone bands. The upper Miocene consists of conglomerate, sandstone, and shale.

The Miocene is deformed in all the graben areas, but the intensity of deformation may be greater in the Enriquillo graben than in the Cibao graben.

The Miocene(?) of Mona Island, between Puerto Rico and the Dominican Republic, consists of flat-lying to very gently dipping, dense, massive to thick-bedded, finely crystalline, very pure, shallow-water limestone and dolomite. Possibly 100 m is exposed (Kaye, 1959b). The almost total lack of deformation of the Miocene of Mona Island (and Puerto Rico farther east) shows that Mona was separated structurally from Hispañola.

The Miocene of northern Puerto Rico consists of up to 1373 m of bank limestone, dolomite, calcarenite, calcareous shale, and quartz sandstone

(Briggs, 1961; Monroe, 1966). Carbonates predominate. A similar section, 1655 m or more thick, overlies the 400 m (est.) of Oligocene along the southern coast of Puerto Rico (Mitchell, 1960). East of Puerto Rico and west of the Virgin Islands, a thin (100± m) shelf limestone is present along the south side of Vieques Island (Fig. 7) (H. A. Meyerhoff, 1927; and May 15, 1968, written commun.). North of the island, on the south slope of the Puerto Rico Trench, greenish-gray to gray lutite, ranging in age from early to late Miocene, has been sampled. Some sand and gravel contain clasts and cobbles of serpentinite (Conolly and Ewing, 1967).

The Miocene of the Virgin Islands has been reported only from St. Croix (Whetten, 1966), where it consists of 180 to 250 m of marl and reefal limestone (van den Bold, 1970). The section is gently folded.

Geologic History and Paleogeography

The distribution of Miocene marine deposits shows that numerous islands, some large and some small, were present on the site of the modern Greater Antilles. However, none of the islands was as large as today's major islands until middle or late Miocene time, when most of the existing land area emerged. Locally the relief on these islands was hilly, but most of the islands were low and flat; broad, shallow-water platforms were abundant. The greatest relief probably was on Hispañola. Large amounts of terrigenous clastic debris in the Hispañola graben sequences and sharp folds, some overturned, indicate continued orogenic movements. Locally, volcanism also continued in Hispañola.

Except in restricted graben-lagoons and local gulfs in Cuba and Hispañola, normal-saline water occupied the basins, shelves, and platforms. In general, conditions were tropical, and the water was warm, as indicated by the diversity of species and genera—pelecypods, gastropods, brachiopods, echinoderms, foraminifers, and numerous other forms. Bank or reef deposits are filled with many type of corals, algae, and other biota of the reef-bank environment. Some cooler marine conditions may have predominated during short periods of time (G. A. Seiglie, 1967, written commun.).

Although the Bartlett Trough had been in existence since at least middle Cretaceous time, and very possibly since late Paleozoic time, major vertical movements along its boundary faults appear to have occurred during the Miocene.

PLIOCENE

Stratigraphy

As much as 500 m of conglomerate, sandstone, shale, and limestone of Pliocene age may underlie the younger Cauto basin of southeastern Cuba. The age of the highest Tertiary beds is not known with certainty (Iturralde-Vinent, 1969). In facies complex II of west-central Cuba (Fig. 30), Iturralde-Vinent (1969) reported the presence of late Pliocene marine limestone and estuarine deposits along the north coast of Matanzas Province. About 250 m

of Pliocene carbonate and clay is present on the Zapata Peninsula along the south coast of Cuba. These occurrences demonstrate that renewed subsidence of the graben on which facies complex II developed took place during a part of Pliocene time.

In Hispañola, at the eastern and western ends of the San Juan and Enriquillo grabens, some Pliocene marine and continental strata accumulated. Pliocene also was deposited in the Azua basin of the southwestern Dominican Republic. In the Cibao graben, 200 to 300 m of Pliocene and Pleistocene fluviatile and brackish-water conglomerate, sandstone, and mudstone accumulated (Weyl, 1966), but near the eastern end of the graben, as much as 300 m of Pliocene reefoid carbonate overlies basal Pliocene and Miocene with an angular unconformity. About 100 m of coarse-grained terrigenous clastic sediments was deposited in the Azua basin.

