TECTONICS, VOL. 4, NO. 1, PAGES 1-39, JANUARY 1985

ALLEGHENIAN RECONSTRUCTION AND SUBSEQUENT EVOLUTION OF THE GULF OF MEXICO, BAHAMAS, AND PROTO-CARIBBEAN

James L. Pindell[1]

Exploration Research Division,
Pennzoil Company, Houston, Texas

Abstract. A detailed model for the evolution of the Gulf of Mexico, the Bahamas and the Proto-Caribbean is built within the framework provided by a detailed initial Alleghenian (western Pangean) reconstruction and an accurate subsequent relative-motion history between North America and Gondwana (northern Africa and South America). The Alleghenian reconstruction closes all pre-Jurassic oceans; accounts for Jurassic attenuation of continental crust by restoring that attenuation to original pre-rift continental thicknesses; incorporates an improved Equatorial Atlantic fit between northern Brazil and the Guinea margin of Africa; quantitatively removes changes in shape of northern South America due to Late Cretaceous and Cenozoic accretion and internal deformation; includes pre-Mesozoic continental crust presently underlying the western Bahamas and southern Florida; and correlates Late Paleozoic geology of Yucatan with its neighboring continental masses. Extension occurred within the Gulf of Mexico from Late Triassic to earliest Cretaceous time, but seafloor spreading was delayed until the Late Callovian. This divided a single Gulf-wide salt basin into the Louann and Campeche salt provinces. The Yucatan block progressively rotated about 43 degrees counterclockwise away from the Texas-Louisiana margin around a pole in northern Florida. The Tamaulipas-Golden Lane-Chiapas fault zone of eastern Mexico is interpreted as the remains of an initially intracontinental transform system along which Yucatan migrated. Attenuated continental crust beneath southern Florida and the western Bahamas, termed here the Florida Straits block, migrated approximately 300 km out of the eastern Gulf, approximately along Central Atlantic flow lines. These rotations are consistent with recently suggested magnetic anomaly trends in the Gulf of Mexico (Shepherd et al., 1982; S. Hall, personal communication, 1984). The Proto-Caribbean formed synchronously by a fan-like rotation of Yucatan away from Venezuela.

[1]Now at Department of Geological Sciences, Durham University, United Kingdom.

Paper number 4T1357.
0278-7407/85/004T-1357$10.00

INTRODUCTION

Evolutionary models of the Gulf of Mexico must integrate the geology of the circum-Gulf region (Figure 1) into a quantitative kinematic framework defined by a Late Paleozoic continental reconstruction of western Pangea (North and South America, Africa and Yucatan) and an

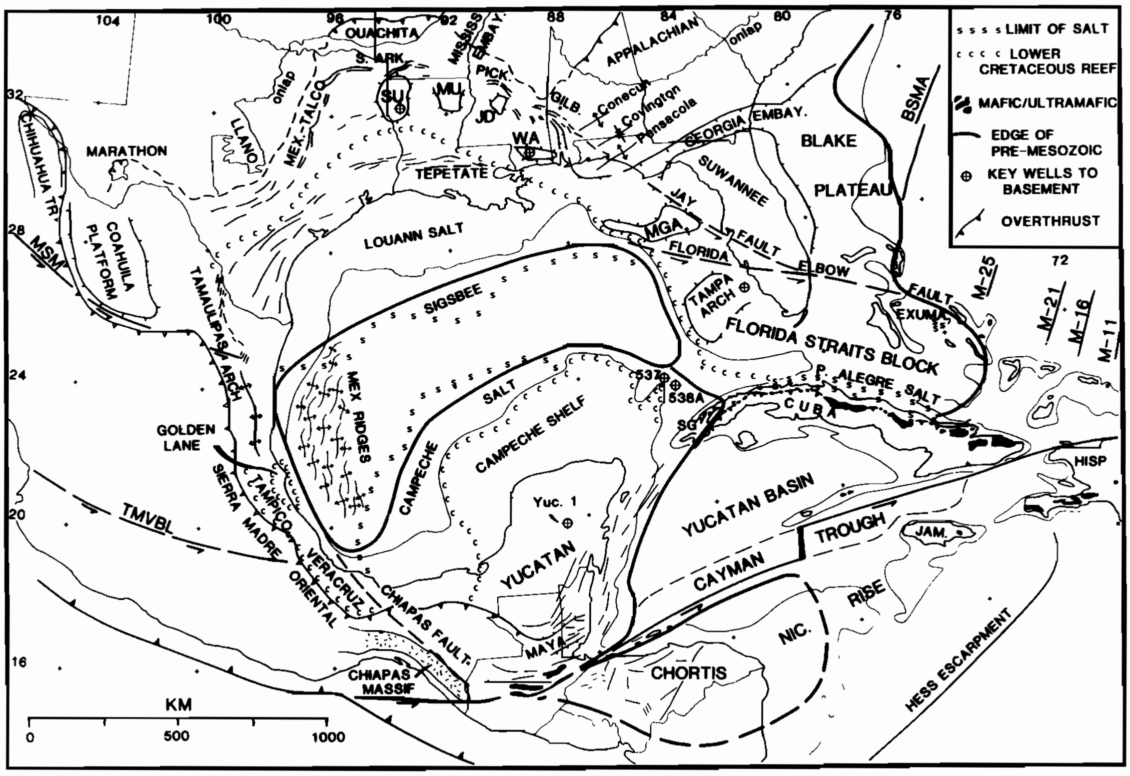

Fig. 1. General tectonic and locality map of the Gulf region, features described in text. MSM, Mojave-Sonora Megashear; TMVBL, Trans-Mexican Volcanic Belt Lineament; SU, Sabine Uplift; MU, Monroe Uplift; JD, Jackson Dome; WA, Wiggins Arch; MGA, Florida Middle Grounds Arch; SG, Sierra Guaniguanico, presently of western Cuba but was northeastern corner of Yucatan block prior to Paleogene; BSMA, Blake Spur Magnetic Anomaly; M-25, M-21, M-16, M-11, Central North Atlantic magnetic anomalies.

accurate subsequent relative motion history between North and South America. The absence of any indication of Upper Permian-Triassic marine conditions in the circum-Gulf region suggests that the initial reconstruction must recognize complete Paleozoic ocean closure. In turn, the way in which closure is achieved in the reconstruction must provide an internally consistent rearrangement of interpreted tectonic provinces and metamorphic zones from the various continental blocks. The rearrangement of provinces is made difficult by the fact that Jurassic continental breakup has followed approximately the lines of Late Paleozoic continental suturing; only rarely can pre-Permian geology be tied across Alleghenian sutures in the reconstruction because the opposing continents had little in common prior to collision, and the majority of Triassic deposition upon each consists of red beds that are lithologically similar and difficult to correlate biostratigraphically.

Because of repeated Paleozoic orogeny in the Appalachians, and because the terms Appalachian, Ouachita, Marathon and Huastecan describe geographic portions of a single continuous, but diachronous, belt of Late Paleozoic deformation, the term Alleghenian orogenesis is used here to describe collectively the diachronous event that produced the Alleghenides, those Late Mississippian-Middle Permian tectonic features and metamorphism that were created by final ocean closure between Gondwana and American portions of Laurussia [Graham et al., 1975; Kluth and Coney, 1981; Pindell and Dewey, 1982; Dewey, 1982; Bradley, 1982].

Before a plausible Alleghenian reconstruction may be attempted, one must (1) identify all pre-Mesozoic continental crust involved in Alleghenian orogenesis, (2) restore to original crustal thickness the attenuation undergone by each margin during Late Triassic and Jurassic rifting, and (3) retract, where possible, post-Permian offsets on intracontinental fault systems such as those in Mexico [Anderson and Schmidt, 1983] and in northwest South America [Dewey and Pindell, 1984]. In addition, proper realignment of the circum-Atlantic continents by closure of the Central-North and the South Atlantic Oceans is critical to Alleghenian paleogeography, by providing the primary framework on which to build more detailed aspects of the western Pangean reconstruction.

In this study, a detailed Alleghenides reconstruction is derived, following the above methodology, which serves as a starting point from which is modeled subsequent evolution of the Gulf of Mexico, the Bahamas and the Proto-Caribbean Sea. The evolutionary model is based upon a framework of relative motions between North America and South America-Africa [Klitgord and Schouten, 1982], the latter of which remained a single continent throughout the opening of the Gulf. Basement geology, intracontinental extension, and general Jurassic sedimentation patterns of the Gulf region are reviewed and interpreted, and are integrated into the evolving plate kinematic framework. The evolutionary model is discussed, and implications are derived.

THE ALLEGHENIAN RECONSTRUCTION

A consensus is emerging that the Late Paleozoic reconstruction of circum-Atlantic continents and blocks in the Gulf and Caribbean realm must achieve total closure in the Gulf of Mexico area [Pindell and Dewey, 1982; Buffler et al., 1980, 1981; Dewey, 1982; Dietz and Holden, 1970; Freeland and Dietz, 1972; Salvador and Green, 1980; Pilger, 1978; Walper, 1980; White, 1980]. The reconstruction must explain deformation patterns in the Alleghenian orogenic belt and the apparent absence of Upper Permian to Late Triassic marine sedimentary rocks in the stratigraphies of the margins involved. Further, it seems most probable that the Yucatan block, but not the Chortis block, fit between the U.S. Gulf Coast and Venezuela in order to match the Louann and Campeche rift-related salt provinces in the Gulf (Figure 1). This positioning of Yucatan provides the necessary geometry of opposing margins for a tight fit between Gondwana and Laurussia. Discussed below are considerations that constrain and substantiate reconstructions of western Pangea in the complex area between North and South America. These collectively produce the Alleghenian paleoreconstruction of Figure 2. Table 1 defines abbreviations, and interprets geological features, portrayed in Figure 2.

The Florida Straits Block

Several lines of evidence suggest that southern Florida and much of the Bahamas Platform are underlain by pre-Mesozoic continental crust, a block (or blocks) referred to here as the Florida Straits block (Figure 1).

The nature and age of basement beneath the Bahamas has been debated for decades, as geophysical and well data have not yet provided a conclusive answer. However, gravimetric, magnetic, and seismic data [Uchupi et al., 1971] suggest that presumably pre-Mesozoic, attenuated continental crust underlies the western half of the platform, whereas the eastern half is oceanic. Basement of the oceanic portion must have been raised to the photic zone early on to initiate carbonate bank development, presumably by plate motions along transform faults, or by volcanism, during the separation of North America and Gondwana. Recently acquired seismic data along the northern Bahamian margin (J. W. Ladd, personal communication, 1984) indicate that the western Bahamas are underlain by attenuated continental crust as far east as Tongue of the Ocean. A similar eastward extent is suggested by the Punta Alegre evaporites of northern Cuba [Pardo, 1975] and by the possible salt occurrence [Lidz, 1973] beneath Exuma Sound (Figure 1), if it is assumed that evaporite sequences pertaining to continental breakup are formed primarily in shallow water, on attenuated continental crust due to initial subsidence during rifting. The southern margin of the Bahamas was imbricated in thrusts as Cuba collided with the Bahamas in the Paleogene [Gealey, 1980; Dickinson and Coney, 1980], providing surface exposures in northern Cuba of early Bahamian stratigraphy. The eastward extent of the Punta Alegre closely matches

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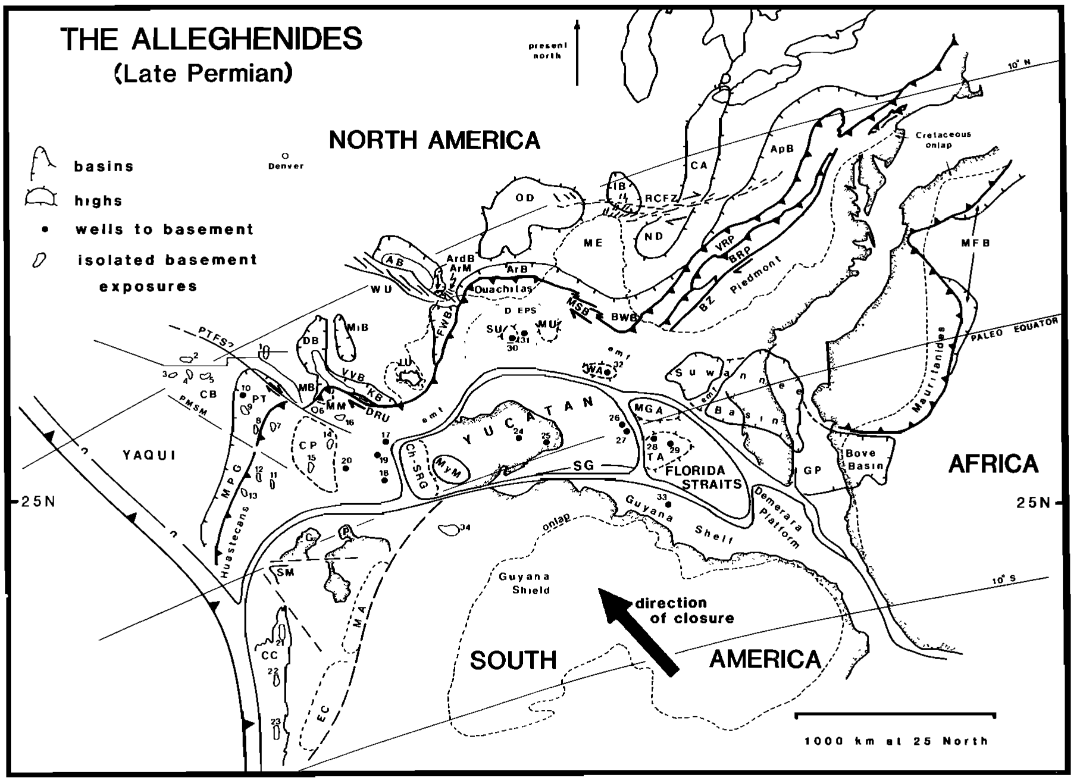

Fig. 2. Late Permian Alleghenides reconstruction derived in text, abbreviations and numeric labels defined in Table 1. Total rotation parameters for closure defined in Table 2. Chortis block and Mexico south of Trans-Mexican Volcanic Belt not included because their Permian positions are unknown.

the extent of continental crust suggested by Uchupi et al. [1971].

In the subsurface of the southern Florida Shelf, the recent drilling of granitic basement rocks of the Tampa Arch (Figure 1) at depths of 3 to 3.7 km (R. N. Erlich, personal communication, 1984) also demonstrates the existence of attenuated continental crust. Further, seismic sections presented in Schlager et al. [1984] show a block-faulted basement beneath the Triassic to Recent sedimentary section of the northern wall of the Florida Straits Channel. The Jurassic rhyolites and basalts of the South Florida Volcanic Province of Klitgord et al. [1984] probably intrude and cover this stretched continental crust, and reflect intracontinental volcanism during Mesozoic rifting between Africa and southeastern North America.

It appears that the Florida Straits block (or blocks) of attenuated pre-Mesozoic continental crust underlies southern Florida, the southern Florida Shelf, and the western half of the Bahamas (Figure 1), and must be included in Alleghenian reconstructions. The fact that much of this crust overlaps Africa when the Atlantic Ocean is closed indicates that crust of the Florida Straits block has migrated some distance into its present position, either by internal extension during rifting or by translation from the site of the present eastern Gulf of Mexico along plate boundaries, as in Pilger [1978]. It will be seen that both mechanisms probably occurred.

