Chapter 1

Caribbean Sedimentary Basins: Classification and Tectonic Setting from Jurassic to Present

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INTRODUCTION

The purpose of this introductory chapter is to describe the active tectonic setting of the Caribbean, its major crustal provinces, and to provide a simple classification for sedimentary basins in the Caribbean region. In addition to this background information on Caribbean basins, I provide a series of thirteen quantitative plate reconstructions based on the revised plate model of Müller et al. (Chapter 2). These reconstructions serve to place individual basins into a better tectonic framework.

ACTIVE TECTONIC SETTING OF CARIBBEAN SEDIMENTARY BASINS

Major plates

The distribution of recorded earthquakes, active calc-alkaline volcanoes, and spreading ridges defines five rigid plates in the Caribbean region: North America, South America, Caribbean, and Nazca (Molnar and Sykes, 1969; Mann et al., 1990) (Fig. 1). Geologic and seismic studies indicate that the Caribbean plate is moving eastward relative to the Americas, and this movement is accommodated by left-lateral strike-slip faults along its boundary with the North America plate, and right-lateral strike-slip faults along its boundary with the South America plate. Oceanic lithosphere of the North and South America plates is consumed along the eastern edge of the Caribbean at the Lesser Antilles subduction zone. Oceanic lithosphere of the Cocos and Nazca plates is consumed along the western and southwestern edge of the plate at the Middle America subduction zone (Fig. 1).

Plate rates

Rates of relative plate motion as predicted by the Nuvel-1A plate motion model of DeMets et al. (1994) are relatively slow (11–13 mm/year) between the Americas and the Caribbean plate but much faster (59–74 mm/year) between the Cocos, Nazca and Caribbean plates (Fig. 1). Recent GPS-based studies of the relative motion between the North America and Caribbean plates in the northeastern Caribbean by Dixon et al. (1998) have shown that the actual North America–Caribbean rate of east–west strike-slip motion may be twice as fast as predicted by the Nuvel-1A plate motion model.

Earthquake studies

There have been many first-motion studies on large Caribbean earthquakes over the past 25 years and I have compiled a representative group from the Harvard focal mechanism catalogue on Fig. 1. Because large earthquakes occur more frequently in subduction zone settings, many more focal mechanisms are available from the Lesser Antilles and Middle America arcs than for the northern and southern dominantly strike-slip plate boundaries. In general, subduction zone earthquakes are characterized by shallow thrust faulting with the auxiliary plane striking approximately parallel to the trend of the trench and dipping steeply away from the arc and with the fault plane striking subparallel to the arc trend and dipping gently beneath the arc. First-motion studies from the strike-slip plate boundaries are consistent with shallow focus left-lateral fault displacements along the northern plate boundary zone and right-lateral displacements along the southern plate boundary zone (Fig. 1).
Fig. 1. Earthquake focal mechanisms and plate motions relative to a fixed Caribbean plate based on the NUVEL-1A global plate motion model of DeMets et al. (1994). Numbers give rate of plate motion in mm/year and arrows give directions of plate motion. Focal mechanisms are color-coded according to depth: red mechanisms are from earthquakes from 0 to 75 km in depth; blue mechanisms are from earthquakes from 75 to 150 km in depth; and green mechanisms are >150 km in depth. Basemap is the Geosat gravity map of the Caribbean compiled by Sandwell and Smith (1997). In accordance with plate motion model predictions, earthquake focal mechanisms show predominantly left-lateral motion along the northern edge of the Caribbean plate, predominantly right-lateral motion along the southeastern edge of the plate, predominantly thrust motion at the eastern and western ends of the plate, and predominately northeast-directed right-lateral motion associated with the displacement of the Maracaibo block in the southwestern Caribbean. The Maracaibo block is a continental-arc fragment of northwestern South America that is escaping to the north and northeast as a response to the late Neogene collision of the Panama arc and oblique subduction of the northern Nazca plate.

First-motion studies along with geologic and GPS-based geodetic studies have shown that the northwestern corner of South America (Maracaibo block of Mann and Burke, 1990) is being displaced northward and northwestward along the Boconó—eastern Andean right-lateral strike-slip fault system in Colombia and western Venezuela (McCann and Pennington, 1990; Kellogg and Vega, 1995) (Fig. 1). This displacement appears to be a consequence of late Neogene collision of the Panama arc with northwestern South America (Mann and Burke, 1990).

Subducted slabs

Inclined subducted slabs extend to depths of 150 km under most of the land areas adjacent to the Lesser Antilles and Middle America arcs (McCann and Pennington, 1990; Dewey and Suárez, 1991) (Fig. 1). Subducted slabs are also present beneath much of the northwestern corner of South America (van der Hilst and Mann, 1994).

MAJOR CRUSTAL PROVINCES OF THE CARIBBEAN REGION

The Caribbean region consists of a rim of Cretaceous–Recent arc terranes and associated back-arc basins molded about a sub-circular core consisting of a continental fragment in the western Caribbean (Chortís block) and an oceanic plateau province beneath the central and eastern Caribbean (cf. Case et al., 1990, for a comprehensive review of all Caribbean crustal provinces) (Fig. 2).

Chortís block

The Chortís block of northern Central America consists of well-dated Mesozoic and Cenozoic formations which unconformably overlie a continental basement of poorly dated metamorphic rocks of Paleozoic and possible Precambrian age (Gordon, 1991) (Fig. 2). Seismic velocities confirm that the Chortís block is continental (Case et al., 1990) but the isotopic ages of metamorphic protolith rocks
exposed in Honduras have not been established. Limited isotopic age dates indicate a late Paleozoic metamorphic event around 300 Ma and show that these rocks are pre-Mesozoic (Gordon, 1991). The dominant basement rock types are phyllitic and graphitic schists which can contain interlayers of metaconglomerate and quartzite. The overlying Mesozoic stratigraphy consists of Middle Jurassic through Early Cretaceous clastic rocks overlain by Aptian-Albian shallow marine limestone (Scott and Finch, Chapter 6). The stratigraphic record indicates that the Chortís block was a region of minimal tectonic activity during the Mesozoic but was subject to regional folding and faulting events in the Late Cretaceous and Cenozoic (Avé Lallemant and Gordon, Chapter 8; Manton and Manton, Chapter 9).

**Caribbean oceanic plateau**

The central and eastern Caribbean is underlain by an oceanic plateau with a 12–15 km thickness that is intermediate between oceans and continents over most of its area (Case et al., 1990; Diebold and Driscoll, Chapter 19) (Fig. 2). Caribbean ocean floor made in Cretaceous or earlier times would normally have subsided as it aged to depths of between 5 and 6 km below sea level, and where it is overlain by 2 km of sediments, it might be expected to lie about 1 km deeper. The shallow depth of most of the Caribbean ocean floor, averaging 1–2 km less than predicted, is commonly attributed to the rapid and widespread emplacement of basaltic flows and sills to form an immense oceanic plateau during Santonian time (~88 Ma) (Burke, 1988; Donnelly et al., 1990; Sinton et al., 1997).

Deformation of the Caribbean plate edges has led to exposure of the edges of the Caribbean oceanic plateau in Costa Rica (Sinton et al., 1997), Panama (Bowland and Rosencrantz, 1988), southern Hispaniola (Sen et al., 1988), Colombia, and northern Venezuela (Kerr et al., 1997). The thickness and geochemistry of the Caribbean oceanic plateau is similar to that of western Pacific oceanic plateaus including the Manihiki and Ontong Java (Bowland and Rosencrantz, 1988; Kerr et al., 1997).

