REGIONAL SYNOPSIS OF GULF OF MEXICO AND CARIBBEAN EVOLUTION

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ABSTRACT

The main elements of the western Pangean reconstruction and the subsequent regional paleogeographic evolution of the Gulf of Mexico, Mexico, and the Caribbean are outlined in a modern plate kinematic framework which brings the Caribbean Plate from the Pacific since the APTIAN. Two primary phases of development occurred. The first, Late Triassic to Aptian, involved the creation of the Proto-Caribbean Seaway and two Cordilleran backarc basins, one in Mexico and one west of Colombia and Ecuador. A west-facing arc stretched and maintained connection from the Chortis Block (SW Mexico) to central Ecuador. The northern margin of South America from northern Ecuador to the Atlantic was a passive margin during Late Jurassic through Cretaceous times. The second phase, mid Aptian to present, records the progressive eastward migration of Caribbean crust from the Pacific to its present position. An Aptian arc polarity reversal brought metamorphic rocks to the surface at that time, and marks the onset of relative eastward migration. Since the medial Cretaceous, after the onset of subduction at the Panama-Costa Rica arc, the Caribbean crust has rested in the mantle reference frame, while the American plates have drifted westward at rates similar to their velocities in the mantle reference frame. Campanian-Maestrichtian interactions between the arc and Yucatan (Jamaican-Cuban portion) and northern Ecuador/Colombia (Amaine-Chaucha Terrane portion) are important events during the relative migration. Emplacement of allochthonous terranes around the Proto-Caribbean passive margins was entirely a function of Caribbean-American relative movements, and is recorded by foredeep sedimentation and subsidence of the various passive margin sections.

INTRODUCTION

Fixist and mobilist views of Caribbean region evolution have been proposed. Strictly fixist views (most recently Morris et al. 1990) are difficult to entertain in light of (1) the very well documented opening history of the Atlantic oceans and (2) fairly accurate Pangean continental assemblages, both of which show that little or no Gulf of Mexico and Caribbean region existed between the larger continents during the Triassic, Jurassic, and Early Cretaceous (Ladd 1976; Klitgord and Schouten 1986; Pindell et al. 1988; Pindell 1985a; Buffler and Sawyer 1985; Rowley and Pindell 1989). Mobilist views all accept significant amounts of eastward Caribbean migration relative to the Americas, but are split between models which generate the Caribbean Plate's lithosphere between the Americas (e.g., Donnelly 1989; James 1990; Salvador and Green 1980; Klitgord and Schouten 1986; Anderson and Schmidt 1983) and models which generate that lithosphere in the Pacific (Dickinson and Coney 1980; Pindell and Dewey 1982; Duncan and Hargraves 1984; Pindell and Barrett 1990). Pindell (1990) lists cogent arguments for the plate's Pacific origin, but definitive proof will only come when the deep interior, and not just the rims, of the Caribbean Plate is shown to be pre-Aptian in age, as plate reconstructions dictate that the Caribbean Plate could not have fit between the Americas until well after that time (discussed later). I note, however, that the recent identification of Jurassic boreal or austral radiolarian fauna in Hispaniola, Puerto Rico, and La Desirade (Montgomery et al. 1992) also attests to the Pacific origin, as the Proto-Caribbean Seaway of Pindell (1985) developed essentially within the Jurassic paleoequatorial zone.

Important elements of (1) the methodology required for regional analysis, and (2) the actual history, of the Caribbean inter-plate realm (Fig. 1) were outlined in progressively more detail, among others, by Ladd (1976), Pindell and Dewey (1982), Mann and Burke (1984b); Pindell (1985a), Buffler and Sawyer (1985), Dewey and Pindell (1986), Klitgord and Schouten (1986), Pindell et al. (1988), Rosencrantz et al. (1988); Burke (1988), Rowley and Pindell (1989), Pindell and Barrett (1990) and other papers in Dengo and Case (1990), Rosencrantz (1990); Pindell (1991), and Pindell et al. (1993, in review b). These papers discuss: the reconstruction of Pangea, including the restoration of syn-rift extension along passive margins during continental breakup, the bulk shape changes due to trans
current and convergent faulting in northern South America during Andean orogenesis, and the removal of Mesozoic-Cenozoic accreted arc terranes from northern South America; for times prior to accretion; Atlantic opening kinematics and implications for North-South America motion; Mesozoic kinematic significance of the Equatorial Atlantic reconstruction; the opening history of the Gulf of Mexico; the eastward relative migration of the Caribbean Plate from the Pacific independent of Cayman Trough magnetics, by tracing the timing of overthrusting of circum-Caribbean foredeep basins by Caribbean terranes; the occurrence of magmatic arcs and their periods and polarities of associated subduction; arc-continent collision suture zones marking the sites of former oceans/basins and their timing and vergence of closure; the opening histories of the Cayman Trough, Grenada Basin, and Yucatan Basin; and plate boundary zone development in the northern and southern Caribbean.

PLATE KINEMATIC CONSTRAINTS

Atlantic Ocean Magnetics

Interpretations of Caribbean evolution must be set in the framework of the former relative positions and motions of the encompassing North and South American plates. This is made especially poignant by Permo-Triassic reconstructions of North and South America and Africa which show that the Caribbean region did not exist at that time, and that the region must have evolved as a co-development of the dispersal of the larger continents. Relative plate motion studies as measured by magnetic anomalies and fracture zone traces are accurate for each paleoposition to a few tens of kms. In contrast, attempts to define the Caribbean tectonic framework by assessments of the latitudinal component of motion between North and South America as measured by onshore determinations of paleo-inclination
through time are less accurate by at least an order of magnitude. The kinematic framework in which Caribbean evolution took place is shown in Figures 2 and 3, thoroughly described in Pindell et al. (1988). The poles determined for the construction of Figure 2 fall within error estimates of more recent pole determinations (e.g., Shaw and Cande 1990).

An accurate reconstruction of pre-Mesozoic continental fragments for Permo-Triassic time, with the Atlantic Oceans closed is, therefore, the natural starting point for models of Caribbean region evolution. During Late Triassic-Jurassic rifting and subsequent drifting, the history of seafloor spreading in the oceans defines the size and shape at any instant of the Caribbean inter-plate realm. Three segments of the Atlantic, the Central North, the South, and the Equatorial, are important for determining the Caribbean kinematic framework. Marine magnetics and fracture zones of the Central North Atlantic between the eastern USA and northwest Africa/South America define the history of separation of North America from Gondwana (two-plate system only) from Late Triassic to Aptian. It is during this stage that Yucatan rotated from its Triassic Pangean position to its present position to form the Gulf of Mexico by or just after anomaly M-16 (Berriasian) time, which is the first time at which overlap with South America can be avoided (Pindell 1985a). Also, within the Neocomian, spreading began in the South Atlantic but significant motion through the Equatorial Atlantic appears to have been delayed until the Aptian, prior to which the early South Atlantic motions were manifested northward into the Central African rift system rather than the Equatorial Atlantic (Pindell and Dewey 1982; Pindell et al. 1988). Therefore, early South Atlantic motions do not appear to have significantly affected Caribbean kinematic history.