In the Gauche River area, Massif de la Selle, Haiti, up to 250 m of alluvium was deposited. Basalt flows of possible Pliocene age are present in several areas of Haiti.

Throughout Haiti and the graben areas of the Dominican Republic, the Pliocene is folded. Folding is strongest on the flanks of the massifs. Pleistocene overlies the Pliocene with angular unconformity in several localities.

Pliocene(?) limestone 3 to 15 m thick was deposited on Mona Island (Kaye, 1959b), and part of the section formerly assigned to the late Miocene may be early Pliocene (Bermúdez and Seiglie, 1970). Pliocene coastal terraces and reefs are widespread in the Greater Antilles islands.

Geologic History and Paleogeography

Most of the Greater Antilles were uplifted in Miocene and later times. This conclusion is supported by the fact that the number of Pliocene marine deposits is very limited. Very pure Pliocene(?) limestone covers Mona Island, a fact which shows that no terrigeneous source areas were nearby. Vertical movements predominated.

Faunal and floral similarities between Central America and the Greater Antilles suggest that direct land connections existed, perhaps via western Cuba or via the Cayman Ridge and Nicaragua Rise. Possibly this connection was in the form of fairly closely spaced island "stepping stones."

PLEISTOCENE

Lack of onshore outcrops, except for coastal terraces and reef deposits, and lack of paleontological information, do not permit detailed reconstructions of Pleistocene paleogeography. Numerous excellent papers have been published on the Pleistocene-Holocene geomorphology and development of Cuba, Jamaica, Puerto Rico, and the Virgin Islands. Data from Hispañola are scarce. Some Pleistocene(?) limestone may cover Mona Island (Kaye, 1959b).

The differential movements of erosion surfaces, marine terraces, and deep-sea troughs in the region prove that major vertical movements took place.

Volcanism continued locally in Haiti and the Dominican Republic, where nepheline basalt and limburgite flows are known (MacDonald and Melson, 1969). Some marine terraces were elevated as high as 350 m in Cuba and Hispañola. The terraces of easternmost Cuba are outstanding examples of large-scale vertical uplift. However, some subsidence has occurred between the various islands, probably along fault zones, and the Greater Antilles assumed their present configuration.

CENOZOIC FAULT ZONES OF GREATER ANTILLES

Numerous fault zones and fault troughs of the Greater Antilles formed during the "Laramide" orogeny and were most active during Tertiary time. The age of many of these fault zones and troughs may be pre-Tertiary but data are insufficient to prove a pre-Tertiary age for most. The pre-Tertiary faults described in a preceding section are not discussed here.

Laramide Thrusting?

Meyerhoff believes that many faults which formed during the "Laramide" orogeny are thrust faults, nappes, and/or gravity slides. Those in Pinar del Río are illustrated in Figure 15, and have been described by Hatten (1957), Rigassi (1961, 1963) and Knipper and others (1967). Thrust faults in central Cuba were described by Wassall (1956), Hatten and others (1958), Hatten (1967), and A. A. Meyerhoff and Hatten (1968). Thrust faults described by Flint and others (1948) in northern Camagüey Province were mapped incorrectly, partly because a tectonic window (fenster) was mistaken for a klippe. Kozary (1956, 1968) described thrust faults or gravity slides from northwestern Oriente Province.

In Meyerhoff's opinion, these thrusts were extremely important in the paleogeographic evolution of Cuba, at least during the "Laramide" orogeny (Hatten, 1957; Hatten and others, 1958; A. A. Meyerhoff, 1964a), because, in front of them, deep, narrow, linear, marine troughs developed into which synorogenic flysch (Tercier, 1947) and Wildflysch were "dumped" and overridden by the thrusts. Hatten's (1957) interpretation of the Alpine-type phenomenon is shown in Figure 15.

Khudoley disagrees thoroughly with thrust interpretations in Cuba and ascribes almost all faulting to vertical movements. His views are expressed in Furrazola-Bermúdez and others (1964, 1965), Judoley (1964, 1966), Khudoley (1967a, 1967b), Núñez-Jiménez and others (1962), Soloviev and others (1964a), and Solsona and Judoley (1964). Khudoley does, however, admit that gravity gliding has taken place locally.

