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Permo-Triassic reconstruction of Western Pangea and the evolution of the Gulf of Mexico-Caribbean region

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

Abstract of
a thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree of
Master of Science

College of Science and Mathematics
Department of Geological Sciences

James Lawrence Pindell

1981

ABSTRACT

A Permo-Triassic reconstruction of western Pangea (North America, South America, Africa) is proposed that is characterized by: 1) definition of the North Atlantic fit by matching of marginal offsets (fracture zones) along the opposing margins, 2) a South Atlantic fit that is tighter than the Bullard fit and that is achieved by treating Africa as two plates astride the Benue Trough and related structures during the Cretaceous, 3) complete closure of the Proto-Atlantic Ocean between North and South America, accomplished by placing the Yucatan block between the Ouachita Mountains and Venezuela, 4) a proposed Hercynian suture zone that separates zones of foreland thrusting from zones of arc-related magmatic activity; to the northwest of this suture lie the Chortis block and Mexico and most of North America, and to the southeast of this suture lie South America, the Yucatan block, Florida and Africa, and 5) satisfaction of paleomagmatic data from North America, South America and Africa. Beginning with the proposed reconstruction, the relative motion history of South America with respect to North America is defined using the finite difference method. Within the framework provided by the proposed relative motion history, an evolutionary model for the development of the Gulf of Mexico and Caribbean region is outlined in a series of 13 plate boundary reconstructions at various time intervals from the Jurassic to the present. The model includes: 1) formation of the Gulf of Mexico by 140ma, 2) Pacific provenance of the Caribbean plate through the North America-South America gap during Cretaceous time, 3) Paleocene-Early Eocene back-arc spreading origin for the Yucatan Basin, whereby Cuba is the frontal arc and the Nicaragua Rise-Jamaica is the remnant arc, and 4) 1400 km of post-Eocene cumulative offset along both the Northern and Southern Caribbean

Plate Boundary Zones, allowing grandiose eastward migration of the Caribbean plate with respect to the North and South American plates.

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INTRODUCTION

The relative motion of two plates separated by a mid-oceanic ridge can be derived by assuming that symmetrically disposed pairs of magnetic anomalies were once adjacent at the ridge at a time which is equivalent to the age of the anomaly pair. Extending this approach to a three-plate system of plates A, B and C where the spreading history is known between the A-B pair and the B-C pair, the relative motion history of the A-C pair, if it is known, may be arrived at by completing the vector circuit (McKenzie and Morgan, 1968) or finite difference circuit (Dewey, 1975) for several intervals through time. The spreading histories for the North and South Atlantic Oceans are fairly well known. However, much of the crust (and its magnetic anomalies) that was produced during the initial separation between North and South America has been later destroyed by Caribbean evolution and cannot be directly evaluated. Therefore, the finite difference method for the North America-Africa-South America three-plate system is the most valuable first-order technique by which to examine Caribbean evolution because it provides the relative positions of the North and South American continents at various times since the initial breakup of Pangea. Within this framework, an evolutionary model for the Caribbean region is presented.

From the relative positions of North and South America through time, the relative motion vector between the two can in turn be defined. Further, if individual time intervals are plotted along the relative motion vector, then the relative motion history may be defined. The relative motion history between North and South America provides valuable information with regards to Caribbean evolution. It indicates whether extension, compression or transcurrent motion (or combinations thereof) occurred between North and South America and, just as important, when these motions occurred. By plate tectonic theory, extensional, compressional or transcurrent periods probably are characterized by plate accretion, subduction and strike-slip motion, respectively. It is possible, however, that more complex plate boundary geometries have existed whose net effects have matched the simplest required geometries. It is to be hoped that analysis of Caribbean geology can account for these possibilities.

Of vital importance to establishing the relative motion and history is the Jurassic pre-drift reconstruction of North America, South America and Africa. Published initial fits of the major continents are varied (see chapter 1 for a review) but all leave a gap in the Gulf of Mexico area that cannot be filled with continental crust without rearranging various blocks of Central America. Two schools have evolved: one that accepts a remnant hole of pre-Mesozoic ocean crust beneath the present Gulf of Mexico, thereby placing Central America out in the Pacific, and another fills the gap by complex arrangement of the Central American blocks in the area now occupied by the Gulf and Gulf coastal plain. The former allows a simpler tectonic emplacement of present-day Central America but fails to explain significant aspects of Pennsylvanian-Permian regional geology. The preservation of a remnant hole seems unlikely because of 1) the intensity and continuity of the Pennsylvanian-Permian orogeny (chapter 1), 2) the rare occurrence of oceanic holes in other orogenic belts around the world, 3) analyses of strike-slip lateral motions within present-day collision zones which inevitably fill or replace topographic lows with thick sediment wedges and/or crustal blocks and 4) the desert-like climatic conditions indicated by the Early Mesozoic geology of southern North America and northern South America. Consequently, I adopt and strongly adhere to the beliefs of the closed-ocean school. Examination of the Late Paleozoic-

Early Mesozoic geology of southern North America, northern South America and Central America and the Cretaceous geology of Africa (chapter 1) had led to a closed paleogeographic reconstruction of western Pangea that provides the initial positions of the major continents for the relative motion vector between North and South America.

CHAPTER I

RECONSTRUCTION OF WESTERN PANGEA

Review of published continental reconstructions:

Various models to match opposing continental margins of the North Atlantic and the South Atlantic Oceans produce different pre-rift relationships between North and South America (see figure 1). Methods of approach to the problem have ranged from least error matching of present-day 2000 meter contours from opposing margins (Bullard, et al., 1965) through paleomagnetism (Van der Voo and French, 1974) to the alignment of major fracture zones from opposing margins (LePichon and Fox, 1971; Klitgord and Schouten, 1980 ; LePichon and Hayes, 1971;others). Probably the most valid criterion is the alignment of fracture zones since they are a direct result of intracontinental rifting. Paleomagnetism depends too heavily on precise dating of samples collected, and least error matching of opposing margins suffers from changes in continental margin morphology through time. The pre-rift fit between Africa and North America is then, probably closely appoximated by LePichon and Fox (1971) and Klitgord and Schouten (1980). while the pre-rift fit between Africa and South America that was originally proposed by Bullard et al. (1965) has been further supported by LePichon and Hayes (1971) using the fracture zone criterion. However, these two fits leave a substantial non-continental gap between North and South America (figure 1), whereas the geology of southern North America and northern South America indicates Penn-Perm continental collision, Triassic-Early Jurassic non-marine sedimentation and Middle to Late Jurassic rifting. It is felt here that continental juxtaposition must have been achieved so that the entire Gulf of Mexico and Caribbean Sea were formed during Middle Jurassic and younger times.

One way to overcome this problem is to fill the gap with both the Yucatan and Chortis blocks (see figure 2) as in White (1980). However, this arrangement leads to exceedingly complex rotations of the Chortis

