Late Jurassic-Late Cretaceous

INTRODUCTION

During Late Jurassic to middle Eocene time (Figs. 8–9, 13–26), the Greater Antilles became a true orthogeosyncline—in the sense of Stille (1940)—consisting of miogeosyncline on the north (in the Cuban part) and a eugeosyncline on the south; the eugeosyncline extended 1800 km from western Pinar del Río Province, Cuba, to the eastern Virgin Islands. The orthogeosyncline attained its maximum development in Albian-Cenomanian-Turonian time. By late Turonian time, crustal movements began to break up the orthogeosyncline; by Campanian time, fragmentation of the once-continuous arc system was well advanced and, during latest Maestrichtian to middle Eocene time, the orthogeosyncline ceased to exist, the Greater Antilles was broken into isolated geological provinces, and an entirely new tectonic cycle began.

Khudoley and Meyerhoff have very different opinions concerning the time of origin of the orthogeosyncline. Khudoley believes that it formed in Early Cretaceous time and that the entire Callovian(?)-middle Tithonian sequence is pre-orthogeosynclinal; Meyerhoff believes that the orthogeosyncline formed in Tithonian time and that only the Callovian(?)-early Tithonian(?) units are pre-orthogeosynclinal. The difference of opinion arises because (1) pre-Aptian fossils are unknown in the eugeosyncline (according to Khudoley, this fact dates the time of origin of the eugeosyncline); (2) in northern Pinar del Río Province, the Tithonian-Kimeridgian[4] sequence contains no unconformities or disconformities; and (3), in Khudoley's opinion, Neocomian deposits are absent in most of Cuba (or, if present, they are very thin). Meyerhoff disagrees with (1) and (3) for reasons given in subsequent sections.

Pre-Orthogeosynclinal Sequence

From Callovian(?) through Oxfordian time, the predominantly nonmarine San Cayetano sedimentation cycle was replaced by a marine depositional

[4] "Kimeridgian" is spelled here with a single "m" (Arkell, 1956) because the type was named for Kimeridge, England. George V. Cohee, in a letter dated June 3, 1968, informed the writers that the use of a single "m" now is preferred. However, the spelling problem still is not resolved.

regime. The sea slowly transgressed Cuba, possibly from all sides. To date, however, the only proved pre-Tithonian marine strata are in the Sierra de los Órganos of northwestern Cuba. By early to middle Tithonian time, marine conditions existed in most of Cuba.

Orogenic pulses may have affected Callovian(?)-Oxfordian sediments, and at least one mild disturbance is recorded in the post-Oxfordian-pre-Kimeridgian(?) interval. Khudoley believes that this "mild disturbance" was a major orogeny—the "Nevadan" equivalent. Meyerhoff believes that this disturbance was of minor importance, and that the principal manifestation of a "Nevadan" orogeny was the formation of the orthogeosyncline during latest Kimeridgian to early Tithonian time.

Pre-Orthogeosynclinal or Early Orthogeosynclinal Basin

Khudoley believes that the Tithonian is represented everywhere in Cuba by a predominantly carbonate facies, except north of the median welt where evaporites also are present. Meyerhoff believes that the orthogeosyncline formed during Tithonian time; that the Tithonian section north of the median welt is limestone, dolomite, and evaporite; that the equivalent section in Pinar del Río is mostly limestone; and that Tithonian rocks are present in southern Cuba as a eugeosynclinal facies—ultramafic, mafic, and spilitic intrusives, flows, breccias, and tuffs.

Orthogeosyncline

The orthogeosyncline consists of several large-scale structural features: on the north is the *Bahamas platform* (Bahama foreland of H. A. Meyerhoff, 1954; *see* Fig. 13). According to Khudoley (1967a), this is a parageosyncline[5] which extended to the south side of the Great Bahama Bank (north side of Old Bahama Channel; Fig. 1). According to Meyerhoff, the Bahamas platform extended into Cuba to the southern edge of the Remedios facies-structural zone (Khudoley, 1967a, p. 671; *see* Fig. 13 and Tables 2, 3, this paper). At least 11 km of sedimentary rock underlies the thickest part of the Bahamas platform; of this thickness, about 9 km is pre-Tertiary according to the Sheridan and others map (Drake, 1966, p. 43). Because about 5 km of this 9 km is believed to be Late Jurassic and Cretaceous, possibly 4 km of pre-Late Jurassic sedimentary rocks underlies the Bahamas.

Correctly speaking, the Bahamas "platform," because it is the site of a very thick (10,000 m) accumulation of shallow-water carbonate and evaporite, is a poor term. The Russian word "plita" is a more satisfactory term for which

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[5] A parageosyncline is defined here as a basin or depression which does not undergo complete tectonic inversion, that is, uplift after depression. Such depressions are preserved during an entire tectonic cycle and participate only partly in the uplift and depression which affect adjacent, more mobile geosynclines. Geographically they commonly lie between an active orthogeosyncline (mobile belt) and a platform. They also have been called semiplatforms (Beloussov, 1962, p. 315, 358, 687).

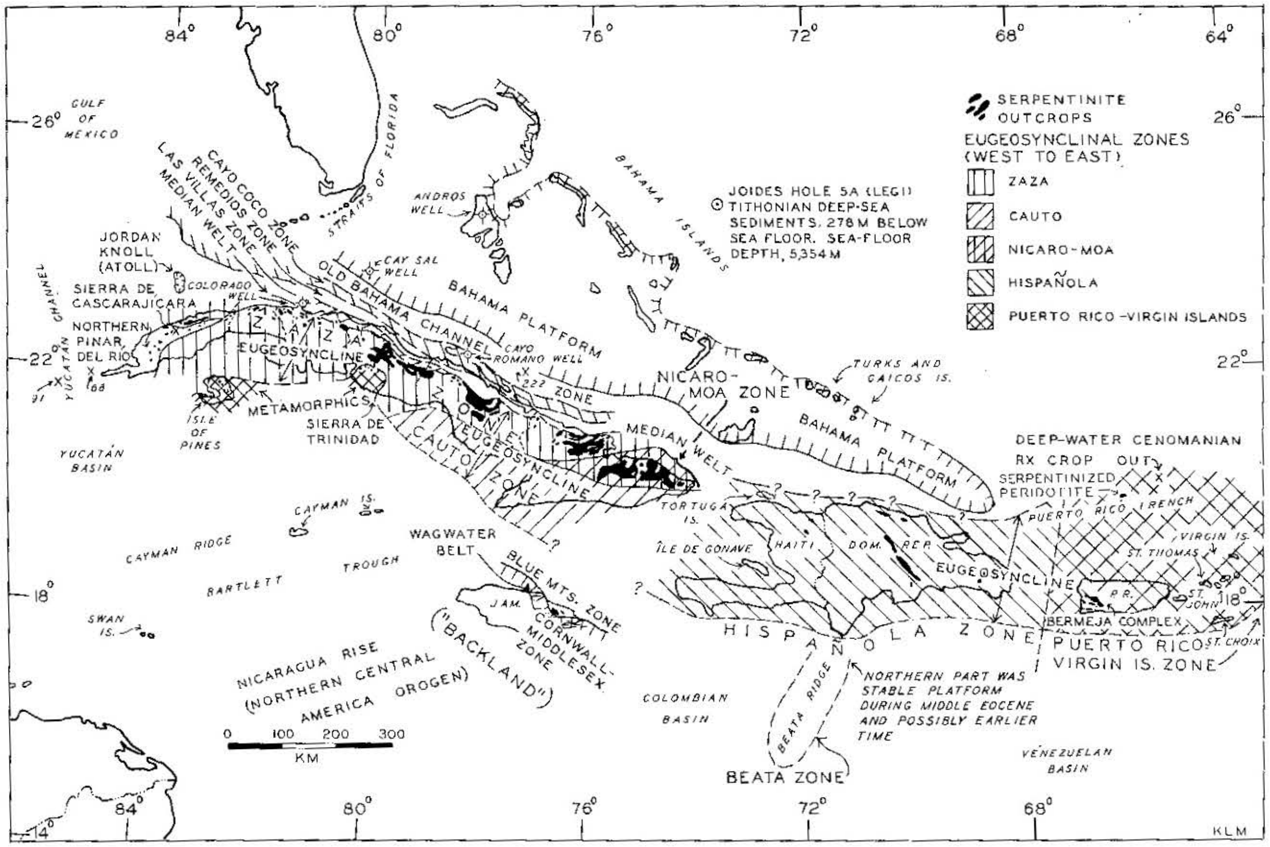

Figure 13. Structural elements (including critical facies-structural zones) and serpentinite bodies, Greater Antilles. Compiled from Núñez-Jiménez and others (1962); Zans and others (1962); unpub. 1960 map of Hispañola by Carl Bowin; Butterlin (1960); Mattson (1964); and Khudoley (1967a).

there is no precise English-language equivalent. A *plita* is a stable basement platform or craton overlain by a thick section of competent sedimentary rocks which act as effectively as a buttress as the basement rocks of the craton. Kay's (1951) term "autogeosyncline" does not include the "plita" concept, but describes the geologic nature of the southern Bahamas, and is more familiar to most American geologists than the term "parageosyncline" which has been used in several ways.

South Florida, the West Florida shelf, and the Turks and Caicos Islands are a part of the Bahamas platform province.

South of the Bahamas platform is the *miogeosyncline*. According to Khudoley (1967a, p. 670–672), the miogeosyncline includes the facies-structural zones of the Old Bahama Channel, Cayo Coco, and Remedios. According to Meyerhoff, the northern half of the Las Villas facies-structural zone is the miogeosyncline.

The miogeosyncline (as used here by Meyerhoff) appears onshore only in Cuba, where its rocks extend from northern Matanzas Province to northwestern Oriente Province. Its westward extent is unknown, but carbonate rocks similar to some of those of the Las Villas facies-structural zone and equivalent to the eugeosynclinal section on the south are present in northern Pinar del Río Province. Toward the east, the miogeosyncline may reach the longitude of Tortuga Island, north of Haiti, or the vicinity of the Turks and Caicos Islands. It probably does not extend the full length of the Greater Antilles because Cenomanian tuffaceous pelagic limestone, chert, radiolarian chert, silicified radiolarian shale, and andesitic volcanic rocks crop out along the north wall of the Puerto Rico Trench (Todd and Low, 1964; Bowin and others, 1966; Hersey, 1966; Conolly and Ewing, 1967). The Cenomanian Foraminifera are in marly stringers associated with chert and volcanic shards (found by T. Saito: R. L. Chase, May 29, 1967, written commun.).

The *median welt* is part of Khudoley's Las Villas facies-structural zone, which also includes Meyerhoff's miogeosyncline. Its presence was recognized implicitly by Wassall (1956) but was first described explicitly by Ducloz and Vuagnat (1962). A. A. Meyerhoff and H. A. Meyerhoff (1964) and A. A. Meyerhoff and Hatten (1968) first called it a "median welt." In the scheme of Hatten and others (1958), from whom most of the names for the facies-structural zones of Cuba were taken, the median welt is a separate facies-structural zone, and is the southern part of Khudoley's Las Villas facies-structural zone.

The *eugeosyncline* extends from western Pinar del Río Province to the eastern Virgin Islands. It is the most extensively developed unit of the Greater Antilles orthogeosyncline, and includes several facies-structural zones: Zaza, Nicaro-Moa, Cauto, Hispañola, and Puerto Rico-Virgin Islands (Fig. 13). The Hispañola zone is unique in that volcanism has continued to Pleistocene time, together with intense faulting and folding.

The *Blue Mountains zone* is present only in northeastern Jamaica. Very little is known of it. Thick nonmetamorphosed to phyllitic Cretaceous shale masses are present; volcanic rocks are abundant, and mafic flows and intrusive serpentinite bodies crop out. Most of the dated units are Late Creta-

ceous but the presence of a thick Early Cretaceous sequence is likely.

The presence of serpentinite and mafic volcanic rocks suggests that the Blue Mountains zone is within the southern part of the eugeosyncline. The facts that shale is so prominent and that volcanic rocks are not so abundant as in the eugeosyncline elsewhere suggest another possibility. Perhaps the Blue Mountains zone was a trough or oceanic trench during Cretaceous time on the Caribbean side of the Greater Antilles arc and subsequently was filled with sedimentary and volcanic rocks derived from the eugeosyncline on the north and the Cornwall-Middlesex zone on the southwest. Extensive field work still must be done in this area to determine the origin of the thick Blue Mountains sequence.

On Figure 13, only the modern Blue Mountains have been included in this zone. It is probable that, tectonically, the Wagwater belt (Figs. 7, 13) should be included with the Blue Mountains zone, but only rocks of Tertiary age have been reported from the Wagwater belt.

The *Cornwall-Middlesex zone* on the southwestern side of the Blue Mountains trough is another platform, foreland, or "backland," which is on the opposite side of the orthogeosyncline from the Bahamas platform. Meyerhoff's opinion that this part of the eastern end of the Northern Central America Paleozoic-Mesozoic orogen already has been given (*see* Meyerhoff, 1967). Khudoley believes, as do many other workers (for example, Chubb, 1960; Zans and others, 1962), that this is part of the continent which once occupied the present Caribbean sea.

South of central Hispañola is the *Beata zone*, a north-south submarine ridge which projects into the present Caribbean. The origin of this ridge is unknown. Edgar's (1968; *see also* J. Ewing and others, 1967) recent work showed that the Beata Ridge is somewhat similar in crustal structure to the Nicaragua Rise. Therefore, the ridge could be underlain by continental-type crust. Fox and others (1968) collected shallow-water Eocene limestone on the ridge from above 2500 m. This limestone apparently overlies a basaltic pile. West of the ridge, south of the Massif de la Selle (Fig. 7), Late Cretaceous pelagic Foraminifera were collected from fractures in basalt below 3000 m. Eocene bathyal Foraminifera were collected in deep water near the south end of the ridge (Edgar, 1968). The relation of the Beata zone to the orthogeosyncline is unknown. When more data are available from the ridge, it may be desirable to include it within the eugeosyncline.

Eastern Limit of Orthogeosyncline

In general, the eastern limit of the orthogeosyncline is the present Anegada Trough (Figs. 1, 7, 13). However, St. Croix is part of the orthogeosyncline, although it is south and east of the trough. The existing Lesser Antilles arc, which did not form until latest Cretaceous or earliest Tertiary time, is related to the Greater Antilles orthogeosyncline only in the sense that the eastern end of the orthogeosyncline apparently controlled the location of the north end of

the Lesser Antilles arc. The tectonic trends of the Greater Antilles arc, therefore, cannot (on the basis of known data) be projected through the Lesser Antilles to Trinidad and Tobago. Ultimately, it is possible that a connection through the Aves Ridge may be found.

Facies-Structural Zone Concept in Cuba

The term "facies-structural zone" has been mentioned in several preceding paragraphs (Fig. 13; Tables 2, 3). Brönnimann and Pardo (1956), as did Trümpy (1958, 1960) in the central and western Alps, called these zones "facies belts," and apparently were the first to recognize that Cuba can be divided into several facies belts. (M. Rutten [1936] actually was the first to recognize that pronounced changes in structural style take place across Cuba.) Hatten (*in* Hatten and others, 1958) recognized that each facies belt was a distinct structural unit, and coined the term *tecto-unit* (Khudoley, 1967a, p. 670, footnote 4). Pardo (1966, p. 1), although not using the terms "tecto-unit," "facies belt," or "facies-structural zone," nevertheless wrote an excellent definition; they are ". . . narrow, linear, and roughly parallel belts," each of which is ". . . characterized by diagnostic structural style and stratigraphy." Trümpy (1960, p. 852) observed that, in the Alps, each facies belt had a different geologic history; the same is true of the various facies-structural belts recognized in the Greater Antilles. The different stratigraphy and structural styles of each facies-structural zone in Cuba have been described by Ducloz and Vuagnat (1962), Furrazola-Bermúdez and others (1964, 1965), and Hatten and Meyerhoff (1968).

Commonly the rock units of a particular facies-structural zone are wholly equivalent to those in the adjacent zones, but the rock types (lithofacies) and structure within each zone make it peculiarly distinctive and easy to identify either in the field or the subsurface. Some of these zones extend for 300 to 400 km along strike in Cuba, yet are only 2 to 15 km wide.

Ducloz and Vuagnat (1962) were the first to publish names for the principal facies-structural zones of Cuba and, for this reason, the Ducloz-Vuagnat scheme was used by A. A. Meyerhoff and Hatten (1968). Now that the Hatten and others' (1958) scheme of facies-structural zones is available in Solsona and Judoley (1964), Furrazola-Bermúdez and others (1964, 1965), and Khudoley (1967a), the writers use the Solsona and Judoley terminology (*as modified from* Hatten and others, 1958; Tables 2, 3).

The stratigraphic characteristics of the facies-structural zones are described briefly in the sections on "Early Cretaceous Stratigraphy" and "Late Cretaceous Stratigraphy."

Tectonic Cycles

Numerous unconformities, of both the angular unconformity and disconformity types, are known in the region. Data are too few in many areas to indicate which unconformities may be regional. Those unconformities which seem to be widespread in each country are given here, but the writers empha-

size that, as more formations are dated, the unconformities mentioned may prove to be only of local importance, and others may be found.

In Cuba, Khudoley (1967a, p. 674) recognizes four Mesozoic-Cenozoic unconformity-bounded tectonic cycles (Fig. 14): (1) Early and Middle Jurassic, terminated by the "Nevadan" orogeny; (2) Late Jurassic-early Turonian, terminated by the "Subhercynian" orogeny (late Turonian-early Campanian); Late Cretaceous-middle Eocene, terminated by the "Laramide" or Cuban orogeny; and (4) middle Eocene-Pliocene. Each of these cycles is subdivided into subcycles by Khudoley. There are possible hiati or unconformities in the Neocomian (Meyerhoff disagrees with this), and Paleocene. Meyerhoff has observed evidence for local unconformities within the Albian(?), Maestrichtian, and late(?) Eocene, and it is probable that local unconformities are present in rocks of several ages.

The writers emphasize that the term "Nevadan" is used here to connote orogeny of Late Jurassic age; that "Subhercynian" includes middle Cretaceous to early Late Cretaceous orogeny; and that "Laramide" refers to orogeny commencing in Late Cretaceous time and ending in Eocene time. Exact correlation of these orogenies with those of the type areas is *not* implied.

Meyerhoff would modify Khudoley's scheme of structural cycles as follows: Early Jurassic through middle Turonian; middle Turonian through Santonian; Campanian to middle Eocene; and middle Eocene to Pliocene.

Khudoley (1967a, p. 674) wrote, regarding Cuba, that the most easily observed unconformities are between the Middle and Late Jurassic, at the base of the Campanian, and in the middle Eocene. The last two unconformi-

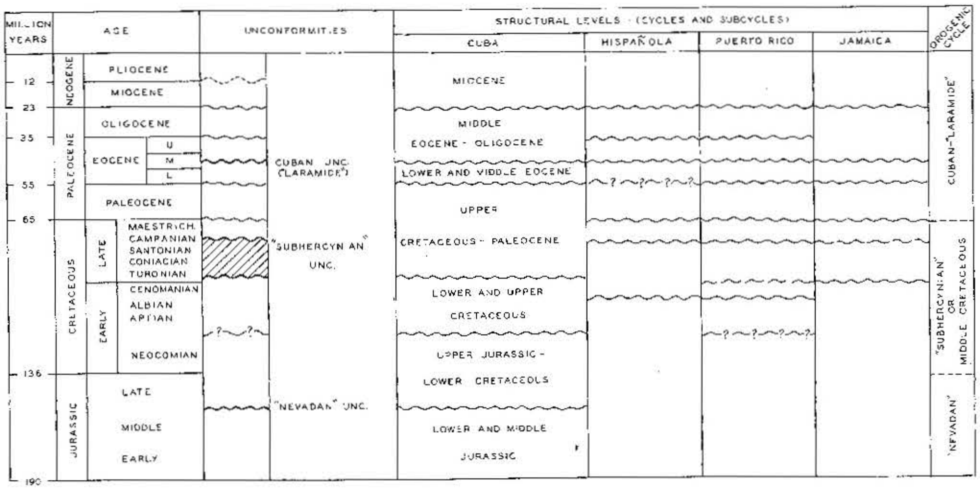

Figure 14. Major unconformities, tectonic cycles, and tectonic subcycles of Greater Antilles. Compiled from Furrazola-Bermúdez and others (1964); Butterlin (1960); Bowin (1960, 1966); Mattson (1962, 1964, 1966a, 1966b, 1967); Pessagno (1960a, 1962); Nelson (1966b); Pease (1968); and numerous other sources. Time scale from Harland and others (1964). "Nevadan" is used in loose sense to denote Late Jurassic orogeny; "Subhercynian" is used to denote middle Cretaceous orogeny; "Laramide" is used to indicate Late Cretaceous-early Tertiary orogeny.

ties are very pronounced, but that between the Middle and Late Jurassic is the subject of controversy and is discussed subsequently. Meyerhoff believes, instead, that there is a major unconformity within the Late Jurassic in southern Cuba. This belief is supported by the evidence from northern Cuba (presented subsequently) that the orthogeosyncline began to form during Tithonian time. The development, in southern Cuba, of a eugeosynclinal facies above older Jurassic strata of completely different facies is proof that an abrupt change in tectonic regime took place in southern Cuba between the time of San Cayetano deposition and that of eugeosynclinal deposition.

The structural cycles in Cuba cannot be extended, except in a most general way, to the rest of the Greater Antilles (Fig. 14). In places, this is true because the section is inadequately known; in other areas, the tectonic history actually is known to differ in many details from that of Cuba.

In Jamaica, scattered data indicate that a major orogenic pulse ("Subhercynian"?) took place between early Turonian and Coniacian times. In the very few areas where pre-Coniacian Late Cretaceous rocks have been observed, Coniacian to Maestrichtian rocks overlie the older sequence either discordantly or with angular unconformity (Chubb, *in* Zans and others, 1962; Coates, 1969). Late Turonian-early Coniacian rocks have not been found, and late Coniacian-Santonian strata are absent in most of the areas where Campanian and Maestrichtian have been observed on older rocks. This may indicate either nondeposition, or erosion before Campanian time.

Well-documented, major orogenic episodes took place in post-Maestrichtian, pre-early Eocene, and middle Eocene times. Chubb (*in* Zans and others, 1962) referred these orogenic episodes to the "Laramide" orogeny.

In Haiti, Butterlin (1960, his Table I) recognized no orogeny before the end of the Cretaceous. Yet it is apparent from the different grades of metamorphism in the Massifs de la Hotte, de la Selle, and du Nord that there was pre-Campanian ("Subhercynian"?) orogeny, and possibly pre-Cretaceous orogeny. Butterlin recognized a major unconformity between the Maestrichtian and Paleocene, and a second unconformity within or at the top of the upper Eocene. He referred the former to the "Laramide" orogeny, and termed the latter the "orogenesis at the end of the Eocene" (p. 22).

H. Palmer (1963) and Bowin (1966) presented data which suggest that a post-Albian-Cenomanian(?) unconformity is present in the Dominican Republic. There may even be two or more significant unconformities in the pre-Cenomanian(?) section. Another angular unconformity is in the upper part of the Maestrichtian, and another is reported in the middle Eocene, near the top of the middle Eocene sequence, or in the lower part of the late Eocene rocks.

In Puerto Rico, which has been mapped in considerable detail during recent years, there is evidence for unconformities of the following ages: pre-Albian (Mattson, 1966a, 1967); early Cenomanian, or late Cenomanian to pre-mid-Turonian (Pessagno, 1962; Mattson, 1964, 1966a, 1966b; Pease, 1968); pre-Maestrichtian (Pease, 1968) or middle Maestrichtian (Pessagno, 1960a, 1962); post-Maestrichtian-pre-Eocene (Pessagno, 1960a, 1962; Mattson, 1962,

1966b, 1967; Nelson, 1966b); and middle Eocene to middle Oligocene (Pessagno, 1960a, 1962; Nelson, 1966b; Pease, 1968).

Donnelly's (1966a) and Whetten's (1966) work in the Virgin Islands suggested the presence of major unconformities at or near the base of the Albian; in the middle or at the top of the Maestrichtian; and in the middle Eocene. None of these unconformities is dated satisfactorily.

In summary, most unconformities reported from the Greater Antilles are in the Albian-Cenomanian-Turonian, Senonian (Fig. 9), Maestrichtian to Paleocene, and middle to upper Eocene. For simplicity, and because of numerous conflicting statements in the published literature, Mattson's (1966a) scheme of unconformities is adopted in modified form on Figure 14.

PRE-ORTHOGEOSYNCLINE STRATIGRAPHY

Late Jurassic: General

Callovian(?)-earliest Tithonian (Fig. 9) sedimentary rocks of the Greater Antilles are identified positively only in the Sierra de los Órganos of northern Pinar del Río Province. Early-late(?) Tithonian is known from northwestern Pinar del Río along and just inland from the Cuban north coast to northwestern Oriente Province. South of the median welt in central Cuba, dated Callovian(?)-Tithonian sedimentary (and volcanic?) rocks are unknown. The stratigraphy of the Late Jurassic has been summarized by Judoley and Furrazola-Bermúdez (1965, 1968). Most of the discussion which follows is based on detailed mapping by Hatten (1957) in the Sierra de los Órganos. The Sierra del Rosario, east of the Sierra de los Órganos, has not been mapped, and only a few reconnaissance traverses have been made in this range. This is unfortunate, because the Sierra del Rosario area is a major key to the geologic history of the western end of the Greater Antilles.

Azúcar and Jagua Formations

In the Sierra del los Órganos, the Early and Middle Jurassic San Cayetano Formation grades upward (Fig. 8) into the Jagua Formation of R. Palmer (1945). The Jagua, according to Khudoley, is about 300 m thick. From base to top, a typical section consists of a lower unit of dark-gray to black, bituminous, hard, dense, pelletal, oölitic, coquinoid, and sublithographic, medium-bedded limestone and sandy limestone; a middle unit of argillaceous sandstone and sandy shale with fossiliferous limestone concretions, some shale beds, and local lenses of conglomeratic sandstone; and an upper unit of gray to dark-gray, thin- to medium-bedded, sublithographic limestone. The middle unit contains the well-known late Oxfordian ammonite, fish, and reptile faunas of Cuba.

R. Palmer (1945) believed that the late Oxfordian ammonite concretions came from the lower unit. Work by Hatten (1957, 1967; *see* A. A. Meyerhoff, 1964a, p. 151–152) demonstrated that the ammonites came from the middle

terrigenous clastic unit. Accordingly, Hatten renamed the lower unit the "Azúcar Formation" (type locality, Mogote Pan de Azúcar, Sierra de los Órganos, Pinar del Río Province; Fig. 6). He assigned the middle and upper units to a redefined Jagua Formation. At the Azúcar type locality, Mogote Pan de Azúcar, the Azúcar is 36 m thick, and the Jagua (redefined) is 120 m thick (maximum). This is a total of 156 m, only half of that reported by Judoley and Furrazola-Bermúdez (1965) for the Jagua (in the sense of R. Palmer) in the same area.

The section exposed at Mogote Pan de Azúcar is important because it is one of the few in the northern Sierra de los Órganos which is unfaulted in the Callovian(?)-Oxfordian-Kimeridgian(?) interval. Herrera (1961, p. 26) described this section, but his paper is only a condensed version of Hatten's (1957) report; Herrera assigned different names to Hatten's units. Rigassi (1963), p. 346) challenged Herrera's stratigraphic divisions on the grounds that the Azùcar (Herrera's "Pan") is a thin local transition zone between two well-defined series. Rigassi, however, did not do the extensive field work which Hatten did, and could not have realized the regional importance of the Azúcar, even though the regional extent may not be great.

A marine fauna is present in the Azúcar (Khudoley's lower unit of the Jagua). It consists of recrystallized ammonites (unstudied), brachiopods (unstudied), pelecypods, *Posidenomyes*(?), and arenaceous Foraminifera, including the genus *Conicospirillina*, identified by M. A. Furrer (unless otherwise stated, all Cuban microfaunal identifications presented here are by M. A. Furrer and P. Norton). Furrer stated that this form is closely related to Callovian *Conicospirillina* in Europe. Seiglie (1961) referred it to *C. basiliensis*.