Diebold and Driscoll (Chapter 19) and Driscoll and Diebold (Chapter 20) show that Caribbean oceanic plateau volcanism was a two-phase event. They suggest that the Santonian age sampled from circum-Caribbean outcrops and from DSDP and ODP cores in the Colombian and Venezuelan basins (Donnelly et al., 1990) dates only the second smaller phase of plateau formation.
Great Arc of the Caribbean

Arc rocks of a Cretaceous–Eocene island-arc chain are found in a semi-continuous belt from Cuba to the north coast of South America (Fig. 2). The northern, or Greater Antilles, segment of the arc from Cuba to the Virgin Islands east of Puerto Rico has been inactive since its collision with the Bahamas Platform in Late Paleocene to earliest Oligocene time. Major pulses of collision were broadly diachronous and occurred in Late Paleocene/earliest Eocene time in western Cuba (Bralower and Iturralde-Vinent, 1997; Gordon et al., 1997), Early to Middle Eocene in central Cuba (Hempton and Barros, 1993), Middle Eocene to Recent in Hispaniola (Mann et al., 1991) and Late Eocene to Early Oligocene in Puerto Rico (Dolan et al., 1991). Arc rocks of Early to Late Cretaceous age are found in a continuous belt along the Aves Ridge, the remnant arc produced by rifting of the Grenada back-arc basin, and the Leeward Antilles along the northern coast of South America (Avé Lallemant, 1997) (Fig. 2). Although the lack of reliable isotopic ages does not allow recognition of diachrony in the arc, the arc is adjacent to a west to east-younging fold-thrust belt along the northern margin of South America (Avé Lallemant, 1997).

Because all arc segments initiated during the Early Cretaceous and exhibit lithologic and geochemical similarities, several groups of workers have interpreted circum-Caribbean island-arc rocks as a continuous volcanic arc chain that ringed the Cretaceous Caribbean oceanic plateau (Malfait and Dinkelman, 1972; Pindell and Barrett, 1990). This apparently continuous volcanic chain has been called the 'Great Arc of the Caribbean' (Burke, 1988), the 'Mesozoic Caribbean Arc' (Bouysse, 1988), and the 'Proto-Antillean Arc' (Donnelly et al., 1990). In this chapter, I adopt the term 'Great Arc' for three reasons: (1) brevity; (2) the age of the arc in the Greater Antilles ranges into the Cenozoic and therefore is not always restricted to the Mesozoic; and (3) the extent of island-arc rocks related to the arc may extend far beyond the present geographic area of the Greater and Lesser Antilles.

Back-arc basins associated with the Great Arc

Paleogene back-arc basins are present along most of the length of the Great Arc of the Caribbean (Fig. 2). Marine heat-flow measurements and depth to basement calculations using marine seismic profiles from the Yucatán basin suggest that it formed during a brief period of northeasterly extension between Paleocene and Early Eocene time (Roscencrantz, 1990). Similar calculations in the Grenada back-arc basin indicate that it formed during the Paleocene hiatus in arc activity along the Lesser Antilles island arc (Bouysse, 1988). Bird et al. (Chapter 15) show that the direction of opening of the Grenada basin was approximately east-west rather than north-south as proposed by Pindell and Barrett (1990). Heubeck et al. (1991) proposed that a narrow belt of now-inverted, Paleogene basal rocks exposed on the island of Hispaniola may represent the continuation of the Grenada and Yucatán back-arc basins in this area (Fig. 2).

Deformation of Caribbean crust and basin formation

Plate tectonics within collages of continental and island-arc lithosphere like the Caribbean is well recognized to be more complicated than that in the oceans because of the existence of many older faults which act as lines of weakness and because silica-rich and feldspar-rich rocks of continents and island arcs deform more easily at low temperatures than do oceanic basalts (Fig. 2). These facts explain the broad (~200–250 km) zones of plate-edge seismicity and late Neogene deformation along all margins of the Caribbean plate as well as the diffuse zones of seismicity and active faulting within the Chortís block suggestive of large-scale, internal plate deformation (Manton, 1987; Gordon and Muehlberger, 1994) (Fig. 1). This complex crustal and active plate setting leads to basin subsidence in response to a variety of subsidence mechanisms as well as basin inversions related to abruptly changing tectonic settings.

PREVIOUS CLASSIFICATIONS AND REGIONAL STUDIES OF CARIBBEAN SEDIMENTARY BASINS

There have been many previous classifications and regional studies of Caribbean sedimentary basins within a plate-tectonic framework. Gonzalez de Juanca et al. (1980) carried out a thorough compilation on sedimentary basins in Venezuela for the Venezuelan oil industry. Burke et al. (1984) compiled information on Mesozoic rifts in the Caribbean and Gulf of Mexico related to the breakup of North and South America along with post-Eocene strike-slip basins from the southern and northern margins of the Caribbean. Ladd and Buffler (1985) compiled data on trench and forearc basins of the Middle America arc and Speed and Westbrook (1984) compiled data on forearc and intra-arc basins of the Lesser Antilles arc as part of data syntheses sponsored by the Ocean Drilling Program. Burkart and Self (1985) and Manton (1987) compiled data on active rift basins of the Chortís block. Eva et al. (1989) compiled information from mainly onland rift, arc and strike-slip basins in Venezuela, Trinidad and the Leeward Antilles. Holcombe et al. (1990)
and Ladd et al. (1990) compiled information on submarine basins from the plate interior and active plate margins, respectively, as part of the GSA Decade of North American Geology volume on the Caribbean. Stéphan et al. (1990) presented fourteen reconstructions of the Caribbean with superimposed paleogeographic information for the period from the Jurassic to the present-day. Dolan et al. (1991) compiled information and presented a tectonic synthesis of onland Paleogene sedimentary basins of Hispaniola and Puerto Rico. Pindell (1995) compiled information on rifts related to North America–South America breakup and along with foreland basins related to the diachronous collision of the Great Arc of the Caribbean and the passive margins of North and South America.

**BASIN CLASSIFICATION USED IN THIS OVERVIEW**

Fig. 3 summarizes the nomenclature I use in this chapter to classify Caribbean sedimentary basins. Four main types of basins are recognized that are associated with strike-slip, island-arc, collisional and rift environments.

**Strike-slip basins**

Using nomenclature developed by geologists in California and New Zealand, I classify Caribbean strike-slip basins into five basin types based on their bounding fault structure: (1) pull-apart basins produced by extension at a discontinuity or ‘step’ along a section of a strike-slip fault; (2) fault-wedge basins occurring at intersections of bifurcating strike-slip faults; (3) fault-angle depressions parallel to a single strike-slip fault trace; (4) fault-flank depressions between transverse secondary folds or normal faults; and (5) ramp or ‘push-down’ basins between reverse or thrust faults related to strike-slip movement (Cobbold et al., 1993) (Fig. 3A). All of these late Neogene basin types typically mark zones of strike-slip-related tectonic subsidence and are found offshore or in topographically low onland depressions or valleys.

Areas of most rapid tectonic uplift in both the northern and southern Caribbean region are often localized on restraining bend strike-slip fault segments or ‘push-ups’ related to shortening at a discontinuity or ‘step’ along a throughgoing strike-slip fault. Because these bends are usually the sites of rapid, long-term (>5 m.y.) uplift, the bends typically form deeply eroded mountainous areas that are typically structural domes exposing Cretaceous and older basement rocks.

**Island-arc basins**

Island-arc basins include trench-fill basins, fore-arc basins, intra-arc basins bounded by highs or volcanoes within the volcanic arc, and back-arc basins (Fig. 3B). The most prominent examples of island-arc basins in the Caribbean include back-arc basins of the active Middle America arc (Median–Nicaraguan, Mann et al., 1990), the extinct Greater Antilles segment of the Great Arc (Yucatán basin, Rosencrantz, 1990), and the active Lesser Antilles arc (Grenada basin, Bird et al., Chapter 15). Island-arc basins of the Great Arc are commonly deformed and require careful mapping to delineate their extent and internal facies.

