PERMO-TRIASSIC RECONSTRUCTION OF WESTERN PANGEA AND THE EVOLUTION OF THE GULF OF MEXICO/CARIBBEAN REGION

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Abstract. A Permo-Triassic reconstruction of western Pangea (North America, South America, Africa) is proposed that is characterized by (1) definition of the North Atlantic fit by matching of marginal offsets (fracture zones) along the opposing margins, (2) a South Atlantic fit that is tighter than the Bullard fit and that is achieved by treating Africa as two plates astride the Benue Trough and related structures during the Cretaceous, (3) complete closure of the Proto-Atlantic Ocean between North and South America, accomplished by placing the Yucatan block between the Ouachita Mountains and Venezuela, (4) a proposed Hercynian suture zone that separates zones of foreland thrusting from zones of arc-related magmatic activity; to the northwest of this suture lie the Chortis block and Mexico and most of North America, and to the southeast lie South America, the Yucatan Block, Florida and Africa, and (5) satisfaction of paleomagmatic data from North America, South America, and Africa. Beginning with the proposed reconstruction, the relative motion history of South America with respect of North America is defined by using the finite difference method. Within the framework provided by the proposed relative motion history, an evolutionary model for the development of the Gulf of Mexico and Caribbean region is outlined in a series of 13 plate boundary reconstructions at time intervals from the Jurassic to the present. The model includes (1) formation of the Gulf of Mexico by 140 Ma, (2) Pacific provenance of the Caribbean plate through the North America-South America gap during Cretaceous time, (3) Paleocene-Early Eocene back arc spreading origin for the Yucatan Basin, whereby Cuba is the frontal arc and the Nicaragua Rise-Jamaica-Southern Hispaniola is the remnant arc, and (4) 1200 km of post-Eocene cumulative offset along both the Northern and Southern Caribbean Plate Boundary Zones, allowing large-scale eastward migration of the Caribbean plate with respect to the North and South American Plates.

INTRODUCTION

The relative motion of two plates separated by an oceanic ridge can be derived by assuming that symmetrically-disposed pairs of magnetic anomalies were once adjacent at the ridge at a time equivalent to the age of the anomaly pair. Extending this approach to the three-plate system of plates A, B, and C where the spreading history is known between the A-B pair and the B-C pair, the relative motion history of the A-C pair, if it is unknown, may be computed by completing the vector circuit [McKenzie and Morgan, 1969] or finite difference circuit [Dewey, 1975]

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for several intervals through time. The spreading histories for the Central and South Atlantic Oceans are fairly well known. However, much of the oceanic crust (and its magnetic anomalies) that was produced during the initial separation between North and South America has been destroyed by Caribbean evolution and cannot be directly evaluated. The finite difference method for the North America-Africa-South America three-plate system is the most valuable first-order technique by which to examine Caribbean evolution because it provides the relative positions of the North and South American continents at various times since the initial breakup of Pangea. The framework provided by this method indicates whether and when extensional, compressional, or transcurrent motions occurred between North and South America; thus plate boundary schemes describing the evolution of the Caribbean Plate may be developed iteratively by integrating the relative motion data with Caribbean geology.

Of vital importance to establishing the relative motion history is the early Mesozoic predrift reconstruction of North America, South America, and Africa. Published initial fits of the major continents are varied, but all leave a noncontiguous gap in the Gulf of Mexico area that can only be filled with either or both the Yucatan and Chortis blocks of Central America. The preservation of a remnant hole seems unlikely because of (1) the intensity and continuity of the Pennsylvanian-Permian orogeny, (2) the rare occurrence of oceanic holes in other 'completed' orogenic belts around the world, (3) analyses of strike-slip lateral motions within present-day collisional zones, which inevitably fill or replace topographic lows with thick sediment wedges and/or crustal blocks, and (4) the desert-like climatic conditions indicated by the Early Mesozoic geology of southern North America and northern South America. We propose an Early Mesozoic continental reconstruction that (1) provides a tight, continuous fit between the three major continents and the blocks of Central America and (2) satisfies late Paleozoic to Early Mesozoic geology in terms of arcs, forelands, accretionary terrains, sedimentary patterns, and paleomagnetism.

Beginning with the proposed continental reconstruction, a relative motion vector history is reconstructed that describes the motion of South America with respect to North America since the middle Jurassic. The relative motion history is produced from an Atlantic opening model proposed herein that varies significantly in the South Atlantic from those previously published. It is upon this relative motion history that the Gulf of Mexico/Caribbean evolutionary model is based.

RECONSTRUCTION OF WESTERN PANGEA

Late Paleozoic Geology of Southern North America
and Evidence for the Hercynian Suture Zone

A fairly continuous belt of Permo-Carboniferous deformation passes from the northern Appalachians, through the southern Appalachians, the Ouachitas and the Marathons, into the Huastecan 'belt' of eastern Mexico (Figure 1). Despite the apparent continuity of this belt, evidence for locating its associated suture or sutures is very sparse. No clearly defined suture zone has yet been identified in North America, nor has one been defined within northwestern South America or western Africa; it must be assumed that it mostly lies beneath thick coastal plain sequences.

Two probable exceptions exist, however, in the southern United States. First, the Suwannee Basin of northern Florida and southernmost Georgia (see Figure 1) contains early Paleozoic faunal assemblages typical of Africa (Gondwanaland) [King, 1975], and thus Wilson [1966] suggested that this portion of present-day North America became 'welded on' during the Late Paleozoic closing of the Proto-Atlantic Ocean. The Hercynian suture probably passes between the Suwannee Basin and the Southern Appalachians. The latter are definitely composed of material that had belonged to North America at least since Devonian times [Hatcher, 1978].
The second lies to the south of the Ouachita system in the subsurface structural high called the Sabine Uplift (Figure 1) where drilling has recovered Mississippian volcanioclastics that may represent the Permo-Carboniferous arc associated with the closure of the Proto-Atlantic. Assuming that the Ouachitas represent allochthonous sheets emplaced onto the North American foreland (as described by Graham et al., [1975] and Kluth and Coney [1981], we suggest that the Hercynian suture passes between the Sabine Uplift and the Ouachita Mountains.

Appalachian system. In the Central and Southern Appalachians, deformation began in the Late Mississippian (Chesterian), and large-scale thrusting continued at least through the late Pennsylvanian, possibly into the Permian. Total shortening within the southern Appalachians is at least 300 km as shown by COCORP seismic reflection studies [Cook et al., 1979]. Deciphering the polarity of subduction before the continent-continent collision that produced the Appalachian deformation is difficult, but the westward emplacement of giant thrust sheets onto the North American craton suggests eastward subduction.