Gutiérrez-Domech (1968) placed the San Cayetano, Jagua, and Azúcar in a single group, the Cayetano Group—which consists of the Cayetano Formation, below, and the Jagua Formation, above. The Azúcar was designated by him as a member of the Jagua Formation. Gutiérrez-Domech was the first to credit Hatten with priority for the term "Azúcar."

The Azúcar and Jagua are not known to be present in the Sierra del Rosario east-northeast of the Sierra de Los Órganos. Herrera (1961) reported that the Artemisa (Tithonian) and the San Cayetano intertongue through a transitional contact. Khudoley believes that the Azúcar and Jagua were removed by erosion from the Sierra del Rosario area (Fig. 16). Meyerhoff believes that the Azúcar and Jagua grade laterally into the San Cayetano of the Sierra del Rosario area.

Jagua-Viñales Contact

The Jagua at Mogote Pan de Azúcar, as well as at several other localities studied in the Sierra de los Órganos, grades upward into the Kimeridgian(?)-early Tithonian Viñales Limestone, first named by DeGolyer (1918). The transition commonly takes place within a thin (15 to 25 m) interval, and represents a major change in depositional conditions and sediment provenance. The various opinions regarding this contact are discussed.

Many Viñales-Jagua contacts are abrupt. Moreover, a limestone conglomerate or breccia unit is at or near the base of the Viñales. In addition, terri-

genous clastic conglomerate lenses occur in the middle unit of the Jagua. These facts suggested to R. Palmer (1945), Furrazola-Bermúdez and others (1964, 1965), Judoley and Furrazola-Bermúdez (1965), and many others that the Jagua-Viñales contact is an unconformity. Regional tracing of the contact shows clearly that the Viñales rests on various units: Jagua, Azúcar, and San Cayetano. However, Hatten (1957; *see* Fig. 15 *taken from* Hatten, 1957, and Fig. 111 of Furrazola-Bermúdez and others, 1964) found one more important fact: the Viñales in many areas also overlies Paleocene(?) and early to middle Eocene Wildflysch which contains exotic blocks of older units, including garnet-mica schist and serpentinite. (Hatten called this Wildflysch unit the "Manacas Formation"; Knipper and others [1967] studied the basal Viñales contact with great care and concurred with Hatten's mapping.) Therefore, Hatten (1957, 1967) concluded that many of the contacts are thrust planes, but that depositional contacts, where preserved, probably are conformable. Meyerhoff agrees with Hatten. Khudoley, however, disagrees with Hatten, Meyerhoff, and Knipper and others, and believes that the contact is an angular unconformity (Fig. 16).

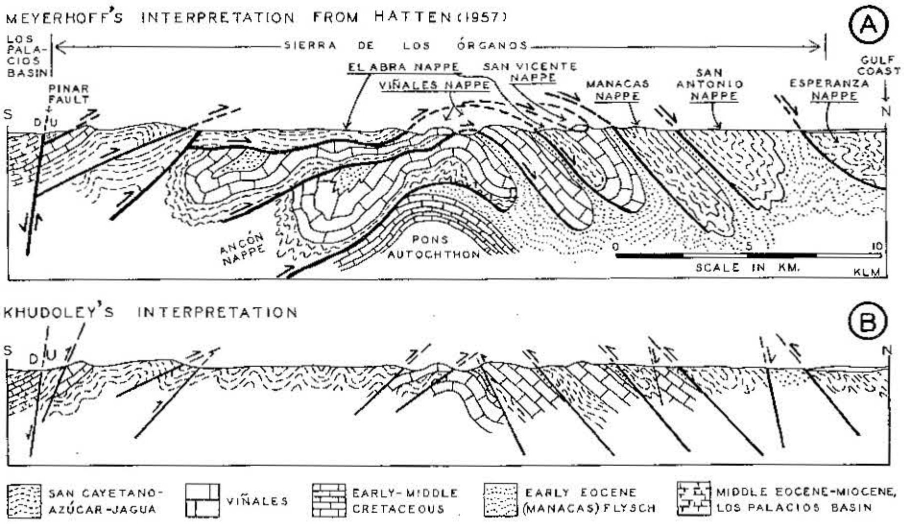

Figure 15. Schematic, interpretative south-north structural cross sections A and B, Sierra de los Órganos, western Cuba. A is Hatten's (1957) interpretation, based on detailed field mapping. Section extends from Los Palacios basin (on left; *see* Fig. 29 for location of this basin) to north coast (on right), Pinar del Río Province, western Cuba. See Figure 6 for location. Taken from Hatten (1957) as modified by Furrazola and others (1964, Fig. 111). Shows Pons autochthon and seven overlying *Überfaltungsdecken* and *Überschiebungsdecken*. Pons authochthon is a nonmetamorphosed sequence exposed several kilometers west of this section. Sedimentary rocks in each nappe and thrust sheet become increasingly metamorphosed upward; hence highest sheets have most metamorphosed strata (very low grade to low grade). A nearly identical situation characterizes nappes and thrust sheets of Alps. Flysch includes *Wildflysch* with exotic blocks of medium-grade garnet-muscovite schist and serpentinite. B: Khudoley's interpretation of same cross section. Khudoley stresses vertical tectonics as principal cause of observed structures, and denies a major role of compressional stress or gravity tectonics in this area.

Structural complexity such as this, and deep subtropical to tropical weathering, are principal causes of conflicting structural and stratigraphic interpretations in area.

The reconstruction of the stratigraphic sequence in the Sierra de los Órganos area is important because of its bearing on the interpretation of the paleogeography and tectonic history. Of equal importance is a thorough knowledge of the equivalent(?) units in the Sierra del Rosario, but data from the latter area are lacking. In the Sierra de los Órganos, the essential points are summarized:

1. In a few areas, the sequence San Cayetano-Azúcar (lower Jagua)-Jagua-Viñales is "normal." The Mogote Pan de Azúcar section is in one of these areas.

2. The lithologic character of the Viñales does indicate a considerable change in depositional environment from that of the San Cayetano. However, the lithologic character of the Azúcar and upper Jagua carbonate beds indicates that there was a period of transition.

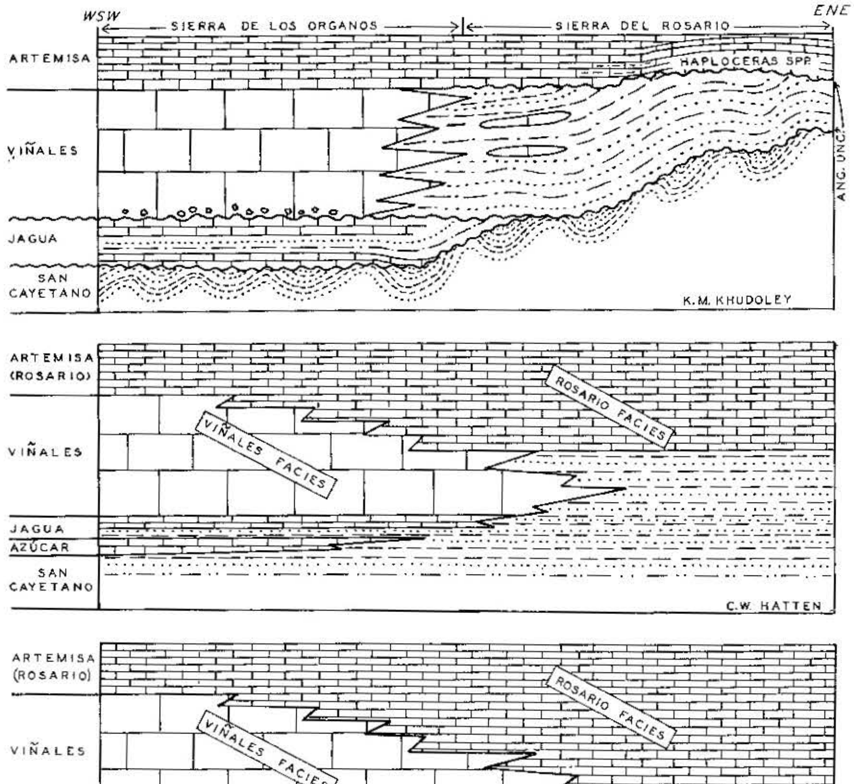

Figure 16. Three schematic south-southwest-north-northeast stratigraphic cross sections of northern Pinar del Río Province, from Sierra de los Órganos to Sierra del Rosario, at end of Tithonian time. Upper section is Khudoley's interpretation. Lower section is modified from Hatten (1957) and is Meyerhoff's preferred interpretation. Interpretation in middle section is one suggested by Hatten (June 10, 1968, written commun.). No vertical or horizontal scale. Location shown on Figure 22.

3. The Viñales does overlie San Cayetano, Azúcar, and Jagua directly in different places. This suggests the presence of an angular unconformity below the Viñales. However, Hatten's (1957, 1967) proof that in places the Viñales overlies Paleocene(?) to early-middle Eocene Wildflysch suggests that the contact interpreted as an "angular unconformity" at these localities actually may be a low-angle thrust, or thrusts.

4. A limestone breccia or conglomerate is at or near the base of the Viñales. Khudoley (Judoley and Furrazola-Bermúdez, 1965, p. 10, 12, 20–21) interpreted this as a "basal conglomerate." Rigassi (1963, p. 342) believed this to be a tectonic breccia. Hatten (1957; and Feb. 5, 1968, written commun.) believes that this is an intraformational conglomerate:

> Although the conglomerate is at the base, as I recall the clasts were more like an intraformational conglomerate; that is, it is composed of limestone clasts of typical Viñales Limestone. If there were an unconformable relationship with the Jagua and older formations, I would expect to see some clasts of San Cayetano, *etc.* I may have missed them, however!

Knipper and others (1967, p. 140) wrote that to date,

> . . . nowhere has there been discovered a contact between the shaly beds (San Cayetano) and the limestones above. Because of this, in our opinion, no basis exists for mapping a sharp limit of transgression at the base of the Late Jurassic limestones and to speak of a pre-Oxfordian folding phase (Furrazola and others, 1964). The contrary is more probable: *i.e.*, because of the gradual increase in limestone beds in the upper part of the clastic section (Jagua), and their Oxfordian age, one may speak more correctly of a gradational or, at least, concordant transition from the shaly beds to the limestones."

Knipper and others (1967, p. 141–142) believed that the breccias are tectonic, and they illustrated several excellent examples of such breccias at the base of the Viñales. Apparently they did not visit Mogote Pan de Azúcar and other localities where sedimentary limestone breccias are clearly visible, and where a gradational contact is exposed.

5. Because Meyerhoff has seen both normal and faulted contacts, it is his opinion that there are two types of breccias or conglomerates in the base of the Viñales: sedimentary in unfaulted sections, and tectonic in faulted sequences. The sedimentary breccias show all the properties of a water-deposited sediment, whereas the tectonic breccias are zones of severely crushed and contorted rock.[6]

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[6]Peter Misch (May 24, 1968, written commun.) has drawn the writers' attention to papers by Günzler-Seiffert (1941) and many others— *summarized in* Trümpy (1960, p. 869–873)—on the marine breccia formations of the Alps. Many of these Alpine marine breccias are pre-orthogeosynclinal (that is, pre-latest Jurassic). Trümpy (1960, p. 870) wrote: "The localization of pre-orogenic marine breccias along the limits between platforms and deeper-lying troughs certainly provides a clue to their genesis. It is linked to the existence of tectonic scarps, in most instances contemporaneous normal faults and flexures. Some of the breccia bodies are simply submarine scree deposits, and they share the absence of medium-sized detritus with subaerial scree. Others may be due to shattering and mixing of consolidated or semiconsolidated rocks by earthquakes." As shown in a subsequent section, the Viñales is a platform deposit close to a deeper basin on the south. Trümpy's interpretations thus may apply to this part of Cuba.

6. The San Cayetano Formation is much more severely deformed than the Viñales. As Hatten (1957), Rigassi (1963), and Knipper and others (1967) pointed out, this very probably reflects the incompetence of the San Cayetano, contrasted with the competence of the Viñales, during orogenic movements. The fact that a tectonic breccia may be common at the base of the very competent Viñales should, therefore, not be surprising. Nevertheless, Khudoley believes that it is too early to dismiss the contention of J. Lewis (1932), Khudoley (1967b), and others that the difference in degree of deformation is additional evidence for an angular unconformity between the Viñales and older formations (*see* Furrazola-Bermúdez and others, 1964).

7. In southern Cuba, there could be an important unconformity in the Late Jurassic part of the section. The metamorphosed San Cayetano[7] which is present there must be overlain across a wide area by volcanic rocks of the eugeosyncline. Therefore, in southern Cuba, Meyerhoff accepts the probability of the existence of a major unconformity. However, where is the unconformity? In the Upper Jurassic or Lower Cretaceous? This is discussed subsequently.

8. It is clear from the above that the problems still are not resolved, but an ultimate solution is far closer than when R. Palmer (1945) wrote that the San Cayetano Formation is of Late Cretaceous age and that it *overlies* the Viñales Limestone! Nevertheless, there is no denying Arkell's (1956, p. 569) comment that, "In the geological literature on this region published during the last 35 years it is standard practice for every account to contradict its predecessors on almost all important points"; or Khudoley's (1967b, p. 790) observation, referring collectively to the works of other geologists, ". . . it looks as though they worked in different parts of the globe."

Viñales Limestone

The Viñales is 840 to 1000 m thick in sections measured by J. W. Low, Meyerhoff, and Hatten, north of the Viñales Valley near the road to San Vicente (Fig. 6). It consists of thick-bedded to massive, light- to dark-gray, and gray-brown, dense, hard limestone and dolomite. Sublithographic limestone (calcilutite) of exceptional purity comprises about 50 percent of the Viñales. The remainder consists of gray and brown dolomite, oölitic limestone, and pelletal limestone. The purity of the carbonates indicates that most nearby land areas were submerged. In places, there are secondary chert and dolomite rhombs.

In some exposures, fine-grained dolomite with crystals and clusters of anhydrite are near the base. The formation appears to have been deposited on a shallow- to middle-neritic shelf.

[7]C. W. Hatten (May 28, 1968, written commun.) pointed out to the writers that the metamorphosed San Cayetano equivalents of southern Cuba are near granitic intrusive bodies which he believes to be of middle Cretaceous age. He therefore suggested that the medium- to high-grade metamorphism of the San Cayetano in southern Cuba may not indicate a pre-eugeosynclinal orogeny but middle Cretaceous thermal metamorphism resulting from intrusion of granitic magma.

Organic remains are scarce in many sections except for some nannofossils. However, in many areas, benthonic arenaceous Foraminifera are present, including species of *Trocholina* and *Nautiloculina* (Hatten, 1957). Species of *Lombardia* also have been found. Imlay (1942, 1944) reported a late Portlandian age for ammonites collected from near the top of the Viñales. On the basis of minimal fossil evidence, Hatten (1957) and Judoley and Furrazola-Bermúdez (1965, 1968) wrote that the Viñales is Kimeridgian–early and middle Tithonian. The contact with the overlying Artemisa Formation is gradational.

Artemisa Formation and Equivalents

Conformably overlying and gradational with the Viñales in the Sierra de los Órganos is the Artemisa Formation (J. Lewis, 1932) (Figs. 8, 18). Hatten (1957) (*see also* A. A. Meyerhoff, 1964a) named this the Rosario Formation for exposures in the Sierra del Rosario, east of the Sierra de los Órganos. In the latter mountains, Hatten noted its presence above the Viñales, but in the Sierra del Rosario, the Viñales is absent. Hatten interpreted this to mean that the Viñales, Jagua, and Azúcar graded eastward into the San Cayetano Rosario (Artemisa) facies (Fig. 16).

In the Viñales-San Vicente area (Fig. 6), the Artemisa is a 300-m unit of brown, gray, dark-gray, and black, well-stratified, thin- to medium-bedded, sublithographic, cherty limestone. Some beds are argillaceous. Numerous thin partings of tuffaceous and calcareous dark gray-brown shale are present. According to Judoley and Furrazola (1965, p. 23), the top of the Artemisa is unknown because of recent erosion. The Artemisa contains an abundant pelagic microfauna and early to middle Tithonian ammonites, and was deposited in deeper water than was the Viñales.

West of San Vicente in the Pons autochothon (Fig. 15; Hatten, 1957), the Artemisa is overlain by Early Cretaceous deep-water carbonates, but the contact with the Artemisa was not seen.

The Artemisa (or a formation very much like it) directly overlies the San Cayetano Formation in the Sierra del Rosario, east of the Sierra de los Órganos. In the Sierra del Rosario, the Artemisa is about 700 m thick. Khudoley believes that the fact that the Artemisa directly overlies the San Cayetano in the Sierra del Rosario area is further proof of a Late Jurassic orogeny in Cuba. However, Hatten (1957; and Feb. 5, 1968, written commun.) wrote, "In the Sierra del Rosario, the typical Viñales Limestone is not well developed. The Rosario facies (Artemisa; *i.e.*, the thin-bedded radiolarian limestone with Tithonian ammonites) appears to rest on the San Cayetano. The Jagua and Azúcar are missing. What, then, takes the place of these? Is it a facies change, a diastem, or an erosional unconformity? I do not really know but I suspect it to be a facies change. More detailed work is necessary."

Figure 16 is a southwest-northeast cross section illustrating three interpretations of the facies relations between the Sierra de los Órganos and the Sierra del

Rosario. Hatten favors the middle interpretation in which the upper part of the Viñales Limestone of the Sierra de los Órganos is equivalent to an Artemisa Limestone facies of Kimeridgian age in the Sierra del Rosario, and the lower part is equivalent to the upper San Cayetano. This interpretation was suggested to Meyerhoff by Hatten (June 10, 1968, written commun.). However, there is a marked absence of terrigenous debris in the lower Viñales, and it is possible that the Artemisa of the Sierra del Rosario area is equivalent to the entire Viñales of the Sierra de los Órganos. This last concept is illustrated in the lower interpretation and is supported by the fact that the Artemisa contains terrigenous debris, and was deposited in deeper water than the Viñales. Thus, if the San Cayetano was exposed during the time of Viñales deposition, the terrigenous debris would have been trapped in the deep-water Artemisa "channel" separating the shallow-water Viñales on the west from San Cayetano exposures on the east. Meyerhoff believes that, if the San Cayetano had been exposed widely, large quantities of terrigenous debris should be present in the Artemisa. Therefore, the hypothesis of a facies change from Viñales to Artemisa toward the Sierra del Rosario has some support. However, Kimeridgian ammonites are not known from the Sierra del Rosario. This may not be surprising if the fact is considered that the Sierra del Rosario is almost unstudied by geologists and paleontologists.

Khudoley, in contrast, believes that a terrigenous clastic facies, equivalent to the Viñales, is present in the Sierra del Rosario (upper interpretation of Fig. 16). No intertonguing of the Viñales and the postulated terrigenous clastic equivalent has been observed.

North of the median welt in central Cuba (Fig. 13), the Tithonian is well developed (Imlay, 1942, 1944, 1952). Pre-Tithonian, post-Punta Alegre formations, if present, must be in the subsurface. The Tithonian, possibly 100 to 500 m thick, consists of well-bedded, medium gray-brown, oölitic and pelletal, shallow-water limestone and, in some areas, of light-gray to brown-gray dolomite and dolomitic limestone. Northwest, in the subsurface, it may be 1000 m thick, but data are insufficient to determine a true subsurface thickness. In deep wells, such as Cayo Coco No. 2 (Fig. 6), it consists of sparsely fossiliferous, dark-gray to brown, bank limestone, dolomite, and anhydrite. The thickness assigned to the Upper Jurassic in Cayo Coco is about 450 m, but the base was not reached.

South of the Sierra de los Órganos and the median welt in Cuba, Khudoley believes that Jagua (Azúcar)-Artemisa rocks are widespread, although metamorphosed. They are believed by Khudoley to be a part of a metamorphic sequence which includes the San Cayetano, or to overlie metamorphosed San Cayetano in the subsurface. The marbles of the Sierra de Trinidad (San Juan) and Isle of Pines (Gerona) are interpreted by Khudoley and many other geologists to be metamorphosed equivalents of the Viñales Limestone. Meyerhoff seriously doubts that post-Kimeridgian Artemisa is present south of northern Pinar del Río and the median welt; the reasons for this doubt are discussed subsequently.

On the median welt itself, no proved Tithonian is known. Strata of Tithonian age may be present in the Jarahueca fenster area of central Cuba (Fig. 6), in the 100- to 300-m section of terrigenous clastics which separate Neocomian (Khudoley questions this age assignment), Aptian, and Albian interbedded spilite, shale, and pelagic limestone from the metamorphic and igneous basement. These clastic strata consist of quartz wacke, quartz siltstone, and lithic arkose which ranges from medium grained to conglomeratic. The conglomeratic beds contain granitic pebbles.

Late Jurassic in Remaining Greater Antilles

Late Jurassic rocks are unknown east of Cuba but may be present. Meyerhoff believes that Tithonian rocks, probably volcanic or ultramafic and mafic, ultimately will be identified in many parts of the Greater Antilles. Callovian-Kimeridgian strata, if present, could be associated with the metamorphic rock outcrops already described from Haiti and the Dominican Republic.

Recent deep-sea drilling on the Atlantic Ocean floor east of San Salvador Island, Bahama Islands, has revealed the presence there of a deep-water, abyssal Tertiary, Cretaceous, and Tithonian section. The base of the Tithonian was not reached (Drake, 1969; Burk and others, 1969).

Neocomian Hiatus?

Khudoley is of the opinion that the Neocomian is absent, thin, or developed only locally in most of Cuba. His opinion is supported by the scarcity of Neocomian ammonites in deep-water limestones currently assigned to the Neocomian on the basis of microfossils, and by the absence of proved pre-Aptian-Albian rocks in the eugeosynclinal facies of southern Cuba and elsewhere (except possibly in Jamaica). However, very few ammonites have been described from the entire post-middle Tithonian section of Cuba.

Kuman and Gavilán (1965) have shown that, on the Isle of Pines, the eugeosynclinal facies is unconformable on the metamorphic rocks which Khudoley and others correlate with the Late Jurassic sequence of Pinar del Río (Fig. 17). Similarly, Rigassi (1961) showed the presence of an angular unconformity between eugeosynclinal volcanic rocks of Albian-Cenomanian age and metamorphic rocks on the west flank of the Sierra de Trinidad.

It should be noted that the metamorphic rocks below the unconformity reported by Rigassi are, in Meyerhoff's opinion, pre-San Cayetano. On the Isle of Pines, Meyerhoff also believes that the volcanic rocks overlie pre-San Cayetano metamorphic rocks, although some San Cayetano equivalents could be present. Should these metamorphic rocks include San Cayetano-Viñales-Artemisa equivalents, certain complications in the geologic history arise.

The principal complication is that the volcanic rocks of the eugeosyncline—no older than Aptian in Khudoley's opinion —would overlie deformed Tithonian. Therefore, in addition to a pre-Kimeridgian unconformity, Khudoley

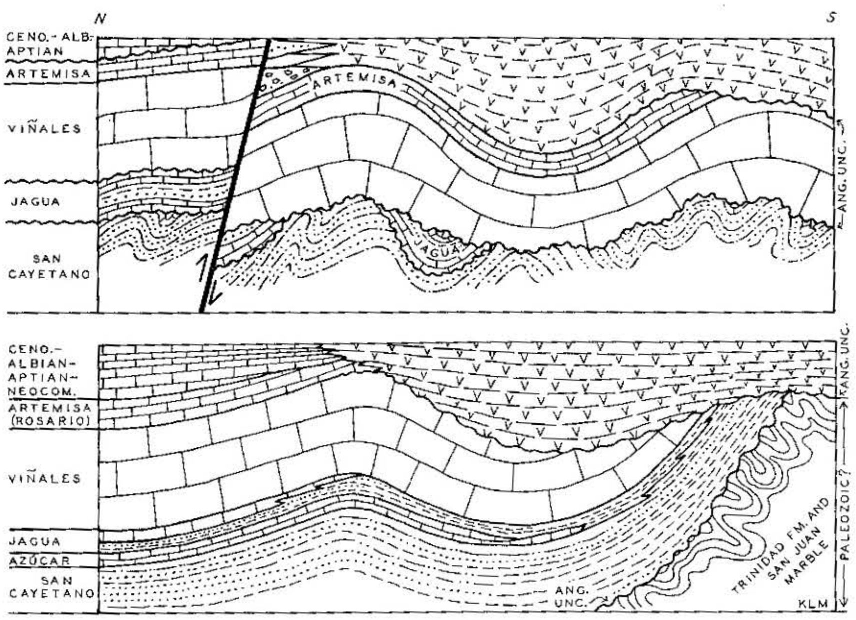

Figure 17. Schematic north-south stratigraphic cross sections showing western Cuba at end of Cenomanian time. Upper section is Khudoley's interpretation of stratigraphic-structural relations of San Cayetano through Cenomanian sequence. Note two unconformities and absence of Neocomian and Paleozoic in Khudoley's interpretation. Lower section is Meyerhoff's interpretation. Note one unconformity and presence of Neocomian and Paleozoic. No vertical or horizontal scales. Location shown in Figure 22.

would have to account for two unconformities, one which is post-Jagua, pre-Viñales, and another which is post-Artemisa, pre-Aptian. This is not beyond the realm of possibility, and is shown schematically in Figure 17, together with Meyerhoff's interpretation.

Meyerhoff believes that Neocomian is widespread across Cuba. In Pinar del Río Province, west of the San Vicente area, the Artemisa is believed to grade upward into Neocomian, Aptian, and Albian limestones, although the contact between Neocomian and Tithonian has not been studied. Hatten (1967, p. 784) reported the following microfauna: *Tintinopsella carpathica, T. oblonga, Nannoconus steinmanni, N. kamptneri, N. colomi, N. bermúdezi, N. globulus,* and *Favelloides balaerica.* Judoley and Furrazola-Bermúdez (1965, p. 22) reported the presence of *T. oblonga, T. carpathica, N. steinmanni,* and *N. bermúdezi* in association with Tithonian ammonites, but the remaining microfauna listed by Hatten has not been reported below the Neocomian. This observation does not *prove* Neocomian age, but is suggestive. Brönnimann's work (1953, 1955), based on careful comparisons with ammonite-dated sections of Europe, would require the extensive presence on Cuba of Neocomian strata. Houša's (1969) identification of Neocomian rhyn-

colites in the Sierra del Rosario of Pinar del Río Province is additional evidence for the presence of Neocomian.

The microfauna listed above has been collected by Brönnimann (1955) and by Hatten and others (1958) in numerous localities north of the median welt from northeastern Matanzas to northwestern Oriente. Specimens of *Tintinopsella elliptica, T. carpathica, T. oblonga, Calpionellites darderi, Nannoconus steinmanni, N. colomi, N. kamptneri, N. bermúdezi,* and *N. globulus* are especially abundant and are found together with poorly preserved ammonites; in some localities of northern Las Villas Province, Neocomian ammonites were listed by MacGillavry (1937, p. 8), but Imlay (1942) and Khudoley subsequently found them to be Tithonian. In the subsurface area offshore, the presence of Neocomian is suspected but is unproved; Meyerhoff believes that at least 1400 m of Neocomian bank carbonates and evaporites was deposited.

Along the north coast, on the Pinar del Río-Habana Provinces boundary, is a severely deformed sequence of pelagic, deep-neritic to bathyal limestone containing microfaunas of Tithonian, Neocomian(?), and Aptian(?)-Albian ages. Details of this large outcrop area, the Martín Mesa area, never have been studied and published in the literature.

In Habana Province, Brönnimann and Rigassi (1963, p. 212) described an outcrop of hard, dense, light- to medium-gray, fractured, radiolarian limestone bearing *Nannoconus steinmanni* and *N. globulus* which these authors considered to be Neocomian.

On the median welt of the Jarahueca fenster, above the terrigenous clastic sedimentary rocks which overlie the basement, are interbedded pelagic limestone, shale, and spilite. The lowest limestone beds contain *Tintinopsella oblonga, Nannoconus steinmanni,* and *N. globulus*. If this assemblage is not Neocomian, it may be late or middle Tithonian, but the fauna indicates that it is not Aptian or Albian. These beds are overlain directly by a limestone sequence bearing typical Aptian, Albian, and Cenomanian assemblages.

South of the median welt, the oldest faunas collected are Aptian-Albian, and these overlie about 3000 to 4000 m of undated ultramafic rocks, gabbro, diabase, basalt, spilite, and andesite, together with radiolarian chert and tuff. Therefore, Khudoley rightfully withholds judgment on the age of the lower part of the eugeosynclinal sequence.