![Fig. 3. Basin classification nomenclature used in this chapter to classify Caribbean sedimentary basins shown on Figs. 5–10. (A) Strike-slip basin types. (B) Island-arc basin types. (C) Collisional basin types. (D) Rift basin types.](image-url)
Collisional basins

This basin type includes foreland or foredeep basins, which are by far the most extensive and thickest of all the basin types shown on Fig. 3. In the Caribbean, these basins mark the flexure of the continental or thinned crust of the North and South America plates beneath the overriding thrust sheets of the Great Arc of the Caribbean. Piggyback basins — which can also form in non-collisional accretionary prism settings like the Barbados Ridge complex in front of the Lesser Antilles arc (Huyghe et al., Chapter 14) — form and are filled while being carried on moving thrust sheets (Ori and Friend, 1984).

Rift basins

This basin type includes full-grabens or rifts and half-grabens or rifts. Full-graben means a graben bounded on both sides by normal faults while half-graben means a graben bounded only on one side by a normal fault. The full and half types can occur singly or together and be linked by transverse strike-slip faults called transfer faults. The best examples of uninverted rifts in the Caribbean are Jurassic rifts related to the breakup of North and South America found in the southeastern Gulf of Mexico (Marton and Buffler, Chapter 3) and Paleogene rifts related to the early formation of the Cayman trough pull-apart basin (Leroy et al., 1996).

Inverted basins

Structural inversion of basins means that the basin-controlling extensional faults reversed their movement because of convergent tectonics and the basin was turned inside out to form a present-day mountain range (Williams et al., 1989). Because of the continuing activity along its margin there are many examples of inverted Caribbean sedimentary basins that include inverted Jurassic rifts in northwestern South America (Lugo and Mann, 1995), inverted intra-arc basins of the Greater Antilles segment of the Great Arc (Mann and Burke, 1990; Dolan et al., 1991), and inverted forearc basins of the Middle America arc (Kolarsky et al., 1995a). Inverted basins provide valuable insights into the early stratigraphic history of basins provided that their sediments can be well dated and their structural overprint can be removed.

USE OF GRAVITY MAPS TO ILLUSTRATE CARIBBEAN SEDIMENTARY BASINS

Gridded, 2-min, satellite-derived free-air gravity data compiled and described by Sandwell and Smith (1997) make an excellent tool for the study and classification of Caribbean sedimentary basins. On these maps, free-air gravity highs marked by the yellow and orange colors correspond to seafloor highs that include active volcanic arcs, remnant volcanic arcs, uplifted oceanic plateau crust, peripheral bulges in flexed Mesozoic oceanic crust of the Atlantic Ocean and Cenozoic crust of the Pacific Ocean and carbonate platforms and isolated banks. Fracture zones in oceanic crust are expressed as fine lineaments traceable over distances up to several hundred kilometers. Trenches at subduction zones, sedimentary accretionary wedges, and major sedimentary basins of the types shown on Fig. 3 are marked by large free-air gravity lows.

I have divided the Caribbean gravity data set into six sub-areas that allow better resolution of basins in the individual areas (Fig. 4). These areas include: (1) basins associated with the Middle America trench, arc, and back-arc in the western Caribbean (Central America) (Fig. 5); (2) basins associated with the North America–Caribbean plate boundary in the northern Caribbean (Fig. 6); (3) basins associated with the Lesser Antilles trench, arc, and back-arc in the eastern Caribbean (Fig. 7); (4) basins associated with the South America–Caribbean plate boundary in the southern Caribbean (Fig. 8); (5) basins associated with the Panama arc–South America collisional zone in the southwestern Caribbean (Panama and Costa Rica) (Fig. 9); and (6) basins associated with the central Caribbean plate (Nicaraguan Rise, Colombian basin, and Venezuelan basin) (Fig. 10).

Because free-air gravity is a close approximation of seafloor bathymetry, only those submarine Cenozoic basins with prominent morphologic expression can be distinguished on these maps. Older deformed basins from previous tectonic phases might be expressed as a gravity high or intermediate gravity value. For this reason, the offshore basins classified in this study are generally Cenozoic basins generated during the more recent phases of Caribbean strike-slip and subduction tectonics. For this reason, these maps should not be considered as complete compilations of all Caribbean sedimentary basins.

BASINS AND MAJOR TECTONIC FEATURES ASSOCIATED WITH THE MIDDLE AMERICA TRENCH, ARC, AND BACK-ARC (WESTERN CARIBBEAN)

Rifts associated with the fragmentation of the western Chortís block

Seven approximately north–south-striking Neogene rifts and half-rifts are present in the northwestern corner of the Caribbean plate (Chortís block) between the Median back-arc basin and the North
America–Caribbean strike-slip zone in Guatemala, Honduras and El Salvador (Nos. 1–7 in Fig. 5). Little is known about the exact age for the onset of rifting and the thickness of the sedimentary fill of these rifts. Several authors have attributed the transverse nature of the faulting to internal deformation of the Caribbean plate as it moves eastward relative to the North America Plate along concave southward, left-lateral strike-slip faults of the Motagua–Polochic system (No. 8 in Fig. 5) (Plafker, 1976; Burkart and Self, 1985).

Median–Nicaraguan back-arc basin

This late Neogene back-arc basin forms a prominent, 800-km-long structural depression parallel to the Middle America volcanic arc and trench (No. 9). This basin is most prominent in Nicaragua where it is occupied by two large lakes (Managua and Nicaragua) (No. 10). Late Quaternary arc volcanoes occur at the edges, in the center and adjacent to the basin. Back-arc basin sedimentary rocks of Oligocene to Neogene age are inverted along the southeastern extension of the back-arc basin in Costa Rica (No. 11). This localized back-arc basin inversion is late Miocene to Recent in age and is related to the shallow subduction of the Cocos Ridge (Kolarsky et al., 1995a) (No. 15). The Median back-arc basin to the north (No. 12) is a less distinctive and linear basinal feature than the Nicaraguan basin to the south.

Inverted forearc basin rocks adjacent to the subducting Cocos Ridge

Shallow subduction of the Cocos Ridge in Late Miocene to Recent time has inverted a marine forearc basin of Oligocene and Miocene age between the arc and trench (Kolarsky et al., 1995a) (No. 13) along with trench-slope facies on the Pacific peninsulas of Panama and Costa Rica (Corrigan et al., 1990; Collins et al., 1995) (No. 14). This inverted basin is collinear with the undisturbed, offshore Sandino forearc basin to the north along the margin of Nicaragua and El Salvador (No. 16).

Cocos Ridge

The Cocos Ridge (No. 15) is a hotspot trace of the Galapagos hotspot that stands 2 to 2.5 km higher than the surrounding seafloor and is presently subducting beneath the southern Middle America trench (Kolarsky et al., 1995a). Collins et al. (1995) propose on the basis of detailed biostratigraphic work that the Cocos Ridge contacted the Middle America trench about 3.6 Ma and inverted the back-arc area of Costa Rica by 1.6 Ma.

Panama fracture zone

This fault (No. 17) is a right-lateral transform fault that separates oceanic crust of the Cocos and Nazca plates.
Fig. 5. Geosat free-air gravity map of marine areas associated with the Middle America trench, arc and back-arc in the western Caribbean (Central America). Gravity highs are shown by darker colors and lows are shown by lighter colors. Numbers identify Cenozoic basins that are described in the text.

Fig. 6. Geosat free-air gravity map of marine areas associated with the North America–Caribbean plate boundary in the northern Caribbean. Gravity highs are shown by darker colors and lows are shown by lighter colors. Numbers identify Cenozoic basins that are described in the text.
Fig. 7. Geosat free-air gravity map of marine areas associated with the Lesser Antilles trench, arc and back-arc in the eastern Caribbean. Gravity highs are shown by darker colors and lows are shown by lighter colors. Numbers identify Cenozoic basins that are described in the text.

Fig. 8. Geosat free-air gravity map of marine areas associated with the South America–Caribbean plate boundary in the southern Caribbean. Gravity highs are shown by darker colors and lows are shown by lighter colors. Numbers identify Cenozoic basins that are described in the text.
north from rough Cocos lithosphere created at the Galapagos rift system to the south (Protti et al., 1995). Forearc morphology adjacent to the Galapagos seafloor and the Cocos Ridge is tectonically eroded by the higher standing and rougher seafloor southeast of the rough-smooth boundary (von Huene et al., 1995; Kolarsky et al., 1995a).

