40. CRUISE SYNTHESIS

John B. Saunders, Texaco Trinidad Inc., Pointe-a-Pierre, Trinidad
N. Terence Edgar, Scripps Institution of Oceanography, La Jolla, California
Thomas W. Donnelly, State University of New York, Binghamton, New York
and
William W. Hay, Rosenstiel School of Marine and Atmospheric Science, Miami, Florida

INTRODUCTION AND BACKGROUND

The concept of sea floor spreading or plate tectonics has been successfully applied to answer many of the classic problems of continental and marine geology and geophysics. The Caribbean area, on the other hand, has posed its own problems for those of us concerned with the application of plate tectonics to the development of the Atlantic Ocean since the breakup of Gondwanaland and Laurasia 180 to 200 million years ago. In every "acceptable" reconstruction of the continents, the area now occupied by the Caribbean Sea and Central America (including some Paleozoic crust) is covered by South America, or is ignored. The solution to the question of the origin of the Caribbean Sea, its role in plate motion, and the overall history of the area were the prime objectives of the fifteenth cruise of *Glomar Challenger*.

The crustal layers of the Caribbean Sea are thicker than typical Pacific or Atlantic oceanic crust, and they are characterized by a totally different seismic velocity structure (Officer et al., 1959). Figure 1 is a comparison of the velocity structure of the Venezuelan Basin crust compared with that of a typical ocean basin. These velocities are also found to underlie the Aves Swell. The Nicaragua Rise and Beata Ridge, on the other hand, are characterized by oceanic velocities, though they are almost of continental thickness. The upper crustal layer, 3.9 to 5.5 km/sec, varies greatly in the velocity range and also in thickness and, in this respect, is similar to Seismic Layer 2 of the main oceanic basins.

Basalt and granodiorite have been recovered from the Aves Swell (Fox et al., 1971) which has led those authors to suggest that the 6.2 km/sec layer, which underlies almost the entire Caribbean Sea, represents granodiorite. Other investigators have pointed out that the dredge was taken on the extreme south end of the swell near Blanquilla, which is underlain by granodiorite of the South American continental margin (Shubert and Moticska, 1972). The same group dredged dolerites and basalts from the steep, west-facing escarpment of the Beata Ridge (Fox et al., 1970). Sonic measurements on those samples yielded velocities significantly greater than those recorded (3.9 km/sec) by seismic refraction methods in the upper crustal layer (Ewing, J. et al., 1960; Edgar et al., 1971).

The sediments of the Caribbean Sea have been examined extensively by seismic reflection methods. Magnetic surveys have revealed only poorly defined, low-amplitude anomalies that trend northeast-southwest in the Venezuelan Basin (Donnelly, Magnetics. . ., this volume) and east-west in the southern Colombian Basin (Christofferson, 1972). Most of the records collected have been by oceanographic institutions whose systems are rarely capable of recording reflectors within the 3.9 to 5.5 km/sec layer. Little is known about the sedimentary sequence in the western Caribbean because the floor of the Colombian Basin is covered almost entirely by turbidites which mask most of the older layers. In contrast, the Venezuelan Basin is covered mainly by pelagic sediments, and good seismic records have shown that these sediments lie beneath the turbidites of the northern Columbian Basin and also lie on the lower southern flanks of the Nicaragua Rise. Only on the northern and southern margins of the Venezuelan Basin are turbidites found. The pelagic sediments lie on a smooth "acoustic basement" layer called Horizon B″ (Ewing, J. et al., 1968). implying a similarity to Horizon B of the Atlantic (Ewing, J. et al., 1966) and Horizon B′ of the Pacific (Ewing, M. et al., 1966). Within the sediments, a single strong reflector, Horizon A″ (Ewing, J. et al., 1968), can be traced throughout most of their areal extent. This reflector was also named for its similarity to the Atlantic Horizon A (Ewing, J. and Ewing, M., 1962) and Pacific Horizon A′ (Ewing, M. et al., 1966). Horizon A″ is exposed on a fault escarpment in the southwestern Venezuelan Basin where early Eocene radiolarian ooze and chert were recovered by piston cores (Talwani et al., 1966; Edgar, 1968; Edgar et al., 1971).

The *Glomar Challenger* drilled three sites in the Caribbean Sea in March of 1969 (Bader and Gerard et al., 1970). The first is Site 29 in the central Venezuelan Basin where they recovered an almost complete stratigraphic record (with the notable exception of the entire Oligocene which may have been missing) to the early Middle Eocene. After penetrating 229 meters of the Late Eocene and Middle Eocene radiolarian ooze, the bits failed on hard cherts, believed to represent reflecting Horizon A″. The second site is located on the Aves Swell, where they recovered an incomplete pelagic sequence down to the Middle Miocene. The Pleistocene sediments are particularly rich in volcanic ash. The site was terminated while still in sediments at 427 meters because of a malfunction with the ship's positioning system, attributed to strong bottom currents. At the last site, they attempted to drill on the escarpment face where Horizon A″ had been piston cored some years earlier. The intention was to start drilling where Horizon A″ appeared to be absent on the seismic records (below the outcrop on the face of the escarpment). However, the drill entered Pleistocene sediment and a

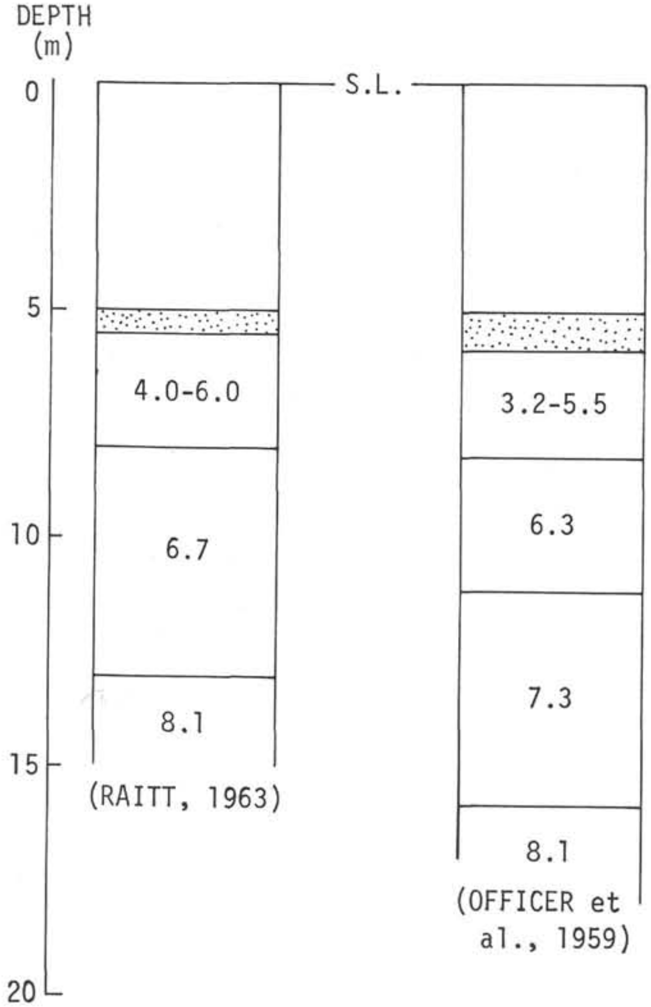

Figure 1. *Comparison of velocity structures of "normal" oceanic crust with that of the Venezuelan Basin.*

section rich in biogenic carbonates (shallower water) was recovered. Rates of sedimentation in the Early Miocene were substantially greater than in the younger, overlying sediment. The hole was terminated in Early Miocene sediments because of a mechanical failure in the coring system.

The objectives of Leg 15, armed with reentry and improved bits, was to penetrate Horizon A″; core Horizon B″ (Sites 146, 150, 151, 152, 153); investigate the nature of the Aves Swell, Beata Ridge, and Nicaragua Rise (Sites 148, 151, and 152, respectively); and improve the knowledge of the biostratigraphy for the Caribbean region.

SITE SUMMARIES

Of the nine sites (Figures 2 and 3) drilled by the *Glomar Challenger* on Leg 15, six are located in the deep basins (Venezuelan and Colombian), two on ridges (Beata and Aves), and one is located in a shallow basin on the Venezuelan continental margin (Cariaco Basin). Igneous rocks were recovered at five sites, where the age of the overlying or intruded sediment ranges in age from Late Turonian to Campanian. They are correlated with Horizon B″, or the deepest seismic reflector commonly recorded by standard oceanographic seismic reflection systems, without the aid of data processing.

Site 146/149

This is a continuously cored site through the sediments of the central Venezuelan Basin and is considered by the Leg 15 scientific staff as the "standard section" for the Caribbean Sea. Two points should be made clear: first, the section is a composite of two sites drilled 2 km apart so there is not a perfect match where the two are joined at about 400 meters (see site report), and second, although continuously cored, only 386 meters of the entire 762 meters cored was recovered (50%). Sites were drilled in 3939 meters of water.

The Tertiary section consists mainly of biogenic oozes and clay. The upper section (Early Miocene to Recent) is dominantly marl and clay, the clay being particularly significant in the Late Miocene and Early Pliocene. The lower section (Early Miocene to about Early Eocene) is characterized by radiolarian-nannofossil ooze that is fairly rich in volcanic components.

Only a few fragments of chert were recovered from the Early Eocene(?) Paleocene(?) section. Although the chert is associated with limestone, it is likely that much of it is associated with relatively soft sediment that washed away when water was pumped down the drill string under high pressure to remove the chert cuttings. The chert and limestone correspond to the seismic reflector Horizon A″. The Paleocene section is a semilithified clay of volcanic origin which is essentially void of fossils.

The Cretaceous is rich in calcium carbonate, although the Campanian-Maastrichtian contains some clay and volcanic sands. The Late Turonian to Campanian is a cherty limestone and contains very little clay. Radiolaria are present in varying amounts but are particularly abundant in the Late Turonian-Santonian limestones. The limestones overlie a dolerite sill near the bottom of the hole, the upper contact of which was not recovered; the sill in turn overlies 1 meter of limestone of the same age as that above the sill. Another dolerite sill underlies this limestone. The top sill corresponds to Horizon B″.

Site 147

The site is located in the Cariaco Basin, a shallow depression in the continental shelf of Venezuela. The basin is of interest because of the anaerobic nature of the water below a depth of about 360 meters. Piston cores taken from the Cariaco Basin indicate that organic-rich sediments, which had accumulated very rapidly during most of the Holocene, contain an exceptionally well-preserved fauna. Chemists were also interested in these sediments to study the transition from organic debris to hydrocarbons and to study the changes in pore water chemistry with depth. Several holes were drilled for lithology, organic geochemistry, and interstitial water chemistry. The site was drilled to 189 meters in 892 meters of water.

Almost the entire section, which is no older than Middle Pleistocene, consists of calcareous olive green anaerobic clay that contains pyrite and dolomite. There are three occurrences of gray and brown clays; the lower two are bounded at the lower contact by a hard dolomite layer. Methane gas occurred at a number of levels within the Section.

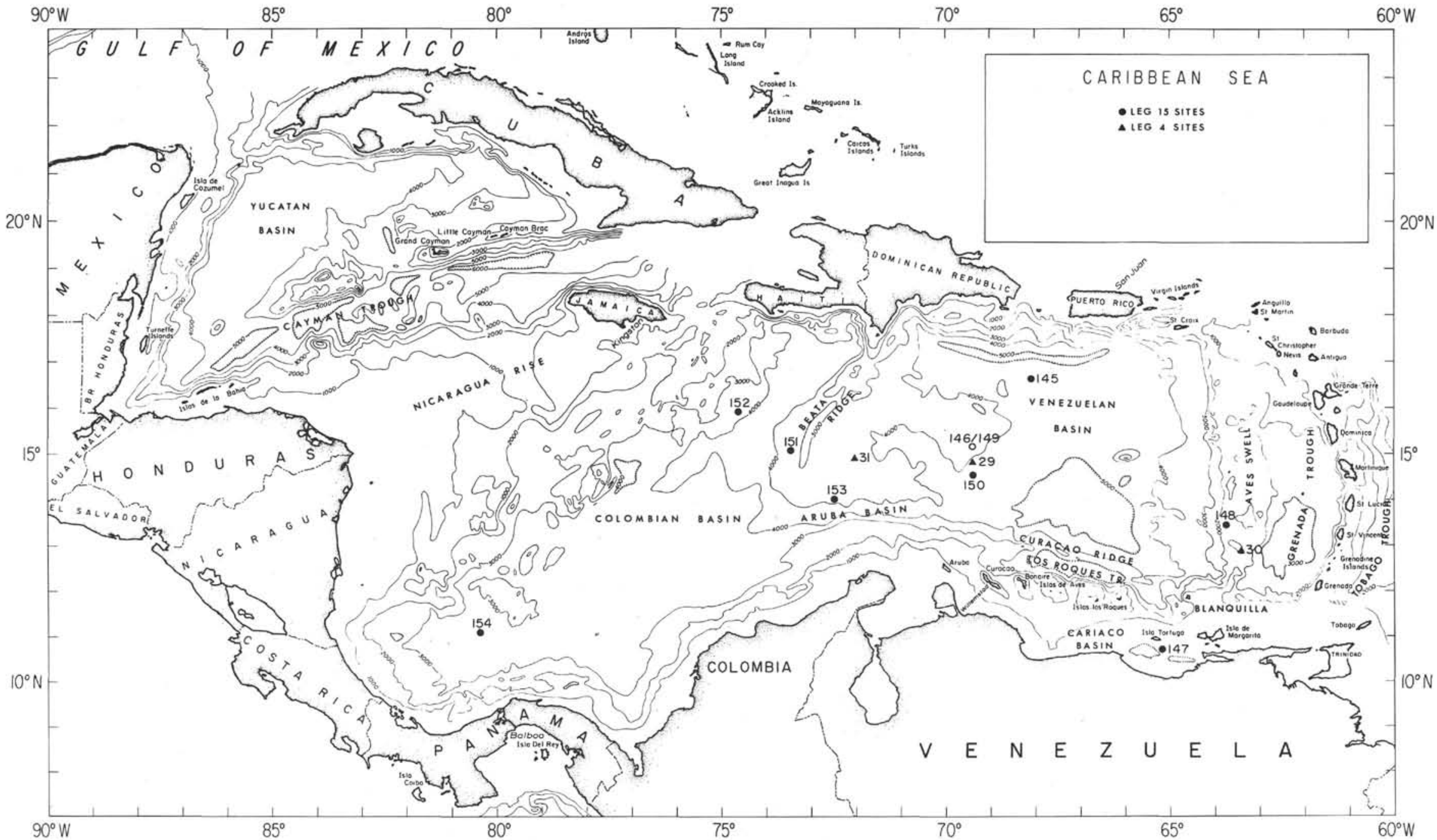

Figure 2. *Location of all drilling locations in the Caribbean Sea from Legs 4 and 15.*

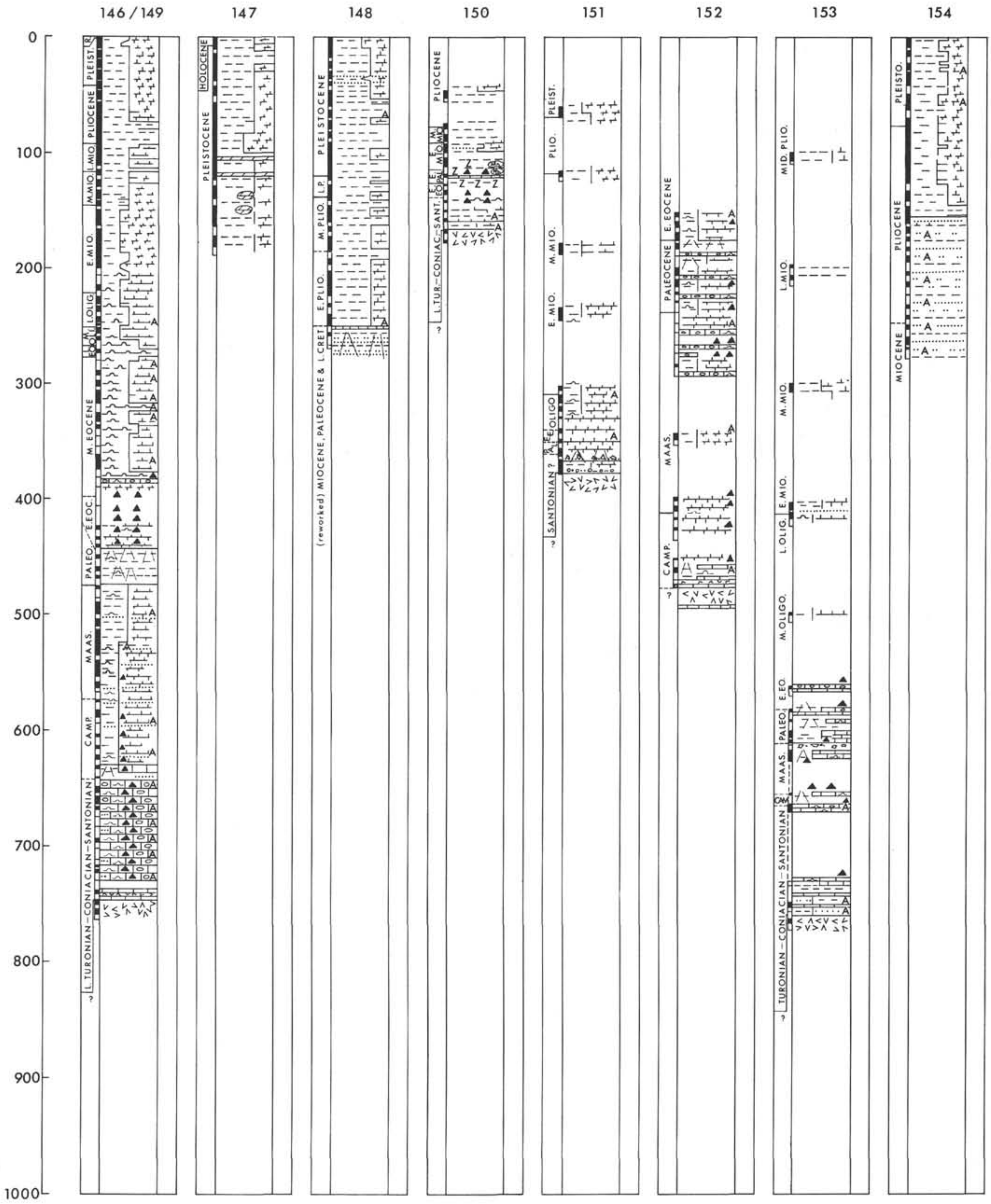

Figure 3. *Columnar sections of all sites drilled on Leg 15.*

Site 148

Site 148 was drilled on the western margin of the Aves Swell, a north-south trending ridge west of the Lesser Antilles. The objective was to recover a section of igneous rock underlaying the sediment and to study the pore water chemistry. Slow drilling in stiff volcanic sands and clays forced the premature termination of the hole at 272 meters. The site was drilled in 1232 meters of water.

The section down to 250 meters consists entirely of clay and calcareous clay that contains an exceptionally fine record of mid-Pleistocene volcanic activity in the Lesser Antilles. The volcanic sands and clays at the bottom of the hole are separated from the overlying calcareous clays by an unconformity that occurs at the depth probably corresponding to the deepest seismic reflector at 0.25 seconds. The unconformity is marked by a brown, phosphatic iron oxide that implies submarine or subaerial weathering during a period of nondeposition or erosion. The volcanic sands consist of porphyritic andesite, plagioclase, and hornblende, suggesting a calc-alkaline volcanic source within the island arc. They may have accumulated around an emergent(?) igneous-metamorphic island.

Site 150

This site is in the Venezuelan Basin, about 60 km south of Site 146/149 and in 4545 meters of water, where the seismic reflection records indicate an anomalous thinning of all sediment layers above Horizon B″. The entire sediment thickness to Horizon B″ is only 180 meters, compared with 762 meters at Site 146/149.

The sediments are mainly clay and marl, with some chalks in the Cretaceous section. Two major unconformities were identified: one from Early Eocene to Early Miocene and the other from Santonian to Early Eocene. Only a thin section of Eocene zeolitic clay and chert separates the two hiatuses. Manganese nodules are associated with the upper unconformity. Coniacian marls with basaltic ash overlie the dolerite of Horizon B″, but the contact was not recovered.

Site 151

Site 151 was drilled on the southern end of the Beata Ridge in 2029 meters of water where seismic reflection records show a single subbottom reflector at about 0.4 second reflection time. The Beata Ridge is a totally submarine feature extending south from Hispaniola almost to the South American continent. The hole was drilled through 367 meters of sediments and 15 meters of basalt.

Oligocene and younger sediments are biogenic chalks and marls. A hiatus extends from the Early Oligocene through the Middle Eocene and from the Paleocene to the Santonian. The unconformity at the top of the Cretaceous is marked by a silicified "hard ground" layer. The Cretaceous sediments consist of highly disturbed organic glauconitic and volcanic clays. The contact of these sediments with the basalt was not recovered. The depth to the basalt corresponds to the deepest reflector recorded.

Site 152

This site is located on the lower slopes of the Nicaragua Rise in 3900 meters of water just above the Colombia Abyssal Plain. The seismic reflection records at the site show two prominent subbottom reflectors 0.3 seconds (reflection time) apart.

Continuous coring started above the upper acoustic reflector, an Eocene chert in chalk (Horizon A″). Siliceous limestones and chalks yielded one of the best (though not complete) planktonic sequences of Early Eocene to Early Paleocene age. All three major planktonic groups – foraminifera, Radiolaria, and nannofossils – coexist and are well preserved.

The Cretaceous sediments are also hard limestones and chalks, some silicified and containing chert. Volcanic constituents are nearly ubiquitous throughout the Site, and a basaltic ash layer was found in Campanian sediments overlying the basalts of Horizon B″. The basalt-limestone contact was not recovered, but large recrystallized limestone fragments containing Campanian foraminifera were found as inclusions in the basalt.

Site 153

Site 153 lies in the Aruba Gap, the area lying between the southernmost end of the Beata Ridge and the South American continental margin. The site is in 3932 meters of water and was drilled to a depth of 776 meters below the ocean floor. The main objective of this site was to penetrate Horizon B″ with the hope of recovering samples of the layered rock indicated by processed industrial seismic records. Basalt corresponding to the depth of Horizon B″ was reached but not penetrated.

Clays to marls comprise the dominant range of lithologies in the Middle Eocene and younger sediments. This is based on only five spot cores. These soft sediments overlie hard siliceous limestones and cherts of Early Eocene age that correspond to Horizon A″. Limestones, clays, and chert are the basic lithologies of the sub-Horizon A″ section. Clays and marls of the Paleocene overlie a silicified breccia resembling the "hard ground" of Site 151. The underlying Cretaceous limestone is interlayered with carbonaceous, phosphatic, volcanic clay that contains abundant fish debris.

The sediment-basalt contact was not recovered. The very fine grain size and vitric groundmass of the uppermost basalt is suggestive of a flow.

Site 154

This site is located 210 km north of Panama on a topographic high that rises above the Colombia Abyssal Plain and is capped by a section of acoustically transparent sediment. A strong reflector underlies the transparent sediment at a depth of about 0.2 seconds (reflection time). The hole was cored to a depth of 278 meters below 3338 meters of water.