In north-central Oriente Province, Adamovich and Chejovich (1964) reported a 120 m.y. date for a pegmatite dike (Table 4). Khudoley states that this date, which was determined by the Laboratory of the All-Union Geological Institute, Leningrad, is 119 m.y. $\pm$ 10 percent. This is Aptian or Albian on the Kulp (1961) scale, but late Neocomian on the Afanassyev and others (1964) and Harland and others (1964) scales.

The existence of an important Neocomian section in Cuba had always been taken for granted by Meyerhoff until Khudoley, beginning in 1964, began to point out in correspondence some of the uncertainties of Meyerhoff's assumption. Therefore, the problem remains unsolved; Khudoley prefers to think that Neocomian sediments are absent, only locally developed, or thin; whereas

Meyerhoff still favors—although now more cautiously—the concept that Neocomian beds are widespread. Certainly, Brönnimann's (1953, 1955) work strongly supports the concept that Neocomian is widespread in Cuba.

Neocomian Elsewhere in Greater Antilles

Chubb (*in* Zans and others, 1962, p. 16) reported that three rudistid limestone beds of the Benbow Inlier (Fig. 7) contain rudistids with Valanginian-Hauterivian, and Barremian-Aptian, age ranges (Fig. 9). *Monopleura* and *Pachytraga* are two genera cited. Norman F. Sohl (May 20, 1968, written commun.) studied gastropods from the Benbow Inlier and dated them as late Barremian (Fig. 9) to Aptian, and definitely pre-Albian.

Mitchell (1953) reported the presence in Haiti of the late Neocomian ammonite, *Crioceras duvali* var. *undulata*. As Butterlin (1960, p. 93) pointed out, this identification was never checked by a specialist and, in the same sequence of strata, a Late Cretaceous microforaminiferal assemblage is present (Butterlin, p. 93). Neocomian fossils have not been reported elsewhere in the Greater Antilles. However, Carl Bowin (March 24, 1968, written commun.) found a hornblendite in the central Dominican Republic which yielded a radiometric date of 127 m.y. (middle Neocomian), and a thin section of Neocomian strata is believed to have been penetrated in the deep Atlantic, east of Bermuda (Drake, 1969).

Carl Bowin, in 1961, collected a sample of gneissic rocks from the Bermeja complex of southwestern Puerto Rico. S. R. Hart (written commun. to Carl Bowin, May 14, 1963) reported a 110 ± 3 m.y. date for this sample (published *in* Mattson, 1964). This date is late Aptian to early Albian on most time scales. A more recent date from the same area yielded an age of 85 m.y. (± 10 percent) (Tobisch, 1968) and, therefore, the meaning of these age data is open to question (Tobisch, June 3, 1968, written commun.).

Beginning of Eugeosyncline

Khudoley believes that the eugeosyncline began to form in Early Cretaceous time (Aptian-Albian) (Fig. 13); Meyerhoff believes that it formed during the Tithonian. Khudoley's principal reasons are: (1) absence of pre-Aptian-Albian fossils in the eugeosyncline; (2) continuous deposition of Kimeridgian(?)-Tithonian sequence in Pinar del Río; (3) apparent absence or thin development of Neocomian as deduced from lack of ammonites; (4) angular relations in southern Cuba between the eugeosynclinal section and underlying beds which Khudoley believes to include metamorphosed equivalents of the Viñales and Artemisa (Fig. 17); and (5) occurrence of Late Jurassic-Neocomian(?) carbonate in serpentinites along the northern margin of the eugeosyncline; these carbonates may have been deposited before the serpentinite was erupted or injected as the eugeosyncline formed.

Meyerhoff believes for the following reasons that the eugeosyncline began to form during Tithonian time: (1) the Viñales Limestone is remarkably pure, having little or no insoluble residue. (2) The first appearance of definite volcanic (tuffaceous) material in the Pinar del Río section is in the Tithonian Artemisa Formation. (3) In northern Cuba, Wassall (1956) reported that the content of volcanic material in Tithonian and younger limestone increases from north to south toward the median welt. (4) On the median welt of the Jarahueca fenster, Neocomian, Aptian, Albian, and Cenomanian microfossils are present in a sequence of interbedded limestone, shale, tuffaceous shale, and spilite. (5) The occurrence of Tithonian and Neocomian limestone blocks in the northern belt of the serpentinite of the eugeosyncline is explained easily by thrusting of the serpentinite over the median welt and miogeosyncline of Meyerhoff (Las Villas facies-structural zone of Khudoley) in mid-Eocene time (for evidence of such thrusting, *see* A. A. Meyerhoff and Hatten, 1968). Although Khudoley disagrees strongly with Meyerhoff on the importance of thrusting in the area, the northernmost serpentinites from Habana to northwestern Oriente contain blocks of deep-water limestone, the Las Villas facies (Fig. 13), ranging in age from Tithonian to Turonian; the serpentinite appears to override Maestrichtian deposits in the Jarahueca fenster (Fig. 6; *see* Hatten and others, 1958); and serpentinite even overrides part of the Cretaceous carbonate bank facies (Remedios zone; Fig. 13). (6) Finally, the late Neocomian-Aptian limestones of Jamaica (Benbow Inlier) are interbedded with tuff and volcanic-derived sediments.

Meyerhoff therefore concludes: (1) the eugeosyncline formed in Tithonian time; (2) a post-Tithonian, pre-Aptian unconformity does not exist; and (3) a Late Jurassic (pre-Tithonian) unconformity separates the volcanic rocks and the Kimeridgian(?) and older metamorphic rocks in *southern* Cuba, south of the median welt, but this unconformity does not extend into northern Cuba, including northern Pinar del Río. The existence of a Late Jurassic unconformity has not been proved in southern Cuba, because the contact between the ultramafic-mafic eugeosynclinal rocks and the San Cayetano-Artemisa has not been observed. However, Albian-Cenomanian volcanic rocks do overlie metamorphic rocks with angular unconformity in the Sierra de Trinidad (Rigassi, 1961) and on the Isle of Pines (Kuman and Gavilán, 1965). H. A. Meyerhoff (1954, p. 155) inferred on similar grounds the existence of a pre-eugeosynclinal unconformity.

Related conclusions are that Tithonian carbonates are not present in southern Cuba, and, if a pre-Viñales unconformity exists, it is minor and local.

EARLY CRETACEOUS STRATIGRAPHY

"Early Cretaceous," as used in this paper, includes Neocomian through Cenomanian (Fig. 9). "Late Cretaceous" includes Turonian through Maestrichtian (Figs. 9, 18). This subdivision does not follow the general European and American practices, but is adopted here because the Greater Antilles Cenomanian cannot be subdivided at this time. Part of the Tithonian section belongs tectonically to the Early Cretaceous sequence—particularly in

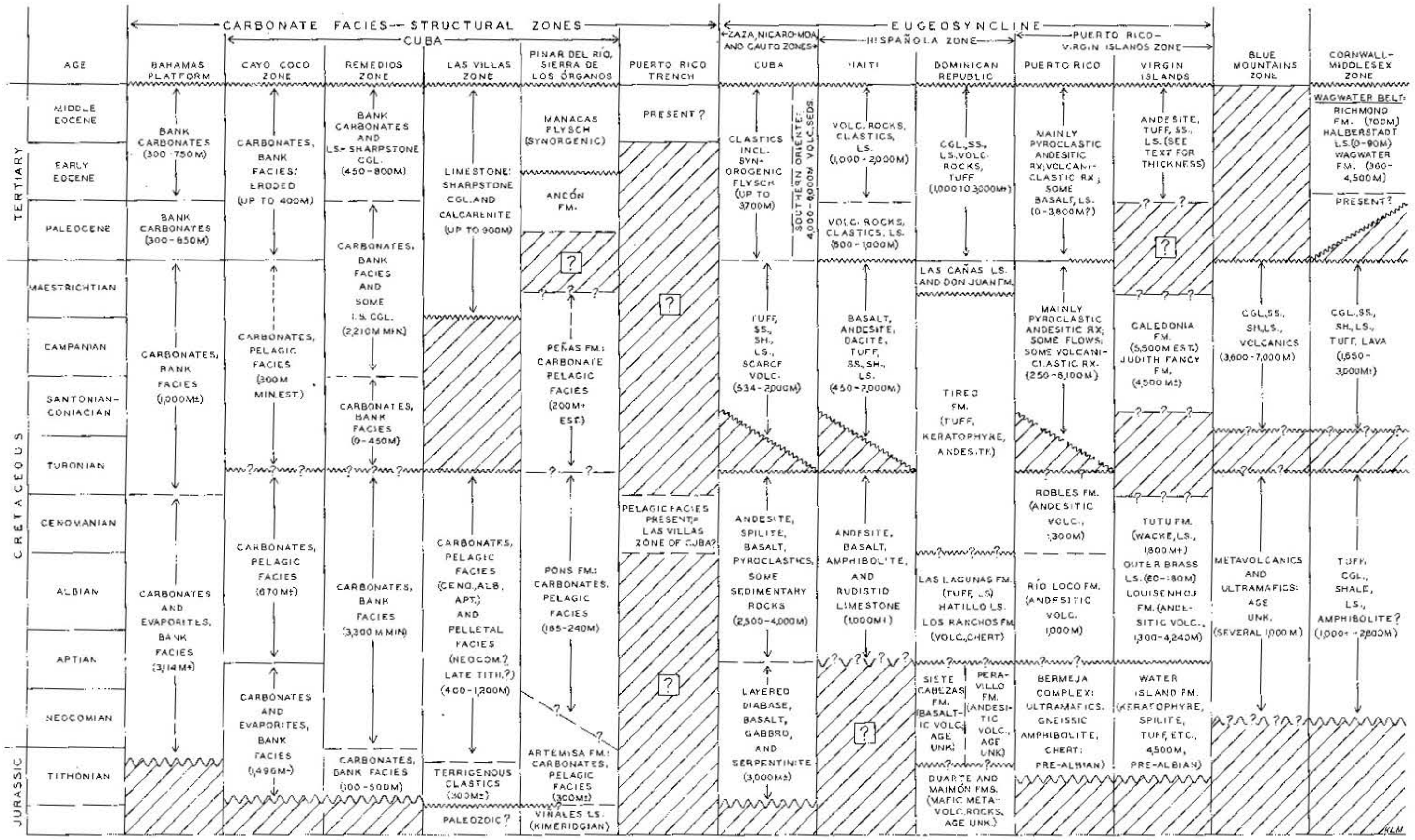

Figure 18. Generalized correlations, Tithonian-Maestrichtian (latest Jurassic through Late Cretaceous), Greater Antilles.

Cuba—but to include Tithonian strata within the Early Cretaceous would violate all accepted usage. Thus, the organization of the text in this manner is somewhat arbitrary.

The term "middle Cretaceous" is *not* used in the European and Middle East senses (that is, Aptian, Albian, and Cenomanian). Instead, it is used loosely to refer to events during Albian, Cenomanian, and Turonian (undifferentiated) times.

Problems relating to the presence of Neocomian already have been discussed.

The presence of Aptian rocks is established throughout northern Las Villas and Camagüey Provinces, Cuba, on and north of the median welt, and in parts of Matanzas, Habana, and Pinar del Río Provinces. Strata of this age also exist in the Cornwall-Middlesex zone (Benbow Inlier) of Jamaica. Aptian is known from the Remedios and Cayo Coco facies-structural zones, and from the Bahamas platform. Aptian-Albian faunas have been identified from the Dominican Republic. In fact, the writers believe that Aptian rocks are present in all major geological provinces of the Greater Antilles. Albian and Cenomanian have been identified positively in all geological provinces except the Blue Mountains zone.

Bahamas Platform

Two wells have been drilled on the modern Bahamas platform (Figs. 13, 18): the Bahamas Oil Company, Ltd., No. 1 Andros, and the Standard Oil Company of California-Gulf Oil Corporation No. IV-1 Cay Sal. The former reached total depth at 4447 m, and the latter at 5764 m (Furrazola-Bermúdez and others, 1964, p. 163–165; Spencer, 1967). A third well was being drilled during 1970, when this volume was in press.

According to Spencer (1967, p. 266–267), the Andros well reached Lower Cretaceous at 3256 m and was still in it at total depth (total thickness of 1190 m plus). According to Furrazola-Bermúdez and others (1964, p. 164), Lower Cretaceous was reached in the Cay Sal well at 2650 m, and was in Neocomian at total depth (total of 3114 m plus). At the bottom of the Andros well (4447 m), anhydrite had not been reached but was reached in the Cay Sal well at about 2800 m. Descriptions of the Cay Sal anhydrite have been published by Holser and Kaplan (1966, p. 109).

Spencer (1967) reported that the Lower Cretaceous of Andros consists mainly of dolomite and some limestone, and she postulated that the Lower Cretaceous strata are part of a reef facies. Furrazola-Bermúdez and others (1964, 1965) reported that the Lower Cretaceous strata of the Cay Sal well consist of alternating beds of dolomite, limestone, and anhydrite—probably a shallow-water bank facies.

Old Bahama Channel-Cayo Coco Facies-Structural Zones

These facies-structural zones are part of what Khudoley calls the miogeosyncline (Figs. 13, 18). Nothing is known of the Old Bahama Channel facies-

structural zone, except from seismic data. Presumably there is very little, if any, difference between the stratigraphy of this zone and that of the Bahamas platform on the north or the Cayo Coco facies-structural zone on the south.

The Cayo Coco facies-structural zone is known from several wells, three of which are of particular importance (Fig. 6). These are the Compañía La Estrella de Cuba (Shell and partners) No. 2 Cayo Coco, and the Ministerio de Industrias (Cuban government) No. 5 Francés and No. 1 Fragoso (Furrazola-Bermúdez and others, 1964, 1965; Echevarría and Veliev, 1967; Furrazola-Bermúdez, 1967).

The Lower Cretaceous of Cayo Coco No. 2 is at least 2167 m thick. The upper 671 m (plus, but not corrected for possible dip of 20°) consists of light- to dark-gray, chalky, porcelaneous, and sublithographic limestone bearing an abundant pelagic microfauna of Aptian, Albian, and Cenomanian ages (Hatten and others, 1958, *in* Furrazola-Bermúdez and others, 1964; Echevarría and Veliev, 1967; Furrazola-Bermúdez, 1967). Underlying the pelagic limestone is another facies—1496 m (uncorrected for about 20° dip) of Aptian(?) and Neocomian(?) dense dolomite, anhydrite, and some limestone—a shallow-water bank facies. A major reverse fault may be present at 1220 m. The highest anhydrite appears 565 m above what is believed to be the base of the Lower Cretaceous. The combined thickness of the various anhydrite beds in the well is more than 300 m.

Similar sections were penetrated in the Francés well (3510 to 4537 m) and in the Fragoso test (3172 to 5014 m) (Echevarría and Veliev, 1967). However, dips in the last-named wells are believed to be very steep, and in places nearly vertical (this conclusion is based on paleontological data supplied by the Instituto Cubano de Recursos Minerales). Some steep reverse faults may have been crossed in the Francés and Fragoso wells. In the Cayo Romano well (drilled in 1969; *see* Figs. 13, 23, 25), Tithonian(?)-early Turonian dolomite and limestone were penetrated from 485 to 2560 m; a reverse fault (or faults) was crossed at 2560 m, and the Late Cretaceous section was re-entered. At total depth 4200 m, the well was in Early Cretaceous dolomite. Steep dips may be present.

Remedios Facies-Structural Zone

The Lower Cretaceous strata of this zone, which Khudoley considers to be a part of the miogeosyncline, consist of a minimum of 3300 m of light- to dark-gray, gray-brown, and pale-orange, miliolid-bearing, medium-bedded to massive limestone (Figs. 13, 18). Rudistid banks occur locally, and in places, the section resembles a typical Urgonian facies. Evaporites have not been found. The Colorado well (Figs. 13, 23, 25) is believed to have penetrated this facies-structural zone; reverse faults were crossed at about 1800 and 2200 m.

This facies-structural zone passes into the Florida Strait at the location of the Colorado well (Fig. 13). Clasts of this facies have been found in cores of late Pliocene sediments in the Florida Strait (Bryant and others, 1969).

Las Villas Facies-Structural Zone

This is the zone of marginal elevation (intrageosynclinal welt) of Khudoley (1967a) (Figs. 13, 18). The northern half, which Meyerhoff calls the miogeosyncline, is the Camajuaní zone of Ducloz and Vuagnat (1962) and A. A. Meyerhoff and Hatten (1968). This pelagic part of the Las Villas facies-structural zone contains about 1000 to 1200 m of Lower Cretaceous limestone and thin shale beds. Structural complications—faults and intense shattering—make it difficult to find measurable sections.

The pelagic limestone of this zone overlies the Tithonian shallow- and deep-water Artemisa equivalents described previously. The most characteristic rock type is microcrystalline to sublithographic, pyritic, hard (although locally soft and marly), medium- to dark-gray, black, bluish-gray, and gray-brown, thin-bedded limestone with dark shale partings. Excellent descriptions of this limestone were published by Ortega y Ros (1937). The fauna characteristically consists of nannoplankton, pelagic Foraminifera, aptychi, and a few ammonites (Brönnimann, 1955). The quantity of volcanic-derived material increases from north to south (Wassall, 1956).

The northern part of this facies zone intertongues locally with the Remedios zone bank limestone. The intertonguing has been observed in several good exposures. Limestone conglomerate-breccia zones and calcarenite are abundant in this lateral transition zone.

The very thin section in this facies structural belt contrasts markedly with the thick bank limestone and dolomite on the north. The situation is similar to that of the Tamaulipas "foredeep" limestone of eastern Mexico between the thick (4000 m or more) El Abra and Golden Lane reefs and banks. This thin sequence might be described most accurately as a leptogeosynclinal (starved, deep basin) deposit (Trümpy, 1960).

The southern half of the Las Villas facies structural zone is the median welt (Placetas zone of Ducloz and Vuagnat, 1962, and A. A. Meyerhoff and Hatten, 1968) of the orthogeosyncline. According to Ducloz and Vuagnat (1962), this welt became topographically prominent in early Neocomian time. However, if it was the southern barrier for the Jurassic Punta Alegre evaporites, the feature is older than Neocomian.

Between 100 and 300 m of basal conglomerate, quartz wacke, and lithic arkose, along with interbedded gray to black shale, tuff, thin-bedded pelagic limestone, and spilite, accumulated in this zone. The terrigenous clastic rocks at the base were described in a preceding section. Their age is unknown. The overlying rocks contain pelagic microfossils of Neocomian(?), Aptian, Albian, and Cenomanian ages.

Northern Pinar del Río

Above the Artemisa, several hundred meters of pelagic limestone accumulated (Hatten, 1957) (Figs. 13, 18). Hatten called this the "Pons Formation" (*see* A. A. Meyerhoff, 1964a). The limestone is medium-bedded to massive,

medium- to dark-gray, hard, dense, and sublithographic and is preserved only locally. Much of this section apparently was removed by pre-middle Eocene erosion. Most geologists working in the area have assumed, without careful study, that this limestone is either Viñales or Artemisa. Microfossils prove the presence of Neocomian(?), Aptian, Albian, and Cenomanian in these post-Artemisa rocks.

Equivalents of Platform, Miogeosyncline, and Median Welt East of Cuba

No equivalent strata are known east of northwestern Oriente Province. The platform, miogeosyncline, and median welt strike offshore in the Gibara area of Oriente Province and may continue to the Turks and Caicos Islands, or to Tortuga Island, north of Haiti. It is improbable that a miogeosynclinal facies extends farther east than Tortuga Island or the Turks and Caicos Islands. Cenomanian sediments reported by Todd and Low (1964) from the north wall of the Puerto Rico Trench are in marly rocks, but the section above and below is predominantly of volcanic origin. Todd and Low estimated that the Puerto Rico Trench Cenomanian was deposited in a minimum water depth of 1800 m.

Eugeosyncline: General

Most of Cuba south of the median welt, possibly all of Hispañola, and the whole of Puerto Rico and the Virgin Islands were part of the eugeosyncline (Figs. 13, 18). The Blue Mountains zone (Fig. 13) may have been part of the eugeosyncline but is treated separately. The writers had considered the possibility that Hispañola north of the Cibao graben (Fig. 29) was part of the miogeosyncline, but Nagle's (1968) work indicates that this probably is not true.

The eugeosyncline should not be regarded as a single trough or depression extending the full length of the Greater Antilles. H. A. Meyerhoff (1933) was the first to propose that the eugeosyncline originated as a volcanic pile on the ocean floor. The concept has been revived again in recent years, and even the term "constructional geanticline" has been applied to the eugeosyncline (Mattson, 1968b). However, the writers prefer the term eugeosyncline because it is a descriptive term without genetic implications. The writers do agree with H. A. Meyerhoff, and believe that the eugeosyncline did form from a series of "in-line" or *en echelon* volcanic piles on the ocean floor. These several volcanic piles must be related genetically, as is demonstrated by the fact that they formed a single aligned volcanic belt or series of arcs. These piles also formed a single broad depression from western Cuba to the eastern Virgin Islands because, as the "piles" built upward, excessive thicknesses of volcanic rock accumulated (8 to 10 km), and a depression had to form to accommodate the continuing upbuilding.

The eugeosyncline is divided into five zones (Fig. 13).

1. The *Zaza facies-structural zone* occupies most of Cuba south of the median welt, and consists of extrusive and intrusive volcanic rocks mainly of Cretaceous age (Aptian through Turonian in Khudoley's opinion; Tithonian

through early Turonian in Meyerhoff's). Post-Turonian volcanic rocks are known from a few localized areas within this facies-structural zone.

The westward extent of the Zaza zone is unknown, and probably it does not extend west of Cuba. However, Zaza-zone rocks do strike west-northwest in an offshore direction from Matanzas Province (Fig. 13). Offshore from Cuba, and north of Habana and Pinar del Río Provinces, several large, positive, magnetic anomalies have been found (Pyle and others, 1969); these may be related to mafic or ultramafic intrusives. Although data are insufficient for reliable contouring, the anomalies appear to be aligned at nearly right angles to those reported by Gough (1967) in south Florida and the eastern Gulf of Mexico.

2. The *Cauto facies-structural zone* of southeastern Cuba is underlain by volcanic and intrusive rocks ranging in age from at least Early Cretaceous through middle Eocene. The feature which distinguishes this zone is the very great thickness of Paleocene-middle Eocene volcanic-derived rocks which are exposed widely in the Sierra Maestra and Sierra de Purial (Fig. 6). This thick sequence underlies the Cauto Valley and offshore parts of Oriente and southern Camagüey Provinces. This zone generally is separated from the Zaza by the Cauto fault system (Fig. 6) and from Hispañola by the Bartlett fault system.

3. Between the Cauto and Zaza zones, in eastern and northeastern Oriente Province, is a triangle-shaped area which is shown on Figure 13 as the *Nicaro-Moa facies-structural zone.* Khudoley relates this to the Zaza zone because (a) extensive serpentinite and peridotite outcrops characterize the area and (b) post-Early Cretaceous volcanic rocks generally are absent. Meyerhoff agrees that these reasons are valid. However, Meyerhoff relates the Nicaro-Moa zone also to the Cauto zone because (a) the Nicaro-Moa zone is separated structurally from the Cauto zone by a deep structural depression, probably underlain by the Cauto fault zone (A. A. Meyerhoff, 1966; Kozary, 1968); (b) the peridotite and serpentinite of the Nicaro-Moa zone are flat, layered sequences—not strongly deformed, alpinotype, linear serpentinite bodies; and (c) the sedimentary section in the Nicaro-Moa zone, including the Tertiary, more closely resembles that of the Cauto zone and exhibits the same slight degree of deformation. Recently, Kozary (1968) summarized the major differences that distinguish the Zaza and Nicaro-Moa zones (although Kozary did not use these terms).

4. The *Hispañola facies-structural zone* includes volcanic and intrusive rocks of Early and Late Cretaceous, Paleocene, Eocene, Oligocene, Miocene, Pliocene, and Quaternary ages. In general, the post-Cretaceous volcanic rocks are found in or adjacent to the existing highlands and coastal areas, but not in the principal graben systems shown on Figure 29. This zone is separated from the Puerto Rico-Virgin Islands zone by north-south fault zones and an intermediate-depth earthquake epicenter zone in the Mona Passage and the eastern Dominican Republic (Figs. 2, 7).

5. The *Puerto Rico-Virgin Islands facies-structural zone* includes volcanic and intrusive rocks ranging in age from Early Cretaceous to middle Eocene.

Younger volcanic rocks are unknown. Earthquakes generally are shallower than those of the eastern Dominican Republic and most are associated with the Puerto Rico Trench north of the island (Figs. 2, 3, 5).

The possibility that the Blue Mountains zone is a part of the eugeosyncline is not excluded.

The Zaza and Cauto facies-structural zones were named by Hatten and others (1958) and published by Furrazola-Bermúdez and others (1964). Ducloz and Vuagnat (1962) included both zones under the name "Santa Clara zone." A. A. Meyerhoff and Hatten (1968) followed Ducloz and Vuagnat's usage because of published priority, but the original terms "Zaza" and "Cauto" are more useful.

The time of formation of the eugeosyncline has been discussed.

Description of Eugeosyncline Zones

In the Zaza zone (Figs. 13, 18), at least 2500 m (according to Khudoley) and possibly 4000 m (according to Meyerhoff) can be assigned to the Lower Cretaceous. In the Jatibonico oil field, 30 km southwest of the Jarahueca Fenster (Fig. 6), well no. 78 penetrated 3879 m of Turonian to Tithonian(?) volcanic rocks and serpentines. The volcanic rocks overlie chloritic schist; the section thickness is not corrected for dip.

Wassall (1956) recorded in the literature for the first time the fact that undisturbed sequences of the Zaza zone consist of a basal layered gabbro-serpentinite sequence about 3000 m thick overlain by a spilite, basalt, andesite, pyroclastic, and sedimentary-rock sequence—possibly 4500 m thick, including Upper Cretaceous. A. A. Meyerhoff and Hatten (1968) described one such sequence from south-central Cuba. However, in most areas, the serpentinite is displaced tectonically and is in fault contact with rocks of many different ages.

At the base of undisturbed eugeosynclinal sequences in south-central Cuba there is a serpentinized harzburgite which grades upward into gabbroic rocks. The transition zone between the serpentinite and gabbro is characterized by a closely interlayered sheared and slickensided sequence of the two rock types. This part of the section may be the original oceanic floor of the eugeosyncline. However, this is only speculation, and some doubt is cast on this hypothesis by the presence of the Trinidad metamorphic rocks south of the Cuban eugeosynclinal sequence.

The gabbroic sequence includes gabbro, dolerite, diabase, basalt, troctolite, and anorthosite. The troctolite and anorthosite occurrences probably are inclusions. Hydrothermal and dynamothermal metamorphism, decreasing northward, has affected these rocks, as well as the ultramafic rocks below. The lower part of the gabbroic section is tholeiitic, whereas the upper part is more strongly albitized and thus spilitic. Pillow structure is common in the diabase and basalt. Both unaltered pillows and pillows with a vitreous matrix are present. The presence of thick tholeiitic gabbro and basalt above the serpentinite supports the ocean-crust hypothesis, because tholeiitic basalt is now

known to comprise much of the ocean floor (Engel and Engel, 1964a, 1964b).

Above the gabbroic section, basaltic, spilitic, and porphyritic pillow lavas are abundant. Andesite is present in lesser amounts. Still higher in the section are increasing proportions of tuff, ranging in composition from basaltic to dacitic or rhyolitic. Dacitic and rhyolitic tuffs are mainly near the upper (Cenomanian-Turonian) part of the section. Tuffaceous limestone, chert, radiolarite, and graywacke are interbedded in many areas. Faunas are largely pelagic microfossils; a few ammonites have been found. Most of the fauna found is in the upper part of the section and is middle and late Aptian, Albian, Cenomanian, and early Turonian. Rudistid reefs are present locally.

K. M. Bandt (1958) made a detailed subsurface study of the eugeosynclinal sequence of the Zaza zone of south-central and central Cuba. He found that the upper part of the ultramafic-gabbro complex thins northward toward the median welt. The amount of tuff and reworked tuff increases northward at the expense of the gabbro, diabase, spilite, and basalt. Bandt interpreted the northward thinning of the mafic flows and sills and concomitant increase in the amount of tuff in the section as strong evidence for lateral facies changes in the section, from predominantly intrusive and flow rocks in the south to predominantly pyroclastic rocks in the north. Surface evidence gathered by Hatten and others (1958) supports Bandt's interpretation.