Unfortunately, the Cretaceous magnetic quiet period prevents resolution of detailed kinematics for Aptian to Santonian times. Opening poles for the Central North and South Atlantic Oceans show that by early Campanian time and until the Eocene (anomaly 34, 84 Ma to anomaly 21, 49 Ma), little or no motion was occurring between North and South America, and it is likely that no significant plate boundary existed between them for that interval (Pindell et al. 1988). An important uncertainty is the exact time at which seafloor spreading actually ceased in the Proto-Caribbean: it certainly had ceased by anomaly 34 time (as shown by the dashed portion of the curve in Fig. 3), but I suggest that the exceedingly rapid Late Albion trangression of cratonic areas (e.g., in Venezuela, Gonzalez de Juana et al. 1980) and drowning of carbonate platforms was due to loss of in-plane stress as a result of the death of the ridge (Pindell et al., in review, a, b 1993). This is supported also by the fact that oceanic crust occurs west of anomaly 34 immediately east of the Lesser Antilles in the western Atlantic, which has the same fabric orientation as that to the east of anomaly 34 (Speed et al. 1984), implying that any adjustments in ridge orientation associated with the death of the ridge (reorganization to a two-plate system again) had already taken place well before anomaly 34 time (Late Albion?). If this is the case, then the period over which the African and North and South American plates behaved as a three-plate system was limited to the Aptian-Albian interval. This indicates that the opening history of both the Central North and the South Atlantic Oceans were essentially co-polar (i.e., one greater American Plate) from Late Albion to the Eocene, although some minor degree of
wrenching probably occurred at Atlantic fracture zones, possibly along those extending to the Bahamas.

Since the Middle Eocene, very slow north-south convergence (dextrally oblique relative to pre-existing fracture zones) occurred, with the magnitude of convergence increasing westward away from the North America-South America pole of rotation to the east of the Lesser Antilles (Fig. 2, 3). It is not yet known whether this convergence was accommodated only by descent, and maintenance of N-S slab-distance, of Atlantic lithosphere into the Benioff zone beneath the eastward migrating Caribbean Plate, or if lithospheric shortening at an overthrust zone east of the migrating Caribbean Plate was also required, possibly along northern South America as put forth as a possibility by Pindell et al. (1991).

Origin of the Caribbean Plate

Within the above framework, there are two possibilities for the origin of the lithosphere of the Caribbean Plate. It was either (1) generated by seafloor spreading between Yucatan and South America and, therefore, represents lithosphere of the arm of the Atlantic called the Proto-Caribbean Seaway by Pindell (1985a), or (2) generated in the Pacific (Farallon Plate lithosphere?), such that Proto-Caribbean crust which was already formed by the separation of the Americas was then subducted beneath the Upper Cretaceous to Cenozoic arc systems of the Caribbean Plate during the westward drift of the Americas from Africa, producing a relative east-west migration history of the Caribbean Plate between the Americas. In either case, westward drift of the Americas across the mantle is mainly responsible for east-
west Caribbean-American relative motion. In the case of a Pacific origin, northerly and southerly extensions of Farallon lithosphere were probably subducted beneath the North and South American Cordilleras, respectively, thereby producing the condition of tectonic rafting of Caribbean lithosphere into the Proto-Caribbean Seaway between the Americas.

The primary difference of these two interpretations lies in the magnitude of the relative east-west migration of Caribbean and American lithospheres. This difference, therefore, suggests different locations for much of the Caribbean region’s Jurassic and Cretaceous-aged magmatism, sediment deposition, deformation, and metamorphism. In models for a Pacific origin, early Caribbean stratigraphies and tectonism must have developed in the Pacific prior to the relative eastward migration, and are thus essentially part of “Cordilleran” evolution. In Proto-Caribbean models of Caribbean Plate origin, such developments are strictly “Caribbean,” and should have involved the Yucatan, Bahamian, and northern South American cratonic margins.

Pindell (1990) outlined several independent arguments favoring a Pacific origin. Briefly, these are (see Fig. 4):

(1) Eastern Caribbean Volcanism. The Aves Ridge and Lesser Antilles volcanic arc complexes (Fig. 1) collectively possess an Upper Cretaceous (~90 Ma) to Recent record of intermediate arc magmatism. Polarity of subduction for the Eocene-Recent Lesser Antilles arc has been eastward facing with westward dipping subduction, as was probably the case for the Cretaceous-Eocene Aves Ridge arc as suggested by its slightly convex-eastward shape and absence of an accretionary prism along its west flank. Assuming a 90 million year period of west-dipping subduction of Atlantic crust beneath the eastern Caribbean even at only slow convergence rates suggests a minimum relative plate migration amount of ~1000 km.

(2) Cayman Trough, seismic tomography, and northern Caribbean strike-slip basins. Assessments of the development of the Cayman Trough (Roser et al. 1988; Wade and Burke 1983), the Tabera and northern San Juan Basins in Hispaniola (Mann et al. 1984; Dolan et al. 1991), the “Eocene Belt” of Puerto Rico (Erikson et al. 1990), and the Cibao Basin and north coastal area of Hispaniola (Erikson 1992; Pindell and Draper 1991) (Fig. 4) indicate Late Eocene-Recent east-west, sinistral strike-slip motion between the Caribbean and North American plates (northern PBZ). Offset of ~1000 km since the Eocene is indicated from the length of the deep oceanic portion of Cayman Trough, and from reconstructions of Cuba, Hispaniola, Puerto Rico, and the Aves Ridge arc fragments into a single pre-middle Eocene Greater Antillean arc (Pindell and Bar-
Seismicity (Molnar and Sykes 1969) and seismic tomography (Hilst 1990) show a distinct west-dipping Atlantic Benioff zone extending at least 1200 km beneath the eastern Caribbean, suggesting a similar minimum magnitude of displacement as the Cayman Trough. If this much motion has occurred since the Eocene, a much larger value for the total relative motion must have occurred as indicated by the Upper Cretaceous period of arc activity of the Aves Ridge.

(3) Caribbean vs. Proto-Caribbean stratigraphic suites. Cretaceous portions of the stratigraphies of two distinct suites of rock in the Caribbean region (Fig. 4 inset, Fig. 5) are genetically incompatible as presently juxtaposed across circum-Caribbean ophiolite belts interpreted to be suture zones (Fig. 4). The “Caribbean suite” occurs “Caribbeanward” of the suture zones, whereas the “Proto-Caribbean suite” occurs “Americaward” of the sutures. The Caribbean suite’s Cretaceous, tuff-dominated stratigraphy differs dramatically from the Proto-Caribbean suite’s coeval Cretaceous non-volcanogenic passive shelf sediments. Spatial separation during deposition of these distinct suites of rock appears necessary for the Proto-Caribbean to contain no record of Caribbean volcanism. As this difference extends from around the Caribbean sea to the Santa Marta massif of Colombia and to Chiapas, Mexico, it is unlikely that the Caribbean arcs were situated any farther east than these locations for most of the Cretaceous.

(4) Pre-Aptian geometrical incompatibility, Caribbean Plate and Proto-Caribbean Seaway. Numerous faunal and isotopic ages from the basements of most Caribbean arcs are pre-Aptian, and seismic sections of the Colombian and Venezuelan Basins (Stoffa et al. 1981), particularly the basement continuity from the Jurassic rock of Costa Rica to the Colombian Basin, suggest that the crust of the internal Caribbean plate is pre-Aptian (probably Jurassic) as well. However, plate separation between North and South America was insufficient (Fig. 4) to house a pre-Aptian Caribbean Plate until the Late Cretaceous, possibly the Albion. Thus, the Caribbean Plate must have formed outside the present Caribbean area, much farther west than the 1100 km of displacement indicated by the Cayman Trough and seismic tomography, and its migration history must have begun well before the Eocene, probably in the early Late Cretaceous as suggested by Aves Ridge subduction-related volcanism and by the Albion to early Tertiary “Antillean phase” of magmatism in the Greater Antilles.