The north-to-south faulting in Cuba—described by R. Palmer (1945), Flint and others (1948), and Knipper and others (1967)—is based on erroneous interpretations of age relations between rock units. Thrusting in these areas, according to Meyerhoff, is from south to north (Hatten, 1957; Hatten and others, 1958; A. A. Meyerhoff, 1964a).

Important thrusts have not been described from Hispañola; steep-angle reverse faults are present along the margins of the Enriquillo graben (Fig. 29), as drilling by petroleum companies has demonstrated.

Low-angle thrusts have been described from the Wagwater belt of Jamaica (Fig. 7), and the evidence is summarized by Zans (1961) and Zans and others (1962).

In Puerto Rico, several gravity thrusts, directed from south to north, have been described in the Ponce (southwest) area by Glover and Mattson (1960), and a thrust fault was described by Whetten (1966, p. 137) on St. Croix in the Virgin Islands.

Pinar Fault

The paleogeographic puzzle related to the Pinar fault (this fault was named in 1956 by Harry Wassall in unpub. repts.) was summarized in a preceding section. The fault is at least 100 km long, and has a vertical throw, down toward the southwest, of more than 2000 m. The thick Eocene to Miocene section of the Palacios basin (Fig. 29) was deposited on the southeast side. The fault cuts off the root zones of the early to middle Eocene nappes and thrust plates of the Sierra de los Órganos, and therefore is middle Eocene or younger. The fault may occupy a much older zone of weakness. It is still active today.

Miocene Graben of Eastern Pinar del Río, Habana, Western Matanzas, and Southwestern Las Villas Provinces

This area, shown on Figure 30, includes the Cochinos graben (Fig. 29) which strikes north-south, perpendicular to regional strike, across most of Cuba. Iturralde-Vinent (1969) has shown that this broad graben zone began to subside in Aquitanian (earliest Miocene) time, and that it continued to subside intermittently until late Pliocene time. Deep-water early and middle Miocene sediments were deposited in this broad, fault-bounded graben.

Tuinicú Fault

This fault (Fig. 6) was named by Hatten and others (1958). Its minimum age is early Eocene, as proved by the deposition along the north side of the fault of more than 3700 m of early to late Eocene chaotic conglomerate, graywacke, siltstone, and shale.

La Trocha Fault

This fault (Fig. 6) also was named by Hatten and others (1958). It shows as a large magnetic and gravity low (Soloviev and others, 1964a; Furazzola-Bermúdez and others, 1964, 1965; A. A. Meyerhoff and Hatten, 1968). It is nearly vertical, and offsets faults of established early to middle Eocene age. The La Trocha fault zone has been active in historic times.

Wagwater Belt

This graben-like depression, which crosses Jamaica from northwest to southeast (Fig. 7), was described in a previous section. Its history of active subsidence as a basin of deposition can be demonstrated most clearly during early and middle Eocene times (Zans, 1961; Zans and others, 1962).

Cibao Graben, San Juan and Azua Basins, and Enriquillo Graben

These west-northwest-east-southeast-trending, fault-bounded grabens and depressions have been described in numerous publications cited previously. As shown by the sedimentary sections penetrated to date, the grabens have subsided several kilometers since Paleocene time. Subsidence and earthquake activity have continued to the present.

St. Croix Graben?

Whetten (1966) has postulated the existence of an east-northeast-west-southwest-trending graben of Eocene or younger age across the island of St. Croix (Fig. 29). H. A. Meyerhoff (June, 1968, oral commun.) doubts the existence of the graben, and suggests that it is either a downwarped depression or a tilted fault block (half-graben) (H. A. Meyerhoff, 1927).