Lower Cretaceous volcanic rocks are known from few places in the Cauto zone (Keijzer, 1945; G. Lewis and Straczek, 1955). Future mapping may reveal the existence of more extensive outcrops. The principal known outcrops are along the southern coast of Oriente Province, from 75°20′W. to 77°20′W. The outcrop belt extends 18 to 20 km inland (Núñez-Jiménez and others, 1962). Faunal control for dating is poor. Some of the rocks are Late Cretaceous, for M. T. Kozary (1957, oral commun.) collected Turonian microfossils from a limestone bed associated with volcanic rocks. The locality which Kozary sampled is near 77°W., a short distance from the coast.

The Nicaro-Moa zone is a layered serpentinite-peridotite belt along coastal northeastern Oriente Province, 74°30′W. to 75°54′W. This vast layered ultramafic complex of Nicaro, Moa, and other areas has been described by many geologists (for example, Hayes, 1911; Thayer, 1942; Guild, 1947; Simons and Straczek, 1958; Adamovich and Chejovich, 1964).

In the Hispañola zone, studies of the eugeosyncline are sparse, and all but a few are superficial or reconnaissance studies. In Haiti, Butterlin (1960) assigned several outcrops of basalt, andesite, amphibolite, hornblende schist, epizonal metamorphic rocks, metasedimentary rocks, and rudistid-bearing limestone to the Lower Cretaceous. In the Massif de la Selle, the oldest rocks, dated on the basis of caprinids, are Aptian-Albian (Woodring, *in* Reeside, 1947, p. 1). The Neocomian ammonite identification reported by Mitchell (1953) is not reliable (Butterlin, 1960, p. 93), because it is associated with Late Cretaceous foraminifers. Cenomanian-Turonian microfossils have been identified in shaly limestone on the Northwest Peninsula (Ayala-Castañares, *in* Butterlin, 1960, p. 111). Some poorly preserved, unidentified fossils are found in other limestone lenses in other parts of the country. The total thickness of

the section is unknown, but probably is in the order of several thousand meters.

Kesler (1968a, 1968b) described 1000 m or more of metamorphosed rock of unknown age in the Northwest Peninsula. These rocks consist of the following mineral assemblage: metamorphic albite, epidote, chlorite, calcite, actinolite, and magnetite. The original mineralogy is obliterated. No schistosity is developed in this section. The present writers believe that this sequence may be Early Cretaceous.

In the central Dominican Republic, Bowin (1966) assigned a thick sequence of volcanic rocks to the Lower Cretaceous. However, the interrelations of the various units which he assigned to the Lower Cretaceous are not understood. Included are the pre-middle Albian Duarte, Siete Cabezas, and Peravillo Formations (Fig. 18), consisting of slightly metamorphosed mafic tuff, chert, keratophyre, flow breccia, diabase, andesite and basalt pillow lavas, wacke, and chert. In the Duarte Formation, no pillows were observed. Units presumed to be younger are the Aptian-Albian Los Ranchos Formation, Hatillo Limestone, and Las Lagunas Formation. These include thick sections of quartz keratophyre, keratophyre, andesite, dacite, tuff, massive chert, and minor limestone and siltstone. Fossils from one locality include *Orbitolina* ex. gr. *concava-texanus, Quinqueloculina* sp., *Cerithium* cf. *C. weeksi, C.* cf. *C. noduliratum, Ringicula* sp., and other fossils. In some deeper water deposits, Radiolaria and unidentified globigerinids were found. In another locality, Aptian-Albian *Cuneolina* and *Coskinolinoides texanus* were collected (Woodring, 1954; Bowin, 1960, 1966; summarized *in* Weyl, 1966, p. 107–109). Northwest of the area which Bowin studied, H. Palmer (1963) found similar rocks.

Possibly belonging to the sequence are serpentinized dunite, wehrlite, lherzolite, and harzburgite. In Bowin's area, these rocks are associated only with the Duarte and Peravillo Formations, but Palmer reported that, in his area, serpentinite is emplaced tectonically as high in the section as lower Oligocene. A norite batholith intrudes the Duarte, but apparently does not intrude younger rocks. Hornblendite also is associated only with the Duarte, and yielded a K-Ar date of 127 ($\pm$ 5 percent) m.y. (Table 4). This is middle Neocomian on the Harland and others (1964) time scale.

In Seibo Province, eastern Dominican Republic, Douglass (1961) described Albian *Orbitolina minuta* from limestone in the Lower Cretaceous volcanic sequence (Fig. 7), and Woodring (1954) reported an occurrence of specimens of the *Orbitolina concava-texana* group from a locality which apparently is close to the Douglass locality.

Most of the rocks described in the preceding paragraphs are believed to be Albian or older. An unconformity may separate these units from the overlying Tireo Formation, to which Bowin (1966) assigned a Cenomanian(?)-Maestrichtian age. The Tireo is discussed with the Upper Cretaceous.

The generalized history of this area, and a summary of facts known to date, were published recently by MacDonald and Moores (1966).

Weyl (1966, p. 110–114) reported that various serpentinite intrusions are

associated with numerous andesite flows in the Sierra del Seibo area of the eastern Dominican Republic (Bowin, 1966; Weyl, 1966). A major Cretaceous volcanic eruptive center apparently was present in this area.

The mapping of the Puerto Rico-Virgin Islands facies-structural zone is much more detailed. In Puerto Rico, the principal problems involve (1) multiple names for equivalent units, (2) great "sameness" of the section in rocks of all ages (with attendant stratigraphic nomenclatural confusion), and (3) possible miscorrelation (for example, the Robles Formation [Fig. 18] has a Cenomanian or Cenomanian-Turonian age in some reports; it is mainly Coniacian-Campanian in others; Mattson (1968a) and Pease (1968) assigned an Albian-Santonian age to the unit (but Pease called it the Río Orocovis Group). Although much more was known about Puerto Rican geology in 1968 than in 1933, and some successful correlations have been made, a statement written in 1933 by H. A. Meyerhoff (p. 202) still is generally correct: "The most extraordinary failure in eighteen [now 55] years of research is the unsuccessful attempt to determine the sequence of Cretaceous formations in Puerto Rico." A careful reading of post-1948 literature on Puerto Rico leads one to a single state of mind—specifically, confusion.

In general (Lidiak, 1968, p. 45), the Early Cretaceous volcanic rocks of Puerto Rico differ from the Late Cretaceous to Eocene volcanic rocks in that they are more mafic in composition (basalt, andesite, and spilite). They are "widespread and copious" and almost no hornblende is in the andesite.

The oldest rocks (undated; probably Albian or older) are in the Bermeja complex in southwestern Puerto Rico (Figs. 7, 13) (Mattson, 1960a, 1960b, 1964, 1968a; Pessagno, 1960a; Renz and Verspyck, 1962; Donnelly, 1964; Tobisch, 1966, 1968). The Bermeja (300 m was penetrated in one drill hole; Burk, 1964) consists of serpentinite (originally harzburgite and dunite), associated with silicified chert and gneissic amphibolite. The total amount of serpentinite is unknown. Tobisch (1968) noted that the composition of the gneiss is much different from that of rocks normally consanguineous with serpentinized peridotite. From this he concluded that the gneiss and the serpentinite are genetically unrelated. Hess (1960, 1964) suggested that the Bermeja complex is ocean crust, but Renz and Verspyck (1962) pointed out that the presence of the gneiss raises the question of which rock is older, the gneiss or the serpentinite. Hurley and others' (1964) study of Rb/Sr relations supports Hess' opinion. The radiogenic dates from the gneiss of 85 and 110 ± 3 m.y. (Mattson, 1964; Tobisch, 1968) solve nothing, except possibly to date the last thermal episodes to affect the gneiss. Mattson (1964, p. 8) and Tobisch (1966, 1968) reported that the serpentinite diapirically intrudes the gneiss, but Mattson (1968a, p. 52–53) subsequently reversed this opinion and concluded that the gneiss intrudes the serpentinite. If Tobisch is correct, the gneissic amphibolite is the oldest rock in the region. Tobisch concluded that the serpentinite is unlikely to be ocean crust as proposed by Hess (1960). If Mattson is correct, where did the gneissic rock come from? The data available provide no compelling reason to reject the possibility that the serpentinite is tectonically remobilized ocean floor, regardless of the intrusive and tectonic relations

between the ultramafic and metamorphic rocks. The gneissic amphibolite could be metamorphosed mafic rocks of the ocean crust, not unlike some of the metamorphic rocks dredged from the Mid-Atlantic Ridge (Melson and van Andel, 1966).

Undated mafic volcanic rocks overlie the Bermeja complex with angular unconformity. These are overlain unconformably by Campanian rocks. The undated mafic rocks are believed to be Early Cretaceous, possibly of the Cenomanian or older Río Loco Formation.

The Río Loco Formation in southern and east-central Puerto Rico consists of a minimum of 1000 m (Mattson, 1966a, p. 135, gives 0 to 5000 m) of interbedded subaerial and submarine andesite, breccia, conglomerate, and tuff (Otálora, 1964). Its total age range is unknown, but Cenomanian and Albian fossils have been found (Pessagno, 1960a; Douglass, 1961). The Río Loco is overlain by the Robles Formation (as used by Pessagno, Otálora, Mattson, and Donnelly), which consists of at least 1300 m of pillowed andesite flows, tuff, and breccia (Pessagno, 1962). In southern and east-central Puerto Rico, the Robles is Cenomanian and possibly Turonian, and its relation to the partly equivalent and younger Fajardo Formation is uncertain. An unconformity separates the Río Loco-Robles sequence from overlying rocks.

Thus, in Puerto Rico, the Lower Cretaceous consists of a minimum of 2300 m of basic to intermediate volcanic flows, associated tuff, tuff-breccia, and chert. Volumetrically, tuff and tuff-breccia comprise most of the Lower Cretaceous (O. T. Tobisch, June 3, 1968, written commun.). At least one (and possibly more) unconformity is in the sequence—between the Bermeja and the Río Loco. Another unconformity may separate the Río Loco from the Robles.

In the Virgin Islands (Fig. 18), the Lower Cretaceous section of St. John and St. Thomas was described by Donnelly (1964, 1966a). He wrote that the section includes the pre-Albian Water Island Formation and an Albian to middle Eocene Virgin Islands Group (Fig. 18). No dated strata between the Albian and Eocene are known in the Virgin Islands Group of St. John and St. Thomas. Additional study of the post-Albian section is needed, because rocks of post-Albian age probably are present.

Helsley (1960, 1968) reported the presence of Cenomanian fossils from the Virgin Islands Group, but this fauna is the same which now is believed to be Albian (C. E. Helsley, May 31, 1968, written commun.).

The Water Island Formation consists of 4500 m or more of keratophyre flows, flow breccia, tuff, and spilite flows. There are some radiolarite beds and dikes and plugs of keratophyre. The presence of pillows and Radiolaria, and the absence of terrigenous debris, suggest that the Water Island was formed in deep water. Radiogenic dates of 106 $\pm$ 10 m.y. and 110 $\pm$ 10 m.y. have been obtained from the Water Island (Table 4; *see* Donnelly, 1966a); this is late Aptian on the Harland and others (1964) scale.

Unconformably above the Water Island, the Virgin Islands Group is approximately 3100 (plus) to 6000 (plus) m thick. From base to top, the group includes the Louisenhoj Formation (1300 to 4240 m), the Outer Brass Lime-

stone (60 to 180 m), and the Tutu Formation (more than 1800 m). The only dated fossil collection includes a rudistid (*Caprinuloidea*) which is believed by B. Perkins and H. J. MacGillavry to be of Albian age (*in* Donnelly, 1966a, p. 130); L. J. Chubb (*in* Donnelly, 1966a, p. 130) interpreted the rudistid to be of Cenomanian age. In view of the well-known difficulties of using rudistids for precise dating, the actual age of the rudistid fauna is in doubt. The total age range of the Virgin Islands Group is unknown.

The Virgin Islands Group shows increasingly shallow-water deposition from base to top. The Louisenhoj consists of andesite breccia and ash, and a basal cobble conglomerate; the Outer Brass is siliceous, tuffaceous, radiolarian limestone; and the Tutu is tuffaceous wacke and breccia, with some limestone beds.

In the Puerto Rico Trench, north of Puerto Rico and the Virgin Islands, Cenomanian and older rocks include flat-lying, poorly bedded, volcanic rocks, andesitic volcanic rocks interbedded with lithified chert, andesitic basalt, and cherty shale (Conolly and Ewing, 1967). Some chert is carbonate-rich (marly), has volcanic shards, and contains a bathyal Cenomanian micro-fauna. Ultramafic rocks appear to be pre-Cenomanian.

Summary of Early Cretaceous Eugeosyncline

Basaltic to intermediate rock types predominate. In some areas, there is good evidence that the earliest deposits formed in deep (oceanic?) water, and that a progressive shallowing took place from the base to the top of the Lower Cretaceous rocks. The volume of tuffaceous deposits increases upward. There is some evidence that the section becomes more silicic in the upper part.

The Lower Cretaceous probably was not deposited in a single depression extending from western Cuba to the eastern Virgin Islands, but as volcanic piles in a series of more or less separated depressions within the broad trough of the geosyncline. The number of separated, or partly separated, eugeosynclinal depositional basins increased markedly between Early and Late Cretaceous times as a result of "Subhercynian" orogenic activity.

Blue Mountains Zone

The Blue Mountains (Fig. 18), which now form the highest mountains in Jamaica, may have been part of the eugeosyncline (Fig. 13). On the other hand, they also could be the deformed and uplifted remnant of a filled island-arc trench which once was south of and parallel with the eugeosyncline or volcanic arc. A conclusive answer is not possible at this time because the Blue Mountains have not been studied thoroughly (*compare* Matley, 1951; Raw, 1951; Zans, 1961; Zans and others, 1962). Regardless, the area was a deep trough during much of Cretaceous time, and many volcanic, as well as sedimentary, rocks accumulated in this trough.

Matley's (1951) "Basal Complex" probably contains some of the Lower Cretaceous rocks. These include ". . . various schists, serpentines, granulites, mylonites, phyllites and marbles," according to Chubb (*in* Zans and others,

1962, p. 18). However, Chubb (p. 19) also pointed out that the metamorphic rocks ". . . are found only in the zones of Laramide or Alpine thrusting and folding. . . ."

Cornwall-Middlesex Zone

This platform-like "backland" (Fig. 13) was a site of Early Cretaceous deposition and volcanism, but details of the Early Cretaceous stratigraphy are poorly known (*see* Fig. 18). Most are volcaniclastic rocks; flows and tuff are subordinate. The rocks are exposed in only a few places, and may have been penetrated in one well. The total thickness is unknown but probably exceeds 1000 m in most places. A minimum thickness of 2800 m is estimated in the Benbow Inlier (Geol. Survey Dept. of Jamaica, 1966, p. 8).

In the Central Inlier, rocks assigned to the Cenomanian-early Turonian consist of a 25°-dipping, mildly metamorphosed, poorly sorted, massive epiclastic, volcanic conglomerate and breccia (1050+ m, below) and an upper 350-m sequence of limestone, mudstone, siltstone, and some sandstone, containing specimens of the *Globotruncana appenninica* group (Zans and others, 1962; Coates, 1969). The age of the section, however, is not proved conclusively. The lower metamorphosed conglomerate and breccia unit was interpreted by Coates to be a volcanic mudflow deposit. Coates (p. 311) also reported the presence of ". . . occasional dioritic pebbles and pebbles of metamorphosed volcaniclastic sediments." The presence of dioritic clasts in this sequence has important paleogeographic implications because, if the sequence is Cenomanian, the existence in this area of pre-Cenomanian orogeny and intrusive activity is proved. Even if the sequence is of Late Cretaceous age, early Late Cretaceous or older intrusive activity is established.

In the Benbow Inlier (Fig. 7), Lower Cretaceous rocks exhibit "low grade regional metamorphism" (zeolite to epidote: Burke and others, 1969). Facies changes take place from northwest to southeast across the Inlier. In the northwest, a shallow-water sequence of volcanic-derived graywacke and siltstone, tuffaceous mudstone and sandstone, rudistid limestone, shale, and conglomerate is present. In the southeast, near the margin of the Wagwater belt and not far from the edge of the Blue Mountains zone, andesitic lava (including pillow lava), tuff, and agglomerate are interbedded with mudstone, banded chert, tuff, sandstone, and small amounts of conglomerate (Geol. Survey Dept. of Jamaica, 1966). The Benbow Inlier sequence has many volcanic flows in the lower part, but upward is characterized mainly by reworked, water-deposited, volcanic-derived rocks, agglomerate, tuff, and sedimentary strata.

Five limestone beds in the Benbow Inlier contain a rudistid fauna assigned by Chubb (*in* Zans and others, 1962) to the Valanginian-Aptian. These strata are underlain by more than 800 m of undated volcanic and volcanic-derived rocks, associated with metamorphosed, argillaceous to arenaceous, sedimentary rocks. N. F. Sohl (May 20, 1968, written commun.) described nerineid gastropods from Chubb's Valanginian-Aptian interval, and concluded that those fossils probably are of late Barremian to Aptian age.

Toward the south, just north of Kingston, a low-grade, regionally metamorphosed section is present that is assigned to the Lower Cretaceous. It consists of mudstone, siliceous mudstone, laminated chert, and lesser amounts of conglomerate, andesitic flows, and andesitic tuff (Geol. Survey Dept. of Jamaica, 1965).

The Santa Cruz well (Fig. 7) of southwestern Jamaica reached total depth in amphibolite and anorthosite (Greiner, 1965). This section could be the counterpart of the lower part of the Cuban eugeosynclinal sequence in which metamorphism has taken place and inclusions of anorthosite are present. However, the higher degree of metamorphism of these Jamaican rocks, compared with the Lower Cretaceous rocks of the Central Inlier, leaves the age of the amphibolite and anorthosite in doubt. Radiometric dating techniques may prove to be of help.

Beata Zone

Edgar (1968; *see also* J. Ewing and others, 1967) reported that the crust beneath the Beata Ridge has characteristics similar to those of the crust beneath the Nicaragua Rise. This suggests that the Beata Ridge is an old feature, possibly pre-Cretaceous. Fox and others (1968) reported the presence of a shallow-water Cretaceous fauna above a depth of 2500 m on the ridge, but this is an error. P. J. Fox (October 9, 1968, written commun.) informed the writers that the fauna is middle Eocene. An early Eocene bathyal fauna was reported by Edgar (1968) from the southern part of the ridge. The occurrence of Eocene faunas on the ridge suggests that the rocks on which the Eocene was deposited may be Cretaceous or older.

TYPES AND AGES OF SERPENTINITES

Figure 13 shows that serpentinite crops out from western Cuba to southwestern Puerto Rico, and that it is restricted mainly to the eugeosyncline (Zaza, Nicaro-Moa, Hispañola, and Puerto Rico-Virgin Islands zones). In the Puerto Rico-Virgin Islands zone, outcrops are present only in southwestern Puerto Rico. Additional serpentinite or serpentinized peridotite crops out within the north wall of Puerto Rico Trench (Bowin and others, 1966), Blue Mountains zone, Isle of Pines-Sierra de Trinidad metamorphics, and northwestern Pinar del Río Province, Cuba. Serpentinite outcrops adjacent to and on the Las Villas facies-structural zone are interpreted to have been emplaced by thrusting (A. A. Meyerhoff and Hatten, 1968). Kozary (1956, 1968) postulated a complex mode of emplacement in this zone by "extrusion" and gravity gliding. Khudoley (*in* Furrazola-Bermúdez and others, 1964, and *in* Soloviev and others, 1964a, 1964b) believes that the Las Villas zone serpentinites are sill-like intrusions, although magnetic data from east of Matanzas City show that the anomalies associated with the serpentinites are small and very shallow; hence, the magnetic data from east of Matanzas City do not support Khudoley's viewpoint (Soloviev and others, 1964b). Elsewhere, serpen-

tinite may be present in the Cornwall-Middlesex zone where Greiner (1965) reported the existence of amphibolite and anorthosite in the Santa Cruz well (Fig. 7).

The most spectacular and widespread serpentinite exposures are on Cuba where more than 6500 sq km of ultramafic rocks is exposed. This area is approximately ten times the total area of all other ultramafic rock exposures in the Greater Antilles. Much additional serpentinite underlies late Eocene and younger strata in Cuba, as shown by its presence at total depth in numerous wildcat petroleum tests drilled in Habana, Matanzas, and Las Villas Provinces. Kozary (1968) estimated that at least 15,000 sq km of serpentinite would be exposed in Cuba if all late Eocene and younger strata were removed.

The "thickness" of some of the serpentinite bodies in the Greater Antilles has been partly determined by the drilling of several wells. All but one of these wells was drilled in Cuba, where most oil production is from fractured serpentinite (Effinger, 1956). A well just east of Habana penetrated 1510 m of serpentinite, beneath which 813 m of early Eocene or Late Cretaceous terrigenous clastic rocks was penetrated to a total depth of 2323 m (Sass and Neff, 1965, p. 1115). In the Jarahueca area (Fig. 6), a producing well was in serpentinite at a total depth of 2221 m (Effinger, 1956, p. 1538). In this well, large slivers of Neocomian deep-water limestone, enclosed in serpentinite, were penetrated (Hatten and others, 1958). Just south of the city of Santa Clara, a well penetrated 1540 m of serpentine without reaching the "base" (A. A. Meyerhoff and Spangler, 1958, p. 1580). The well was abandoned because of the presence in the serpentine of numerous exotic, exceedingly hard blocks of medium- to high-grade metamorphic rocks. In Puerto Rico, a 305-m well was drilled into the serpentinite of the Bermeja complex (Burk, 1964).

Although much has been written about serpentinite occurrences in Cuba (*see* Kozary, 1968, for a summary of the principal pre-1956 literature), the most comprehensive review is that by Ducloz and Vuagnat (1962). Until recently (Burk, 1964), almost nothing was known of the Puerto Rican serpentinites. Those of Jamaica and the Dominican Republic have been studied only cursorily, and in Haiti, not at all.

Ultramafic rock occurrences have been classified by many workers. Possibly the most useful classification is that summarized by Wyllie (1967, p. 3–7). His classification is utilized here, with two major modifications. First, the "serpentinites of the oceans" (Wyllie, p. 5) are given separate status ("peridotites and serpentinites of the oceans") and are removed from his "alpine-type peridotite-serpentinite association" (p. 4), although the writers believe that there is a close relation between oceanic and alpine-type associations. Second, the Wyllie order is changed to emphasize possible genetic relations. This revised classification follows.

A. Tiefkraton (Ocean) Associations

1. Peridotites and serpentinites of the oceans. Such rocks may comprise a peridotitic crust and upper mantle and they are characteristic of the stable

Tiefkraton environment (oceanic cratons). The concept of Hess (1959, 1960) that the oceanic crust is serpentinized peridotite has not been proved, but the possibility that it, the upper mantle, or both are partly serpentinized peridotite is very possible. Meyerhoff concurs with Hess' (1960, 1964) belief that the ultramafic complexes of the Nicaro-Moa zone and southwestern Puerto Rico may be oceanic crust or mantle. However, if these outcrops are oceanic crust or mantle, they have undergone a more complex history than that of simple uplift, erosion of overlying rocks, and exposure. Tobisch (1968) and Mattson (1968a) have demonstrated this for the Bermeja complex of southwestern Puerto Rico, and the inclusion of exotic metamorphic rock blocks in the serpentinite of south-central Cuba shows that the history of serpentinite emplacement in that area also is very complex.

Ultramafic rocks of the oceans exhibit layering, and therefore some differentiation—if the Nicaro-Moa and related complexes are examples of exposed oceanic-peridotite-serpentinite complexes. Ultramafic rocks of the oceans have been found along numerous shear zones (for example, St. Paul and Peter Rocks, equatorial Atlantic).

B. Orogenic Associations

2. Alpine-type peridotite-serpentinite association. These are linear bodies of partly to completely serpentinized peridotitic rocks. They are characteristic of most eugeosynclinal belts bordering continents, or island arcs both adjacent to continents and extending into oceanic basins. The ultramafic rocks are strongly deformed, elongated parallel with regional structural strike, and repeatedly remobilized tectonically as "cold" intrusions. They generally are associated with gabbro and related rock types.

3. Concentrically zoned dunite-peridotite association. These are smaller than alpine-type bodies, but occur in alpine-type belts. They commonly have an ovate to nearly circular plan view. Dunite generally occupies the core of such intrusions and grades outward to peridotite. Gabbro "sheaths" are common. They are not severely deformed and show less deformation than alpine-type bodies. This fact suggests that they are late orogenic intrusions.

4. Minor associates of batholithic complexes. Wyllie (1967, p. 5) listed at least three associations of silicic to ultramafic rocks in "granitic" batholiths of orogenic belts.

C. Continental-Cratonic Associations

5. Alkalic rocks in ring complexes. These are circular to ovate bodies which range from small diatremes to larger masses several miles across. The different rock types may be arranged concentrically, and many show gravity layering. Commonly these complexes are arranged in linear patterns.

6. Kimberlites. These may be small pipes, diatremes, dikes, or sheets.

7. Layered gabbro-norite-peridotite association in major intrusions. These include both large- and intermediate-size layered complexes, such as the Stillwater and Bushveld complexes, and Skaergaard intrusion.

8. Ultramafic rocks in differentiated basic sills and in minor intrusions. These include numerous small, layered, basic sills or laccoliths in which picrite is common.

D. Mixed Associations

9. Ultrabasic lavas are found in the *Tiefkraton,* orogenic belts, and continental-cratonic areas. Layering by flow differentiation or by crystal setting is characteristic.

10. Ultrabasic nodules are known from oceanic, island arc, and continental-cratonic areas in many parts of the world.

11. Metamorphic and metasomatic ultramafic rocks are found in all environments. They are the products of shearing, orogeny, and accompanying metamorphism, or may be formed by metamorphic differentiation or metasomatic processes.

Occurrences in Greater Antilles

In the Greater Antilles, linear alpine-type bodies (class B-2) are most characteristic. In Cuba, they extend 850 km from the northwestern side of the Sierra de los Órganos to northwestern Oriente Province, and are mainly in the Zaza and Las Villas facies-structural zones. In the Gibara area (Kozary, 1956, 1968; Knipper and Puig, 1967), great masses of alpine-type serpentinite have been detached from their roots and apparently have been emplaced tectonically as imbricate "thrusts" by northward gravity gliding (Khudoley believes that these serpentinite bodies are intrusive sills). The serpentinites of Jamaica, Hispañola, and Puerto Rico also show the characteristics of linear alpine-type bodies.

In the Sierra de Guajaibón, north of the Sierra de los Órganos, Pinar del Río Province, and in the Nicaro-Moa zone (Fig. 13) of northern and northeastern Oriente Province, the serpentinite bodies are stratiform (class A-1?) and only partly serpentinized. Chromite and gabbroid rocks are interlayered with the harzburgite, lherzolite, wehrlite, and dunite. The stratiform masses of Cuba comprise nearly a third of all Cuban ultramafic bodies, and thus occupy more than three times the area of all known Greater Antillean ultramafic bodies outside of Cuba.

The stratiform bodies of serpentinite, peridotite, and gabbroic rocks beneath the Aptian-Albian of south-central Cuba (Wassall, 1956; Meyerhoff and Hatten, 1968) (class A-1?) are believed by Meyerhoff to be original ocean floor or mantle, or part of an extrusive-intrusive complex onto the then ocean floor. Shearing, brecciation, and slickensiding of the serpentinized layers of the stratiform sequences suggest some tectonic remobilization, but the basal position of the stratiform bodies in the total volcanic section of south-central Cuba cannot be denied. Their gradation upward into a more mafic and, near the top, more silicic sequence, is a phenomenon which has been observed in many other parts of the world.

It is important to note that the linear alpine-type serpentinites described by

Bowin (1966) from the central Dominican Republic—deformed as they are—have preserved in them a layering of different rock types, including metallic ore deposits. Subsequent deformation during the "Subhercynian" (middle Cretaceous) and "Laramide" orogenies remobilized the original stratiform layers, elevated the peridotitic rocks to higher stratigraphic positions by "cold" tectonic intrusion, and caused them to be hydrated and serpentinized. Careful observations recorded by Wassall (1956), Hatten and others (1958), and Bowin (1966) permit speculation that, in the Greater Antilles, a complete gradational sequence of ultramafic bodies exists from nearly undeformed, stratiform ultramafic bodies to severely crushed, tectonically remobilized, linear, wholly serpentinized, alpine-type bodies. Thus class A-1 ultramafic rocks would represent one end member of a gradational series from class A-1 to class B-2 ultramafic rocks.