(5) Truncation and uplift of the southwestern margin of Mexico. Structural trends and the Paleogene arc of southwest Mexico have been truncated (King 1969) either by subduction erosion or by strike-slip removal of arc and forearc areas. Paleogene arc rocks in Mexico are largely restricted to the Sierra Madre Occidental; the Trans-Mexican Volcanic Belt arc is mainly Neogene in age, with volcanism commencing earlier in the west than in the east, implying an eastward migration of arc inception (Fig. 4). In the Chorizs Block of Central America evidence for Paleogene arc activity is abundant, with volcanism extending back into the Cretaceous. The Paleogene arc sequences likely were continuous from western Mexico into Chorizs, prior to eastward strike-slip offset of Chorizs to its present position and progressive development of volcanism in the Trans-Mexican Volcanic Belt (Wadge and Burke 1983). In addition, Precambrian rocks of the southwest margin of Mexico (King 1969) yield cooling ages that indicate uplift and erosion since Oligocene time, younging eastwards (Damon and Coney 1983), probably as a function of an intra-continental strike-slip fault zone (between Mexico and Chorizs) progressively becoming a Neogene subduction margin as Chorizs migrated to the east, with associated uplift of the hanging wall (Mexico). Thus, it appears that Chorizs has migrated with the Caribbean crust during Cenozoic time from a more westerly position (e.g., Wadge and Burke 1983; Pindell and Dewey 1982; Johnson, this volume).

(6) Faunal provinciality: Pacific vs. Proto-Caribbean Realm. According to Johnson and Kauffman (1989), two differing Cretaceous faunal realms exist across the Mexican-Caribbean region that remained distinct until Campanian time, suggesting spatial separation of shallow water organisms prior to that time. The areas of occurrence for the two realms closely match the areas of the Caribbean and Proto-Caribbean stratigraphic suites. The Campanian initiation of faunal merging of the two realms relates to the onset of tectonic juxtaposition of the shelfal areas they occupied, presumably during relative eastward migration of the Caribbean Plate between the Americas. Further, Montgomery, et al. (1992) have identified cold water forms of Upper Jurassic Radiolaria in the Puerto Plata Basin Complex of Hispaniola (Pindell and Draper 1991), the Bermeja Complex of Puerto Rico (Matsson and Pessagno 1979), and on La Désirade, which can only be explained by a Pacific, non-Tethyan, origin for the basements of those localities.

The above arguments collectively indicate that the crust of the Caribbean Plate and the Chorizs block was situated west of the Cretaceous shelf sections of Yucatan, the Bahamas, and northern South America prior to the latter Cretaceous (Campanian). Seafloor spreading between North and South America had ceased probably in the Albion, leaving a Proto-Caribbean oceanic arm of the Atlantic to subside thermally in the absence of plate boundaries. In addition to understanding regional evolution, acknowledgment of the existence of this Proto-Caribbean Seaway, with the Caribbean Plate situated to the west, is critical to the hydrocarbon story of the circum-Caribbean region because it was along this seaway’s margins that the region’s best source rocks were deposited, from Albion to Campanian time (Pindell 1991).
In light of these arguments, the concept of the present-day Caribbean lithosphere representing a piece of the Proto-Caribbean Seaway is difficult to entertain. The implication is that the entire Caribbean Plate is allochthonous relative to the Americas and has migrated from well over 2000 km to the west, and that now-adjacent Mesozoic portions of the Caribbean and American (Proto-Caribbean) stratigraphic suites should not be correlated due to the large spatial separation during original deposition. Deep drilling within the interior of the Caribbean plate would likely return an undeformed stratigraphic sampling of the eastern Pacific’s Late Jurassic? and Early Cretaceous section, which elsewhere is only poorly preserved.

Merging the relative motions between North and South America (Fig. 2) with a Jurassic or Early Cretaceous Pacific origin of the Caribbean lithosphere implies a very simple history of Caribbean evolution that can be described generally by two phases. The first phase was Triassic-medial Cretaceous NW-SE relative separation of North and South America and the opening of the Proto-Caribbean Atlantic-type seaway bound by passive margins along the Bahamas, eastern Yucatan, and northern South America. The second phase involved the Albion to Recent subduction of that Proto-Caribbean lithosphere beneath arcs along the eastern Caribbean border, during westward drift of the Americas from Africa. Eastwardly progressive destruction of the Proto-Caribbean passive margins by the relative motion of the Caribbean Plate would be recorded by foredeep basin development above the pre-existing Proto-Caribbean shelf sections. Figure 4 shows four large basins formed by this process whose eastward-younging ages of foredeep loading are: Sepur (Guatemala), Campanian-Maastrichtian; Cuban, early Paleogene; northern Maracaibo, Eocene; and Eastern Venezuelan, Miocene.

The often-cited Cretaceous orogenesis along northern South America (e.g., Barr 1963; Maresch 1974; Beets et al. 1984; Chevalier et al. 1988) does not fit the simple scenario of Caribbean-South American interaction (Pindell 1985b; Dewey and Pindell 1986) implied by the above kinematics, and this discrepancy has been the object of much recent study. Algar and Pindell (1991a,b) and Algar (1993) have shown that no Cretaceous orogenesis affected Trinidad. Similarly, Pindell et al. (1991) and Pindell and Erikson (1993, in press) showed that passive margin conditions prevailed across northern South America until the Tertiary. An implication of these concepts is that all rocks in northern South America containing Cretaceous aged metamorphism are Caribbean-derived and allochthonous. Flysch units containing South American shelf debris once believed to be Cretaceous in age on the basis of clasts are now known to have Tertiary matrices (Garapata, Paracotos formations), in keeping with the simple, two-phase tectonic model. A second important implication is that the belts of Cretaceous metamorphic rocks are not viable markers for assessing total Tertiary strike-slip displacements, because they were not in place at the onset of the strike-slip dislocations. In the simple two-phase model, the emplacement of allochthons occurs as a direct consequence of mainly Tertiary Caribbean-South American relative motion. Therefore, most of the Caribbean-South American transcurent offset occurred along the basal thrusts of the allochthons. Thus, the high angle strike-slip faults within the orogen, which are secondary in magnitude of offset, record only a minor portion (<150 km) of the total relative motion which is in excess of 1000 km in the vicinity of Guajira Peninsula. I point out, however, that as one heads east, the actual total fault offset between South American and Caribbean terranes becomes progressively less, because the Caribbean-South America plate boundary did not exist until progressively younger times toward the east.

CARIBBEAN EVOLUTION: PHASE 1, NORTH AND SOUTH AMERICAN DRIFT STAGE

The following discussion on regional Caribbean evolution is adapted from a full synthesis by Pindell et al. (in review, b 1993). The first phase of evolution (Triassic to Albion) was primarily associated with the development of the Proto-Caribbean Seaway. The second phase (Albion to Present) involved the progressive consumption of Proto-Caribbean crust beneath Caribbean arcs during westward drift of the Americas across the mantle, leading to the present plate configuration.

Late Triassic-Jurassic

The western Pangean reconstruction of Figure 6A is modified after Pindell (1985a) and Rowley and Pindell (1989). The total closure pole for Yucatan/North America relative to North America is latitude 28.4, longitude -82.1, angle -47.7 (Rowley and Pindell 1989) and lies in northern Florida, and the Atlantic closure poles are after Pindell et al. (1988). The Chiapas Massif is not included with the Yucatan Block. Andean deformations in northwest South America have been restored in a similar but more rigorous way as that by Dewey and Pindell (1986). Mexican terranes have been displaced by the minimum amount necessary to avoid overlap with South America. Chortis is not included along western Colombia as it is in some reconstructions because the Central Cordillera of Colombia possessed a Triassic-Jurassic arc axis and must have been adjacent to the Pacific lithosphere.