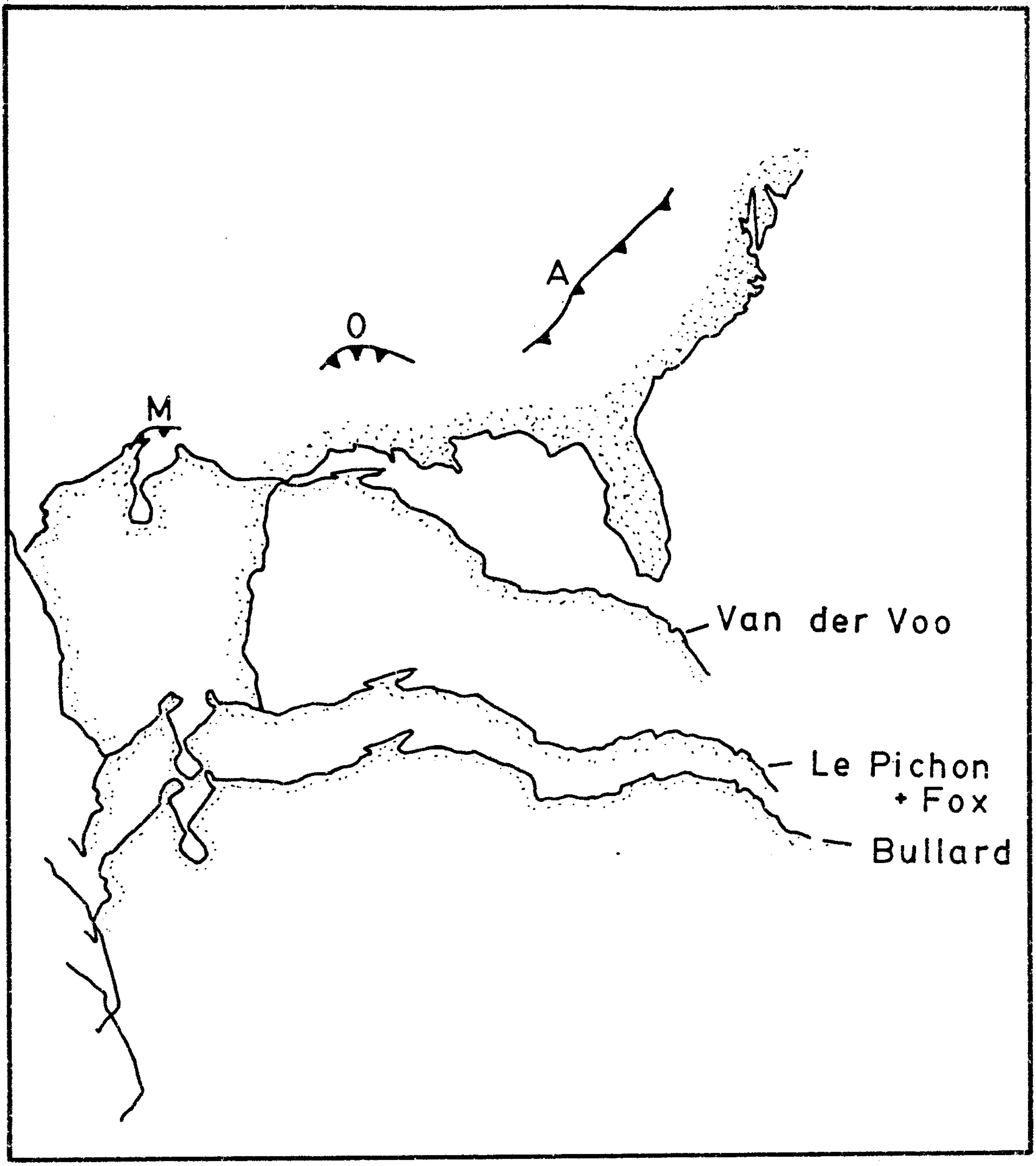

Figure 1. Variations in the initial relationship between North and South America provided by different methods of continental juxtaposition. All assume Bullard's fit for the South Atlantic. M = Marathon; O = Ouachita; A = Appalachian.

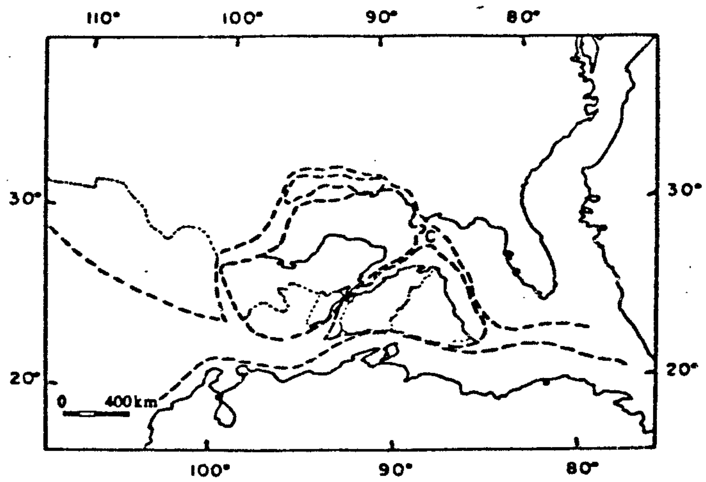

Figure 2. White's (1980) reconstruction filling the non-continental gap of LePichon and Fox (1971) with the Yucatan and Chortis blocks.

block in order for it to achieve its present position. The Yucatan block alone cannot fill the entire gap, and thus it is apparent that a simple resolution to the problem is lacking.

Van der Voo and French (1974) suggested major right-lateral shear between North America and Africa during Triassic time, starting with a closed situation between North and South America and ending with a pre-Atlantic reconstruction that is similar to that of Bullard et al. (1965). Geologic evidence along the Atlantic seaboard for this magnitude of shearing is lacking, although some may have occurred as suggested by dike orientations (Swanson, personal communication). Another, better evidenced explanation is required.

Examination of central African geology suggests that Africa may have acted as two plates during the Cretaceous (Burke and Dewey, 1974) so that its present shape is not equivalent to its Jurassic, pre-drift shape. Following this approach, a new pre-drift fit between Africa and South America is obtained that satisfies the marginal fracture zone criterion. This new fit, combined with regional analysis of Late Paleozoic-Early Mesozoic geology of the circum-Caribbean/Gulf of Mexico continents and continental fragments, leads to a reconstruction of western Pangea that completely closes the Paleozoic ocean and produces a very continuous, internally consistent belt of Hercynian deformation.

Two plates in Africa hypothesis and the revised South Atlantic fit:

The most commonly accepted South Atlantic fit is that of Bullard et al. (1965) which is further supported by alignment of marginal fracture zones (LePichon and Hayes, 1971). However, this fit assumes that continental material underlies the entire Amazon portion of the South American shelf. The enormous thickness of post-rifting sediments (figure 3a)

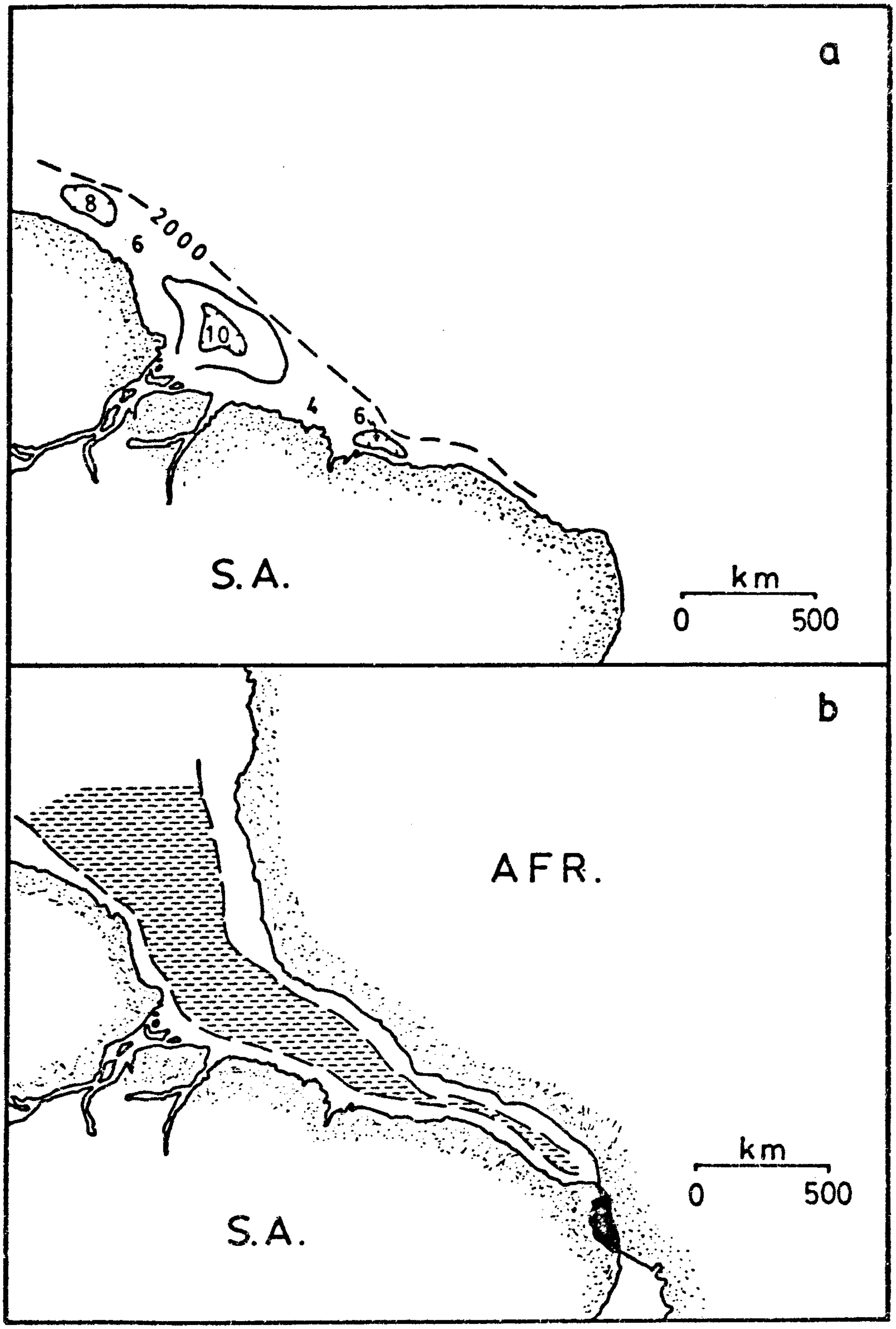

Figure 3. a) Sediment isopachs and 2000m contour along the Amazon Shelf, assumed by Bullard et al. (1965) to be underlain by continental crust. b) Revised interpretation of continental limit following the principle that 8 to 10 km of sediment cannot lie upon normal continental crust. Stipled pattern is the gap in the Bullard fit.

beneath most of this portion of the shelf (5-10 km, Kumar, et al., 1979) indicates that only oceanic or extremely thinned continental crust can be present there. Thus, the Bullard fit apparently leaves a substantial gap (see figure 3b) between the northern Brazilian and Guinea margins. In light of the fact that Gondwana was one of the most stable cratonic masses of the Phanerozoic until the Cretaceous, the existence of this gap during Late Paleozoic to Cretaceous time is highly unlikely and thus the Bullard fit can probably be improved. It is apparent that a satisfactory fit for the South Atlantic cannot be made if torsional rigidity is assumed; rotation of Africa with respect to South America to close the Amazon gap simultaneously produces a gap in the southern South Atlantic.