Ouachita system. In the Ouachita segment of the belt, deformation gradually increased from Late Mississippian into the early Pennsylvanian [Tomlinson and McBee, 1959; Flawn, 1961; Goldstein, 1961; Frezon and Dixon, 1975], with the climax of folding and thrusting occurring in the Late Atokan [Goldstein, 1961] or early Desmoinesian [Frezon and Dixon, 1975]. The Ouachita Mountains are characterized by northward-verging
recumbent folds and southward-dipping thrust faults, the motion upon which has emplaced pre-Pennsylvanian Paleozoic deep-sea sediments and Appalachian-Ouachita flysch [Graham et al., 1975] onto the shallow water Paleozoic shelf of Arkansas, Oklahoma, and northern Mississippi. The Ouachitas have been interpreted as having been caused by continent-continent collision about various subduction geometries (see Wickham et al. [1976] for a review), but the likeliest is that of continent-continent collision across a southward-dipping subduction zone with emplacement of allochthonous thrust sheets composed of continental rise, abyssal and flysch type sediments onto the southward-facing Paleozoic shelf of southern North America [Briggs and Roeder, 1975; Graham et al., 1975].

Marathon system. Stratigraphy and deformation in the Marathon region, West Texas, is similar to that in the Ouachita system. The two systems are continuous beneath the Cretaceous and Cenozoic cover that overlies the Marathon Uplift (Figure 1). Right-lateral Late Paleozoic motion on the Devil's River Uplift or fault system (Figure 1) produced the apparent offset between the Ouachita and Marathon belts [Muehberger, 1965]. Marathon folding and thrusting occurred during Late Pennsylvanian to early Permian time, culminating in the Wolfcampian [King, 1977], and thus the final Marathon deformation postdates the final Ouachita deformation by perhaps 15-20 million years.

Huastecan system. South of the Marathons it is difficult to trace the continuation of the Hercynian deformation belt with confidence. There is, however, a somewhat disrupted trend of Paleozoic rocks that continues to the south in eastern Mexico (Figure 1) known as the Huastecan Structural Belt [de Cserna, 1976], which enjoyed Late Paleozoic folding and westward migrating thrusting similar to that in the Marathon-Ouachita areas. These rocks range from early Paleozoic [de Cserna, 1971] to Late Paleozoic [Denison et al., 1970] age and contain ophiolite bodies (Figure 1) at Catorce, west of Ciudad Victoria, in the Tecomatlan area of Puebla, and north of Oaxaca City [de Cserna, 1976]. The Huastecan belt has been described as 'consisting of a sedimentary nonmetamorphosed external part or outer zone, and a metamorphosed internal part or inner zone...where in several localities the two parts are interposed, due to the allochthonous nature of the sequence or sequences' [de Cserna, 1976], probably by the Mid-Permian.

The present-day disrupted nature of the Huastecan belt probably resulted from Jurassic left-lateral motions upon several NW trending strike-slip faults through Mexico. This motion was at least partially responsible for the emplacement of Mexico into its 'overlap position' with South America, a problem that characterizes most circum-Atlantic continental reconstructions. Major left-lateral offset of Jurassic age has also occurred along the Texas Lineament (Figure 1) which sinistrally offsets the Huastecan Belt from the Marathon Belt by about 700 km. Motion along the Texas Lineament was probably responsible for most of Mexico's southeastward migration into the overlap position with South America, after North America had rifted from South America-Africa. Silver and Anderson [1974] proposed that a similar offset occurred across the Mohave-Sonoran Megashear. Exact offsets on the various faults are still uncertain, but it is clear that motions of this kind must have occurred if we are to accept most circum-Atlantic reconstructions of Pangea.

Sedimentary basins of the foreland. In south-central and southwestern North America, in the foreland of the main zones of Hercynian thrusting, basin development was extensive. The basins are of two general types; some formed as a result of transtensional strike-slip (pull-apart basins), while others are clearly foreland trough or foredeep-type basins, which were partially overridden by, and included in, Hercynian thrusting. Pull-apart basins include the Anadarko, Palo Duro, Central Colorado Trough, Rowe-Mora, Oquirrh, Paradox, Orogrande,
Pedregosa, Delaware, and Midland basins (although many of the basins have been modified by thrusting); and foreland troughs include the Appalachian, Black Warrior, Arkoma, Fort Worth, Kerr, Val Verde, and Marfa basins (Figure 1). The 'sedimentary nonmetamorphosed external zone' of the Huastecan Belt [de Cserna, 1976] includes Permian sediments that were probably deposited in foreland troughs. Pull-apart basins in Mexico are poorly known, although Permian deposits in the Chihuaha Trough (Figure 1) [Gries, 1979] may indicate an early episode of right-lateral transtensional motion of the Texas Lineament. Kluth and Coney [1981] equate the development of the pull-apart basins and associated strike-slip activity to foreland deformation as southern North America underwent collision with South America-Africa. Several west to northwest trending strike-slip faults formed in response to the stress field created by the collision, and some of these reactivated older crustal structures (for example, the South Oklahoma and Tabosa aulacogens), which were related to the Late Precambrian-Early Paleozoic rifting event of eastern North America [Hoffman et al., 1974; Stewart, 1976].

Time-stratigraphic analysis of the foredeep basins and the pull-apart basins indicates an east to west migration of Hercynian thrusting and foreland deformation from Late Mississippian to Early Permian time, indicating oblique collision and progression of suturing toward the southwest [Graham et al., 1975; Kluth and Coney, 1981]. Most of the rift-type basins show minor early deposition beginning in the Late Mississippian coeval with the beginning of the Alleghanian Orogeny (Southern Appalachians). Many basins also show two periods of very rapid subsidence coeval with the climax of deformation in the Ouachita (Atokan-Desmoinesian) and Marathon (Wolfcampian) belts, separated and followed by periods of relatively slow subsidence. The Southern Appalachians, the Ouachita and the Marathon systems probably represent localized climaxes during the suturing process, when promontories in the opposing margins produced episodes of greater deformation, and thus episodic periods of intense foreland reactivation occurred synchronously with the individual collisional episodes. The alternating periods of fast and relatively slow subsidence rates can be related respectively to crustal stretching [McKenzie, 1978] and thermal subsidence.

**Summary of Hercynian deformation.** The Hercynian collision between North America and South America-Africa produced deformations, all of which suggest that subduction before collision was down to the east and/or south. North America served as the foreland during oblique continent-continent collision, and as a result suffered much foreland deformation. The major zones of Hercynian thrusting and the timing of the thrusting as evidenced by the youngest overthrust flysch in the foredeeps are outlined in Table 1.

**TABLE 1. Summary of Hercynian Deformation**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Time of Thrusting/Collision</th>
</tr>
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<tbody>
<tr>
<td>Southern Appalachians</td>
<td>began in Late Mississippian (Chesterian), continued into the Late Pennsylvanian</td>
</tr>
<tr>
<td>Ouachitas</td>
<td>Atokan to Desmoinesian</td>
</tr>
<tr>
<td>Marathons</td>
<td>Virgilian to Wolfcampian</td>
</tr>
<tr>
<td>Huastecans</td>
<td>Early to Middle Permian</td>
</tr>
</tbody>
</table>
Late Paleozoic Geology of Northern South America

As noted earlier, direct evidence to indicate the location of the suture zone(s) associated with the Hercynian collision between southern North America and South America-Africa is minimal. In the South American Andes from Colombia to at least as far south as northern Chile, pre-Upper Devonian igneous and sedimentary rocks show late Devonian uplift and deformation and are unconformably overlain by thick sequences of Carboniferous to Permian granodiorites, andesitic volcanics, and volcano-clastic sediments [Irving, 1975; Almeida, 1978]. In the Colombian Andes, volcanics related to this active arc form significant portions of the Cordillera Central, the Sierra de Santa Marta, and the Guajira Peninsula (see Figure 2). Deep water sediments of equivalent age flank and are interbedded with the andesites on the western shoulders of the three complexes. The three complexes appear as separate masses, but Tertiary strike-slip faulting has segmented the once continuous arc complex [Case and MacDonald, 1973]. To the east of the arc complex, Carboniferous to Permian black shales and limestones accumulated, probably in an environment similar to that of the Java Sea, a shallow basin overlying continental crust. During Permian time, the arc and related sediments underwent deformation with the most intense deformation occurring in the Central Cordillera, the Guajira Peninsula, and the Sierra Nevada de Santa Marta of Colombia [Almeida, 1978].