In Late Triassic to Early Jurassic time, North America began to rift from Gondwana along widespread, poorly-defined zones of intracontinental block-faulting, redbed deposition, and dike emplacement (Fig. 6A and B). In the southern U.S., north-south extension (Rodgers 1984) pro-
duced an extensive graben system filled with Eagle Mills redbeds, and along the eastern United States, redbeds, dikes, and sills of the Newark Group and its equivalents were deposited and emplaced in a belt of grabens paralleling the coast from the Piedmont out to the continental shelf. The Eagle Mills and Newark systems are lithologically and tectonically equivalent. These systems relate to hanging wall collapse of pre-existing thrust faults of the Alleghanian Orogen, as the latter went into extension. Judging from subsidence history, in which post-rift thermal re-equilibration is lacking, these basins are upper crustal detachments rather than true lithospheric rifts. The true lithospheric rifts developed farther south and east, respectively, during the Jurassic.

Drift between Africa and North America was underway in Middle Jurassic time (Figure 6B). The Punta Alegre and ?Exuma Sound salt of the Bahamas might correlate with the portions of the Louann and Campeche in the Gulf, but these units are probably older and appear to relate to the opening of the Central North Atlantic rather than to the Gulf of Mexico. Such is the case with the Senegal Basin and Guinea Plateau salt deposits (Jansa and Weidmann 1982) which opposed the Bahamas at that time. The Blake Spur Magnetic Anomaly (Fig. 6B) can be symmetrically correlated about
the mid-Atlantic Ridge with the western margin of Africa, but internal stretching within the Blake Plateau accounts for divergence between North America and Africa until the time when the BSMA formed to the north (approximately 170 Ma). The crust to the north of the Blake Plateau that was created by seafloor spreading prior to formation of the BSMA produced the Central North Atlantic’s asymmetry with respect to the present ridge axis. An early ridge apparently was abandoned as the spreading center jumped to the site of the BSMA (Vogt et al. 1971; Sheridan et al. 1981).

A complex region of continental blocks comprises the northeastern Gulf, Florida, the western Florida Shelf, the Blake Plateau, and the western Bahamas (Klitgord et al. 1984; Pindell 1985a; Buffler and Sawyer 1985). Sinistral motion along the Jay Fault began such that continental horsts (Sabine, Monroe, Wiggins, Middle Grounds or Florida Elbow, and Tampa or Sarasota Arches) became separated by rifts along the NE Gulf coast margin. Extension was far greater south of the Jay than it was to the north, requiring a sinistral component of displacement in addition to normal offset at essentially a transfer zone. Total offset, which continued into the Jurassic, increased southeastwards relative to North America (differential shear) and perhaps was as much as 100 to 150 km between the Sarasota Arch and the Ouachitas, the latter of which serves as a fixed, North American reference frame. Thus, the North Louisiana and Mississippi Salt Basins (although no salt was yet deposited), the Northeast Gulf Basin, and the Florida Elbow Basin between the aforementioned highs came into existence. Pindell (1985a) noted that there is a sufficient (1) overlap between the present day limit of continental crust in the Bahamas and that in the Guinea Plateau of western Africa during Pangean closure and (2) unfilled gap in the eastern Gulf during closure, to warrant the suggestion that a fault zone in addition to the Jay exists between the Florida Elbow and Sarasota Arches (Florida Elbow Basin) along which crust of South Florida and the Bahamas migrated eastwards during Gulf opening. Although the Guinea overlap could be explained also by magmatic addition during crustal stretching in the South Florida Volcanic Belt, this still does not satisfy the Gulf gap problem suggesting that one or more faults cross Florida to allow the marginal offset between the Bahamas and the Blake Plateau. Buffler et al. (this volume) show faulted basement at the west flank of the Florida Elbow Basin which could coincide with the Florida Elbow Fault zone of Pindell (1985a), but the strike of the faults is not clear. In any case, I note that assessments of relative motion between North America and the Yucatan Block based on structural or tectonic style cannot be made in the eastern Gulf during the period over which the blocks south of the Jay Fault, including the Sabine and Wiggins Arches, were moving, because the blocks were independent, intervening terranes with their own relative motion (Pindell 1985a).

To the west, the Yucatan Block began to migrate southwards along the eastern flank of the Tamaulipas Arch, producing the arcuate shear zone along eastern Mexico (Tamaulipas-Golden Lane-Chiapas transform fault of Pindell (1985a), not a rifted margin) which helps define the North America-Yucatan pole of rotation in Florida (Fig. 6B, C). This shear zone truncates any important faults entering the Gulf from Mexico, including hypothetical extensions of

Figure 6C. Paleogeography, Late Oxfordian.
the Mojave-Sonora trace. The absence of a major marginal offset (~700 km, e.g., Anderson and Schmidt 1983; Kligord and Schouten 1986) on basement isochron maps of eastern Mexico (e.g., Buffle and Thomas, in press 1993) precludes the possibility that a Mojave Sonora fault zone entered the Gulf of Mexico during rifting, and renders unlikely all tectonic models which open the Gulf by moving Yucatan along Atlantic flowlines.

Thus, the terranes of Mexico must have moved into the South American overlap position along faults from the northwest that approached, but did not cross, the Tamaulipas Arch. Strike slip systems to the northwest such as the Mojave-Sonora and the Nacimiento Fault (Dickinson 1983) may have been active during the Late Jurassic and Early Cretaceous, but they must have trended southwards, always lying to the west of the Tamaulipas Arch. Unfortunately, the area of Central Mexico west of the Tamaulipas Arch (and Golden Lane High) has been overthrust by the Sierra Madre Oriental, so that this hypothesis is not easily tested. However, the suggestion would provide a logical mechanism for the production of the deeper water depocenter of the section now comprising the Sierra Madre. I suggest that the southwestern trace of Cordilleran transcurrent fault system(s) became transtensional in central Mexico, creating a Mexican backarc trough. This trough may have formed in order to maintain subduction at the subduction zone outboard of Mexico: in the southwest USA, sinistrally transpressive Neovadian orogenesis occurred in Late Jurassic time (Avé Lallemant and Oldow 1988) due to migration of North America from Gondwana, but the margin became progressively more oblique toward the south along Mexico. Slow rates of trench-normal convergence, leading to rollback, may have driven backarc extension in Mexico, and a significant sinistral component in the backarc basin is predicted in order to help maintain trench-normal subduction at the trench. In this way, the terranes of Mexico could have migrated southwards, but in a more extensional direction relative to the Atlantic flowlines. Later, during Late Cretaceous-Eocene shortening in the Sierra Madre thrustbelt, which was directed essentially toward the ENE, the terranes encroached upon the Gulf of Mexico. The net travel path of southward transtension followed by ENE thrusting (2 sides of triangle) may have produced an apparent transcurrent offset (3rd leg of triangle) along the hypothetical SW-ward extension of the Mojave-Sonora trace. This suggested history (1) explains basement offsets in NW Mexico and SW USA along the Mojave Sonora and other faults (Anderson and Schmidt 1983), (2) provides a mechanism for Mexican Terranes to migrate into the South American overlap position in Pangean reconstructions, (3) accounts for Sierra Madre shortening, (4) avoids predictions of a large and missing marginal offset along the eastern Mexican margin, (5) suggests a mechanism for deeper water deposition across central Mexico, the depocenter for the Sierra Madre section, and (6) fits very well into our understanding of plate kinematics of the region at that time. The proposed basin probably began its formation in the Callovian, concurrent with the earliest known marine spils into the Gulf of Mexico in the area (Tepexic Formation? in southern Mexico). Depending on the degree and variability of the obliquity of opening, the basin could have had variable water depths, with limited basaltic intrusion or production of oceanic basement.