Mona Passage

A north-south zone of earthquakes parallels and coincides with the Mona Passage (Figs. 2, 7). The age of the fault zone can be inferred with some certainty. The "Laramide" orogeny ended in both Hispañola and Puerto Rico in middle to late Eocene time. Major faulting and volcanism continued in Hispañola, together with episodes of folding. In contrast, the sediments of Mona Island are exceptionally pure and nearly free of noncarbonate detritus; tectonically both it and the Puerto Rico-Virgin Islands area were almost dormant after middle Eocene time. Thus the shallow fault activity shown on Figures 2 and 3A (Mona Passage), and the intermediate-depth earthquake activity (Figs. 2, 3B) are inferred to be fault zones—or zones of structural separation—which isolated Hispañola tectonically from the Puerto Rico-Virgin Islands zone during the "Laramide" orogeny.

Puerto Rico Trench

The west-northwest-east-southeast-trending magnetic anomalies which underlie this trench suggest that the Cretaceous to middle Eocene structural trends of Puerto Rico continue beneath the trench. Therefore, the trench probably is middle Eocene or younger. Monroe (1968) noted that the trench is parallel with the Oligocene and Miocene trends of the northwest of Puerto Rico. He concluded (p. 492) that,

> From the evidence on Puerto Rico, the trench began to form, either as a downwarp or a shallow graben, at the time that the sea transgressed over the older rocks, probably

early in the Oligocene epoch. Probably the trench deepened gradually during Oligocene and Miocene time concurrently with the sporadic arching of the Puerto Rico upland, but it appears likely that its development as an abyssal oceanic feature took place later, concurrent with the uplift of Puerto Rico to its present height during late Miocene and possibly Pliocene time.

This conclusion appears to be the most logical of those published. However, other opinions have been expressed and are summarized briefly. Hersey (1966, p. 160–163) wrote, regarding dredge hauls along the north side of the trench:

The sedimentary rocks and mudstones in our dredge hauls were fossiliferous. A limestone fragment contained Cenomanian fossils . . . (Todd and Low, 1964); and other fragments contained radiolaria of Late Cretaceous, Eocene, and Oligocene age (W. R. Riedel and D. B. Ericson, personal communication, 1962). We do not know exactly where these rocks came from, but it is quite clear that they could have come from the transparent layer by rolling downhill or they could have come from the layered section [beneath the transparent layer] but not from any deeper structure . . .

. . . The transparent layer covers most of the outer ridge, but thins northerly toward the Nares Basin and southerly toward the Puerto Rico Trench . . .

On a few of our profiles the transparent layer can be traced to where it underlies the flat-lying sediments of the deepest part of the Puerto Rico Trench. Since the transparent layer has to be Oligocene or younger, the Puerto Rico Trench, in its present form, must be younger than Oligocene. This speculation appears to be in accord with geological evidence in Hispaniola, reported to us by Carl Bowin, that the trench may have started to form during approximately late Eocene or later.

Bunce and Hersey (1966) have speculated . . . that the transparent layer is a remnant of a continental rise made of sediment, but possibly largely volcanic, that was derived from land where Puerto Rico and Hispaniola are now located.

Bunce (1966, p. 170) wrote:

The continuity of the transparent layer on the slope and beneath the upper section of sediments of the trench is evidence that the layer is older than the formation of the trench.

On a subsequent page in the same volume, Bunce wrote (p. 172):

The existence of the transparent layer of the outer ridge beneath the uniform sedimentary layers of the trench is evidence that the trench was formed after this layer was deposited. Eocene rocks have been dredged from the region of the transparent layer on the north wall (Bowin et al., 1966; Hersey, 1966). Thus the trench may be as old as Eocene.

R. L. Chase (May 29, 1967, written commun.), wrote:

The oldest paleontologically dated rock from the north slope is Cenomanian. T. Saito of Lamont, in an unpublished report on dredgings by R. V. *Conrad* during Operation DEEPSCAN in 1964, found volcanic shards associated with Cenomanian Foraminifera. Thus it is possible that the Cenomanian sedimentary rocks, which are reasonably consolidated, are interbedded with the flows of basalt which have also been sampled from the north slope at several places . . .