Two major lithic units were recovered: an upper calcareous marl (transparent sediments) overlying a volcanic-terrigenous sequence which correlates with the depth of the strong seismic reflector (178 meters). The marls range in age from Early Pliocene to Pleistocene. The volcanic-terrigenous sediments consist of volcanic sands, silts, and clays of Late Miocene to Early Pliocene age and contain minor amounts of wood debris and reworked fossils. Methane gas was encountered in the volcanic sands, causing expansion voids in the core.

BIOSTRATIGRAPHY

Pleistocene and Pliocene

The most significant new biostratigraphic information obtained from studies of cores taken on Leg 15 is from the Pliocene-Pleistocene interval.

A refinement of the existing zonation for this sequence is proposed by Bolli and Premoli Silva (this volume). In the Pliocene, the new breakdown is a confirmation of what was already suggested by the Leg 4 results, the main change being centered on the recognition of *Globorotalia margaritae evoluta*; this subspecies was defined in the Mediterranean by Cita (1972). Leg 15 results also allow separation of the *Globorotalia exilis/miocenica* Zone of Leg 4 into two subzones; the boundary between them being based on the extinction point *Globigerinoides trilobus fistulosus.*

Site 147, drilled in the Cariaco Trench, provided an excellent section through the later Pleistocene and Holocene and enabled a subdivision to be made of the *Globorotalia truncatulinoides truncatulinoides* Zone which was confirmed and extended downwards using Site 148, on the Aves Swell, and Site 154, in the Colombian Basin. A summary of these results is given on Figure 12 of Bolli and Premoli Silva (this volume). The amount missing from the top of both Site 148 and Site 154, as compared with Site 147 and the *Vema* piston core 26-119, is graphically illustrated on Bolli and Premoli Silva's Figure 13 and shows the problems of obtaining the youngest layers when these are thin.

Quantitative changes in planktonic foraminiferal assemblages through the Late Pleistocene and Holocene of Site 147 are fully documented by Bolli and Rögl (this volume). It must be emphasized that these changes, and the subzonal subdivison for this interval, are subject to local climatic control and must be tested out with this in mind.

A large number of important biostratigraphic events occur within the Pliocene-Pleistocene interval. Documentation of these results is included below because it represents a significant increase in biostratigraphic knowledge for the Caribbean area.

The highest stratigraphic event recognized as being of significance is the lowest occurrence of *Globorotalia fimbriata*, which is correlated with the Pleistocene – Holocene boundary and believed by Rögl and Bolli to have an age of 11,000 years B.P.

The lowest occurrence of *Globorotalia fimbriata* overlies the highest occurrence of *Syracosphaera clava*, which in turn overlies the highest occurrence of *Syracosphaera decussata* at Site 147. These same events are probably present in Site 149, but all lie between samples from the base of the first core and a sample from near the top of the second core, suggesting a condensed sequence.

The highest occurrence of *Syracosphaera decussata* overlies the highest occurrence of *Gephyrocapsa kamptneri* in Sites 147, 148, 149, and Hole 154A, so this sequence is consistent in widely separated parts of the Venezuelan and Colombian basins.

The relation of the next pair of events is less certain. The highest occurrence of *Gephyrocapsa kamptneri* overlies the highest occurrence of *Globorotalia tumida flexuosa* at Site 147, but the relation is indeterminate at Hole 154A. This relation between a calcareous nannofossil and planktonic foraminifer would be important in establishing a fine dual zonation and should be investigated further in piston cores from the area. The highest occurrence of *Globorotalia tumida flexuosa* in this area is believed by Rogl and Bolli to be 80,000 years B.P.

The highest occurrence of *Globorotalia tumida flexuosa* overlies the highest occurrence of *Globorotalia hessi* at Sites 148 and 149; the relation is indeterminate at Hole 154A.

The relationship between the highest occurrence of *Globorotalia hessi* and the highest occurrence of *Gephyrocapsa sinuosa* is indeterminate at Sites 148 and 149 and Hole 154A, but the distribution of samples suggests that the former may overlie the latter.

The highest occurrence of *Gephyrocapsa sinuosa* consistently overlies the lowest occurrence of *Emiliania huxleyi* in Sites 147, 148, and 149 and Hole 154A.

In Site 147, the lowest occurrence of *Globigerinoides hexagona* and *Emiliania huxleyi* overlies the highest occurrence of *Globigerinoides hexagona*, which in turn overlies the lowest occurrence of *Globigerina calida calida*.

The lowest occurrence of *Globigerina calida calida* overlies the highest occurrence of circular forms of *Pseudoemiliania lacunosa* in Sites 147, 148, and 149 and Hole 154A.

The highest occurrence of *Pseudoemiliania lacunosa* having a circular outline is consistently above that of forms having an elliptical one. This relationship has been noted in Sites 30 and 31 drilled on Leg 4, and in Sites 148 and 149 and Hole 154A of Leg 15.

The relationship between the highest occurrence of elliptical forms of *Pseudoemiliania lacunosa* and the lowest occurrence of *Globorotalia hessi* is also consistent and is known at even more sites. It has been found in Sites 30 and 31 of Leg 4 and in Sites 148, 149, 151, and 154 and Hole 154A of Leg 15. This is especially useful, as it provides a ready means of subdividing the *Globorotalia hessi* Subzone of the *Globorotalia truncatulinoides truncatulinoides* Zone; the base of the subzone being defined by the lowest occurrence of the name species.

The relationship between the lowest occurrence of *Gephyrocapsa oceanica* and the lowest occurrence of *Globorotalia hessi* is less clear. *Pseudoemiliania emiliania lacunosa* consistently has its highest occurrence above the lowest occurrence of *Gephyrocapsa oceanica*; but the lowest occurrence of *Gephyrocapsa oceanica* overlies the lowest occurrence of *Globorotalia hessi* at DSDP Sites 30 and 31, and Hole 154A; lies beneath it at Site 148; and the relationship is indeterminate at Sites 29, 149, and 151. Present evidence is that the two events very nearly coincide in the Caribbean.

The lowest occurrence of *Globorotalia hessi* overlies the highest occurrence of *Globorotalia crassaformis viola* in Sites 29 and 31 of Leg 4, 148 and 151 of Leg 15; and the relationship between these two events is indeterminate in Site 30 and Hole 154A. The lowest occurrence of *Gephyrocapsa oceanica* overlies the highest occurrence of *Globorotalia crassaformis viola* at Sites 29, 30, and 31 of Leg 4 and in Site 151 and Hole 154A of Leg 15. The relation between this pair of events is indeterminate in Site 148.

The relationship between the highest occurrence of *Globorotalia crassaformis viola* and the lowest occurrence of *Globorotalia truncatulinoides truncatulinoides* is generally consistent; the former overlying the latter in Sites 29, 30, 148, and 151 and Hole 154A in this area. However, in Site 31, drilled on the Beata Rise during Leg 4, the relation between this pair of events appears to be reversed. The lowest occurrence of *Globorotalia truncatulinoides truncatulinoides* is widely accepted as the base of the Pleistocene and is considered to have an age of 1.8 million years. This event marks, by definition, the base of the *Globorotalia crassaformis* Subzone, the lowest subunit of the *Globorotalia truncatulinoides truncatulinoides* Zone.

The lowest occurrence of *Globorotalia truncatulinoides truncatulinoides* and the highest occurrence of *Discoaster brouweri* closely approximate each other. The former overlies the latter in Sites 30 and 148, both on the Aves Swell, but the opposite relation was found in Site 29, drilled in the Venezuelan Basin during Leg 4. The relation between this pair of events is indeterminate in Sites 31 and 151 and Hole 154A.

The highest occurrence of *Globigerinoides trilobus fistulosus* overlies the highest occurrence of *Discoaster surculus*, which marks the top of the *Discoaster surculus* Zone, in Site 148 and Hole 154A.

The highest occurrence of *Discoaster surculus* overlies the highest occurrence of *Globorotalia margaritae evoluta*, which marks the base of the *Globigerinoides trilobus fistulosus* Subzone of the *Globorotalia miocenica* Zone in Site 148. No definite relationship between these events can be established in Hole 154A because of the rarity there of the calcareous nannofossil in this part of the sequence.

The highest occurrence of *Globorotalia margaritae evoluta* must, of course, overly the lowest occurrence of the same species. This interval is the *Globorotalia margarita evoluta* Subzone of the *Globorotalia margaritae* Zone, and apparently there are no biostratigraphic events known which can subdivide it in a consistent manner. The lowest occurrences of *Globorotalia inflata A*, *Globorotalia exilis*, *Globorotalia miocenica*, and *Sphaeroidinella dehiscens* all lie within this interval, and further investigation may demonstrate one or more of these to be useful.

The highest occurrence of *Sphenolithus abies* lies below the lowest occurrence of *Globorotalia margaritae evoluta* and above the highest occurrence of *Reticulofenestra pseudoumbilica* in Site 148 and Hole 154A.

The highest occurrence of *Reticulofenestra pseudoumbilica*, which marks the base of the *Discoaster surculus* Zone and top of the *Reticulofenestra pseudoumbilica* Zone, overlies the lowest occurrence of *Pulleniatina obliquiloculata primalis*.

The relationship between the highest occurrence of *Discoaster brouweri* and the lowest occurrence of *Globorotalia inflata* is indeterminate, the former overlying the latter in Hole 154A and the opposite relationship being found in Site 148.

The lowest occurrence of *Globorotalia inflata* overlies the highest occurrence of *Globorotalia exilis* in Site 148 and Hole 154A.

The highest occurrence of *Globorotalia exilis* overlies the highest occurrence of *Globorotalia miocenica* and the lowest occurrence of *Globorotalia truncatulinoides* cf. *tosaensis* in Site 148 and Hole 154A, but the relationship between the latter two events is indeterminate at both sites. Bolli and Premoli Silva have chosen to alter the definition of the base of the *Globorotalia truncatulinoides* cf. *tosaensis* Zone to be the highest occurrence of *Globorotalia miocenica*.

The highest occurrence of *Globorotalia inflata A* overlies the highest occurrence of *Discoaster pentaradiatus* in Hole 154A; the relation is indeterminate but not inconsistent in Site 148.

The highest occurrence of *Discoaster pentaradiatus* overlies the highest occurrence of *Globigerinoides obliquus extremus* in Site 148 and Hole 154A.

The highest occurrence of *Globigerinoides obliquus extremus*, overlies the highest occurrence of *Globigerinoides trilobus fistulosus* at Site 148. The highest occurrence of *Globigerinoides trilobus fistulosus*, marks the base of the *Globorotalia exilis* Zone of Bolli and Premoli Silva in Site 148 and Hole 154A.

Relations in the early Pliocene, particularly between calcareous nannofossils and planktonic foraminifera, are still largely unknown in this area. Deep-sea sediments of this age have not been recovered in calcareous facies in holes drilled thus far.

Miocene and Oligocene

The major site for this interval is 149, which was continuously cored to give as far as possible a "standard biostratigraphic section" for the central Caribbean and one that could be compared with results already obtained from Site 29 of Leg 4. The overall result was achieved, though drilling disturbance caused considerable complication through the Pliocene and topmost Miocene.

As regards the foraminiferal results for the interval, dissolution of the tests poses the major problem through the upper part of the Middle and the Late Miocene and, in Site 149, also affects older zones (Figure 12, Bolli and Premoli Silva, this volume). However, the figure does illustrate the considerably greater success obtained from Site 149 than from Site 29 where a number of missing intervals, that might have been considered due to hiatuses, are now seen to be due to poor recovery at the earlier site. No improvement on the present zonation is possible using the Leg 15 results due to the frequency of poor preservation.

The apparent absence of the *Globigerinoides ruber* zone of the Middle Miocene from both land and marine sections in the Caribbean area is further confirmed by the Leg 15 results.

Early Oligocene, as represented by the *Cassigerinella chipolensis/Hastigerina micra* zone, has not so far been found in any marine site, though it is present in a number of land sections.

The nannofossils of the upper part of the Miocene show less disturbance due to coring in Site 149 than do the foraminifera, and it has been possible to establish a good zonation here and through most of the rest of the Miocene and Oligocene. Dissolution is again a problem though not to the extent found in the foarminifera. Comparison of nannofossil and foraminiferal ranges, as documented in detail elsewhere in this volume and as summarized on the charts (contained in the back pocket), shows the considerable refinement of earlier knowledge that is an outcome of the drilling of Site 149.

A study of the Radiolaria from Leg 15 has confirmed earlier findings that this group of microfossils is almost entirely missing from Caribbean sediments younger than Early or Middle Miocene. This is discussed by Riedel and Sanfilippo (this volume) and is graphically shown on their Figure 1. In Sites 149, 151, and 153, cores in the Early Miocene and Middle and Late Oligocene contain a reasonable radiolarian fauna which allows zonation and comparison with the other microfossil groups.

Middle and Late Eocene

This interval, as represented by the continuously cored section of Site 149, is almost totally devoid of planktonic foraminifera; it is also poor in nannofossils, which have suffered badly from solution though they are present in enough numbers to allow a zonation.

The semi-indurated Radiolaria oozes and Radiolaria-nannofossil chalks of Cores 31 through 43 of Site 149 have enabled the first good Radiolaria zonation to be produced for this interval in the Caribbean area (Riedel and Sanfilippo, this volume). The lack of foraminifera has made a direct tie with the standard planktonic zonation difficult, though the presence of a somewhat sparse nannofossil flora has allowed some bridging of the gap. The charts (back pocket of this volume) are a first attempt at an overall correlation.

From Venezuela, Trinidad, and Barbados, indurated radiolarian oozes and chalks containing Radiolaria, foraminifera, and nannofossils are known, though the preservation of the microfossils is frequently rather poor. Where possible, correlations have been made between the fossil group (see e.g., Hay, 1967), but the rather unsatisfactory results achieved so far led us to hope for a better return from the Caribbean basins; we remain disappointed in this aspect of the work.

Early Eocene

A planktonic foraminiferal fauna is developed in the lower part of the Early Eocene where a new zone, the *Globorotalia edgari* Zone, has been erected. The best section is in Site 152 where the *Globorotalia edgari* Zone and the overlying *Globorotalia subbotinae* Zone are recognized. The *Globorotalia edgari* Zone has been erected from the Leg 15 results (Premoli Silva and Bolli, this volume) for an interval at the base of the Eocene that was already recognized as probably being absent when the original zonation was set up in Trinidad (Bolli, 1957). It has now been recovered from Sites 146, 150, 151, and 152. The *Globorotalia subbotinae* Zone, recognized only in Site 152, replaces the *Globorotalia rex* Zone of Bolli's Trinidad zonation (1957). The next younger *Globorotalia formosa formosa* Zone has been found in Sites 151 and 153, but above this level planktonic foraminiferal faunas virtually disappear.

Nannofossil assemblages in the Early Eocene are poor.

Radiolaria from the Early Eocene are found in Site 146 (Cores 5 to 7) and Site 152 (Cores 1 to 3). The *Globorotalia edgari* Zone corresponds to the *Bekoma bidarfensis* Zone.

Paleocene

From no site on Leg 15 has a complete sequence of the Paleocene been recovered. Of the eight foraminiferal zones used in this volume (charts in back pocket), six have been definitely identified, with four recorded from the most complete location, Site 152. Nowhere has the *Globorotalia pseudomenardii* Zone been found. Nannofossil results suggest that the top of the *Globorotalia pusilla pusilla* Zone, the whole of the *Globorotalia pseudomenardii* Zone, and the base of the *Globorotalia velascoensis* Zone may be missing in the deep Caribbean. This could represent as much as four million of the eleven million year span of the Paleocene. The missing section belongs to the *Discoaster gemmeus* and *Heliolithus riedeli* zones. There exists a possibility that all, or a part of the missing interval, is represented by indurated siliceous sediments recovered from Site 152 (Core 5).

At Site 152 (Core 10), a single sample contains a well-preserved assemblage of the *Globigerina eugubina* Zone of basal Paleocene age. This is the first time that this stratigraphic level has been identified in the Caribbean area; the preservation of the fauna of Site 152 is better than that from the type area of central Italy. The assemblage is associated with an intraformational breccia that rests directly on early Middle Maastrichtian chalk. No nannofossils were found in the *Globigerina eugubina* sample, though the section above can be zoned with the exception of the missing interval of the *Discoaster gemmeus* and *Heliolithus riedeli* zones.

Radiolaria are present in the Paleocene of Sites 152 and 153 but are poorly represented and not well preserved. The *Bekoma bidarfensis* Zone can be recognized at the top of the interval, but the rest of the section is placed in an "unzoned interval" by Riedel and Sanfilippo (this volume).

Late Cretaceous

Of the three microfossil groups studied in the Late Cretaceous sections of Leg 15, only the planktonic foraminifera have so far proved of value. The nannofossils are present only as monotonous assemblages of long ranging forms. This is a feature of this time interval where the deep-sea forms are long ranging and only on the shelves has good diversity been found. The species found are the robustly constructed, resistant ones, and even these are badly preserved in many instances. In considerably parts of the section in Site 146, the chalks have a groundmass that appears to be composed of fragments derived from calcareous nannofossils, but these are unrecognizable. In Site 152, the floras are somewhat more diverse and better preserved than in the other sites. The results from Leg 15 have not allowed the erection of a firm nannofossil zonation in the Late Cretaceous.

The Radiolaria have not been exhaustively studied, but, even when this is done, it is unlikely that a refinement of presently used zonation will be possible. In Sites 150, 151, 152, and 153, Radiolaria are either absent or poorly represented and often somewhat dissolved. In Site 146, the normal radiolarian faunas from the Late Cretaceous section are sparse with rare and only moderately well-preserved specimens, representing a small number of taxa. In addition, a number of "sandy" layers contain common to abundant, poorly preserved radiolarians, representing large numbers of taxa. A discussion of this fact is given in the site report for Site 146, and the suggestion is made that the second group is allochthonous and has been transported into the area by some mechanism such as turbidity currents.

The zonation used for the Late Cretaceous planktonic foraminifera is largely that erected by Bolli (1957) with minor modifications due to later taxonomic changes. In Premoli Silva and Bolli (this volume), there is a discussion of zonal schemes presently in use, with a review of the megafossil evidence for the allocation of these zones to the classical European stages (ibid., Figure 6).

The importance of the foraminiferal work on the Leg is illustrated by its contribution to the dating of the basalts and dolerites of Horizon B″. Fortunately, good control was available from the limestones associated with the igneous rocks and the overlying basaltic ashes. The youngest occurrence of basaltic ash is within the *Globotruncana elevata* Zone of the Campanian, the earliest within the *Globotruncana schneegansi* Zone of the Late Turonian to Early Coniacian; this is also the age range through which the basaltic and doleritic flows and sills are found. The question of the age of the sediments in contact with the igneous rocks is fully discussed in Premoli Silva and Bolli (this volume).

Site 146 has produced the first continuously cored section through a complete succession of the upper part of the Late Cretaceous in the Caribbean. All planktonic foraminiferal zones from the Late Turonian–Early Coniacian *Globotruncana schneegansi* Zone to the Late Maastrichtian *Abathomphalus mayaroensis* Zone are recognized here, though assemblages are often poor suggesting deposition below the lysocline (Premoli Silva and Bolli, this volume). Levels of sandy textured limestones are found, and these are frequently rich in planktonic foraminifera. Introduction of allochthonous material is again suggested as it is on the radiolarian findings.

All Cretaceous sites, other than Site 146, show considerable hiatuses with varying time intervals at the top of the Late Cretaceous missing. Particularly large is the missing section at Site 150 where the Late Santonian, Campanian, and Maastrichtian are absent; the Early Eocene *Globorotalia edgari* Zone resting directly on probable *Globotruncana concavata* Zone of the Late Santonian. The time interval involved is approximately 25 million years. At Site 151, a "hard-ground" replaces the time interval from the Late Santonian *Globotruncana concavata concavata* Zone to the *Globorotalia trinidadensis* Zone within the Early Paleocene; this represents a break of 5 to 6 million years. At Site 153, an intraformational breccia is found at the contact of the Cretaceous and Tertiary where the *Globigerina eugubina* Zone at the base of the Paleocene rests directly on the *Globotruncana gansseri* Zone of the early Middle Maastrichtian.

The presence of large hiatuses in the deep Caribbean Sea was first proved by results from Leg 4 and has gained much more strength from the Leg 15 results. It is a most interesting aspect of the results of the drilling has received special attention in two papers in this volume (Edgar et al.; Premoli Silva and Bolli). The particular question of the abruptness of the change between the Late Cretaceous and the base of the Tertiary is also reviewed by Premoli Silva and Bolli. They remark on the fact that DSDP results from this and other legs show the break to be possibly more accentuated in the deep-sea basins than in shallower-water deposits exposed on land. Evidently, the events which results in the abrupt change of organic life at the end of the Cretaceous affected the water masses of the open oceans more than those of nearshore and shelf areas.

A point of interest from a study of the individual planktonic foraminiferal species is the presence in the Late Turonian-Early Coniacian of Sites 146, 150, and 153 of *Globotruncana cachensis* which is considered to be endemic to the Pacific area. This gives some support to an open connection between Pacific and Caribbean waters at that time.

LITHOLOGIC SUMMARY[1]

Introduction

Although the holes drilled during Leg 15 were entirely within the Caribbean Sea, and none were more than a few hundred kilometers from continental land, this proximity to land was not impressively reflected in sediment lithologies (with the exception of Site 147, which was located in a basin within the continental shelf of South America). Sediment types included almost the entire spectrum of pelagic lithologies, including calcareous (oozes, chalks, limestones), siliceous (oozes, cherts, siliceous clays), brown clays, zeolitic clays, volcanic ashes, and reduced, or sapropelic, limestones and clays. Sands of evident terrestrial origin were limited to the lower parts of Sites 148 and 154 and appeared in miniscule quantities as thin turbidite beds, or as dispersed turbiditic debris, at several Venezuelan Basin sites.

The lithologies are discussed under six headings; four are basic divisions reflecting changes in lithologic type within particular time intervals and the remaining two are used to discuss special sedimentary environments.

Lithologies of the Late Turonian/Coniacian-Santonian

The oldest sediments recovered on Leg 15 are varicolored limestones and carbonaceous (sapropelic) clays (see Frontispiece C, dark layers are carbonaceous). The limestones are thoroughly lithified, burrowed, and pale-colored, with abundant burrows and minor chert (Frontispiece D). Both Radiolaria and foraminifera are abundant in thin section, and preservation is commonly good (with, however, calcitic infilling of chambers). Burrows are generally either of the *Zoophycos* type, or of less distinguished horizontal types, flattened into a variety of elliptical shapes. One of the most outstanding characteristics of these limestones is the abundance of fish bones, many of which are very well preserved. Barite and pyrite (large nodule shown in Frontispiece C) are widespread. Clay beds interbedded with the limestones at

[1] A more detailed treatment of several of the matters discussed in this summary account are found in individual site reports and in Chapters by Donnelly (Circum-Caribbean Volcanic Activity. . .), Donnelly et al. (Basalts and Dolerites. . .), and Roberson.

Sites 146/149, 150, and 151 derive their color from greenish mica (glauconite?). Their chemical composition is essentially that of the basalt drilled at these sites,[2] and the clays are interpreted as basaltic ash. Potassium addition is reflected not only in the mica but, in several cases, in authigenic K-feldspar. Similar feldspars have been reported on Legs 11 (Lancelot et al., 1972) and 14 (Berger and von Rad, 1972). In both cases the term "sanidine" was used to describe the minerals. The K-feldspar of Leg 15 would appear to be very similar; however, its optic angle is not typical for sanidine and its euhedral habit and large content of inclusions indicate that it is of low-temperature origin.