Rough-smooth boundary of the Cocos plate

This boundary (No. 18) separates a smooth Cocos lithosphere created at the East Pacific Rise to the

BASINS AND MAJOR TECTONIC FEATURES ASSOCIATED WITH THE NORTH AMERICA–CARIBBEAN PLATE BOUNDARY (NORTHERN CARIBBEAN)

North America–Caribbean foreland basin and active plate boundary in Central America, Cuba, Hispaniola, and the Puerto Rico trench

A semi-continuous foreland basin recording the collision between the Great Arc of the Caribbean and the passive margin of North America can be traced from the Sepur foreland basin of northern Central America (No. 1 in Fig. 6), along the eastern edge of the Yucatán Peninsula (Rosencrantz, 1990; Lara, 1993; No. 2), along the northern (Denny et al., 1994; No. 3) and northeastern coasts of Cuba (Ball et al., 1985; No. 4), along the northwestern (Dillon et al., 1992; No. 5) and northeastern (Dolan et al., 1998; No. 6) coasts of Hispaniola, and in the Puerto Rico trench (Masson and Scanlon, 1991; Grindlay et al., 1997; No. 7). The age of the foreland basin is diachronous with Late Cretaceous thrust-related subsidence in northern Central America (Rosenfeld, 1990), Paleocene–Early Eocene subsidence in western Cuba (Bralower and Iturralde-Vinent, 1997), Early to Middle Eocene in central Cuba (Hempton and Barros, 1993), Middle Eocene to Recent in Hispaniola (Mann et al., 1994) and Late Eocene to Early Oligocene in Puerto Rico (Dolan et al., 1991).
CARIBBEAN SEDIMENTARY BASINS: CLASSIFICATION AND TECTONIC SETTING

Yucatán back-arc basin

The Yucatán basin formed in Paleocene time behind the Cuban segment of the Great Arc of the Caribbean as it moved to the north and northeast prior to its collision with the Bahama Platform (Rosencrantz, 1990). The basin exhibits three sub-basins. The West Yucatán basin (No. 8) is an oceanic-floored pull-apart basin formed along left-lateral faults bounding the Yucatán Peninsula. The Central Yucatán basin (No. 9) and Cayman Rise (No. 10) are basins formed on stretched arc or continental crust thinned in a back-arc setting. The Cayman Ridge (No. 11) south of the Cayman Rise could be considered a remnant arc although it has been strongly overprinted by strike-slip faulting related to the active plate boundary in the Cayman trough (No. 12).

Cayman trough

The Cayman trough (No. 12) is an 1100-km-long pull-apart basin that began its protracted history of oceanic spreading at a 100-km-long spreading ridge during the Early Eocene (Rosencrantz et al., 1988). The eastern end of the trough (No. 14) is marked by half-grabens of Paleocene–Eocene age (Leroy et al., 1996) that may be coeval with an inverted Paleocene–Eocene graben in Jamaica (Mann and Burke, 1990).

Basins and inverted basins associated with the southern edge of the Cayman trough

Late Neogene basin formation, restraining bend uplifts, and inverted Paleogene rifts in this area are linked to left-lateral strike-slip movements along the Enriquillo–Plantain Garden fault zone (No. 13). Some basins like the Tela of northern Honduras (No. 14) (Avé Lallemant and Gordon, Chapter 8; Manton and Manton, Chapter 9) are not clearly linked to a specific fault zone and instead appear to be part of broad structural borderland within the broad strike-slip plate boundary zone.

Convergent strike-slip basins of the Hispaniola restraining bend

Convergence of the eastward-moving Caribbean plate relative to the southeastern extension of the Bahama Platform has led to localized convergence and topographic uplift in Hispaniola (Mann et al., 1995). Three late Neogene basins in Hispaniola (Nos. 15, 16, 17) are the thrust-bounded ramp type (Mann et al., Chapter 12) (Fig. 3A).

Muertos trough and ‘forearc’ basin

The Muertos trench (No. 18) accommodates northward underthrusting of the Caribbean oceanic plateau of the Venezuelan basin beneath Hispaniola (Ladd et al., 1990; Dolan et al., 1998). A forearc-type basin has formed on the overriding plate south of Hispaniola (Ladd et al., 1990; No. 19) but is not associated with a volcanic arc probably because the angle of subduction of the Caribbean plate is too low to generate welling.

Basins associated with the Anegada fault zone

This fault (No. 20) has been interpreted by Jany et al. (1990) as an active right-lateral fault bounding the eastern edge of a Puerto Rico–Hispaniola microplate (Jany et al., 1990). Two right-steps along the fault are interpreted as pull-apart basins that formed by right-lateral motion in Late Miocene to Recent time. Gill et al. (Chapter 13) propose that motion along the Anegada fault zone is left-lateral, rather than right-lateral on the basis of detailed stratigraphic studies on St. Croix (U.S. Virgin Islands) to the south of the fault.

BASINS AND MAJOR TECTONIC FEATURES ASSOCIATED WITH THE LESSER ANTILLES TRENCH, ARC, AND BACK-ARC (EASTERN CARIBBEAN)

Aves Ridge remnant arc

The Aves Ridge (No. 1 in Fig. 7) is a remnant arc formed when Paleogene east–west opening of the Grenada back-arc basin separated the ridge from the Lesser Antilles arc (Bouysse, 1988; Bird et al., Chapter 15). Dredge hauls and marine geophysics indicate that the ridge formed part of the Late Cretaceous Great Arc that ceased activity by the time of back-arc opening of the Grenada basin in Early Paleogene time.

Grenada back-arc basin

The Grenada back-arc basin (No. 2) with an average water depth of 2–3 km, contains 2 km (north) to 9 km (south) of Cenozoic sediment derived from both the erosion of South America and the Lesser Antilles arc (Bouysse, 1988). Opening of the basin was in an east–west direction (Bird et al., 1993). The gravity low of the Grenada basin can be traced along much of the margin of northern South America where it is oriented east–west, is narrower, and parallel to collisional structures of the margin.
**Lesser Antilles volcanic arc**

The Lesser Antilles volcanic arc (No. 3) initiated in Early Cretaceous and has remained active to the present (Speed and Westbrook, 1984; Bouysse, 1988). Its position at the leading edge of the eastward-moving Caribbean plate means that it may be far-traveled and probably originated somewhere in the eastern Pacific Ocean (Pindell and Barrett, 1990). Underthrusting of Jurassic–Cretaceous age oceanic crust of the Atlantic Ocean beneath the Lesser Antilles results in line of active calc-alkaline volcanoes forming the volcanic arc. The gravity high of the volcanic arc can be traced to the southwest along the northern margin of South America and to the northeast through the Virgin Islands and Puerto Rico.

**Kallinago basin**

This basin (No. 4) forms an intra-arc basin with the northern Lesser Antilles volcanic arc and formed in the Late Miocene by the westward migration of the volcanic line from the islands on its eastern flank (Limestone Caribbees). The Kallinago basin is not a typical rift basin related to back-arc spreading because the volcanic line jumped westward away from the trench and not toward the trench as found in most back-arc basins. McCann and Pennington (1990) attributed this unusual behavior related to the subduction of the Barracuda fracture zone ridge (No. 9) which lowered the angle of subduction and caused the volcanic arc to migrate westward.

**Tobago trough**

This 10-km-thick, Miocene to Recent basin (No. 5) is bounded on its eastern edge by back-thrusts within the accretionary wedge of the Lesser Antilles arc (Barbados Ridge complex, No. 7) (Speed et al., 1989). The Tobago trough extends to the west along the northern margin of South America.