If most of the linear ultramafic bodies of the Greater Antilles are of the same age (that is, pre-Aptian-Albian), "cold" tectonic re-intrusion at various times is necessary to explain the widely divergent ages assigned to the Greater Antillean serpentinites. In the central Dominican Republic, Bowin (1960, 1966) reported that the serpentinite bodies intrude only Albian or pre-Albian rocks, but H. Palmer's (1963) study in the area next to Bowin's showed at least one "cold" intrusion into rocks of early Oligocene age. Similarly, in Cuba, intrusions into rocks as young as the basal Miocene have been reported (R. Palmer, 1945). In Jamaica, "cold" serpentinite intrusion into Late Cretaceous strata seems to be well established.

The situation is somewhat simpler in Puerto Rico where the serpentinite of the Bermeja complex underlies probable Albian-Cenomanian rocks. On that island, serpentinite is found only near the base of the eugeosynclinal sequence, and it is likely that the original ultramafic rocks (now serpentinite) are pre-Albian, as they are in many parts of Cuba. However, Tobisch (June 3, 1968, written commun.) informed the writers that there is evidence that some serpentinite intrusion in Puerto Rico is younger.

The only other type of ultramafic occurrence reported in the Greater Antilles is along the north wall of the Puerto Rico Trench (Bowin and Nalwalk, 1963; Bowin and others, 1966). J. Ewing and M. Ewing (1962) and Hersey (1962) have described the north wall as a series of east-west fault planes. If the Puerto Rico Trench has been downdropped along these east-west faults, peridotitic mantle may have been exposed and serpentinization may have taken place along the shear zones. This is a class A-1 ultramafic rock.

Age of Serpentinites

The ages of the serpentinites, as the foregoing discussion shows, are controversial. However, Khudoley and Meyerhoff do agree that, at least in Cuba, two periods of serpentinite-peridotite emplacement took place (excluding "cold" tectonically remobilized intrusions). In the remainder of the Greater Antilles, only one period of serpentinite emplacement (excluding "cold" tectonic remobilization) appears to have taken place, and this was during Mesozoic time.

In Cuba, one group of small serpentinite intrusions is in the Isle of Pines and Sierra de Trinidad metamorphics (Fig. 13). There are also intrusions in the Sierra de los Órganos area, Pinar del Río Province—mainly in rocks of Jurassic age. If Khudoley's assumption that the Isle of Pines metamorphics, Trinidad metamorphics, and San Cayetano Formation are of Early and Middle Jurassic ages, an episode of ultramafic intrusion during a "Nevadan" orogeny is not unreasonable. Khudoley believes that there was an episode of "Nevadan" ultramafic intrusion.

However, Meyerhoff believes that the ultramafic intrusions of the Isle of Pines and Sierra de Trinidad are Paleozoic. Their composition and degree of metamorphism differ from those of the rest of Cuba and the Greater Antilles, and field relations on the Isle of Pines suggest that the ultramafic intrusions there are the oldest rocks in the island (Kuman and Gavilán, 1965).

Meyerhoff also believes that the serpentinites of the Sierra de los Órganos region are related to the "cold" tectonic re-intrusion of Late Jurassic or Early Cretaceous peridotites during the "Laramide" orogeny. Some may not have been re-intruded, because Ducloz and Vuagnat (1962) presented evidence that one serpentinite body in northern Pinar del Río is surrounded by a narrow contact aureole. This observation, however, proves only that the true age of the intrusion is post-San Cayetano.

Nothing presented here excludes the possibility that the serpentinite intrusions of Pinar del Río are "Nevadan" (pre-orthogeosynclinal), but one important fact suggests that such an interpretation is not correct. The Sierra de los Órganos ultramafic rocks are in fault zones which are on strike with, or parallel to, the "Laramide" structures of the area, and have the same trend as identical serpentinite bodies north of the adjacent Sierra del Rosario in a Zaza facies of probable Cretaceous age. If Hatten's (1957) allochthon interpretation of the Sierra del los Órganos is correct, the presence of many serpentinite bodies in the thrust planes is understandable. Nevertheless, some serpentinite bodies—such as that described by Ducloz and Vuagnat as having a contact-metamorphic aureole—are not explained so easily by thrust emplacement.

Tijomirov (1967, p. 18) concluded independently, "Our investigations showed that it was an error to assign the ultramafic rocks of Pinar del Río Province to the Early and Middle Jurassic. . . . In actual fact, geologically, there is only one age for the ultramafic intrusions . . . and that is the Late Cretaceous, *i.e.*, pre-Maestrichtian." Tijomirov did not, however, present his evidence, but the contents of his paper suggest that his evidence is based on the chemical composition, which differs from that of the Isle of Pines-Sierra de Trinidad serpentinites.

Thiadens (1937) believed that the second episode of ultramafic intrusions was Turonian to Campanian (that is, during the "Subhercynian" orogeny), and Khudoley as well as Tijomirov (1967) arrived at the same conclusion. At least 95 percent or more of the exposed ultramafic rocks of the Greater Antilles are believed by Khudoley to be of this age. The reasons are that the serpentinites intrude Albian-early Turonian volcanic rocks in many places in

Cuba, and are overlain unconformably by Campanian to Maestrichtian conglomerate bearing serpentinite clasts (Adamovich and Chejovich, 1964; Furrazola-Bermúdez and others, 1964, 1965; Kozary, 1968).

Meyerhoff, in contrast, believes that most of the Greater Antillean ultramafic rocks are either mantle or ocean floor—in which case they could be very ancient—or that they comprise an early intrusive-extrusive complex onto the ocean floor during the early stages (Tithonian-Neocomian) of eugeosyncline formation. The ultramafics are pre-Aptian-Albian in southern Cuba (Las Villas Province), pre-Albian in parts of the central Dominican Republic, and possibly pre-Albian in southwestern Puerto Rico. The first post-Tithonian orogeny to affect the entire region was the "Subhercynian" (Albian to Santonian), and no folding, faulting, and unroofing of the ultramafic complex at the base of the eugeosynclinal section are known to have taken place in the region prior to the "Subhercynian" orogeny. This would explain the lack of serpentinite clasts in most rocks older than the Campanian. In actual fact, studies of clasts within the entire Cretaceous eugeosynclinal sequence are so incomplete that it is possible that serpentinite clasts *are* present in pre-Campanian rocks in many parts of the eugeosyncline. Abundant serpentinite clasts did not appear in the section until Maestrichtian and younger strata were deposited. This is a direct result of the "Laramide" orogeny during which tectonic remobilization and "cold" intrusion of the ultramafic rocks took place.

Role of Serpentinites in History of Greater Antilles

The serpentinites locally have played an important role in orogeny. Outstanding examples are in northern Pinar del Río and the median welt area of Cuba. One of the most complex structural belts in the world is the Gibara area of northeastern Oriente where Kozary (1956, 1968) and Knipper and Puig (1967) demonstrated that serpentinite was an important "lubricant" in thrusting or gravity gliding from the eugeosyncline onto the miogeosyncline. A. A. Meyerhoff and Hatten (1968) described a similar, but not nearly so complex, role for serpentinites in parts of north-central Cuba where these bodies behaved as a "lubricant" for thrusts (or gravity slides) overriding the Las Villas facies-structural zone onto the southern edge of the Remedios facies-structural zone. Windows of the deep-water limestones of the Las Villas zone are exposed in northern Camagüey and Las Villas Provinces (Hatten and others, 1958; A. A. Meyerhoff and Hatten, 1968), and huge exotic blocks of Neocomian through early Turonian deep-water limestone are in the serpentinites of northwestern Matanzas Province (just northwest of Matanzas city) and northern Habana Province (Brönnimann and Rigassi, 1963). These occurrences, in Meyerhoff's opinion, provide evidence for large-scale thrusting or gravity sliding of the serpentinities. Khudoley disagrees with Meyerhoff's interpretation involving thrusting. Arguments *pro* and *con* are presented in another paper in preparation.

LATE CRETACEOUS STRATIGRAPHY

Late Cretaceous rocks are widespread in the Greater Antilles (Fig. 18). They are widely exposed and, therefore, better known than the older sequences.

Orogeny, termed here the "Subhercynian," appears to have been widespread during Early Cretaceous time, but became more intense during Late Cretaceous time, particularly from the Cenomanian through the Coniacian. The large eugeosynclinal trough from western Cuba to the Virgin Islands was fragmented into numerous depositional basins, and many areas rose above sea level. Upper Cretaceous rocks overlie Lower Cretaceous rocks in many areas with angular unconformity.

Bahamas Platform

Nearly 1000 m of shallow-water limestone and dolomite was penetrated in both the Cay Sal and Andros wells (Furrazola-Bermúdez and others, 1964, 1965, p. 164; Spencer, 1967, p. 265) (Figs. 13, 18). Open-marine, deep-water "chalk" like that which was deposited at the same time in southern and central Florida was not observed in the samples, but some deeper water tongues may be present.

Old Bahama Channel-Cayo Coco Facies-Structural Zones

Late Cretaceous (post-Cenomanian) strata are very thin or absent in much of the Cayo Coco facies-structural zone (Late Cretaceous has not been studied beneath the Old Bahama Channel) (Fig. 13, 18). Their absence, or thinness, seems to be partly the result of erosion, but also is a result of nondeposition. A pronounced angular unconformity separates the early Turonian from Campanian-Maestrichtian; where Coniacian-Santonian sediments are present, one unconformity seems to be at the base and another at the top. The general absence of Coniacian-Santonian in Cuba has been noted by several authors (for example, Brönnimann and Rigassi, 1963; A. A. Meyerhoff and Hatten, 1968).

The principal deposits of Turonian through Maestrichtian ages in this zone are pelagic limestones, although bank limestone is known locally. Because of the scarcity of surface outcrops and the paucity of subsurface data, reconstruction of Late Cretaceous history in this zone is difficult.

The thickness of the pelagic limestone is about 700 m (Cayo Coco No. 2 well). The rock is dense, thin to medium bedded, light to dark gray, and porcelaneous. It contains abundant pelagic microfossils, some benthonic Foraminifera, nannoplankton, and a few ammonites. This sequence is believed to be continuous and gradational with the Cenomanian and older pelagic limestones of the same area. The deposits probably formed in an open sea between the equivalent bank carbonates of the Remedios zone on the south and the Bahamas platform on the north. This deep-water basin may have been formed as a result of uplift of the median welt and downwarping of the north side of

Cuba during Aptian and later times. Thus the trough may have been a precursor of the modern Old Bahama Channel.

Echevarría and Veliev (1967) reported Upper Cretaceous thicknesses of 2308 and 2645 m for the Fragoso and Francés wells, respectively. The strata in both wells consist of bank limestone and dolomite. However, the beds dip very steeply, and part of Echevarría and Veliev's thickness values contains Cenomanian strata (based on the presence of large *Nummoloculina heimi*). At least one reverse fault may have been crossed in the Francés well, although conclusive proof for this fault is not available. Therefore, not only is the section steeply dipping and possibly repeated, but also some of the beds assigned by Echevarría and Veliev to the Upper Cretaceous are Lower Cretaceous as used in this paper.

Remedios Facies-Structural Zone

At least 450 m of Turonian-Santonian bank limestone and dolomite was deposited locally above the pre-Turonian section (Figs. 13, 18). An unconformity may be present in the Turonian section. Another unconformity may separate the Santonian from the Campanian-Maestrichtian bank carbonates above. In many areas, Campanian-Maestrichtian shallow-water facies appears to overlie directly the Cenomanian-early Turonian. The Campanian-Maestrichtian-Paleocene bank carbonates (the Paleocene cannot be separated in most places) are 2210 m thick (minimum thickness). Thus, the minimum thickness of Turonian-Maestrichtian in this zone exceeds 2600 m in many areas, and in others probably is more than 3000 m. Several wells along the Cuban north coast have penetrated this facies-structural zone.

Las Villas Facies-Structural Zone

Turonian-Campanian rocks generally are absent in this zone (Figs. 3, 18). A Maestrichtian-middle Eocene sharpstone-limestone conglomerate and calcarenite, derived from the shallow-water bank on the north, commonly overlies pre-Turonian rocks with a pronounced angular unconformity. The thickness of this conglomerate ranges up to 900 m. Separation of the Maestrichtian part from the Tertiary part generally is not possible.

In the Colorado well (Fig. 13), a deep-water Senonian-Maestrichtian limestone and marl sequence was penetrated. In the Florida Strait, clasts of bathyal limestone of Turonian through Maestrichtian ages have been recovered from a late Pliocene, abyssal carbonate mud (Bryant and others, 1969).

Northern Pinar del Río

Locally, remnants of ammonite-bearing deep-water limestone are found (Peñas Formation of Hatten, 1957) (Figs. 13, 18). Thus far, microfossils of Turonian, Santonian, and Campanian ages have been identified (Hatten, 1957; *also* Feb. 13, 1968, written commun.).

Eugeosyncline

Volcanic rocks and their sedimentary products cover most of Cuba south of the median welt (Figs. 13, 18). In the Zaza zone, the early Turonian overlies the Cenomanian and older rocks conformably. Andesitic, dacitic, rhyolitic, and some mafic volcanics are present. Water-laid tuffaceous shale, siltstone, and shale are common. The average composition of the volcanics is more silicic than that of the Early Cretaceous volcanics. Volcanic rocks are uncommon above the Turonian in Cuba, in contrast to the remainder of the Greater Antilles.

In some places within the Zaza zone, late Turonian-Santonian is present (for example, central Oriente Province; parts of southern Camagüey), but more commonly, Campanian-Maestrichtian overlies the pre-late Turonian sequence with a slight to sharp angular unconformity. The thickness of the Campanian-Maestrichtian in southern Matanzas, Las Villas, and Camagüey Provinces ranges from 534 to 1630 m in measured sections. The total Turonian-Maestrichtian section is thicker than 2000 m.

Whereas the pre-early Turonian rocks are in large part of volcanic origin, the post-early Turonian section consists principally of interbedded dark olive-green to dark-gray, silty, calcareous shale, claystone, siltstone, and graywacke. Abrupt lateral facies changes are characteristic. Dense, argillaceous limestone beds and bioclastic rudistid limestone reefs (as thick as 240 m) occur locally. Near topographically high areas, coarse conglomerate is present, some with granitic boulders. The source areas for these sediments were mainly exposures of volcanic rocks of early Turonian and older ages. Wrench faulting, which probably began in Late Cretaceous time, is related to the subsidence of at least one basin on the Cuban mainland. This is the Central Basin depression which, by Maestrichtian time, was a prominent depocenter (Fig. 29).

Locally, volcanic centers remained active. One, along the southern margin of the median welt in the Las Villas-Camagüey border area, was the site of many violent eruptions. From 500 to 1600 m or more of dark-gray or black porphyritic basalt agglomerate, overlain by andesitic to rhyolitic flow breccia and ignimbrite, formed in a local basin in this area. The sequence is post-early Turonian. Campanian and Maestrichtian marine limestone tongues are present near the top.

In the Cauto zone, south-central Oriente Province, Campanian-Maestrichtian sandstone, calcareous fossiliferous sandstone, massive to poorly bedded conglomerate, sandy shale, and argillaceous dark-gray limestone have been described by G. Lewis and Straczek (1955). Some volcanic-derived rocks are present (Keijzer, 1945). Turonian limestone interbedded with volcanic rocks has been reported by M. T. Kozary (1957, oral commun.) from the south coast of the Sierra Maestra between 76°10′ and 77°20′ W.

In the remaining Greater Antilles, particularly Hispañola, Puerto Rico, and the Virgin Islands, volcanic activity during the Late Cretaceous and Tertiary was far more important than it was in Cuba. Possibly the abrupt decrease of volcanism in most of western and central Cuba is in some way related to fault movements in eastern Cuba along the Cauto and Bartlett fault zones, move-

ments which somehow isolated most of Cuba from the orthogeosyncline and fragmented it into various geologic subprovinces and basins (Meyerhoff, 1966).

In the Haitian part of the Hispañola zone, most dated Late Cretaceous rocks (Fig. 18) are Campanian and Maestrichtian. Only one occurrence of Santonian has been reported and, to the writers' knowledge, Coniacian samples have not been found. The apparent absence of late Turonian-Coniacian results partly from the fact that the Cretaceous section is very poorly studied, but also could be indicative of a widespread unconformity between the Lower and Upper Cretaceous. The existence of such an unconformity is known in some areas.

In southern Haiti, Reeside (1947) studied an extensive late Santonian ammonite fauna in float adjacent to the Massif de la Selle. Campanian-Maestrichtian rocks (Macaya Formation) are widespread, and include more than 2000 m of basalt, andesite, dolerite, tuff, massive limestone, marl, and black-to-gray, cherty, and argillaceous limestone. Many of the lavas are pillowed. The entire section is strongly deformed and intruded by dacite and dolerite. Offshore, south of the Massif de la Selle, Fox and his colleagues (October 9, 1968, written commun.) collected a Maestrichtian deep-water fauna on the submarine slope.

Equivalent rocks from central Haiti include folded basalt and andesite flows, massive beds of black limestone, and gray-brown argillite and shale, intruded by dacite.

In northern Haiti, the Trois Rivières Formation also is Campanian-Maestrichtian. The formation consists of more than 500 m of dark shale and argillite, graywacke, radiolarite, limestone (including rudistid banks), and andesite and dacite flows. The sequence is strongly deformed, and is intruded by peridotite, dolerite, and stocks and batholiths of quartz diorite. In the Terre Neuve Mountains of the Northwest Peninsula, Kesler (1968a, 1968b) described a 450-m section of Upper Cretaceous(?). The section consists of terrestrial flows of pyroxene andesite and trachyandesite. Smaller amounts of basalt and dacite are present.

In the Dominican Republic (Fig. 18), H. Palmer (1963) and Bowin (1966) mapped an unspecified thickness of Cenomanian(?)-Maestrichtian volcanic rocks which Bowin called the Tireo Formation. Above are the Campanian (?)-Maestrichtian(?) Las Cañas Limestone and the Don Juan Formation. The Las Cañas is partly equivalent to the Don Juan.

The Tireo consists of coarse- to fine-grained tuff and lapilli tuff, interbedded with quartz keratophyre and andesitic flows. The Don Juan is composed of conglomerate, sandstone, siltstone, and tuff which bear rudistids, Radiolaria, globigerinids, and other microfossils. The Las Cañas is a gray, hard, dense, sublithographic, massive limestone with rudistids and other shallow-water forms.

In the Sierra del Seibo area of the eastern Dominican Republic, Weyl (1966, p. 110–114) reported the presence of fossiliferous Late Cretaceous andesite and dacite flows, tuff, radiolarite, mudstone, and limestone.

In the Puerto Rico part of the Puerto Rico-Virgin Islands zone, the best-developed sequences of marine Upper Cretaceous are in two areas, one in southwestern, western, and southern Puerto Rico, and the other in northeastern Puerto Rico (Berryhill and others, 1960; Berryhill, 1966). Lidiak (1968, p. 45) observed that Late Cretaceous-Eocene volcanic rocks in Puerto Rico are predominantly pyroclastic, in contrast to the Early Cretaceous volcanic rocks. In addition, the Late Cretaceous-Eocene volcanics are more silicic (andesite, dacite, rhyodacite), and the andesites commonly bear hornblende.

Berryhill's (1966) reconstruction of Puerto Rico during Late Cretaceous time is shown in Figure 19. A deep basin was in the northeast and a shallower "shelf basin" on the southeast. The two "basins" were separated by a west-northwest-trending volcanic source area. Berryhill (1966, p. 37) noted that the volcanic source area is underlain by ". . . a thick sequence of lava, pillow lava, volcanic breccia, submarine tuff, and ash-flow deposits." This source area includes thick sections of Late Cretaceous age (Berryhill and others, 1960, Figs. 6, 8, 10, and 12; Berryhill, 1966, p. 37). Early and middle Cretaceous rocks in this region (Albian and Cenomanian: Mattson, 1960a, p. 329; Pessagno, 1960b, p. 83; Douglass, 1961, p. 476–477; and others) also could have been sources of Late Cretaceous deposits.

The Late Cretaceous section of western, southwestern, and southern Puerto Rico is thinner than that of northeastern Puerto Rico (Berryhill and others, 1960; Berryhill, 1966; Mattson, 1966a). Turonian strata appear to be absent (Berryhill, 1966, p. 37) and several unconformities are known to be present. The section ranges in thickness from about 250 m to more than 5170 m (Mattson, 1960a, 1960b, 1966a; Pessagno, 1960a, 1962, 1966). The succession is characterized by marked lateral facies changes. Pre-Maestrichtian rocks have little or no quartz (H. A. Meyerhoff, 1933; Mattson and Glover, 1960). Although shallow-water sediments are more abundant here than in northeastern Puerto Rico, they are particularly abundant in the upper part of the section, and in some areas evidently are littoral and nearshore deposits (reefs

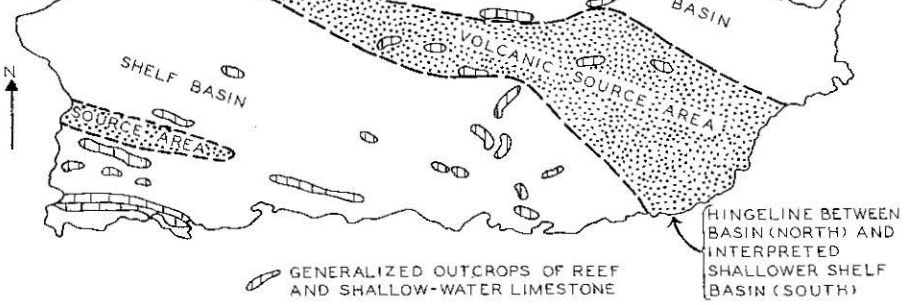

Figure 19. Generalized interpretative map showing possible major tectonic features of Puerto Rico during Late Cretaceous time (*from* Berryhill, 1966, Fig. 5, p. 40, published with permission).

grew in parts of the "basin"). Some of the latest Cretaceous sediments (for example, Cariblanco Formation and Río Yauco Mudstone) may have been deposited in great water depths. Submarine slumps, faunal content (90 to 100 percent plankton), and local preponderance of Radiolaria suggest—but do not prove—local water depths as great as 2800 m, according to Pessagno (1960a, 1962, 1963b, 1966). However, Pessagno (1963b, 1966) emphasized the uncertainty of using Radiolaria for paleoenvironmental reconstructions.

The southwestern Puerto Rico section consists of conglomerate, mudstone, chert, volcanic rocks (including tuff and tuff breccia), calcarenite, and calcilutite; upward the section includes submarine andesite and basalt flows, tuff, graywacke, siltstone, calcareous mudstone, marl, and local accumulations (as much as 600 m) of limestone (Parguera Limestone).

In northeastern Puerto Rico (Berryhill's [1966] northeastern basin), the hiatus between Lower and Upper Cretaceous seems to involve a shorter time interval, and rocks from Turonian through Maestrichtian are present. The published thickness range is from 4350 m (central Puerto Rico) to about 8100 m (northeastern and north-central; 1000 to 6700 according to Mattson, 1966a, p. 135; *see also* Kaye, 1959a; Berryhill and others, 1960; Pease and Briggs, 1960; Briggs, 1961; Briggs and Gelabert, 1962; Berryhill, 1965, 1966; Lidiak, 1965; Nelson, 1966a, 1966b, 1966c; U.S. Geol. Survey, 1967a; Pease, 1968).

The section is made up of massive units of pillowed and nonpillowed basalt, spilite, and andesite, basalt tuff, tuff breccia, volcanic conglomerate and breccia, volcanic sandstone, siltstone, silty limestone, lutite, and calcilutite. Dacitic flows, tuff, and breccia appear in the upper part of the section. As in southwestern Puerto Rico, quartz detritus is scarce in rocks older than Tertiary. Depositional conditions were largely deep-water and submarine in the lower part of the section, but became shallow neritic to subaerial upward (Berryhill, 1966). Deposition and extrusion were followed in some areas by much uplift and erosion near the end of Maestrichtian time (Mattson, 1962, 1966b). Some granitic intrusions were emplaced during late Maestrichtian time (Weaver, 1958; U.S. Geol. Survey, 1967a; and others). Locally these were unroofed and transgressed by middle Eocene rocks of the eugeosynclinal sequence (Pessagno, 1961; Mattson, 1966b).

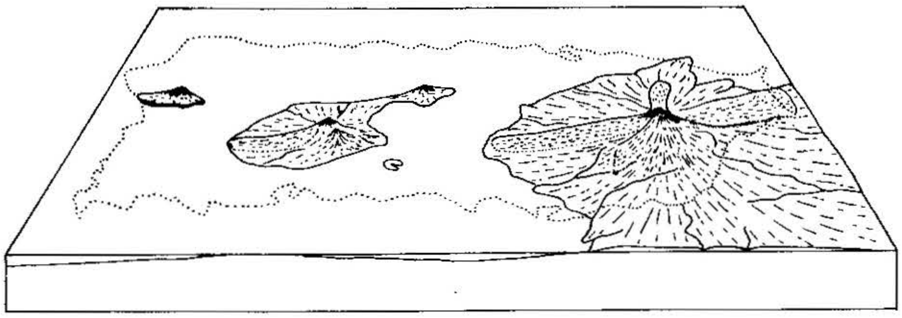

Figure 20. Generalized interpretative map showing Puerto Rico during Late Cretaceous time (*from* H. A. Meyerhoff, 1933, Fig. 6, p. 50) (published with permission).

Berryhill's concept of two basins separated by a volcanic source area seems to the writers to be a misuse of the term "basin." From Berryhill's own evidence, the volcanic and sedimentary rocks northeast and southwest of the volcanic source area are equivalent to the "thick sequence" (Berryhill, 1966, p. 37) in the volcanic source area. Therefore, the writers prefer H. A. Meyerhoff's (1933, p. 44–50) original interpretation of this area (Fig. 20). Meyerhoff regarded the Cretaceous sections of southwestern, central, and northeastern Puerto Rico as having been deposited in a single basin, in the center of which was a WNW.-trending zone of volcanic centers (a "volcanic pile") which were the sources for the Late Cretaceous successions of southern, southwestern, and western Puerto Rico, on one side, and northeastern Puerto Rico, on the other. The writers agree with H. A. Meyerhoff in regarding the WNW.-trending volcanic source area as a volcanic pile largely equivalent to the Late Cretaceous volcanic rocks and marine deposits on both sides. H. A. Meyerhoff showed the volcanic pile to extend essentially the full length of the island and presented evidence to support his conclusions. The observation by several geologists (for example, Nelson, 1969) that the Puerto Rican Cretaceous grades upward from mafic, submarine volcanic rocks to more silicic, subaerial volcanic rocks supports the volcanic pile interpretation. Thus the writers believe that Puerto Rico was a single basin in Late Cretaceous time. Furthermore, this basin was more stable on the southwest where uplift caused shelf conditions to prevail temporarily in some areas, and erosion could produce unconformities in the section.

Presumably a very similar paleogeographic reconstruction would be valid for Early Cretaceous time.

Berryhill (1966, p. 37) also wrote that ". . . it may be suspected that the tremendous volume of clastic volcanic rock now exposed in Puerto Rico did not all come from subaerial sources within the present confines of the island. Neither localized volcanic cones nor uplift of the relatively small belt of pillow lava and volcanic breccia described above could have supplied all of this material." Elsewhere on the same page, Berryhill speculated that a major source area of volcanic materials may have been south of the island. Edgar's (1968) recent study of the submarine cores and seismic data adjacent to both southern and northern Puerto Rico eliminate this possibility. The volcanic centers which produced the volcanic piles of Puerto Rico, the Virgin Islands, and Hispañola, are on those islands and their bordering shelves. Drilling by the *Glomar Challenger* in the deep Caribbean during 1970–1971 confirms the writers' interpretation.

The Late Cretaceous sequence of the Virgin Islands (Fig. 18) is either not exposed or poorly known on St. Thomas and St. John (Donnelly, 1966a). However, Whetten (1966) described the section on St. Croix. Here, an estimated 10,000 m of Santonian(?)-Campanian-Maestrichtian(?) (Mt. Eagle Group) is exposed. The base has not been seen. Most fossils indicate a Campanian age.