Rabinowitz and LaBrecque (1979) noted that the rifting history of the South Atlantic was such that rifting occurred earlier in the southern South Atlantic (~130 ma) than in the equatorial Atlantic (anomaly MO)[1]. Starting from an initial fit similar to that of Bullard et al. (1965), they attributed this to a counterclockwise rotation of all of the African continent with respect to South America from 130 ma to MO (110 ma) about a pole just off the northeast coastline of Brazil. This rotation requires that ~150 km of shortening and compression occurred between the Ivory Coast section of Africa and northern Brazil for the period 130-110 ma. Although minor compression probably associated with imperfect transform motion during the opening phase of the equatorial Atlantic is known from beneath the Demerara Plateau (Hayes, et al., 1972), evidence for major shortening (150 km) has not been documented. Of great importance though, is that the post rotational configuration (110 ma) of the equatorial

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[1] Anomaly MO was assigned an age of 107 ma in Rabinowitz and LaBrecque (1979) but I adopt the time scale of Van Hinte (1976 a,b) for the Mesozoic/Cenozoic. In this study, it is assumed that the age of MO is 110 ma.

portions of South America and Africa fills the Amazon gap in the Bullard fit. Further, 110 ma is about the time of initial rifting in the equatorial Atlantic (Kumar, et al., 1976; Asmus and Ponte, 1973; Rabinowitz and LaBrecque, 1979). These considerations lead to the conclusion that the MO configuration of Rabinowitz and LaBrecque (1979) closely approximated the Early Mesozoic configuration as well, and that the (130-110 ma) rotation of northern Africa with respect to South America never occurred. Thus, the Amazon gap in the Bullard et al. (1965) fit can be disposed of in this manner. However, satisfactory closure of the entire South Atlantic Ocean cannot be achieved by assuming rigid plates; post-Jurassic internal deformation must have occurred within Africa and/or South America.

Although Grabert (1977) reports evidence for Late Jurassic faulting and minor strike-slip motion in the upper Amazon Valley of South America, large-scale post-Jurassic tectonic deformation of this continent is not supported by geological or geophysical evidence. In contrast, intense internal deformation in central Africa of Cretaceous age is abundant. Burke and Dewey (1974) call attention to widespread basaltic magmatism and block-faulting across central and northern Africa (summarized in figure 4) that they consider to be a poorly defined plate boundary zone, where net differential motion between northwest and southeast Africa occurred over a wide zone of strain. The only true plate boundary within this system may have developed in the Benue Trough, whose stratigraphic column is shown in figure 4. Burke and Dewey (1974) interpret the Cretaceous tectonic history of the Benue Trough as follows: 1) Hauterivian to Albian rifting and plate accretion; 2) Albian to early Santonian (108-86) marine sedimentation in a narrow oceanic trough; 3) late Coniacian to Santonian (88-80 ma) closure of the trough resulting in deformation of the whole Benue sequence. The amount of spreading and closure that occurred cannot

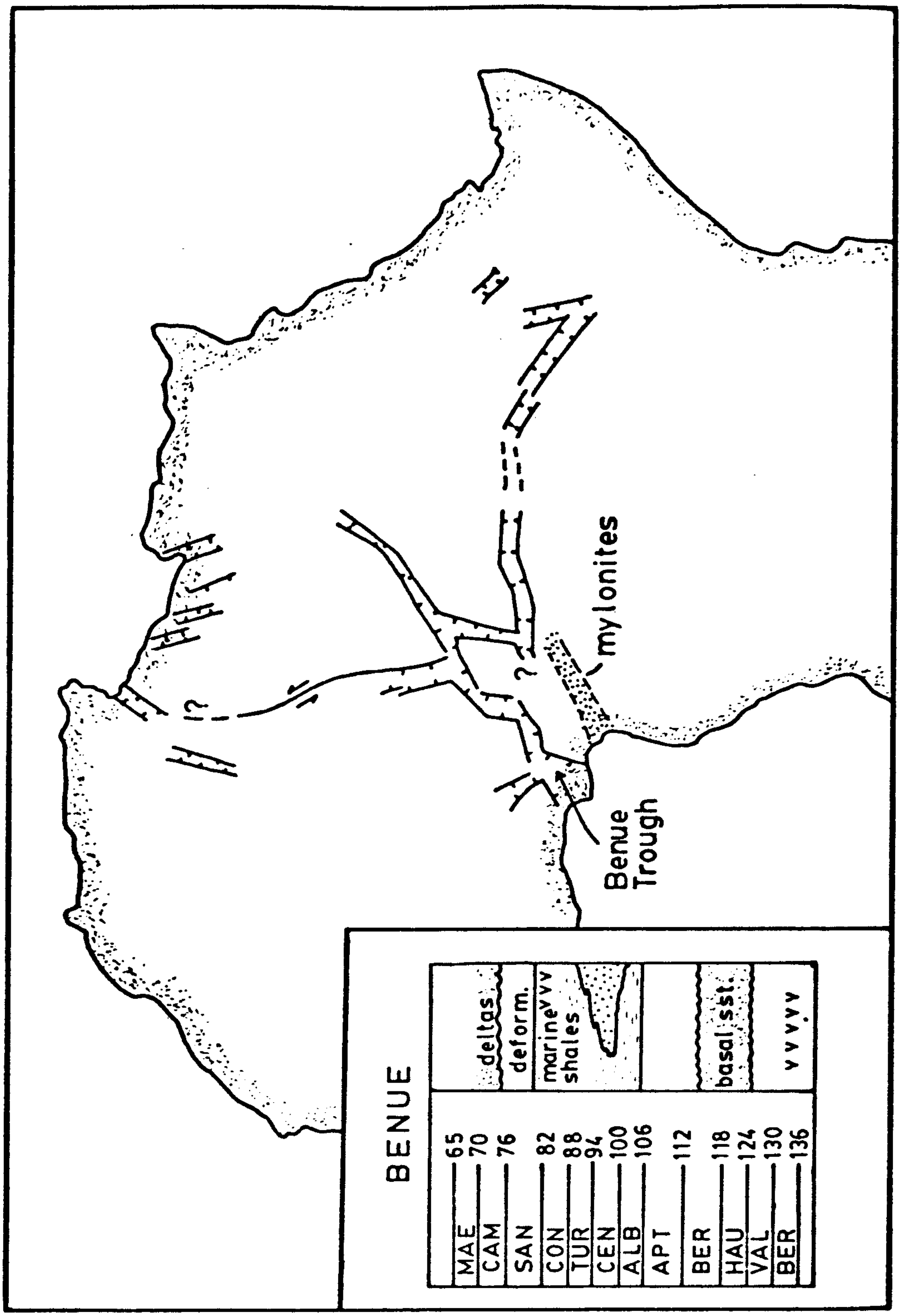


Figure 4. Generalized map of Africa showing Early Cretaceous rift and strike-slip fault systems; Cooper, personal communication. Inset: schematic stratigraphic column of Benue Trough area; after Burke, 1976, page 100; Burke and Dewey, 1974; Murat, 1972.

be defined. Any relative motions between northwest and southeast Africa that may have led to differences in spreading rates along the early South Atlantic ridge cannot be observed because most of the Benue episode occurred during the Cretaceous quiet period. All that can be said of the Benue episode (and its extensions into central and northern Africa) is that the amount of extension exceeded the amount of closure. This is indicated by a pronounced positive gravity anomaly and the subdued, trough-like character of the underlying basement. Therefore, it is inferred that "remnant extension" exists today which did not exist before Early Cretaceous time, and that the present day shape of Africa should not be used in pre-Cretaceous paleoreconstructions.

The net effect of the Cretaceous deformation cannot be determined by African geology, but it is here suggested that the net deformation is equivalent to the difference between Africa's present shape and the shape that is required to produce a fit with South America that is closed in both the Amazon and southern South Atlantic regions. Figure 5 shows this closed fit and also compares the pre-deformational and post-deformational shapes of the African continent. Marginal fracture zones commonly used for matching the opposing margins in the southern South Atlantic are also shown in figure 5, and it is clear that the proposed pre-drift reconstruction satisfies the fracture zone alignment criterion.

The new pre-drift geometry of the southern continents will be matched with the geometry of southern North America to obtain the western Pangean reassembly. But first, a regional review of southern North America and of northern South America is presented in order to 1) define more precisely the margin geometries to be fitted, 2) identify tectonic environments (e.g., foreland, arc, etc.) along the margins to be fitted, and 3) show that the final closed reconstruction produces a continuous belt