Paleomagnetic studies [Valencio and Vilas, 1976; Smith and Briden, 1977] and paleoclimatic studies [Ziegler et al., 1979] indicate that Permo-Carboniferous plate motion of South America (Gondwana) possessed a strong northward component. The presence of the Upper Paleozoic arc indicates subduction of oceanic crust beneath northwestern and western South America; the andesitic volcanics and granodiorites are interpreted as the arc complex that must have formed during the convergence between North and South America. Continental collision between the Colombian portion of the Andes and the Marathon-Huastecan segment of the North American foreland is indicated by synchronous deformation (Early

Fig. 2. Late Paleozoic terrains of northern South America. 1, Cordillera Central (arc); 2, Sierra Nevada de Santa Marta (arc); 3, Guajira Peninsula (arc); 4, Deformed granites and gneisses of Venezuela; 5, shallow water seaway behind Late Paleozoic Arc, similar to the Java Sea.
to Middle Permian) and the ceasing of arc-related volcanism in Colombia during Middle Permian time.

To the east of Guajira, Colombia, evidence for a well-developed Upper Paleozoic arc is largely lacking. In northern Venezuela, the most significant aspect of Upper Paleozoic geology is the presence of Pennsylvanian-Permian granitic intrusions and metamorphics. Whether the granitic intrusions are related to the arc in northwest Colombia or to simple heating of the crust due to thickening cannot be specified.

Extent of Pre-Mesozoic Continental Crust:
The Margins to be Fitted

For the purposes of the Permo-Triassic reconstruction, the islands of the Greater and Lesser Antilles, the Panama-Costa Rica isthmus, and the Bahamas Platform may be disregarded because they are all Jurassic or younger, developed during the course of Caribbean evolution. Pre-Mesozoic continental crust to be considered is limited to the continents of North and South America and Africa, and the blocks of Yucatan and Chortis. The basement of Mexico is probably best considered as a set of several blocks because of the deformation it underwent during emplacement into the 'overlap position' with South America in most circum-Atlantic reconstructions.

Northern limit of continental crust of South America. Complex post-Jurassic tectonic events have obscured and greatly modified the rifted margin of northern South America. Late Cretaceous collision with the Aruba-Blanquilla island arc [Gealy, 1980; Maresch, 1974] emplaced giant thrust sheets onto the Venezuelan margin. The arc is preserved offshore, and the suture apparently lies within the Bonaire Basin and continues into the Trinidad-Tobago area [Maxwell, 1948]. In western Colombia, Neogene collision with the Panama arc has led to accretion of significant amounts of deep water and oceanic material [Irving, 1975].

Development of the South Caribbean Plate Boundary Zone [Burke et al., 1978] during late Cenozoic time has greatly modified the morphology of the margin. Fortunately, no single onshore fault has been shown to have accumulated a large offset, and thus it is likely that much of the relative displacement between the Caribbean and South American plates has occurred along transform faults to the north of the island-arc chain.

Despite these modifications, Figure 3 approximately defines the limit of the Jurassic rifted margin. Precambrian and Paleozoic basement outcrops continuously along northern Colombia [Tschanz et al., 1974; MacDonald, 1965], and it is inferred that basement extends offshore to the continental shelf break. In central and southern Colombia, the edge of the Early Mesozoic basement was approximately defined by the western margin of the Cordillera Central arc [Irving, 1975]. In the north, from Peninsula de Paraguauna to the Cariaco Basin, the Jurassic basement limit probably closely approximates the suture zone of the Late Cretaceous arc-continent collision. To the east of the Cariaco Basin, basement is difficult to define. Much of the sediment of the Paria and Trinidad area has been accreted to the continent in the Late Cretaceous, and high rates of sediment influx from the Orinoco River have produced a massive delta, beneath which lies oceanic and/or attenuated continental crust.

It is speculated that the Jurassic limit of basement lies slightly inland of these areas (Figure 3). Continuing to the southeast, the limit again returns offshore to the continental margin.

Southern limit of continental crust of North America. Whether the basement of the Gulf Coastal Plains south of the Ouachita-Marathon belts is comprised of continental or oceanic basement has been heavily debated (see Cebull and Shurbet [1980] for a review). The presence of more than 15 km of post-Triassic sediments within the Gulf Coast 'Geosyncline' [Antoine et al., 1974] dictates that if continental crust is present, it is extremely attenuated. It has also been suggested that oceanic crust
of Paleozoic age is present beneath the coastal plains [Cebull and Shurbet, 1980], a position, however, that fails to explain adequately the intensely thrusted Ouachita-Marathon belt to the north. Late Paleozoic continental suturing followed by Jurassic rifting is the most satisfactory explanation for the observed geology. Whether the coastal plain basement is oceanic (Jurassic) or highly attenuated continental crust is a trivial matter; either means that the original limit of continental crust lay well inland of the present-day coastline. The position adopted here is that the pre-rift limit of continental crust of southern North America falls between the northern limit of the Louann Salt and the Cretaceous reef trend to the south (Figure 4). Structural highs such as the Sabine Uplift and the Wiggins arch in the rifted margin are considered to be stranded horsts separated from the mainland by marginal grabens.

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Fig. 3. Northern limit of continental crust of South America in Jurassic times. 1, Cordillera Central; 2, Santa Marta; 3, Guajira; 4, Basement of Panama arc (Late Cretaceous-Tertiary); 5, Paraguana; 6, Bonaire Basin (Tertiary); 7, Cariaco Basin (Tertiary); 8, Trinidad-Paria area.

Fig. 4. Limit of continental crust along the Gulf margin of the United States.
In southernmost Florida (Figure 4), Klitgord et al. [1982] show that pre-Mesozoic crust is absent and that Lower Cretaceous isopachs indicate a sharply rifted margin, probably attributable to transform faulting rather than to extension rifting. The transforms (Sunniland and Bahama) were probably very long, connecting the ridge system of the Atlantic Ocean to that in the Gulf of Mexico.

In eastern Mexico, continental crust seems to exist very near the present coastline. However, considerable left-lateral syn- or post-rifting offset may have occurred upon the Texas Lineament so that, in northeastern Mexico, there exists an extensive embayment of salts, clastics, and marine deposits (Figure 4).