In northern South America, rifting, igneous intrusion, and redbed deposition occurred over Triassic-Jurassic times, but rifts can be divided between those east of Maracaibo (Takatu, Espino, Uribante/Tachira, Cocinas?) which are due to continental breakup from Yucatan/Florida-Bahamas and those west of Maracaibo (Machiques, Cocinas?, Bogota/Cocuy, Santiago, Payande) which are Andean backarc basins with arc related volcanism, as well as rift related volcanism, in or adjacent to them. The Machiques, Uribante, and Bogota/Cocuy would become the sites of Andean uplift during Neogene times (Perija, Merida, Eastern Cordillera, respectively) (Irving 1975; Gonzalez de Juana et al. 1980). The continental margin to the north formed at this time, and as Upper and possibly Middle Jurassic marine passive margin sediments were deposited from Guajira to Trinidad (Gonzalez de Juana et al. 1980; Algar and Pindell 1991b. The platformal areas between these rifts behaved as basement highs during subsequent Late Jurassic and Early Cretaceous thermal subsidence. The backarc marginal trough predicted for Mexico, above, is also predicted for offshore Colombia, as Triassic to Jurassic arc magmatism ceased in Colombia by the end of the Jurassic, and all of autochthonous Colombia became a part of the northern South American passive margin (Pindell and Erikson 1993, in press). The plate vector circuit for North America, South America, and Cordilleran Mexico can be satisfied by a single RRR triple junction within the backarc basinal area, connecting the Mexican, Colombian, and Proto-Caribbean zones of displacement (Fig. 6C, D). This allows continuity of the Cordilleran arc systems in an outboard position away from passive margin elements of Colombia and eastern Mexico: the back arc systems would collapse during the Late Cretaceous Sevier-Peruvian orogenesis after Aptian-Albian onset of westward drift of South America from Africa and plate re-organization in the eastern Pacific.

By the Middle Oxfordian, intra-continental extension in the Gulf of Mexico had reached a point (constrained by South American divergence rate) where the Gulf had opened enough to accommodate the entire extent of the Louann and Campeche evaporite basin, but salt deposition may have begun in the Callovian or earlier. Oxfordian salt deposition is supported by seismic studies which show no erosion of the salt below the Oxfordian Norphlet/Smackover, suggesting very little time between the deposition of the two units
(Imlay 1980). In most places, the salt appears to cover or mark the breakup unconformity around the Gulf: elevation and exposure of the surface across the Gulf Basin prior to salt deposition was probably controlled by the ratio of crustal to lithospheric thickness until a critical value (Dewey 1982) was reached during continued extension. The salt often marks the onset of thermal subsidence which led to establishment of open marine conditions around the bulk of the Gulf, but isolated pockets may have been well below sea level during the Oxfordian advance of the seas, resulting in rapidly deepening conditions. Two likely entrances for marine waters into the Gulf during the Callovian-Oxfordian times are between Florida and Yucatan, as DSDP leg 77 documented Jurassic extension and marine sedimentation (Schlager et al. 1984), and the southern Mexican Isthmus, where Callovian marine rocks of the Tepecice Formation occur.

During the entire Late Jurassic, seafloor spreading was occurring in the Gulf of Mexico where it separated the salt basin into halves, and also in the Proto-Caribbean Sea (Fig. 6C). The crust of southern Florida/Bahamas may have been mobile relative to North America as well, by faulting along the Florida Elbow Fault Zone. The three components of motion must have approximately summed to match the opening rate and azimuth of the Central Atlantic Ocean. By Oxfordian times, rifting appears to have ceased between the blocks south of the Jay Fault, such that Gulf of Mexico marine magnetics and structural trends west of, but not southeast of, the Florida Elbow Arch probably define Yucatan-North America motion. Hall et al. (1993, in press) suggest a pole for this time based on magnetics that is farther south in Florida than my total closure pole defined earlier, and it may be that crustal stretching during the rift stage in the Gulf Coast was NW-SE directed, followed by more N-S rotational seafloor spreading. If so, the two stages of opening may sum to match the total closure pole. Given, among other things, the slight bend to the NW in basement structure contours in the Burgos Basin area at the north end of the Tamaulipas Arch (Buffler and Thomas 1993, in press), this two stage model appears to be justified (Marton and Buffler 1993, in press). To the north of the migrating junction between the Tamaulipas-Golden Lane-Chiapas fault zone (TGLC) and the central Gulf ridge system, the TGLC evolved as a fracture zone separating zones of differential subsidence. The abrupt topographic low, or freeboard, east of TGLC has received enormous volumes of sediment through time (for example, Burgos Basin east of Monterrey, Mexico) (King 1969). As strike-slip motion ceased along the Tamaulipas Arch after passage of the ridge system, it thermally subsided and eventually was onlapped by uppermost Jurassic and Cretaceous carbonates. In Chiapas, deposits of the Todos Santos “rift facies” are younger (Late Jurassic-Early Cretaceous) (Anderson et al. 1973) than those in the northern Gulf. This is probably because shear along the active TGLC continued longer in the south, well into the thermal subsidence stage of the north.

The whereabouts of the Chortis block relative to North America during the Jurassic and Early Cretaceous is un-
known. However, by Aptian times the carbonate units of southern Mexico and Chortis became very similar, and it could be argued that the Cretaceous magmatic rocks of Chortis formed a southerly extension of the Cretaceous Mexican arc as well. This relative position is shown for the Chortis block in the reconstructions until the Valanginian.

To the east, the juvenile Proto-Caribbean continued to open, fanlike, between Yucatan and Venezuela. The mid-ocean ridge in this basin must have been joined in some way with the plate boundary separating the Florida/Bahamas and Yucatan Blocks, which in turn must have been connected to the Central North Atlantic ridge system by a long transform along the south side of the Bahamas. A single triple junction is portrayed connecting these plate boundaries in the northern Proto-Caribbean, for simplicity, but Late Cretaceous to Paleogene subduction of this crust has eliminated direct evidence for this proposition. The crust east of Yucatan and south of the Bahamas may have had a rough bathymetric character (stretched continental blocks or raised oceanic fracture zones?), such that a complex pattern of carbonate highs and lows developed into the Cretaceous. Sediment originally deposited in the northern Proto-Caribbean depocenter is now represented in the Cuban thrust belt north of and underneath the Cuban ophiolite/arc belt. Clastic sands in those sections were probably derived laterally from Yucatan rather than the Bahamas. Hence, sedimentary evidence in Cuba for the Cuba-Bahamas collision appears older (Late Cretaceous) than it actually was (Paleogene).

The opening of the Gulf of Mexico was achieved probably within the Berriasian, when sufficient room existed between North and South America to avoid overlap between Yucatan and South America (anomaly M-16). At that time, the Yucatan block became part of the North American Plate (NOAM) as spreading ceased in the Gulf, and a Neocomian circum-Gulf carbonate bank was established. Starting in the Berriasian, North America-Gondwana plate separation occurred solely within the Proto-Caribbean Sea, an arm of the Central North Atlantic (Fig. 6D). Most margins of the Proto-Caribbean Sea had been formed by rifting, and carbonate and terrigenous shelf deposits accumulated on the subsiding shelves throughout the Cretaceous. The Proto-Caribbean ridge system connected the Central North Atlantic ridge system to plate boundaries in the Pacific realm, presumably the backarc spreading centers of central Mexico and offshore Colombia.