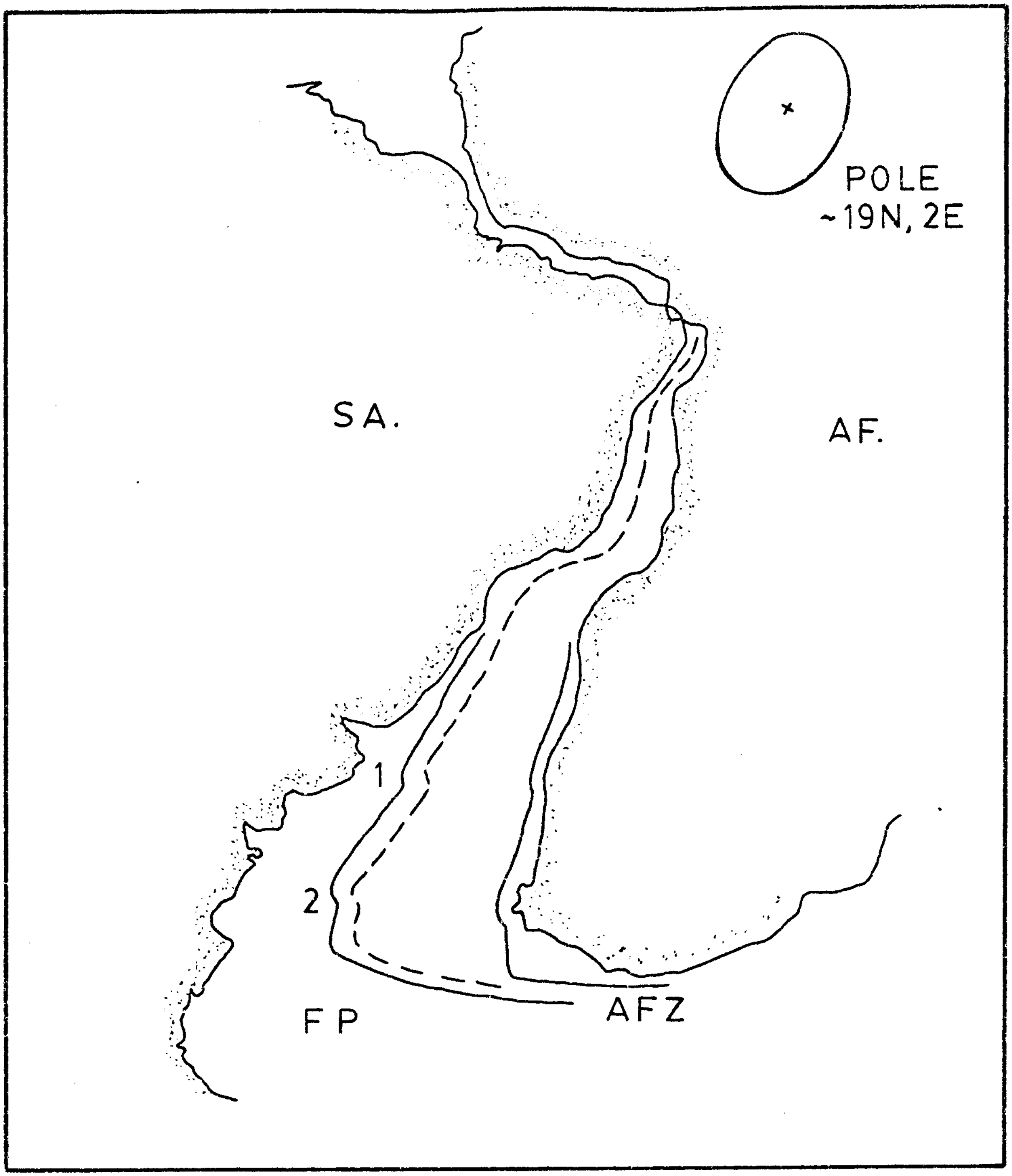


Figure 5. Difference between pre-Cretaceous and present shapes of Africa. Solid lines are present shapes of the continents and continental shelves, dashed line is proposed pre-deformational position of southern Africa with respect to South America. FP = Falkland Plateau; AFZ = Agulhas Fracture Zone; 1 and 2 = other fracture zones proposed by Rabinowitz and LaBrecque (1979). Pole position is that which defines early motion of southern Africa with respect to North Africa-South America.

of Hercynian deformation that is internally consistent with respect to the tectonic environments described therein.

Late Paleozoic geology of southern North America and evidence for the Hercynian suture zone:

A fairly continuous belt of deformation of Permo-Carboniferous age runs from the northern Appalachians through the southern Appalachians, the Ouachitas and the Marathons and into the Huastecan "belt" of eastern Mexico (see figure 6). Despite the apparent continuity of this belt, evidence for locating its associated suture is very sparse. No clearly defined suture zone has yet been identified in North America, nor has one been defined within northwestern South America or western Africa. It must be assumed that much of the suture lies beneath the thick coastal plains sequence or within the continental margins of the continents.

Two probable exceptions to this rule exist, however, both of which occur in the southern United States. First, the Suwannee Basin of northern Florida and southernmost Georgia (see figure 6) contains early Paleozoic faunal assemblages typical of Africa (Gondwanaland) (King, 1975) and thus Wilson (1966) suggested that this portion of present-day North America became "welded on" during the Late Paleozoic closing of the Proto-Atlantic Ocean. The Hercynian suture probably passes between the Suwannee Basin and the Southern Appalachians. The latter are definitely composed of material that had belonged to North America at least since Devonian times (Hatcher, 1978). The second exception lies to the south of the Ouachita system in the subsurface structural high called the Sabine Uplift (figure 6). Drilling has recovered Mississippian aged volcaniclastics that may, in fact, represent the Permo-Carboniferous arc associated with the closure of the Proto-Atlantic (Dewey, personal communication). Assuming that the

Figure 6. Simplified tectonic map of Late Paleozoic geology of southern North America.

Legend:

1. Appalachian Front
2. Ouachita Front
3. Marathon Front
4. Huastecan Zones X = locations of ophiolitic bodies
5. Suwannee Basin
6. Sabine Uplift
7. Llano Uplift
8. Devil's River Uplift
9. Texas Lineament
10. Chihuahua Trough

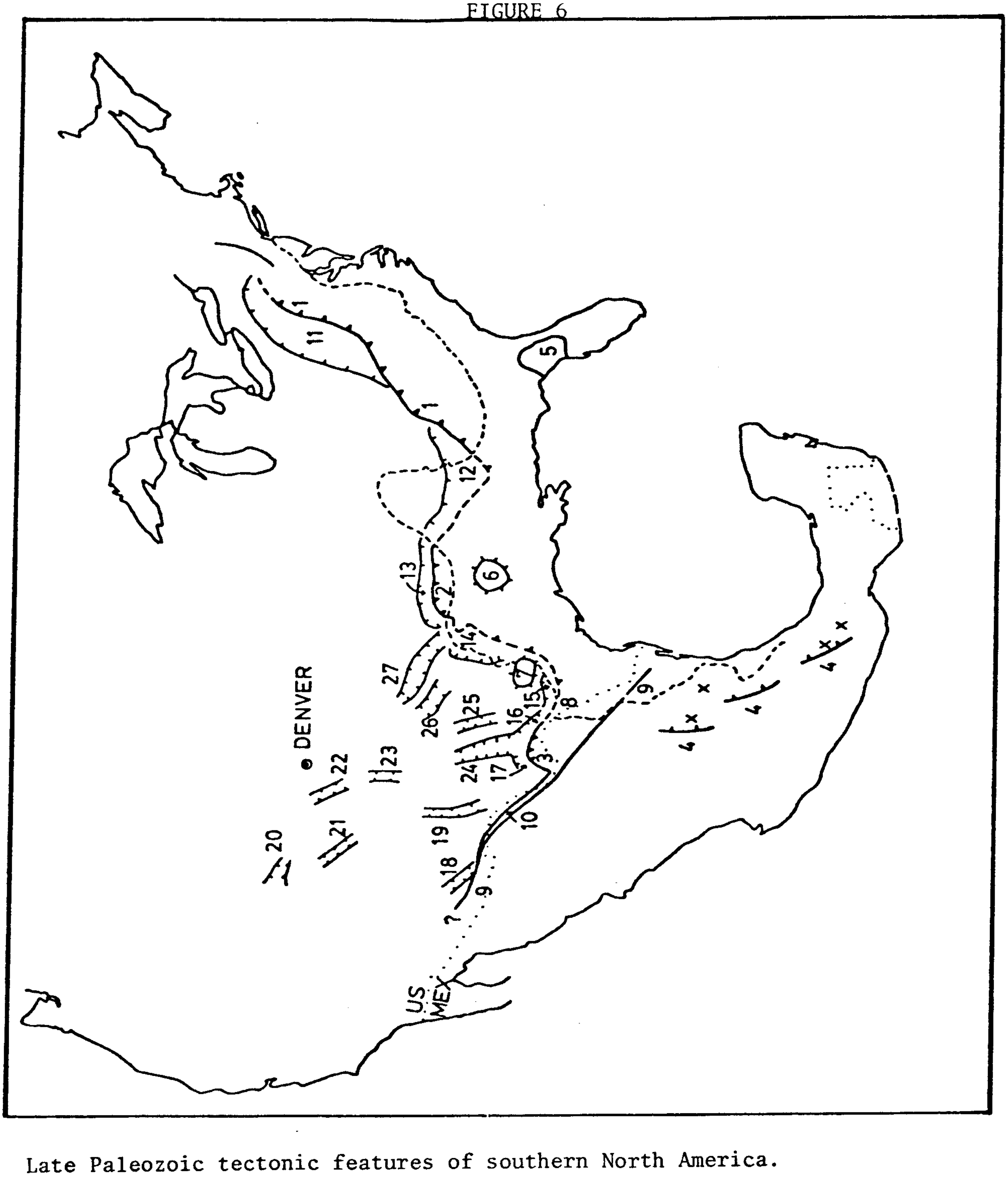
Foredeep Basins:

11. Appalachian
12. Black Warrior
13. Arkoma
14. Fort Worth
15. Kerr
16. Val Verde
17. Marfa

Pull-apart Basins

18. Pedregosa
19. Orogrande
20. Oquirrh
21. Paradox
22. Central Colorado Trough
23. Rowe-Mora
24. Delaware
25. Midland
26. Palo Dúro
27. Anadarko

FIGURE 6



Late Paleozoic tectonic features of southern North America.