The younger ages, ranging from Eocene to Miocene, which have been found for Foraminifera and Radiolaria in sediments dredged and cored from the north slope

during several cruises (*Chain* 19, 34, 57, *Atlantis II*-11), presumably come from outcrops of sedimentary rock overlying the basalt, including the "layered series" and "transparent layer" seen in sparker records. I doubt whether the layered series contains volcanic flows because sparker records from the Mid-Atlantic Ridge, where we know volcanic extrusion is going on, do not show such layering. The layered series resembles more the layering seen in abyssal plains and sediment ponds.

The mid-Miocene age determination was made by Robert Goll from Radiolaria in a dredge made last spring [1966] during *Chain* Cruise 57. The dredge was so placed on the slope, according to our nearest sparker profile, that both the transparent layer or underlying layers could have contributed material. It seems likely, however, that it sampled the transparent layer.

Accumulation of the transparent layer appears to be continuing at present on the outer ridge north of the trench. The transparent layer is overlain both by layered sediments of the Nares abyssal plain, north of the outer ridge, and by layered sediments in the floor of the Puerto Rico Trench. There is some suggestion on sparker profiles that the upper part of the transparent layer interfingers with the layered sediments of the trench floor. I would expect these relationships if the transparent layer and the trench sediments were being deposited simultaneously, with the rate of sedimentation of the latter being greater. Thus we know that the transparent layer is at least as old as Miocene on the north slope, and is still being deposited today on the outer ridge.

The great thinning of the transparent layer that occurs southward across the outer ridge toward the trench may mean (1) that the thin part is a "fossil" deposit cut off from its source by topographic or oceanographic changes, or (2) that deposition has proceeded much more slowly near the north slope because of topography or oceanic currents, or (3) that sediment cannot accumulate thickly on the relatively steep slopes of the trench. I favor the second of these explanations, though the third may also apply to the steeper parts of the north slope.

A question . . . now pertinent to ask is whether the transparent layer is older or younger than the trench itself.

Up to a year or so ago [1966], we had always considered that the transparent layer was older than the trench. If this assumption is made, one then deduces that the trench is post-Miocene. However, I now consider it possible that the transparent layer was deposited after the present outlines of the trench were formed, or while they were forming. Although the transparent layer is older than the sediments on the floor of the trench, the latter may have only been coming into the trench in quantity since the Miocene uparching of Puerto Rico along the east-west geanticlinal axis mentioned in USGS reports. Thus before the Miocene the trench may have existed in its present form but without the sediments in the bottom, the transparent layer accumulating on the outer ridge and north slope much as it is today.

We thus have no unequivocal evidence from marine investigations as to the age of the trench. It could have existed in some form before Cenomanian time if it was a dynamic feature, the locus of underthrusting of oceanic crust beneath continental crust.

Bunce and Fahlquist (1962), Talwani (1964), and Bunce (1966, p. 172) suggested that the trench is a downfaulted block, but Bunce (1966, p. 172) suggested alternately that the trench is a downwarped feature. J. Ewing and M. Ewing (1962) reported the southward tilt of the trench-floor sediments into Puerto Rico. Edgar (1968) reported this and a northward tilt of the deep-sea sediments south of Puerto Rico—observations which suggest northward

rotation of Puerto Rico. J. Ewing and M. Ewing (1962) and Hersey (1962) have described the structure of the north wall as a series of parallel east-west fault planes. Focal mechanisms reported by Molnar and Sykes (1968) show predominant dip-slip movement on the faults in the area. On the basis of these data, the downfaulted block hypothesis seems to be the most likely, but it is not proved conclusively.

The epicenter data (Figs. 2–5) show a very strong concentration of foci beneath the Puerto Rico Trench—87 percent of all shocks for this region during the period 1950–1964. Only 13 percent of the shocks were beneath or south of Puerto Rico. Certainly no south-dipping Benioff zone of earthquake epicenters underlies the trench and Puerto Rico, as implied by Sykes and Ewing (compare Fig. 3A with Fig. 4, 1965). Several points rule out the hypothesis that the Puerto Rico Trench is an island-arc-type trench.

1. If there is any cross-section shape to the earthquake pattern beneath Puerto Rico, it is that of a "V" whose apex is at about 131 km. However, 87 percent of the epicenters are beneath the trench and 85 percent are shallower than 70 km. The focal mechanisms which have been studied show that dip-slip movement predominates (Molnar and Sykes, 1968).