The Yucatan Block

Although the Yucatan Block (Figure 5) is of limited geographic extent, it contains critical information for Gulf and Caribbean evolution, comprising six stages of development as follows: (1) Devonian uplift, deformation, and metamorphism along the southern portion of the block (present coordinates); (2) Late Paleozoic Andean-type arc volcanism along the southern border of the block (Central Guatemalan arc); (3) Middle Jurassic rifting that produced a highly stretched rifted margin along the northern and western margins; (4) Late Cretaceous collision with Nicaragua Rise-Jamaica, with Yucatan acting as the foreland; (5) Late Cretaceous-Paleocene uplift, erosion, and subsequent block-faulting along the entire eastern margin; and (6) considerable left-lateral offset between the Yucatan and Chortis Blocks since Oligocene time that has produced a complex plate boundary zone between the two. The Devonian deformational episode [McBirney and Bass, 1969] is based on isotopic ages of Late Devonian age from the Chuacus Group, which is unconformably
overlain by Carboniferous strata. A late Paleozoic Andean arc is inferred from stratigraphic descriptions from Central Guatemala (see Figure 6 for a summary). The Late Paleozoic evolution of southern Yucatan is strikingly similar to that of the Cordillera of western South America, where Devonian uplift was followed also by the arc-related magmatic activity. It is suggested that the two may be correlated and that the Central Guatemalan arc was a northern, westward-facing extension of the Andean arc during Mid to Late Paleozoic time. The only significant difference between the two terrains is that volcanism apparently ceased during Pennsylvanian time in Yucatan, whereas it continued into the Permian in the Andean Cordillera. Seismic and drilling data [Buffler et al., 1980, 1981] indicate that the Gulf of Mexico was formed by the separation of the Yucatan Block from the southern margin of the United States in Middle to Late Jurassic.

<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td>Todos Santos Red Beds</td>
<td>Rifting, subsidence</td>
</tr>
<tr>
<td>Triassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oligocene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td></td>
<td></td>
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<tr>
<td>Cenozoic</td>
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</tbody>
</table>

Fig. 6. Stratigraphic column and tectonic interpretation of the Late Paleozoic section of central Guatemala, Yucatan Block. The proposed arc is represented by the Chicol Formation. After Anderson (1969), Anderson et al. (1973), and Mc Birney and Bass (1969).
time. However, the opposing rifted margins are so highly attenuated that an accurate location of the ocean-continent transition cannot readily be made. Both margins contain a thick evaporitic section, indicating the existence of a restricted basin along the site of the developing rift. While geological data from the Gulf of Mexico are sufficient to substantiate a Jurassic origin by rifting between Yucatan and North America, flow lines and the pre-rift alignment of the margins cannot yet be proven. First, much of the opening of the Gulf probably occurred during the Jurassic quiet zone, and thus no magnetic anomalies may exist. Second, considerable down-slope migration of the salt section [Antoine et al., 1974] has distorted its original geographic extent. Third, the thick post-Triassic carbonate and evaporite section (1-4 km) across the entire Yucatan Platform indicates that the Yucatan basement was significantly stretched during the rifting episode; the original extent of the block may have been 10-20% smaller.

In the Ouachita system, deformation and thrusting culminated in early Desmoinesian time. To obtain a closed ocean fit between North and South America, continental mass must have been present between Venezuela and the Ouachitas. It is suggested that the Yucatan Block occupied this position on the basis of (1) the correlation of Jurassic aged salt sequences known from the northwestern margin of Yucatan and the southern margin of the United States, (2) the nearly identical pre-rift geometries of the Yucatan Block and the unclosed 'hole' between the margins of North America and Venezuela, (3) the presumption that the Central Guatemalan arc formed a northern, westward-facing extension of the Upper Paleozoic Andean Cordillera, and (4) the equivalent ages of thrusting in the Ouachitas and the termination of volcanism in the Central Guatemalan arc of Yucatan.

The Chortis Block

Little is known of the pre-Mesozoic basement of the Chortis Block but its extent is roughly defined by the Motagua-Swan transform fault on the north and the Santa Elena Peridotite on the south (Figure 7).

A thick accretionary pile has accumulated along the western margin as a result of slightly extensional Tertiary subduction at the Middle Amer-
ica Trench. The Nicaragua Depression [Muehlberger, 1976] (Figure 7) is the site of normal faulting and active arc-related vulcanism. The western margin of the Paleozoic basement is roughly coincident with the eastern boundary of the Nicaraguan Depression. To the east of the block lies the Nicaragua Rise, a submarine western extension of the southern Greater Antilles. Delineation of a precise boundary separating the Chortis continental basement from the Antillean arc-related basement is probably not possible, but block-faulting in the basement beneath the 100-fm contour east of Nicaragua (Figure 7) suggests a possible eastern limit of basement; the 100-fm contour is assumed to mark the extent of Paleozoic basement along the Nicaragua Rise.

The African Connection

The most valid criterion for obtaining a fit between opposing rifted margins is the realignment of marginal offsets because they are a direct result of intracontinental rifting [LePichon and Fox, 1971; Klitgord and Schouten, 1980]. If we assume (1) tortional rigidity for the circum-Atlantic continents and (2) that the Bullard fit for the South Atlantic is valid, proper correlation of the Late Paleozoic features between North and South America cannot be achieved. Two solutions are plausible: (1) that right-lateral strike-slip motion occurred between Africa and eastern North America after the Late Paleozoic orogeny to approximate the LePichon and Fox configuration before middle Jurassic rifting, so that formation of much of the Gulf of Mexico predates the Atlantic Ocean (following Van der Voo and French [1974]), or (2) that Africa was not a torsionally rigid single plate during Cretaceous times [Burke and Dewey, 1974] so that the Bullard fit in the South Atlantic may be improved by closing an apparently noncontinental gap along the Amazon section of the South American shelf. The second solution allows excellent correlation of Late Paleozoic features between North and South America without any pre-rift differential motion between Africa and North America; this alternative is favored here and is discussed in detail below.

Two Plates in Africa and the Revised South Atlantic Fit

The most commonly accepted South Atlantic fit is that of Bullard et al., [1965], which is further supported by alignment of marginal fracture zones [LePichon and Hayes, 1971]. However, this fit assumes that continental material underlies the entire Amazon portion of the South American shelf. The enormous thickness of post-rifting sediments (Figure 8a) beneath most of that portion of the shelf (8-10 km, Kumar et al., [1979]) indicates that only oceanic or extremely thinned continental crust can be present there. Thus the Bullard fit apparently leaves a substantial gap (Figure 8b) between the northern Brazilian and Guinean margins. In light of the fact that Gondwana was one of the most stable cratonic masses of the Phanerozoic until the Cretaceous, the existence of this gap during Late Paleozoic to Cretaceous time is highly unlikely, and thus the Bullard fit probably can be improved. It is apparent that a satisfactory fit for the South Atlantic cannot be made if torsional rigidity is assumed; rotation of Africa with respect to South America to close the Amazon gap produces a gap in the southern South Atlantic.