The basal strata, Caledonia Formation, consist of 5500 m (est.) of sandstone, mudstone, and tuff; clasts in the Caledonia were derived from older

keratophyre and spilite (Water Island Formation?; Donnelly, 1964, p. 686). The upper section, Judith Fancy Formation, has an estimated thickness of 4500 m. It consists of tuff, tuffaceous sandstone, and some limestone, volcanic pebble conglomerate, siltstone, and mudstone. A few lava flows are present.

H. A. Meyerhoff (May 15, 1968, written commun.) interprets the history of the Virgin Islands in much the same manner as he interpreted (1933) the history of Puerto Rico; that is, the islands are a volcanic pile which grew upward from the deep ocean floor.

Much of the Hans Lollik Formation of the British Virgin Islands (Helsley, 1960), in the writers' opinion, will be found to be of Late Cretaceous age.

Summary of Late Cretaceous Eugeosyncline

Volcanic activity continued in Cuba, but was less extensive during Late Cretaceous time than during the Early Cretaceous. The most intensive volcanism was in Hispañola, Puerto Rico, and the Virgin Islands.

The principal characteristics of the Late Cretaceous eugeosyncline are thick accumulations in many local basins and great diversity of lithologic types—that is, abrupt lateral and vertical facies changes. Such abrupt changes do not characterize the Early Cretaceous sequence. The existence of numerous depositional basins, the lithologic diversity, and the abrupt facies changes show that, tectonically, the region was very unstable, and that constant crustal movements were in progress during deposition.

Blue Mountains Zone

Until recently, only Campanian-Maestrichtian conglomerate, sandstone, shale, limestone, tuff, and tuffite had been recorded from the Blue Mountains (Chubb, 1960; Zans, 1961; Zans and others, 1962) (Figs. 13, 18). A few late Campanian or younger ammonites, Campanian to Maestrichtian rudistids, and some Campanian-Maestrichtian Foraminifera had been collected. The thickness was unknown. Although some of the strata were deposited in shallow water, the over-all fauna indicated deposition in water deeper than that in the Cornwall-Middlesex zone on the west.

More recently, in the northeastern Blue Mountains, two sections of Late Cretaceous rocks were studied by personnel of the Geological Survey Department of Jamaica (1966). One section consists of an estimated 7000 m, from top to base, of (1) gray shale and limestone; (2) massive sandstone and conglomerate with smaller amounts of shale, andesitic and basaltic lava, agglomerate, breccia, tuff, reef limestone, and foraminiferal limestone; and (3) basaltic lava, greenstone, tuffaceous sandstone and shale, and andesite porphyry dikes. Foraminifera collected from a limestone associated with basalt include *Sulcoperculina, Pseudorbitoides, Sulcorbitoides,* and *Pseudolepidina.* On the basis of these foraminifers, E. Robinson (*in* Geol. Survey Dept. of Jamaica, 1966, p. 12) assigned a Turonian through Maestrichtian age range to the

sequence. The second section, estimated to be 3600 m thick, is just south of the first section. It includes, from top to base, (1) gray conglomerate, sandstone, and mudstone; (2) purplish conglomerate, coarse-grained sandstone, and reef limestone; (3) interbedded basaltic lava and tuff, with sandstone; and (4) gray conglomerate, sandstone, limestone, and shale. Mollusks, including rudistids, suggest a Turonian to early Campanian age (Geol. Survey Dept. of Jamaica, 1966, p. 12), and massive limestones higher in the section contain corals, pelecypods, and Foraminifera which suggest an early Campanian to Maestrichtian age (E. Robinson, *in* Geol. Survey Dept. of Jamaica, 1966, p. 12). The entire Cretaceous section is intruded by granodioritic and related rocks which yielded a radiometric age of about 65 m.y. (Chubb and Burke, 1963; *see also* Fig. 7 and Table 4, this paper).

If the thickness estimates (3600 and 7000 m) given by the Geological Survey Department of Jamaica (1966) are correct, the strongly subsiding character of the Blue Mountains zone is well established.

Cornwall-Middlesex Zone

At least 3000 m of late Coniacian through Maestrichtian strata is present (Figs. 13, 18). Chubb (*in* Zans and others, 1962) divided the section into 12 "cycles" of conglomerate, water-deposited tuff, tuff, tuffaceous shale, shale, and limestone. The entire section was deposited in shallow water. In places, the sequence consists wholly of claystone, mudstone, siliceous mudstone, laminated chert, and conglomerate which grade laterally within a few kilometers into sections composed predominantly of andesitic tuff cut by andesite dikes (Geol. Survey Dept. of Jamaica, 1964). Evidently several volcanic centers were located in or adjacent to this zone. Most of the Late Cretaceous rocks are volcaniclastic.

The greater part of the Cornwall-Middlesex zone was above sea level during pre-Campanian time, although a few areas received older sediments. For example, in the St. Ann Inlier (Fig. 7), pre-Campanian, ammonite-bearing shale and related sediments ("*Inoceramus* beds" of the literature) were deposited, but sedimentary rocks as old as those of the St. Ann Inler have not been found in most areas of Jamaica. The strata of the Inlier long have been assigned a late Turonian through Coniacian age (Zans and others, 1962). More recently, Kauffman (1966) and Esker (1968, 1969) proved that the "*Inoceramus* beds" range in age from late Coniacian through Santonian. These strata are overlain by Campanian through Maestrichtian conglomerate, shale, and limestone. The uppermost beds, long believed to be no younger than Campanian, were found by Esker (1968, 1969) to contain an early to middle Eocene fauna.

Elsewhere, in the St. James and Central Inliers, more than 1330 to 2400 m of Campanian through Maestrichtian conglomerate, shale, tuff, and limestone is exposed. Coates (1969) described the Central Inlier section as a sequence of more than 2400 m of volcaniclastic sandstone, fine-grained conglomerate, coarse-grained volcanic conglomerate, and coarse volcanic breccia. Some

andesitic and trachytic flows are in the lower 2000 m. Minor shale and some rudistid-bearing limestone are in the upper 400 to 500 m.

A total of 2061 m (not corrected for possible dip) of Campanian through Maestrichtian was penetrated in the Jamaica Stanolind West Negril well (Fig. 7), and 1650 m (not corrected for possible dip) was found in the Santa Cruz well (Fig. 7; *see* Greiner, 1965). The West Negril section includes andesitic conglomerate, grit, tuffaceous shale, and porous limestone and dolomite (A. A. Meyerhoff and Spangler, 1958; Zans, 1960; Greiner, 1965).

Beata Zone

The possible age of the Beata Ridge was discussed in the section on "Early Cretaceous Stratigraphy."

CRETACEOUS (OR OLDER) FAULT ZONES OF GREATER ANTILLES

Age estimates of most major fault zones and fault troughs in the Greater Antilles have been controversial since their discoveries. Although positive proof is lacking, at least four fault zones apparently are Cretaceous or older: the Bartlett Trough, the parallel Cauto fault zone, the Anegada fault zone (Figs. 2, 6, 7, 13, 29), and the west-northwest-east-southeast–trending major fault zones of Puerto Rico (Fig. 7). Some similarly trending fault zones of Hispañola (Fig. 29) and central Cuba (Fig. 6) probably also are Cretaceous. Examples are the Cibao graben in Hispañola and the Tuinicú and Jatibonico faults in central Cuba. Other major fault zones in Jamaica, the Puerto Rico Trench, and in the Mona Passage (Figs. 2, 7) may be as old as Cretaceous.

The effects of the major fault zones on the geologic history and paleogeography of the Greater Antilles became increasingly important through geological time. Although Tertiary and Quaternary orogenic events have obscured pre-Tertiary effects of fault-zone development, there are areas where older events can be observed or inferred. In this section, only those major fault zones which are almost certainly Cretaceous or older are discussed. The other fault zones are reviewed in a subsequent section.

Bartlett Trough

Various ages and origins have been ascribed to this fault zone which extends at least 1600 km from central Guatemala to the Windward Passage between Cuba and Hispañola. Age estimates range from Paleozoic to Quaternary, and the proposed origins include block faulting with tensional or extensional stresses, compression accompanied by downbuckling, and compression or shear, accompanied by strike-slip movements. More recently, this fault zone has been considered to be a transform fault (*see* Wilson, 1966; Edgar, 1968, for summary; *also* Glover, 1968). A review of the literature was published by A. A. Meyerhoff (1966). Except for Suess (1909, p. 524–525), Woodring (1928, p. 413–415), and A. A. Meyerhoff (1966), most age esti-

mates have ranged from latest Cretaceous or early Tertiary to Quaternary (Vaughan, 1918; Taber, 1922, 1934; H. A. Meyerhoff, 1933; Hess, 1933, 1938; Schuchert, 1935; Bucher, 1947; Hess and Maxwell, 1953; Eardley, 1954; Woodring, 1954; G. Lewis and Straczek, 1955; Butterlin, 1956; Hersey and Rutstein, 1958; J. Ewing and others, 1960; Bowin, 1968; and numerous others). Hess and Maxwell (1953) proposed that 1100 km of left-lateral displacement has taken place along the fault zone, but this is not possible because (1) the trough terminates at both the eastern and western ends, and (2) offsets of Early Cretaceous strata and lithofacies across the fault zone are negligible (A. A. Meyerhoff, 1966; Dengo, 1968). These same facts eliminate Wilson's (1966) suggestion that the Bartlett Trough is part of a transform fault extending to the Puerto Rico Trench. Vertical movements have been predominant in the trough, although some strike-slip movements are indicated by the relatively straight traces of individual faults.

The Bartlett Trough parallels the north side of the Nicaragua Rise, which has been interpreted to be the eastern continuation of the Northern Central America orogen (Suess, 1909; A. A. Meyerhoff, 1966, 1967). Because of the parallelism, Suess interpreted the Bartlett to be a Paleozoic oceanic foredeep (trench) similar to those which front the Pacific island arcs today. A. A. Meyerhoff (1966), on the basis of field mapping in Guatemala and British Honduras, interpreted the Bartlett to have formed no later than middle Cretaceous time along pre-existing Paleozoic tectonic lines of weakness. The reasoning for this interpretation was summarized in the section on "Nicaragua Rise-Bartlett Trough-Cayman Ridge." The existence of a pre-Pennsylvanian-age Bartlett Trough in Guatemala has been demonstrated by Anderson (1969) and Bonis (1969). Donnelly and others' (1969) field work showed the Bartlett Trough in Guatemala to have been active during Albian to Maestrichtian time.

The *present* form of the Bartlett Trough very probably is a late Cenozoic development. However, *present* form and time of origin are two different concepts, as is demonstrated clearly in the area of the East African rift system. Parts of that rift system were in existence by Mississippian (or Devonian) time in Egypt and by Permian or Triassic time south of Kenya, but the *present* form was acquired mainly during late Cenozoic time. This has been proved by detailed field studies and drilling in many parts of the East African rift system.

Evidence for the age of the Bartlett Trough is derived from the orthogeosynclinal rocks themselves. The Early Cretaceous sequence on either side of the Bartlett Trough—from Cuba to Haiti and the Dominican Republic—is very similar. In contrast, marked lithofacies and biologic differences characterize the Late Cretaceous sequences on either side of the trough. By late Turonian time, separate basins had begun to develop on the two sides of the trough and a thick late Turonian and younger sequence appears to be present in southern Oriente Province, Cuba, along the north side of the Bartlett Trough. By Campanian or Maestrichtian time, if not earlier, the "older Cauto basin" (Fig. 29) had formed along the southern coasts of Oriente and Camagü-

ey Provinces (*see* M. T. Kozary's maps, *in* Bowin, 1968, Fig. 5). Great thicknesses of volcanic and volcanic-derived rocks accumulated in a basin parallel to and adjoining the Bartlett Trough in southernmost Cuba from at least Campanian through middle Eocene time. This fault zone bounds one of the most active subsiding basins in the Greater Antilles today.

Cauto Fault Zone

This fault zone parallels the Bartlett Trough, is of approximately the same length, and extends from British Honduras, along the north side of the Cayman Ridge, to the Nipe basin in northeastern Oriente Province, Cuba (Figs. 6, 29). The minimum age of the fault zone is not difficult to establish.

Except for a part of the offshore area of southern Camagüey Province and a very few local areas elsewhere in Cuba, the fault zone is the northern limit of Late Cretaceous (late Turonian-Maestrichtian) and early Tertiary (Paleocene-Eocene) volcanism in Cuba. Several thousand meters of volcanic and volcanic-derived rocks of the "older Cauto basin" (Fig. 29) are concentrated in the zone south of the Cauto fault zone (*see* M. T. Kozary maps, *in* Bowin, 1968, Fig. 5). Moreover, the tectonic style of the Cretaceous-middle Eocene strata, and the degree of serpentinite deformation, are completely different on the two sides of the Cauto fault zone. Therefore, the fault zone was in existence at least by the "Laramide" orogeny which began during Campanian to Maestrichtian times. The Cauto fault zone appears to be inactive today.

Anegada Trough

Donnelly (1964, 1966a) and Whetten (1966) have noted the absence of pre-Late Cretaceous volcanic rocks on St. Croix, south of the Anegada Trough. North of the trough, Early Cretaceous rocks are exposed widely. Donnelly and Whetten have provided evidence that the Late Cretaceous sequence of St. Croix was derived from the Albian and associated rocks of St. John and St. Thomas. Thus, the existence of a fault zone, or hinge zone, in the vicinity of the Anegada Trough, seems to be established. This conclusion may be modified as more faunal control is acquired.

West-Northwest-East-Southeast–Trending Faults of Puerto Rico

These faults of Puerto Rico generally flank both sides of the volcanic pile of H. A. Meyerhoff (1933) (Fig. 20); the northernmost of these faults underlies the "volcanic source area" of Berryhill (1966) (Fig. 19). These facts suggest that the mapped fault zones are related to or coincident with faults that were active from middle Cretaceous to middle Eocene time. More recently, Glover (1968) found fossil fault-line scarps of middle Cretaceous age associated with this system.

Other Fault Zones of Probable Cretaceous Age

In Cuba the Jatibonico fault zone (Fig. 6) probably is of middle Cretaceous

or Late Cretaceous to middle Eocene age. The Jatibonico fault separates rock types of different ages and facies (Hatten and others, 1958; Furrazola-Bermúdez and others, 1964, 1965; A. A. Meyerhoff and Hatten, 1968)—specifically, the Las Villas facies-structural zone from the Remedios facies-structural zone (that is, the deep-water Cretaceous from the shallow-water bank facies). The zone between the two facies evidently was a pre-Tithonian, possibly a pre-Jurassic, zone of weakness but the existence of a fault along this zone before the "Laramide" orogeny cannot be proved conclusively. Nevertheless, the general absence of post-early Turonian deep-water deposits in the Las Villas facies-structural zone on the south, and the local presence of up to 450 m of Turonian-Santonian and the widespread occurrence of at least 2150 m of Campanian-Maestrichtian bank carbonates north of the Jatibonico fault, strongly support a middle Cretaceous date for the fault.

In Jamaica, the Wagwater belt—a fault-bounded depression along the western margin of the Blue Mountains zone—separates the Blue Mountains from the Cornwall-Middlesex zone. The existence of shallow-water Early and Late Cretaceous deposits on the west, and of very thick, deeper water, equivalent deposits in the east and northeast, demonstrates that a hinge zone existed beneath the Wagwater belt during Cretaceous time. Chubb's (1960) study of rudistid distribution corroborates this conclusion. Nevertheless, the boundary faults of the Wagwater belt cannot be proved to be older than early Eocene. This fault-bounded graben is active tectonically today.

In Hispañola, the ages of the Enriquillo graben, San Juan-Azua basin, and Cibao graben cannot be demonstrated to be older than Paleocene or early Eocene, but the fault zones may be as old as Cretaceous.

The Puerto Rico Trench may be as old as Cretaceous. This conclusion is based only on the presence of Cenomanian (late Early Cretaceous of this paper) Foraminifera in samples recovered from the north wall of the trench (Todd and Low, 1964). However, Van Voorhis and Davis (1964) and Griscom and Geddes (1966) reported west-northwest-east-southeast-striking magnetic highs and lows crossing parts of the trench. These magnetic trends parallel the trends of the Cretaceous-middle Eocene structures in Puerto Rico and, therefore, substantiate Monroe's (1968) conclusion that the age of the trench is post-middle Eocene. West-northwest-east-southeast-trending topographic features were found in the trench by M. Ewing and Heezen (1955), and seismicity alignments with the same west-northwest trends were reported by Sykes and Ewing (1965).

RECAPITULATION OF LATE JURASSIC-LATE CRETACEOUS GEOLOGIC HISTORY

Late Jurassic History

Marine tongues in the upper(?) part of the San Cayetano (Figs. 21, 22, 24) presaged a general marine transgression across Cuba during Callovian and Oxfordian times. During the transgression, the Jagua Formation (R. Palmer,

1945; Azúcar and Jagua Formations of Hatten, 1957) was deposited. There may be a disconformity beneath the Jagua. Conglomeratic sandstone beds in the middle Jagua (Judoley and Furrazola-Bermúdez, 1965) suggest that local earth movements occurred.

Khudoley believes that, after Jagua deposition, the San Cayetano-Jagua terrane was uplifted, folded, and exposed to erosion; this, according to Khudoley, was the "Nevadan" orogeny. Subsequently, the sea transgressed the erosion surface cut into the Jagua and San Cayetano, and deposited the Viñales, Artemisa, and equivalent units elsewhere in Cuba (Fig. 16).

Khudoley is not certain whether one, two, or more pulses constituted the "Nevadan" orogeny, or whether the orogenic activity extended east of Cuba. Khudoley also believes that the orogeny was accompanied by mild metamorphism of the San Cayetano and by the intrusion of small bodies of ultramafic, mafic, and granitic rocks.

Meyerhoff believes that the Jagua-Viñales contact is transitional. He believes that many of the abrupt contacts observed in the field are thrust-fault contacts of the "Laramide" orogeny (Hatten, 1957). According to Meyerhoff, the sea covered the source area for the terrigenous clastics of the San Cayetano and Jagua Formations (probably north of Cuba). As a result, the Viñales Limestone began to form in the Sierra de los Órganos area and the Artemisa Formation in the Sierra del Rosario (Fig. 16). Later during Tithonian time, the "Nevadan" orogeny manifested itself in Cuba south of the median welt (Fig. 13) by the formation of a eugeosyncline. Some volcanic materials reached northern Pinar del Río and the part of northern Cuba north of the median welt. These are now the tuffaceous shale partings and insoluble residues of the Artemisa Formation and the equivalent Tithonian limestone of northern Cuba.

The small ultramafic to granitic intrusions in the metamorphic rocks of south Cuba, in Meyerhoff's opinion, are late Paleozoic intrusives into the Trinidad Formation-San Juan Marble complex of the Sierra de Trinidad and their equivalent units on the Isle of Pines. Some intrusions of ultramafic rocks probably accompanied the formation of the eugeosyncline, but such intrusions are believed to comprise parts of the Mesozoic serpentinite belts north of the Sierra de Trinidad and Isle of Pines.

Late Jurassic Paleogeography

According to Khudoley (Fig. 21), continental landmasses occupied the Caribbean and a seaway covered the site of the Greater Antilles. Two parallel basins developed—at least in Cuba—separated by an island chain on the site of the median welt. North of the welt, bank and shoal limestone, dolomite, and anhydrite accumulated. In the southern basin, limestone is the principal sedimentary rock, but some terrigenous clastics entered the area from the landmass on the south.

According to Meyerhoff (Fig. 22), the present Caribbean and Gulf of Mexico were ocean basins during Late Jurassic time. The median welt, ele-

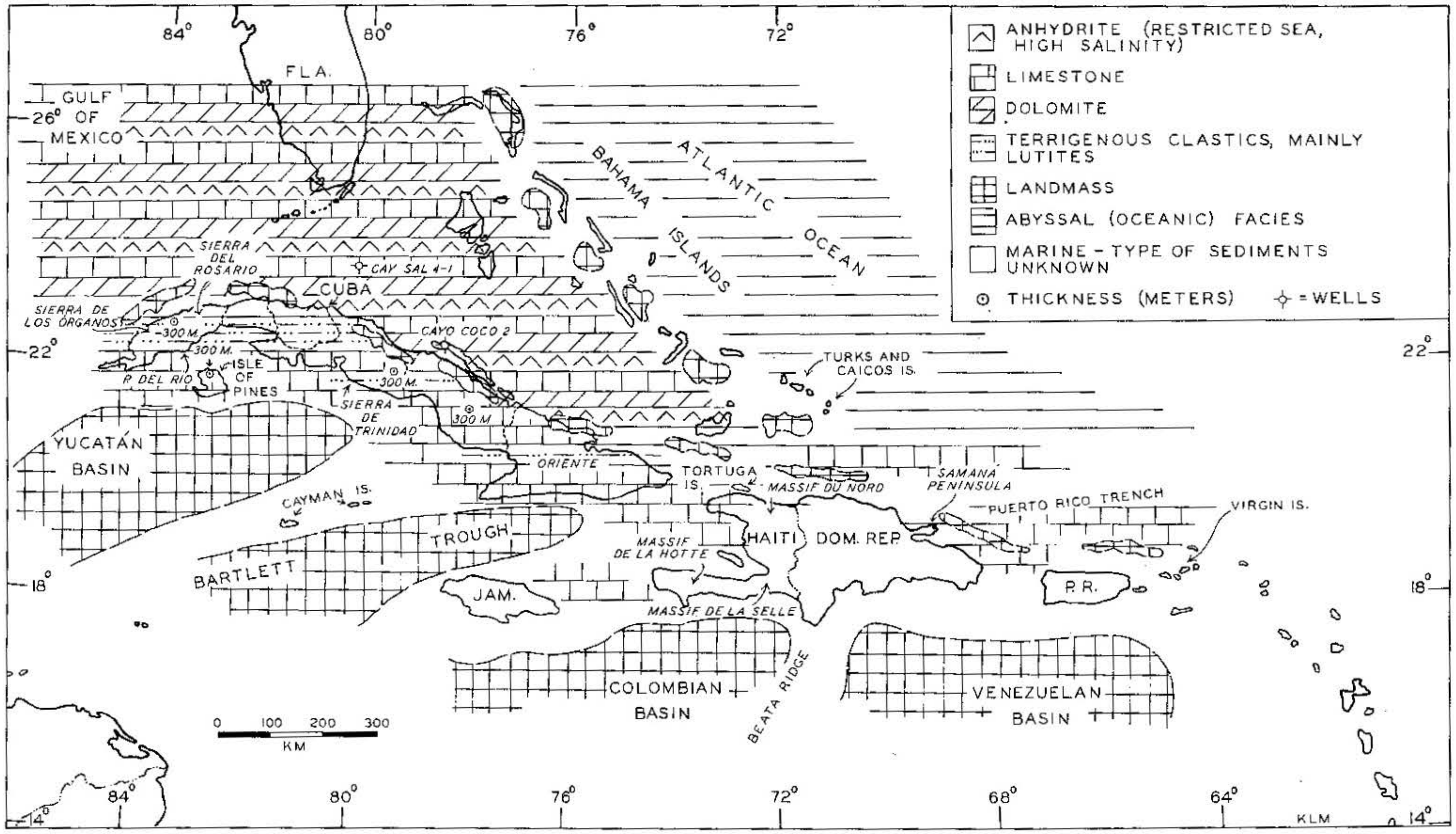

Figure 21. Paleogeography of Greater Antilles during Late Jurassic, according to Khudoley.

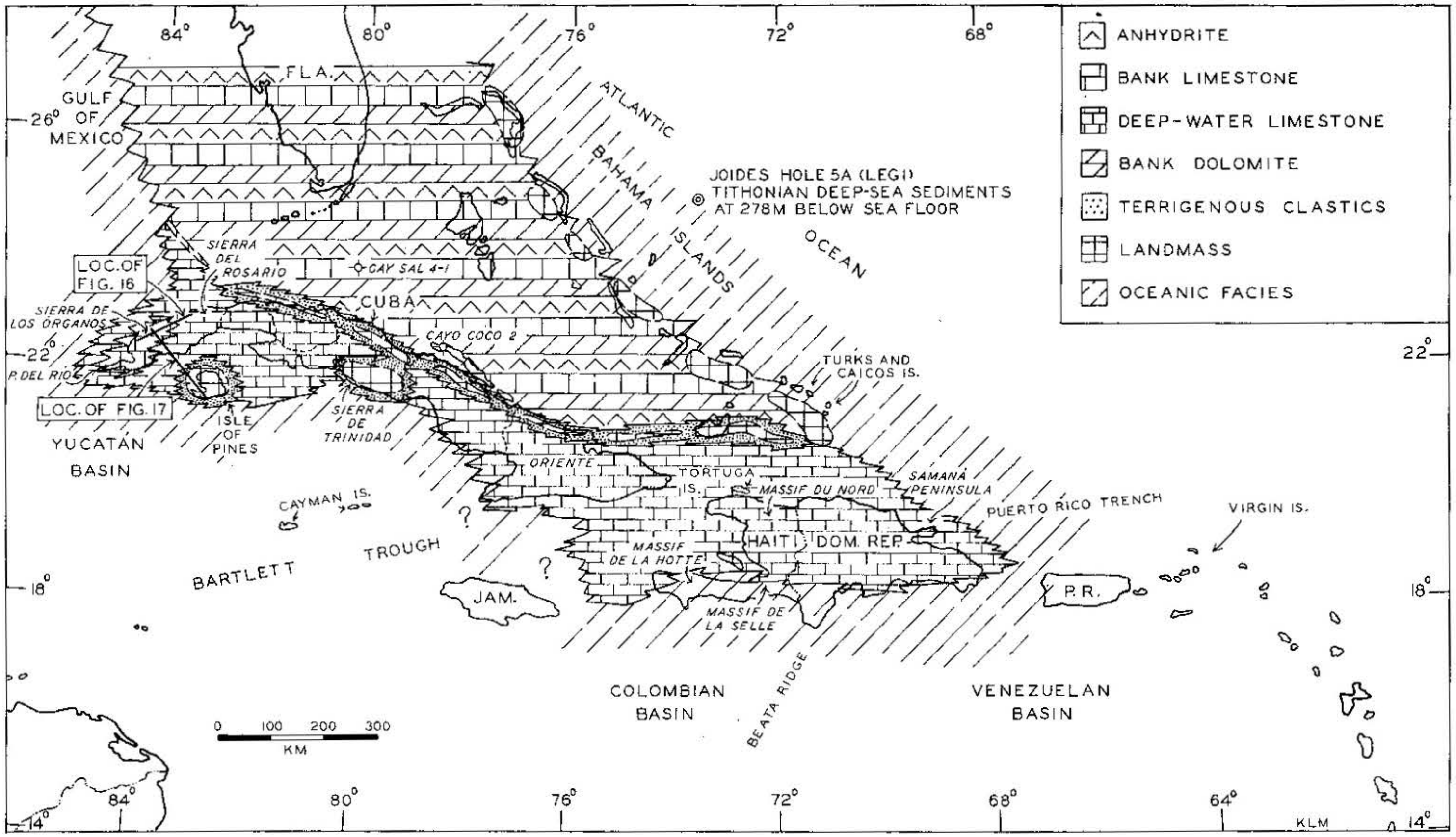

Figure 22. Paleogeography of Greater Antilles during late Callovian and Kimeridgian times (latest Middle Jurassic through middle Late Jurassic), according to Meyerhoff. Locations of Figures 16 and 17 are shown.

vated by stresses preceding the "Nevadan" orogeny, formed in north Cuba. The influx of clastic materials from the Florida area gradually ceased as marine waters began to transgress southern Florida from the Atlantic and the Gulf of Mexico. By Tithonian time, a narrow seaway separated Cuba from Florida. The sea was silled, possibly by reefs or limestone islands. This permitted anhydrite deposition north of the median welt in Cuba. Very saline conditions existed even during deposition of limestone, as is shown by the abundance of miliolids in the carbonates.