Ouachitas represent allochthonous sheets emplaced onto the North American foreland (as described in Graham, et al., 1975; Kluth and Coney, 1981), I suggest that the Hercynian suture passes between the Sabine Uplift and the Ouachita Mountains. Both potential segments of the Hercynian suture zone are deeply buried beneath coastal plain deposits, however, and thus no firm evidence exists to prove the suture's existence in these areas. The geology of the Appalachian-Ouachita-Marathon-Huastecan deformation belt is described briefly below in an attempt to gain a better understanding of the Hercynian Orogeny of eastern and southern North America.

Appalachian System

Evidence that the Hercynian suture lies to the east and south of the Appalachian-Ouachita-Marathon-Huastecan belt is abundant. In the northern Appalachians, Late Pennsylvanian-Early Permian Hercynian foreland effects were felt in Rhode Island (high potassium granites, high temperature metamorphism, Skehan, et al., 1979) and the Canadian Maritimes (halokinesis, strike-slip motions). In the Central and Southern Appalachians, deformation began in the Late Mississippian (Chesterian) (Dewey, personal communication) and large-scale thrusting continued at least through the Late Pennsylvanian, possibly into the Permian. Total shortening within the southern Appalachians is at least 300 km as shown by COCORP seismic reflection studies (Cook, et al., 1979). Deciphering the polarity of subduction before the continent-continent collision that produced the Appalachian deformation is difficult, but the westward emplacement of giant thrust sheets onto the North American craton suggests that subduction was down to the east.

Ouachita System

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

Marathon System

Stratigraphy and deformation in the Marathon region, West Texas is similar to that in the Ouachita system to the northeast. The two systems continue toward one another beneath the Cretaceous and Cenozoic cover that onlaps the Llano Uplift, a domal structure containing Precambrian rocks that occupies a salient in the Hercynian deformation belt (figure 6). Right-lateral syntectonic motion on the Devil's River Uplift or fault system (see figure 6) produced the apparent offset between the Ouachita and Marathon belts (Muehlberger, 1965). Marathon folding and thrusting occurred during Late Pennsylvanian to early Permian time, culminating in the Wolfcampian (King, 1977), and thus the final Marathon deformation post-dates the final Ouachita deformation by perhaps 15 to 20 million years.

Huastecan System

South of the Marathon area it becomes difficult to trace the continuation of the Hercynian deformation belt with confidence. There is, however, a somewhat disrupted trend of Paleozoic rocks that continues to the south along eastern Mexico (see figure 6) known as the Huastecan Structural Belt (de Cserna, 1976) which has undergone Late Paleozoic folding and westward migrating thrusting similar to that in the Marathon-Ouachita areas. These rocks range from early Paleozoic (de Cserna, 1971) to Late Paleozoic (Denison and others, 1970) in age and contain ophiolite bodies (figure 6) at Catorce, west of Ciudad Victoria, in the Tecomatlan area of Puebla, and north of Oaxaca City (de Cserna, 1976). The Huastecan belt has been described as "consisting of a sedimentary nonmetamorphosed external part or outer zone, and a metamorphosed internal part or inner zone ... where in several localities the two parts are interposed or superposed, due to the allochthonous nature of the sequence or sequences" (de Cserna, 1976), probably by middle Permian time.

The present-day distrupted nature of the Huastecan belt is probably due to Jurassic left-lateral motions upon several WNW trending strike-slip faults through Mexico. This motion was at least partially responsible for the emplacement of Mexico into its "overlap position" with South America which is encountered with most circum-Atlantic continental reconstructions. Major left-lateral offset of Jurassic age has also occurred along the Texas Lineament (figure 6). The Texas Lineament sinistrally offsets the Huastecan Belt from the Marathon Belt by about 700 km and thus it is felt here that motion along the Texas Lineament was responsible for most of Mexico's southeastward migration into the overlap position with South America, after North America had rifted from South America-Africa. Silver and Anderson (1974) have proposed a similar offset to have occurred upon the Mohave-Sonora Megashear. The exact offsets on the various faults are still uncertain, but it is clear that motions of this kind must have occurred if we are to accept most circum-Atlantic reconstructions of Pangea. These matters are considered further in chapter 3.

Sedimentary Basins of the foreland

In south-central and southwestern North America, in front of the main zones of Hercynian thrusting, basin development was extensive. The basins are of two general types; some formed as a result of transtensional strike-slip (pull-apart basins) while others are clearly foreland trough or foredeep-type basins which were partially overridden by and included in Hercynian thrusting. Pull-apart basins include the Anadarko, Palo Duro, Central Colorado Trough, Rowe-Mora, Oquirrh, Paradox, Orogrande, Pedregosa, Delaware and Midland basins; and foreland troughs include the Appalachian, Black Warrior, Arkoma, Fort Worth, Kerr, Val Verde and Marfa basins (figure 6). The "sedimentary nonmetamorphosed external zone" of the Huastecan Belt (de Cserna, 1976) includes Permian sediments that were probably deposited in foreland troughs as well. Pull-apart basins in Mexico are poorly known (at least to the public), although Permian deposits in the Chihuahua Trough (figure 6) (Gries, 1979) may indicate an early episode of right-lateral transtensional motion upon the Texas Lineament. Kluth and Coney (1981) equate the development of the pull-apart basins and associated strike-slip activity to foreland deformation as southern North America underwent collision with South America-Africa. Several west to northwest trending strike-slip faults formed in response to the stress field created by the collision, and some of these reactivated older crustal structures (for example, Anadarko, Delaware aulacogens) which were related to the Late Precambrian-Early Paleozoic rifting event of eastern North America (Hoffman, et al., 1974; Stewart, 1976).

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

Summary of Hercynian deformation

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

Zone	Time of thrusting/collision
Southern Appalachians	Began in Late Mississippian (Chesterian) continued into the Late Pennsylvanian
Ouachitas	Atokan to Desmoinesian
Marathons	Virgilian to Wolfcampian
Huastecans	Early to Middle Permian

Late Paleozoic geology of northern South America:

As noted earlier, direct evidence to indicate the location of the suture zone(s) associated with the Hercynian collision between southern North America and South America-Africa is minimal. In the South American Andes from Colombia to at least as far south as northern Chile, pre-Upper Devonian igneous and sedimentary rocks show Late Devonian uplift and deformation and are unconformably overlain by thick sequences of Carboniferous to Permian granodiorites, andesitic volcanics and volcano-clastic sediments (Irving, 1975; Almeida, 1978). In the Colombian Andes, volcanics related to this active arc form significant portions of the Cordillera Central, the Sierra de Santa Marta and the Guajira Peninsula (see figure 7). Deep water sediments of equivalent age flank and are interbedded with the andesites on the western shoulders of the three complexes. The three complexes appear as separate masses, but Tertiary strike-slip faulting has segmented the once continuous arc complex (Case and MacDonald, 1973). To the east of the arc complex, Carboniferous to Permian black shales and