Rabinowitz and Labrecque [1979] noted that the rifting history of the South Atlantic was such that rifting occurred earlier in the southern South Atlantic (150 Ma) than in the equatorial Atlantic (anomaly MO, which is 110 Ma, after Van Hinte [1979a]). Starting from an initial fit similar to that of Bullard et al. [1965], they attributed this to a counterclockwise rotation of the whole African continent with respect to South America from 150 Ma to MO (110 Ma) about a pole just off the
northeast coastline of Brazil. This rotation requires that 100 km of shortening and compression occurred between the Ivory Coast section of Africa and northernmost Brazil for the period 130-110 Ma. Although minor compression probably associated with imperfect transform motion during the opening phase of the equatorial Atlantic is known from beneath the Demerara Plateau [Hayes et al., 1972], evidence for major shortening (100 km) has not been documented. Of great importance, though, is that the postrotational configuration (110 Ma) of the equatorial portions of South America and Africa fills the Amazon gap of Figure 8b in the Bullard fit. Further, 110 Ma has been suggested as the time of initial rifting in the equatorial Atlantic [Kumar et al., 1976; Asmus and Ponte, 1973; Rabinowitz and Labrecque, 1979]. These considerations lead to the conclusion that the MO configuration of Rabinowitz and Labrecque [1979] closely approximates the Early Mesozoic configuration as well, but that their (130-110 Ma) rotation of northern Africa with respect to South America did not occur. Thus we can dispose of the Amazon gap of Bullard et al. [1965]. However, satisfactory closure of the entire South Atlantic Ocean cannot be achieved by assuming perfectly rigid plates; post-Jurassic internal deformation must have occurred within Africa and/or South America.
Although Grabert [1977] reported Late Jurassic faulting and minor strike-slip motion in the upper Amazon Valley of South America, large-scale post-Jurassic deformation of this continent is not supported by geological or geophysical evidence. By contrast, intense internal deformation in central Africa of Cretaceous age is abundant. Burke and Dewey [1974] called attention to widespread basaltic magmatism and block-faulting across central and northern Africa (summarized in Figure 9) that they consider to have been a poorly defined plate boundary zone of net differential motion between northwest and southeast Africa. The only narrow plate boundary within this system may have developed in the Benue Trough, whose stratigraphic column is shown in Figure 9. The amount of early Cretaceous extension and late Cretaceous shortening that occurred cannot be defined. Any relative motions between northwest and southeast Africa that may have led to differences in spreading rates along the early South Atlantic ridge cannot be observed because most of the Benue episode occurred during the Cretaceous quiet period. All that can be said of the Benue episode (and its extensions into central and northern Africa) is that the amount of extension exceeded the amount of closure; this is indicated by a pronounced positive gravity anomaly and the subdued, trough-like character of the underlying basement. Therefore, it is inferred that 'remnant extension' exists today which did not exist before Early Cretaceous time, and that the present-day shape of Africa should not be used in pre-Cretaceous paleoreconstructions.

The net effect of the Cretaceous deformation cannot be determined from African geology, but it is suggested here that the net deformation is equivalent to the difference between Africa's present shape and the shape that is required to produce a fit with South America closed in both the Amazon and southern South Atlantic regions. Figure 10 shows this closed fit and compares the predeformational and postdeformational shapes of the African continent. Marginal fracture zones commonly used for matching the opposing margins in the southern South Atlantic are also shown in Figure 10, showing clearly that the proposed predrift reconstruction satisfies the fracture zone alignment criterion.

A pole of rotation that defines the early motion of southeastern Africa with respect to northwestern Africa-South America must satisfy fracture zone trends and magnetic anomalies associated with the early
opening phase of the southern South Atlantic Ocean (M11-MO, or 125-110 Ma). The pole used by Rabinowitz and LaBrecque [1979] lies at 2.5⁰S, 45.0⁰W with an angular rotation of +11.0⁰, all with respect to South America. This rotation is based upon alignment of the ocean/continent boundaries, the seaward edge of salt boundaries and the trend of marginal fracture zones, particularly the Agulhas-Falkland fracture zone. We propose an additional constraint that requires minor adjustment of the pole position and angular rotation of Rabinowitz and LaBrecque [1979]; the early South Atlantic pole must be located so that the left-lateral motion across the Benue Trough be accompanied by an extensional component to account for the rift-like nature of the trough. This requires that the pole be located at a more northerly position and, according to J. LaBrecque (personal communication, 1981), the play in the data allows northward adjustment. The pole suggested here that seems to satisfy all constraining data lies at 19⁰N, 2⁰E with respect to present-day Africa (Figure 10), with an angular rotation of about 8⁰. It is assumed here that Africa had attained approximately its present shape by 110 Ma. Any further opening in the Benue area followed by significant closure cannot be recognized from ocean data because of the Cretaceous quiet period from 110 Ma to 80 Ma. Thus Africa is regarded as a rigid plate after 110 Ma in the proposed South Atlantic opening data (Table 3).
Reconstruction of Western Pangea

Figure 11 depicts the pre-rift relationship of the circum-Atlantic continents and Central American blocks following the considerations and constraints presented in this paper. It is suggested that this configuration existed from Middle Permian to Middle Jurassic time with little tectonic activity or relative motions between the individual constituents. The excellent fit was achieved by a gradual oblique closing of an ocean with subduction to the south and east, whereby deformation external to the plate boundary zones (particularly the North American foreland) accommodated salients with complex strike-slip motions of crustal segments. The southwest peninsular extension of North America (Mexico) probably migrated an unknown but considerable distance toward the northwest during the collision, possibly allowed by 'free face' overriding of plates in the Pacific.

Paleomagnetic data for Permian rocks of the circum-Atlantic continents [Van der Voo and French, 1974] are satisfied by the proposed reconstruction. South America and southern Africa are in approximately the same position as that suggested by Van der Voo and French [1974], which is based on paleomagnetic data.

EVOLUTION OF THE GULF OF MEXICO/CARIBBEAN REGION

Relative Motion History of the Major Continents

The following data sources are used to define the poles and rotations for the opening histories of the Central and South Atlantic oceans, and these in turn have been used to compute the relative motion history of South America with respect to North America.

Africa with respect to North America. In the Central Atlantic the poles and rotations of Sclater et al. [1977] were used and are summarized in Table 2. These poles are based on LePichon and Fox [1971] for 165-80 Ma, and on Francheteau [1973] for 80 Ma to the present. Fol-
TABLE 2. Relative Motion Poles, Africa With Respect to North America

<table>
<thead>
<tr>
<th>Time Ma</th>
<th>Magnetic Anomaly</th>
<th>Finite Difference</th>
<th>Stage Poles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude, Longitude, Angle, deg.</td>
<td>Latitude, Longitude, Angle, deg.</td>
</tr>
<tr>
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<td>55.9, -17.3, 11.3</td>
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<tr>
<td>150</td>
<td>interpolated</td>
<td>67.8, -13.8, -63.7</td>
<td>57.9, -21.7, 5.4</td>
</tr>
<tr>
<td>140</td>
<td>M-22</td>
<td>68.8, -14.2, -58.4</td>
<td>60.9, -29.5, 7.2</td>
</tr>
<tr>
<td>125</td>
<td>M-6</td>
<td>70.2, -12.9, -51.3</td>
<td>58.1, -22.0, 7.2</td>
</tr>
<tr>
<td>110</td>
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<td>58.4, -21.9, 7.3</td>
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<tr>
<td>95</td>
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<td>75.1, -14.0, -37.3</td>
<td>58.5, -21.7, 7.3</td>
</tr>
<tr>
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<td>82.9, 153.7, 9.9</td>
</tr>
<tr>
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<td>70.9, -10.9, -21.2</td>
<td>70.3, -3.8, 4.8</td>
</tr>
<tr>
<td>53</td>
<td>22</td>
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</tr>
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</tr>
<tr>
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<td>6</td>
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<td>5</td>
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</tr>
<tr>
<td>0</td>
<td>...</td>
<td>...</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Following Sclater et al. [1977], the time scales of Sclater et al. [1974] and Van Hinte [1976a,b] are used for the Cenozoic and Mesozoic, respectively.