Stretching Analysis of Rifted Margins

Areas presently underlain by pre-Mesozoic continental crust that must be integrated into the Alleghenian assembly are shown in Figure 3, excluding western Africa, and include the U.S. Gulf Coast

TABLE 1. Key and Interpretive Glossary to Figure 2

Abbreviation	Explanation
AB	Anadarko Basin. Carboniferous extensional and right-lateral strike-slip basin, compressed in Late Pennsylvanian and/or Early Permian.
ApB	Appalachian Basin. Devonian to Carboniferous foreland sedimentary basin resulting from load of Appalachian thrust sheets.
ArB	Arkoma Basin. Carboniferous foreland basin resulting from load of Ouachita thrust sheets to the south.
ArdB	Ardmore Basin. Subbasin of Anadarko Basin, sits amidst dextral strike-slip zone.
ArM	Arbuckle Mountains. Dextral shear zone in North American foreland, probably related to Wichita Uplift. Active during Pennsylvanian.
BB	Bove Basin. Platform sequence (terrigenous) of Paleozoic age, rocks correlatable to Florida's Suwannee Basin.
BRP	Blue Ridge Province. Metamorphic thrusted nappes in central Appalachians, thrusting caused by collision of Africa with North America.
BWB	Black Warrior Basin. Carboniferous foreland basin resulting from load of Appalachian thrust sheets.
BZ	Brevard Zone. High-angle reverse and/or strike-slip fault in southern Appalachians, possible zone of lateral escape during Alleghenian compression.
CA	Cincinnati Arch. Foreland bulge caused by lithospheric flexure from load of Appalachians.
CB	Chihuahua Block. Zone north of Mojave-Sonora Megashear but south of Rio Grande which underwent basement reactivation during Jurassic (sinistral shear) and Cretaceous (compression). In Figure 2, a homogeneous simple shear totalling 100 km across the block has been restored to the northwest.
CP	Coahuila Platform. Block accreted to North America during Alleghenian assembly, possibly originally part of Gondwana but stranded during rifting, may represent Late Paleozoic arc created by closure between North America and Gondwana.
CC	Cordillera Central, Colombia. Presumably formed northwest margin of South America throughout Paleozoic to Late Cretaceous. Age and chemistry of Paleozoic and Mesozoic plutonic rocks questionable, but may have been Late Paleozoic arc prior to ocean closure. Mesozoic-Cenozoic arc volcanism has occurred here as well.
Ch-SRG	Chuacus-Santa Rosa Group. Chuacus Group are metamorphosed (in early Carboniferous) igneous and sedimentary rocks of Guatemala belonging to Yucatan block. Metamorphism relates to continental collision. The Upper Pennsylvanian to Lower Permian Santa Rosa Group unconformably overlies the Chuacus, and was deposited in a shallow sea behind the main Alleghenian thrust belts.
DB	Delaware Basin. Extensional, right-lateral strike-slip basin of Early Permian age. Relates to the escape of the Mexican peninsula during continental collision.

TABLE 1. (continued)

Abbreviation	Explanation
D-EPS	Desmoinesian-Lower Permian Sediments. Postorogenic shallow-water molasse deposited behind Ouachita thrust zone. Correlated with Santa Rosa Group (Yucatan Block) and Permian of Colombia.
DRU	Devil's River Uplift. Right-lateral shear zone created by northwestward migration of Marathon region along southern side of Llano Uplift during ocean closure.
EC	Eastern Cordillera. Uplifted since Late Miocene due to compression and dextral strike-slip motion caused by Panama-Colombia collision. Was shallow-water sea and received Permian molasse from adjacent uplifted Cordillera Central during collision.
emf	Eagle Mills Formation. Predominantly Upper Triassic continental red beds filling grabens and obscuring basement.
FWB	Fort Worth Basin. Pennsylvanian foreland basin related to loading of Ouachita structural belt.
G	Guajira Block. A northern extension of Cordillera Central (see Cordillera Central).
GP	Guinea Plateau. Extended and submerged pre-Mesozoic continental crust which must be included in Alleghenian reconstruction.
IB	Illinois Basin. Intracontinental basin initiated during Early Paleozoic, reactivated in Alleghenian orogeny with the intersection of Mississippi Embayment and Rough Creek fault trends.
KB	Kerr Basin. Early Permian foreland basin, related to loading by Marathon thrust sheets (Ouachita structural belt).
LU	Llano Uplift. Stable buttress of North America during collision, foreland bulge to the Ouachita structural belt.
MA	Merida Andes. Uplifted since Late Miocene during Andean Orogeny. Was shallow-water sea and received Permian molasse from nearby uplifted Cordillera Central (Santa Marta and Guajira).
MB	Marfa Basin. Early Permian foreland basin related to loading of Marathon thrust sheets.
ME	Mississippi Embayment. Structural low, floored by Precambrian rift, only slightly reactivated during Alleghenian collision and Mesozoic rifting, but underwent extension and volcanism in Cretaceous.
MFB	Mauritanides Foreland Basins. Devonian to Permian foreland basins related to loading by Mauritanides thrust sheets during collision.
MiB	Midland Basin. Shallow, cratonic basin adjacent to Delaware Basin, cause uncertain.
MGA	Middle Grounds Arch of Northwest Florida Platform. Structural basement high, or horst, defines edge of pre-Mesozoic continental crust in northeast Gulf.
MM	Marathon Mountains. Metamorphosed Paleozoic continental rise and slope sediments and orogenic flysch thrust up onto North American shelf sequence during Late Pennsylvanian to Early Permian time.

TABLE 1. (continued)

Abbreviation	Explanation
MPG	Mexican Paleozoic Geosyncline. Foreland basin related to emplacement of Huastecan thrust sheets during Early to Middle Permian time.
MSB	Mississippi Slate Belt. Dextral shear zone created by migration of Ouachita region and Yucatan along southern end of Appalachians during Carboniferous ocean closure.
MU	Monroe Uplift. Basement high, possibly stranded continental remnant of Gondwana.
MyM	Maya Mountains. Deformed Upper Paleozoic igneous and sedimentary rocks. Shales and sands (Maya Series) correlated to Santa Rosa of Guatemala, Desmoinesian-Early Permian sediments of U.S. Gulf Coast, and Lower Permian of Colombia.
ND	Nashville Dome. Southern portion of Cincinnati Arch (see Cincinnati Arch).
OD	Ozark Dome. Structural basement high, foreland bulge related to loading of Ouachita thrust belt.
P	Paraguana Block. Northward extension of Cordillera Central (see Cordillera Central).
PMSM	Proto-Mojave-Sonora Megashear. Possible? zone of dextral continental escape during collision.
PT	Pedregosa Trough. Foreland basin related to emplacement of Huastecan thrusts in Permian time. May also be site of dextral transform motion allowing continental escape of Mexican peninsula.
PTFS	Pedregosa Trough Fault System. Postulated zone of dextral slip enhancing development of Pedregosa Trough and allowing continental escape of Mexican peninsula.
RCFZ	Rough Creek Fault Zone. Zone of intracontinental dextral shear, accommodating shortening in southern Appalachians during Carboniferous.
SG	Sierra Guaniguanico, Cuba. Prior to Paleogene Cuba-Bahamas collision, this continental crust belonged to northeast margin of Yucatan.
SM	Santa Marta Block. Northern extension of Cordillera Central (see Cordillera Central).
TA	Tampa Arch. Pre-Mesozoic basement high off southwest Florida Platform, forms western portion of Florida Straits Block.
VRP	Valley and Ridge Province. Folded platform cover in front of primary Appalachian thrust sheets.
VVB	Val Verde Basin. Early Permian foreland basin related to loading by Marathon thrust sheets.
WA	Wiggins Arch. Metamorphic pre-Mesozoic basement high, originally part of Gondwana.
WU	Wichita Uplift. Dextral shear zone related to minor Pennsylvanian northwestward displacement of Llano block relative to midcontinent.
1	Franklin Mountains. Upper Paleozoic carbonate shelf of North America [Bridges, 1970].

TABLE 1. (continued)

Abbreviation	Explanation
2	Bisbee, Arizona. Upper Paleozoic carbonate shelf of North America [Bridges, 1970].
3	Cananea. Upper Paleozoic carbonate shelf of North America [Bridges, 1970].
4	Sierra Los Ajos. Upper Paleozoic carbonate shelf of North America [Bridges, 1970].
5	El Tigre. Upper Paleozoic carbonate shelf of North America [Bridges, 1970].
6	Solitario. Surface exposure of southern continuation of Marathon belt [Bridges, 1970].
7	Mina Plomosas-Placer de Guadalupe. Marathon equivalent, Ordovician to Devonian limestone, dolostone, chert, Carboniferous shale and carbonate, Permian reefs and shale [King, 1975].
8	Sierra del Cuervo. Wolfcampian highly deformed but little metamorphosed shale and sand [King, 1975].
9	Sierra de la Mojina. Lower Cretaceous conglomerate with metasedimentary clasts with ages of 330-350 Ma [King, 1975].
10	Villa Ahumada Borehole. 1600 m of shale and silt, upper part Wolfcampian [Bridges, 1970].
11	Ciudad Victoria (west of). Thrust slices of Precambrian gneiss, schists, Silurian to Devonian black shale, cleaved Carboniferous-Permian flysch, ultramafics [King, 1975; De Cserna, 1976; Salas, 1970].
12	Aramberri. Pre-Mesozoic phyllites, schists, metavolcanics [King, 1975].
13	Catorce. Ultramafic (ophiolite?) obducted with the Huastecans [de Cserna, 1976].
14	Potrero de la Mula. Granodiorite plutons dated at 206 Ma, dating is questionable [King, 1975].
15	Las Delicias. Permian volcaniclastic shale and greywacke, reefy carbonates, highly folded, and intruded by Triassic (cooling age) granite [King, 1975].
16	Sierra del Carmen. Phyllite, marble, quartzite, greenschists, 263-275 Ma on metamorphics [King, 1975].
17	Borehole. Bottomed in Paleozoic schists [King, 1975].
18	Borehole. Bottomed in Paleozoic slate and quartzite [King, 1975].
19	Borehole. Bottomed in granite-gneiss, 358 Ma [King, 1975; Flawn et al., 1961].
20	Borehole. Bottomed in Paleozoic granite [King, 1975].
21	Cajamarca Group. Exposures of orthogneiss, tuffs, basic lavas, metatonalites. Metamorphic cooling ages: biotite, 239 Ma; muscovite, 214 Ma [Irving, 1971, 1975; Shagam, 1975].
22	Granitic schists, metamorphism 215 Ma [Irving, 1975].
23	Granitic schists, metamorphism 220 Ma [Irving, 1975].
24	Borehole. Yucatan no. 1. Meta-andesite, 330 Ma and 290 Ma [Marshall, 1974].
25	Borehole. Yucatan no. 4. Metaquartzite [Marshall, 1974].
26	Borehole. DSDP 537. Phyllite, 449 Ma and 456 Ma [Schlager et al. 1984].

TABLE 1. (continued)

Abbreviation	Explanation
27	Borehole. DSDP 538A. Amphibolite gneiss, 496 Ma and 348 Ma. Also diabase, 190 Ma and 165 Ma on different sills [Schlager et al. 1984].
28	Borehole. Pre-Jurassic(?) granodiorite R. N. Erlich, personal communication, 1984).
29	Borehole. Pre-Jurassic(?) granite (R. N. Erlich, personal communication, 1984).
30	Borehole. Mississippian rhyolitic tuffs [Nicholas and Waddell, 1982].
31	Borehole. Desmoinesian-Early Permian shallow-water, undeformed clastics and carbonates [Nicholas and Waddell, 1982].
32	Borehole. Granite and phyllite, metamorphic ages of 270 Ma to 325 Ma [Cagle and Khan, 1983; J. Cagle, personal communication, 1984].
33	Borehole. Precambrian at 8,877 feet [Case and Holcombe, 1980].
34	El Baul. Paleozoic sediments metamorphosed in Late Paleozoic, granite intrusion 287 Ma [Feo-Codecido et al., 1984].

margin and eastern Mexico, northern South America, the Yucatan block, Florida, the Blake Plateau, and the Florida Straits block. The Antilles and the Panama-Costa Rican isthmus are post-Alleghenian, Cretaceous and Cenozoic island arc complexes built on Late Mesozoic ocean floor. The continental crust of the Chortis block (Figure 1) entered the Caribbean region from the Pacific realm during the Late Cretaceous-Paleogene [Dickinson and Coney, 1980; Wadge and Burke, 1983] and, hence, does not need to be considered in the reconstruction. The margins of the pre-Mesozoic blocks were considerably attenuated during Mesozoic rifting, so that their present geographic dimensions greatly exceed their former, prerift dimensions, and this extension must be restored in proper reconstructions of western Pangea.

The cross-sectional geometry of continental crust along each margin may be estimated by isostatically balancing various thicknesses of sediment, crust, upper mantle, and water, at several locations across the margin, with an equivalent column of "normal" continental crust. The depth to the sediment-crust interface can be determined seismically (reflection and refraction), but identification of the crust-upper mantle boundary is more difficult. Where possible, a component of subsidence due to flexure at the margin should be accounted for, which reduces the apparent stretching factor in the flexural wings of margins [Watts, 1981]. Within the stretched zone itself, the effects of flexure are not well understood because the crust undergoes complex changes in flexural rigidity during rifting. Hence, an Airy model is used here in highly attenuated portions of margins. From lithospheric cross sections, total crustal extension may be estimated, assuming plane strain and conservation of continental crust, and discounting subsidence in the wings due to flexure, by defining a line that divides equally the cross-sectional area of continental crust on its oceanward side and the cross-sectional area of sediment and raised mantle on its landward side (Figure 4). By estimating the position of this line intermittently along each margin, the restored, prerift geometries may be approximated.

U.S. Gulf Coast and eastern Mexico. Figure 4 illustrates the restoration of attenuation in the case of the U.S. Gulf Coast, where crustal attenuation across a 760-km-wide zone was extreme. Sediment thicknesses of 13.4 to 14.6 km beneath 0 to 1 km of water in the Gulf Coast basin [Antoine et al., 1974] suggest beta values approaching 4. In northern Louisiana, southern Mississippi and east Texas, as far north as the Talco-South

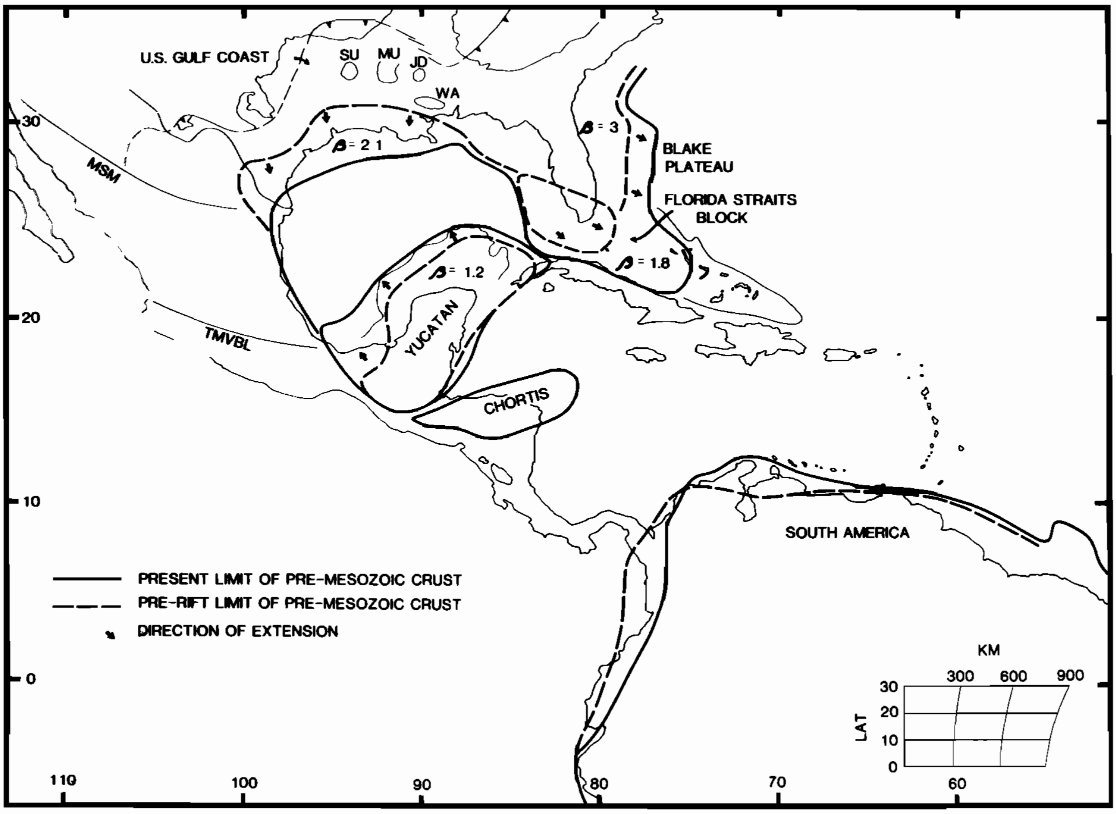

Fig. 3. Areas of pre-Mesozoic continental crust in the Gulf-Caribbean region and amount of synrift extension and/or subsequent change in shape. Prerift shapes are used in the Alleghenian reconstruction of Figure 2. Abbreviations as in Figure 1.