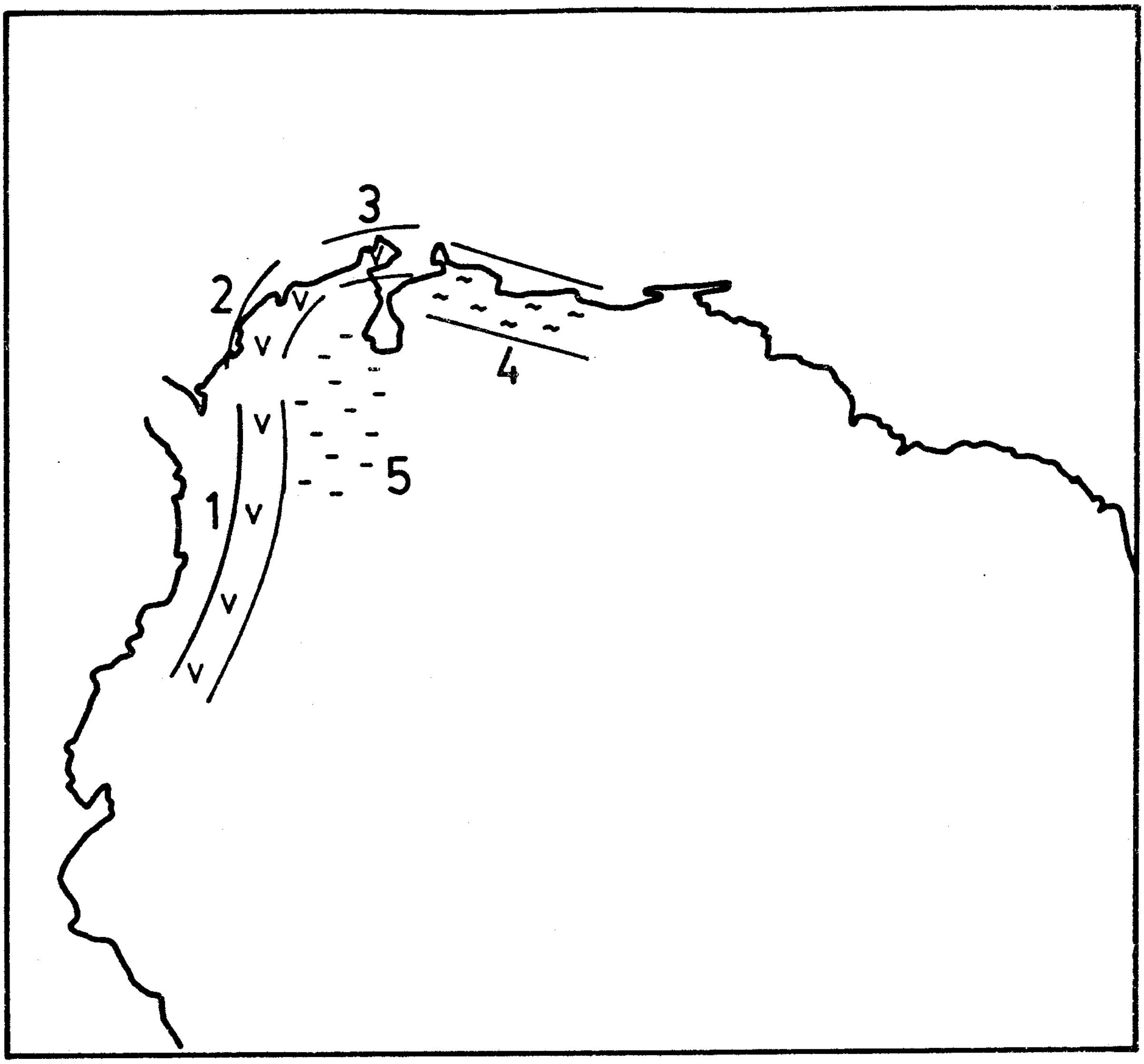


Figure 7. Late Paleozoic Terrains of Northern South America.

1. Cordillera Central (arc)
2. Sierra Nevada de Santa Marta (arc)
3. Guajira Peninsula (arc)
4. Deformed Granites and Gneisses of Venezuela
5. Shallow Water Seaway Behind Late Paleozoic Arc, Similar to Java Sea

limestones accumulated, probably in an environment similar to that of the Java Sea, a shallow basin overlying continental crust. During Permian time, the arc and related sediments underwent deformation with the most intense deformation occurring in the Central Cordillera, the Guajira Peninsula and the Sierra Nevada de Santa Marta of Colombia (Almeida, 1978).

Paleomagnetic studies (Valencio and Vilas, 1976; Smith and Briden, 1977) and paleoclimatic studies (Ziegler, et al., 1979) indicate that Permo-Carboniferous plate motion of South America (Gondwana) possessed a strong northward component. The presence of the Upper Paleozoic arc indicates subduction of oceanic crust beneath northwestern and western South America, and thus it is evident that during the upper Paleozoic South America moved northwards and westwards with respect to largely oceanic plate or plates lying to the north and west. The andesitic volcanics and granodiorites are interpreted as the arc complex that must have formed during the convergence between North and South America. Continental collision between the Colombian portion of the Andes and the Marathon-Huastecan segment of the North American foreland is indicated by synchronous deformation (Early to Middle Permian) and the ceasing of arc-related volcanism in Colombia during Middle Permian time.

To the east of Guajira, Colombia evidence for a well developed Upper Paleozoic arc is largely lacking. In northern Venezuela, the most significant aspect of Upper Paleozoic geology is the presence of Pennsylvanian-Permian aged granitic intrusions and metamorphics. Little else is known and all that can be said is that the area was regionally heated during the Penn-Perm Orogeny. Whether the granitic intrusions are related to the arc in northwest Colombia or to simple heating of the crust due to thickening cannot be specified at this time.

Extent of pre-Mesozoic continental crust: the margins to be fitted :

For the purposes of the Permo-Triassic reconstruction, the islands of the Greater and Lesser Antilles, the Panama-Costa Rica isthmus and the Bahamas Platform may be disregarded. These features are all Jurassic and younger and have developed during the course of Caribbean evolution. Only in western Cuba has it been suggested that Paleozoic rocks occur (Mattson, 1979), but this is not readily accepted by most authors. A simple explanation for this potential anomality is offered in chapter 5; for the purposes of the reconstruction this issue is disregarded. Pre-Mesozoic continental crust to be considered, then, is limited to the continents of North and South America and Africa, and the blocks of Yucatan and Chortis. The basement of Mexico is probably best considered as a set of several blocks because of the deformation it underwent during emplacement into the "overlap position" with South America encountered in most circum-Atlantic reconstructions (see chapter 3).

Northern limit of continental crust of South America :

Complex post-Jurassic tectonic events have obscured and greatly modified the rifted margin of northern South America. Late Cretaceous collision with the Aruba-Blanquilla island arc (Gealey, 1980; Maresch, 1974) emplaced giant thrust sheets onto the Venezuelan margin. The arc is preserved offshore and the suture apparently lies within the Bonaire Basin and continues into the Trinidad-Tobago area (Maxwell, 1948). In western Colombia, Neogene collision with the Panama arc (chapter 4) has led to accretion of significant amounts of deep water and oceanic material (Irving, 1975). Development of the South Caribbean Plate Boundary Zone (Burke, et al., 1978) during later Cenozoic time has greatly modified the morphology of the margin. Fortunately, no single on-shore fault has been shown to have accumulated grandiose offsets and thus it is likely that much of the relative displacement between the Caribbean and South American plates has occurred to the north of the island-arc chain.

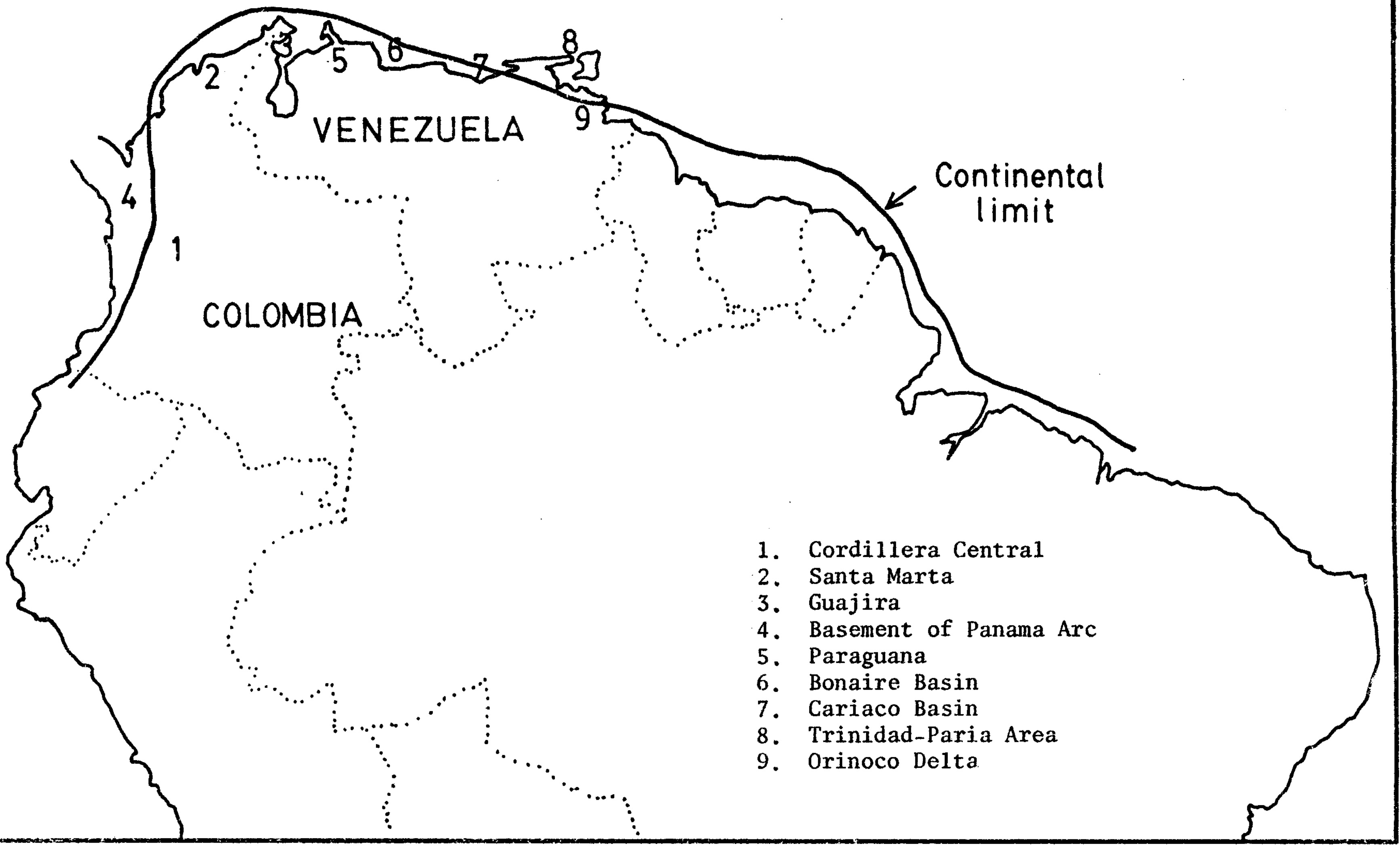
Despite these modifications, figure 8 approximately defines the limit of the Jurassic rifted margin. Precambrian and Paleozoic basement outcrops continuously along northern Colombia (Tschanz, et al., 1974; MacDonald, 1965), and thus it is inferred that basement extends offshore to the continental shelf break. In central and southern Colombia, the edge of the Early Mesozoic basement was approximately defined by the western margin of the Cordillera Central arc (Irving, 1975). In the north from Peninsula de Paraguana to the Cariaco Basin, the Jurassic basement limit probably closely approximates the suture zone of the Late Cretaceous arc-continent collision. To the east of the Cariaco Basin, basement is difficult to define. Much of the sediment of the Paria and Trinidad area has been accreted to the continent in the Late Cretaceous, and high rates of sediment influx from the Orinoco River have produced a massive delta, beneath which most certainly lies oceanic and/or attenuated continental crust. From these considerations, it is speculated that the Jurassic limit of basement lies slightly inland of these areas, as shown in figure 8. Continuing to the southeast, the limit again returns offshore to the continental margin. Such are the margins of northern South America to be fitted with southern North America and the blocks of Mexico and Central America.