At Site 146/149 these greenish clays occur with basaltic sands which consist of altered palagonite clinopyroxene, and plagioclase grains (Figure 4). These sands are interpreted as basaltic ash beds which may have been fragmented by thermal shock (rather than by explosion of entrained volatiles, which is virtually impossible at abyssal depths) and accumulated as local turbidites in topographic lows.

Interbedded with the limestones and clays at Site 146/149 are radiolarian sands, which commonly have sharp lower contacts. These beds, whose high degree of sorting reflect a content of uniformly sized particles, are interpreted as intra-basinal turbidites. The superior preservation of the Radiolaria in the sands indicates that their initial accumulation was in less corrosive, and, presumably, shallower waters than the place of final deposition.

The general character of the sediments of this interval are reminiscent of coeval and slightly older sediments of the western North Atlantic (Lancelot et al., 1972) and the central-southern North Atlantic (Berger and von Rad, 1972). Distinguishing characters of the Leg 15 sediments, however, are the presence of recognizable basaltic ash (directly above and obviously related to the basalt/dolerite acoustic basement of the Caribbean) and the abundance of well-preserved phosphatic debris.

Lithologies of the Late Cretaceous-Early Tertiary

The mixed lithologies characteristic of the Coniacian-Santonian give way upwards to a more monotonous radiolarian limestone which, in turn, gives way to a siliceous clay at Site 146/149. At Sites 152 and 153, limestone or chalk persists upward to the level of Horizon A″ (early and middle Eocene). At Sites 150 and 151, little recovered sediment was identifiable within the interval between the Santonian and Horizon A″.

The typical calcareous sediment of this interval is a thoroughly recrystallized compact limestone, rich in moderately to poorly preserved Radiolaria and foraminifera. The limestones are thoroughly burrowed, exhibiting a broad range of exceptionally well-preserved (Figure 5 and Frontispiece B) horizontal, and vertical burrow types. No opaline material is present; Radiolaria are generally represented by chalcedonic (at greater depths) or cristobalite (at shallower depths) micronodules. Barite and clinoptilolite are widespread, but fish debris, although widespread, are less conspicuous than in the older interval.

Interbedded with the calcareous sediments are marly layers whose clay content undoubtedly originates in large part from altered volcanic ash. Crystals of biotite, quartz, alkali feldspar, zircon, and apatite are widespread (Donnelly, Circum-Caribbean Explosive Volcanic Activity. . ., this volume), and the montmorillonite is thoroughly bentonitic in character (Roberson, this volume).

At each site with a representative recovery of this interval, the silica content is persistent or increasing upwards. At Site 146, the carbonate decreases to nil in the Maastrichtian, and the later Maastrichtian-Paleocene section is dominantly siliceous (cristobalite-montmorillonite-clinoptilolite) clay with scattered cherts. At Site 153, the limestones of this interval persist throughout but are conspicuously, locally silicified upwards. At Site 152, the carbonate content is lower in the early Tertiary.

The radiolarian sands, which are conspicuous at Site 146 in the Santonian, are present in this interval but diminish in abundance upwards and disappear in the middle Maestrichtian. Dark beds rich in reduced carbon or altered basaltic ashes are totally absent from this interval, and pyrite is rare. One mineral of interest is of brownish garnet, which is considered to be authigenic spessartite (Donnelly and Nalli, this volume).

Early Tertiary Silicified Limestones and Cherts

Horizon A″, which is persistent through most of the Venezuelan Basin and much of the Colombian Basin, has been identified at Site 146/149 with the onset of lithification (Seismic Reflectors, this chapter), which occurs at the early and middle Eocene. At this level, radiolarian oozes and foraminiferal-nannofossil-radiolarian oozes and chalks give way to cristobaltic chert and interbedded compact chalks and limestones (Figure 6). Low recoveries in this interval prevent a complete assessment of the proportion of the rock types involved, but drilling rates suggest that a few relatively thin cherts occur interbedded with limestones and less lithified materials The lithification boundary is fairly sharp; however, the unlithified sediments above the first chert are noticeably more compact that the overlying oozes, and cristobalite, which is characteristic of the lithification process, first appears in the core barrel above the chert.

Beneath the chert at Site 146/149, no opaline material appears, porosity abruptly decreases, and clinoptilolite and cristobalite are widespread. The formation of the chert involves redistribution of silica from radiolarian tests, but the silica content of the chert itself is no higher than that of compact siliceous clays beneath the chert (Donnelly and Nalli, this volume). Therefore, no addition of silica relative to unlithified beds is required; the process of chertification is one of recrystallization and not silicification.

At Site 150, the chert appears at approximately the same stratigraphic horizon, although paleontological control at this site is weaker. At Site 151, Horizon A″ is absent and a pelagic sequence with notable sedimentary hiatuses (evidently most of the Eocene and Paleocene is missing) rests on a hard ground of silicified, brecciated foraminiferal limestone. Beneath the limestone only drilling rubble was

[2]Recent, and unpublished, rare-earth analyses of one of these clays by Donnelly shows a rare-earth pattern identical to the underlying dolerite (Site 146/149).

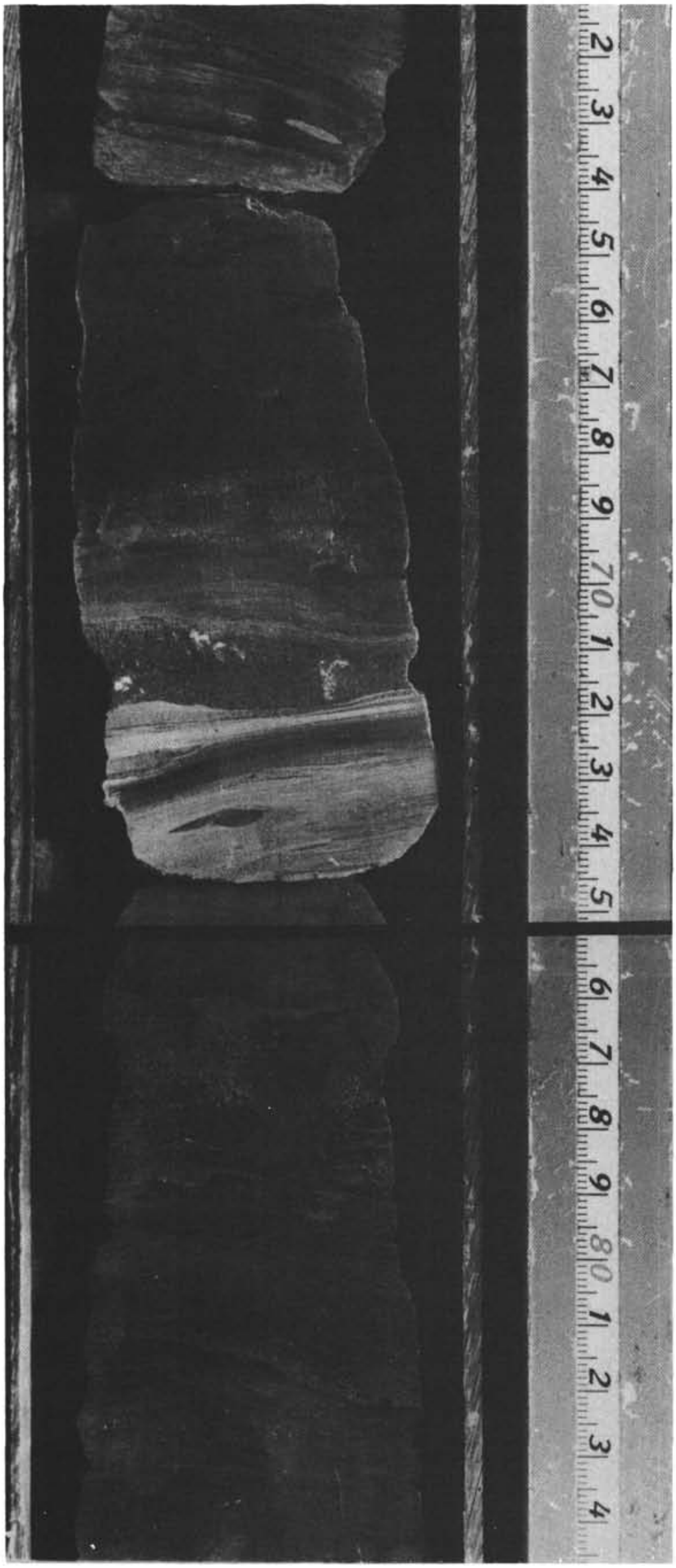

Figure 4. *Photograph of basaltic ash beds (sands) of Late Turonian-Coniacian age at Site 146/149 (146/149-39R-2). Prominent beds of basaltic ash are at 71-72 cm, 76-68 cm and 82 cm.*

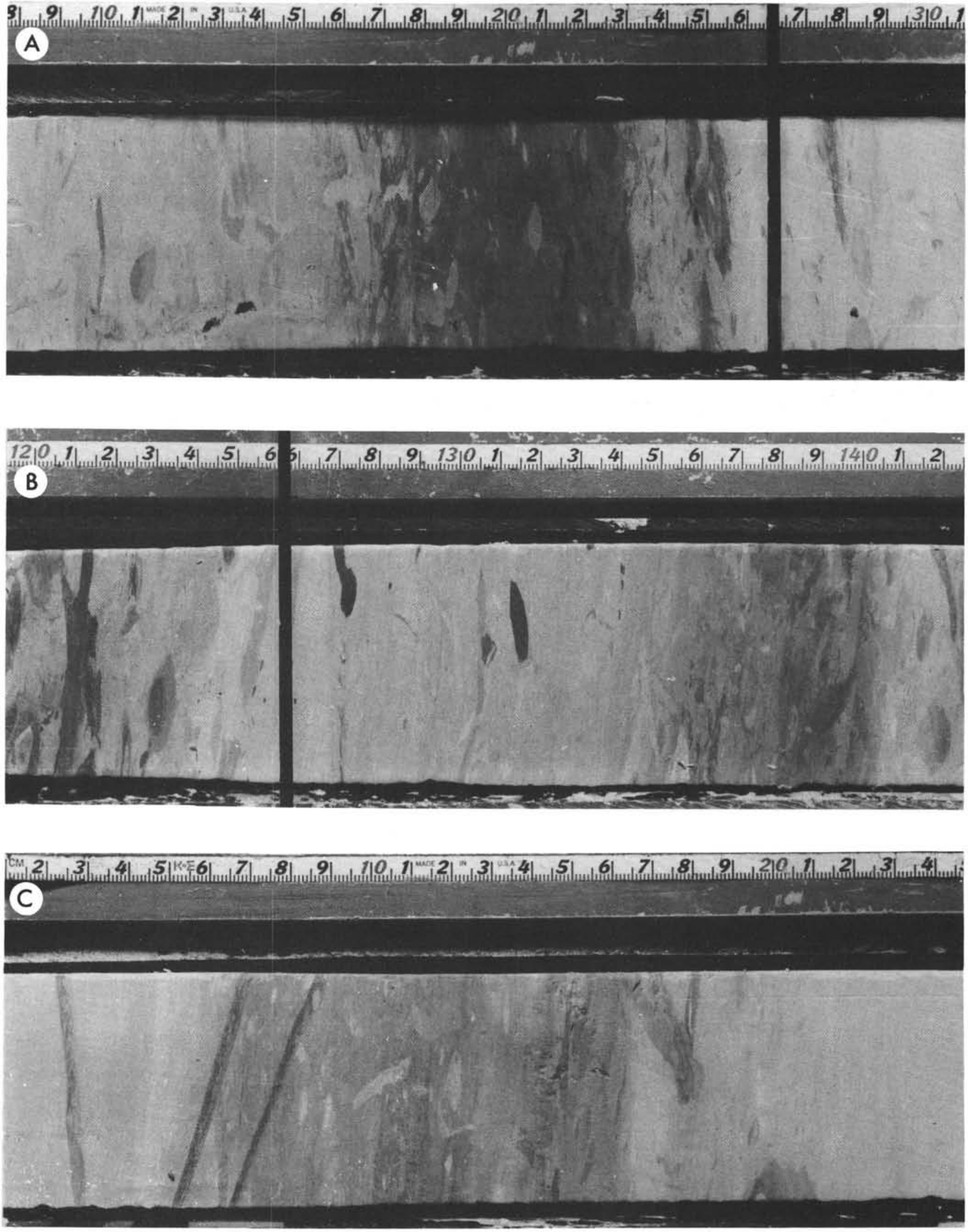

Figure 5. *Photographs of well preserved biogenic structures typical of the Late Cretaceous sediments, "A" & "B" (Site 146/149-16-6) and "C" (Site 146/149-18-4). Straight, subhorizontal features with chevron interval structures are* Zoophycos *traces.*

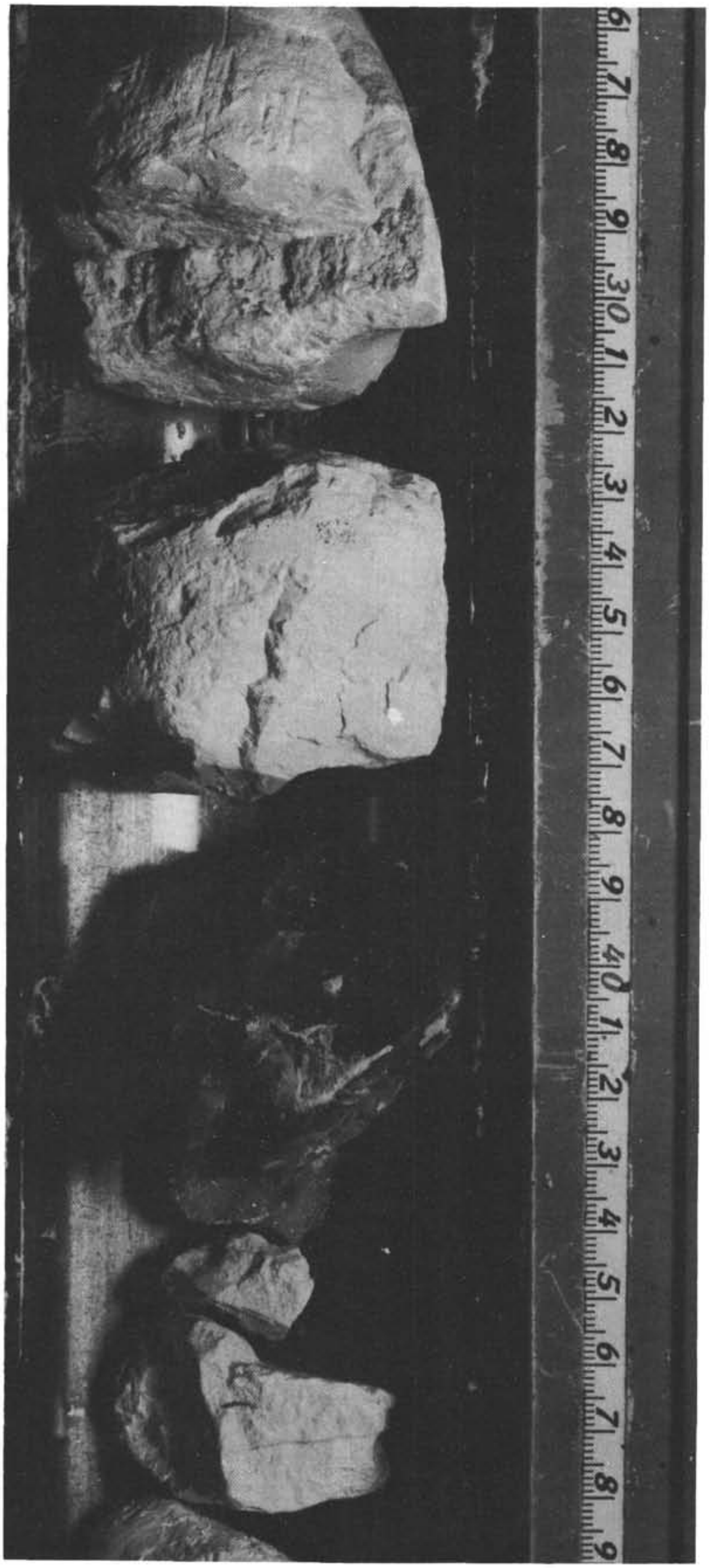

Figure 6. *Christobalitic chert and limestones of the lithified unit of Early and Middle Eocene age. The top of this unit correlates with the seismic reflector Horizon A″.*

recovered, and the only dates obtained were Santonian; consequently, we do not know whether, or not, there might have occurred here a later Cretaceous section analogous to that at Site 146/149. However, from the drilling intervals, such a section would have to be very thin.

Site 152 has a more calcareous, thicker lower Tertiary and late Cretaceous section than Site 146/149. Horizon A″ was cored with relative ease; limestones of varying degrees of silicification and scattered chert fragments were recovered. In the Late Paleocene part of this section, fresh radiolarian remains and unaltered volcanic glass is widespread, but, beneath the middle Paleocene level, preservation of both of these deteriorates and cristobalite becomes widespread.

At Site 153 beneath a moderate chert layer, Early Eocene to Campanian silicified limestones were drilled. Silicified limestones, with scattered chert nodules, occur. In Core 12 a silicified breccia, higher in carbonate but texturally reminiscent of the silicified hard ground at Site 151, occurs in a limestone sequence bracketed by early Paleocene and early Maastrichtian dates.

Middle-Late Tertiary Oozes and Clays: Venezuelan Basin

Sediments recovered above the level of Horizon A″ in the Venezuelan Basin vary in lithology from radiolarian oozes to calcareous (foraminifera-nannofossil) oozes, to brown clay. The radiolarian oozes are restricted to the Eocene of Sites 146/149 and 29, but Radiolaria, themselves, occur as high as Early Miocene at Sites 29, 146/149, 151, and 153. At Sites 151 and 153, the carbonate content throughout this interval is relatively high. The radiolarian oozes of Sites 29 and 146/149 are relatively unlithified, have variable carbonate contents (mainly as nannofossils; foraminifera are scarce and partially dissolved), and have widespread volcanic glass and plagioclase and pyroxenes. Fish teeth are common. Pumice lumps are scattered through the ooze, but only distinctive volcanic ash bed was seen in Site 146/149.

The radiolarian ooze grades upward (Oligocene to Early Miocene) at Site 146/149 into a radiolarian marl and thence into a foraminiferal-nannofossil ooze, similar to that found at Sites 151 and 153 in this interval. Oligocene sediments at shallower sites are more calcareous, except for 153, which is anomalously deep. At Sites 29 and 150, a hiatus between the Miocene and Eocene occurs; at Site 146/149, part of this interval is one of low carbonate and slow accumulation rate but no real hiatus occurs.

Foraminiferal-nannofossil oozes in the middle-late Tertiary of the Venezuelan Basin are unlithified or slightly compacted. Where there is some clay content and minimal drilling disturbance, they show some layering. Pyrite is a relatively scarce mineral. As discussed by Donnelly and Nalli (this volume), there are discrete and dispersed examples of turbidite terrestrial minerals at several levels in the Miocene and Pliocene sediments. Volcanic detritus occurs throughout but is noticeably less abundant in the Middle Miocene-Middle Pliocene (Donnelly, Circum-Caribbean Explosive Volcanic. . ., this volume).

Pelagic clays of the middle-late Tertiary are brownish and contain scattered anatase and dolomite crystals. Pyrite is variable but generally scarce. Native copper was found in the Pliocene of Site 146/149. Zeolites (phillipsite at higher levels, clinoptilolite at lower) are widespread in the middle Tertiary but absent in younger clays. The clay mineral assemblage of the clays change distinctively from the lower part of this interval (dominantly montmorillonite, of bentonitic character; Roberson, this volume) to the upper (dominantly mica, with kaolin and quartz).

The Miocene-Pliocene of the Aves Ridge and Southwestern Columbian Basin

Sites 154 and 148, although at the eastern and western extremities of the Caribbean, have so much in common that they are best discussed together. At both sites, pelagic Pliocene-Pleistocene marls and calcareous clays unconformably overlie coarse volcanic sands. At both sites, the contributions of Pliocene-Pleistocene volcanic activity are impressive, and both sites show high sediment accumulation rates.

The volcanic sands of Site 148 were poorly sampled; recoveries were limited and drilling disturbances so severe as to destroy original sedimentary structures. The sands are calc-alkaline igneous in character, with a minority of minerals of low-grade metamorphism. They are believed to be derived from an emergent volcanic island within the area of the Aves Ridge. On top of these sands is a phosphatic iron oxide coating, evidently representing weathering (possibly emergent, but most probably shallowly submergent). The overlying series of pelagic clays and marls accumulated rapidly throughout the Pliocene and Pleistocene. Pyrite is widespread throughout these clays, and marls and volcanic ash (mostly crystals; glass is rare) are especially common in the upper eight core barrels. Some authigenic carbonate (siderite?) occurs in several places. Glauconite, partly as fillings of foraminifera, is widespread. Nannofossils occur throughout, and foraminifera are well preserved. Echinoid spines and molluscan remains are also found. The low carbonate content results from a high accumulation rate of the noncarbonate sediment rather than from solution of the foraminifera or exceptionally high productivity.

The sequence at Site 154 is remarkably similar to that of Site 148. A lower volcanic sand was penetrated to nearly 120 meters. These sands are poorly graded and rich in organic matter (maximum 5.9 percent reduced carbon). The predominant constituents are calc-alkaline volcanic crystals including secondary phillipsite and clinoptilolite, but minerals of possible shallow plutonic or metamorphic origin also occur. Other debris includes benthonic foraminifera (possibly of shallow-water origin) and sporadic wood fragments, mollusc shells, and leaves. We interpret this sequence as being derived from Panamanian volcanic centers.

Overlying this sand sequence is a clay and marl pelagic clay very similar to that of Site 148. Fossils are well preserved and diverse, even with low total carbonate contents. The volcanic contribution is impressive but includes, in contrast to that of Site 148, abundant glass, phillipsite, clinoptilolite, and scattered authigenic K-feldspar. Again, pyrite is persistent and dolomite widespread.

The persistence of pyrite in these sections accompanies the higher content of reduced carbon (2 or 3 times the average for pelagic clays). Rapid accumulation hindered the decomposition of organic debris whose subsurface decomposition reduced pore-water sulfate to sulfide.

The Pleistocene Clays and Marls of the Cariaco Basin

The clays and marls of the Cariaco Basin represent a special case of a terrestrial source and an anaerobic site of accumulation. These clays are highly organic (maximum reduced carbon 4.5 percent but very few values less than 1 percent) with abundant pyrite and conspicuous, nearly pure beds of dolomite.

A persistent silty fraction of quartz and feldspar of terrestrial origin occurs throughout this sequence. Some metamorphic minerals (including glaucophane) suggest a provenance which includes the blue schist belt of northern Venezuela (as seen on Margarita Island, for example). The clay minerals are dominantly illite and kaolin, with montmorillonite very minor. The calcareous content varies from nearly nil to about one-half. Preservation of fossils is good. Pteropods are very conspicuous and echinoid spines common. Pollen is seen in many samples.