Arkansas-Pickens-Gilbertown fault system, shallow listric faults and rift structures indicate that basement attenuation occurred, but was relatively minor compared to southern Louisiana and offshore. Subsidence has been due largely to flexure caused by sediment loading in the Gulf, although significant rifting occurred in the East Texas, North Louisiana and Central Mississippi salt basins. Nunn [1982] estimated beta values in these basins between 1.5 and 2, but these are perhaps overestimates because flexure was ignored. Integration across the 760-km-wide Gulf Coast Plain and margin yields a net north-south extension due to rifting of about 400 km, or an average beta factor of 2.1 (Figure 4). Thus, the prerift limit of pre-Mesozoic continental crust through central Louisiana lies at about 30.5 N, approximately along the Tepetate fault system (Figure 1). Similar analyses at other locations along the margin lead to the prerift limit of pre-Mesozoic crust shown in Figure 3.

Along eastern Mexico, basement drops off quickly along the eastern side of the Tamaulipas Arch, the Golden Lane high, and offshore along Veracruz (Figure 1). As will be discussed later, this curvilinear line defines a margin viewed here as the remains of a transform fault between Mexico and Yucatan which formed as the latter migrated away from the U.S. Gulf Coast. Hence, crustal attenuation due to rifting is believed to be negligible.

The Yucatan block. Basement beneath the Yucatan Peninsula lies beneath a 4-km-thick predominantly Late Jurassic to Cretaceous carbonate-evaporate section [Lopez Ramos, 1975], except in the southern, orogenically active portion and

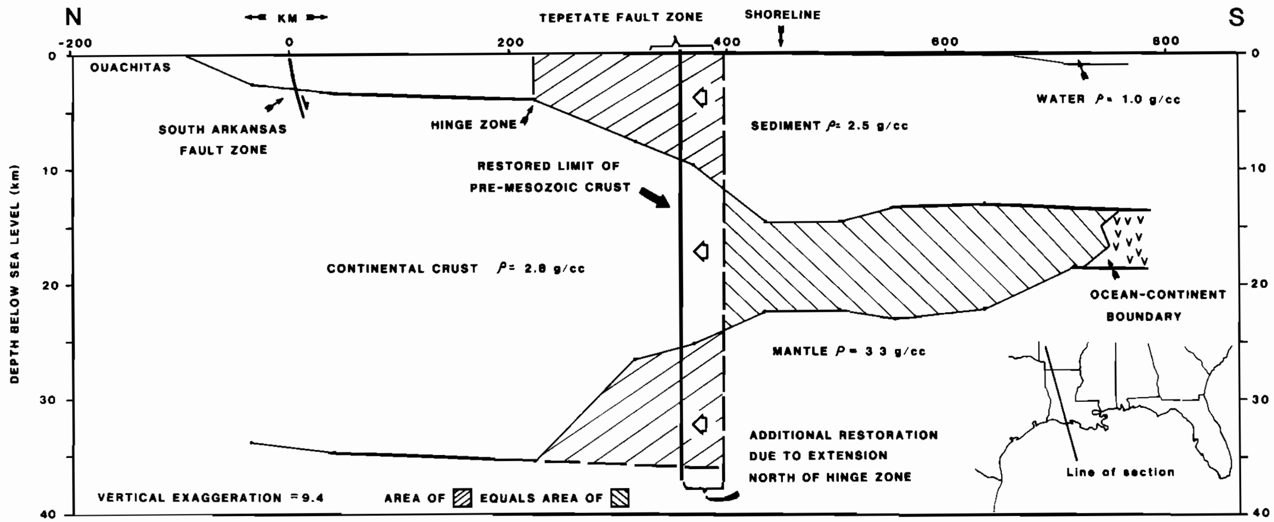

Fig. 4. Theoretical cross section of the U.S. Gulf Coast margin through and offshore Louisiana, crossing the Sabine Uplift. Estimated depth to basement after Antoine et al. [1974] and Woods and Addington [1973], ocean-continent boundary after Buffler et al. [1981]. South of the apparent hinge zone, crust, mantle, sediment and water are balanced with an equivalent column of normal crust using an isostatic Airy model ignoring flexure, which is an adequate approximation in this area as the effective rigidity of the lithosphere was thermally reset (reduced) during rifting. Subsidence over the 220 km of the Gulf Coast to the north of the hinge zone is largely due to flexure, but extensional basement faulting did occur (South Arkansas fault zone, Gulf Coast salt basins, for example). An average extension of 20% (beta=1.2) is estimated for this zone, considering that little or no rifting occurred within Sabine Uplift and that beta estimations of 1.5 to 2 for stretching in the salt basins which neglect flexure [Nunn, 1982] are probably overestimates. Hence, only an additional 44 km are removed from the restored limit determined by Airy balancing south of the hinge zone.

along the eastern basement high. The thickness of this section suggests a 20% extension of crust, but the absence of a well developed rift-related clastic section may indicate that much of this deposition is due to flexure-induced subsidence relating to the cooling and loading of the surrounding oceanic crust. Greater but uncertain sedimentary thicknesses occur beneath the Campeche Shelf, where rifting probably was more severe. Northwest of the Campeche Escarpment, an 80-km-wide rifted margin is overlain by 7 to 8 km of sediment and about 3 km of water [Buffler et al., 1980], suggesting a beta factor of about 5 and 64 km of extension within this narrow belt. Sediment thicknesses beneath Tabasco and westernmost Campeche (6 km) and offshore beneath Campeche Bay (8.5 km, under 2 km of water) [Buffler et al., 1984] indicate beta values of 1.5 to 3.7 over a 400-km-long, northwest trending, cross-section. In addition to stretching, Cenozoic faulting also has altered the original shape of Yucatan. First, continental, terrigenous shelf sediments and crust originally belonging to the northeastern Yucatan block but presently in Sierra Guaniguanico of western Cuba (Figure 1) was caught up in the Paleogene collision of Cuba with the Bahamas. Second, sinistral displacement (about 130 km) of Yucatan basement has occurred along the Polochic Fault of Guatemala during the Neogene [Burkart, 1978, 1983; Deaton and Burkart, 1984]. Both offsets must be restored to original geometry.

Following these considerations, and assuming that the Yucatan Platform's 4 to 5 km thick sedimentary section is half due to subsidence arising from stretching and half from flexure, the prerift shape of the Yucatan block (Figure 3) was approximately 20% smaller than it is today. The direction of extension is northwest (present coordinates), perpendicular to the Campeche Escarpment.

Synrift continental extension in Yucatan combined with that in the U.S. Gulf coast, then, is about 500 to 520 km, in close agreement with the estimate of 490 km by Sawyer [1984].

Blake Plateau and Florida Straits block. Crustal attenuation in the Blake Plateau and Florida Straits block appears to be genetically related to the separation of Africa from North America. The sedimentary section lying upon block-faulted basement beneath the Blake Plateau is about 11 km thick [Grow and Sheridan, 1981] and water depths average 1 km. These values indicate beta values of about 3. The extension appears to be in a southeast direction, parallel to the divergence of Africa from North America. Thus, in the Alleghenian reconstruction the Blake Plateau must be restored to about 33% of its present size in a northwest direction.

Beneath the northern half of the Florida Straits block, the postrifting sedimentary section is 7 to 8 km thick (J. W. Ladd, personal communication, 1984), but in the South Florida Basin (south of Tampa Arch, Figure 1) and north of Cuba thicknesses may reach 12 km [Meyerhoff and Hatten, 1974]. In the area of Cay Sal Bank, the 12 km sediment thickness is partly due to thrust imbrication pertaining to the Paleogene Cuba-Bahamas collision [Dickinson and Coney, 1980; Gealey, 1980], whereas the 9 km thick section in the Andros area ahead of the thrusts [Meyerhoff and Hatten, 1974] is largely due to increased subsidence and sedimentation rates caused by foreland loading. In the Andros well, Paleocene-Middle Eocene deposition occurred 5 times faster than before and after this foredeep development [Paulus, 1972], leading to an accumulation of about 1.5 km greater than would have been allowed by subsidence arising from thermal decay and sedimentary loading; therefore, only about 7.5 km of the total deposition was driven by stretching and thermally induced sedimentary loading. Offshore at Tampa Arch and its flanking Florida Elbow and South Florida Basins, depth to basement ranges from 3 km to over 6 km (R. N. Erlich, personal communication, 1984), suggesting beta values of 1.2 to 1.8.

Because of the complexity of the Florida Straits region, flexure is only considered as it pertains to the Paleogene collision with Cuba. By integrating the above sediment thicknesses over the geographic area for which they exist and discounting the effects of the collision, a rifting-induced sedimentary sequence averaging about 8 km is indicated for the Florida Straits block as a whole, which suggests a beta factor of about 1.8 that must be restored in the Alleghenian reconstruction.

Northern South America. Because the northern South American rifted margin has been so highly obscured by compressive deformation related to Caribbean evolution, crustal attenuation due to rifting cannot be estimated. However, significant changes in

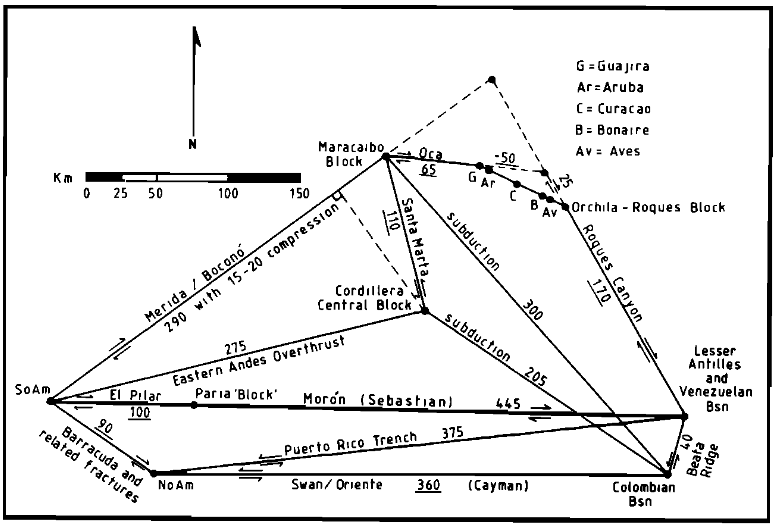

Fig. 5. Vector-triangle diagram showing trend and magnitude of Neogene offsets between blocks and plates of the circum-Caribbean region, after Dewey and Pindell [1984]. Restoration of offsets derives pre-Late Miocene shape of northern South America, shown in Figure 6.

the shape of northern South America due to accretion and to internal strike-slip motions may be quantified, as outlined in the next section.

Change in the Shape of Northern South America

Three episodes of tectonism have significantly altered the Jurassic shape of northern South America since the breakup of Pangea. The first was the accretion of Cretaceous aged basement of the Western Cordillera of Colombia and Ecuador in Late Cretaceous time [Barrero, 1979; Mooney, 1980]. The second was the accretion of the Netherlands-Venezuelan Antilles volcanic arc (Aruba, Curacao, Bonaire, Aves, Roques, and Orchila) against the northern margin of Venezuela in Late Cretaceous to Paleogene time [Maresch, 1974; Gealey, 1980; Beets et al., 1984]. The third has been internal deformation, mainly by motion along several strike-slip faults, of northern South America over the last 9 Ma amounting essentially to 290 km of northeastward migration of the Andean Cordilleran terranes of Ecuador, Colombia and northwestern Venezuela, relative to cratonic South America [Dewey and Pindell, 1984]. The effects of each episode on northern South American geography are approximated below.

Quantifying the late Neogene deformation of northern South America to determine its paleogeography at 9 Ma is achieved by restoring known and inferred post-nine Ma offsets upon faults and plate boundaries separating terranes and plates of the southern Caribbean realm [Dewey and Pindell, 1984]. Late Neogene motions between the terranes and plates can be described by a vector-triangle diagram (Figure 5), the restoration of which produces the 9 Ma paleogeography of Figure 6. The cause of this uplift and deformation, and drastic paleogeographic change, is, most likely, the progressive collision of the Panama arc with western Colombia [Pindell and Dewey, 1982; Wadge and Burke, 1983], and the subduction of buoyant, young crust produced at the Galapagos spreading center, which includes the Carnegie and Cocos aseismic ridges, beneath the Cordilleran terrane of Colombia and Ecuador.

The islands offshore northern Venezuela (Aruba to Orchila, Figure 6, inset) are composed largely of Upper Cretaceous plutonic and volcanic rocks intruding and overlying a Lower Cretaceous mafic series which probably represents oceanic crust [Maresch, 1974; Beets et al., 1984]. Hence, the islands comprise an intraoceanic arc which developed and collided with Venezuela subsequent to the breakup of Pangea. La Blanquilla (southern portion of Aves Ridge),

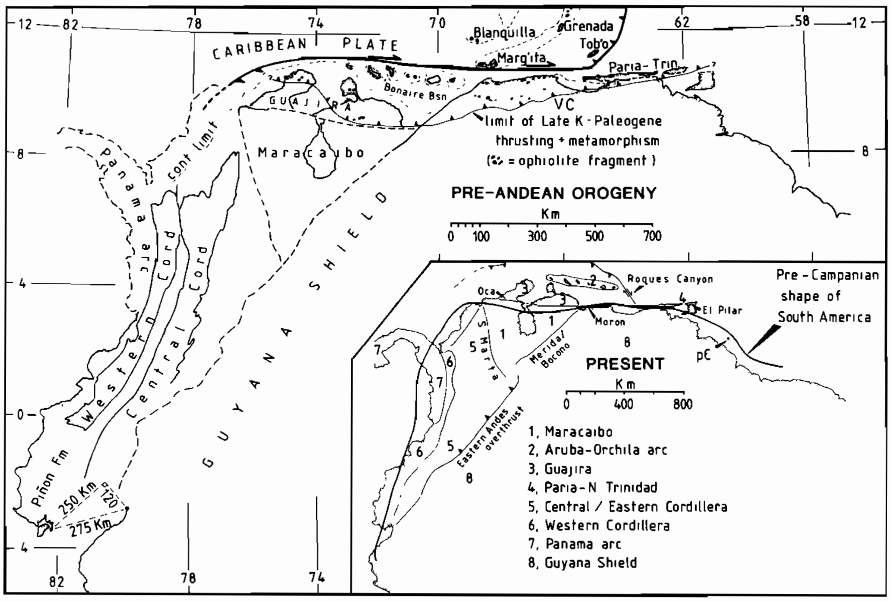

Fig. 6. Pre-Late Miocene paleogeography of blocks and plates of circum-Caribbean realm, derived by restoring offsets defined in Figure 5. Inset: Blocks of northern South America which have undergone relative motion, on the faults shown, over the last 9 Ma. VC, thrust front of Villa de Cura and other nappes. Heavy line is pre-Campanian shape of northern South America used in Alleghenian reconstruction, derived by removing Aruba-Orchila and Western Cordillera accreted terranes from pre-Late Miocene paleogeographic reconstruction. Modified after Dewey and Pindell [1984].