**Lithospheric trace of the Lesser Antilles subduction zone**

The contact or lithospheric trace between crystalline rocks of the Lesser Antilles arc and downgoing oceanic crust of the Atlantic Ocean (No. 6) lies at a depth of about 20 km north of Trinidad but is marked by the line of demarcation between faint northeast gravity trends on strike with Atlantic fracture zone trends and prominent north–south trends of the Lesser Antilles arc. The island of Tobago with a Cretaceous to Eocene record of arc activity is located just to the west of this contact and is therefore the most eastward outcrop of arc rocks of the Caribbean plate. The north–south lithospheric trace and the east–west El Pilar fault zone of Trinidad and northern Venezuela (No. 13) can be seen to form a continuous and curving lineament.

**Barbados Ridge accretionary complex and deformation front**

This accretionary wedge (No. 7) between 100 and 300 km wide and from 0.5 (toe of slope) to 20 km (above lithospheric trace) thick consists of the mainly clastic fluvial and pelagic sediments offscraped from the downgoing Atlantic ocean floor (Ladd et al., 1990). Southward widening of the complex reflects the fluvial addition of material from the Orinoco delta area south of Trinidad (No. 6). The deformation front is marked by the most eastward thrust fault juxtaposing the Barbados Ridge accretionary complex with undeformed seafloor of the Atlantic Ocean. This front is roughly east–west and irregular in the area to the east of Trinidad. Piggyback basins (Fig. 3C) and shale diapirs derived from muds in the prodelta area of the Orinoco River are common in this area (Huyghe et al., Chapter 14).

**Basins and major tectonic features associated with the South America–Caribbean Plate Boundary (Southern Caribbean)**

The Aves Ridge (No. 1 in Fig. 8), the Grenada back-arc basin (No. 2), the Lesser Antilles volcanic arc (No. 3), and the Tobago trough (No. 4), which extend into this area, are described above and are also shown on Fig. 7.

**Guyana passive margin of South America**

This Cretaceous–Recent margin (No. 5 in Fig. 8) formed by rifting and strike-slip of the Africa plate past the South America Plate in earliest Cretaceous time (Pindell and Barrett, 1990). The margin projects into a buried passive margin buried beneath the Gulf of Paria west of Trinidad and may control the location of strike-slip faults in this area (Babb and Mann, Chapter 18).

**Orinoco delta**

The Orinoco River drains a large area of the northeastern South American continent and forms one of the major shelf-margin deltas in the world (No. 6).
Eastern Venezuelan and Maracaibo basins

This basin is a major foreland basin marked by a 150 mGal gravity low formed by oblique convergence between the South American continent (Guyana Shield) and the Caribbean arc system in Oligocene and Miocene time (di Croce et al., Chapter 16; Flinch et al., Chapter 17). The basin is subdivided into two sub-basins which increase in age from east (Maturín, Oligocene to Recent, No. 7) to west (Guarico, Eocene to Pliocene, No. 8). The western extension of the foreland basins is represented by the Maracaibo basin (Late Paleocene–Eocene, No. 9) (Lugo and Mann, 1995). The change in strike of the older, western part of the foreland basin (Maracaibo, No. 9) is related to late Neogene northward displacement of the Maracaibo block along the right-lateral Boconó fault (No. 13) and the left-lateral Santa Marta–Bucaramanga fault (No. 14).

BASINS AND MAJOR TECTONIC FEATURES ASSOCIATED WITH THE PANAMA ARC–SOUTHWESTERN CARIBBEAN COLLISIONAL ZONE (SOUTHWESTERN CARIBBEAN)

Cébaco basin complex

This submarine basin complex in a shelf setting (No. 1 in Fig. 9) is an active pull-apart formed at a left-step in the Azuero–Soná fault zone of western Panama (Kolarsky et al., 1995b).

Tonosí basin

This now folded and uplifted Oligocene–Miocene turbiditic basin (No. 2) appears to have been a forearc basin that has now become inverted as a result of strike-slip movements along the oblique-slip margin of southwestern Panama (Kolarsky et al., 1995b).

Rifts of the Canal area

These late Neogene basins (No. 3) formed as a consequence of diffuse east–west extension within this topographically lowest part of the Panama Isthmus. These basins may have formed as a response to bending of the isthmus of Panama following its collision with northwestern South America in Late Miocene to Early Pliocene time (Mann and Kolarsky, 1995).

San Blas ‘forearc’ basin

This basin (No. 4) has formed in a ‘forearc’ setting above the accreted North Panama deformed belt in late Neogene times (Reed and Silver, 1995).

Bayano–Chucanqué basin

This basin (No. 5) has formed in a large syncline formed in response to the bending and strike-slip deformation of the Isthmus of Panama following its collision with the South America margin (Mann and Kolarsky, 1995).

Sambú basin

This basin (No. 6) appears to be a pull-apart basin formed at a left-step in the left-lateral Sambú fault zone.

Pearl Islands basin

This Middle Miocene–Pleistocene basin (No. 7) formed as a small foreland basin in front of east-dipping reverse faults of the East Panama deformed belt (Mann and Kolarsky, 1995).
Colombian accretionary complex and forearc basin

This margin (No. 8) developed in response to eastward subduction of oceanic crust of the Nazca plate beneath Colombia (Westbrook et al., 1995).

Atrato–San Juan basin

This basin (No. 9) formed along the approximate suture zone between the Panama arc and the South American continent (Bueno Salazar, 1989; Kellogg and Vega, 1995).

Basins and carbonate banks of the Nicaraguan Rise

The Nicaraguan Rise is a broad submarine swell underlain by island arc and continental crust of the Chortís block that extends from northern Central America to Jamaica and is bounded on the north by the Cayman trough and on the south by the Hess Escarpment (No. 1 in Fig. 10). Carbonate banks of Cenozoic age occupy structural highs formed by poorly understood faults with a predominantly northeast strike. Holcombe et al. (1990) interpreted the northeast faults as a set of left-lateral strike-slip faults bounding a set or more northward-striking rift basins associated in one case (San Andres trough) with Quaternary basaltic volcanism present on the island of San Andres (No. 2). The linear Hess Escarpment (No. 3) has been interpreted by Mann et al. (1990) as a possible Neogene strike-slip feature whereas others like Driscoll and Diebold (Chapter 20) have interpreted it as Cretaceous normal fault linked to the Beata Ridge (No. 4) and to the formation of the Caribbean oceanic plateau (Fig. 2).

Colombian basin

The low-relief Colombian basin (No. 5 in Fig. 10) is underlain by the Cretaceous Caribbean oceanic plateau (Bowland and Rosencrantz, 1988) and is bounded to the north by the Hess Escarpment, to the south by the South Caribbean margin fault (Ladd et al., 1990; No. 6), and to the east by the Beata Ridge (No. 4). van der Hilst and Mann (1994) used tomographic data to show that the oceanic plateau crust of the Colombian basin is underthrust at the South Caribbean front fault (No. 6) by a distance of several hundred kilometers beneath the South America margin.

Beata Ridge

The Beata Ridge (No. 4) is marked by a triangular-shaped uplift of oceanic plateau crust at the place where the Caribbean sea is narrowest, between northern South America and Hispaniola. Driscoll and Diebold (Chapter 20) interpret the uplift as a mainly relict extensional fault block related to the formation of the Cretaceous oceanic plateau while Mauffret and Leroy (Chapter 21) emphasize its late Neogene uplift history on thrust faults and its role as major tectonic boundary between the Colombian and Venezuelan basins.

Venezuelan basin

The low-relief Venezuelan basin (No. 7) is a rectangular area of oceanic plateau crust bounded on the north by the Muertos trench, on the south by the South Caribbean marginal fault, on the west by the Beata Ridge, and on the east by the Aves Ridge, the remnant volcanic arc of the Lesser Antilles. A prominent east–west arch trends parallel to the long axis of the basin and may be a regional flexure of the Caribbean plate produced by its ongoing subduction at the Muertos trough to the north and the South Caribbean marginal fault (No. 6) to the south.