Summary

The sedimentation in the Caribbean is roughly divisible into three phases. In the earliest, lithologically mixed limestones include intercalations or organic clays with phosphatic remains indicating topographic ruggedness and local stagnation. Basalt ash reflects the very widespread basaltic eruptions of this interval. This episode gradually passes into a second phase: a more normal pelagic regime of carbonate accumulation, with a variable silica component depending on water depth, and with intercalated volcanic ash beds. In the Middle Eocene, lithification was widespread (with formation of chert) but is absent or reduced at some localities. Following this event, a third phase of pelagic sedimentation was dominated by Radiolaria which diminish in importance upward and disappear in the Early Miocene. During the third phase, clay minerals with a distinctive terrestrial (probably dominantly Amazonian) provenance appear and gradually increase in rate of supply upwards. Sites 148 and 154 reflect especially high accumulation rates of thin terrestrial debris. The intracontinental Site 147 represents an especially impressive supply of such debris deposited in a basin which was anaerobic during most of the time represented in the cores taken on this leg. In no case does vulcanism seem to provide the bulk of the non-calcareous sediment. However, the supply of terrestrial debris was so limited in the late Cretaceous-early Tertiary that, relatively speaking, the contribution of the volcanic debris was very important.

A consideration of sedimentation patterns for other Atlantic legs (notably 11, Lancelot et al., 1972 and 14, Berger and von Rad, 1972) shows the Coniacian-Santonian mixed lithologies with implied stagnation seen in both the western North Atlantic and south-central North Atlantic. In both cases it extends to earlier ages; however, failure to penetrate the widespread Caribbean basalts and dolerites of this interval prevented any deeper sampling here. The diminution in accumulation rates and the increasing importance of siliceous fossils in the late Cretaceous-early Tertiary is seen especially well in Leg 11 (Lancelot et al., 1972). The occurrence of cherts is somewhat sporadic in Leg 14 (Berger and von Rad, 1972), with several first occurrences slightly older (base of Eocene) and one younger (Early Miocene). In the western North Atlantic, cherts and other uppermost lithified sediments are approximately coeval with the Caribbean cherts (Ewing and Worzel et al., 1969; Peterson and Edgar et al., 1970; Ewing, J. et al., 1970). Following the chert interval, the increased sedimentation rates of the Caribbean are mirrored sharply in the Leg 11 sediments. The fluctuations of the lysocline (inferred to rise during the Middle Miocene-Early Pliocene) is reflected in the south and central Atlantic, although the Oligocene fluctuation upwards is not so clearly seen outside the Caribbean.

Very likely, the factors controlling Caribbean sedimentation are more regional than local. Undoubtedly, the opening of the Atlantic and development of marginal basins, the movement of South America relative to North America, uplift of South America in the Miocene, and the final closing of the Central American isthmus all played major roles in determining the distribution and character of the sediments, character of surface and deep currents, and the chemistry of the water mass.

SEISMIC REFLECTORS

Two prominent seismic reflectors that could be mapped over a wide area of the western North Atlantic were identified as Horizon A (Ewing, J., and Ewing, M., 1962) and, the deeper one, Horizon B (Ewing, J. et al., 1966). Similar reflectors were noted in other ocean basins and were designated Horizon A′ and B′ in the Pacific Ocean (Ewing, M. et al., 1966) and, in the Caribbean Sea, Horizon A″ and B″ (Ewing, J. et al., 1968).

In the Caribbean Sea, these two reflectors can be traced throughout most of the Venezuelan Basin, onto the eastern flank of the Beata Ridge, below the turbidites of the northern Colombian Basin and onto the southern flank of the Beata Ridge (Figure 7). It is uncertain if the layer extends into the southern Columbian Basin because of the failure of conventional oceanographic seismic systems to record layers deeply buried below thick terrigenous sediments found there. The uniformity in thickness of the sediment above and below Horizon A″ suggests that the two reflectors are approximately synchronous over the entire area.

Horizon A″ was first identified as chert from piston cores taken on a fault scarp in the southwestern part of the Venezuelan Basin (Talwani et al., 1966; Edgar, 1968). Subsequently, chert was recovered from early Middle Eocene sediments at Site 29, Leg 4 of the *Glomar Challenger* (Bader and Gerard et al., 1970), but the chert also prevented further penetration to Horizon B″. On Leg 15, Horizon A″ was penetrated at three sites (146, 152, and 153), and Horizon B″ was sampled at five sites (146, 150, 151, 152, and 153). Horizon A″ was not clearly identified at Sites 150 and 151 although chert is present at Site 150.

Although it can be said that Horizon A″ is approximately synchronous in the Caribbean Sea, there is a minor variation in age worth noting. At Site 146/149, Horizon A″ is fairly well identified as early Middle Eocene (*Theocampe mongolfieri; Discoaster sublodoensis*) although

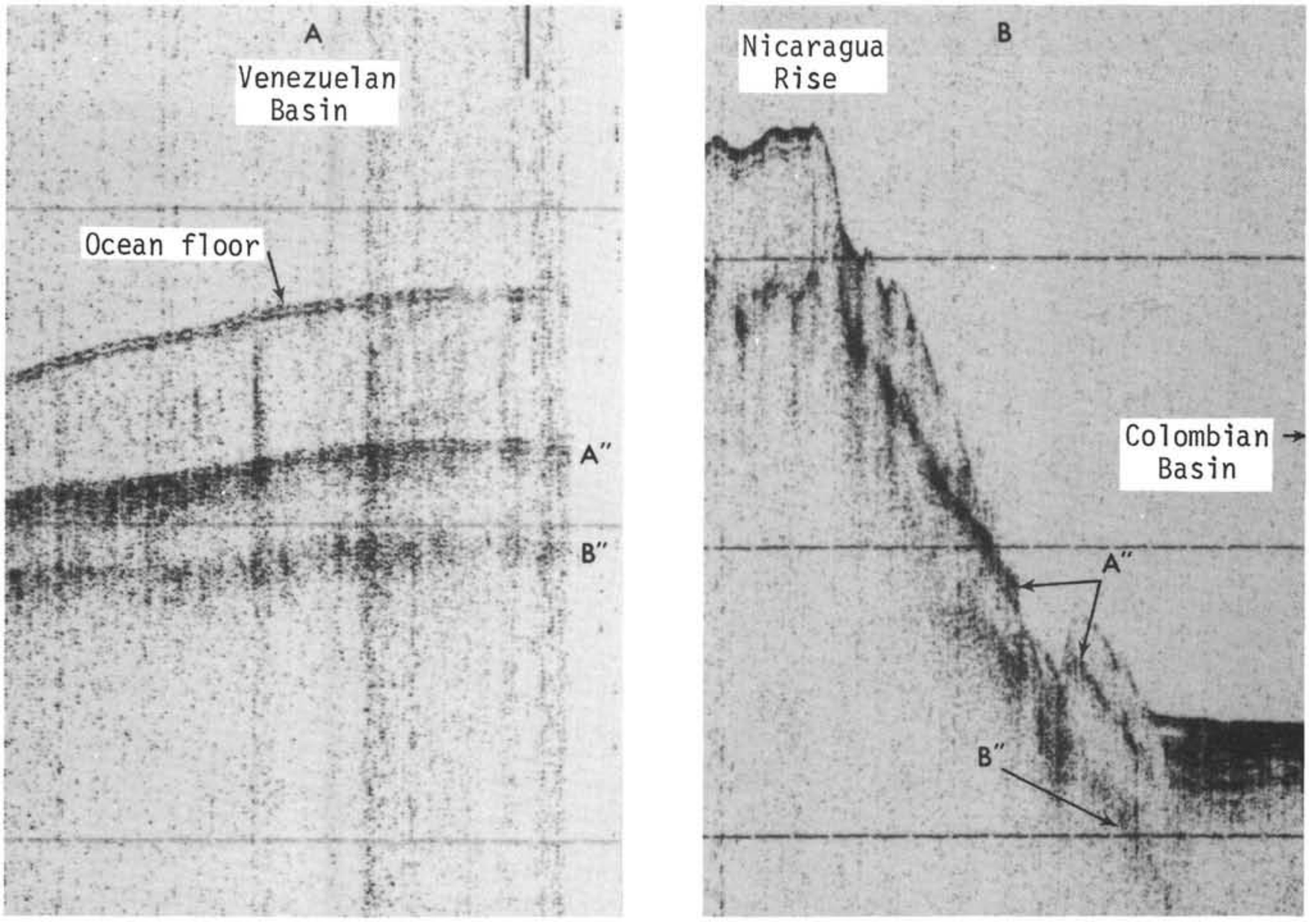

Figure 7. *Reflection profiler records showing reflecting Horizons A″ and B″ at (A) Site 146/149 in the Venezuelan Basin and (B) Site 152 on the lower flank of the Nicaragua Rise.*

no foraminiferal age determination is available. At Site 29, no calcareous microfossils were preserved, but hard chert layers identified with Horizon A″ were encountered in the *Theocampe mongolfieri* Zone of early Middle Eocene age.

Further to the west, at Site 153 in the Aruba Gap, the resistant layer at 555 meters (not cored) probably identifies Horizon A″. The underlying core (563 meters) of Early Eocene age suggests an Early Eocene date (*Globorotalia formosa formosa* for Horizon A″ in this area but does not preclude the possibility of an early Middle Eocene age.

On the lower part of the Nicaragua Rise, at Site 152, Horizon A″ was identified in Late Paleocene (*Globorotalia velascoensis; Discoaster multiradiatus*).

Chert is commonly associated with sediments at the Horizon A or A″ interval to the extent that chert has been thought to be responsible for the reflector. Leg 11 scientists (Ewing, J. and Hollister, 1972) recognized that other factors may be contributing to the reflection. They pointed out that Horizon A is a prominent reflector at Sites 101 and 105 where only minor amounts of chert were recovered and considered the impedance contrast across the early Tertiary hiatus as a possible alternative. A similar lack of thick chert beds at the level of Horizon A″ was noted in the Caribbean on Leg 15. Horizon A″ at Site 146/149 is associated with minor chert, siliceous limestone, and other carbonates. It was difficult to establish the proportions of each because of the poor recovery, but the drilling record indicates that only a few cherts were penetrated. At Sites 152 and 153 recovery was better. Siliceous limestones and very compact carbonates were encountered below soft oozes. Chert is present only in minor amounts suggesting that Horizon A″ is caused by the impedence contrast between the oozes and the underlying harder lithic unit as a whole. Very hard limestones were suddenly encountered at Site 153 and the drilling rate decreased sharply, but again, only minor chert was encountered.

It is concluded that Horizon A″ in the Caribbean results from the impedence contrast between oozes and underlying lithified sediment, commonly associated with silicification. Chert may be a minor or insignificant part of the overall lithologic change.

Horizon B″ is correlated with dolerites and basalts recovered at five locations throughout the Caribbean Sea. There was some question concerning the possibility that Horizon B″ could correlate with the top of the Late Turonian-Santonian limestones at Site 146, but the combined shipboard velocity data, drilling depth and reflection time data and sonobuoy measurements leaves little doubt that the reflector corresponds to the dolerites (site report 146/149, this volume).

The clear identification of a seismic reflector with the drill offers the opportunity to calculate the average velocity measured vertically through the sediment column. These were calculated at all sites except 150 where the level of the reflector in the sediment column is uncertain, and at Site 147 where no prominent reflector was recorded. These calculated velocities are shown adjacent to the sedimentary columns in Figure 8. The average velocity in the sediment above Horizon A″ is 1.63 km/sec. Sound velocity in the interval between Horizon A″ and B″ at Sites 146 and 153 is 2.5 and 2.6 km/sec, respectively, but in the younger Campanian-Maastrichtian sediments at Site 152 (Nicaraguan Rise), the velocity is only 1.9 km/sec. In the Venezuelan Basin, the velocities may be summarized as 1.63 km/sec down to Horizon A″ and 2.55 km/sec for the A″ to B″ interval.

CALCIUM CARBONATE COMPENSATION

Dissolution of calcite at depths in the Caribbean was discussed by Hay (Benson et al., 1970) who presented Atlantic and Caribbean data in a schematic diagram relating vertical fluctuations in depth of calcium carbonate compensation for foraminifera and calcareous nannofossils to time. In constructing the diagram, it must be assumed that the depth of original depositional surface has remained unchanged, an invalid assumption based on the ridge subsidence curve presented by Sclater et al. (1971) and discussed by Berger and von Rad (1972). The curve of the lower limit of nannofossils, which is consistently deeper than the same curve plotted for foraminifera, shows four peaks representing shallowings of the calcite compensation depth during the early Paleocene, mid-Eocene, mid Miocene, and early Pliocene. Both the foraminiferal and nannofossil data indicate a general shallowing since the Cretaceous.

Ramsay et al. (this volume) also produced a curve of calcite compensation depth (CCD) plotted with respect to time. Only Sites 146/149 of Leg 15 and 29 and 3 of Leg 4 were represented on the graph, but this additional data provided considerably more detail. Site 10 in the North Atlantic and Sites 15 and 20 in the South Atlantic are on the flank of the mid-Atlantic Ridge, and although they have probably been subject to considerable subsidence (Sclater et al., 1971; Berger and von Rad, 1972), the Oligocene and Neogene data are consistent with those of the other sites.

The subsidence history in the Caribbean may not be similar to that of the main ocean basins. The thicker crust with non-oceanic velocity characteristics may well indicate a very different paleobathymetric history. In any event, this curve does not show Hay's shallowing trend of the CCD through the Cenozoic, but instead, a constant average depth of about 4500 meters with peaks of remarkably uniform amplitude of about 500 meters above and below the median. Apparently their curve was drawn based on present water depths at each site (note 3972 meters water depth at Site 146/149 and the curve of CCD in the Paleocene at 4000 meters) rather than depth to the appropriate cored interval (Paleocene at Site 146/149 is over 4400 m).

On Figure 8 we have plotted all the other sites drilled in the Caribbean that bear on the history of the compensation depth. As a first approximation it is clear that either the depth of calcite compensation was deeper during the Coniacian and Santonian or the entire Caribbean Sea was shallower. Only at Site 150 is there any substantial clay noted in the carbonates, suggesting that this site was deeper at that time and that it had remained below the CCD throughout most of the Cenozoic. The clay indicated at Site 153 is predominantly volcanic clay.

The increase in clay during the Campanian and Maastrichtian, especially well displayed at Site 146/149, would indicate shallowing of the CCD or subsidence as the accumulating sediment raised the sea floor through about 130 meters. The subsidence from isostatic adjustment due to sediment load is insignificant, contrary to the value of 1/2 the sediment thickness suggested by Berger and von Rad (1972). In their calculation they assumed a sediment density of 2.4 gm/cc. In general, the wet-bulk density of ooze is about 1.4 to 1.6 gm/cc. The difference in density between water and sediment is only about 0.5 gm/cc.

The Paleocene sediments of Sites 146/149, 152, and 153 combined tell an interesting story. At Site 146/149, virtually no carbonate was found in the green clays which at present lie about 4400 meters below sea level. The section at Site 152 which lies at about 4100 meters is rich in calcium carbonate, but surprisingly so is the Paleocene of Site 153 which lies at 4500 meters. We conclude that, relative to Sites 146/149 and 152, Site 153 has subsided sometime since the Paleocene and that vertical tectonics in the Caribbean Sea cannot be ignored in evaluating the history of the CCD.

A comparison of the radiolarian-rich carbonates of Eocene age at Site 146/149 with the Eocene radiolarian oozes at Site 29 demonstrates, if we accept the premise of no vertical movements, that the CCD at this time was at a level between the two, or at about 4350 meters.

The only other significant event is the shallowing of CCD during the Late Miocene and Early Pliocene as indicated by the noncalcareous clays recovered at all these sites. Unfortunately, at Site 31, which is significantly shallower, the Late Miocene and Early Pliocene was not cored. As a result, the only statement that can be made is that the CCD was at least shallower than 4050 meters (Site 146/149).

SEDIMENT ACCUMULATION RATES

Several sites were cored continuously and others cored extensively on Leg 15, so that it is possible to determine temporal variations in sedimentation rates at a number of localities. The time scales for biostratigraphic events used here are those of van Hinte (1971) and Berggren (1971), reproduced in Laughton et al. (1972).

The sediment accumulation rates are plotted on Figure 9 for all sites except Sites 147 and 154. The rates are too rapid to illustrate on that scale, but they are included in Figure 10, where high Quaternary sedimentation rates for Leg 15 and Site 30 of Leg 4 have been plotted.

For these graphs some general trends in sediment accumulation rates are evident. With the exception of the post-Coniacian sediments of Site 153, the rate in the Late Cretaceous of the Caribbean was higher than in the Paleogene. In the Venezuelan Basin, Cretaceous sedimentation rates averaged 1.2 cm/10^3 years but in the Colombian Basin rates ranged widely from 0.3 cm/10^3 years (Site 153) to 4.6 cm/10^3 years (Site 152). The relatively lower rates

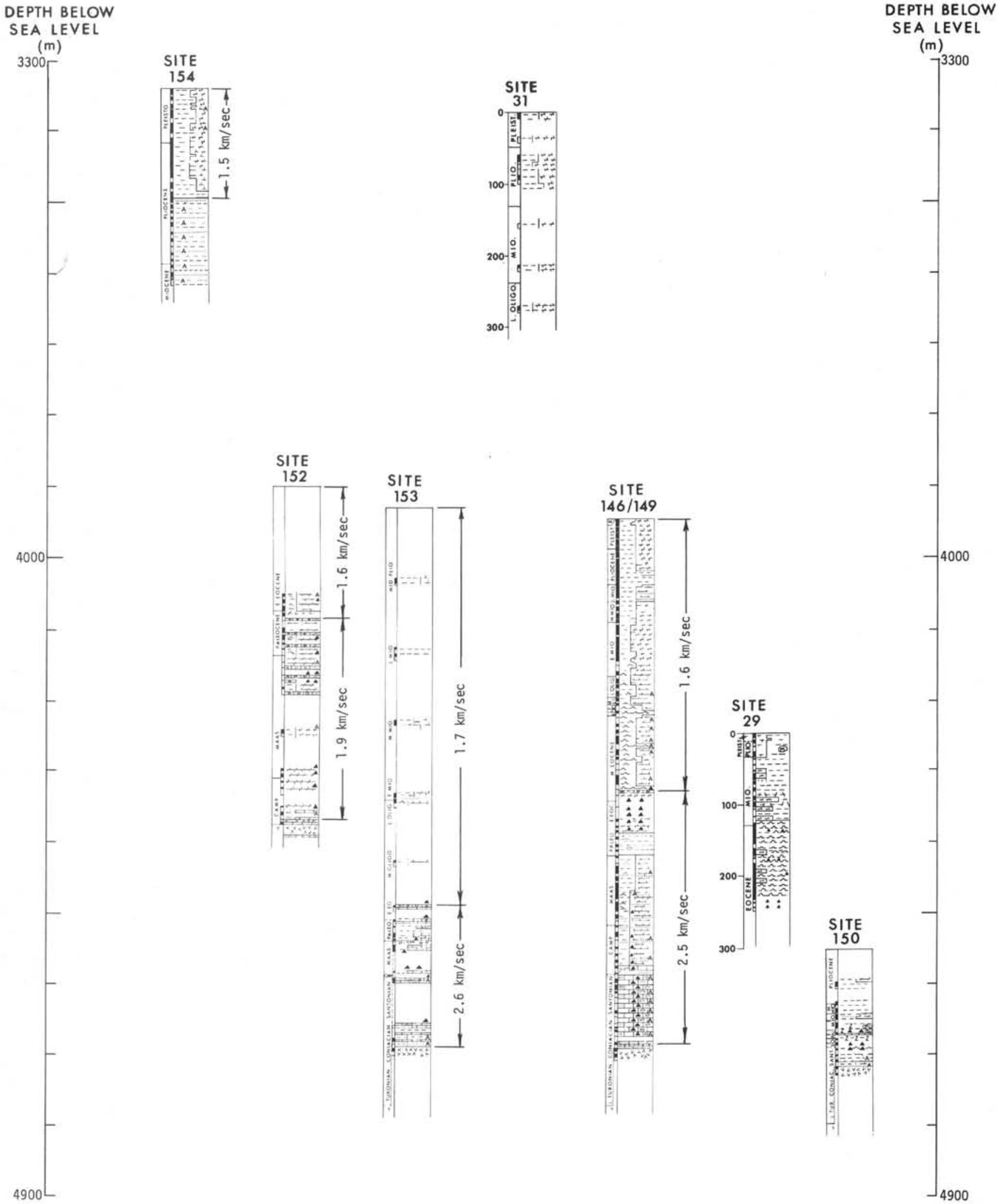

Figure 8. *Deep-water sites plotted with respect to water depth. Numbers on right side of section are seismic velocities determined from reflection time and drilling depth to prominent reflectors.*

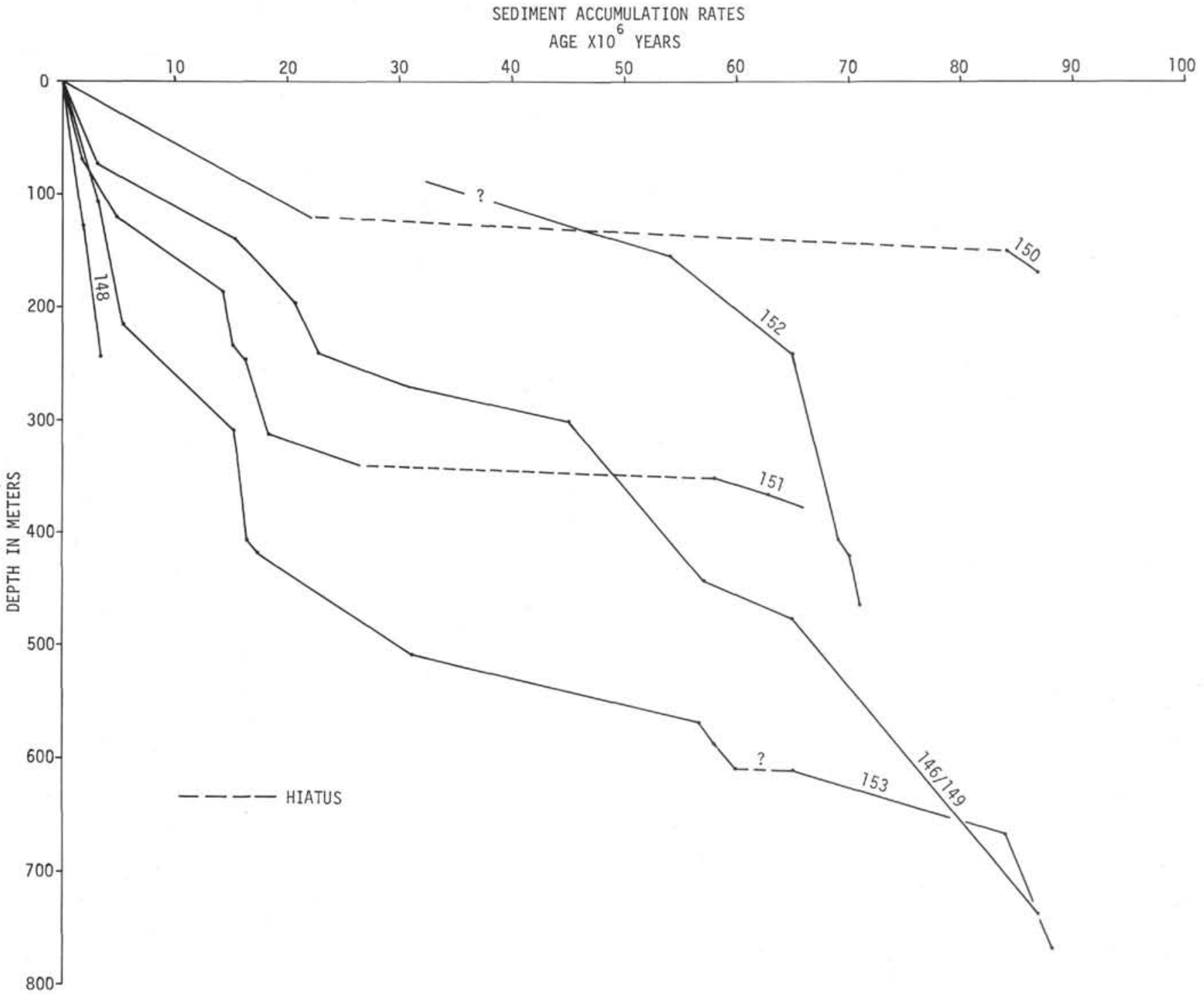

Figure 9. *Sediment accumulation rates for Leg 15 sites. Time scales for biostratigraphic events from van Hinte (1971) and Berggren (1971). Sites 148 and 154 plotted separately in Figure 9 for clarity.*

(less than 1.0 cm/10^3 years) of the Paleogene persisted until the Early Miocene when rates increased significantly in both basins. Particularly high rates (10 cm/10^3 years) were noted for short periods of time in the *Globorotalia fohsi fohsi* and *Globorotalia fohsi peripheroronda* zones of Sites 151 and 153. Coring was insufficient to observe this feature at Site 152. The rates declined again in the Middle and Late Miocene to the level characteristic of the Paleogene. At about 3 to 5 million years ago the sedimentation rates increased sharply at all sites sufficiently well cored to allow analysis. This increase can also be noted, but in less detail, in the sediments of the North Atlantic, but not of the South Atlantic (Pimm and Hayes, 1972). It is difficult to isolate any one particular cause for the sudden increase, but some possible factors are: the waning of strong Tertiary bottom currents, the closing of Panama, an increase in depth of calcium carbonate compensation (Ramsey et al., this volume), and the change in ocean environment associated with the deterioration of the earth's climate prior to glaciation. Using Gartner's (1972) value of 350,000 years for the highest occurrence of *Pseudoemiliana lacunosa*, the sediment accumulation rate for the late Quaternary can be established (Figure 9).