South of the median welt and in Pinar del Río Province (Sierra de los Órganos), the Jagua (Azúcar and Jagua of Hatten) was deposited. The overlying Viñales formed in the Sierra de los Órganos, Pinar del Río Province. Elsewhere in Pinar del Río, and in central Cuba south of the median welt, a deep-water Artemisa facies, whose lower part may be equivalent to the upper Viñales, was deposited. (This latter conclusion is based on the fact that the probable Artemisa equivalent north of the Sierra de Trinidad, Las Villas Province, is a black, thin- to medium-bedded, recrystallized limestone resembling Artemisa, not Viñales.) From late Oxfordian time on, the almost total absence of strata derived from continental-type basement rocks is strong evidence against the presence of a landmass in the Caribbean (H. A. Meyerhoff, 1954, p. 149). The oceanographic data reported by Edgar (1968) and by the *Glomar Challenger* scientists during 1970–1971 support this conclusion.

In Tithonian time, deep faults (a Benioff zone) formed along the southern edge of Cuba. Ultramafic and mafic intrusions and eruptions of eugeosynclinal type began. Thus the Greater Antilles arc, or orthogeosyncline, formed from western Cuba to the eastern Virgin Islands.

Khudoley notes that the existence of Jurassic in Greater Antillean islands other than Cuba is unproved. Therefore he does not believe that an orthogeosyncline formed before Early Cretaceous time. Khudoley suggests that the lack of dated Late Jurassic rocks in the other Greater Antillean islands may be the result of orogenic activity and subsequent erosion which removed deposits of this age.

Ammonites and Late Jurassic Paleogeography

Oxfordian ammonites include the genus *Perisphinctes* (subgenera *Arisphinctes, Dichotomosphinctes, Discosphinctes*). These subgenera are well known in the Oxfordian of Mexico, the United States, and England. Another genus, *Euaspidoceras*, is closely related to the English genus *Decipia*. However, certain Cuban genera are unknown outside of Cuba (for example, *Vinalesphinctes, Cubasphinctes*, and *Cubaochetoceras*). Open-marine seaways evidently connected England, the United States, Cuba, and Mexico. Oxfordian ammonites from Portugal, in contrast, are very different from those in Cuba.

The study of Cuban ammonite data indicates that Cuba was far removed from Europe during Oxfordian time, and constitutes strong evidence against the existence of "Pangea" or of continental drift during this part of the Mesozoic. The presence of bathyal Tithonian sediments in the deep Atlantic east of the Bahamas supports this conclusion.

Tithonian ammonites include the genera *Subplanites*, *Haploceras*, *Pseudolissoceras*, *Virgatosphinctes*, *Aulacosphinctes*, and *Berriasella* which are widespread in the world. From this it is evident that Cuba was connected freely with all ocean basins during the Tithonian. Some genera, such as *Parodontoceras*, *Corongoceras*, and *Primoryites* (further reference to *Primoryites* is in Khudoley, 1959), are common around the Pacific Ocean borders. Others including *Dickersonia* and *Pseudoanahamulina* are unknown outside of Cuba.

Most of the Late Jurassic faunas collected in Cuba suggest warm, shallow-water conditions.

Early Cretaceous History

The two depressions that existed in Tithonian time became more pronounced (Figs. 23, 24). North of the median welt, shallow-water limestone which characterized the Tithonian grades upward, adjacent to the welt, into deep-water pelagic limestone. A bank and evaporite facies (southern edge of Remedios facies-structural zone) began to accumulate just north of the pelagic facies.

South of the median welt in Cuba and eastward to the Virgin Islands, volcanogenic rocks accumulated.

The importance of the median welt as a barrier between the volcanic and deep-water and bank carbonate facies cannot be overemphasized. The existence of a thin Cretaceous section on the welt itself, and the fact that it is only on the welt where a very few volcanic flows and tuffs are interbedded with the carbonates, prove the effectiveness of this elevation as a barrier.

Early Cretaceous Paleogeography

According to Khudoley (Fig. 23), the Caribbean landmass, possibly reduced in size, occupied parts of the area south of the Greater Antilles. A marine seaway covered most of the Greater Antilles; very few islands existed in this seaway, as shown by the close similarity of volcanic and plutonic facies from western Cuba to the Virgin Islands. Facies changes along strike are not major. Therefore, Meyerhoff agrees with Khudoley regarding the scarcity of islands or other barriers.

Meyerhoff differs (Fig. 24) in that he believes that the area of the present Caribbean Sea was an ocean basin, and that the Greater Antilles "seaway" was a submarine volcanic chain on the north side of the present Caribbean Sea. It is almost certain that most of the Lower Cretaceous rocks formed subaqueously, as shown by the general absence of reworked sediments, the slight facies changes in most areas, the abundance of pillow lava, and the predominance of a radiolarian fauna. Only in the upper part of the Lower Cretaceous sequence did shallow-water conditions develop locally, with attendant facies changes, reworked deposits, rudistid reefs, and related phenomena.

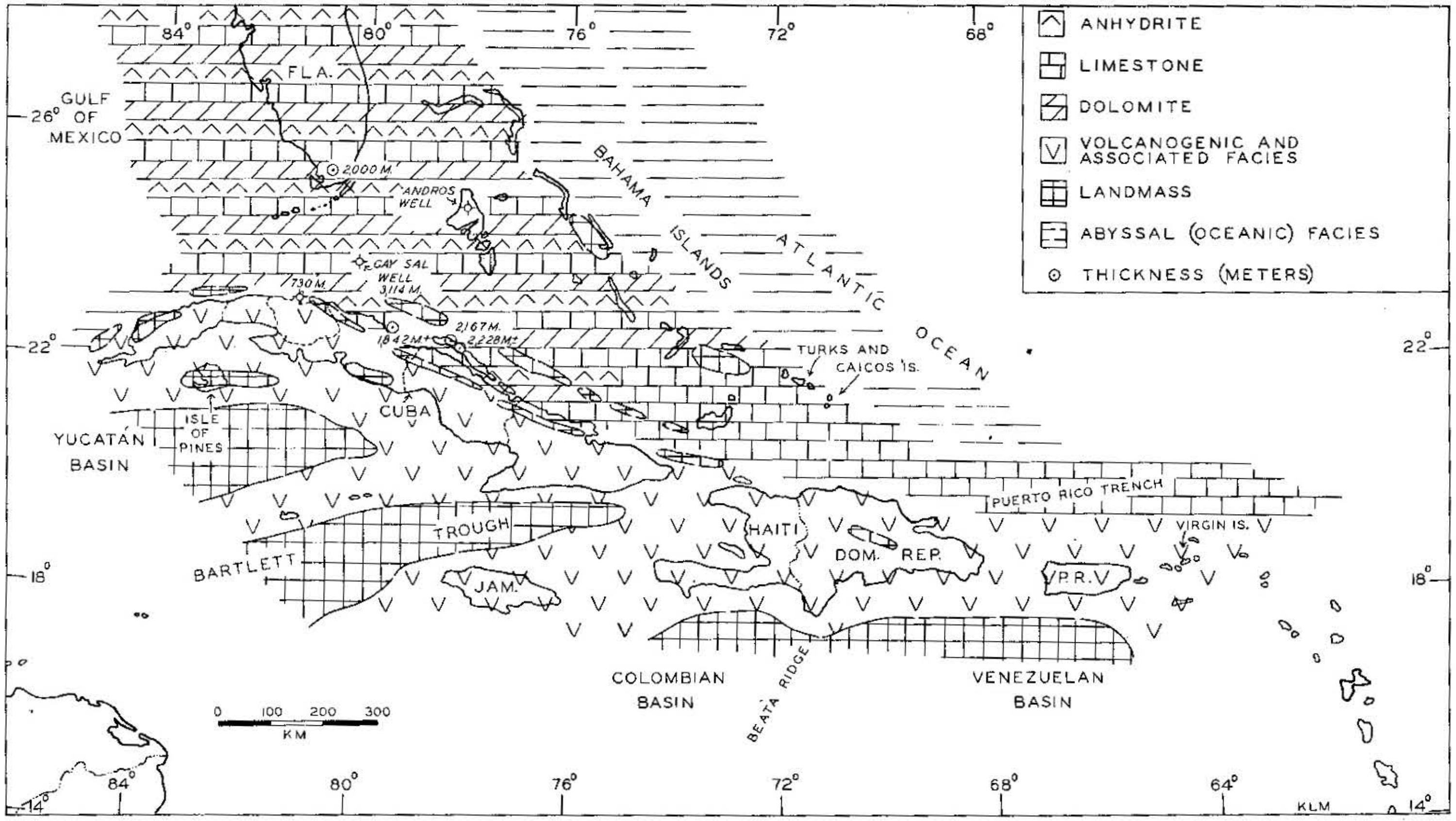

Figure 23. Paleogeography of Greater Antilles during Early Cretaceous time, according to Khudoley. Compiled from many sources. Carbonates south to Hispañola are based on Fox and others (1968).

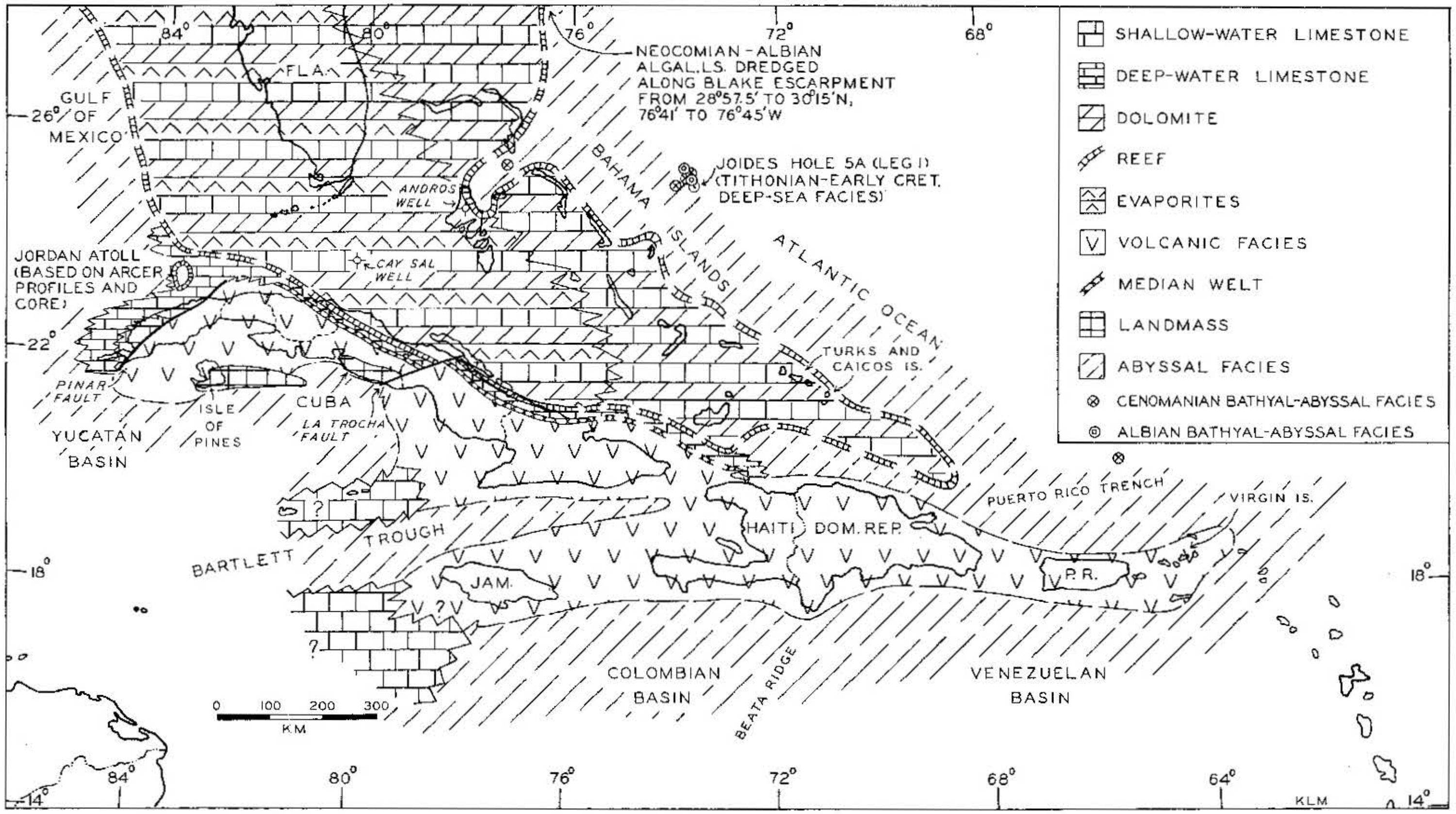

Figure 24. Paleogeography of Greater Antilles during Tithonian through early Turonian (latest Jurassic-early Late Cretaceous) time, according to Meyerhoff. Compiled from many sources. Deep-sea data from Todd and Low (1964), Saito and others (1966), Habib (1968c, 1969), Bryant and others (1969), Burk and others (1969), and Drake (1969).

The barrier role of the median welt in Cuba continued. North of the median welt, a deep-water seaway separated the welt from the banks and platform on the north. On the banks, very saline conditions generally were like those which prevailed during the Tithonian. From time to time, open-marine conditions returned and limestone with normal-salinity faunas was deposited.

At the eastern end of the orthogeosyncline, deep-water Cenomanian sediments have been dredged from the north side of the Puerto Rico Trench.

Early Cretaceous Faunas

Ammonites have been reported from Cuba and the other islands, but only a few have been studied (for summary, *see* Chubb, 1960). The specimens are from the volcanic facies in Cuba and Hispañola, and from the deep-water limestones of north Cuba.

Specimens listed by MacGillavry (1937; p. 8) from the deep-water "Neocomian" limestone of northern Las Villas include *"Toxoceras"* sp., *Crioceras pulcherrimus*, *Crioceras* sp., *Neocomites* cf. *N. neocomiensis*, and *Oppelia* cf. *O. nisoides*. Imlay (1942) subsequently showed these identifications to be in error, and identified the faunas as Portlandian (Fig. 9). Khudoley believes that *"Toxoceras"* sp., *Crioceras* sp., and *Crioceras pulcherrimus* are species of *Protancyloceras;* that *Neocomites* cf. *N. neocomiensis* is *Berriasella* sp.; and that *Oppelia* cf. *O. nisoides* is either *Haploceras* sp. or *Pseudolissoceras* sp. Khudoley's identifications thus lead to the same conclusions made in 1942 by Imlay.

Specimens collected by N. R. Giedt along the Cuban north coast of Camagüey Province in deep-water limestone of the Cayo Coco facies-structural zone include *Melchiorites* cf. *M. emerici* and *Pseudohaploceras* sp. These were identified by R. W. Imlay in 1958 (unpub. rept.) and were considered by him to be of Aptian age.

N. F. Sohl (*in* Pease, 1968, p. 14) reported an Albian ammonite from the Robles Formation of central Puerto Rico.

The following genera and species are typical of the pelagic microfauna found in the Neocomian(?)-Albian deep-water limestones of Viñales type in the Sierra de los Órganos, northern Pinar del Río Province: (1) Neocomian(?): *Tintinnopsella carpathica*, *T. oblonga*, *Nannoconus steinmanni*, *N. kamptneri*, *N. colomi*, *N. bermúdezi*, *N. globulus*, and *Favelloides balearica;* and (2) Aptian-Albian: *Nannoconus truitti*, *N. elongatus*, *N. bucheri*, *N. wassalli*, *Globigerina* cf. *G. cretacea*, *Globigerinelloides algeriana*, and *Ticinella roberti*. (Judoley and Furrazola [1965] have pointed out that some of the Neocomian forms range through the early-middle Tithonian.)

Within the deep-water facies of north Cuba (Las Villas and Cayo Coco facies-structural zones), the following genera and species are known: (1) Neocomian(?): *Tintinnopsella oblonga*, *T. elliptica*, *T. carpathica*, *Calpionellites darderi*, *Nannoconus steinmanni*, *N. globulus*, *N. colomi*, *N. kamptneri*, *N. bermúdezi*, Radiolaria, and poorly preserved ammonites; (2) Aptian: *Nannoconus wassalli*, *N. bucheri*, *N. elongatus*, *N. minutus*, *N. truitti*, *Colomiella mexicana*, *C. recta*, and *Globigerina washitensis;* (3) Albian: *Nanno-*

conus spp., *Colomiella* spp., *Hedbergella cretacea* group, "*Globigerina*" *cretacea* group, *Ticinella roberti*, *Globigerinelloides* sp., *Praeglobotruncana delrioensis*, *Gümbelina* sp., and *Planomalina buxtorfi*; and (4) Cenomanian: *Gümbelina* sp., *Thalmanninella* sp., *Praeglobotruncana delrioensis*, *Planomalina buxtorfi*, *Rotalipora appenninica*, *Schackoina* sp., *Pithonella ovalis*, *Ticinella roberti*, *Globigerinella* sp., and *Globotruncana* cf. *Gl. alpina*.

Some of the Aptian-Albian-Cenomanian forms are found in deep-water limestone tongues of the eugeosyncline, together with Radiolaria.

The bank carbonates of the Cayo Coco and Remedios facies-structural zones, and rudistid reefs or banks within the eugeosyncline, from Cuba to Puerto Rico, contain the following Aptian, Albian, and Cenomanian fossils, in addition to rudistids, caprinids, pelecypods, gastropods, and arenaceous and calcareous Foraminifera (including very abundant miliolids): *Orbitolina concava*, *O. oculata*, *O. minuta*, *Dictyoconus walnutensis*, *D. floridanus*, *Bolivinopsis* sp., *Choffatella* sp., *Cuneolina* spp., *Nummoloculina heimi*, and *Coskinolinoides texanus*. *Favreina joukowskyi* and certain species of *Nautiloculina* may indicate either Tithonian or Neocomian ages.

Many genera and species of rudistids and caprinids have been used to date rocks in Haiti, Puerto Rico, Cuba, and Jamaica, although with limited success. Among these are *Monopleura*, a primitive form, *Pachytraga*, *Toucasia* (?), and *Caprinuloidea* cf. *C. perfecta*. More recently, Norman F. Sohl (May 20, 1968, written commun.) has studied gastropod faunas from the Benbow Inlier of Jamaica (Fig. 7) for A. G. Coates, University of the West Indies. This is the same area from which Chubb (*in* Zans and others, 1962, p. 16) reported Valanginian-Hauterivian and Barremian-Aptian rudistids. In the lowest limestone sampled (Copper Limestone), Sohl identified *Itieria* n. sp. He could not give a definite age assignment to this gastropod. From a younger limestone (Benbow Limestone), Sohl listed *Diozoptyxis* n. sp.? of the *D. coquandi-renauxiana* complex, *D.* cf. *D. coquandiana*, *Nerinea* cf. *N. galatea*, and *Archimedea* n. sp. On the basis of these occurrences, and some specimens which he could not assign definitely to genera, Sohl concluded (May 20, 1968, written commun.) that the forms from the Benbow Limestone probably are late Barremian-Aptian. Both the Benbow and Copper Limestones ". . . are older than any I have encountered in Puerto Rico. In Puerto Rico, the oldest fossils so far encountered are from lower middle Albian rocks; however [in Puerto Rico], unfossiliferous units of unknown age are present below the dated units."

Late Cretaceous History

Intense crustal movements, beginning in late Aptian or early Albian time, continued intermittently through the remainder of Cretaceous time (Figs. 25, 26). Although referred to collectively as "Subhercynian" orogeny, the writers do not mean to imply that a single orogenic episode took place. Instead, if the Greater Antilles as a whole is considered, orogenic uplift and the development of angular unconformities seem to have been in progress somewhere within the orthogeosyncline at all times. The several unconformities have been discussed.

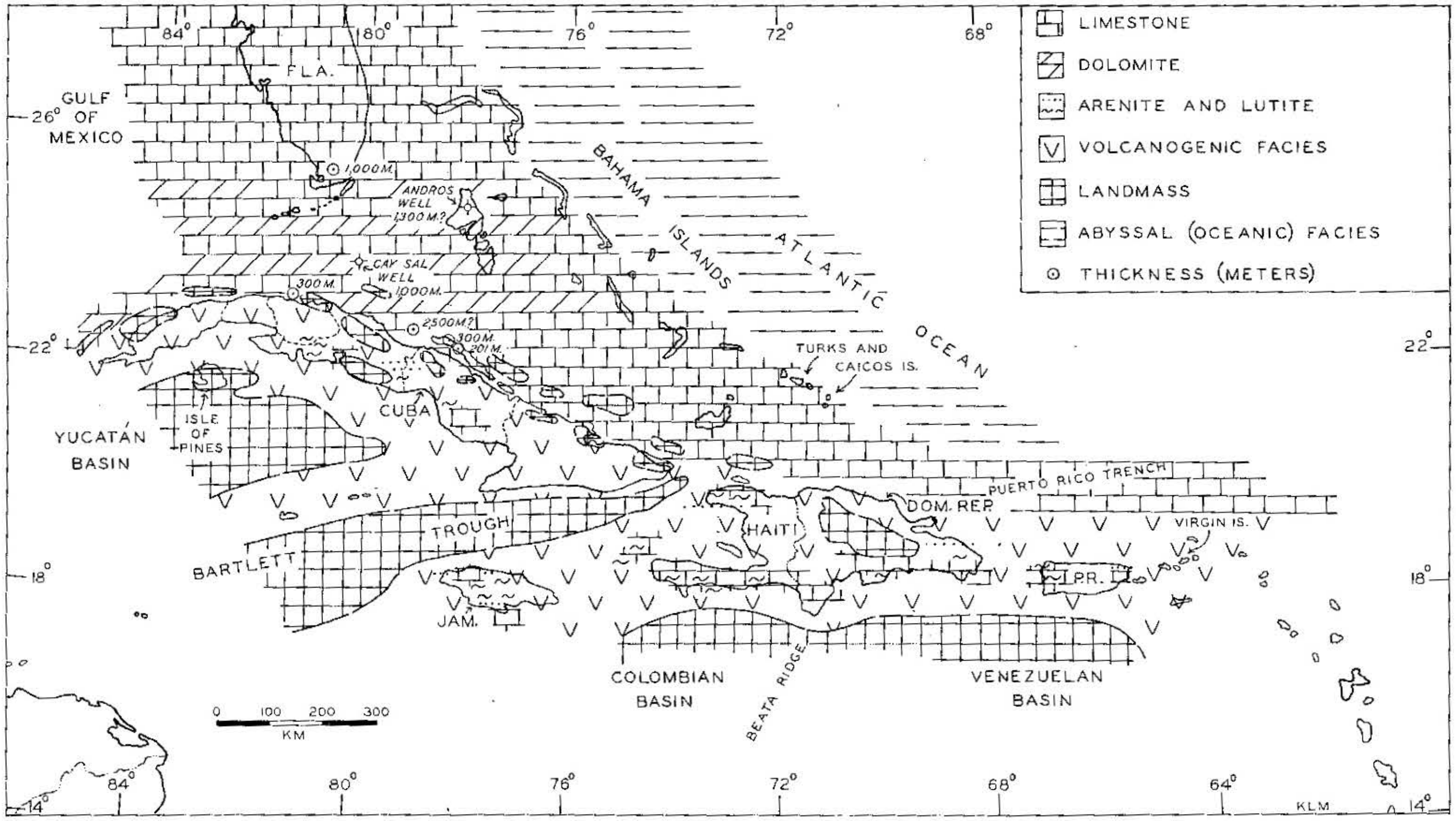

Figure 25. Paleogeography of Greater Antilles during Late Cretaceous time, according to Khudoley. Andros well thickness of 1300 m probably is closer to 1000 m according to Spencer (1967). The 2500-m thickness in northern Cuba is average of Cayos Francés and Fragoso wells, is uncorrected for dip, includes some Cenomanian, and possibly is repeated by a steep reverse fault.

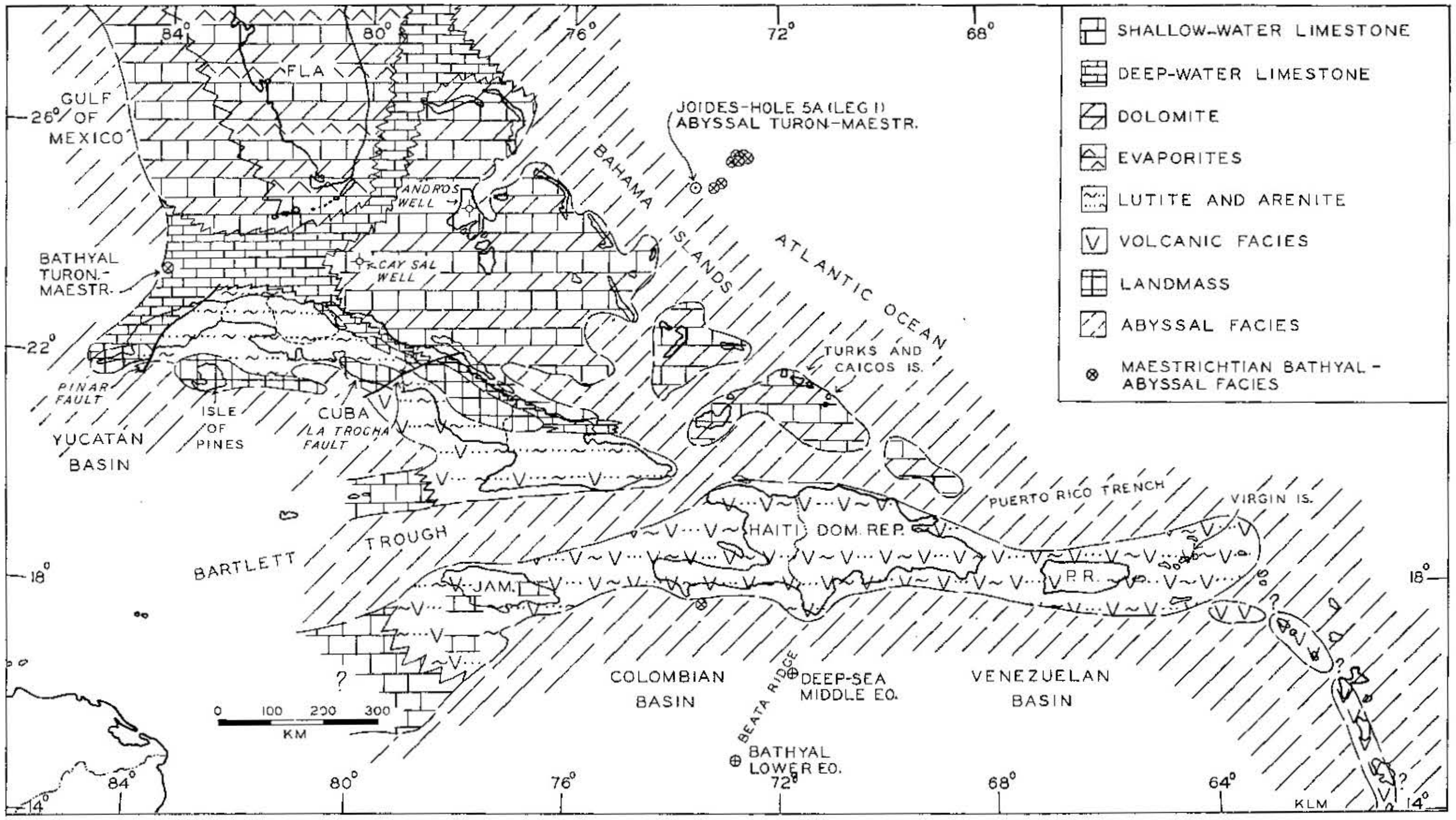

Figure 26. Paleogeography of Greater Antilles during late Turonian (Late Cretaceous) through middle Eocene time, according to Meyerhoff. Data from many sources. Deep-sea data from Ericson and others (1952, 1961), Heezen and Sheridan (1966), Saito and others (1966), and Bryant and others (1969).

Within the Upper Cretaceous, one major break—generally an angular unconformity—is found nearly everywhere: between the Cenomanian or early Turonian, below, and the Campanian or Maestrichtian, above. Turonian to Santonian rocks appear to be scarce in many parts of the western Greater Antilles, particularly in Cuba and Jamaica, although they may be more abundant in Puerto Rico and the Virgin Islands. Little is known about the distribution of Turonian-Santonian rocks in Hispañola because of the paucity of field and subsurface data. Where Turonian-Santonian strata have been found, they commonly are angularly unconformable on the Lower Cretaceous. Thus, during the time interval between early Turonian or Cenomanian and Campanian-Maestrichtian, many parts of the western Greater Antilles were exposed to erosion, and only a few basins were receiving sediments. This seems to have been true not only in the western part of the eugeosyncline and in Jamaica, but also in the carbonate province of northern Cuba. It is also possible that Campanian to Maestrichtian generally is unconformable on Turonian to Santonian where these stages are represented, but the number of Santonian-Campanian contacts which have been studied are negligible. Turonian-Santonian strata *appear* to be more abundant in Puerto Rico and St. Croix (Virgin Islands) and may be present on St. Thomas and St. John. Paleontological data are so sparse that even the generalized statements given here are risky.