TECTONIC EVOLUTION OF THE CARIBBEAN PLATE AND ITS SEDIMENTARY BASINS

Two models for Caribbean evolution

There are two contrasting models for the plate-tectonic evolution of the Caribbean. The first model most recently put forward by Frisch et al. (1992) proposes that the Caribbean region formed during the period of 130 Ma to 80 Ma as South America moved southeast away from North America (Fig. 11A). Igneous upwelling in the space that formed between the two continents is thought to have produced the anomalously thick oceanic plateau crust of the Caribbean and Central America (Kerr et al., 1997; Diebold and Driscoll, Chapter 19; Driscoll and Diebold, Chapter 20). This model recognizes some strike-slip motion along the northern and southern margins of the plate but does not view these offsets as large enough to restore the Caribbean to a position in the eastern Pacific.

An alternative school of thought and adopted in the reconstructions shown in this review was first formulated by Wilson (1966) and later elaborated by Malfait and Dinkelman (1972), Ross and Scotese (1988), Pindell and Barrett (1990), and others. This mobilistic view is that the Caribbean was originally an area of eastern Pacific Ocean floor and oceanic
plateau that has been rafted behind the eastward-moving Great Arc of the Caribbean of Burke (1988) (Fig. 11B). This area of Pacific normal ocean crust appears to have been modified and thickened into the present-day Caribbean oceanic plateau province in the Cretaceous when the crust drifted over the Galapagos hotspot (Duncan and Hargraves, 1984; Sinton et al., 1997) (Fig. 11B). The passage of this area of crust from a Pacific realm to an Atlantic one is recorded by the diachronous history of collisions between the Great Arc at the leading edge of the plateau and the passive margins of North and South America (Pindell and Barrett, 1990). These collisions commence in Late Creta-
Relative motion path of South America relative to North America

The path shows South America moving away from North America during the Jurassic through the Late Cretaceous, a process that led to the formation of ocean floor on the sites of the Caribbean and Gulf of Mexico. The orientation of Mesozoic graben is generally perpendicular to this direction except in regions affected by the independent rotation of the Yucatán block (Marton and Buffler, Chapter 3). While the age of most circum-Caribbean rifts is confined to the Jurassic, the path shows continued separation of the Americas up through the Maastrichtian. Numerous geological studies such as those by Pessagno et al. (Chapter 5), Marton and Buffler (Chapter 3), Masaferrro and Eberli (Chapter 7), Scott and Finch (Chapter 6), and di Croce et al. (Chapter 16) show that the Cretaceous was a time of carbonate passive margin formation atop these early rift structures. These bank margins probably fronted large expanses of Jurassic and Cretaceous ocean crust that formed following the separation of the two plates in Late Jurassic–earliest Cretaceous time.

The behavior of the Great Arc of the Caribbean in response to the convergence or strike-slip motion of North and South America during the period of 71 Ma to the present-day cannot be predicted with accuracy given that these larger plate motions will only be indirectly manifested across multiple strike-slip and subduction Caribbean boundaries. Mann et al. (1995) and Gordon et al. (1997) propose that the trend and direction of the Great Arc during the Late Cretaceous and Cenozoic is governed mainly the direction of a free face, or area of subductable oceanic crust in front of the moving arc. For example, the presence of the Bahamas Platform led to arc collision and reorientation of the arc to subduct Atlantic oceanic crust in a more eastward direction. Müller et al. (Chapter 2) propose that 200–300 km of post-Early Miocene north–south convergence across the Caribbean plate may have led to significant underthrusting of the Caribbean plate beneath North and South America and may have modified existing sedimentary basins.

MAIN PHASES OF CARIBBEAN BASIN DEVELOPMENT
WITHIN THE FRAMEWORK OF NORTH AMERICA–SOUTH AMERICA RELATIVE MOTION HISTORY

Using the second plate-tectonic model shown in Fig. 11B, five main phases of basin evolution can be predicted for the margins of the North and South America plates. These phases include pre-rift phase, Late Jurassic rift phase, Cretaceous passive

Using North America–South America motion to infer Caribbean tectonics

Because magnetic anomalies and fracture zones nearly as old as the times of separation between North and South America have been mapped in the Atlantic Ocean, the motions of North and South America with respect to Africa can be fully described using the vectorial closure condition required by a three-plate system (Pindell and Barrett, 1990; Müller et al., Chapter 2). Improved maps of Atlantic fracture zones using Geosat gravity data by Müller et al. (Chapter 2) has allowed them to more precisely reconstruct the motion history of the two Americas. A summary of the Jurassic to recent path of two points on northern South America relative to a fixed North America using the data of Müller et al. (Chapter 2) is shown on Fig. 12. This diagram illustrates the steadily widening space between the two Americas that was presumably filled by oceanic crust of Jurassic and Early Cretaceous age. This expansion of crust known as the proto-Caribbean Ocean is thought to have been consumed by the Great Arc of the Caribbean from the Late Cretaceous to Recent time. Remnants of the proto-Caribbean Ocean are preserved only as small fragments within rocks of the Great Arc (Montgomery and Pessagno, Chapter 10).

The vector diagram in Fig. 12 can be used to make general inferences about the regional deformational style of the intervening Caribbean plate. For example, from the Late Jurassic to Maastrichtian, one would expect a generally divergent tectonic style to pervade much of this region and from Maastrichtian to the Present one would expect a convergent or strike-slip style to be present (Fig. 12). However, this direct dependence of Caribbean deformational style on the relative motion of North and South America assumes that motion is taken up along a single plate boundary, such as during Jurassic separation. Studies including Marton and Buffler (Chapter 3) show that even the young North America–South America Plate boundary during Jurassic time was multi-branched and involved the motion of an intervening microcontinent, the Yucatán block. As the gap between the Americas widened, later Cretaceous–Cenozoic relative plate motions acted across at least two plate boundaries (northern and southern Caribbean arc or strike-slip boundaries). Therefore, the North America–South America motions shown on Fig. 12 are only indirectly manifested in Caribbean deformation.

Pre-Cretaceous time in northern Central America and northwestern South America and continue through to the present-day in the northeastern and southeastern Caribbean (Fig. 11B).
Fig. 12. Relative plate motion vectors of three points of northern South America with respect to a fixed North America based on data presented by Müller et al. in Chapter 2 of this volume. The position of South America with respect to North America provides a framework in which to base key events in Caribbean evolution such as the entry and diachronous collision of the Great Arc of the Caribbean. Points in millions of years along the vectors correspond to the ages of plate reconstructions given in Figs. 13–25 of this chapter.

margin phase, Late Cretaceous–Recent arc–passive margin collisional phase, and late Cenozoic strike-slip phase. I subdivide thirteen plate reconstructions of the Caribbean based on the plate parameters of Müller et al. (Chapter 2) into these four phases.

Several Cretaceous and Cenozoic structural phases characterize the overriding Great Arc and the adjacent oceanic plateau and Chortís block. For example, the oceanic plateau undergoes a two-phase Cretaceous volcanic and stretching event (Driscoll and Diebold, Chapter 20), the Great Arc may have experienced a subduction polarity reversal (Lébron and Perfit, 1994; Draper et al., 1996; Kerr et al., 1997; Montgomery and Pessagno, Chapter 10) and the Chortís block experienced a Late Cretaceous folding and faulting event (Scott and Finch, Chapter 6).

Pre-rift phase

Plate reconstructions such as those by Pindell and Barrett (1990), Marton and Buffler (Chapter 3) and Pszczółkowski (Chapter 4) leave no space for the Caribbean–Gulf of Mexico region in its present position when South America is closed up against North America to reform western Pangea in pre-Late Jurassic time (Fig. 13). Prior to rifting of the Americas in the Middle Jurassic, three crustal age provinces are present in the future area of rifting between North and South America shown in Fig. 13. These provinces include: (1) Pan-African crustal age province of Africa and Brazil; (2) Grenville crustal age province of North and South America that includes a possible continuation through the Oaxaca area of southern Mexico and the Chortís block (Renne et al., 1989; Hutson et al., 1998); and (3) Guyana Shield of pre-Grenville age (>1.2 Ga) of northern South America. The Yucatán block fills the central part of the Gulf of Mexico and is presumably underlain by a prong of the Appalachian–Marathon–Ouachita orogenic belt (Marton and Buffler, Chapter 3).