GEOLOGIC HISTORY

In our discussion of the geologic history of the Caribbean we emphasize the marine aspects based on Leg 15 drilling but refer to coeval events in the surrounding lands. In order to relate the significant events in time and space, we have prepared a chart (in pocket on back cover) of columnar sections for Leg 4 and Leg 15 and from particular regions around the Caribbean. The land sections are an attempt to synthesize only the general geology of significant areas, and it should be recognized that in many regions the geology varies considerably over very short distances, and that this cannot be accommodated on the chart.

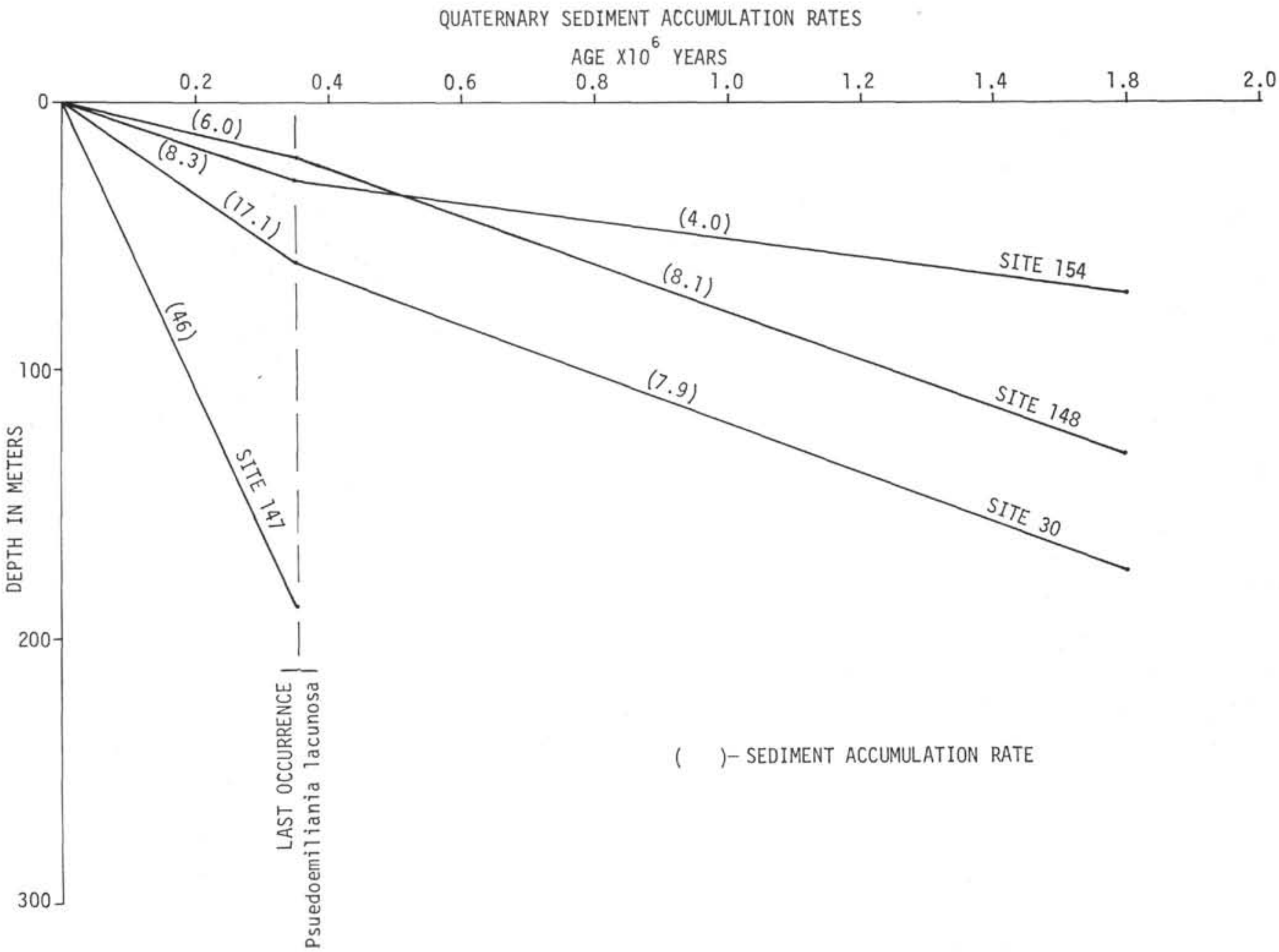

Figure 10. *Sediment accumulation rates for the Quaternary in the Caribbean Sea.*

The Paleozoic history is not pertinent to our drilling results, and it is sufficient to state here that rocks of this age are found as far south as Nicaragua in Central America, are inferred but not identified in the western Greater Antilles, and have been mapped in structures trending into the Caribbean Sea in Colombia; in Venezuela they are exposed in the Merida Andes and, further east, on the El Baul uplift. Early Mesozoic rocks are of little significance, but in Late Jurassic-Cretaceous time, two orthogeosynclines developed: one in the Greater Antilles and another along the northern margin of South America. The major orogenic phase commenced at the beginning of the Late Cretaceous and continued into the Eocene. During this time, folding, metamorphism, and intrusion took place with concommitant breaking up of the orthogeosynclines. In the southern geosynclinal belt, no volcanism is known later than the Cretaceous. In the Greater Antilles, the termination of the orogeny was characterized by the cessation of volcanism in this region and the start of volcanic activity in the southern Lesser Antilles. Apparently the northern Lesser Antilles are considerably older than Tertiary, based on Jurassic isotope dates from rocks on Desirade (Fink, 1972; Fink et al., 1972).

Igneous Rocks

Igneous rocks were rocovered at five sites on Leg 15, three occurrences are associated with Late Turonian-Early Coniacian sediments (Sites 146, 150, and 153), one is associated with Santonian sediments (Site 151), and one with Campanian sediments (Site 152). All of them will be discussed under this section heading. Basalts were recovered from Sites 151 (Beata Ridge), 152 (Nicaragua Rise), and 153 (Aruba Gap) and dolerite was found at Sites 146 and 150 (both in the Venezuelan Basin). A detailed description of the basalts and dolerites recovered on this cruise is presented elsewhere in this volume by Donnelly et al. (Basalts and Dolerites. . .).

The basalts are fine grained with ragged and skeletal plagioclase, have amygdules and, at Site 152, glomeroporphyritic aggregates. The amygdules are filled with a greenish mica. The basalts are fractured and veined with calcite and, like the amygdules, a greenish mica. The dolerites are more uniformly coarse grained, homogeneous, lack amygdules, fractures and veins, and are characterized by ophitic structure. As Donnelly et al. (Basalts and Dolerites. . . , this volume) note, there is no clear distinction between basalts and dolerites, in fact the lower part of the basalt cored at Site 153 may be called a dolerite.

Major element analyses show that the basalts and dolerites cored from the basins (Sites 146, 150, and 153) are similar to typical oceanic tholeiites, whereas those cored from the ridges (Sites 151 and 152) have higher potassium and titanium contents. All the samples are depleted in light rare earths and barium except those from Site 151. Light rare earth depleted rocks are most commonly found among the mid-ocean ridge basalts. The thorium content, typically low for oceanic tholeiites, is high in the samples from Sites 151 and 152 (Beata Ridge and Nicaragua Rise).

The sediment-basalt contact was not recovered intact at any of the five sites. A dolerite sill was penetrated in the Venezuelan Basin (Site 146), and a 35-cm layer of slightly metamorphosed limestone was recovered; more dolerite lies beneath the limestone. Bedding in the limestone is horizontal, suggesting it is not just a zenolith, commonly found in the upper few meters of oceanic basalts, but a relatively undisturbed layer of limestone. This leads one to suspect that the sediment was fairly competent at the time of intrusion rather than a thin surface layer of biogenic ooze. In contrast, the basalt on the Nicaragua Rise (Site 152) contains xenoliths of limestone in various states of metamorphism. The uppermost inclusions are slightly metamorphosed, but microfossils can be readily seen. Those sediment deeper in the basalt layer are highly metamorphosed carbonates (marble). They are reddish and no trace of microfossils can be seen (see Frontispiece E).

The reliability of K-A dating on oceanic basalts has not been satisfactorily established and the absence of glass precluded fission track measurements. Consequently, the age of basalts and dolerites is inferred from the age of limestone inclusions, the age of overlying sediments, and the age of the sediments associated with the youngest basaltic ash. Basaltic ash was found in the sediments overlying the basaltic rocks at each site except Site 151, where the sediments are too badly deformed to permit identification. The age of the sediment associated with the flows or sills, the age of the youngest basaltic ash, and the distance this ash is located above the basaltic rocks are listed in Table 1. The stratigraphic interval of the basalts and dolerites and basaltic ashes in the sediments is the same, i.e., latest Turonian to Campanian. No younger basaltic ashes are known from the sediments recovered on this cruise which is a strong indication that all the basalts and dolerites were emplaced within this time period. There is presumably a significant correspondence between the stratigraphic levels of the flows and sills and of the basaltic ashes which may mean that the sills and flows are of about the same age as the surrounding sediments. It is possible that the two flow occurrences (Sites 151 and 152), which are Santonian and Campanian, represent the time of the outpouring, and that the sills in the *Globotruncana schneegansi* are also of Santonian to Campanian age.

The uncertainty as to the time of emplacement of the basaltic rocks within the age range from Turonian to Campanian precludes any meaningful attempt to relate age to geographic distribution.

The completion of the igneous event in the basins that led to the formations of Horizon B″ coincides approximately with what is regarded as the start of the major orogenic phase primarily affecting the geosyncline in northern South America. Massive basaltic rock emplacement occurred at about this time, although the chemistry

TABLE 1
Relationship of Basaltic Ash to Underlying Basalts and Dolerites, Leg 15

Basalt/Dolerite					Basaltic Ash		
Site		Age/Zone[a]	Core	Depth[b] (m)	Age/Zone[a]	Core/ Depth[b] (m)	Distance Above Basalt (m)
146	flow	Dolerite *Gt. schneegansi* Zone L. Turonian-Coniacian-	41R	738	*Gt. schneegansi* Zone L. Turonian-Coniacian	39R (720)	18
150	sill	Dolerite *Gt. schneegansi* Zone L. Turonian-Coniacian	11	169	*Gt. concavata* Zone Coniacian-Santonian	9 (151)	18
151	flow	Basalt *Gt. c. concavata* Zone Santonian	13	179	Probable ash but cores too disturbed to use		
152	flow	Basalt *Gt. elevata* Zone Campanian	23	471	*Gt. elevata* Zone	22 (469)	2
153	sill	Basalt *Gt. schneegansi* Zone L. Turonian-Coniacian	19	759	*Gt. concavata concavata* Zone Coniacian-Santonian	15 (669)	90

[a]*Gt. = Globotruncana*

[b]Approximate depth below sea floor to top of basalt/dolerite or basaltic ash.

of these basalts is quite different from those recovered in the basins. The true relationship of these events is probably not coincidental, but may be related to a change in poles of rotation of the Americas, as discussed in more detail later in the chapter under "the Origin of the Caribbean Crust."

Late Turonian-Coniacian-Santonian

Sediments of this age recovered on Leg 15 reflect periods of current activity interrupted by periods of stagnation.

The limestones overlying the basaltic rocks at Sites 146 and 153 contain volcanic sands that are graded and laminated, indicating transportation or reworking, or both. Radiolarian sand (both graded and not graded) contain mixed assemblages representing large numbers of taxa. These layers at Site 146, found in an orderly sequence of foraminiferal faunas, contain Radiolaria not significantly older than the sediment above and below. The autochthonous radiolarian assemblage indicates paleoecological conditions that restricted the development of the assemblage, whereas a much more diverse fauna flourished at the site of origin of the allochthonous component. The site of original deposition, where these Radiolaria accumulated must have been in shallower water, which typically favors the accumulation of biogenic carbonate rather than siliceous organisms. None of the sites drilled on this leg yielded as much as a hint as to their original site of deposition, although the Beata Ridge, marked by a significant Cretaceous unconformity at Site 151, is a possibility.

For the most part, the organic-rich layers and limestones with biogenic structures constitute the typical rock type of this period, suggesting quiet bottom conditions that lead to periodic stagnation.

Organic-rich sediments have been noted in several widely separated areas in the Atlantic-Caribbean region. In the western North Atlantic, the Leg 11 scientific party (Hollister and Ewing et al., 1972; Lancelot et al., 1972) recovered black organic-rich clays that ranged in age from late Neocomian to Cenomanian (Site 105) or Albian (Site 101). In the Cenomanian sediments, the black carbonaceous clays alternate with burrowed dark olive green layers; similar to that found in the Caribbean except that burrowed limestones separate the black layers. The preferred paleoenvironment is the same for both areas; quiet bottom conditions with periodic stagnation.

In the eastern North Atlantic, carbonaceous sediments were recovered at Sites 135 (between Early Aptian and Late Campanian), 137 (Cenomanian-Early Turonian), and 138 (Cenomanian) (Hayes and Pimm et al., 1972; Berger and von Rad, 1972), and in the extreme southern part of the western Atlantic Basin (Guyana Basin) at Site 144 (Early Turonian to Coniacian-Santonian).

The intervals characterized by the deposition of carbonaceous sediment in the Atlantic and Caribbean are summarized in a diagram in Figure 11. The time of initiation of stagnation is well documented only in the western North Atlantic (Early Barremian to Late Valanginian). Coring was terminated at Sites 135 and 144 before the carbonaceous interval was penetrated; other sites terminated in basalts before the interval was completely penetrated. The stagnant conditions came to a decisive end some time in the Coniacian-Santonian, probably the Santonian. No organic-rich sediments were reported in post-Santonian sediments.

The occurrence of organic-rich layers in the Caribbean sediments that correspond so closely with similar occurrences in the North Atlantic (Site 144) indicates that in the Late Cretaceous the Caribbean Sea had a much closer affinity to the Atlantic environment than to the Pacific. In fact, the absence of carbonaceous sediment in Pacific cores of the same age demands a barrier between the Pacific and Caribbean separating the bottom water regime of the two basins. The nature or present disposition of the barrier is a matter for speculation.

As noted above, stagnation was initiated in the western North Atlantic in the Early Barremian to Late Valanginian, but earlier sediments were deposited in an aerobic environment. The beginning and end to the stagnant and quiet bottom water conditions in the North Atlantic and Caribbean is probably related to a critical change in the geometry during development of the Atlantic Ocean and bordering continents. Little is known about the role played by the hypothetical "Panamian barrier" suggested above in controlling the bottom water circulation of the North Atlantic during the Cretaceous, but the development and break-up of such a barrier could explain the period of stagnation. Regardless of the cause of the initiation of stagnation, the separation of South America from Africa may provide an equally plausible explanation (D. Kinsman, Princeton University; personal communication).

As South America and Africa began to separate 120 to 140 m.y. ago (Maxwell and von Herzen et al. 1970; Allard and Hurst, 1969), marine water encroached from the south, but Rayment and Tait (1972) noted, in their studies of ammonites, that until the early Turonian, the South Atlantic fauna was isolated from Atlantic-Caribbean fauna. During early Turonian time, the occurrence of *Benueites* and its associates in the North and South Atlantic indicated the first interchange of this nektoplanktonic fauna between the two oceans – a condition that has prevailed until today.

The discrepancy between the age range of 120 to 140 m.y. for the opening of the South Atlantic and the first interchange of surface waters between the North and South Atlantic (90 m.y.) can be explained in terms of the transcurrent nature of the separation of the two continents along the Nigeria-Ivory Coast of Africa and northern Brazil. Actual separation of the continents at the last point of contact along the 1000 to 12000 km transcurrent margin would have been in the order of 50 or 60 m.y. after separation of the divergent margin (assuming a constant spreading rate of 2 cm/year and total transcurrent movement). In actuality, part of the movement was probably divergent, and the development of ridges (LePichon and Hayes, 1971) complicates the picture. However, the basic geometry of two continents separating along a transcurrent margin would permit pelagic fauna to interchange sometime before an exchange of bottom water. Geophysical evidence indicates that a divergent continental crust terminates seaward within 40 to 80 km, consequently, a 10 m.y. difference between surface (Lower Turonian) and bottom water (Santonian) interchange is not unreasonable. Evidence from hiatuses at Site 150 (Edgar et al., this

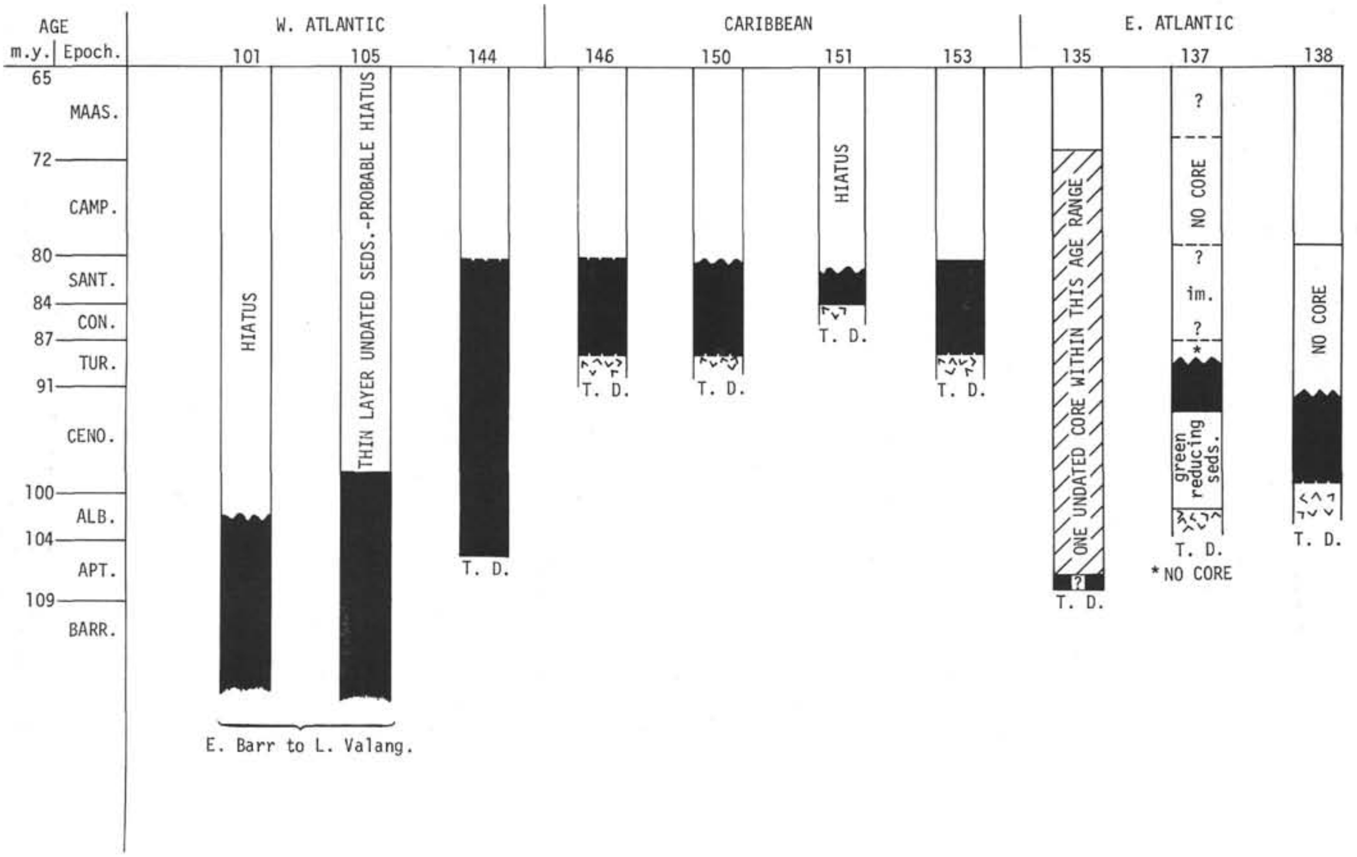

Figure 11. *Summary of occurrences of carbonaceous sediments in the Atlantic and Caribbean.*

volume) indicates strong bottom currents during Campanian-Maastrichtian time, but not during the Late Turonian-Santonian. The complete separation of the continents along this margin initiated bottom water exchange and circulation that precluded further stagnation in the Caribbean basin sediments.

Of interest to this discussion is the presence of Radiolaria in all the Cretaceous sediments in the Caribbean. No Radiolaria have been reported from pre-Maastrichtian sediments anywhere in the Atlantic sites with the exception of isolated occurrences in Early Campanian and Early Cenomanian sediments in the Gulf of Mexico (Worzel and Bryant et al., 1973) and at Site 9, Leg 2 (Peterson and Edgar et al., 1970). In contrast, Cretaceous sediments of the Pacific contain abundant Radiolaria (Winterer and Ewing et al., 1971; see Site 167 in particular). Figure 12 compares a Cretaceous Pacific site (167) with Site 146 of the Caribbean and Site 144 of the western equatorial Atlantic. The pacific site is located only 7° north of the present equator. Consequently, the biogenic content of the sediment may be affected by the associated belt of high productivity. Because the Atlantic site is close to the South American continent, the sediments show a terrigenous influence, but there are no better Late Cretaceous sections available from the Atlantic. Note the correspondence between the limestones of the pre-Campanian and the softer overlying Campanian and Maastrichtian chalks and marls at both the Pacific and Caribbean sites. Even the Coniacian-Santonian carbonates of the Atlantic site show some increase in degree of lithification. The poor recovery of Late Cretaceous sediments in the Atlantic makes it difficult to argue conclusively that sediments of this age are poorer in Radiolaria than the Pacific counterparts, but certainly it appears to be so. A comparison of the Early Cretaceous sediments of both oceans demonstrates convincingly that the Atlantic sediments are barren of Radiolaria. With reference to Figure 12, one might conclude that in the Cretaceous the Caribbean had a much closer affinity to the Pacific sedimentary regime than that of the Atlantic.