Margarita (origin uncertain) and Tobago (accreted to leading edge of Caribbean Plate at an unknown time) also are composed entirely of post-Paleozoic rocks. In Venezuela, the ultramafic bearing Villa de Cura Klippe and associated nappes have been interpreted as the oceanic forearc [but see Beets et al., 1984] of this Netherlands-Venezuelan Antilles arc, which was obducted onto northern Venezuela during Late Cretaceous to Paleogene arc-continent collision [Maresch, 1974; Gealey, 1980]. Because pre-Mesozoic basement occurs near the coast to the north of the Villa de Cura, the precollision edge of northern South America apparently lies along the coast or offshore within the Bonaire Basin, but the offshore islands must be excluded from Pangean reconstructions.

In the Western Cordillera of Colombia and Ecuador (Figure 6, inset), pre-Cretaceous rocks are absent. Cretaceous basic igneous rocks (Pinon, Basic Igneous Complex, Diabase Group) overlain by deep-water abyssal sediments may represent oceanic crust accreted to the Cordillera Central in the Late Cretaceous [Mooney, 1980; Irving, 1975; Shagam, 1975; Feininger and Bristow, 1980; Barrero, 1979; Goossens and Rose, 1973; Duque-Caro, 1979]. Rocks typical of island-arc volcanism are present [Henderson, 1979], but these probably postdate the accretion of the basement complex to South America and, hence, represent arc volcanism along the newly accreted South American margin rather than volcanism at a preexisting arc of Pacific provenance that collided with Cordillera Central. The cause of accretion may have been due to the young age and consequent buoyancy of the oceanic crust; accretion occurred only a short time after formation. The basement complex may, in fact, be an occurrence of oceanic crust that was affected by the mid-Cretaceous B" extrusion event of the Caribbean Plate

[Burke et al., 1978] that, rather than entering the Caribbean, was accreted to western South America. In addition to the Western Cordillera, the Neogene-accreted Panama arc also must be removed from South America.

The removal of post-Paleozoic accreted terranes and restoration of Neogene deformation produces the pre-Campanian shape of northern South America shown in Figure 6, inset. This shape is believed to represent the Jurassic shape of northern South America, although Sierra de Santa Marta and the Guajira Peninsula may have migrated northeastward during the Late Cretaceous-Paleogene(?) from the area of the Lower Magdelena Valley [Duque-Caro, 1979]. Also, deformation prior to the Campanian is possible, but the stable shelf conditions that prevailed during the Early Cretaceous over much of northern South America [Maresch, 1974; Irving, 1975] suggests relative tectonic quiescence at that time.

The Equatorial Atlantic Assembly

The opening of the Equatorial Atlantic between northeast Brazil and the Guinea margin of Africa postdated the opening of the Gulf of Mexico. Because Africa's relative motion with respect to North America during the opening of the Gulf can be traced by magnetic anomalies in the Central Atlantic, the pre-rift reconstruction of South America with northern Africa defines, through the three-plate circuit, the relative relationship between North and South America during Gulf evolution.

Pindell and Dewey [1982] and Klitgord et al. [1984] suggested that the mid-Cretaceous South America-northern Africa fit of Rabinowitz and LaBrecque [1979], which is tighter than the South Atlantic fit of Bullard et al. [1965], existed also during the Jurassic, and should be used when modelling the Gulf of Mexico. However, this tighter fit overlaps Precambrian crust between Liberia and northernmost Brazil by about 30 km, demonstrating the need for minor improvement. A revised Equatorial Atlantic reconstruction is shown in Figure 7, which aligns the prerift limits of continental crust along the northern Brazil and Guinea margins. These limits were determined by removing marginal sediments and restoring the inferred syn-rift extension, as in Figure 4 for the Gulf margin. This fit describes the interplate relationship between northern Africa and South America prior to Aptian plate divergence in the Equatorial Atlantic and throughout the opening of the Gulf of Mexcico.

The Yucatan Block

The Yucatan block played an important role in the evolution of the Gulf of Mexico. Its rotated prerift position against Texas and Louisiana as portrayed by Pindell and Dewey [1982] accounts for such problems as the Ouachita salient and the apparent absence of Late Permian to Triassic marine rocks in the Gulf region by allowing complete continental closure by the Permian. Further, magnetic anomaly lineations in the central Gulf of Mexico are oriented nearly east-west and diverge to the west [Shepherd et al., 1982; S. Hall, personal communication, 1984]. This trend is clearly distinct from the Central North Atlantic trend and is consistent with an origin of the Gulf of Mexico by counterclockwise rotation of Yucatan, as suggested by Pindell and Dewey [1982].

Rock types also constrain this initial position of Yucatan. The Chuacus Group in Central Guatemala is a metamorphosed (greenschist to amphibolite) collection of marbles, quartzites, greenstones, schists, serpentinites and volcanic rocks, with granodioritic intrusions, whose age is known only to be pre-Permian on the basis that it is unconformably overlain by the Permian Santa Rosa Group [Roper, 1978; Van den Boom, 1972; Anderson et al., 1973]. Preserved within a section apparently of the Chuacus Group that was only moderately metamorphosed, however, are Carboniferous (probably Lower Carboniferous) fossils [Van den Boom, 1972]. Thus, regardless of the age-range of the Chuacus stratigraphy, the age of metamorphism apparently is Carboniferous. Isotopic evidence [Gomberg et al., 1968] on the Rabinal Granite, a probable synmetamorphic melt from the granitization of a Chuacus arkose [Van den Boom, 1972], produces possible ages of 1075 Ma plus or minus 25 and 345 Ma plus or minus 20. The latter is compatible with a Lower Carboniferous age. It appears, therefore, that the deformation and metamorphism exhibited by the Chuacus Group can be attributed to Alleghenian orogenesis. Alleghenian orogenesis as modeled by Dewey [1982] would suggest a prolonged period of deformation and metamorphism for the rocks of Yucatan, as they occupied a shear

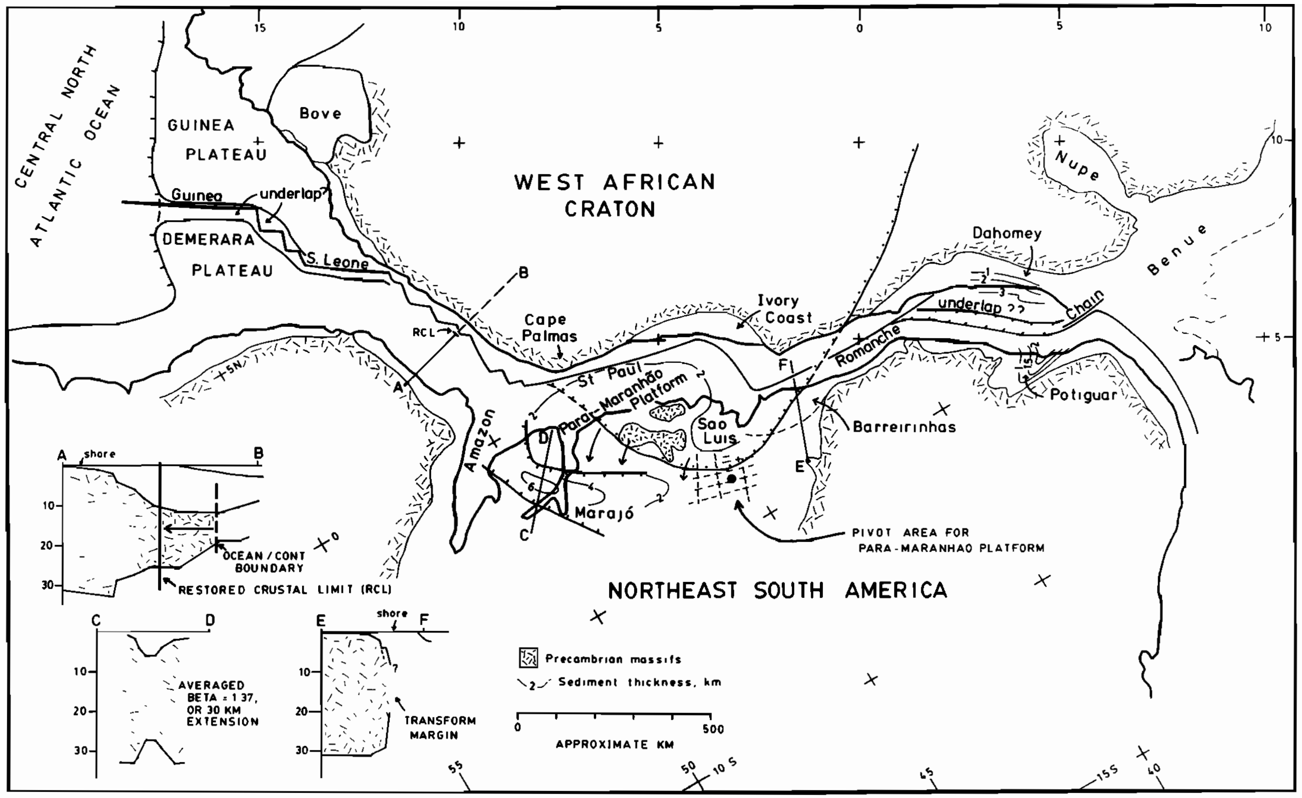

Fig. 7. Prerift Equatorial Atlantic reconstruction, matching restored limits of pre-Mesozoic continental crust of the continental margins, methodology for which shown in Figure 4. Following "Hypothesis II" of Delteil et al. [1976], St. Paul fracture zone juxtaposes Cape Palmas with the mouth of the Amazon, the Romanche juxtaposes Cape of Three Points with the Berreirinhas Basin and the Chain juxtaposes the Ilesha Spur of southwest Nigeria with the Potiguar Basin. Guinea fracture zone margins well defined by Behrendt et al. [1974], Delteil et al. [1976], McMaster and Ashraf [1973], and Sibuet and Mascle [1978]. Isopachous data from Asmus and Ponte [1975], Milliman [1979], and Whiteman [1982]. Restoration of prerift continental limit beneath Niger Delta from Delteil et al. [1976]. Cross sections AB and CD constructed from Figure 5 of Milliman [1979], and section EF from Ojeda [1982] and Asmus and Ponte [1975]. Removal of sediment at Amazon mouth, and restoration of attenuation in the Amazon and Marajo Basins, allows this tighter fit. Clockwise rotation of the Para-Maranhao Platform during plate separation produced the westward deepening Marajo Basin. The suggested pivot point for closure of Marajo Basin (arrows denote closure direction) is amidst area of basement fractures, as shown. Northern edge of Para-Maranhao Platform is a fracture zone. Note good alignment of Sao Luis and West African Cratons (heavy line with adjacent dots). Also, gap between Demerara and Guinea Plateaus seen in the Bullard et al. [1965] fit is avoided, which explains the absence of Jurassic marine sediment east of the plateaus. The adverse effect of this Equatorial fit on the southern South Atlantic fit can be reconciled by restoring extensional deformation in central Africa [Wright, 1968], and in Argentina. See Table 2 for total rotation parameters.

zone between North and South America from latest Devonian to earliest Permian time. Further support for proximity of northwestern South America and North America by Late Devonian time is based on the presence of Appalachian basin marine invertebrate fauna of that age in Colombia and Venezuela [Boucot, 1975; Barrett, 1983]. Sediments of the unconformably overlying Santa Rosa Group (Permian) probably were shed from exposed portions of the Chuacus, and other structural highs in the orogenic zone, into shallow marine molasse basins during the final stages of orogenesis, as they are far less deformed and relatively unmetamorphosed.

In the Maya Mountains of Belize (Figure 1), a variably deformed, argillaceous to conglomeratic sequence of Pennsylvanian-Middle Permian age overlies older (?)gneissic basement with granitic intrusions [Dawe, 1984; Nelson, 1984; Bateson and Hall, 1977; Dixon, 1957]. At least the upper part of the sedimentary section consists of shallow-water, fossiliferous molassic sands, shales and conglomerates, and is lithologically and biostratigraphically correlative with the Santa Rosa Group of Central Guatemala [Anderson et al., 1973]. These deposits are very similar in lithology and age to the Desmoinesian to Lower Permian late to post-orogenic molasse deposits in the subsurface of the U.S. Gulf Coast [Woods and Addington, 1973] and to the Lower Permian strata of northwest South America [Shagam, 1975]. These localities align in a continuous belt behind the main Alleghenian thrusted zone to the north, providing support for the reconstruction from a sedimentological perspective.

In the subsurface of northern Yucatan, meta-andesite/dacite was drilled (Yucatan No. 1, see Figure 1) and isotopically dated as 330 Ma and 290 Ma [Marshall, 1974]. The andesite may represent an occurrence of the Alleghenian arc that theoretically should have existed; the isotopic age is consistent with a thermal resetting during the period of closure between Gondwana and Laurussia. At Catoche and a neighboring knoll of the Yucatan block, DSDP holes 538A and 537 (Figure 1) reached Paleozoic basement as well [Schlager et al., 1984]. Hole 538A sampled amphibolite gneiss with isotopic ages of 496 and 348 Ma, and hole 537 obtained phyllite with ages of 449 and 456 Ma. The 348 Ma age can be attributed to thermal resetting during the Alleghenian orogeny [Schlager et al., 1984], whereas the older ages are similar to many of those recovered from the basement of Florida [Smith, 1982]. That Florida belonged to Gondwana prior to Alleghenian collision is clear from its pre-Carboniferous Afro-South American fauna [Cramer, 1971; Pojeta et al., 1976]. Similarities between Yucatan and Florida would imply the same for Yucatan. Lithologies and Upper Paleozoic isotopic ages of 270 to 325 Ma on rocks (phyllite, granite) from a well penetrating the Wiggins Arch (Figure 1) [Cagle and Khan, 1983; J. Cagle, personal communication, 1984] are similar to those recovered from the Yucatan block and may suggest that the Wiggins Arch was part of Gondwana as well. All lie to the south of the proposed Alleghenian suture.

Synthesis of the Alleghenian Reconstruction

The above considerations provide geological and quantitative geometrical constraints on reconstuctions of western Pangea. Although Middle to Late Paleozoic convergence between Laurussia and Gondwana is poorly understood, patterns of Alleghenian orogenesis and Late Paleozoic sedimentation appear to be best explained by complete ocean closure during continent-continent collision, within which the Yucatan block filled the gap between Venezuela and the U.S. Gulf Coast margin (Figure 2). The probable suture zone, from east to west, lies between the Appalachians and the Mauritanides of western Africa; crosses Georgia between the Suwannee Basin and the Southern Appalachians; continues north of the Wiggins Arch and Sabine Uplift, following approximately the trend of the Gilbertown-South Arkansas-Mexia graben system; is offset by the Texas Lineament along the Devil's River Uplift (essentially a tear fault); swings to the south of the Marathons but again is offset, possibly by a proto-Pedregosa Trough fault system, and passes to the northwest of the Coahuila Platform and then south between the Huastecan belt of Mexico and northwest South America. Whether the Chortis block was part of Mexico during Late Paleozoic time or whether it arrived later after migration along the Cordillera is unknown and, hence, Chortis is excluded from the reconstruction.