Southern limit of continental crust of North America :

Whether the basement of the Gulf Coastal Plains south of the Ouachita-Marathon belts is comprised of continental or oceanic basement has been heavily debated in the literature (see Cebull and Shurbet, 1980, for a

FIGURE 8

Figure 8. Northern Limit of Continental Crust of South America in Pre-Rift Times.



1. Cordillera Central
2. Santa Marta
3. Guajira
4. Basement of Panama Arc
5. Paraguana
6. Bonaire Basin
7. Cariaco Basin
8. Trinidad-Paria Area
9. Orinoco Delta

review). The presence of more than 15 km of post-Triassic sediments within the Gulf Coast "Geosyncline" (Antoine, et al., 1974) dictates that if continental crust is present, it is extremely attenuated and may be considered as "tectonic oceanic crust" (see figure 9). It has also been suggested that oceanic crust of Paleozoic age is present beneath the coastal plains (Cebull and Shurbet, 1980). This position, however, fails to adequately explain the intensely thrusted Ouachita-Marathon belt to the north and thus is not entertained here. Late Paleozoic continental suturing followed by Jurassic rifting is the most satisfactory explanation for the observed geology. Whether the coastal plain basement is oceanic (Jurassic) or highly attenuated continental crust is a trivial matter; either position indicates that the limit of continental crust lies well inland of the present-day coastline. The position adopted here is that the pre-rift limit of continental crust of southern North America falls between the northern limit of the Louann Salt and the Cretaceous reef trend to the south (see figure 10). Structural highs in the rifted margin such as the Sabine Uplift and Wiggins Arch are considered to be stranded horsts separated from the mainland by marginal grabens.

In southernmost Florida (figure 10), Klitgord, Popenoe and Schouten (in press) show that pre-Mesozoic crust is absent and that Lower Cretaceous isopachs indicate a sharply rifted margin, probably attributable to transform faulting rather than to extensional rifting. The transforms (Sunniland and Bahama) were probably long transforms, connecting the ridge system of the Atlantic Ocean to that in the Gulf of Mexico (see chapter 3).

In eastern Mexico, continental crust seems to be present very near the present coastline. Recall, however, that considerable left-lateral syn- or post-rifting offset may have occurred upon the Texas Lineament so that in northeastern Mexico there exists an extensive embayment of salts,

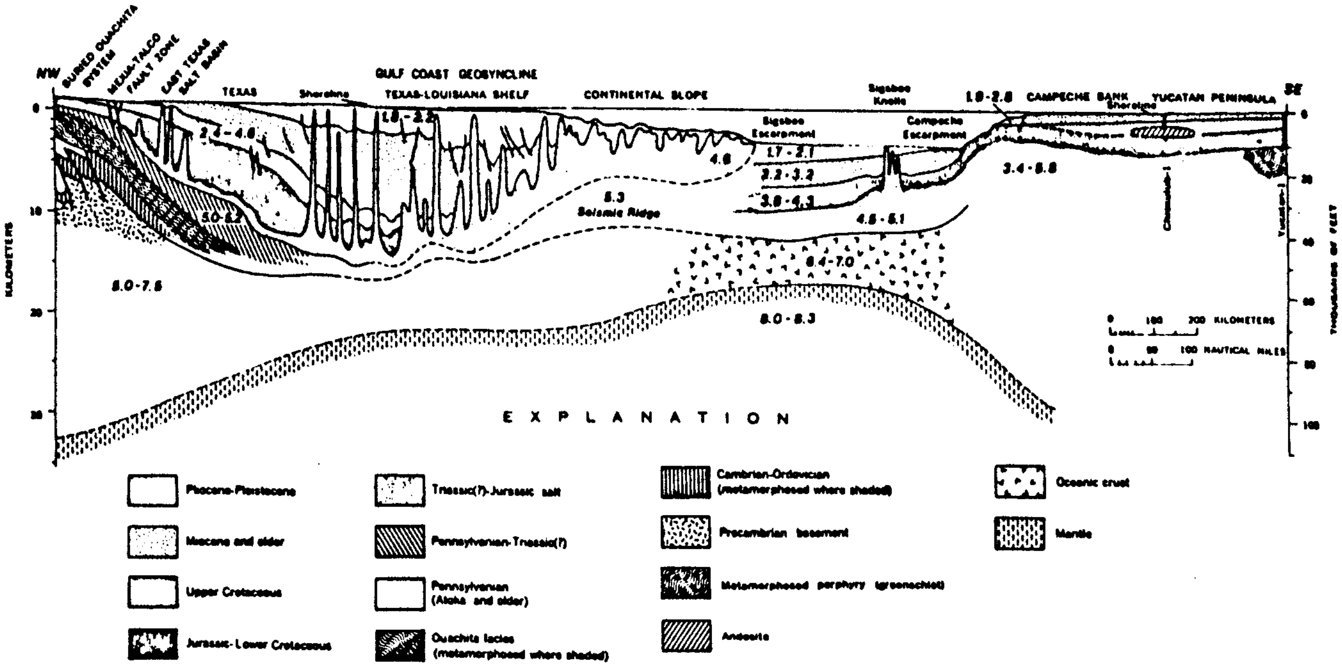


Figure 9. Cross-section of the Gulf of Mexico from eastern Texas to central Yucatan showing generalized stratigraphy and crustal structure. Velocities are in km./second. After Antoine *et al.* (1974).

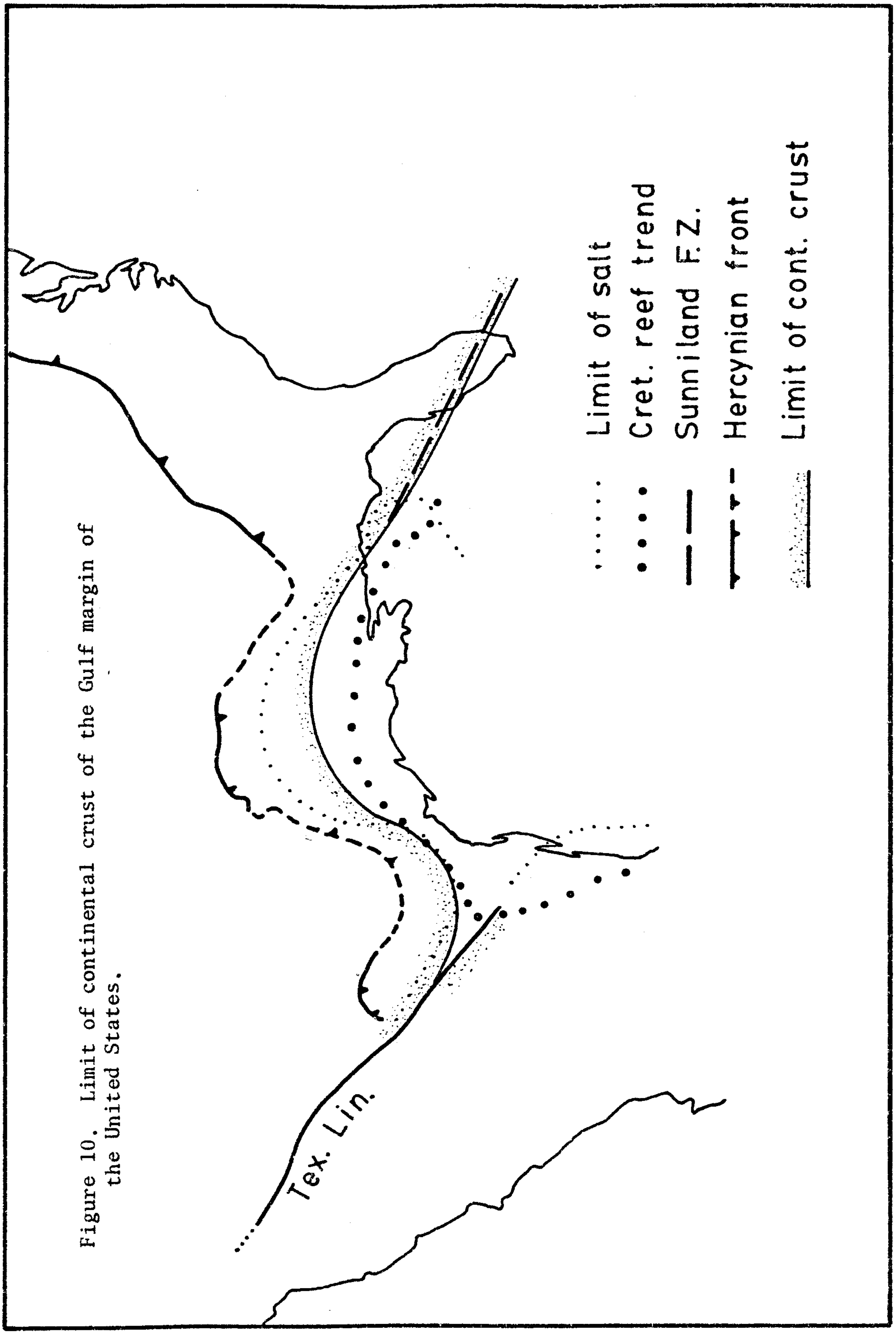


Figure 10. Limit of continental crust of the Gulf margin of the United States.

clastics and marine deposits (figure 10).