The conflicting evidence that the Cretaceous Caribbean Sea had an Atlantic affinity based on stagnation and a Pacific affinity based on Radiolaria content in the sediment is certainly intriguing. As mentioned above, the absence of stagnant conditions in the Cretaceous of the Pacific already implies a barrier between the Atlantic-Caribbean bottom waters and those of the Pacific. The barrier may have been at about the present location of Panama, but, with the uncertainty as to paleophysiography of the eastern Pacific, it is possible that it lay further to the west and may even have been the ancient spreading ridge. In any event, the barrier permitted restricted flow of Pacific surface waters into the Caribbean, but it was not a strong flow and did not penetrate east of the present Lesser Antilles.

In summary, after the central Caribbean basin igneous and associated volcanic activity terminated, biogenic carbonates were deposited in dominantly quiet bottom water conditions and were mixed with a large radiolarian fraction, suggesting that Pacific surface water circulated through the area. Ocean circulation was extremely weak,

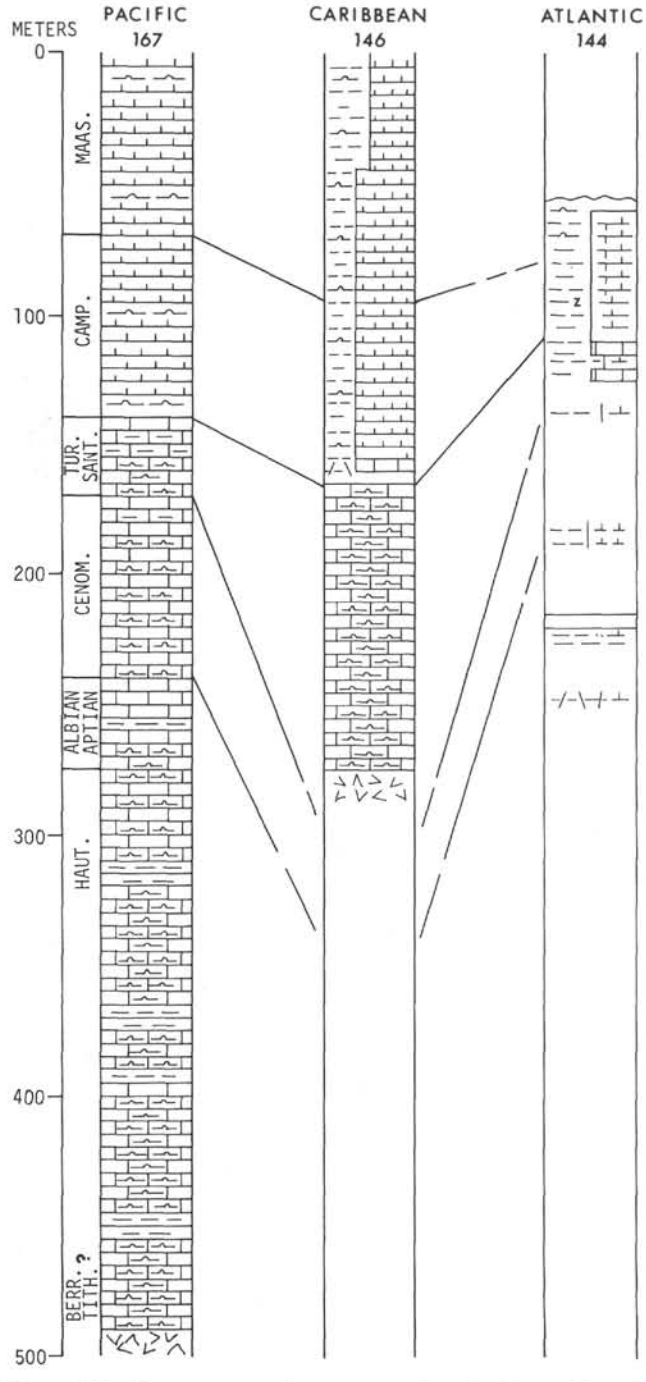

Figure 12. *Comparison of Cretaceous Pacific Site 167 with 146 of the Caribbean and Site 144 of the western equatorial Atlantic.*

allowing stagnant conditions to exist periodically. North Atlantic and Caribbean deep-water circulation was activated when South America and Africa were sufficiently separated to permit a free interchange of bottom water.

In the central Caribbean basins, the cessation of volcanic activity and the pelagic sedimentation in a quiet bottom water environment contrasts with the orogenic activity on the northern and southern margins. In the eugeosynclinal belt of northern South America, this time interval is largely one of folding, metamorphism, and erosion, particularly towards the east; in the west, on the Goajira Peninsula, the section appears to be essentially complete. Between the eugeosynclinal belt and the Guayana Shield, the time interval is represented by relatively continuous basin deposits suggesting a quiet water environment. The Greater Antillean eugeosyncline throughout this time period was strongly volcanic and suffered erosion from uplift at the end of the Santonian. Late Cretaceous rocks of a deep-ocean environment have been reported from Costa Rica (Henningsen 1968; Henningsen and Weyl, 1967) and eastern Panama (Case, in press; Bandy and Casey, in press). Lloyd (1963) and Henningsen (1968) believe that volcanic islands lay to the west of Panama at this time. This view is consistent with our requirement for a submarine ridge or sill to isolate the stagnant Caribbean-Atlantic bottom waters from the well-oxygenated Pacific bottom waters.

Bituminous, pyritic limestones and shales are also found on land in the Late Cretaceous in northern South America from Colombia eastwards through Venezuela to Trinidad, and one is tempted to compare these with the organic-rich intervals found in Sites 146, 150, 151, and 153.

On the Goajira Peninsula, the Upper Yuruma Formation, the Cogollo Group, and the La Luna Formation are considered to span the time interval from Barremian to Santonian (Rollins, 1960). In western Venezuela, the La Luna Formation is widespread in the Maracaibo Basin and in the adjacent states of Zulia and Lara. In eastern Venezuela, bituminous, organic-rich rocks comprise the Querecual Formation of predominantly Turonian age while in Trinidad, similar rock types are found in the Gautier and Lower Naparima Hill formations of Cenomanian to Turonian-Coniacian age. The possible euxinic nature of the deposition in eastern Venezuela and Trinidad has been commented on by Hedberg (1937, 1950), Kugler (1953), and Barr and Saunders (1968).

The organic-rich sediments in the Caribbean basin extend downwards at least to the level of Horizon B″, and, based on occurrences of similar sediments in the North Atlantic (ref. Legs 11 and 14) and in northern South America, it would not be surprising to find them below Horizon B″ in areas where there are sedimentary accumulations.

Comparable organic-rich sediments appear to be absent in Central America and the Greater Antilles, where the sections are much more volcanic.

Campanian-Maastrichtian

In the Venezuelan Basin (Site 146), thick biogenic carbonates were being deposited but with increasing amounts of clay in the younger sediments. Radiolaria were present but not in great abundance. Cherts are found infrequently in the Campanian but rarely in the Maestrichtian sediments. General silicification of the carbonates did not occur as it did at other localities (Sites 152 and 153). Sandy layers, rich in Radiolaria and/or foraminifera, occur commonly throughout these sediments as they did in the underlying beds.

The Campanian-Maestrichtian carbonates in the Aruba Gap area are very thin in comparison to Sites 146 and 152. It is not clear whether sedimentation was restricted, dissolution was more active, or unconformities are present in this area. The seismic profiler records clearly show a thinning between Horizons A″ and B″. No radiolarian sands were noted although this may be explained by poor core recovery. Lithification and silicification of the carbonates was extensive and chert is common.

Thick carbonates accumulated at Site 152 on the Nicaragua Rise, but the clay component is minor compared to Site 146. Silicification was particularly common in the Late Maestrichtian sediments in contrast to the Venezuelan Basin sediments. The extremely thick section of carbonate sediments, especially of the Maestrichtian section, suggests deposition in shallower water and/or higher productivity.

One of the most striking visual characteristics of the late Cretaceous carbonates recovered on Leg 15 is the abundance of trace fossils (Sites 146, 152, and 153; illustrated in Maurrasse, this volume; Figure 7, this chapter). The unusually good preservation of these structures is pointed out by Warme et al. (this volume) who have drawn attention to their similarity to those of land-based sections in North America, Europe, and Iran. They consider the trace fossil assemblage seen on Leg 15 to be most similar to those described as quiet and deep-water assemblages; most notably to those of the *Zoophycos* ichnofaces of Seilacher (1963).

The lithologic character and biogenic structures of the Leg 15 carbonates have a counterpart in the land-based sections of northern South America. Rocks that have been described as cherts, cherty limestones, chalks, "siltstones", and "mudstones" are widely distributed from Colombia to Trinidad and, as in the deep sea, range in age from Coniacian to Maestrichtian. The formations involved include the Guadaloupe in Colombia, the Frailes in Margarita, the San Antonia in eastern Venezuela, and the Naparima Hill and Guayaguayare in Trinidad. It is interesting to see the very great similarity between the form of the trace fossils from the DSDP sites and those from cores taken in the Naparima Hill Formation of south Trinidad (Figure 13).

Although orogenic activity that characterized the earlier Late Cretaceous continued in both the geosynclines, sedimentation in the Caribbean basins was isolated from the effects of this activity. Sediments in the Venezuelan Basin indicate that volcanic activity had declined relative to earlier times, but there are indications that this was not so at sites further to the west.

Donnelly (this volume) notes that the abundance of hornblende and clinoproxene in Sites 151 and 152 indicates that the activity was centered in the northern Colombian Basin at that time.

Paleocene-Early Eocene

Paleocene sediments are of two distinct types: a green siliceous clay, essentially barren of fossils (Site 146), and a clay-rich carbonate ooze and limestone (Sites 152 and 153). The siliceous clay is composed primarily of cristobalite but has as much as 22% montmorillonite in some samples. It is uncertain whether they are altered ash layers or were deposited as a montmorillonite clay. Glover and Mattson (1967) and Mattson and Pessagno (1971) note that the Paleocene-Middle Eocene Jacqguas group in Puerto Rico contains cherty, light green and vitric tuff with the glass devitrified largely to montmorillonite. Mattson and Pessagno suggested that these beds may be correlative with the chert horizons of the same age found in the DSDP sites. It would appear that the silica needed would require greater volcanism than was available; the greatest volcanic activity occurred in post-Horizon A″ time. It would appear equally probable, if not more so, that the beds correlate with the green siliceous Paleocene clays at Site 146, although it is strange that the volcanic material could accumulate as far away as Site 146 without a trace being found at any of the other sites. Only a few nannofossils were found in these clays, demonstrating that they were deposited below the depth of calcium carbonate compensation. The contact between the clays and the overlying carbonates is very sharp, suggesting a rapid relative deepening of the carbonate compensation level or a minor hiatus in sedimentation.

The siliceous clays of Site 146 contrast markedly with the clayey biogenic carbonates and limestones of the Paleocene and Early Eocene of Sites 152 and 153. At these sites, deposition was well above the depth of compensation as indicated by the presence of both nannofossils and foraminifera. Differences in carbonate content among sites in the late Cretaceous and early Tertiary are not easily established owing to incomplete recovery at Site 153. Probably, Site 146/149 is the least calcareous and Site 152 the most, with Site 153 being intermediate. The present depths below sea level to the Cretaceous-Tertiary boundary are: Site 146/149 (4450 meters); Site 153 (450 meters); and Site 152 (4150 meters). Thus it might appear that the relative positions of Sites 146/149 and 152 are about the same as they were at that time and that Site 153 most probably has subsided relative to the other two since that time. Shallowing of the compensation depth in the Paleocene has been suggested by Jay in Benson et al. (1970) in a compilation of drilling data from other cruises. Ramsay et al. (this volume) updated the curve showing the compensation depth shallowing to a minimum of about 3 km or less and a maximum of 4 km.

Although there is evidence that the Paleocene sediments of Site 146 are of volcanic origin, there is no indication of extensive volcanism in the Paleocene of Sites 152 and 153.

A widespread facies in the Paleocene and Early Eocene of northern South America is flysch which is even found as far east as Barbados. Despite this abundance in the land sections there is a conspicuous absence of flysch facies in the Leg 4 and 15 sites, suggesting extremely effective circum-Caribbean sediment traps (Edgar et al., 1971).

Throughout the Greater Antilles, the period is marked by an almost complete absence of sediments; this is linked with known intrusion, uplift, and erosion at this time.

Middle Eocene-Early Miocene

The most striking feature of the sediments deposited during this period is the abundance of Radiolaria. The Radiolaria-rich sediments overlie earliest Middle Eocene siliceous limestones and cherts which are correlated with Horizon A″ at this site and are also found in the Middle Eocene at Sites 27 and 28 east of the Lesser Antilles and north of the Greater Antilles, respectively. Radiolarian oozes of Middle Eocene age were also cored in the North Atlantic on Leg 2 (Peterson and Edgar et al., 1970).

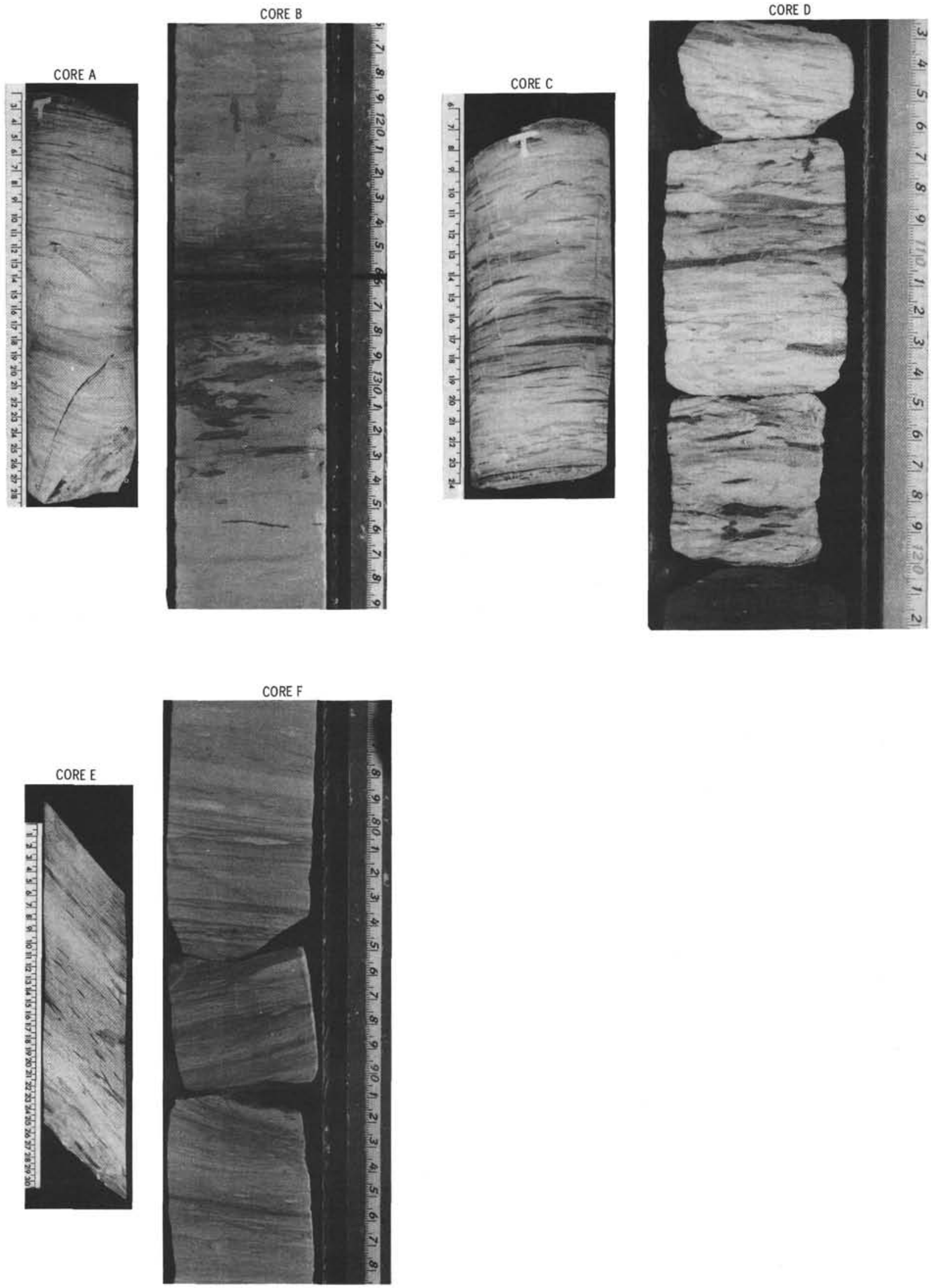

Figure 13. *Comparison of trace fossils from Late Cretaceous cores of the Caribbean Basin and the Naparima Hill Formation of the Brighton Marine Field in Trinidad. Cores A, C, and E: Naparima Hill Formation (Campanian); Core B: Site 146/149, Core 17, Section 4 (Maastrichtian); Core D: Site 153, Core 16, Section 2 (Santonian); Core F: Site 146/149, Core 28, Section 3 (Campanian).*

In Barbados, similar radiolarian-rich sediments appeared suddenly within the Middle Eocene and are now exposed as indurated radiolarian oozes. Upwards, these radiolarites become more calcareous with an increase in nannofossils and foraminifera. Thin ash beds occur frequently throughout the section, attesting again to the volcanic activity in the Lesser Antilles. Similar deep-water chalks are found in Trinidad from Middle to Late Eocene, but here there is no sign of volcanicity.

In the southern part of the Lesser Antilles the oldest known volcanic rocks can only be dated as "pre-Oligocene" but are still presumed to be Paleogene. The oldest known fossiliferous limestone is from the Grenadines, and this carries a Middle or Early Eocene planktonic foraminiferal fauna (Martin-Kaye, 1969). The volcanics of the north end of Grenada are underlain by Late Eocene flysch that shows derivation from an active arc close by. This documents what may be the beginning of volcanic activity in the present Lesser Antillean arc.

The sediment deposited in the Caribbean basins at this time contains considerable pumice, glass (probably devitrified from pumice), and plagioclases, presumably derived from the Lesser Antilles or Central America since volcanism had just about ceased by this time in the Greater Antilles and South America.

From this time onward the Greater Antilles were characterized by block faulting, minor intrusions, and a few documented cases of local volcanism (Butterlin, 1956; Roobol, 1972). It is interesting to note the coincidence in time between the presence of Radiolaria and the pumice. Both occur during the entire time interval from Middle Eocene to Early Miocene.

Early Miocene to Pleistocene

During the Miocene there was an influx of clays composed of mica, kaolin, and chlorite. The change in character of the clay fraction of the middle-late Tertiary interval signifies the inception of a massive supply of terrigenous debris to the Caribbean during this time. The increasing rate of supply of Al_2O_3 during this interval (Donnelly and Nalli, this volume) shows quantitatively that the supply increased evenly with time. The character of the clay is similar to that being carried in the modern Amazon River and can be traced to the present day Caribbean (Jacobs and Ewing, M., 1969). About this time the major drainage of the Orinoco was initiated and deltas in other areas were also being built.

At Site 150, the first occurrence of these clays was found in the Early Miocene, and they continued to be deposited into the Pliocene, the youngest core taken at that site. At the other sites, these clays are first recognized in the Middle Miocene and continued into the Holocene. Site 150 lies in deep water in proximity to the Venezuelan Abyssal Plain and has been in a good position to receive these sediments before the other sites, suggesting that some of the sediment came from local sources along the northern South American continent. These clays represent the first major nonvolcanic influx into the sediments of the Caribbean Sea. Until this time, trenches apparently protected the Venezuelan Basin from terrigenous input and the breeching of these traps in the Miocene may mark a period of tectonic relaxation along the Venezuelan continental margins. Trenches and troughs along the margin soon filled and spilled sediments into the main Caribbean basin.

It is worth noting that the top of the Middle Miocene represents the time in Trinidad when fully marine conditions were replaced by the onset of deltaic deposition (the proto-Orinoco delta). It would seem that there could be a correspondence between the development of this drainage pattern in eastern Venezuela and Trinidad and the occurrence of an increased terrigeneous clay component in the deep Caribbean Sea. Local origin for at least a part of the terrigeneous sediments finds support from a mineral suite found in a Miocene turbidite at Site 150 (Donnelly and Nalli, this volume).

The floor of the Venezuelan Basin presently is bowed up in the middle, forming deeps along the northern and southern margins. Apparently the bottom topography has not changed much since the Miocene, when one would speculate that the Venezuelan Abyssal Plain began to receive continental sediments. The coarsest sediments are still trapped in these marginal depressions, but the finer fraction finds its way to all parts of the basin.

The clay content of the sediment increases substantially in the Late Miocene and Early Pliocene, and foraminifera become increasing rare as the relative depth of calcium carbonate compensation shallows in the younger sediments. Only sparse nannofossils are present in the Early Pliocene. The shallowing of this depth of calcium carbonate compensation in the Late Miocene and Early Pliocene is consistent with the graph of compensation depth with time prepared by W. Hay in Benson et al. (1970) and Ramsay et al. (this volume).

The combination of a high noncalcareous accumulation rate, conspicuous volcanic debris, and proximity to sources of volcanic activity at Sites 148 and 154 make irresistible the conclusion that the accumulation represents either dominantly volcanic ash or weathered debris from near the volcanic center. However, either conclusion would appear to be unwarranted. In both sites, the upper clays and marls have persistently high quartz and illite content and high illite/chlorite ratios.

This mineral assemblage is more typically representative of a mature continental interior than of a young calc-alkaline volcanic center, where quartz is relatively scarce and sedimentary micas nearly absent. The difference between hypothetical continental and volcanic island sources is especially clear at Site 148, where the sediment is dominantly South American in origin and probably largely Amazonian. At Site 154, the provenance is less clear; isthmian Central America exposes a greater range of rock types than do the Lesser Antilles. However, the abundance of quartz in the pelagic sequence (though illite is less abundant) again argues against a dominantly volcanic ash contribution and points towards a basically nonvolcanic Central or South American provenance or African source (wind-blown debris).

There is very little evidence for volcanic activity in the sediments of the deep basins of this time period; even the montmorillonite content is low. This is in keeping with the interpretation mentioned above suggesting a period of tectonic relaxation rather than active subduction at the margins of the Caribbean—particularly the Venezuelan coast.

Sedimentation in the southern Colombian Basin was marked by volcanic sands, silts, and clays transported from shallower regions. In the Early Pliocene at Site 154, the volcanic sediments give way abruptly to pelagic, calcareous clays and marls. From examination of the profiler record, it is apparent that uplift (faulting?) of this block in the Colombian Basin coincided with the time of the final closing of the Isthmus of Panama (Kaneps, 1970). Perhaps the two events are related, but there is nothing in the data to indicate this except for the coincidence in time.