Accretionary complexes that were developed during ocean closure include the Ouachitas, the Marathons and the Huastecans. All of these accretionary complexes overthrust Paleozoic shelf rocks of North America, suggesting that final convergence was achieved by southeast dipping subduction with North America as the downgoing plate. The case for Alleghenian accretionary prisms in the southern Appalachians is questionable, but these may lie to the east beneath the coastal plain.

Alleghenian thrust-loaded foreland basins which developed on North America include the Appalachian, Black Warrior, Arkoma, Fort Worth, Ker, Val Verde, Marfa, Pedregosa basins and the Mexican Paleozoic "Geosyncline." Distal, foreland bulges include the Cincinnati Arch, Nashville Dome, Ozark Dome, and Llano Uplift.

Possible remnants of the expected arc between Gondwana and North America include the Upper Paleozoic granodiorites, andesites or volcanics presently found in the Central Cordillera of Colombia [Irving, 1975], the Chuacus Group of Guatemala, Yucatan No. 1 well of Yucatan, the Coahuila Platform, the Sabine Uplift, and the basement of Florida. Zones of Late Paleozoic strike-slip motion leading into the North American foreland which may have allowed escape of continental fragments include the Rough Creek Fault Zone, the Anadarko Basin/Wichita Uplift, the Delaware Basin [Dewey, 1982] and, possibly, the Pedregosa Trough. Closure was achieved by east to west oblique collision from the latest Devonian through the middle Permian, with probable migrations of various blocks within the suture zone.

INTERPRETIVE REVIEW OF PRIMARY GULF-REGION GEOLOGICAL FEATURES

The generalized tectonic map of the Gulf of Mexico region (Figure 1) shows primary tectonic features that any model of Gulf-region evolution must explain. These features are reviewed and interpreted below.

Basement

Three types of crust exist in the Gulf region: normal-thickness continental crust, variably-attenuated continental crust, and oceanic crust. Prior to seafloor spreading in the Gulf, relative plate motions were accommodated by continental attenuation (as much as 500 km between the southern U.S. and Yucatan, see above). This attenuation must be incorporated when modeling Gulf evolution. Attenuated basement around the northern Gulf includes a collection of highs (Sabine, Monroe, Wiggins) separated by intervening basins (Gulf Coast Salt Basins). The Sabine and Wiggins basement highs consist of Paleozoic metamorphics, volcanics and granite [Nicholas and Waddell, 1982; Cagle and Khan, 1983], which may be interpreted as remnants of the leading edge of Gondwana which were sutured to and overthrusted onto the margin of North America during the Alleghenian Orogeny and subsequently left behind during Late Triassic to Early Jurassic rifting [Pindell and Dewey, 1982; Smith et al., 1981]. The same applies for Florida, on the basis of Early Paleozoic fauna in Suwannee Basin [Cramer, 1971], and for the Coahuila Platform of northeastern Mexico, which possesses Late Paleozoic granodioritic intrusions [King, 1975] possibly representative of an arc. Basement in the attenuated margin of northwestern Yucatan block is unknown.

Extensive salt deposits overlie the zones of attenuated continental crust, and seaward limits of the Louann and Campeche salt provinces match reasonably the ocean-continent boundaries [Buffler et al., 1981], although oceanward halokinesis has occurred, particularly in the Sigsbee Escarpment [Lehner, 1969]. It seems likely that the onset of emplacement of oceanic crust by seafloor spreading in the Gulf at oceanic isostatic depths (2.6 km depth) allowed sufficiently open marine circulation to terminate salt deposition, and split the once continuous salt province into the distinct provinces known today. Unfortunately, the halokinesis on both sides of the Gulf prevents direct matching of opposing margins for paleogeographic reconstructions.

The oceanic portion of the Gulf of Mexico was created by primarily Late Jurassic seafloor spreading at a ridge system that must be included in plate-boundary reconstructions. Linear magnetic anomaly trends in the central Gulf fan slightly to the west and generally parallel the U.S. Gulf Coast margin and the Campeche Escarpment of Yucatan [Shepherd et al., 1982; S. Hall, personal communication, 1984]. This leads independently to the conclusion that Yucatan originated from the Texas-Louisiana margin and rotated counterclockwise to its present position, and further substantiates the geological arguments presented earlier for this initial position in Alleghenian paleogeography.

When the Equatorial Atlantic is closed (see above) and South America-Africa is then refitted to North America following Central North Atlantic flow lines [Klitgord and Schouten, 1982], overlap occurs between the Florida Straits block and the Guinea and Demerara Plateaus of Africa and South America, respectively. Also, the closure of Yucatan against the Texas-Louisiana margin leaves an oceanic hole in the northeastern Gulf with a southeasterly magnetic anomaly trend that is discordant with the trend in the central Gulf [Shepherd et al., 1982]. It appears that crust of the Florida Straits block migrated to the east-southeast, in addition to undergoing internal extension, during Gulf evolution. This motion relative to the remainder of Florida was left-lateral strike-slip, as discussed below, while motion relative to Yucatan was extensional, as defined by the eastern Gulf's magnetic anomalies.

Fault Systems of the Gulf Region

U.S. Gulf Coast. In the U.S. Gulf Coast margin, the Mexia-Talco-South Arkansas-Pickens-Gilbertown fault system defines the northern limit of significant normal faulting in basement. This system coincides closely with the probable Alleghenian suture. Assuming Yucatan originated from the Texas-Louisiana margin and rotated to its present position, the direction of extension in the U.S. Gulf Coast was north-south. Therefore, the Mexia-Talco fault zone owes its origin to differential subsidence and minor dextral shear between the basement of the stable Llano area and the basement of the Gulf Coast during attenuation. Similarly, motion in the Mobile Bay system may have been slightly sinistral.

Mexico. In most reconstructions of western Pangea, much of Mexico overlaps South America, if Mexico is kept in its present position with respect to North America. Understanding the emplacement of Mexico into this "overlap position" has been problematic because known evidence for large-scale motions upon one or more intracontinental transform faults across Mexico and the southwesternmost U.S. is meager. Evidence in favor of such large offset faults includes the interruption of northeasterly striking Precambrian tectonic belts, and a 700 to 800 km sinistral displacement of stratigraphic columns having "provocative similarities" [Anderson and Schmidt, 1983]. The theoretical structure responsible for these discontinuities has been termed the Mojave-Sonora Megashear (MSM) [Silver and Anderson, 1974]. The timing of motion along the postulated MSM is constrained between the first major motions of the breakup of Pangea (Late Triassic, first stretching, but early Mid-Jurassic is first significant motion) and deposition of the Oxfordian Zuloaga Group (Smackover equivalent), as the latter apparently masks the fault zone in northeast Mexico and is not offset. A 700 to 800 km offset during Bajocian-Callovian time (about 20-25 million years) indicates displacement rates between 2.8 to 4 cm/yr. It appears as though, in effect, blocks or slices of Cordilleran Mexico migrated more or less with South America during initial breakup, maintaining a land bridge from North to South America at least until Callovian time, when saline waters finally entered the Gulf of Mexico region and evaporated to form the once continuous Louann and Campeche salt deposits. From which ocean the saline waters entered, the Pacific or the Atlantic, is unknown. Another potential, but unproved, zone of major Mesozoic offset across Mexico is along the Trans-Mexican Volcanic belt. This area, during Late Cenozoic time, has been the site of significant calc-alkaline volcanism, possibly because it is a zone of weakened crust [Mooser, 1969; Anderson and Schmidt, 1983].

The number of major faults through Mexico and their offsets are poorly understood; proposed offsets are based largely on geometry alone. It is very possible that all of Mexico, since it resided on the western, convergent margin of Pangea during breakup, experienced severe internal shearing of the sort seen along the western North American margin today. If studies of North America/Farallon relative motion for Late Jurassic-Early Cretaceous time are accepted, Farallon subduction beneath southwestern North America possessed a strong left-lateral oblique component [Engebretson, 1982, but see Duncan and Hargraves, 1984]. This is in agreement with the postulation of a simple shear regime for Mexico during the Late Jurassic [Beck, 1983], and possibly Middle Jurassic as well.

Along the eastern Mexican margin, continental basement falls off abruptly along a linear trend defined by the eastern side of the Tamaulipas Arch, the Golden Lane high, and offshore at Veracruz. If extended to the south, this trend crosses into Chiapas, approximately along the northern flank of the Chiapas Massif. Sediment thickness adjacent to this flank exceeds 4500 metres [Viniegra, 1971], suggesting the existence of a major structural break. The linear trend as a whole is perpendicular to magnetic anomaly trends in the Gulf of Mexico [Shepherd et al., 1982; S. Hall, personal communication, 1984], and defines a small circle about a pole located in the vicinity of northern Florida. It is suggested that this trend, termed here the Tamaulipas-Golden Lane-Chiapas fault zone, was a right-lateral transform zone between Yucatan and eastern Mexico, that allowed migration of Yucatan away from the Texas-Louisiana margin. This is further supported by the conspicuous absence of salt diapirs marginal to the central portion of this trend, in the area of the Mexican Ridges [Buffler et al., 1979], in contrast to areas of the Gulf where attenuated continental basement exists with thick salt deposits and diapirs [Buffler et al., 1980, 1981]. A transform origin for the eastern Mexican margin which postdated salt deposition explains the absence of salt. In addition, the Tamaulipas Arch, during Late Jurassic time, was a linear basement high of Paleozoic rocks that supplied significant amounts of debris to proximal deposits of the Huizachal and Zuloaga Groups during initial rifting and platform subsidence [Sandstrom, 1982; Stabler, 1982; Meyer and Ward, 1982; Bracken, 1982]. The linearity and positive structural relief of the Arch during the Jurassic suggest strike-slip faulting as a possible cause of its uplift. In Chiapas, coarse, Upper Jurassic-Lower Cretaceous Todos Santos red beds fill northwest trending structural valleys and ridges whose relief reached 1000 to 2000 m at the time of deposition [Burkart and Clemons, 1971]. This scenario accords with models of strike-slip faulting equally as well as it does with rifting, and the northwest trend of the basins is perpendicular to the expected extension direction between North and South America. Finally, definition of a Mexico-Yucatan shear zone along the northeast side of the Chiapas Massif avoids the often invoked hypothesis that major displacement has occurred across the Isthmus of Tehuantepec; crystalline rocks cross the isthmus from southern Mexico into the Chiapas Massif with no obvious structural break [King, 1969; Case and Holcombe, 1980].

Florida region. Basement structure in Florida and the southeasternmost U.S. can only be inferred from gravimetric, magnetic and borehole information, but basement appears to be irregular and to consist of a collection of horstlike Paleozoic highs separated by grabens filled with red beds [Smith, 1983; Barnett, 1975; Klitgord et al., 1984]. Primary structural features include the Jay Fault, the Georgia Embayment "graben" system, and the Florida Elbow basin which separates the Middle Grounds and Tampa Arches (Figure 1).

The northwest trending Jay fault [Smith, 1983] aligns with the Pickens-Gilbertown fault system and the Bahamas fracture zone of Klitgord et al. [1984], and defines a steep, down to the south drop-off in basement. Sinistral motion along this fault is speculative, but it clearly defines the northern limit of significant basement attenuation, as do the Pickens-Gilbertown fault system in the Gulf Coast and the Bahamas fracture zone across the Florida Peninsula. This attenuation probably occurred in the Middle Jurassic, as it did throughout the entire Gulf of Mexico. North of the Jay, relatively minor basement structures such as the Covington Embayment and Conecuh and Pensacola Arches formed due to general extension between North America and Gondwana.

Development of the northeast trending, Triassic Georgia Embayment system is older than the other fault zones, and is often referred to as an extensional rift on the basis of its Triassic red beds and basalts filling narrow troughs [Barnett, 1975]. If the system's formation were due to crustal extension, then a well-developed Jurassic sedimentary section related to basin subsidence could be expected. However, such a section is absent across southern Georgia and north-central Florida [Barnett, 1975; Smith, 1983] and, therefore, it is suggested that the Georgia Embayment system probably was formed by strike-slip shear, which caused local uplift and erosion, and deposition of Upper Triassic red beds into associated strike-slip basins. On the basis of geometry alone, the suggested sense of offset is right-lateral (discussed later).

Basement structure beneath southern Florida and the south Florida shelf is poorly known due to the thick post-Triassic sedimentary section. As mentioned earlier, the eastern part of Florida Straits block overlaps Africa when the continents are reassembled. This is true even after 80%

internal extension is restored to the northwest (see above). In addition, the Yucatan block alone cannot fill the oceanic portion of the Gulf of Mexico; a small oceanic swath remains in the northeastern deep Gulf. Therefore, it is apparent that crust of the Florida Straits block migrated out of the eastern Gulf, in addition to undergoing severe internal extension. Hypothesized here is the existence of a fault (Florida Elbow Fault, Figure 1) along which the Florida Straits block, subsequent to crustal attenuation south of the Jay Fault, migrated 300 km east-southeast out of the eastern Gulf to its present position beneath the south Florida shelf and western half of the Bahamas. The Florida Elbow Fault runs from the southern escarpment of the Paleozoic Florida Middle Grounds Arch, continues through the Florida Elbow basin and crosses Florida near Lake Okeechobee, underlies the northwest Providence Channel, and defines the northern margin of Great Bahama Bank. Such a trend is readily seen on a magnetic anomaly contour map [Klitgord et al., 1984, figure 5]. It is further suggested that sinistral motion along the fault system produced the Florida Middle Grounds escarpment by translating the Tampa Arch away from the Middle Grounds Arch.

Tectonism Following Gulf Formation

Since the Gulf of Mexico's formation, which was completed by or during the earliest Cretaceous, the Gulf region has experienced at least two periods of plate-tectonic deformation. The first was the eastward advance of thrust sheets of the Sierra Madre Oriental of Mexico (Figure 1) in Late Cretaceous to Eocene time [Dengo, 1975]. The cause of thrusting is still debated, but the load of the thrusts, which travelled across Jurassic salt, depressed the western portion of the eastern Mexican margin, reactivating the Tampico-Tuxpan and Veracruz sedimentary basins by flexural loading. The Laramide orogenesis also elevated and reactivated the Tamaulipas-Golden Lane highs, probably due to lithospheric flexure in response to loading by the Sierra Madre to the west, or by sedimentation offshore to the east, or both. The second period of tectonism was the early Paleogene arrival and collision of Cuba (Greater Antilles) with the Bahamas/southern Florida shelf [Dickinson and Coney, 1980; Gealey, 1980]. The emplacement of thrust sheets of the Cuban forearc tectonically loaded the southern Florida/Bahamian margin, depressing the carbonates of the latter to oil-maturation depths. Oil has since migrated upward into the fractured serpentinites that presently form small reservoirs in and offshore northern central Cuba [Wassal, 1956]. The causes of other possible "events" during the Cretaceous, including the Gulf-wide mid-Cretaceous unconformity [Buffler et al., 1980], volcanism and local plutonism in the Gulf Coast [Zartman, 1977; Smith et al., 1981], uplift of the Wiggins, Monroe and Sabine highs, and reactivation of the Mississippi Embayment [Ervin and McGinnis, 1975] are unclear. In addition to these plate-tectonic deformations, much of the northern and western Gulf has experienced severe sedimentary gravity sliding and halokinesis.