Late Jurassic rift phase

Rifts of Late Jurassic age in the Caribbean form part of a band of rifts associated with the early opening of the central and northern Atlantic that crudely follow orogenic grains from the North Atlantic to Guyana. By Oxfordian time, rifts are active along the northern Gulf of Mexico, the southeastern Gulf of Mexico (Marton and Buffler, Chapter 3), the Bahamas Platform (Masaferro and Eberli, Chapter 7), the northeastern margin of South America (di Croce et al., Chapter 16), and the northwestern margin of South America (Eva et al., 1989; Lugo and Mann, 1995) (Fig. 14). Rifts which extend southward along the western margin of South America may be related
Fig. 13. Reconstruction of the Caribbean region at 180 Ma (Bajocian). Key to abbreviations: $\text{MSM} = \text{Mohave–Sonora megashear}$; $\text{TMVB} = \text{Trans-Mexican volcanic belt}$; $\text{EAFZ} = \text{eastern Andean fault zone}$.

Fig. 14. Reconstruction of the Caribbean region at 156 Ma (Oxfordian, magnetic anomaly M29). Gray areas represent oceanic crust of normal thickness. Stippled areas indicate rifted areas. Key to abbreviations: $\text{PC} = \text{proto-Caribbean oceanic crust}$ (dark line represents speculative position of spreading ridge); $\text{NBFZ} = \text{northern Bahamas fracture zone}$; $\text{MSM} = \text{Mohave–Sonora megashear}$; $\text{TMVB} = \text{Trans-Mexican volcanic belt}$; $\text{EAFZ} = \text{eastern Andean fault zone}$.
to back-arc rifting produced by subduction at that margin. The widening gap between North and South America was presumably occupied by oceanic crust generated at a proto-Caribbean spreading ridge. This early oceanic corridor between the Atlantic and Pacific widens through continued rifting and oceanic spreading into the Tithonian (Fig. 15).

**Cretaceous passive margin phase**

By earliest Cretaceous time, rifting had ceased, the Yucatán block had rotated to its present-day position, and a post-rift passive margin section composed mainly of carbonate rocks had blanketed the rift topography in the southeastern Gulf of Mexico (Marton and Buffler, Chapter 3), the Bahamas Platform (Masaferro and Eberli, Chapter 7), the northeastern margin of South America (di Croce et al., Chapter 16; Babb and Mann, Chapter 18), and the northwestern margin of South America (Lugo and Mann, 1995). These passive margins enjoyed open ocean circulation and probably fronted a proto-Caribbean oceanic basin that was several hundred kilometers wide (Fig. 16). It is interesting to note that the Chortís block experienced a similar rifting and passive margin history to the above intra-Caribbean margins (Scott and Finch, Chapter 6). Presumably the Chortís block occupied a southern extension of Precambrian and Paleozoic orogenic belts in Mexico and was subsequently displaced eastwards by strike-slip faults in the Cenozoic (Avé Lallemant and Gordon, Chapter 8; Manton and Manton, Chapter 9) (Fig. 16).

**Late Cretaceous–Recent arc–passive margin collisional phase**

By Late Cretaceous time, the Great Arc of the Caribbean and its adjacent oceanic plateau province was colliding with the passive margin of northwestern South America and the southern margin of northern Central America (Pindell and Barrett, 1990; Kerr et al., 1997) (Fig. 17). In northwestern South America, extensive areas of the plateau and arc rocks accreted to the continental cratonic rocks of northwestern South America (Kerr et al., 1997). In these areas, ages of rocks of the Great Arc extend back to the Early Cretaceous but ages of the oceanic plateau are generally confined to the Santonian (Kerr et al., 1997). Sinton et al., 1997). Diebold and Driscoll (Chapter 19) and Driscoll and Diebold (Chapter 20) present evidence that the oceanic plateau eruption event was a two-phase event with the Santonian event probably corresponding to the younger event.
Fig. 16. Reconstruction of the Caribbean region at 118 Ma (Aptian, magnetic anomaly C34n). Key to abbreviations: MSM = Mohave–Sonora megashear; TMVB = Trans-Mexican volcanic belt; EAFZ = eastern Andean fault zone.

Fig. 17. Reconstruction of the Caribbean region at 83 Ma (Campanian, magnetic anomaly C34n). Key to abbreviation: EAFZ = eastern Andean fault zone.
By Maastrichtian time, subsidence of the Sepur foreland basin was ending as the Chortis block was sutured to the area of southern Mexico and the Yucatán block (Fig. 18) and the Great Arc was migrating to the northeast towards its eventual collision with the Bahama Platform in the Late Paleocene and Eocene (Fig. 19). In Paleocene time, the end of the arc moved along a complex strike-slip zone at the eastern edge of the Yucatán Peninsula (Lara, 1993) and opened the Yucatán back-arc basin in its wake (Rosencrantz, 1990) (Fig. 19). In northwestern South America, a Maastrichtian foreland basin associated with the accretion of oceanic plateau material widened and began to affect the area of western Venezuela (Pindell and Barrett, 1990) (Fig. 18). These foreland basin deposits will later become overprinted by the effects of the late Neogene collision of the Panama arc with northwestern South America.

By Early Eocene, arc–continent collision was complete in western Cuba and collision proceeded in a diachronous manner along the edge of the Bahamas Platform (Gordon et al., 1997; Masaferro and Eberli, Chapter 7) (Figs. 19 and 20). This diachronous collision accompanied transfer of microplates from the Caribbean plate to the North America Plate in a clockwise fashion as forward progress of the Great Arc was halted by its collision with the Bahamas Platform (Mann et al., 1995). A thin foreland basin formed between the collision zone and the Bahamas carbonate platform (Hempton and Barros, 1993). Similarly, in northern South America, collision ended in Eocene time in the Lake Maracaibo area of western Venezuela and proceeded in a diachronous manner eastward along the northern margin of South America in Middle to Late Eocene time (Fig. 20). Initiation of oceanic spreading in the Cayman trough in Middle Eocene time may be the result of a change in the direction of the Great Arc from a northeastward to an eastward direction to move around the salient formed by the southeastern Bahama Platform (Mann et al., 1995). By Late Oligocene, the zone of active collision is in the present-day area of Puerto Rico on the northern plate boundary and eastern Venezuela on the southern boundary (Fig. 21).

**Late Cenozoic strike-slip phase**

The Miocene to Recent period of Caribbean history corresponds to its strike-slip phase since by this time the arc–continent collisional zones have lengthened and converted into long strike-slip faults along the northern and southern edges of the Caribbean plate. During the Middle Miocene, the Cocos and Nazca plates ruptured along the Galapagos rift probably as a response to simultaneous subduction in two directions beneath the Middle America arc to the north and the Colombian trench to the south (Wortel and Cloetingh, 1981) (Figs. 22 and 23). By Late Miocene, localized convergence between the eastward-moving Caribbean plate and the southeastern extension of the Bahama Platform led to thrusting and topographic uplift in Hispaniola (Mann et al., Chapter 12; de Zoeten et al., Chapter 11) (Fig. 24). Along the southeastern margin of the plate, tectonic activity involved the Trinidad area (Babb and Mann, Chapter 18; di Croce et al., Chapter 16; Fiinch et al., Chapter 17) (Fig. 24). By Late Pliocene, the margins of the Caribbean had reached its present-day configuration (Fig. 25). Two important tectonic and paleoceanographic events of this time was closure of the Panama seaway by collision of the Panama arc against northwestern South America (Kellogg and Vega, 1995; Mann et al., 1995) (Fig. 25) and the collision of the Cocos Ridge with southern Central America by about 1.6 Ma. The Panama arc collisional event may have accelerated the northward expulsion of the Maracaibo block into the Caribbean.