Early Cretaceous, and Aptian-Albian Cordilleran Orogenesis

Plate separation continued between North and South America in the Proto-Caribbean, whose passive margin sections (Fig. 5) continued to develop during thermal subsidence (Fig. 6D, E). However, tectonically driven uplift of unknown magnitude in northeastern South America may have been caused at the end of the Jurassic and earliest Cretaceous by a transient shift in the Central North Atlantic

*Figure 6E. Paleogeography, Barremian.*

*Barremian/Early Aptian ~120Ma*
spreading center between M-21 and M-10 (Erikson and Pindell, in review). Also at this time, the eastern Bahamas was elevated to sea level so that carbonate banks developed there, either by tectonism related to the shift in the Atlantic spreading ridge (Pindell 1985a) or by igneous intrusion and extrusion which may have been associated with a hot spot trace extending from the Jurassic Florida Volcanic Belt.

Along the Cordillera, the Mexican (Sierra Madre) and Colombian backarc extensional zones probably continued to expand as divergence between North and South America continued. Deep water sedimentation has been suggested from rocks of central Mexico, and ophiolitic rocks occur in the Juarez Terrane east of Oaxaca (Campa and Coney 1983), but it is difficult to suggest how wide the basin was. In continental portions of Colombia and northern Ecuador, there is no record of arc magmatism during the Early and Middle Cretaceous, suggesting that the trenches of whatever arc systems existed west of the Proto-Caribbean area did not intersect the South American Andes until southern Ecuador. I speculate that an evolving and lengthening intra-oceanic arc system from Chortis/Mexico to southern Ecuador would form the roots of the Greater Antilles and Aves Ridge arcs of the Caribbean and the Amaime-Chaucha terrane of Colombia/Ecuador, although at this point the arc was westward facing. Subduction of Pacific (Farallon?) lithosphere at this speculative arc configuration may have been accompanied by accretion of Jurassic ophiolitic fragments and cold water cherts now found in Dominican Republic, Puerto Rico, and La Désirade (Montgomery et al. 1992). The relative velocity triangles of Figure 6D might describe the relative plate motions at this time.

By the Barremian/Aptian (Fig. 6E), a plate boundary reorganization in at least the eastern portion of the Proto-Caribbean is required to accommodate the onset of opening in the Equatorial Atlantic. The trace of the fracture zone which originally existed along the Guyana margin must have shifted north, possibly as a result of the kinematic adjustments made during the M-21 to M-10 kink in Atlantic fracture zones. Final development of the eastern Bahamas basement uplift also probably was associated with this reorganization.

Other important plate boundary reorganizations were about to take place, too. Engebretson (1982) suggested that Farallon crust may have begun to converge in a more NE direction relative to North America during Aptian-Albian times, which would have relieved the sinistral component of strain along the Mexican Cordillera. The opening of the Equatorial Atlantic was presumably well underway by the Albian, as evidenced by Albian marine inundation of all Equatorial Atlantic rift basins, such that for the first time the South American lithosphere accelerated westward across the mantle. The Proto-Caribbean spreading ridge probably ceased to exist in the Late Albian (Fig. 2, 3), but the spreading rate in the Central Atlantic increased dramatically during the Cretaceous Quiet Period (Kitigord and Schouten 1986). Thus, South America accelerated from Africa faster than did North America in order to “catch up” with North America, but in fact both American plates must have accelerated westward across the mantle. This would drive the Cordilleran arc systems into a compressional arc configuration in the sense of Dewey (1980), in which the overriding plate was actively thrust across the trace of the pre-existing trench. This process was a chief cause of Sevier and Peruvian orogenesis in the continental arc portions of the Cordillera, which involved Cordilleran uplift, reduction of the subduction angle, a general eastward shift in the axis of volcanism, and backthrusting and associated foredeep basin development.

However, the Aleutian-like, Aniillean-Amaime intra-oceanic arc between Chortis/Mexico and southern Ecuador appears to have flipped its polarity (Fig. 6F, G), possibly by the evolution of backthrusting taken to the extreme by the creation of a new Benioff zone. Aptian/Albian metamorphic ages, often from high-pressure minerals, are common around the Antilles, Tobago, the Villa de Cura complex of Venezuela, the Ruma zone of northern Colombia, and in the Amaime terrane of Colombia, and possibly relate to the orogenesis pertaining to the flip and/or to the onset of west-dipping subduction (possible mechanism to elevate blueschists toward the surface) on the east side of the arc (Pindell and Erikson 1993, in press). Albian metamorphic ages, such as from the Villa de Cura of Venezuela (Beets, et al. 1984), probably pertain to terranes which were preserved at relatively shallow levels after the flip, such that the metamorphic age was preserved. Other terranes, such as the rocks of the northern Cordillera de la Costa Belt of central Venezuela (Avé Lallemant and Sisson 1993, in press), probably remained deeper in the forearc or the trench setting such that they continued to develop metamorphic fabrics and ages at younger times and at progressively lesser depths. In some locations, the magmatic axis of the arc itself shifted during the Albian, for example in Dominican Republic from the Los Ranchos area to the Central Cordillera, possibly as a result of the reversal.

The polarity reversal theoretically should have transformed the configuration of the intra-oceanic arc from generally convex to the west, to generally convex to the east. Given that the arc was probably over 2,000 km long, the structural disruption within the arc as it changed convexity could have been intense; the arc may have been first shortened (uplift) and then extended (subsidence with much rifting) during the flip. Most of the arc's pre-Albian paleogeographic elements were probably rendered beyond recognition, with many "new" areas of the arc infilling gaps (e.g., larger batholiths) between older rearranged fragments. Likewise, seismic sections of the internal Caribbean Sea's
Figure 6F. Paleogeography, Late Albion.

Figure 6G. Paleogeography, Turonian.
lithosphere indicate that it underwent significant deformation in mid-Cretaceous times, including extrusion and intrusion of basalts and diabases (seismic horizon B") onto and into pre-existing Pacific-derived sediments and crust of probable Lower Cretaceous and Jurassic age. It has been suggested that the arrival from the Pacific of buoyant B" lithosphere at the west-facing arc helped to cause the flip in polarity (e.g., Livacarri et al. 1981), and this may be so, but the age of the B" material (approximately ?Albian to Coniacian) suggests that its extrusion may be a result, rather than a cause, of the flip.

Although many details of this event remain to be worked out, I will assume here that the well-known Late Albion to Eocene phase of magmatc activity in many Caribbean arc terranes with Aptian-Albian, possibly amalgamated, metamorphic basements is due to subduction of Proto-Caribbean and Colombian backarc oceanic crust beneath the Greater Caribbean arc after a highly orogenic Aptian-Albian reversal of subduction polarity (e.g., Fig. 6G). The reversal correlates tectonically to the Sevier and Peruvian orogenesis in continental areas to the north and south. From Late Albion to Santonian times, the arc system may have defined the eastern edge of Farallon crust, but the Santonian onset of subduction at the Panama-Costa Rica arc isolated the Caribbean lithosphere by Campanian time as an independent plate with its own relative motion history for the first time (Pinell and Barrett 1990). Once this was achieved, the east-west component of motion of the Caribbean lithosphere remained approximately in the mantle reference frame, unable to shift east or west because of its bounding Benioff zones. Continued westward drift of the Americas from Africa produced the apparent Late Cretaceous to Recent eastward migration of the Caribbean relative to the Americas, at rates very close to the Atlantic spreading rate through time.