EVOLUTION OF THE GULF OF MEXICO REGION

Figures 8 through 14 outline a model for the Mesozoic plate-tectonic evolution and early sedimentary history of the Gulf of Mexico region derived from the Alleghenian reconstruction and the interpretations of fault systems and internal extension summarized above. The model is developed within the plate-kinematic framework defined by rotation parameters in Table 2. An Upper Oxfordian deposition map shows generalized lithofacies in the paleogeographic framework defined by the evolutionary model at that time and further constrains the proposed evolutionary model.

Late Triassic

In the Late Triassic, western Pangea began to rift along widespread, poorly defined zones of intracontinental block-faulting and dike emplacement (Figure 8). Minor associated motions, recorded by the Late Triassic geology outlined below, led to the pre-Atlantic, early Middle Jurassic relationship between Africa and North America defined by Klitgord and Schouten [1982].

In the southern U.S., north-south extension produced an extensive graben system filled with Eagle Mills red beds. Along the eastern United States, red beds, 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.

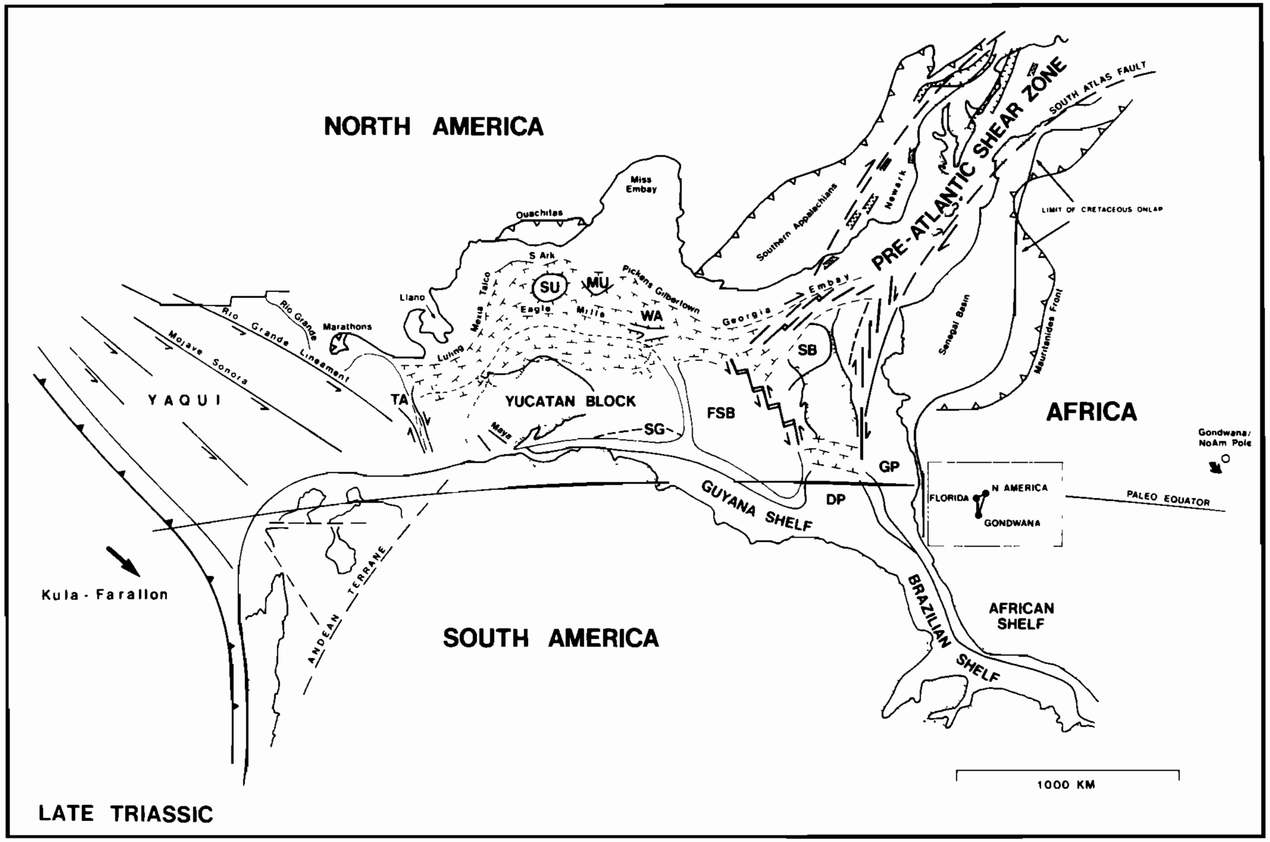

Fig. 8. Late Triassic paleogeography of the Gulf region, about 210 Ma. Relative motion of plates and blocks during time increment to next reconstruction defined by vector triangles in boxes. DP, Demerara Plateau; FSB, Florida Straits Block; GP, Guinea Plateau; MU, Monroe Uplift; SB, Suwannee Basin; SG, Sierra Guaniguanico of present-day western Cuba; SU, Sabine Uplift; TA, Tampa Arch; WA, Wiggins Arch. Strike and dip symbols schematic for rifting.

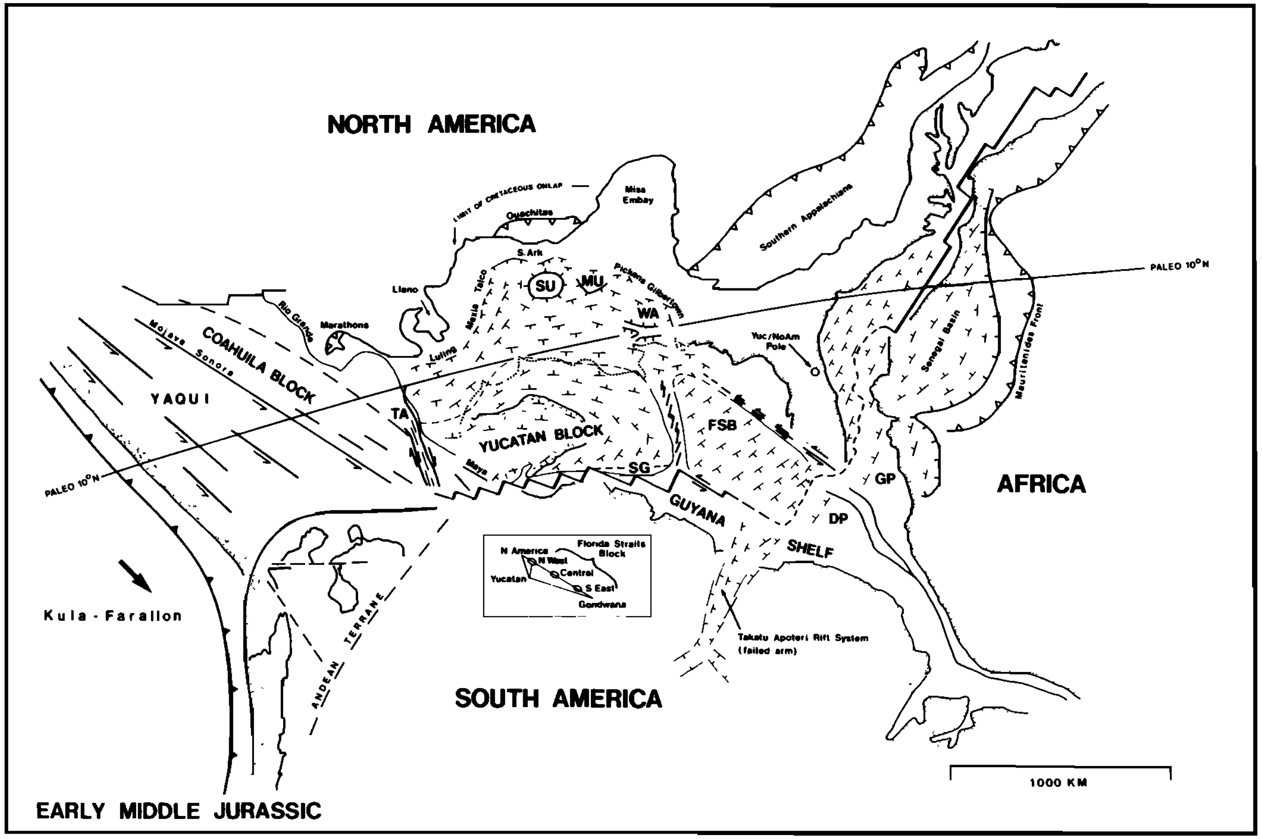

Fig. 9. Early Middle Jurassic paleogeography of the Gulf region, about 180 Ma. Abbreviations and conventions as in Figure 8.

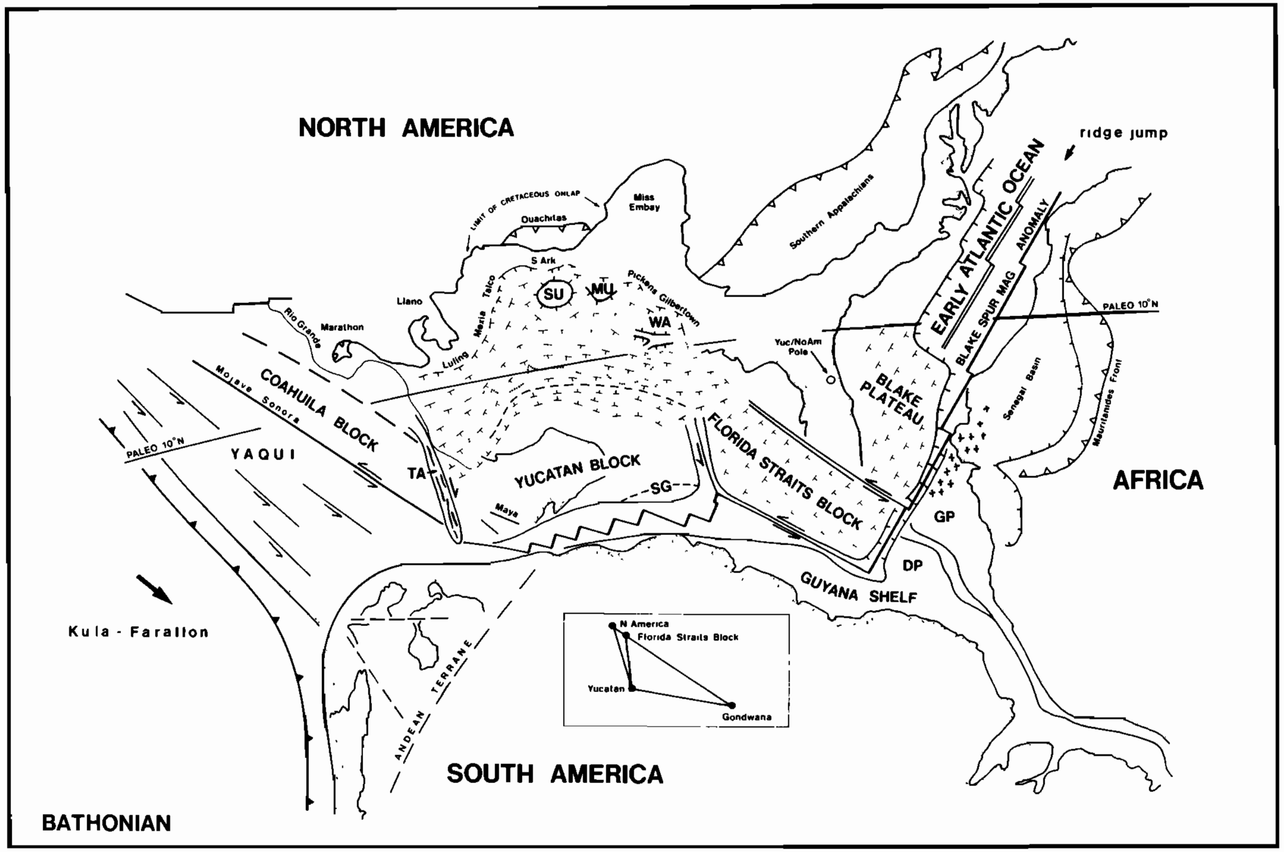

Fig. 10. Middle Jurassic (Bathonian) paleogeography of the Gulf region, about 170-172 Ma. Abbreviations as in Figure 8. Cross pattern represents rift-related salt of the African margin [Jansa and Weidman, 1982], which may correlate with Punta Alegre and Exuma Sound? salt on the opposing margin.

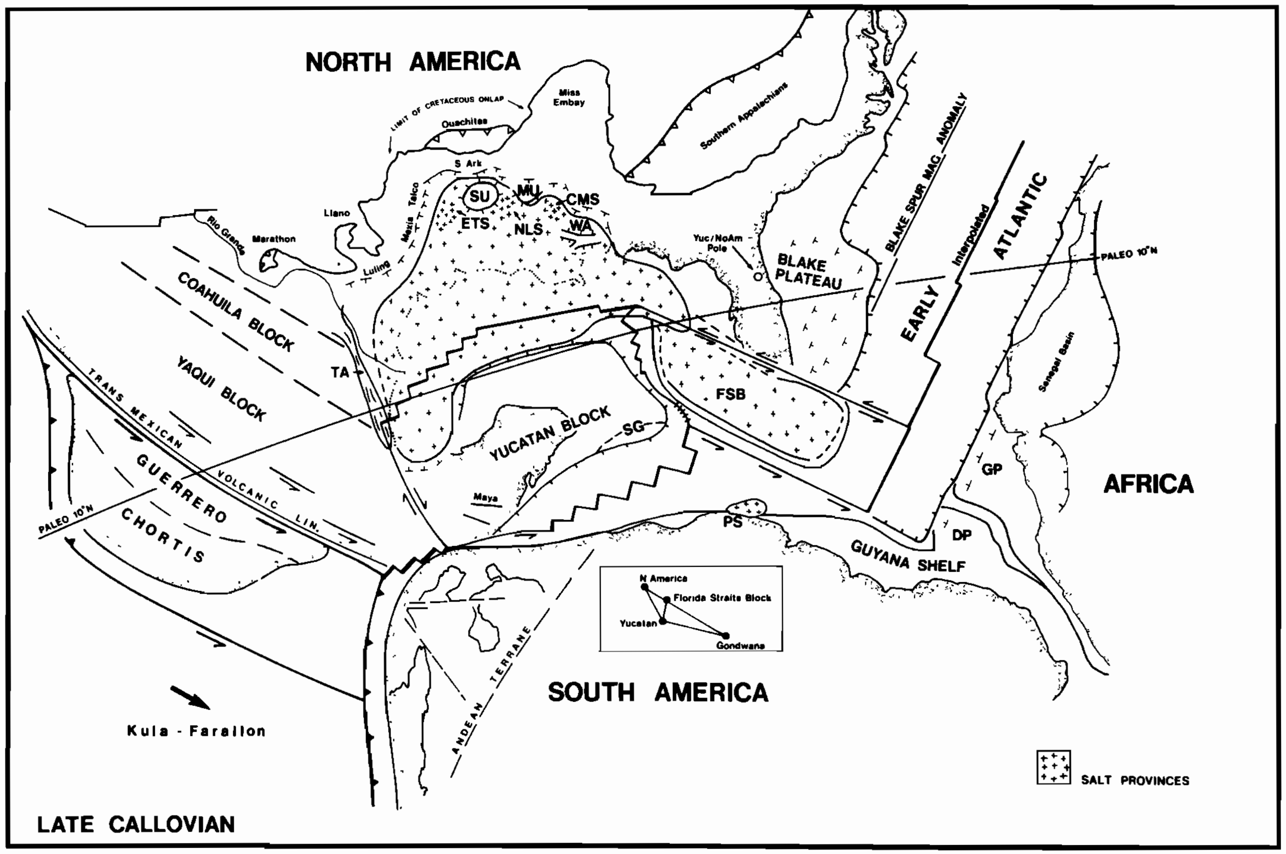

Fig. 11. Late Middle Jurassic (Callovian) paleogeography of the Gulf region, about 160 Ma. At this time, Gulf-wide salt had been deposited, seafloor spreading ridges were developed in the Gulf, and Chortis Guerrero (Mexico south of Trans-Mexican Volcanic belt) may have been migrating along the Pacific margin from the north. CMS, Central Mississippi salt basin; ETS, East Texas salt basin; NLS, North Louisiana salt basin; PS, Gulf of Paria salt basin. Other abbreviations as in Figure 8. Whether the Florida Straits block migrated out of the Gulf as a single, coherent block or as a collection of smaller blocks separated by anastomozing transcurrent faults is unknown.