**FUTURE WORK ON CARIBBEAN SEDIMENTARY BASINS**

To conclude this review, I would like to leave the reader with some large-scale Caribbean tectonic problems that could be addressed by future studies of Caribbean sedimentary basins.

**Pacific vs. in situ origin of the Caribbean**

The problem of the origin of the Caribbean is by no means solved despite the Pacific-origin approach that I have followed in this introduction and in the tectonic reconstructions. There are several problem areas for the Caribbean origin problem. First, North America–South America relative plate motion history (Müller et al., Chapter 2) (Fig. 12) only indirectly bears on the position of this intervening Caribbean plate and Great Arc through time. Second, paleomagnetic studies in the Caribbean are handicapped by several factors: (1) the problem of distinguishing large-scale plate-tectonic rotation from local structural rotation about vertical axes and apparent tectonic rotation (cf. MacDonald, 1980, for a discussion of paleomagnetic data from the Chortis block); (2) the inability of paleomagnetism to address longitudinal changes in plate position of the type assumed for an eastward-moving Caribbean Great Arc and oceanic plateau in Cenozoic time; and (3) large error limits on existing data (Gose, 1985). And, third, studies of individual strike-slip offsets are problematic because, as shown on the reconstructions, these faults form somewhat late in the Caribbean tectonic history and therefore represent
Fig. 18. Reconstruction of the Caribbean region at 71 Ma (Maastrichtian, magnetic anomaly C32n.2n). Key to abbreviation: EAFZ = eastern Andean fault zone.

Fig. 19. Reconstruction of the Caribbean region at 55.9 Ma (Early Eocene, magnetic anomaly C25n). Key to abbreviations: YB = Yucatán back-arc basin; GB = Grenada back-arc basin; MB = Maracaibo foreland basin.
Fig. 20. Reconstruction of the Caribbean region at 41.3 Ma (Middle Eocene, magnetic anomaly C19n). Key to abbreviations: MB = Maracaibo foreland basin; EAFZ = eastern Andean fault zone.

Fig. 21. Reconstruction of the Caribbean region at 25.5 Ma (Late Oligocene, magnetic anomaly C7An). Key to abbreviation: GB = Guárico foreland basin.
Fig. 22. Reconstruction of the Caribbean region at 15.1 Ma (Middle Miocene, magnetic anomaly C32n.2n). Key to abbreviations: GB = Guárico foreland basin; MB = Maturín foreland basin.

Fig. 23. Reconstruction of the Caribbean region at 11.5 Ma (latest Middle Miocene, magnetic anomaly C5r.2n). Key to abbreviations: GB = Guárico foreland basin; MB = Maturín foreland basin.
Fig. 24. Reconstruction of the Caribbean region at 9.2 Ma (Late Miocene, magnetic anomaly C4Ar.2n). Key to abbreviations: GB = Guárico foreland basin; MB = Maturín foreland basin.

Fig. 25. Reconstruction of the Caribbean region at 3.1 Ma (Late Pliocene, magnetic anomaly C2An.2n). Key to abbreviation: MB = Maturín foreland basin.
only a small part of the total Caribbean displacement.

There are several promising new approaches for study of the origin of the Caribbean plate that can augment traditional plate reconstruction and paleomagnetic methods. Paleoenvironmental studies such as those by Pessagno et al. (Chapter 5) attempt to define changes in the paleolatitude of terranes using macro- and micropaleontologic data. Montgomery and Pessagno (Chapter 10) point out key indicator rocks, such as red cherts, that can be used to distinguish a Pacific vs. Atlantic environment of deposition. Finally, geochemical and high-resolution dating of igneous and metamorphic rocks of rocks of the Great Arc and oceanic plateau (e.g., Sinton et al., 1997) or the grains in sedimentary rocks from the allochthonous areas (e.g., Hutson et al., 1998) allows better constraints on plate reconstructions.

**Age and environments of the Caribbean oceanic plateau**

Diebold and Driscoll (Chapter 19) and Driscoll and Diebold (Chapter 20) present data showing a two-stage Cretaceous evolution of the plateau and suggest that existing DSDP and ODP dated drill samples from the plateau may constrain only the later, smaller plateau-building event. Further outcrop studies and deep ocean drilling are needed to constrain this hypothesis.

**Polarity reversal of the Caribbean arc**

Montgomery and Pessagno (Chapter 10) note two types of accreted sedimentary material in the Great Arc of the Caribbean: Pacific-derived material accreted when the arc was west or southwest-facing and Atlantic-type material accreted when the arc was east or northeastward-facing as it is today. Structural and stratigraphic outcrop studies are needed to confirm the existence and age of the proposed Early Cretaceous arc polarity reversal discussed by these authors and previous workers like Lebron and Perfit (1994) and Draper et al. (1996).

**Origin of Caribbean ophiolites**

Extensive ophiolites were obducted during collision of the Great Arc with the passive margins of North and South America in northern Central America, the Greater Antilles, and northern South America. Gealey (1980) proposed that these ophiolites represent the basement of the forearc basement of the Great Arc. Other possible origins for the ophiolites include proto-Caribbean oceanic crust involved in the arc–continent collision and Caribbean oceanic plateau crust (Kerr et al., 1997). The overlying and interbedded sedimentary rocks could provide important clues to the origin of the ophiolites and their paleolatitudes through time.

**Triggering of back-arc basins formation**

Depth to basement calculations and heat-flow measurements for the Yucatán (Rosencrantz, 1990) and Grenada back-arc basins (Bird et al., Chapter 15) indicate that both basins formed rapidly over a short time interval in the Paleogene. Further geophysical work and deep-sea drilling is needed to confirm this history and understand why this basins opened rapidly and then became dormant despite continued subduction beneath the Great Arc.

**Diachronous arc–continent collision and termination of arc activity**

The timing of this event summarized on Fig. 11B could be improved through careful biostratigraphic and stratigraphic studies as done by Bralower and Iturralde-Vinent (1997) in Cuba and several of the papers in this volume.

**Amount of allochthony of Caribbean arcs**

The amount of overthrusting of the Great Arc over the passive margins of North and South America is not well understood because deep seismic data has not been attempted over the arc–continent collision zones. If the arc is far-traveled on a predominantly unmetamorphosed passive margin sequence, potential hydrocarbon deposits may exist at depth in areas where crystalline rocks are present at the surface.

**Driving forces of Caribbean plate motion**

Mann et al. (1995) and Mann (1996) proposed that the Caribbean plate is driven as a response to dense oceanic slabs sinking beneath the Great Arc at the leading edge of the plate. The direction of the arc movement is therefore always oriented in the direction of oceanic crust or the 'free face'. However, Müller et al. (Chapter 2) have noted that the Caribbean plate remains fixed in a mantle reference frame since Middle Eocene time. For a stationary Caribbean plate, North America–South America post-Eocene north–south convergence rather than the presence of an oceanic free face may be the dominant plate-driving force affecting the Caribbean. GPS-based geodetic studies spanning the Caribbean plate could be used to test these differing dynamic scenarios.
Nature and driving forces of internal Caribbean plate deformation

Diebold and Driscoll (Chapter 19) and Driscoll and Diebold (Chapter 10) propose that internal deformation of the Caribbean plate in the Colombian and Venezuelan basins and along the Beata Ridge and Hess Escarpment is a response to divergent deformation associated with the formation of the Cretaceous Caribbean oceanic plateau. In their view, modern escarpments on the seafloor are largely relict features that lack significant neotectonic deformation. In contrast, Mauffret and Leroy (Chapter 21) propose that the scarps in this region reflect internal disruption of the Caribbean plate along the line of the Beata Ridge. Faulting reflects mainly shortening in this intra-plate zone of deformation. Continued geophysical studies, reexamination of existing data, and GPS-based geodetic studies spanning the Caribbean plate are needed to distinguish these two ideas.

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REFERENCES