Late Pleistocene carbonate maxima at both Sites 148 and 154 could be related to glacial maxima, though such a relationship is not generally clear in the Atlantic Ocean. At Site 154, a gradual increase in carbonate in the early Pliocene might reflect the tectonic rise of the elevation on which this site is located. Such a rise might involve a gradual diminution of noncalcareous debris diluting a steady contribution of calcareous debris, or the supply of calcareous debris could have increased during this interval. Whatever the explanation, the coincidence between this increase in carbonate proportion and the final emergence of isthmian Panama is noteworthy. Evidently the closing of the isthmian seaway either changed patterns of sediment carrying currents or patterns of primary productivity.

Quaternary

The Pleistocene sediments are little changed from the Pliocene at Site 154 in the western Caribbean, but on the Aves Swell (Sites 148 and 30) a record of volcanic activity for the southern Lesser Antilles is revealed (Donnelly, this volume). The period of volcanic quiescence in Late Miocene times extended through the mid-Pliocene, and increasing volcanic activity was evident in the Late Pliocene and Early Pleistocene. Highly explosive andesites suddenly appeared in the mid-Pleistocene. This pattern of events had already been suggested from work on the Antillean islands (Robson and Tomblin, 1966; Martin-Kaye, 1969).

A very fine section of the Middle to Late Pleistocene sediments was recovered at Site 147 in the Cariaco Basin. The site is located on a ridge that separates the basin into two deeps each of which contains a thick sequence of turbidites, based on seismic and piston core data (D. Needham, L-DGO, personal communication). Of particular importance is the fact that below 360 meters, the waters are anaerobic. The general lithology at the site is a foraminiferal nannofossil clay, rich in organic material and without any evidence of turbidite deposits. Within the olive green clays are several layers of distinctive gray and brown clays (Frontispiece A; Figure 14). The lower two clay layers are each underlain by a thin hard dolomite layer.

The sediment at the contact between the olive green and gray brown clays at 4.6 meters in piston core V12-99 was found to be 11,000 years old (Heezen et al., 1959), the date commonly accepted as the end of the last glacial stage. It was therefore believed that the anaerobic sediments represented interglacial sedimentary conditions and the gray brown clays represented conditions during glacial times or perhaps during the transition. It was hoped that

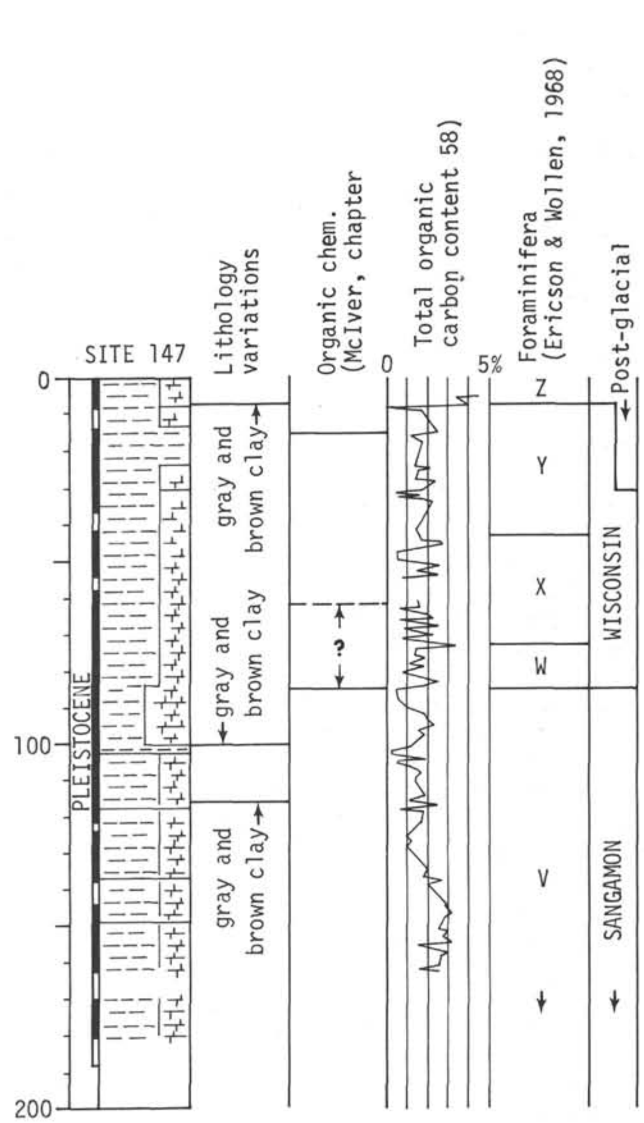

Figure 14. *Comparison of lithologies at Site 147 with organic chemistry analysis of McIver (this volume); Ericson and Wollin (1968) glacial zonation; the classical North American glacial events; total organic carbon content.*

these clays would be found at greater depths and would mark the glacial-interglacial boundaries in the sediment. Two additional layers of gray brown clays were recovered at 105 and 115 meters, but they did not appear to correspond to classical glacial events (Figure 14) based on foraminiferal zones (Rögl and Bolli, this volume; Ericson and Wollen, 1968) or organic geochemistry (McIver, this volume). Both the lower clays occurred in sediments of the Sangamon interglacial. Based on the ratio of isotopically lighter hydrocarbons (terrestrial origin) and the heavier (marine origin) hydrocarbons, McIver places the beginning of Wisconsin glaciation at slightly above the 85 meter level or just about where Rogl and Bolli place it on foraminiferal data.

The total organic content is also plotted on Figure 14 to determine if there is any relationship to the glacial events. The average content is about 1.5%, compared with 0.8% for average oceanic sediments, but there is no apparent correspondence with the Ericson and Wollin zonation. The very high organic content of the Holocene sediments appears to be unique to this time.

THE ORIGIN OF THE CARIBBEAN CRUST–A DISCUSSION

The identification of Horizon B″ as an extensive dolerite and basalt complex, overlain by Late Cretaceous sediments is the discovery from Leg 15 that is most pertinent to the problem of the origin of Caribbean crust. Although it cannot be established without question that the age of the top basalt or dolerite is the same as the overlying sediment, the basaltic ash layers found in the overlying few meters of sediment strongly suggests that the igneous rock and sediments are about the same age (Donnelly et al., this volume). We do not have the evidence to support the positive statement of Meyerhoff and Meyerhoff (1971) that the drill did not reach the bottom of the sedimentation column, but certainly we do have reason to believe that Horizon B″ represents only the last phase of volcanic and intrusive activity during crustal development. The sedimentary component may be substantial or merely a trace. The evidence that the crust is significantly older than Late Cretaceous is found in seismic reflection and refraction data, magnetic studies, continental drift considerations, and circum-Caribbean geology.

The seismic evidence is drawn from two-ship refraction data, sonobuoy measurements (refracted and interval velocities), and reflection techniques processed to yield velocities. Considerable variability (Edgar et al., 1971) in the thickness (2-6 km) and velocity measurements (3.2-5.5 km/sec) of the material lying between Horizon B″ and the 6.2 km/sec crustal layer suggests lithologic inhomogeneity one would associate with a layer of mixed igneous and sedimentary composition. These data have been confirmed by sonobuoy measurements (Ludwig, L-DGO, personal communication). Particularly, thick accumulation of low-velocity sub-Horizon B″ material was measured near the continental margin on Aruba Gap (Edgar et al., 1971) and the southern Colombian Basin (Ewing, J. et al., 1960). These layers thin toward the central Venezuelan Basin to the point that it could not be detected by the reflection profiles (Officer et al., 1957) although they are again recorded in the northern part of the basin (Officer et al., 1959).

Reflection records (unprocessed, single trace) routinely show no reflections below Horizon B″, but indications of reflectors beneath B″ in some areas led Edgar et al. (1971) to suggest that the layer may be composed partly of sedimentary rocks. Processed multichannel records contributed by the Gulf Oil Company clearly show layers below B″ (Eaton and Driver, 1967); a sample of their data recorded by Gulfrex is shown in Figure 15. The deeper layers are coherent, well-defined reflectors in some areas but discontinuous and jumbled in others. Hopkins' reflection records (this volume and Figure 16 this chapter), which are also processed multichannel data, show a thick wedge of low-velocity material below Horizon B″ in the Aruba Gap where the two-ship refraction yielded similar results. The wedge clearly thickens toward the continental margin. Hopkins states that, based on these seismic velocities, there is a thick volcanic-sedimentation section below the oldest dated (Late Cretaceous) sediment in Aruba Gap, therefore, the age of the crust must be older than Late Cretaceous.

Donnelly suggests (Magnetic Anomalies. . . this volume) that, based on a comparison of airborne and shiptowed magnetometer records, the source of the magnetic anomalies in the Venezuelean Basin is well below the level of igneous rocks corresponding to Horizon B″.

The pattern of continental drift also leads us to conclude that the formation of the Caribbean crust must have taken place prior to 80 m.y. ago. It is difficult to reconcile the fact that North America began separation from Europe and Africa about 180 m.y. ago with a postulation of Caribbean crustal formation 80 m.y. ago. Following this line of reasoning, Le Pichon and Fox (1971) indicate that Caribbean crustal development probably started with the opening of the North Atlantic in the Early Jurassic, and by the end of Jurassic almost the entire sea floor of these basins would have been created.

Certainly the presence of Cretaceous rocks (Horizon B″) from the northern to southern margin of the Caribbean Sea would further indicate that at that time the Venezuelan Basin was as fully developed as it is today.

The geology of the Greater Antilles and northern Venezuela also indicates that the formation of the Caribbean crust could have started earlier than indicated from the Leg 15 drilling results. Orthogeosynclinal development started in the Greater Antilles in the Late Jurassic-Early Cretaceous (Bowen, 1966; Donnelly, 1964, 1966; Mattson, 1966; Meyerhoff, 1967) and at the same time in Venezuela, Colombia, Margarita, Trinidad, and Tobago (Renz, 1956; Hedberg, 1950; Mencher, 1951, 1963, etc.) suggesting the presence of a basin between them.

The identification of Horizon B″ with the basalts and dolerites at each site where this reflector was encountered unveils an igneous event that encompassed the entire Venezuelan Basin and parts of the Nicaragua Rise and Colombian Basin. The widespread occurrence of these igneous rocks, traced over 450,000 km^2 as reflector Horizon B″, must represent one of the most extensive penecontemporaneous basaltic flows and sites, exceeding that of the Columbia basalt fields of the northwestern United States.

From these data we conclude that the Caribbean crust is older than the Late Cretaceous sediments recovered on Leg 15, but because of constraints imposed by continental drift reconstructions of the relative positions of North and South America, we are unable to support the formation of pre-Mesozoic crust in situ. An hypothesis of an ancient Caribbean crust could only be subscribed to if the plate had a long history as part of some adjacent ocean basin before emplacement between the Americas.

Paleomagnetic evidence from magnetic studies on Leg 15 samples and from the circum-Caribbean lands indicates that the Caribbean plate, including the northern parts of Colombia and Venezuela, have moved relative to the adjacent North and South American plates since the Cretaceous (Lowrie and Opdyke, this volume). Magnetization inclinations on Caribbean basin samples, the Greater Antilles, and the Goajira Peninsula (Lowrie and Opdyke) of

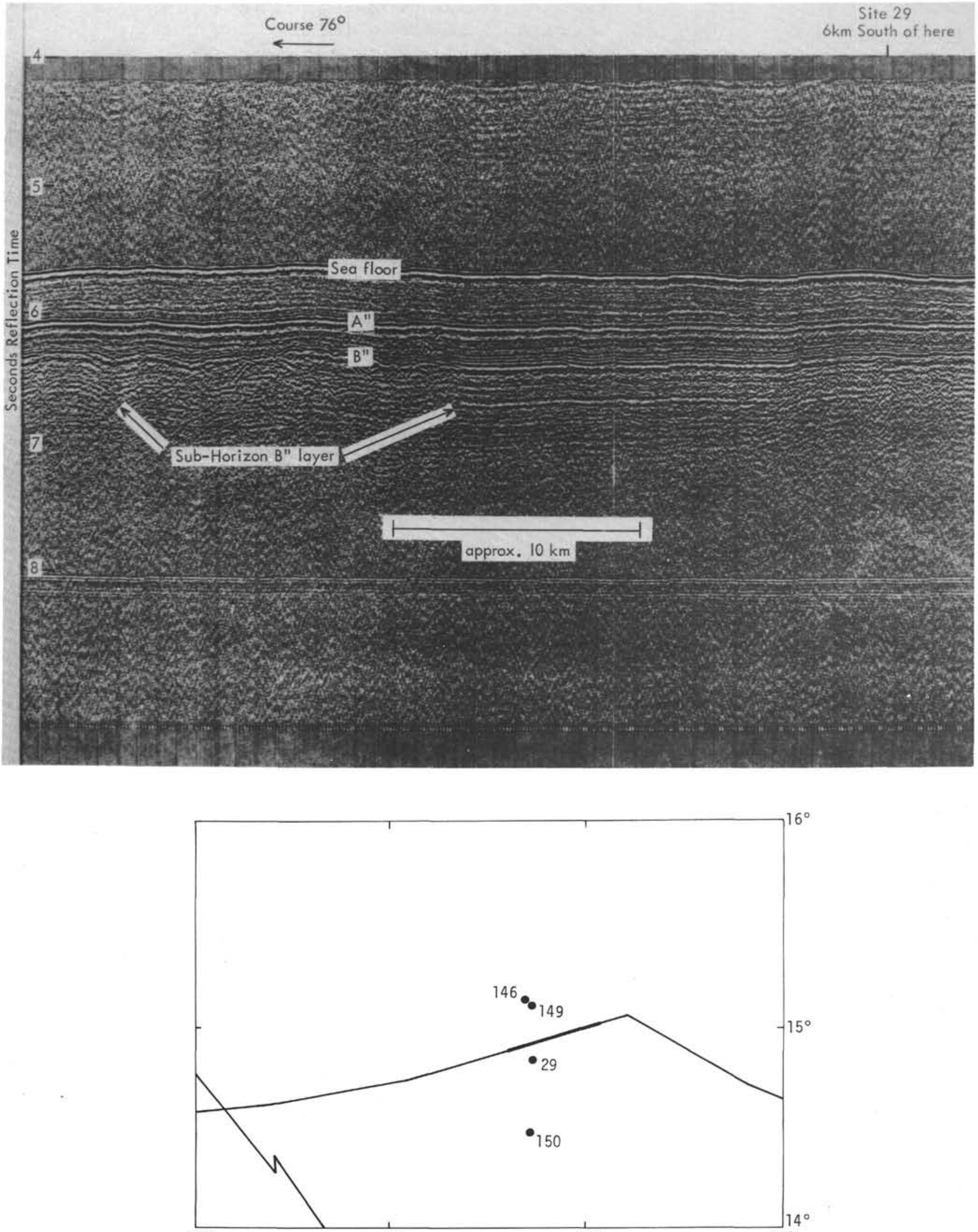

Figure 15. *Processed multichannel reflection record showing horizons below Horizon B" in the central Venezuelan Basin near Site 29 of Leg 4. Heavy line on track chart shows location of reflection record (courtesy Gulf Oil Company).*

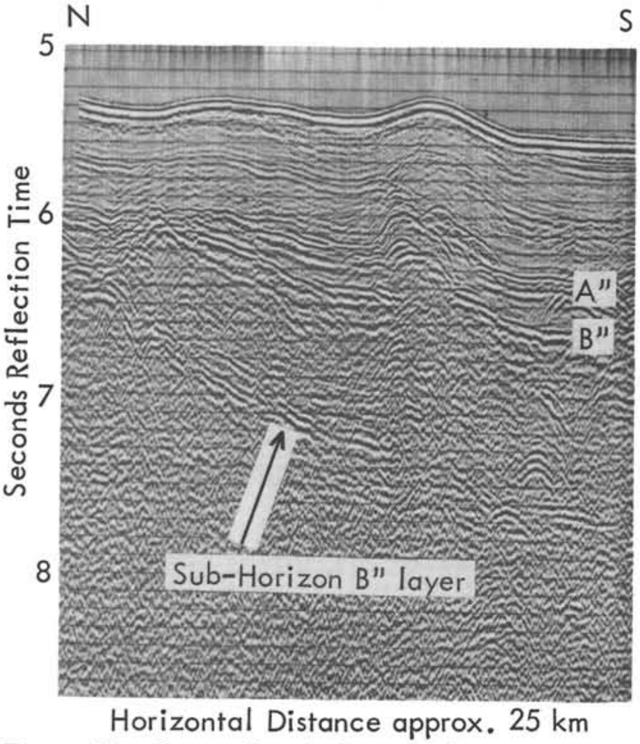

Figure 16. *Processed multichannel reflection record in Aruba Gap showing reflector beneath Horizon B" (courtesy Esso Production Research Corporation).*

northern Colombia indicate that these areas all occupied lower latitude sites in Cretaceous time. Independently, Raff (this volume) arrived at the same conclusions in a study of a magnetic anomaly over a seamount in the northern Venezuelan Basin. The consistency in the results of paleomagnetic data in the Caribbean cannot be ignored. The more southerly latitude in the Cretaceous can be explained as a natural consequence of rotation of South America from Africa, but the other data suggesting rotations of up to 90° during and since the Cretaceous and the involvement of northern South America in these rotations (but not further south in the continent) strains the constraints imposed by geologic considerations. Based on the limited available paleomagnetic data from the region it may be premature to further pursue this line of evidence at this time, but clearly the consistency of the results to date warrant close monitoring in the future.

We concur with the basic model of Caribbean crustal development outlined by Le Pichon and Fox (1971). They postulate that the Caribbean crust was almost entirely created by differential movement (divergent and transcurrent) between North and South America at about the end of Jurassic time and subsequent differential movement (predominently transcurrent) in Early and mid-Cretaceous affected only the margins of the basins. Late Cretaceous and Cenozoic differential movement was slight and still only affected the continental margins.

We do not agree with their conclusions that Early and mid-Cretaceous differential movement between the Americas affected only the margins. The ubiquitous Late Cretaceous basalts, dolerites, and basaltic ash recovered from the basins and ridges is evidence of basin-wide igneous activity that came to a halt about 80 million years ago. Apart from this difference, we believe they have established an acceptable framework to be developed.

New crust could have formed as a result of spreading within the Caribbean Sea itself or alternatively by shear and fracture extension. A fragment of older crust from the Pacific could have been wedged between the Americas as they separated.

Spreading within the Caribbean Sea has been discussed by Le Pichon (1968), Stainforth (1969), and Dietz and Holden (1970). LePichon (1968) noted that the divergence of flow lines in the boundary region between North and South American drifts resulted in the creation of the Caribbean, presumably by "subsidiary spreading." Stainforth described a model in which an expanding convection cell formed within the Caribbean Sea during the Cretaceous, thus explaining the south-directed orogeny in Venezuela that continued into early Tertiary. Dietz and Holden proposed a spreading center between the Americas that connected with the spreading ridge in the North Atlantic. By the end of Cretaceous, crustal spreading ceased and the North and South Atlantic spreading system had become a single active system.

It is also possible that the Caribbean crust could have been created in the Jurassic by rifting and extension as described by Funnel and Smith (1968), Ball and Harrison (1969) and Ball, Harrison and Supko (1969). They based their concept on the track of the continents during drift and noted that divergence between the Americas should result in crustal formation through rifting and extension.

Following this basic reasoning, others concluded that a divergent transcurrent westward movement of the Americas should result in a fragment of Pacific crust being bypassed and trapped or wedged between the continents (North, 1965; Mattson, 1966; Wilson, 1966; Edgar et al., 1971; Malfait and Dinkelman, 1971). After emplacement, the crust became decoupled from the rest of the Pacific and a subduction zone formed along the present location of south Central America.

To establish which of these is correct will certainly prove to be challenging. However, there are some points worth mentioning that bear on the subject. During the Jurassic-Early Cretaceous, orthogeosynclines developed in the Greater Antilles and along the north coast of Venezuela. In each case the eugeosyncline faced or was adjacent to the Caribbean Sea. Our concepts of geosynclinical formation lead us to conclude that compression between two plates is required to form a geosyncline. If this is correct then it is difficult to reconcile rifting and extension with the development of these geosynclines. They could, however, have been formed by a spreading center within the Caribbean or by the wedging effect of a piece of Pacific crust.

With regard to the spreading concept, there is no apparent spreading center and only weak, poorly defined magnetic anomalies in the Venezuelan Basin that are oriented northeast-southwest and some east-west anomalies in the southern Colombian Basin. Overall, the evidence for spreading is not impressive, but not entirely negative.

In any case, the crust, whatever the origin, probably covered an area equivalent to the present Caribbean Sea by the end of the Jurassic. Later differentional motion between the Americas caused shear, and possibly tension, in the newly created or emplaced Caribbean crust. Evidence of structural disturbance is found in the Gulfrex record (Figure 15) where areas of disturbed and nondisturbed pre-Horizon B″ layers are recorded. These stresses caused massive basalt outpouring and intrusion into the Late Jurassic-Early Cretaceous volcanic-sedimentary complex. About Turonian-Santonian time, there was a relative shift in the poles of rotation of North and South America caused by the removal of mechanical constraints resulting from the interference of continental lithospheric blocks (Le Pichon and Hayes, 1971; Le Pichon and Fox, 1971). Relative motion between the Americas was reduced and what there was affected only the continental margins and not the floor of the basins (Le Pichon and Fox, 1971). Thus the last volcanic phase (Caribbean basins, Horizon B″) could represent the transition from major shear and tension resulting from considerable differential movement of the Americas to a period of little differential movement manifested in marginal tectonic activity. The seismic data presented by Hopkins (this volume, Figure 3a) indicate that Horizon B″ and older layers extended below the continental margin of South America which suggests the basin was larger in the past and has been reduced in size by compression and overriding by the continental block.

SUMMARY

Basalts and dolerites associated with sediments of late Cretaceous age recovered at five sites represent the last phase of igneous activity within the deep basins of the Caribbean Sea. The crust was probably formed at a much earlier time, perhaps in the early Mesozoic when North America began to separate from Europe and Africa. It is uncertain whether the Caribbean crust was generated at this time or whether it was emplaced from the Pacific.

Divergent and transcurrent differential movement between the Americas continued until the end of Jurassic time when the crust was almost entirely created or fully emplaced. At this time orthogeosynclines developed in the Greater Antilles and along the northern margin of South America. Ocean circulation in the normal marine environment of the North Atlantic became increasing weak and the water experienced periods of stagnation. A massive emplacement of basalts and dolerites in the late Cretaceous marks the end of major igneous activity in the main Caribbean basin. Orogenic activity was felt in the orthogeosynclines at this time. Periods of stagnation in the Caribbean, but not indicated in the corresponding Pacific sediments suggesting the presence of a sill, was of the Caribbean. The periods of stagnation came to an end in Santonian time. The renewed ocean circulation may be identified with the removal of the sill or the generation of bottom water interchange from the newly developing South Atlantic. Volcanic activity was centered in the western Greater Antilles and granodiorite was intruded into the Venezuelan continental margin. Normal marine pelagic sedimentation continued into the Early Tertiary with a notable shallowing of the depth of calcium carbonate compensation, but widespread flysch facies characterizes sedimentation of northern South America, suggesting extremely effective circum-Caribbean sediment traps. The Greater Antilles experienced intrusion, uplift, and erosion at this time. In the Middle Eocene to Early Miocene, pelagic sedimentation was dominated by the sudden appearance of abundant Radiolaria. Similar Radiolaria-rich sediments appeared in the Middle Eocene of Barbados and otherparts of the North Atlantic. Volcanic activity in the Greater Antilles ceased but was probably initiated in the Lesser Antilles at about this time. The rest of the Radiolaria-rich sediments were deposited in the very Early Miocene and a new period of sedimentation began; a period of tremendous influx of terrigenous clay, apparently, from a South American source. Probably not by coincidence, this was also the time of the initiation of major deltaic deposition in northern South America. Evidence of volcanic activity in the Miocene and Early Pliocene sediments of the deep basins is meager except as transported shallow-water volcanic sands near Panama. In the Early Pliocene, the Panamian Isthmus was finally completed. By mid-Pliocene volcanic activity was renewed in the Lesser Antilles and increased in the early and mid-Pleistocene. Sedimentation rates and the calcium carbonate component of the sediments increased markedly in the Late Pleistocene.