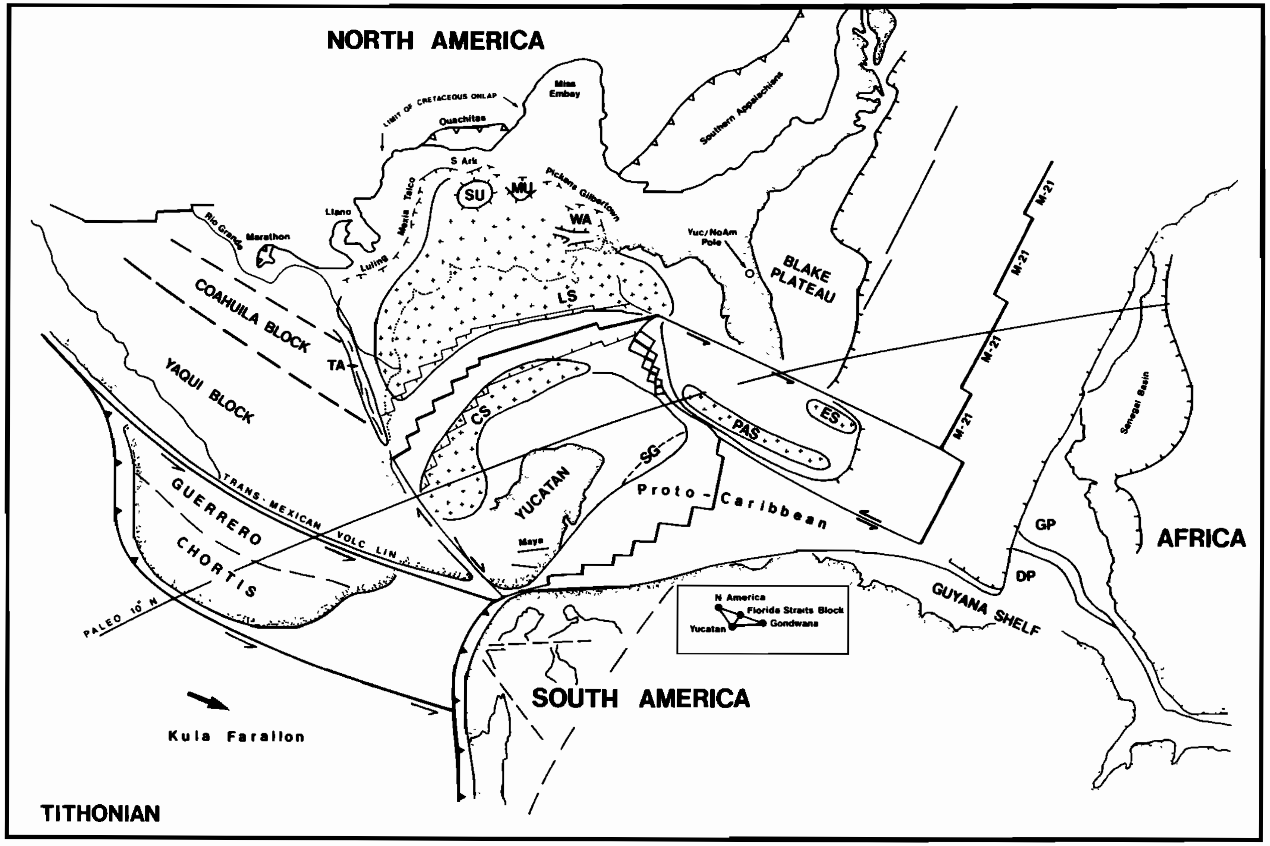

Fig 12. Late Jurassic (Tithonian) paleogeography of the Gulf region, about 150 Ma. Seafloor spreading had separated the Gulf salt deposits into component members. CS, Campeche salt; ES, Exuma Sound? salt; LS, Louann salt; PAS, Punta Alegre salt. Other abbreviations and conventions as in Figure 8.

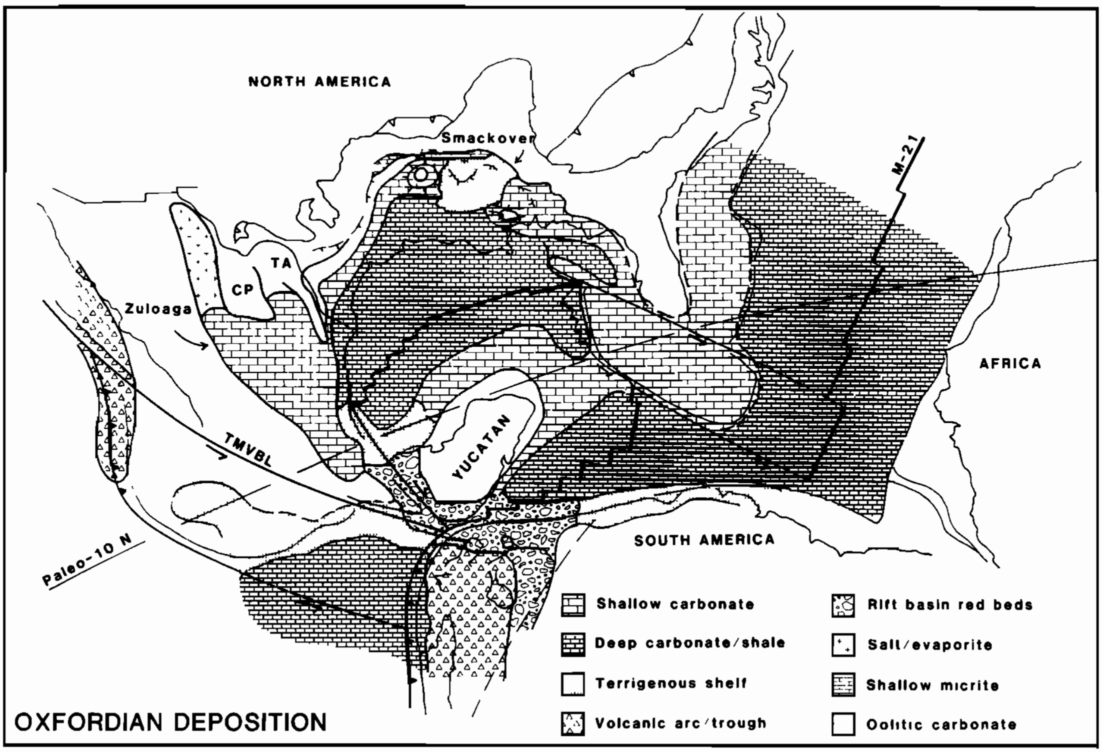

Fig. 13. Depositional facies of the Gulf region at the close of Smackover deposition, plotted on Late Jurassic plate reconstruction. CP, Coahuila Platform. Other abbreviations and conventions as in Figure 8.

This system has generally been attributed to extension between Africa and North America, but the distribution and orientation of dikes with 200-220 Ma isotopic ages fit a right-lateral shear model within the arcuate zone (pre-Atlantic shear zone, Figure 8) along the eastern U.S. and western African margins [Swanson, 1982]. It is not implied that each graben of the Newark series is a pull-apart basin sensu stricto, but extension was probably accompanied by dextral slip. Dextral shear along the eastern U.S. is compatible with north-south extension along the U.S. Gulf Coast; thus, the Eagle Mills and Newark systems may be attributed to the same relative plate motion.

Lying amidst the eastern and southern U.S. shear and extensional zones, respectively, is the complex region of continental blocks comprising Florida, the Blake Plateau and the western Bahamas. Dextral shear between North America and Africa would have led to convergence between western Africa and the Blake Plateau/eastern Florida. A possible origin for the Georgia Embayment is that of dextral shear, which would have allowed Florida to escape laterally from the Africa-Blake Plateau convergence. A shearing origin for the Georgia Embayment is suggested by the absence of a Jurassic sedimentary section there, as would be expected had the Embayment formed purely by extension.

To the west, southeasterly tectonic transport of blocks within Mexico began at this time, along one or several shear zones, or by internal strain. This motion effectively maintained a land bridge from North to South America until the Callovian or later. A speculative cause of this early motion is left-lateral oblique subduction of the Kula/Farallon Plate.

Middle Jurassic

Divergence between Africa and North America began in early Middle Jurassic time (Figures 9 and 10) by seafloor

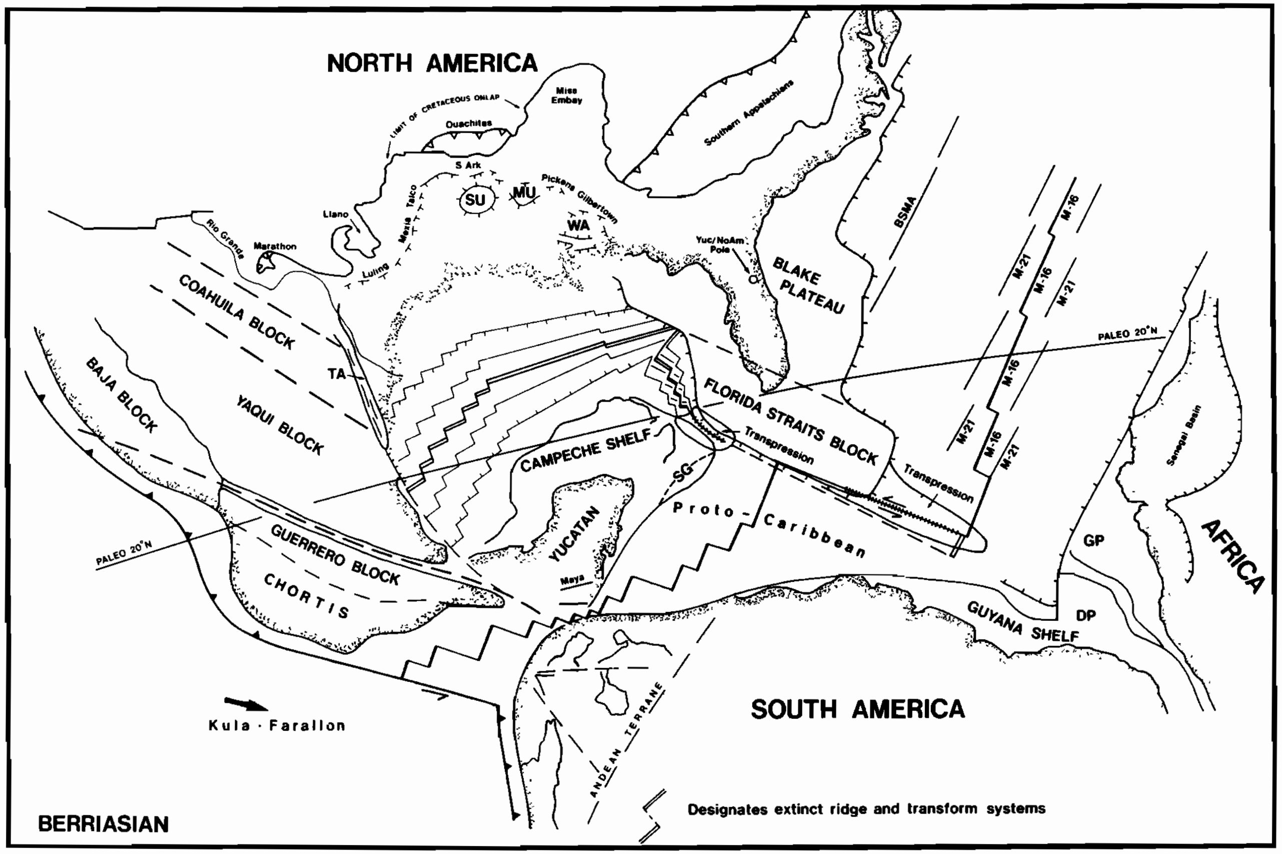

Fig. 14. Early Cretaceous (Berriasian) paleogeography of the Gulf region, about 140 Ma. Seafloor spreading terminated in the Gulf, and a change in position of the Central North Atlantic opening pole produced compression and uplift at the long left-lateral transform bounding the eastern Bahamas. Carbonate deposition has since kept pace with subsidence. Abbreviations and conventions as in Figure 8.

spreading north of the Blake Plateau, and by continental attenuation in the area of Blake Plateau and the Florida Straits block. The Blake Spur Magnetic Anomaly (BSMA) can be symmetrically correlated about the mid-Atlantic Ridge with the western margin of Africa, and aligns with the eastern boundary of the present Blake Plateau (Figure 11). Hence, it is evident that internal stretching within the Blake Plateau accounts for divergence between North America and Africa until the time when the BSMA formed (approximately 170 Ma). The crust to the north of the Blake Plateau that was created by seafloor spreading prior to formation of the BSMA produces 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], associated with which was ridge formation between the Blake Plateau/Florida Straits block and Africa.

In the developing Gulf of Mexico, Yucatan's progressive divergence from Texas-Louisiana was achieved by severe continental attenuation until probably Callovian or early Oxfordian time (postsalt), at which time seafloor spreading began. During this early rift stage in Gulf development, intracontinental extension was accompanied by subaerial deposition of the Werner red beds and anhydrites.

In the west, southeastward transport of blocks accelerated along the Mexican Cordillera, preventing the incursion of significant amounts of sea water into the Gulf realm (Figures 10 and 11). One probable zone of concentrated sinistral shear strain was the Mojave-Sonora megashear [Anderson and Schmidt, 1983; Silver and Anderson, 1974], although strike-slip fault motions may have occurred as far inland as the "Rio Grande lineament" (Figures 8 and 9), a term used here to define that line which bounds the northeastward extent of significant basement reactivation during both Jurassic and Laramide tectonism. Based on geometry, it is suggested that left-lateral offsets within the "Chihuahua block" north of the Mojave-Sonora megashear total approximately 100 km. Motions upon the Mojave-Sonora and faults within the "Yaqui" block (of Anderson and Schmidt [1983]) to the south collectively approach 800 km. These motions were completed by Oxfordian time, as the Zuloaga Group (Oxfordian) masks the Mojave-Sonora Megashear. Collectively, the motions are responsible for the emplacement of central Cordilleran Mexico into its present position with respect to North America, which was formerly occupied by northwest South America.

The postulation that Yucatan rotated out of the Gulf realm in turn implies that a corresponding, synchronous rotational opening occurred between Yucatan and Venezuela (Figures 9, 10, 11, and 12). This basin may be termed the "Proto-Caribbean" as it occupied the future site of the Caribbean but was subducted beneath the true Caribbean Plate during Late Cretaceous to Eocene time [Dickinson and Coney, 1980]. Whether this Proto-Caribbean basin was marine during Middle Jurassic time is debatable. However, the fact that it was subducted suggests that it was floored by oceanic or extremely attenuated continental crust, and that it was probably marine. Furthermore, Middle Jurassic marine sedimentary rocks are found in the northern ophiolitic belt of Cuba [Pardo, 1975] that were accreted to the Greater Antilles arc at the leading edge of the Caribbean Plate during subduction of the Proto-Caribbean. Finally, Middle Jurassic, terrigenous, partially marine sediments (San Cayetano Group) [Meyerhoff, 1964] are preserved upon presumably continental crust in the Sierra Guaniguanico of western Cuba; the latter is interpreted here as a portion of the rifted margin of the northeastern corner of the Yucatan block which was obliquely overridden and caught up by Cuba in the early Paleogene Bahamas-Cuba collision. That this margin of Yucatan bordered the Proto-Caribbean also suggests a marine character for the latter during the Middle Jurassic.