CARIBBEAN EVOLUTION, PHASE 2:
CONSUMPTION OF THE PROTO-CARIBBEAN SEAWAY BENEATH THE CARIBBEAN PLATE

Late Cretaceous

Generally non-volcanogenic shelf sedimentation continued along the margins of the Proto-Caribbean during thermal subsidence in the absence of plate boundaries (Fig. 6G). The Late Albion drowning of carbonate shelves and rapid landward transgression at most portions of the Proto-Caribbean margins may have been enhanced by the death of the Proto-Caribbean spreading ridge. The death of the ridge would reduce in-plane stress around the region, due to the loss of the ridge push force as the ridge subsided, allowing the margins to subside. In contrast, arc activity was underway along the Greater Antilles, the Amaima-Chaucha Terrane (e.g., Buga Batholith), and the Mexico/Chortis and southern Ecuador/Peruvian margins.

The onset of relative eastward migration of the Cordilleran systems led to the progressive closure of the Mexican and Colombian backarc basins (Fig. 6G, H). In Mexico, closure probably began in the Albion like the rest of the Cordillera, but orogenic facies did not commonly appear until the Campanian because the thrust belt would not become emergent until enough shortening had accumulated to roughly match the amount of extension which had taken place during the Early Cretaceous. To the southeast, arcocontinental collision and northward obduction of the Santa Cruz ophiolite took place along southern Yucatan during the Campanian-Maastrichtian (Rosenfeld 1993, in press; Wilson 1974), as marked by the drowning of Cohen shelf carbonates by deeper-water Campur carbonates and eventually Sepur Formation foredeep flysch derived largely from the arc. Similar flysch sequences probably flowed eastwards along the Cuban trench to be accreted to the Cuban thrust belt during its journey toward the Bahamas. In the Antillean segment of the arc, subduction of Proto-Caribbean crust continued throughout the Late Cretaceous, but the Campanian was a time of uplift, erosion and deformation (e.g., Hispaniola, Bovin 1975) probably related to plate interactions accommodating the Proto-Caribbean bottleneck between Yucatan and Colombia.

In Colombia, the Amaima-Chaucha Terrane had been diachronously accreted by eastward-vergent thrusting onto the Central Cordilleran passive margin by end of Campanian time, which (1) thermally reset many older radiogenic systems in the Central Cordillera, producing the appearance of Cretaceous magmatism there, and (2) drove foredeep basinal subsidence (Colon, Umir Formations) east of the Central Cordillera by tectonic loading from the west (Pinell and Erikson 1993, in press). Toward the end of the Campanian, continued convergence began to occur at an east-dipping trench outboard of the Amaima Terrane, leading to the progressive accretion of Caribbean B" and other sedimentary materials into the Western Cordillera Belt during Maastrichtian and early Paleogene times (Fig. 6H).

Eastward-dipping subduction began in the Panama-Costa Rican arc along the Pacific side of B"-affected crust in the Santonian as evidenced by rapid uplift and the onset of Campanian volcanogenic sandstone and shallow water carbonate deposition (Lundberg 1983). The formation of this arc at this particular time was required in order to take up the rapidly accelerating Farallon-North America convergence rate of about 150 mm/yr (Engelder 1982). The Caribbean proceeded to move at about 30 mm/yr (Pinell et al. 1988), so that the new arc, which defined the Caribbean Plate for the first time, took up the difference of over 100 mm/yr. I suggest that the arc stretched from west of Chortis, southeastwards to southern Ecuador. The Ecuadorian site
for the TTT triple junction is indicated by the boundary between voluminous and nearly absent Andean volcanism at this time to the south and north, respectively: to the north, Caribbean plate convergence with the Andes was only approximately 20 mm/yr, whereas to the south the Farallon Plate’s convergence rate with the Andes was over 100 mm/yr. During the remainder of the Cretaceous and into the Tertiary, the triple junction appears to have migrated northwards eventually into southern Colombia (Fig. 6I, J, K), at the rate of the northward component of motion in this area between the Caribbean and South American plates, with a corresponding increase in magmatism in the wake. However, this level of detail cannot be stated with confidence without further work.

Finally, in regard to the Cretaceous, the problem of having both the Chortis Block as well as the Caribbean Plate move synchronously eastwards relative to the Americas still appears to be best solved by northward underthrusting or subduction along the Lower Nicaragua Rise (Pindell and Barrett 1990). The character of the Rise is not unlike a submarine, oceanic crust-bearing accretionary prism (Dengo and Case 1990), and volcanism in the Upper Nicaragua Rise to the north continued at least into the Paleocene. The Chortis Block must have moved relatively eastwards, while the Caribbean must have moved ENE, thereby producing convergence between the two at the Nicaragua Rise.

Cenozoic

The Caribbean Plate continued migrating relatively east-northeastwards, subducting oceanic crust of the proto-Caribbean. The Yucatan Basin opened by intra-arc spreading and extreme attenuation of Greater Antilles arc crust (Rosencrentz 1990) in a three-plate system (Fig. 6J, vector inset) between Cuba, the Cayman Ridge, and North America (Pindell and Barrett 1990). The bulk of the Cuban portion of the Greater Antilles magmatic arc is split between the basement of the Cayman Ridge and Cuba’s southern arc belt. The Cretaceous volcanic assemblages of onshore Cuba may represent mainly the forearc complex if rifting occurred nearly along the arc axis. A possible reason that Cuba lacks latest Cretaceous-Paleogene magmatic rocks is that the presently subaerial portion of Cuba was too close to the former trench: the arc-trench gap should have been greater, and plutons and volcanics of that age may exist offshore to the south. The opening of Yucatan basin is defined by the three-plate system (NOAM-Caribbean-Cuba); trends and magnitudes of the relative motions may be calculated by vector completion (Pindell and Barrett 1990). Collision between the Greater Antilles and the Bahamas began in the Paleocene, although subduction accretion packages occur onshore Cuba which formed during Late Cretaceous and included Late Cretaceous orogenic sediments probably de-
SYNOPSIS OF GULF OF MEXICO AND CARIBBEAN EVOLUTION

Figure 6.1. Paleogeography, Maestrichtian.

Figure 6.1. Paleogeography, Paleocene.
rived from Yucatan, confusing the definition of the exact age of the onset of the Cuba-Bahamas collision.

A Paleogene age is generally accepted for the opening of Grenada Basin, too (Speed et al. 1984). North-south extension best explains the E-W magnetic pattern and orientation of normal faults in and around the basin, and also the sharp SE boundary of the Aves Ridge (transform faulted?). Dextral oblique subduction of the Proto-Caribbean crust, dextral transform drag along South America, and subduction zone rollback of the Jurassic oceanic crust along the northern South American passive margin may have combined to drive the Andaman-Sea type intra-arc extension. The opening of both the Yucatan and the Grenada intra-arc basins was the mechanism by which the Caribbean
Plate accommodated the shape of the Proto-Caribbean basin. It was apparently easier to rift the arc complexes (driven by rollback of existing Benioff zones) than to tear railroad transforms in the Jurassic Proto-Caribbean oceanic crust.

To the west, the Yucatan block prevented simple east-northeastward motion of Chortis and Nicaragua Rise/Jamaica with the rest of the Caribbean Plate, and compression was consequently set up between Chortis and the Caribbean Plate. Chortis, Nicaragua Rise, and Jamaica were internally deformed during the Paleogene (Wagwater, Montpelier Troughs, rifts of Nicaragua Rise) (Mann and Burke 1984a).

The Middle Eocene is marked by the termination of Bahamian-Antillean collision and the onset of platformal deposition in Cuba (overlap assemblage). Extension in Yucatan Basin ceased as Cubi came to rest against the Bahamas. The reconstruction of Figure 6K is constrained by 1) restoring 1050 km of offset in Cayman Trough, 2) the alignment of Late Cretaceous-Eocene subduction-related plutons throughout the Greater Antilles and Aves Ridge, and 3) sedimentary facies changes across the Greater Antilles (Pindell and Barrett 1990). Volcanism shifted eastwards from the Aves Ridge to the Lesser Antilles arc, beginning in the Eocene in the northern Lesser Antilles, but possibly not until the Oligocene or Early Miocene in the south. This diachronicity probably relates to north-south opening of Grenada Basin and a consequently lesser subduction rate (component of eastward migration) in the south during the Eocene.