With the breaking up of the orthogeosyncline during "Subhercynian" orogeny, wrench faulting may have commenced as, for example, in the Bartlett Trough, Cauto fault zone, Anegada Trough, and other areas (A. A. Meyerhoff, 1966). Although deep-water basins are known to have existed locally, many basins were relatively shallow.

Additional characteristics of Late Cretaceous history are great diversity of lithologic types, major changes of ecologic conditions within short distances, and abrupt lateral and vertical lithofacies changes. Quartz became abundant in clastic deposits of Cuba, Jamaica, and Hispañola; reworked sediments appear in significant amounts for the first time. Related to this is a gradual decline in the intensity of volcanism. In fact, in Cuba north and west of the Cauto fault zone (Fig. 13), almost no post-early Turonian igneous activity took place.

During the Late Cretaceous, the character of the volcanic rocks became increasingly silicic. Rocks of andesitic composition dominate, and tuff is very abundant, much more so than flows. Dacite and rhyolite also are more common.

Igneous intrusion accompanied the "Subhercynian" folding and uplift in Cuba, Hispañola, and probably in other parts of the Greater Antilles. Khudoley believes that mid-Turonian time was the period during which major ultramafic and mafic intrusion took place, but Meyerhoff believes that most of the Late Cretaceous intrusions of ultramafic rocks were "cold" intrusions—that is, tectonic remobilization of the early orthogeosynclinal ultramafic bodies. Ultramafic plutons also were remobilized tectonically as "cold" intrusions during the "Laramide" orogeny which began in Campanian or Maestrichtian time and continued into the Eocene.

During the "Laramide" orogeny, many diorite, quartz diorite, and granodiorite stocks and batholiths were intruded, and older metamorphic rocks, such as those of the Isle of Pines, were further deformed, and possibly intruded (Kuman and Gavilán, 1965). A few rock types have been dated radiometrically (Table 4; Figs. 6, 7). Schists on the Isle of Pines yield K-Ar dates of 73 to 78 m.y. (Fig. 6) (Lab. of the All-Union Geol. Inst., Leningrad; Laverov and others, *in* Pushcharovsky, 1967). These dates are only a minimum age and probably do not indicate the time when the schist originally formed. Secondary biotites in granitic rocks of the Jarahueca fenster yielded a K-Ar date of 61 m.y. (Fig. 6). A whole-rock determination from a diorite near Santiago de Cuba gave a date of 58 ± m.y. (Fig. 6) (Laverov and others, *in* Pushcharovsky, 1967). The granodiorite of Jamaica yielded K-Ar, Rb-Sr, and Pb dates of 65 ± 5 m.y. (Fig. 7) (Chubb and Burke, 1963). Kesler (1968a, 1968b) reported a 66 m.y. date from a quartz monozonite stock in northwestern Haiti. H. Palmer (1963) recorded a 68 m.y. date from a tonalite intrusion in the Dominican Republic (Figs. 7, 25, 26; Table 4). The Utuado quartz diorite to granodiorite pluton of northwestern Puerto Rico is well dated by fossils in the surrounding rocks (pre-early Eocene, probably latest Maestrichtian-Paleocene: Weaver, 1958; U.S. Geol. Survey, 1967a). Radiogenic dates (Table 4, Fig. 7) range from 50 ± 10 m.y. to 65 ± 3 m.y. Elsewhere in Puerto Rico, the San Lorenzo granodiorite batholith has been dated at 53 to 58 m.y. (Jaffe and others, 1959); the Ciales granodiorite stock yielded a 70 ± 20 m.y. date (Berryhill, 1965; Nelson, 1968a); and two unnamed quartz diorite bodies east of the Ciales stock gave dates of 60 ± 10 m.y.

Late Cretaceous Paleogeography

In general outline, the Late Cretaceous paleogeography of the Greater Antilles was similar to that of the Early Cretaceous. However, numerous islands and separated-to-partly separated basins were formed on the site of the present Greater Antilles. North of Cuba, anhydrite deposition ceased. Banks continued to occupy the Remedios facies-structural zone, and part of the Cayo Coco zone. A deep-water seaway divided the two zones. Bank limestone deposition continued on the Bahamas platform.

South of the Greater Antilles, Khudoley (Fig. 25) believes that landmasses occupied the Caribbean Sea. Meyerhoff believes (Fig. 26) that the area was ocean basin much like today. In general the marine waters covering the region were shallow, warm, and of normal salinity. The fauna was extremely varied and abundant. Locally, very deep-water conditions existed (for example, in western Cuba and southwestern Puerto Rico). Free communication for faunas existed throughout the region for, with only a few exceptions, the pelagic—and many benthonic—types listed below are found throughout the Gulf of Mexico-Caribbean region.

Late Cretaceous Faunas

Ammonites have been collected from all of the islands. In Cuba, ammonites collected by M. Rutten (1936, p. 35–36; Imlay, 1944, p. 1011–1012) in

central Las Villas Province are Turonian-Coniacian: *Austiniceras dibleyi, Pachydiscus* cf. *P. colligatus, Peroniceras* aff. *P. tricorinatum, P.* cf. *P. czörnigi, P. cocchi, Barroisiceras,* and *Crioceras.* G. Lewis and Straczek (1955) found *Baculites* and *Pachydiscus* in Campanian-Maestrichtian strata of Oriente Province.

In Jamaica, a late Coniacian or early Santonian ammonite, *Nowakites* aff. *N. paillettei,* is known (Trechmann, 1936; Imlay, 1944, p. 1010) from the Cornwall-Middlesex block. In the Blue Mountains trough province, the following ammonites of Campanian, and possibly Maestrichtian, ages have been identified (Spath, 1925; Imlay, 1944; Reeside, 1947): *Epigoniceras, Parapachydiscus* aff. *P. stallauensis, P.* aff. *P. gollevillensis, Glyptoxoceras* cf. *G. rugatum, Baculites* sp., *Hamites,* and *Desmophyllites.*

In Haiti, in pebbles of float north of the Massif de la Selle area, Reeside (1947) reported the following latest Santonian ammonite assemblage: *Baculites* sp., *Parapuzosia*(?) sp., *Pachydiscus (Parapachydiscus) gardneri, P. (P.) woodringi, Paralenticeras sieversi,* and *Texanites (Mortoniceras)* cf. *T. (M.) cañaensis.* This fauna could be slightly older, that is, Coniacian.

Ammonites from Puerto Rico were first reported by H. A. Meyerhoff (1932), and identified by Reeside (*in* H. A. Meyerhoff, 1932, p. 342): *Barroisiceras* aff. *B. haberfellneri* and *Parapuzosia* aff. *P. corbarica.* These ammonites are Coniacian. More recently, Berryhill and others (1960, p. 143) listed the following ammonites from northeastern Puerto Rico: *Collignoniceras* and *Prionotropis* of Turonian age and *Parapuzosia* of Coniacian age. Later, Berryhill (1966), apparently referring to the same specimens, listed them as *Collignoniceras, Prionocyclus*(?), and *Parapuzosia*(?) of Turonian age. Kaye (1959a, p. 20) listed the following Santonian(?) ammonites, also from northeastern Puerto Rico: *Pachydiscus* sp. and *Texanites* sp.

Other types of fauna are extremely abundant, but only a few are mentioned here. The rudistids show that the area was well differentiated into separate faunal provinces during the Late Cretaceous (Chubb, 1960). For example, the rudistids of the Cornwall-Middlesex zone include five genera (*Monopleura, Gyropleura, Agriopleura, Praeradiolites,* and *Sauvagesia*) and several species unknown elsewhere in the orthogeosynclinal province (for example, *Barrettia gigas* characterizes the Cornwall-Middlesex zone; *B. monilifera* characterizes the Blue Mountains zone). Cuban genera unknown on the Cornwall-Middlesex block include *Tepeyacia, Parabournonia, Tampsia, Vaccinites, Torreites, Pironaea, Parastroma, Sabinia, Caprinuloidea,* and *Coalcomana.* In all of the islands, several genera are widespread: *Barrettia, Durania, Titanosarcolites, Bournonia, Caprinuloidea, Vaccinites, Parastroma,* and *Radiolites.* Chubb (1960, p. 20) wrote, regarding a study of Puerto Rican rudistids, that ". . . the Cretaceous fauna of Puerto Rico has close affinities with that of Cuba and considerable differences from that of the Cornwall-Middlesex Block of Jamaica."

Echinoderms *(Echinocorys, Linthia, Lanieria),* gastropods *(Actaeonella, Nerinea),* pelecypods *(Inoceramus, Ostrea, Pecten),* and algae (Dasycladaceae, Codiaceae) grew in profusion.

Norman F. Sohl (May 20, 1968, written commun.) studied gastropods from the Central Inlier (Fig. 7) of Jamaica. Among the genera which he found are *Cassiope* n. sp., *Actaeonella (Trochactaeon)* aff. *A. (T.) acutissima*, *A.* cf. *A. (T.)* n. sp. A, *A. (T.)* n. sp. B, *A. (T.)* n. sp. C, *A. (T.)* sp., *Actaeonella (Actaeonella)* sp., *Turritella* cf. *T. prelissoni*, *Turritella* n. sp., *Mesalia* cf. *M. janja*, *Cerithium* sp., *Discotectus?* sp., Naticidae, Strombidae, Aporrhaidae?, and a nerineid. Except for *Cassiope* n. sp., the other forms are from a single unit—the Guinea Corn Formation. Sohl concluded: "The Guinea Corn Formation possesses a fauna that has much in common with the widespread late Campanian-Maestrichtian faunas of northern South America, Mexico and the Antilles. . . . The actaeonellas here provisionally placed in new species find counterparts in the Habana Formation (s.l.) of Cuba and in the higher stratigraphic units of Puerto Rico."

The pelagic microfauna is abundant in limestone lenses and shale beds. Turonian assemblages of Cuba include *Globotruncana saratogaensis*, *Gl. renzi*, and *Gl. sigali*. Coniacian-Santonian assemblages include *Gl. ventricosa*, *Gl. concavata*, *Gl. coronata*, and *Gl. saratogaensis*. From the Campanian of Cuba are *Rugotruncana calcarata*, *Globotruncana linneiana*, *Gl. fornicata*, *Gl. lapparenti* group, *Gl. globigerinoides*, *Gl. marginata*, *Rugoglobigerina* sp., and *Pseudogümbelina* sp. Cuban Maestrichtian assemblages include *Globotruncana contusa*, *Gl. stuarti*, *Gl. arca*, *Gl. tricarinata*, *Gl. lapparenti* group, *Gublerina hedbergi*, *Pseudogümbelina* sp., *Pseudotextularia brönnimanni*, *P. elegans*, and *Rugoglobigerina hantkeninoides*. Many of these same and related genera and species are widespread in the Greater Antilles.

Because the age of the "*Inoceramus* beds" of Jamaica (St. Ann Inlier, Fig. 7) has long been considered to be Turonian-Coniacian, and even Cenomanian-Campanian, Kauffman's (1966) and Esker's (1968, 1969) evidence for changing the age range of this unit to late Coniacian-late Santonian is important. Among the fossils collected from the base of the "*Inoceramus* beds," Esker listed the following (interpreted as late Coniacian): *Praeglobotruncana algeriana*, *Marginotruncana (Globotruncana) renzi renzi*, *M. (Gl.) renzi angusticarinata*, *M. (Gl.) sigali*, *M. (Gl.) coronata*, *M. (Gl.) indica*, and scarce *M. (Gl.) concavata*. From the middle of the unit, the following forms were collected (interpreted as early Santonian): *Gublerina decoratissima*, abundant *M. (Gl.) concavata*, *M. (Gl.) renzi renzi*, *M. (Gl.) renzi angusticarinata*, *M. (Gl.) coronata*, and *M. (Gl.) sigali*. Assigned to the late Santonian, from the top of the unit, were *M. (Gl.) concavata*, *M. (Gl.) renzi renzi*, *M. (Gl.) renzi angusticarinata*, *Planoglobulina glabrata*, *Globotruncana fornicata*, and *Gl. linneiana*.

From the base of the overlying "*Barrettia* limestone," long considered to be early Campanian, Campanian foraminifers were found. They include *Globotruncana arca*, *Gl. bulloides*, *Gl. elevata*, *Gl. fornicata*, *Gl. linneiana*, and *Gl.* cf. *Gl. stuartiformis*. At the top of the "*Barrettia* limestone," the "Campanian" "New Ground conglomerate" contains Eocene foraminifers. Kauffman's (1966) independent study of the inoceramids from the same units revealed the presence of only Coniacian, Santonian, Campanian, and Maestrichtian species.

Benthonic Foraminifera diagnostic of only the Turonian-Santonian have not been reported to the writers' knowledge from the Greater Antilles, although abundant benthonic Foraminifera are present in some Turonian, Coniacian, and Santonian localities. The Campanian and Maestrichtian, in contrast, are characterized by many distinctive Foraminifera. Maestrichtian-Campanian assemblages include *Sulcoperculina dickersoni* and *Vaughanina cubensis*. Mainly Campanian assemblages include *Pseudorbitoides trechmanni* and *P. israelskyi*. Assemblages principally of Maestrichtian age include *Torreina torrei*, *Asterorbis* sp., *Lepidorbitoides* sp., *Rhabdorbitoides hedbergi*, *Vaughanina* sp., *Siderolites vanbelleni*, *S. skourensis*, *Eponides haemisphaericus*, *Stromatorbina binkhorsti*, *Dicyclina* sp., *Polygonella* sp., *Cosinella* sp., *Gavelinella* sp., *Valvulineria* sp., *Rhapydionina* sp., and *Ataxophragmium* sp.

POSITION OF NORTHERN PINAR DEL RÍO PROVINCE, CUBA, IN TITHONIAN-MAESTRICHTIAN PALEOGEOGRAPHY OF GREATER ANTILLES

The Sierras de los Órganos and del Rosario of northwestern Pinar del Río Province, Cuba, never have been integrated satisfactorily into reconstructions of Greater Antillean paleogeography. Most geologists are unaware that this area is a major question mark in such reconstructions. A problem exists for a variety of reasons. First, the area is poorly known and little mapped. Second, the great structural complexity has led to serious interpretation errors (as an example, the San Cayetano Formation was regarded as Late Cretaceous for many years because of its similarity to an Eocene unit which contains reworked Late Cretaceous faunas). Third, the existence of many units was not recognized because of their outward resemblance to units of known ages. As a result, the presence of Aptian through Campanian deep-water carbonates was not recognized until Hatten's studies from 1954 through 1957. Finally, recent published literature is difficult to obtain and Hatten's (1957) detailed report never has been published, although Herrera (1961) summarized Hatten's work. Seiglie (1961) and Judoley and others (1963) provided some new information on the area. Fortunately, Hatten's (1957) report is being prepared for publication, and it is from that paper, loaned by Hatten, and from nearly five months of field checks of Hatten's mapping that Meyerhoff acquired much of the information given here from northern Pinar del Río. The basic elements of the problem are described briefly.

1. The Aptian-Campanian deep-water carbonates which crop out in the Pons autochthon of the Sierra de los Órganos (Fig. 15) appear to be absent or very scarce in the Sierra del Rosario, which is between the Sierra de los Órganos and the deep-water carbonates of the Las Villas facies-structural zone (Fig. 13). However, this scarcity or absence could be more apparent than real. In the Sierra del Rosario, one outcrop of Aptian and Santonian is shown on the Judoley and others (1963) map, at 22°46'N., 83°05'W., and many other such outcrops ultimately may be found. Hatten (1957) reported the presence of a deep-water limestone of probable Albian-Cenomanian age at Sierra de

Cascarajícara, in the northwestern part of the Sierra del Rosario (Fig. 6).

East of the Sierra del Rosario, along the north coast at the Habana-Pinar del Río boundary, is a large outcrop (several square kilometers) of Early Cretaceous pelagic limestone which closely resembles the Artemisa; this is the Martín Mesa area. The outcrops are shown on the Brodermann and others (1946) and de Albear and others (1965) maps, but not on the Núñez-Jiménez and others (1962) and Judoley and others (1963) maps. Strata from these outcrops are shown by de Albear and others (1965) to include rocks of Tithonian age. Samples collected by J. W. Low and Meyerhoff in 1952 contain a Tithonian and Neocomian microfauna, as well as younger fossils of Aptian(?)-Albian age (C. W. Hatten, October 3, 1968, oral commun.). Brönnimann and Rigassi (1963, p. 213) also reported a Neocomian microfauna from this general area. The outcrop is surrounded on three sides by volcanic facies of the Zaza zone; the limestones are severely faulted, folded, shattered, and crushed.

Farther east, near Habana city, Brönnimann and Rigassi (1963) reported the presence of slivers or slump masses (or both) of Neocomian deep-water limestone associated with Late Cretaceous strata and Early Cretaceous serpentinite of the Zaza facies-structural zone. Numerous slivers of deep-water carbonates are known in the Zaza zone from Habana Province to northwestern Oriente Province. Many are associated with, or in contact with, serpentinite, but their relations to the serpentinite are unknown. A. A. Meyerhoff and Hatten (1968) suggested that these carbonate bodies are slivers from the Las Villas zone (Placetas zone in their terminology) that were caught in serpentinite at the base of major thrust sheets or gravity-slide masses which, in many parts of Cuba, cover the Las Villas zone.

At Mina Margot, 14 km west-northwest of Matanzas city (Fig. 6), C. W. Hatten, O. E. Schooler, N. R. Giedt, D. T. Gleim, and A. A. Meyerhoff, in 1957 and 1958, found large blocks, 100-200 m long and 20-30 m thick, of deep-water carbonates containing planktonic Foraminifera of the following ages: late Albian, Cenomanian, and early Turonian. These carbonate rocks have a high insoluble residue content. If one excludes secondary minerals such as pyrite, the insoluble residue is principally of volcanic origin. This is an important characteristic which distinguishes these rocks from the deep-water carbonates of the Sierra de los Órganos. Those of the Sierra de los Órganos are only a few kilometers from the Zaza facies-structural zone, but appear to have almost no insoluble residue.

On the assumption that the Aptian to Campanian deep-water limestone once covered the Sierra del Rosario, Meyerhoff shows this facies in that area on Figures 24 and 26. However, until the Sierra del Rosario is mapped and collected in detail, and until more is known of the limestone occurrences in the Zaza zone east of the Sierra del Rosario, the original relations between the Sierra de los Órganos and the Las Villas zone deep-water carbonates will remain unknown. If strata younger than Tithonian and Neocomian were not present on the Sierra del Rosario, a major regional paleogeographic problem remains. Even if it is discovered that post-Neocomian deep-water carbonates

once covered the area, the absence of a lateral facies gradation from the deep-water carbonates on the north to the volcanic rocks on the south still requires explanation.

2. The absence, or near-absence, of volcanic residue in the post-Neocomian strata north of the Pinar fault (Figs. 24, 26) might be explained by an abrupt facies change across some ancient barrier which now is obscured by the fault. However, such an abrupt facies change seems unlikely if the Pinar fault, which separates the two facies, is a normal fault. It is true that the insoluble residue content of the post-Neocomian strata has been studied in very few samples, and future detailed studies may reveal that more lateral gradation takes place than is suspected or known. Moreover, well control in the Cretaceous rocks southeast of the Pinar fault is too sparse to ascertain whether or not the volcanic and carbonate facies are interbedded in the vicinity of the fault, and whether or not a median welt is present close to the fault. The Meyerhoff interpretation of intertonguing (Fig. 17) is speculative and without positive evidence. The Khudoley interpretation (Fig. 17) is equally speculative.

3. Along the northwest (Gulf of Mexico) side of the Sierra del Rosario, Hatten (1957) discovered a limestone unit which he named the Cascarajícara Formation. The name is derived from the Sierra de Cascarajícara, the highest mountain in Pinar del Río Province (772 m; Fig. 6). Typical exposures of the formation occur along the flanks of the Sierra de Cascarajícara on the road south from La Mulata to Finca Mil Cumbres.

The Cascarajícara Formation is a limestone-sharpstone conglomerate, 650 m (est.) thick, consisting of angular limestone clasts up to several centimeters in diameter in a matrix of calculutite. The matrix contains *Asterocyclina* sp. and abundant spinose species of *Globigerina;* thus, the age is middle to late Eocene. The unit is well indurated, medium gray, and characterized by a lack of bedding. It resembles a talus deposit in deep water adjacent to a fault scarp or carbonate bank edge.

The top of the formation is eroded. The base was not seen, but the formation appears to overlie a deep-water limestone of Albian to Cenomanian age.

The distribution of the Cascarajícara Formation is poorly known. The unit has been found in several localities along the north flank of the Sierra del Rosario. Southwestward, along the north side of the Sierra de los Órganos, the Cascarajícara appears to grade laterally into a terrigenous clastic deposit which contains lenses and beds of calcarenite and limestone conglomerate. This observation suggests that the source of the limestone clasts was close to the Sierra de Cascarajícara, possibly the Sierra del Rosario.

The limestone clasts consist of deep-water, reefal, near-reef, and bank carbonates which range in age from Albian through Maestrichtian. The formation is very important in regional paleogeographical reconstructions because it provides evidence that the Remedios facies-structural zone did extend as far west as the longitude of Pinar del Río Province. The writers believe that the Remedios zone now is north of and offshore from the Sierra del Rosario area (Hatten, 1957).

W. R. Bryant, J. W. Antoine, N. K. Brown, Jr., T. E. Pyle, M. A. Furrer, A. A. Meyerhoff, and several others currently are conducting a study of samples and seismic sections in the Straits of Florida, off the north coast of Pinar del Río Province, and along the northeast side of Campeche Bank (Bryant and others, 1969). Miocene-Pliocene bathyal deposits sampled on Jordan Knoll (named by Thomas E. Pyle; Figs. 6, 13) contain clasts of deep-water Late Cretaceous, Paleocene, and Eocene limestone, together with bank-type, shallow-water Early Cretaceous limestone. These deposits, although much younger than the Cascarajícara Formation, are believed to be of similar origin: that is, derived from the erosion of a nearby fault scarp or exposed bank edge.

4. Further complicating the interpretation of northern Pinar del Río is the presence of large areas, north and east of the Sierra del Rosario, that are underlain by volcanic rocks and serpentinite of the Zaza facies-structural zone (Furrazola-Bermúdez and others, 1964, 1965; Judoley and others, 1963; *see* Fig. 13). The presence of these rocks in this area, north of a deep-water carbonate facies, and apparently south of the Remedios zone which supplied clasts to the Cascarajícara Formation, presents various problems of interpretation.

5. Serpentinite and peridotite plugs, of both alpinotype and layered type, are widespread in northern Pinar del Río (Fig. 13; Hatten, 1957; Ducloz and Vuagnat, 1962; Núñez-Jiménez and others, 1962; Furrazola-Bermúdez and others, 1964, 1965; Judoley and others, 1963). Some intrude the Early and Middle Jurassic San Cayetano; some contacts are faulted; but others are not obviously faulted. Other peridotite bodies "intrude" Viñales and Artemisa; still others are associated with gabbroic rocks in the Zaza-like facies north and east of the Sierra del Rosario.

6. The Viñales Limestone ranges in age from Kimeridgian(?) through middle Tithonian. Late Tithonian ammonites are found in the overlying Artemisa, and volcanic debris (tuffaceous shale partings) does not appear in the section below the Artemisa. If the eugeosyncline did not form until the beginning of deposition of the Artemisa of the Sierra de los Órganos, then the Artemisa of the Sierra del Rosario probably is not older than that of the Sierra de los Órganos. If this is true, the absence of terrigenous debris in the Viñales Limestone is difficult to explain. Regardless, neither Khudoley nor Meyerhoff's interpretation, shown in Figure 16, is wholly satisfactory. A major problem is that the whole of the Artemisa of the Sierra del Rosario has not been measured, sampled, described, dated, and correlated.

7. If the Viñales *is* equivalent to much of the Artemisa, and hence to the Zaza facies on the south side of the Pinar fault, an even more complicated paleogeographic pattern results from Tithonian time. The Viñales Limestone is a shallow-water bank limestone. It is southwest of the Sierra del Rosario. If the Artemisa of the Sierra del Rosario is part of the deep-water limestone facies of the Las Villas facies-structural zone (Meyerhoff's miogeosyncline), the Viñales is *south*, instead of north, of the deep-water facies.

8. An explanation involving extensive strike-slip fault movement along the Pinar fault is not satisfactory, whether or not the Viñales Limestone is equivalent to part of the Artemisa. The presence of the Zaza-like volcanic facies north and east of the Sierra del Rosario reduces the likelihood of a solution by strike-slip faulting alone. If strike-slip faulting is important, the pattern of such faulting has to be very complex to account for the presence of Zaza-like facies north and east of the Sierra del Rosario. Moreover, the northeastward extent of the Pinar fault is unknown. Meyerhoff at one time believed the fault to extend into the Straits of Florida a short distance west of Habana. If the Núñez-Jiménez and others (1962) map is correct, this is not true. Nevertheless, aerial photos of the fault zone reveal topographic and linear characteristics nearly identical with those along the San Andreas fault of California, and some strike-slip movement is almost certain to have taken place along this fault.

9. Khudoley's Figures 23 and 25 contrast sharply with Meyerhoff's Figures 24 and 26. Khudoley's pair of maps does not admit a problem; Meyerhoff's maps attempt a solution, but ignore the presence of the Zaza-like facies north and east of the Sierra del Rosario. A solution, in Meyerhoff's opinion, involves compressional or gravity tectonics.

Hatten (1957; *see* Fig. 15) interpreted the Sierra de los Órganos to be a region of extensive nappe and thrust development (*see also* Rigassi, 1961, 1963), and his views are supported strongly by Knipper and others (1967). (In early 1968, Knipper gave a lecture at the University of Habana in which he interpreted the Sierra de los Órganos in a manner similar to that of Hatten [1957]). Khudoley (Fig. 15) does not agree with Hatten, although Meyerhoff does.

If Hatten's interpretation of the Sierra de los Órganos is correct, most of this range is allochthonous. The Pons autochthon (Fig. 15), at the center of the range, is the only tectonic unit in which Hatten mapped Neocomian, and Aptian-Campanian. In a written communication (dated June 10, 1968) to Meyerhoff, Hatten wrote: "Unfortunately, we do not know enough about the structural relationship between the Sierra del Rosario and Sierra de los Órganos to piece together the paleogeography. Are the various structural elements in the Sierra del Rosario autochthonous? Was the Viñales deposited west, south or north of the present-day Sierra del Rosario stratigraphic sequence? I can't safely comment on this at the present state of knowledge."

Along the same lines, Meyerhoff believes that most of the Zaza-like facies north and east of the Sierra del Rosario will be found to be part of a major series of thrust sheets, nappes, or gravity slides—younger than those in the Sierra de los Órganos—which have overridden the Sierra del Rosario and even the eastern part of the Sierra de los Órganos. This would involve a thrust displacement of the order of 35 km. Such a displacement does not seem unreasonable in view of the observation that about 35 to 40 km of displacement is probable in the area of the San Adrián diapir complex west of Matanzas city (Fig. 6) and approximately 30 km of thrust displacement is estab-

lished by well control along the La Trocha fault of central Cuba (Fig. 6; *see* A. A. Meyerhoff and Hatten, 1968). Such a thrust interpretation in the Sierra del Rosario area also explains the position of Zaza volcanic facies between the Remedios zone clasts in the Eocene Cascarajícara Formation and the probable offshore source of these clasts north and northeast of Pinar del Río. If there were no thrusting, Zaza-facies clasts also should be present in the Cascarajícara. Thus, the postulated thrusting of the Zaza to the north side of the Sierra del Rosario took place after deposition of the Cascarajícara, that is, in late middle or early late Eocene time.

In summary, Meyerhoff, at least, has no firm explanation for the anomalous geological-paleogeographical situation of the Sierra de los Órganos-Sierra del Rosario, but, in his opinion, thrusting and nappe development, followed by some strike-slip movement along the Pinar fault, are involved (*see* MacGillavry, 1970). This is a major problem, and its solution is not likely to be found easily.