Late Callovian (Latter Middle Jurassic)

By the Callovian (Figure 11), basement attenuation had produced a broad, subsiding platform of continental crust. As this platform subsided through sea level, or as a tectonic barrier to either the Pacific or juvenile Atlantic was repeatedly breached, flooding of the Gulf realm and subsequent evaporation produced the once continuous Louann and Campeche salt deposits. The Punta Alegre and (?) Exuma Sound salt may also correlate with the Louann and Campeche, but may be slightly older (Bathonian) and relate to the opening of the Central North Atlantic rather than to the Gulf of Mexico. Such is the case with the

TABLE 2. Finite Rotation Parameters

Anomaly/Age	Latitude	Longitude	Angle[a]	Source
		Equatorial Atlantic Closure		
Jurassic to Early Cretaceous	52.08°N	34.03°W	51.39	e
		Gondwana With Respect to North America[b]		
Permo-Triassic[c] (Pangea)	65.55°N	13.69°W	-77.15	e
Mid-Jurassic (pre-Atlantic)	66.95°N	12.02°W	-75.55	f
Blake Spur Mag. Anomaly	67.02°N	13.17°W	-72.10	f
Late Callovian (Louann Salt)	67.13°N	15.49°W	-65.93	g
Anomaly M-21 (Tithonian)	66.50°N	18.10°W	-61.92	f
Anomaly M-16 (Berriasian)	66.10°N	18.40°W	-59.79	f
		Yucatan With Respect to North America[d]		
Permo-Triassic (Pangea)	29.74°N	80.36°W	-43.41	e
Mid-Jurassic	29.50°N	81.40°W	-41.00	e
Blake Spur time	29.50°N	81.40°W	-34.00	e
Late Callovian	29.50°N	81.40°W	-20.00	e
Anomaly-21 time	29.50°N	81.40°W	-9.00	e
Anomaly-16 time	...	...	...	h

a Positive angle is anticlockwise rotation looking down at pole.
b South America and northern Africa are treated as a single plate.
c Stage-pole from Permo-Triassic to Mid-Jurassic is 26.7°N, 63.4°W, 2.5° with respect to North America.
d Yucatan parameters measured in Mercator and contain inherent error.
e This study.
f Klitgord and Schouten [1982]. Klitgord (personal communication,1982).
g Interpolated between M-25 and BSMA of Klitgord and Schouten [1982].
h Early Cretaceous and Present position.

Senegal Basin and Guinea Plateau salt deposits [Jansa and Weidmann, 1982] which opposed the eastern Florida Straits block at that time (Figure 10). A Callovian age has not actually been proved for the Louann, but the majority of evidence [Scott, 1984] indicates a late Middle Jurassic age, probably late Callovian [Salvador and Green, 1980; Imlay, 1980]. Seismic stratigraphic studies [Buffler et al., 1980; 1981] suggest correlation of the Campeche and Louann deposits. The Louann (and probably Campeche) possesses shallow-water characteristics, and its clean, pure nature implies rapid deposition, perhaps on the order of only hundreds of thousands of years (C. Schreiber, personal communication, 1983). The environmental picture associated with the Gulf of Mexico's salt deposits consists of a subsiding basin/platform, during lithospheric attenuation, located possibly behind a foundering tectonic barrier to marine waters. Flooding by marine waters produced numerous or continued shallow-water influxes perhaps only tens of meters deep, the evaporation of which led to salt deposition at rates which easily matched rates of basin subsidence [Schreiber and Hsu, 1980].

Except for local occurrences such as the Buckner facies of the northern Gulf Coast, Gulf-wide salt deposition ceased by early Oxfordian time at the onset of relatively open marine circulation. Open circulation probably was structurally controlled by the establishment of the Gulf of Mexico's mid-ocean ridge system (Figures 11 and 12). The emplacement of oceanic crust at typical isostatic elevations (2.6 km below present sea level) produced a deep central Gulf trough sufficient to allow open marine circulation throughout most of the Gulf. Furthermore, it was not until about this time that the separation between South America and North America, incorporating all basement attenuation in the Gulf, was sufficient to accommodate the present size of the Yucatan block. The most likely entrance for marine waters into the Gulf during the Late Jurassic is between Florida and Yucatan, as DSDP leg 77 documented Jurassic extension and marine sedimentation [Schlager et al., 1984], and the Proto-Caribbean certainly had become marine by Oxfordian time. Spreading at the Gulf's ridge system isolated the main salt provinces, accounted for continued separation between the U.S. Gulf Coast and Yucatan without further basement attenuation within their margins, and translated the Florida Straits block to its present position beneath the western Bahamas and southern Florida (Figures 11, 12 and 14). Norphlet and Smackover deposition on the attenuated Gulf Coast margin was not controlled by primary rifting but by differential subsidence between adjacent basement blocks within a thermally subsiding platform and, perhaps locally, by salt migration where salt accumulations were sufficiently thick. The Norphlet effectively blanketed basement features (except Sabine and Wiggins) [Nicholas and Waddell, 1982; Cagle and Khan, 1983] so that by Smackover time (Figure 13), a true platform or carbonate ramp had developed [Budd and Loucks, 1981].

In the western Gulf, migration of Yucatan continued along the Tamaulipas-Golden Lane-Chiapas transform fault (TGLC). To the north of the migrating junction of TGLC and the central Gulf ridge system, TGLC evolved as a fracture zone separating zones of differential subsidence. The abrupt topographic low, or freeboard, east of TGLC received enormous volumes of sediment (for example, Burgos Basin east of Monterrey, Mexico) [King, 1969]. As strike-slip motion ceased along the Tamaulipas Arch, it subsided and eventually was onlapped by Upper Jurassic carbonates.

Along the Pacific margin, left-lateral migration of Mexican blocks may have occurred at this time primarily along the Trans-Mexican Volcanic Belt lineament. The portion of proto-Mexico referred to here as the Guerrero block could not yet have reached its present position because of overlap with South America. Models of Caribbean evolution [Wadge and Burke, 1983; Pindell and Dewey, 1982] assume a pre-Eocene connection between the Guerrero and pre-Mesozoic Chortis blocks; Chortis may have been connected to the Guerrero block at this time. Arc-related volcanism within Colombia is indicated for the Late Jurassic by radiometrically determined ages on presumably subduction-related plutons [Tschanz et al., 1974]. Convergence between Chortis-Guerrero and Colombia is, therefore, seen as likely. This can only have been possible if the Kula/Farallon Plate convergence rate with South America exceeded the spreading rate between North and South America, and if the Guerrero-Chortis terrane essentially belonged to the Kula/Farallon Plate, as the Salinian block of western California essentially belongs to the Pacific Plate today.

Early Tithonian (Late Jurassic)

Oxfordian-Kimmeridgian seafloor spreading at the Gulf ridge system separated the Yucatan and Florida Straits blocks from the U.S. Gulf Coast margin and isolated the three main salt provinces (Figure 13). Figure 13 summarizes lithofacies deposited in the Gulf area during Oxfordian time (primarily Smackover and equivalents). A postulated triple junction off of DeSoto Canyon in the northeast Gulf connected the central and eastern Gulf ridge systems to the postulated Florida Elbow transform. Southeastward migration of the Florida Straits block may have produced the steep, east-southeast trending portion of the northwestern Florida Escarpment. In the southwestern Gulf, transform motion between Yucatan and Mexico continued along the Golden Lane-Chiapas portion of TGLC. No salt was deposited along the Mexican margin where seafloor spreading occurred. In Chiapas, deposits of the Todos Santos "rift facies" are younger (Late Jurassic-Early Cretaceous) [Anderson et al., 1973] than those to the north (Werner and equivalents). This is because shear along the active transform between Yucatan and eastern Mexico continued longer in the south; that portion of TGLC north of the southward migrating central-Gulf spreading center progressively became a fracture zone, typified by simple thermal subsidence and carbonate deposition.

In Mexico, shearing, perhaps localized along the Trans-Mexican Volcanic Belt lineament, brought the Guerrero block (and Chortis-Nicaragua Rise) near its final position. To the east, the 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 Straits 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 Paleogene subduction of this crust has eliminated direct evidence for this proposition.

Berriasian (Earliest Cretaceous)

Horizontal plate motions associated with the opening of the Gulf of Mexico were completed by the earliest Cretaceous (Figure 14). It was not until this time that South America had migrated sufficiently far from North America to accommodate Yucatan in its present position relative to North America. Likewise, the Guerrero block of Mexico may have reached its final position as well. Termination of its southeastward migration may relate to cessation of a shearing component of subduction, as is indicated by the Early Cretaceous initiation of head-on convergence (northeast relative motion) between North America and the Kula/Farallon plates [Engebretson, 1982]. The termination of seafloor spreading in the Gulf of Mexico affixed the Yucatan and Florida Straits blocks to the North American Plate. Thus, continued spreading between North and South America occurred at a ridge system(s) in the Proto-Caribbean basin. This ridge must have been connected to the mid-Atlantic Ridge via a long left-lateral transform, and must have extended out into the Pacific realm between Yucatan and Colombia.

Beginning at magnetic anomaly M-21 and ending at M-4, fracture zone traces in the western Central North Atlantic possess a kink that indicates a westward shift in the Central North Atlantic pole position during that time interval [Klitgord and Schouten, 1982; Klitgord et al., 1984]. Such a shift should produce compression at any long left-lateral transforms in the system. Assuming that the eastern Bahamas is underlain by oceanic crust (see above), the origin of the eastern Bahamas platform (oceanic basement uplift to, or formation at, the photic zone) is probably due either to compression at the long left-lateral Bahamian transform zone, similar to the Recent 3 km uplift of basement at the Mussau Ridge of the eastern Caroline Plate [Hegarty et al., 1983] and the Pliocene emergence of the Romanche transform in the Equatorial Atlantic [Bonatti et al., 1977], or to extension and volcanism along the transform zone (hot spot). However, due to the kinematic prediction of compression arising from the temporary change in the Central Atlantic pole position, a compressional origin is favored here (Figure 14).

Post-Berriasian Development

Throughout most of the Cretaceous, carbonate banks developed across nearly all of the shelf margins of the Gulf, Bahamas, and Proto-Caribbean region. Terrigenous clastics were largely restricted to the arc systems bounding the Pacific realm. During the Late Cretaceous, however, thrusting, uplift and erosion in the Sierra Madre Oriental and the Rocky Mountain Overthrust provided enormous quantities of terrigenous clastics to the western and central Gulf realm. The Florida Banks were protected from clastic deposition by the DeSoto Canyon bathymetric barrier. The probable cause of this orogenesis is the arrival of buoyant oceanic masses at western North American trench systems. Also associated with this orogenesis was the migration of the present Caribbean Plate, led by the Greater Antilles arc system, into the Proto-Caribbean realm, thereby subducting crust of the Proto-Caribbean basin. The Caribbean Plate as a whole probably is a buoyant mass of Pacific origin [Burke et al., 1978]. Orogeny and clastic deposition has occurred progressively eastward along the margins of the Proto-Caribbean, associated with the northeastward migration of arc systems at the leading edge of the Caribbean Plate [Dickinson and Coney, 1980; Pindell and Dewey, 1982]. The Caribbean Plate interacted with the southern Yucatan shelf and northwest South America in the Late Cretaceous, the western and central Bahamas and north-central Venezuela in the Paleogene, and with northeastern Venezuela and the easternmost Bahamas in the Neogene [Pindell and Barrett, in press, 1985].

DISCUSSION

This evolutionary model of the Gulf of Mexico, Bahamas and Proto-Caribbean was constructed by integrating Gulf-region geology within a framework of empirical geometric and plate-kinematic constraints, including the North America-Africa relative-motion history, the initial Africa-South America reconstruction, restoration of continental attenuation in rifted margins, and a revised shape of northern South America. Any model of Gulf evolution is highly dependent upon the prerift position of Yucatan with respect to North America; this position largely defines the rotation required to move Yucatan to its present position. That Yucatan originated between Venezuela and the U.S. Gulf Coast margin is strongly suggested by (1) the close match between the Triassic shape of Yucatan and the continental void remaining between Venezuela and the U.S. Gulf Coast margin after consideration of the above geometric constraints, (2) the absence of Upper Permian to Middle Jurassic marine sediments in Gulf-region stratigraphic columns, and (3) the geometry of Alleghenian orogenesis, which indicates the former existence of a buoyant (continental) mass directly south of the Ouachita-Marathon thrust belts during collision (the so-called Llanoria Plate). In addition, Late Paleozoic geology correlates well across this reconstruction of North America, Yucatan and South America. Finally, the rotation required to move Yucatan from its suggested prerift position to its present position both explains and is supported by the majority of post-Triassic Gulf-region geology, providing further iterative evidence favoring the proposed Alleghenian reconstruction.

This study illustrates the importance of basing regional models of evolution within a framework provided by paleopositions and relative motions of major plates. In the case of the Gulf of Mexico, the motions of Yucatan, the Florida Straits block, and blocks within Mexico are constrained by the presence and motions of the larger North and South American plates. The significance of internal continental attenuation prior to seafloor spreading has been stressed, and evolutionary models of other regions such as the Mediterranean also should incorporate internal extension during initial rifting. In the Gulf of Mexico, only about half of the separation between Yucatan and the U.S. Gulf Coast was accomplished by seafloor spreading, whereas the other half was achieved by intracontinental extension.

Thick occurrences of salt in extensional regimes around the world are deposited primarily upon rifted, subsiding continental crust. Rift-related salt deposits in the Gulf of Mexico occur primarily in realms of attenuated continental crust as defined by seismic reflection and refraction methods [Buffler et al., 1980, 1981; Ibrahim et al., 1981]. Thus, reconstructing boundaries defining the original depositional limits of salt, prior to halokinesis, is useful for estimating paleogeography at the onset of seafloor spreading. The Gulf of Mexico provides an example which, despite salt migration beneath Sigsbee Escarpment, suggests that in areas of poorly known basement structure, the occurrence of salt deposits may be used to roughly approximate the extent of attenuated continental crust.

Acknowledgments. This work was done largely during the author's employment by the Exploration Research Division of Pennzoil Exploration and Production Company from October 1982 to June 1983. Many thanks are due to all those at Pennzoil who contributed to the project. In particular, I am indebted to Kent Johnson, Pamela Moore, Dietmar Schumacher, Robert Spoelhof, Carol Tessier and Stanton White for valuable discussion and assistance. I sincerely thank John Dewey and Walter Pitman for involving and supporting me in regional studies of Alleghenian paleogeography, and for continuing to assist with those efforts. In addition, Steven Barrett, Richard Buffler, John Cagle, Robert Erlich, Stuart Hall, Garry Karner, Kim Klitgord, John Ladd, Chad McCabe, Clyde Moore, Charlotte Schreiber, and Graham Westbrook have provided me with valuable input, criticism and advice. Walter Pitman, Steven Barrett, and two anonymous persons reviewed and improved the manuscript.

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J. L. Pindell, Department of Geological Sciences, Durham University, Durham DH1 3LE, United Kingdom.

(Received October 4, 1984;
revised December 14, 1984;
accepted December 15, 1984.)