South America with respect to Africa. In the South Atlantic, because the Bullard et al. [1965] initial fit is not employed, several data sources are used. The initial Jurassic fit is that of Rabinowitz and LaBrecque [1979] for the time of anomaly MO (110 Ma). The additional rotation of the 'southern plate' of Africa which is required to close the southern South Atlantic Ocean is defined in this study and occurred from the Valanginian (125 Ma) to 110 Ma. The motion of South America with respect to Africa during the interval 110-80 Ma (Cretaceous Quiet Zone) is that of Rabinowitz and LaBrecque [1979], whose 80 Ma position is taken from Ladd [1974, 1976]. From 80 Ma to present, the poles and rotations of Sibuet and Mascle [1978] are used. They too have taken Ladd's [1974, 1976] 80 Ma position of South America with respect to Africa and have recognized one minor change in spreading history at 36 Ma (anomaly 13). This provides additional control over the analysis of Sclater et al. [1977] for the South Atlantic, who assume a single pole from 80 Ma to present, after Francheteau [1973]. Table 3 summarizes poles and rotations used in this study for the opening of the South Atlantic.

South America with respect to North America. Using the finite difference method, relative motion poles of South America with respect
TABLE 3. Relative Motion Poles, South America with Respect to Africa

<table>
<thead>
<tr>
<th>Time Ma</th>
<th>Magnetic Anomaly</th>
<th>Finite Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude, deg.</td>
</tr>
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</tr>
<tr>
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<td>interpolated</td>
<td>58.3</td>
</tr>
<tr>
<td>80</td>
<td>34</td>
<td>63.0</td>
</tr>
<tr>
<td>65</td>
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<td>53</td>
<td>22</td>
<td>60.8</td>
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<td>interpolated</td>
<td>57.4</td>
</tr>
<tr>
<td>0</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Relative motion vectors (Figure 12) have been plotted (equal angular rotations). The relative motion vectors are plotted with respect to present-day North American coordinates and provide the framework for the evolutionary model of the Gulf of Mexico/Caribbean region.

Plate Boundary Reconstructions, 165 Ma to the Present

Figures 13-25 are a set of 13 plate tectonic reconstructions that outline the proposed model of Gulf and Caribbean evolution since the middle Jurassic breakup of Pangea. Each reconstruction depicts a plate boundary system that appears to satisfy Gulf/Caribbean geology for the period ranging from the age of that to the subsequent reconstruction. Major geologic features incorporated into the model are shown throughout the sequence. Where appropriate, instantaneous vector triangles are shown, as well as arrows defining the motions of Africa and South America with respect to North America for the time period following a particular figure. The orientations of extensional and transform plate boundaries are defined in this way. Note that the relative motions between the 36 Ma, 21 Ma, 10 Ma, and 0 Ma reconstructions are so small, although generally compressional, that a well-defined plate boundary between North and South America may not have existed during these periods.

165 Ma. Throughout Late Triassic to Middle Jurassic time, a widespread belt of doming and rifting formed within Pangea that closely followed the line of Hercynian suturing. By 165 Ma, a discrete plate boundary system had formed and plate accretion had begun. Figure 13 shows a plate boundary system that may have been responsible for the breakup of Pangea with some of the major failed rifts. The geometry of the spreading system in the Central Atlantic is that defined by Klitgord...
et al. [1982]; that surrounding the Yucatan block (Y) is poorly constrained, although a system similar to that shown is required to move Yucatan to its present position. The Chortis block (C) is viewed as a southern extension of Mexico. Extensional left-lateral motion along the Chihuahua Trough (CT) and Texas Lineament allowed southeastward migration of Mexico into its 'overlap position,' which was occupied by South America during the early Mesozoic.

150 Ma. Spreading between North America and Gondwana continued; by 150 Ma, a ridge jump had occurred in the Central Atlantic that is responsible for the apparent asymmetry of the Atlantic Ocean with respect to its ridge. Rotation of Yucatan with respect to South America is considered analogous to the early Cretaceous motion of Iberia with respect to Africa; the formation of the Bay of Biscay, then, can be compared to that of the Gulf of Mexico. The rifting of Yucatan from North America left stranded horsts such as the Sabine Uplift (S) and Wiggins Arch (W) along southern North America. Louann salts (small cross patterns) were deposited around these structures and along the north-facing rifted margin of Yucatan in the restricted seaway between Yucatan and North America. Salts of Jurassic and Early Cretaceous age are found in the Chihuahua Trough [Gries, 1979] indicating extension and subsidence of that age along this feature. Left-lateral motion on other faults in Mexico [de Czerna, 1976] was responsible for the completion of Mexico's emplacement into the 'overlap position' probably by 140 Ma.

<table>
<thead>
<tr>
<th>Time Ma</th>
<th>Magnetic Anomaly</th>
<th>Finite Difference</th>
<th>Stage Poles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude, Longitude, Angle</td>
<td>Latitude, Longitude, Angle</td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>... 52.1</td>
<td>37.6 -28.8</td>
<td>55.9 -17.3 11.3</td>
</tr>
<tr>
<td>150</td>
<td>... 45.2</td>
<td>61.6 -20.1</td>
<td>57.9 -21.7 5.4</td>
</tr>
<tr>
<td>140</td>
<td>... 35.9</td>
<td>75.5 -17.1</td>
<td>60.9 -29.5 7.2</td>
</tr>
<tr>
<td>125</td>
<td>... 15.4</td>
<td>91.8 -15.6</td>
<td>58.1 -22.0 7.2</td>
</tr>
<tr>
<td>110</td>
<td>... 5.0</td>
<td>-73.5 17.0</td>
<td>5.2  -92.7 -3.6</td>
</tr>
<tr>
<td>95</td>
<td>... 4.1</td>
<td>-68.5 13.6</td>
<td>2.4  -85.3 -3.8</td>
</tr>
<tr>
<td>80</td>
<td>... 3.9</td>
<td>-62.1 10.0</td>
<td>41.9 138.7  4.8</td>
</tr>
<tr>
<td>65</td>
<td>... 30.6</td>
<td>-70.3  7.8</td>
<td>28.2  -98.9 -1.4</td>
</tr>
<tr>
<td>53</td>
<td>... 30.0</td>
<td>-64.6  6.6</td>
<td>43.5  -81.1 -2.5</td>
</tr>
<tr>
<td>36</td>
<td>... 21.1</td>
<td>-57.7  4.3</td>
<td>11.1  -63.3 -1.5</td>
</tr>
<tr>
<td>21</td>
<td>... 26.4</td>
<td>-54.1  2.8</td>
<td>26.5  -55.1 -1.5</td>
</tr>
<tr>
<td>10</td>
<td>... 26.2</td>
<td>-52.9  1.3</td>
<td>23.8  -54.2 -0.6</td>
</tr>
<tr>
<td>5</td>
<td>... 28.2</td>
<td>-51.7  0.7</td>
<td>28.2  -51.7 -0.7</td>
</tr>
<tr>
<td>0</td>
<td>...  ...</td>
<td>...  0.0</td>
<td>...  ...  ...</td>
</tr>
</tbody>
</table>
In the Bahamas area (B), the probable existence of a long transform provides a situation in which compression and extension are likely during subtle changes in relative motion. The parallel relationship of the Bahamas with Atlantic fracture zones nearby to the north supports the hypothesis that compressional transform motion caused uplift of oceanic basement to the photic zone so that carbonate deposition could be initiated.