REFERENCES

Allard, G. O., and Jurst, V. J., 1969. Brazil-Gabon geological link supports continental drift: Science, v. 163, p. 528-532.

Baadsgaard, P. H., 1960. Barbados, W. I.: Exploration results 1950-1958: Internat. Geol. Congress, XXI, Copenhagen, Norden, 1960, Proc., p. 21-27.

Bader, R. G., Gerard, R. D., et al., 1970. Initial Reports of the Deep Sea Drilling Project, Volume IV. Washington (U. S. Government Printing Office).

Ball, M. M., and Harrison, C. G. A., 1969. Origin of the Gulf and Caribbean and implications regarding ocean ridge extension, migration, and shear: Gulf Coast Assoc. Geol. Socs., Trans., v. 19, p. 287-294.

Ball, M. M., Harrison, C. G. A., and Supko, P. R., 1969. Atlantic opening and the origin of the Caribbean: Nature, v. 223, p. 167.

Barr, K. W., 1963a. The geology of the Toco District, Trinidad, West Indies: Overseas Geol. and Min. Res., Her Majesty's Stationery Office, London.

————, 1963b. The structural framework of the Caribbean region: Tulsa Geol. Soc. Digest, v. 31, p. 75-102.

Barr, K. W., and Saunders, J. B., 1968. An outline of the geology of Trinidad: Caribbean Geol. Conf., IV, Trinidad and Tobago, 1965, Trans., p. 1-10.

Beets, D. J., 1972. Lithology and stratigraphy of the Cretaceous and Danian succession of Curacao: Natuurwetensch. Studiek, voor Suriname Neder. Antillen, Utrecht, p. 70.

Benson, W. E., Gerard, R. D., and Hay, W. W., 1970. Summary and conclusions: Initial Reports of the Deep Sea Drilling Project, Volume IV. Washington (U. S. Government Printing Office), p. 659.

Berger, W. H., and von Rad, Ulrich, 1972. Cretaceous and Cenozoic sediments from the Atlantic Ocean: Initial Reports of the Deep Sea Drilling Project, Volume XIV. Washington (U. S. Government Printing Office), p. 787.

Berggren, W. A., 1971. A Cenozoic time-scale: some implication for regional geology and biogeography: J. Foram. Res., v. 1, p. 1.

Bolli, H. M., 1957a. The genera *Globigerina* and *Globorotalia* in the Paleocene-lower Eocene Lizard Springs Formation of Trinidad, B. W. I.: U. S. Nat. Mus., Bull. 215, p. 61-81.

———, 1957b. The genera *Praeglobotruncana, Rotalipora, Globotruncana,* and *Abathomphalus* in the Upper Cretaceous of Trinidad, B. W. I.: U. S. Nat. Mus., Bull. 215, p. 51-60.

Bowin, C. O., 1966. Geology of Central Dominican Republic (A case history of part of an island arc): Geol. Soc. America, Mem. 98, p. 11-84.

Butterlin, Jacques, 1956. La constitution geologique et la structure des Antilles: Centre National de la Recherche Scientifique.

Christofferson, E., 1972. Colombia Basin magnetic anomalies (Abs.). *In* Caribbean Geol. Conf., Sixth, Trans., Mattson, P. H. (Ed.) 1971, Margarita, p. 303.

Chubb, L. J., 1960. The Antillean Cretaceous geosyncline: Caribbean Geol. Conf., 2nd, Trans., Mayaguez, 1959, p. 17-26.

Cita, M. B., 1973. Pliocene biostratigraphy and chronostratigraphy: Initial Reports of the Deep Sea Drilling Project, Volume XIII. Washington (U. S. Government Printing Office), p. 1343.

Dengo, G., 1962. Tectonic-igneous sequence in Costa Rica. *In* Petrologic studies: a volume in honor of A. F. Buddington: Geol. Soc. America, p. 133.

———, 1969. Problems of tectonic relations between Central America and the Caribbean: Gulf Coast Assoc. Geol. Socs. Trans., v. 19, p. 311-320.

Dietz, R. S., and Holden, J. C., 1970. Reconstruction of Pangaea: breakup and dispersion of continents, Permian to present: J. Geophys. Res., v. 75, p. 4939-4956.

Donnelly, T. W., 1964. Evolution of eastern Greater Antillean island arc: Am. Assoc. Petroleum Geologists Bull., v. 48, p. 680-696.

———, 1966. Geology of St. Thomas and St. John, U. S. Virgin Islands: Geol. Soc. America Mem. 98, p. 85-176.

, 1970. Summary of the Cretaceous stratigraphy of north-central Puerto Rico: I. F. I. Caribbean Guidebook.

Edgar, N. T., Ewing, J. I., and Hennion, John, 1971. Seismic refraction and reflection in Caribbean Sea: Amer. Assoc. Petrol. Geol. Bull., v. 55, p. 833-870.

Ericson, D. B., and Wollin, G., 1968. Pleistocene climates and chronology in deep-sea sediments: Science, v. 162, p. 1227.

Ewing, J. I., Antoine, J., and Ewing, Maurice, 1960. Geophysical measurements in the western Caribbean Sea and in the Gulf of Mexico: J. Geophys. Res., v. 65, p. 4087-4126.

Ewing, J. I., and Hollister, C. D., 1972. Regional aspects of deep sea drilling in the Western North Atlantic: Initial Reports of the Deep Sea Drilling Project, Volume XI. Washington (U. S. Government Printing Office), p. 951.

Ewing, J. I., Windisch, C., and Ewing, Maurice, 1970. Correlation of Horizon A with JOIDES bore-hole results: J. Geophys. Res., v. 75, p. 5645.

Ewing, J. I., Worzel, J. L., Ewing, Maurice, and Windisch, Charles, 1966. Ages of Horizon A and the oldest Atlantic sediments: Science, v. 154, p. 1125-1134.

Ewing, Maurice, and Ewing, J. I., 1962. Rate of salt-dome growth: Am. Assoc. Petrol. Geol. Bull. v. 46, p. 708-709.

Ewing, Maurice, Saito, Tsunemasa, Ewing, J. I., and Burkle, L. H., 1966. Lower Cretaceous sediments from the northwestern Pacific: Science, v. 152, p. 751-755.

Ewing, Maurice, Worzel, J. L., et al., 1969. Initial Reports of the Deep Sea Drilling Project, Volume I. Washington (U. S. Government Printing Office).

Fink, K. L., Harper, C. T., Stipp, J. J., and Nagle, Fred, 1972. Tectonic significance of La Desirade – possible relict sea floor crust (Abs.). *In* Caribbean Geol. Conf., 6th, Margarita, 1971, Trans., Mattson, P. H., (Ed.), p. 302.

Fink, K. L., and Harrison, C. G. A., 1972. Paleomagnetic investigations of selected lava units on Puerto Rico (Abs.). *In* Caribbean Geol. Conf., 6th, Margarita, 1971, Trans., Matson, P. H. (Ed.), p. 379.

Fischer, A. G., Heezen, B. C., et al., 1971. Initial Reports of the Deep Sea Drilling Project, Volume VI. Washington (U. S. Government Printing Office), 1329 p.

Fox, P. J., Heezen, B. C., and Johnson, G. L., 1970. Jurassic sandstone from the tropical Atlantic: Science, v. 170, p. 1402.

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

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

Funnel, Brian, and Smith, A., 1968. Opening of the Atlantic: Nature, v. 219, p. 1329-1333.

Gartner, Stefan, Jr., 1972. Late Pleistocene calcareous nannofossils in the Caribbean and their interoceanic correlation: Paleogeogr., Paleoclimatol., Paleoecol., v. 12, p. 169-191.

Glover, Lynn, III, and Mattson, P. H., 1967. The Jacuguas Group in central-southern Puerto Rico. *In* Cohee, G. V., West, W. S., and Wilke, L. C., 1967. Changes in Stratigraphic Nomenclature by the U. S. Geological Survey, 1966: Geological Survey Bull. 1254A, p. A29-A39.

Gonzalez de Juana, C., et al., 1968. On the geology of Eastern Paria (Venezuela): Caribbean Geol. Conf., 4th, Trinidad and Tobago, 1965, Trans., p. 25-29.

Hay, W. W., Mohler, H. P., Roth, P. H., Schmidt, R. R., and Boudreaux, J. E., 1967. Calcareous nannoplankton zonation of the Cenozoic of the Gulf Coast and Caribbean-Antillean area and trans-oceanic correlation: Gulf Coast Assoc. Geol. Socs., Trans., v. 17, p. 428-480.

Hayes, D. E., Pimm, A. C., et al., 1972. Initial Reports of the Deep Sea Drilling Project, Volume XIV. Washington (U. S. Government Printing Office), 975 p.

Hedberg, H. D., 1937. Stratigraphy of the Rio Querecual Section of Northeastern Venezuela: Geol. Soc. Amer. Bull., v. 48, p. 1971-2204.

———, 1950. Geology of eastern Venezuela. Geol. Soc. Amer. Bull., v. 61, p. 1173.

Heezen, B. C., and Pimm, A. C., 1971. Underway observations, Leg 6, Deep Sea Drilling Project: Initial Reports of the Deep Sea Drilling Project, Volume VI. Washington (U. S. Government Printing Office), p. 691-708.

Heezen, B. C., Tharp, Marie, and Ewing, Maurice, 1959. The floors of the oceans: Geol. Soc. Amer. Spec. Paper 65, 122 p.

Helsley, C. E., 1971. Summary of the geology of the British Virgin Islands (Abs.). *In* Mattson, P. H. (Ed.), Trans. of the Fifth Caribbean Geological Conference, St. Thomas, 1968, p. 69.

Henningsen, D. W., 1968. Stratigraphy and paleogeography of Upper Cretaceous and Tertiary sediments in southern Costa Rica: Caribbean Geol. Conf., Trinidad and Tobago, 1965, Trans., p. 353.

Henningsen, D. W., and Weyl, Richard, 1967. Ozeanische kruste im Nicoya-Complex von Costa Rica (Mittleamerika): Geol. Rundschau, v. 57, p. 33.

Hoffstetter, R., and Bracci, L. Z., 1960. Nicaragua: Lexique Stratigraphique International, Amerique Latine, v. 5, Fasc. 2a, p. 172.

Hoffstetter, R., Dengo, G., and Weyl, Richard, 1960. Costa Rica: Lexique Stratigraphique International, Amerique Latine, v. 5, FASC. 2a, p. 226.

Hollister, C. D., Ewing, J. I., et al., 1972. Initial Reports of the Deep Sea Drilling Project, Volume XI. Washington (U. S. Government Printing Office), 1077 p.

Jacobs, M., and Ewing, Maurice, 1969. Mineral source and transport in waters of the Gulf of Mexico and Caribbean Sea: Science, v. 163, p. 805.

Kaneps, A. G., 1970. Late Neogene biostratigraphy (planktonic foraminifera), biostratigraphy and depositional history: Columbia University, PhD thesis, No. 71-17.509, Univ. Microfilms, Ann Arbor, Michigan, 179 p.

Khudoley, K. M., and Meyerhoff, A. A., 1971. Paleogeography and geological history of Greater Antilles: Geol. Soc. Amer. Mem. 129.

Kugler, H. G., 1953. Jurassic to recent sedimentary environments in Trinidad: Bull. Assoc. Suisse des Geol. et Ing. du Petrole, v. 20, p. 27-60.

———, 1961. Tertiary of Barbados, W. I.: Geol. Mag., v. 98, p. 348-350.

Lancelot, Yves, Hathaway, J. C., and Hollister, C. D., 1972. Lithology of sediments from the western North Atlantic, Leg XI, Deep Sea Drilling Project: Initial Reports of the Deep Sea Drilling Project, Volume XI. Washington (U. S. Government Printing Office), p. 901.

Laughton, A. S., Berggren, W. A., et al., 1972. Explanatory notes: Initial Reports of the Deep Sea Drilling Project, Volume XII. Washington (U. S. Government Printing Office), p. 9.

Le Pichon, Xavier, 1968. Sea-floor spreading and continental drift: J. Geophys. Res., v. 73, p. 3661-3698.

Le Pichon, Xavier, and Fox, P. J., 1971. Marginal offsets, fracture zones, and the early opening of the North Atlantic: J. Geophys. Res., v. 76, p. 6292.

Le Pichon, Xavier, and Hayes, D. E., 1971. Marginal offsets, fracture zones, and the early opening of the South Atlantic: J. Geophys. Res., v. 76, p. 6283-6293.

Lexico Estratigrafico de Venezuela (Segunda Edicion), 1970. Vol. Geol., Publ. Esp. No. 4.

Lidiak, E. G., 1970. Volcanic rocks in the Puerto Rican Orogen: I.F.I. Caribbean Guidebook.

Lloyd, J. J., 1963. Tectonic history of the south Central-American orogen: *In* Backbone of the Americas, Childs, O. E., and Beebe, B. W. (Eds.): Amer. Assoc. Petrol. Geol., Mem. 2, p. 88.

MacDonald, W. D., 1968. Geology of the Serrania de Macuira Area, Guajira Peninsula, Northeast Colombia: Caribbean Geol. Conf., 4th, 1965, Trinidad and Tobago, Trans., p. 267-273.

MacDonald, W. D., and Opdyke, N. D., 1972. Tectonic rotations suggested by paleomagnetic results from northern Colombia, South America: J. Geophys, Res., v. 77, p. 5720.

MacGillavary, H. J., 1970. Geological history of the Caribbean: Koninkl. Nederl. Akademie van Wetenschappen, Amsterdam, Proc., Series B., v. 73, No. 1, p. 64-96.

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

Martin Bellizzia, C., et al., 1968. Resena geologica y descripcion de las muestras de rocas Venezolanas sometidas a analisis de edades radiometricas: Bol. Geol., Caracas, v. 10, p. 339.

Martin-Kaye, P. H. A., 1969. A summary of the geology of the Lesser Antilles: Overseas Geol. and Min. Res., v. 10, p. 172.

Mattson, P. H., 1966. Geological characteristics of Puerto Rico. *In* Continental Margins and Island Arcs, International Upper Mantle Project, Poole, W. H. (Ed.): Canada Geol. Survey Paper 66-15, 124-138.

———, 1973. Middle Cretaceous nappe structures in Puerto Rican ophiolites and their relation to the tectonic history of the Greater Antilles: Geol. Soc. Amer., v. 84, p. 21.

Mattson, P. H., Pessagno, E. A., Jr., 1971. Caribbean Eocene volcanism and the extent of Horizon A: Science, v. 174, p. 138.

Maxwell, A. E., von Herzen, R. P., et al., 1970. Initial Reports of the Deep Sea Drilling Project, Volume III. Washington. (U. S. Government Printing Office), 806 p.

Maxwell, J. C., 1948. Geology of Tobago, British West Indies: Geol. Soc. Amer. Bull., v. 59, p. 801-854.

Mencher, E., 1963. Tectonic history of Venezuela. *In* Backbone of the Americas, Childs, O. E., and Beebe, B. W. (Eds.): Amer. Assoc. Petrol. Geol., Mem. 2, p. 73-87.

Mencher, E., Ficter, H., Renz, H., Wallis, W., Patterson, J., and Robie, R., 1951. Geologic review: Natl. Petroleum Conv., Caracas, Ministerio de Minas e Hidrocarburos, p. 1-75.

Meyerhoff, A. A., 1967. Future hydrocarbon provinces of Gulf of Mexico-Caribbean region. *In* Symposium on the Geological History of the Gulf of Mexico, Antillean-Caribbean region, Sandidge, J. (Ed.): Gulf Coast Assoc. Geol. Socs. Trans., v. 17, p. 217-260.

Meyerhoff, A. A., and Meyerhoff, H. A., 1972. Continental Drift, IV: The Caribbean "plate": Jour. Geol., v. 80, p. 34-60.

North, F. K., 1965. The curvature of the Antilles: Geologie en Mijnbouw, v. 44, p. 73-86.

Officer, C. B., Ewing, J. I., Edwards, R. S., and Johnson, H. R., 1957. Geophysical investigations in the Caribbean: Geol. Soc. Amer. Bull., v. 68, p. 359-378.

Officer, C. B., Ewing, J. I., Hennion, J. F., Harkrider, D. G., and Miller, D. E., 1959. Geophysical investigations in the eastern Caribbean – Summary of the 1955 and 1956 cruises. *In* Physics and Chemistry of the Earth, Ahrens, L. H., et al., v. 3: London, Pergamon Press, p. 17-109.

Pessagno, E. A., 1971.

Pessagno, E. A., 1972. Cretaceous radiolaria: Bull. Amer. Paleontology, v. 61, p. 269-328.

Peterson, M. N. A., Edgar, N. T., et al., 1970. Initial Reports of the Deep Sea Drilling Project, Volume II. Washington (U. S. Government Printing Office).

Pimm, A. C., and Hayes, D. E., 1972. General synthesis: Initial Reports of the Deep Sea Drilling Project, Volume XIV. Washington (U. S. Government Printing Office), p. 955-975.

Reyment, R. A., and Tait, E. A., 1972. Biostratigraphical dating of the early history of the South Atlantic Ocean: Phil. Trans. Roy. Soc. London, Ser. B, v. 264, p. 55.

Renz, O., 1956. Cretaceous in western Venezuela and the Guajira (Abs.). *In* Resumenes de los trabajos presentados: 20th International Geol. Cong., Mexico, p. 342.

Robinson, E., Lewis, J. F., and Cant, R. V., 1970. Field guide to aspects of the geology of Jamaica: I. F. I. Caribbean Guidebook.

Robson, G. R., and Tomblin, J. F., 1966. Catalogue of the active volcanoes of the World including Solfatara fields.

Part XX West Indies: Stabilimento Tipografico Francesco Giannini and Figli, Via Cisterna dell'Olio, Napoli.

Rollins, J. F., 1960. Stratigraphy and structures of the Goajira Peninsula, Northwestern Venezuela, and Northeastern Colombia. Unpublished thesis.

Roobol, M. J., 1972. The volcanic geology of Jamaica: Caribbean Geol. Conf., 6th Margarita, 1971, Trans., p. 100.

Saunders, J. B., 1968. Field trip guide: Barbados: Caribbean Geol. Conf., 4th, Trinidad and Tobago, 1965, Trans., p. 443-449.

———, . Trinidad in data for orogenic studies: Geol. Soc. London (in press).

Schuchert, Carlos, and Moticska, Peter, 1972. Geological reconnaissance of the Venezuelan Islands in the Caribbean Sea between Los Roques and Los Testigos: Caribbean Geol. Conf., 6th, Margarita, 1971, Trans., p. 81.

Sclater, J. G., Anderson, R. N., and Bell, M. L., 1971. Elevation of ridges and evolution of the Central Eastern Pacific: J. Geophys. Res., v. 76, p. 7888.

Seilacher, A., 1964. Biogenic sedimentary structures. *In* Approaches to Paleoecology, Imbrie, J., and Newell, N. D. (Eds.): New York (Wiley), p. 296.

Senn, A., 1940. Paleogene of Barbados and its bearing on history and structure of Antillean-Caribbean region: Amer. Assoc. Petrol. Geol. Bull., v. 24, p. 1548.

Stainforth, R. M., 1969. The concept of sea floor spreading applied to Venezuela: Caracas Assoc. Venezolana Geologia, Mineria y Petroleo, Boletin Informativo, v. 12, p. 257-274.

Talwani, Manik, 1966. Gravity anomaly belts in the Caribbean (Abs.). *In* Continental Margins and Island Arcs, Poole, W. H. (Ed.): Geol. Survey Canada Paper 66-15, p. 177.

Talwani, Manik, Worzel, J. L., Ewing, W. M., 1960. Gravity anomalies and structure of the Bahamas: Caribbean Geol. Conf., 2nd, Mayaguez, Puerto Rico, Trans., p. 156-161.

Taylor, G. C., 1960. Geologia de la Isla de Margarita, Venezuela: Tercer Cong. Geol. Venez., Tomo II, Bol. Geol., Publ. Esp. No. 3, p. 838.

Terry, R. A., 1956. A geological reconnaissance of Panama: Calif. Acad. Sci. Occ. Paper 23, 91 p.

Tomblin, J. F., 1968. The geology of Soufriere volcanic centre, St. Lucia: Caribbean Geol. Conf., 4th, 1965, Trinidad and Tobago, Trans., p. 367-376.

———, 1970. Field guide to Tobago, Lesser Antilles: I. F. I. Caribbean Fieldbook.

van Andel, T. H., Heath, G. R., Bennett, R. H., Charleston, Santiago, Cronan, David, Rodolfo, K. S., Yeats, Robert, Bukry, David, Dinkelman, Menno, and Kaneps, Ansis, 1971. Deep Sea Drilling Project, Leg 16: Geotimes, v. 16, No. 6, p. 12.

van Hinte, J. E., 1971. The Cretaceous time-scale and planktonic foraminiferal zones: Proc. Konikl. Ned. Akad. Wetenschap. Amsterdam, Ser. B, v. 74, p. 1.

Weyl, Richard, 1961. Die Geologie Mittelamerikas: Gebruder Borntraeger, Berlin, Nikolassee, p. 50.

———, 1966. Die geologic der Antillen: Gebruder Borntraeger, Berlin, 410 p.

Whetten, J. T., 1966. Geology of St. Croix, U. S. Virgin Islands: Geol. Soc. Amer., Mem. 98, p. 177-239.

Williams, H., and McBirney, A. R., 1969. Volcanic history of Honduras: Calif. Univ. Pubs. Geol. Sci., v. 85, 101 p.

Wilson, J. T., 1966. Did the Atlantic close and then re-open?: Nature, v. 211, p. 676-681.

Winterer, E. L., Ewing, J. I., Schlanger, S. O., Moberly, R. M., Lancelot, Yves, Jarrard, R. D., Douglas, R. G., Moore, T. C., and Roth, Peter, 1971. Deep Sea Drilling Project, Leg 17: Geotimes, v. 16, No. 9, p. 12.

Woodring, W. P., 1957. Geology and Paleontology of Canal Zone and adjoining parts of Panama: Geology and description of Tertiary Mollusks (Gastropods: Trochidae to Turritellidae): Geol. Survey, Prof. Paper 306A, p. 1-145.

Worzel, J. L., and Bryant, William, 1973. Regional aspects: Initial Reports of the Deep Sea Drilling Project, Volume X. Washington (U. S. Government Printing Office), p. 737.

Zans, V. A., et al., 1962. Synopsis of the geology of Jamaica: an explanation of the 1958 provisional geological map of Jamaica: Geol. Survey Dept., Jamaica, Bull. 4.