In the Middle to Late Eocene, just after the Antilles-Bahamas collision, east-northeast migration of the Caribbean Plate relative to North America continued along a new plate boundary system which became the northern Caribbean plate boundary zone. The Cayman Trough nucleated as a pull-apart basin between Yucatan and Jamaica. Cuba, the Cayman Ridge, and the Yucatan Basin were left as a part of the North American Plate by the development of the northern PBZ.

To the south, subduction of Caribbean crust beneath NW Colombia produced an accretory prism of Andean, Incaic phase orogenic sediments (San Jacinto Belt) which grew until the Miocene (Duque-Caro 1979; 1984). Progressive development of the early Barbados accretionary prism (Speed 1985) was due to southeastward migration relative to South America of the terrane to the east of the Grenada Basin (Grenada Terrane) during the opening of Grenada Basin (three-plate system, Fig. 6J). Quartzose sands of Barbados and the Piemontine nappes of central Venezuela were accreted to the arc complex in the Eocene prior to emplacement onto the shelf, and probably originated from 1) western and central Venezuela where Precambrian acidic massifs were exposed at that time, and 2) the peripheral bulge ahead of the Venezuelan foredeep basin.

Post-Eocene subduction of Proto-Caribbean crust is indicated by subduction-related magmatism in the Lesser Antilles. In the northern PBZ, the Cayman Trough progressively opened by seafloor spreading at the Mid-Cayman Spreading Center, which linked transform faults connecting to the Middle America and Lesser Antilles subduction zones (Fig. 6J, K). These transforms have changed location through time, forming anastomosing fault systems across central Guatemala, in the west, and across Hispaniola/Puerto Rico in the east. Large-offset transcurrent motions between blocks of Hispaniola are indicated by drastically different Tertiary sedimentary facies which are presently juxtaposed across fault zones. The primary offset during the Late Eocene and Oligocene occurred along faults of the northern San Juan Basin, juxtaposing the San Juan block with the Cordillera Central-Massif du Nord arc by the Early Miocene, as indicated by the flooding of arc-derived clastics into San Juan Basin at that time (Michael 1979; Cooper 1983). Motion on eastward extensions of this fault system separated Puerto Rico from central Hispaniola, and may have brought the Bermeja area of southwest Puerto Rico into contact with central Puerto Rico along the "Eocene Tectonic Belt."

In the developing southern PBZ (Silver et al. 1975; Bijou-Duval et al. 1983), eastward migration of the Caribbean Plate progressively lengthened the zone of Caribbean-South American interaction (Fig. 6I). Nappes have been emplaced south-eastwards onto the Venezuelan margin since the Paleocene; initiation of thrusting upon the autochthon becomes progressively younger to the east. Subsidence of the Venezuelan shelf near Maracaibo is Paleocene-Lower Eocene (Zambrano et al. 1972), and subsidence in the Eastern Venezuela Basin is Miocene-Pliocene (Vierbuchner 1984). A transform between the Caribbean Plate and the obducted terranes on South American basement developed progressively after thrust emplacement, and assisted with continuing strike-slip offset of the Caribbean but not the obducted terranes after emplacement. The Falcon (Mueussig 1984) and Cararico (Schubert 1982) Basins are two examples of Oligo-Early Miocene and Miocene to Recent, respectively, transtensional basins that developed in previously overthrust areas. I note that both opened only after the development of the Grenada Basin, when the relative motion vector was extremely oblique.

Motion through Hispaniola during the Early to Middle Miocene (Fig. 6M) continued along the northern San Juan Basin, and possibly along the south flank of Sierra Neiba, but the main locus of motion became the Oriente Fault between Cuba and Hispaniola at about 20-25 Ma. This was responsible for the present separation of the two islands. By the Late Miocene, convergence and uplift in Sierra Neiba had structurally separated the San Juan and Enriquillo Basins. The logical eastward continuation of this fault system
is the Muertos Foldbelt (Ladd and Watkins 1978), which has become a south-vergent overthrust zone probably since Miocene time.

In the south, the North Venezuelan and Piemontine nappes reached final emplacement onto the Venezuelan shelf, overthrusting the Oligocene-Early Miocene foredeep basin (Robleciito Formation). Out in the Pacific, spreading was initiated at the Galapagos spreading center; its relationship to the Caribbean plate boundary circuit is unclear because its eastern portions have already been subducted.

The Panama arc, a part of the Caribbean Plate, has often been shown as having collided with Colombia in the
Miocene. In Figure 6K-N, I show a speculative, more prolonged history of interaction, which (1) considers slower relative motion rates as one goes farther south such that Panama was always closer to Colombia than previously thought (16 mm/yr for Neogene, 24 mm/yr for Paleogene), (2) portrays the Panamanian orocline as a slowly developing feature as plate convergence continued, (3) allows for the east-vergent obduction of the Panamanian arc, or Choco Terrane, onto the Western Cordillera, marking the suture zone within the Western Cordillera rather than at the Atotora Basin, and (4) shows that arc magmatism, which does not begin in Colombia until the Middle Miocene, pertains to subduction of the Cocos or Nazca Plates, rather than of the Caribbean Plate. In any case, the progressive collision hindered and eventually blocked circulation between the Caribbean and Pacific (Keigwin 1978), and was a major cause of northern Andean compression and uplift, helping to drive the Maracaibo Block northwards from the Eastern Colombian Cordillera. This escape produced the South Caribbean Foldbelt north of the Maracaibo block and offshore terranes (Dewey and Pindell 1985), and development of the Panama Orocline produced the North Panama Foldbelt (Lu and McMillan 1983). The arc terranes of Cuba and Hispaniola continued to separate by transform motion along the present-day Oriente Fault. Compression has continued in the Sierra Neiba/Enriquillo systems, contributing to the present-day complexity of the northern PBZ.

Miocene to Recent deformations around the Caribbean are common and very strong. This Neo-Caribbean Phase of deformation (Pindell and Barrett 1990) results from the continued drift of the Americas westward past the Caribbean, and from a general state of compression which can be related to at least three causes. First, North-South American relative motion vectors (Fig. 2) show convergence during the Neogene, which constrains the Caribbean Plate. Second, the restraining bend in the Oriente-Puerto Rico Trench transform fault northeast of Dominican Republic (Bracey and Vogt 1970) constrains the eastward migration of the north-central Caribbean and is responsible for much transpression in Hispaniola. The eastern part of Hispaniola, which has already passed this bend, has subdued topography relative to the western part. Third, the northeastward migration, relative to the Guyana Shield, of the Andean Cordilleran Terranes has induced a compression upon the Caribbean Plate to the north-northwest, because the Caribbean Plate possesses an eastward component of motion relative to the Guyana Shield that is slightly greater than that of the Cordilleran Terrane (Dewey and Pindell 1986). In the southeast Caribbean, where the Caribbean and South American plates nearly come into contact, the relative motion of the two has been slightly north of east since the Late Miocene (Algar and Pindell, in review), but was more convergent (transpressional to the ESE) in the Early and Middle Miocene. A fourth cause, which pertains mainly to Colombia, is that the crust of the Caribbean Plate is buoyant and resists subduction, as attested to by the Andean orogenesis which has occurred in the absence of volcanism throughout much of the Cenozoic.

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