2. The only true island arc still active in the region is that of the Lesser Antilles. Compressive stress in the region should be directed east-west, and Molnar and Sykes' (1968) fault-plane solutions for the Lesser Antilles suggest the existence there of east-west–directed stress. Such a stress field would not produce an island-arc-type trench north of Puerto Rico (the east-west scarps along the north wall of the trench, if they are real, confirm this observation).

3. The age of the present trench must be middle Eocene or younger, if Monroe's (1968) reasoning is correct; the facts certainly support him. The Greater Antilles was no longer an island arc after middle Eocene time and was isolated tectonically from Hispañola.

4. If Puerto Rico is part of a middle Eocene and younger island arc, where are the volcanoes which normally are associated with island arcs? The Lesser Antilles has them; why are they absent on Puerto Rico? The Japanese islands have been part of an active arc system since Cambrian time, and volcanic activity has been an integral part of the history of that arc from earliest Paleozoic time to the present.

Thus, the available evidence refutes the concept that the Puerto Rico Trench is an island-arc-type trench underlain by a south-dipping Benioff zone. Instead, the data suggest that the trench is a downfaulted graben.

A final observation regarding the Puerto Rico Trench is its relation (or lack of relation) to the Cibao graben and Bartlett Trough. Many geologists and geophysicists have related the three structures and have connected them as part of a single east-west structure. Several factors must be considered before such a conclusion can be made.

1. The Bartlett Trough was active during middle Cretaceous time and may be much older than either the Cibao graben or the Puerto Rico Trench. The Bartlett Trough terminates in central Guatemala on the west and in the

Windward Passage on the east. Its strike is about 30° from that of the Cibao graben. It has a moderate level of seismic activity.

2. The Cibao graben may have formed first during the Cretaceous, but can be dated positively only as a Paleocene or Eocene feature. The amount of seismic activity seems to be slightly greater than that of the Bartlett Trough. The strike of the graben is different from those of the Bartlett Trough and of the Puerto Rico Trench (Fig. 7). Nagle (1968) proposed, on the grounds of stratigraphic similarity, that the Puerto Plata area (Fig. 7) along the north coast of the Dominican Republic is an emerged part of the Puerto Rico Trench. However, the Puerto Plata area is *north* of the Cibao graben.

3. The Puerto Rico Trench is no older than middle Eocene and very possibly is younger. It terminates on the west near two north-south lines of earthquakes: one line of shallow shocks through the Mona Passage (Figs. 2A–2C), and one line of intermediate-depth shocks beneath the eastern Dominican Republic (Fig. 3). The strike of the Puerto Rico Trench is east-west, and does not connect directly with the Cibao graben. Earthquake activity is greater beneath the Puerto Rico Trench than beneath either the Bartlett Trough or the Cibao graben.

4. Bowin's (1968) excellent study of the gravity and magnetic data of the region shows conclusively that the negative Bouguer gravity anomaly belt which underlies the Puerto Rico Trench extends west-northwest along the northern coast of Hispañola into the area northeast of Cuba. In contrast, the Bartlett Trough is underlain by a positive Bouguer gravity anomaly belt which bends southeastward toward the Île de Gonave (Fig. 1).

5. Thus the evidence summarized here indicates that the Bartlett, Cibao, and Puerto Rico fault troughs are separate features probably of different ages. They could not have formed a single transform fault as proposed by Wilson (1966). Undoubtedly all three features are related to the tectonic and paleogeographic development of the Greater Antilles, and in this sense are related to one another. Very probably they formed within the same general regional stress field. Their apparent increase in age from east to west, and their increase in seismic activity from west to east, support the surface geological data which indicate that the Greater Antilles arc in general, and the Caribbean block as a whole, developed tectonically from west to east. The same conclusion was reached previously on other grounds by H. A. Meyerhoff (1946, 1954) and Bucher (1947). However, the development of the Cibao and Puerto Rico fault troughs took place later than the development of the Bartlett Trough and the Greater Antilles arc. The latter is a Tithonian to Aptian feature which formed at nearly the same time from western Cuba to the Virgin Islands.