140 Ma. By about 140 Ma, formation of the Gulf of Mexico is considered complete. The rotation of Yucatan and the eastward migration of the Mexican blocks led to juxtaposition of Yucatan and southern Mexico in the Tehuantepec area. The juxtaposition was probably achieved mainly by strike-slip, although some amount of compression may have occurred. Present knowledge of the geology of the Tehuantepec area is too obscure to obtain a clear understanding of this event.

Klitgord et al. [1982] have mapped fracture zones just north of the Bahamas that have a consistent kink such that left-lateral motion upon a transform fault of the ridge system would enter compression around 140 Ma. We suggest that the minor pole change associated with this kink was substantial enough to raise oceanic crust adjacent to the long transform in the Bahamas area to the photic zone. Since then, carbonate deposition has kept pace with subsidence, which occurred at rates several times greater than thermal rates during the remainder of the early Cretaceous.

125 Ma. Continued spreading between North America and Gondwana produced an oceanic seaway between North and South America into which crust of Pacific provenance was able to enter. This was accomplished by initiation of southward dipping subduction at a previously formed Atlantic fracture zone (zone of weakened crust). Proto-Caribbean crust was subducted beneath Pacific crust as the Pacific crust entered the Caribbean area. Northern and southern portions of Pacific crust were subducted beneath the Andean margins of North and South America, respectively. Volcanics that were formed along the leading edge of the entering Pacific crust would become the Greater Antilles Island Arc.

At 125 Ma, the southern South Atlantic began to open by eastward migration of southeast Africa with respect to South America/northwest...
Fig. 13. Paleoreconstruction at 165 Ma.

Africa; this, however, had no effect on the Caribbean area because we are assuming no significant motion in the Equatorial Atlantic until 110 Ma, although doming and initial phases of rifting had begun.

110 Ma. At 110 Ma, separation between South America and northwest Africa began, thus producing a three-plate system. The independent motion of South America requires a new orientation for the ridge between North and South America. It is suggested that the ridge jumped from its Bahamian position to that shown in Figure 17; at 80 Ma, this new ridge position would become the site of a northward dipping subduction zone (Venezuelan Antilles). The Greater Antilles Arc (GA) continued its migration toward the Yucatan and Bahamas platforms.

95 Ma. At 95 Ma, opening of the Equatorial Atlantic continued and the Greater Antilles Arc migrated farther into the North-South American gap consuming the Proto-Caribbean ridge system continuously.

Fig. 14. Paleoreconstruction at 150 Ma.
80 Ma. The Late Cretaceous was a time of great complexity. The western portion of the Greater Antilles Arc, which would become the Nicaragua Rise and Jamaica, collided with the Yucatan block sending thrust sheets northward onto the shelf bank of southern Yucatan [Donnelly, 1977]. Remnants of rocks involved in this collision are seen today in the Motagua Suture Zone (msz). The eastern remainder of the arc continued to migrate northwards, with much internal deformation (Wagwater and Montpellier-Newmarket Troughs), toward the Bahamas Platform. Volcaniclastic, flysch-like sequences of Late Cretaceous age in southern Haiti [F. Maurrasse, personal communication, 1982] may have originated at the Jamaica-Yucatan orogenic zone.

Because of a major change in the relative motion of South America with respect to North America, the plate boundary between the two became compressional and thus plate convergence was initiated. The former ridge became the site of a north dipping subduction zone whose associated andesitic volcanism formed the Netherlands-Venezuelan Antilles Arc (nva). Subduction of oceanic crust of the South America Plate led to arc-continent collision at the end of the Cretaceous [Gealey, 1980].

The dashed lines of Figure 19 indicate that these features, apparently, did not become active until later in the 80 Ma to 65 Ma interval. Initiation of subduction of Pacific crust beneath the Panama-Costa Rica
Arc (p-cr) [Galli-Oliver, 1979] and motion on the Hess Escarpment (h.e.) occurred during this interval. These features apparently formed in oceanic crust that was affected by the widespread B'' volcanic event during early Late Cretaceous time [Burke et al., 1978]. Apparent B'' occurrences at Nicoya [Schmidt-Effing, 1979] and within the Caribbean Sea indicate that the Caribbean has a deep, plateau-type crust.

As the leading edge of the Caribbean Plate migrated north of the North America-South America plate boundary, a new plate boundary was formed that would become the site of subduction whose volcanism would
form the calc-alkaline rocks of the Aves Ridge (ar) in latest Cretaceous-early Tertiary time.

At about 65 Ma, arc-continent collision occurred between South America and the Venezuelan Antilles. The subsequent relative motion between North and South America from 65 to 53 Ma had a slightly extensional component and it is suggested that early Eocene rifting (Bonaire, Maracaibo-Falcon) in northern South America are related to this minor extensional phase.

In the Greater Antilles, continued northward migration was complex.
The Yucatan Basin (yb) was formed by back-arc spreading between Cuba (frontal arc) and the southern Hispaniola block (remnant arc) from latest Cretaceous to middle Eocene times [Gealey, 1980]. Age-depth relationships of the Yucatan Basin floor indicate an age within the early Eocene-Paleocene interval, and grabens of southern Cuba which are probably associated with the extensional event are filled with Paleocene-Lower Eocene basalts and clastics [Iturralde-Vinent, 1978]. Uplift and erosion along the eastern Yucatan Peninsula in Paleocene time [Weidie et al., 1980] are interpreted as a result of strike-slip passage of the frontal arc (Cuba). Thus Cuba migrated toward eventual collision with the Bahamas Platform by the formation of a back-arc basin behind it.

To the east, the remainder of the Greater Antilles migrated toward the Bahamas in a different fashion. Motion along the Hess Escarpment (h.e.) severed the southern portion of the arc and allowed northward migration at a rate similar to the rate of spreading in the Yucatan
Thus the Hess Escarpment was connected to the Yucatan Basin ridge system, in the Cauto Basin of Cuba (cb), and to the trench associated with the Panama-Costa Rica Arc. The motion on the Hess Escarpment also allowed juxtaposition of the Panama-Costa Rica Arc with the Chortis block; the suture between the two is defined by the Santa-Elena Peridotite [deBoer, 1979].

53 Ma. In about middle Eocene time, the Greater Antilles collided with the Bahamas Platform [Gealey, 1980]. Eocene migration of rodents from North America to South America [C. Woods, personal communication, 1982] may have been achieved via the Bahamas/Greater Antilles-Aves Ridge connection. In the Greater Antilles, carbonate deposition accompanied general subsidence and tectonic quiescence throughout the remainder of the Eocene. Similarly, subduction at the Aves Ridge effectively ceased as the Caribbean Plate moved very little with respect to the North American Plate. Motion between the North and South American plates, although minor, was approximately strike-slip and probably occurred along the northern South American borderland.
36 Ma. At 36 Ma, eastward migration of the Caribbean Plate with respect to North and South America began and was accompanied by development of the North and South Caribbean Plate Boundary Zones [Burke et al., 1978, 1980]. In a mantle reference frame, westward migration of North and South America probably has exceeded eastward migration of the Caribbean Plate. For simplicity and because the relative motion between North and South America since 36 Ma is very minor, the motions of the Caribbean Plate are described in terms of North and South America reference frames.

Post-Eocene tectonics in the Greater Antilles have been complex, involving large scale strike-slip and associated basin and thrust development (transtension and transpression). Spreading began at the Cayman spreading center and transform motion has occurred predominantly along the Motagua-Swan-Oriente fault system. Estimates of the length of the Cayman Trough indicate that about 1200 km of strike-slip has occurred between the North American and Caribbean plates. This figure is a minimum, owing to the fact that many smaller scale strike-slip faults in Jamaica and southern Hispaniola have undergone motion of the same sense. The Oriente fault apparently developed within the remnant arc of the Greater Antilles, thereby separating the Cayman Ridge and Oriente Province of Cuba from southern Hispaniola and central Hispaniola. One result of the Oligocene to present strike-slip phase has been the juxtaposition of at least three blocks that comprise the island of Hispaniola. Figure 22 shows one major splay of the fault system passing between the central and northern blocks of Hispaniola, which today are separated by the Cibao Valley. The Tabera Basin in the southern Cibao has recently been interpreted as an Oligocene aged pull-apart basin associated with early eastward migration of the Caribbean Plate (J. C. Cooper, M.S. thesis in preparation). Another feature in this area probably associated with the transform motion is the uplift of serpentine slivers along the northern flank of the Cordillera Central. The timing of relative motion between central and southern Hispaniola remains unclear, although basalts interbedded with Oligocene (?) limestones in the Sierra Neiba [F. Maurrasse, personal communication, 1982] may be related to strike-slip motions in this area at that time as well.

In the east, renewed subduction of Atlantic crust beneath the Caribbean Plate led to development of the Lesser Antilles Arc (1a). It is suggested that a temporary lull in subduction or perhaps back-arc spreading from 53 to 36 Ma is responsible for the eastward migration of
the volcanic axis along the eastern Caribbean Plate boundary. In the south, a large portion of the Caribbean Plate was subducted beneath Colombia/Ecuador throughout the latter part of the Tertiary. The fact that the Netherlands-Venezuelan Antilles arc has not been greatly separated from the Villa de Cura basement thrust which was obducted onto northern South America [Gealey, 1980] indicates that most of the Caribbean-South American plate offset has occurred to the north of the island chain. The complex South Caribbean Plate Boundary Zone has developed due to the shear couple created at the primary strike-slip interface. Thus, plate boundary zone related deformation swept eastward across Venezuela, having begun earlier in western Venezuela than in eastern Venezuela.

21 Ma. Eastward migration of the Caribbean Plate continued. The Lesser Antilles overrode Atlantic oceanic crust so that magnetic data pertaining to relative motions between North and South America were destroyed. Motion between central and southern Hispaniola had definitely begun by this time [J. C. Cooper, M.S. thesis, in preparation].

10 Ma. Continued eastward migration consumed more Atlantic crust, juxtaposed the three masses of Hispaniola via compressional strike-slip motion along the flanks of the Cibao and San Juan/Enriquillo Valleys, and led to arc-continent collision between Panama and northwest Colombia in late Miocene or early Pliocene time, which led to the uplift of the three cordilleras of Colombia [Irving, 1975]. Numerous pull-apart basins within the North and South Caribbean Plate Boundary Zones formed in Late Miocene time due to imperfect strike-slip motion on many minor faults. Three causes for this seem likely. First, the Panama-Colombia arc-continent collision may have complicated continued eastward motion of the Caribbean Plate. Second, convergent relative motion between North and South America during the past 21 million years (Figure 12) may have reached a critical point by Late Miocene time that was sufficient to create internal deformation within the Caribbean Plate, thereby affecting Plate boundary flow lines. The position and the Neogene uplift of the Beata Ridge support this viewpoint. Third, the pole describing the
motion of the Caribbean Plate with respect to North and South America may have shifted position in Late Miocene times so that strike-slip faults and flow lines about the new pole became non-parallel.

0 Ma: the present. The present plate boundary configuration differs little from the 10 Ma reconstruction except that an exceedingly complex zone of deformation has developed in the Panama-Colombia region in response to continued eastward migration of the Caribbean Plate today. Strike-slip faulting with associated basin and thrust development is continuing throughout the Northern and Southern Plate Boundary Zones. In the western portion of the Chortis block, a back-arc basin may be developing along the Nicaragua Depression. If this is so, the Caribbean Plate may be moving eastward at a slow rate with respect to the mantle.

DISCUSSION

To be sure, the preceding evolutionary model is not intended as a definitive statement on the evolution of the Caribbean Plate. It is merely presented as a model to be chewed over and improved. The authors are aware that considerable error may exist in the finite difference data of Table 4.

Both the initial Pangean reconstruction and the relative motion vectors are highly dependent upon the proposed South Atlantic fit which requires 1) considerable Cretaceous African deformation and 2) a pre-rift relationship between Brazil and the Guinea margin that is tighter than that described by Bullard et al. [1965]. It is felt that substantial evidence for this proposal exists, in so far as a qualitative analysis may be made, but more quantitative work is needed to gain a more confident assessment of the plate kinematics involved. Perhaps a simple re-examination of existing raw data would suffice.

If the proposal turns out to be unacceptable after examination of the data, the authors suggest that the most plausible alternative would involve a continental reconstruction similar to that proposed by Van der Voo and French [1974]. The Yucatan block could remain in its Gulf of Mexico position described in this study so that North and South American Late Paleozoic geology is satisfied. However, to establish the pre-rift relationship between North America and Africa of LePichon and Fox [1971] and Klitgord and Schouten [1980], major right-lateral shear must have occurred along the Atlantic borderlands about a pole in the Sahara region of Africa [as proposed by Van der Voo and French, 1974].

Following this approach and using data presented in Scater et al. [1977], the relative motion vectors of South America with respect to North America are as shown in Figure 26. Another similar model of Gulf/Caribbean evolution could be constructed but significant differences would result accordingly. For example, the model would predict 1) an earlier age of origin for the Gulf of Mexico than for the Atlantic Ocean; 2) subduction at the Venezuelan Antilles from 125 Ma to 65 Ma; and 3) a period of oceanic spreading between the North and South American Plates during the 65 to 56 Ma interval.

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