The Yucatan Block

Although the Yucatan Block (figure 11) is of limited geographic extent, its complex geology contains critical information with regards to Gulf and Caribbean evolution. Six important stages of development may be seen: 1) Devonian uplift, deformation and metamorphism along the southern portion of the block (present coordinates), 2) Late Paleozoic Andean-type arc vulcanism along the southern border of the block (Central Guatemalan arc), 3) Middle Jurassic rifting that produced a highly stretched rifted margin along the northern and western margins, 4) Late Cretaceous collision with the Chortis Block, with Yucatan acting as the foreland, 5) Late Cretaceous-Paleocene uplift, erosion and subsequent block-faulting along the entire eastern margin, and 6)considerable left-lateral offset between the Yucatan and Chortis Blocks since Oligocene time that has produced a complex plate boundary zone between the two. In addition, it is postulated (see chapter 3) that complex strike-slip dominated rifting occurred along the eastern coastline (present coordinates) in Late Jurassic times.

The Devonian deformational episode (McBirney and Bass, 1969) is based on isotopic ages of Late Devonian age from rocks (Chuacus Group) unconformably overlain by Carboniferous strata. The existence of a Late Paleozoic Andean arc is inferred from stratigraphic descriptions from Central Guatemala (see figure 12, for a summary). The Late Paleozoic evolution of southern Yucatan is strikingly similar to that of the Cordillera of western South America, where Devonian uplifting was also followed by arc-related magmatic activity. On these grounds it is suggested that the two may be correlated and that the Central Guatemalan arc was a northern, westward facing extension of the Andean arc in the Middle to Late Paleozoic

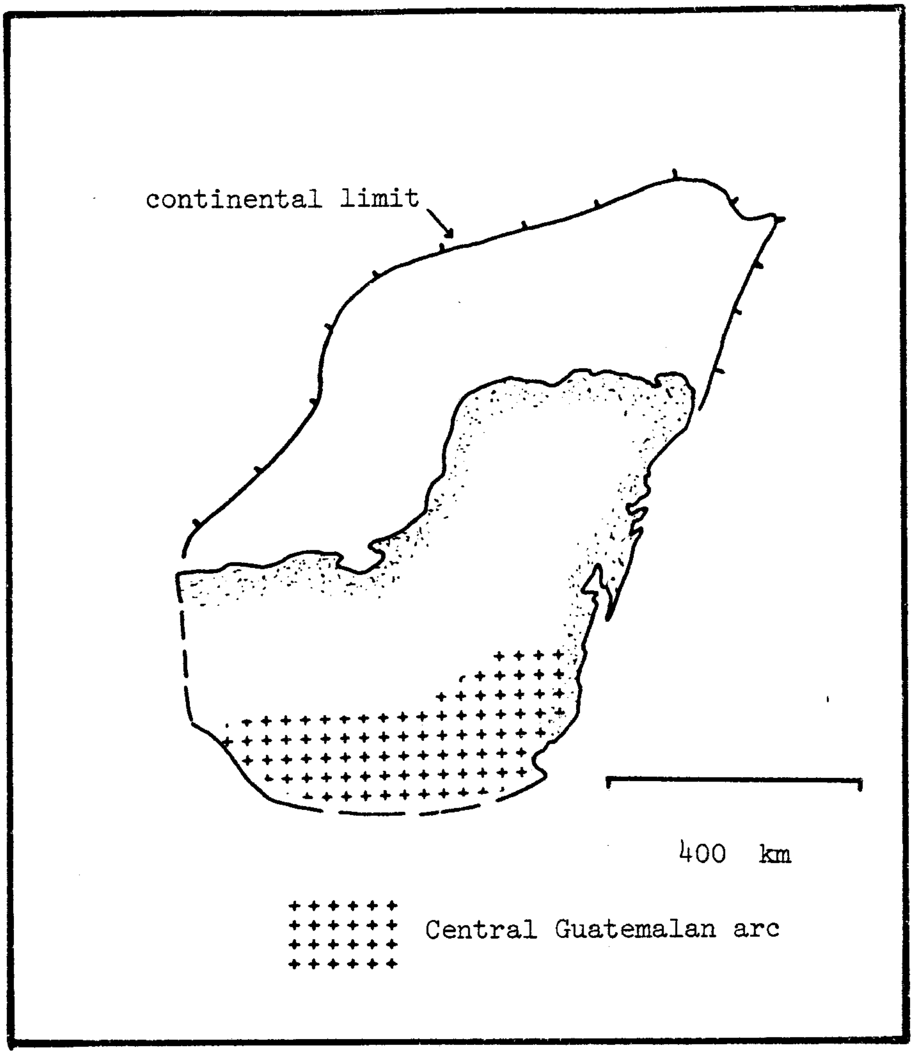


Figure 11. Generalized map of the Yucatan block showing 1) the area occupied by the Central Guatemalan Arc, and 2) the limit of continental crust to be considered in the fit of western Pangea.

Figure 12. Stratigraphic column and tectonic interpretation of Late Paleozoic section of central Guatemala, Yucatan block. The proposed central Guatemalan arc is represented by the Chicol Formation. After Anderson (1969) ; Anderson et al. (1973) ; McBirney and Bass (1969) .

Figure 12. Stratigraphic column, Central Guatemalan arc.

	Jurass.		Todos Santos Red Beds	Rifting, subsidence
	195			
	Triass.			
	225			
PERMIAN	Ochoan			
	240			
	Guadal.			
	255			
	Leona.		— Tuilon SS — Chocal LS	Crustal readjustment
	268			
	Wolf.		Esperanza Fm. shale, minor LS dolo.	
	280			
PENNSYLVANIAN	Virgil	TACTIC FM.	>800 meters brown, black	
	290			
	Missour		shales, silts, sands	
	300			UPLIFT (COLLISION)
	Desmoin	? — CHICOL FM. —		
	305			
	Atokan		>1ooo meters conglomeratic sandy, tuffaceous	Proposed central-Guatemalan ARC.
	310			
	Morrow		volcanics, lavas, volcaniclastics,	
	317			
MISSISSIPPIAN	Chester		leucocratic dikes, ANDESITIC breccia	
	330			
	Meramec			
	335			
	Osage			
	340			
	Kinder			
	346			
	UPPER DEVONIAN		Chuacus Group	UPLIFT, DEFORMATION, METAMORPHISM

— — — — — — — =UNCONFORMITY

time. The only significant difference between the two terrains is that vulcanism apparently ceased during Pennsylvanian time in Yucatan, whereas vulcanism continued into the Permian in the Andean Cordillera.

Seismic and drilling data (Buffler, et al., 1980, 1981) indicate that the Gulf of Mexico was formed by the separation of the Yucatan Block from the southern margin of the United States in Middle to Late Jurassic time. However, the opposing rifted margins are so highly attenuated than an accurate location of the ocean-continent transition cannot readily be made. Both margins contain a thick evaporitic section, indicating the existence of a restricted basin along the site of the developing rift. While geological data from the Gulf of Mexico is sufficient to substantiate a Jurassic origin by rifting between Yucatan and North America, flow lines and the pre-rift alignment of the margins cannot yet be proven. First of all, much of the opening of the Gulf probably occurred during the Jurassic quiet zone and thus no magnetic anomalies have been defined. Second, considerable down-slope migration of the salt section (Antoine, et al., 1974) has distorted its original geographic extent so that an accurate pre-drift correlation is not possible. Third, the thick post-Triassic carbonate and evaporite section (1 to 4 km) across the entire Yucatan Platform indicates that the Yucatan basement was significantly stretched during the rifting episode; the present geographic extent of the block may be 10-20% greater than that during pre-rift times. Further treatment of Gulf of Mexico rifting is given in chapter 3, but it is clear that the pre-rift position of the Yucatan Block was against the southern margin of the United States.

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

The Chortis Block

Little is known of the pre-Mesozoic basement of the Chortis Block. Its geographical extent, however, is roughly defined by the Motagua-Swan transform fault on the north and the Santa Elena Peridotite on the south (see figure 13). A thick accretionary pile has accumulated along the western margin as a result of slightly extensional Tertiary subduction at the Middle America Trench. The Nicaragua Depression (Muehlberger, 1976) (figure 13) is the site of normal faulting and active arc-related vulcanism. The western margin of the Paleozoic basement is roughly coincident with the eastern boundary of the Nicaraguan Depression. To the east of the block lies the Nicaraguan Rise, a sub-marine western extension of the southern Greater Antilles. Delineation of a boundary separating the Chortis continental basement from the Antillean arc-related basement has not been achieved as yet, but block-faulting in the basement beneath the 100 fathom contour (Phillips Petroleum, personal communication) east of Nicaragua (figure 13) suggests a possible eastern limit of basement. For lack of any contrasting evidence, the 100 fathom contour is assumed to mark the extent of Paleozoic

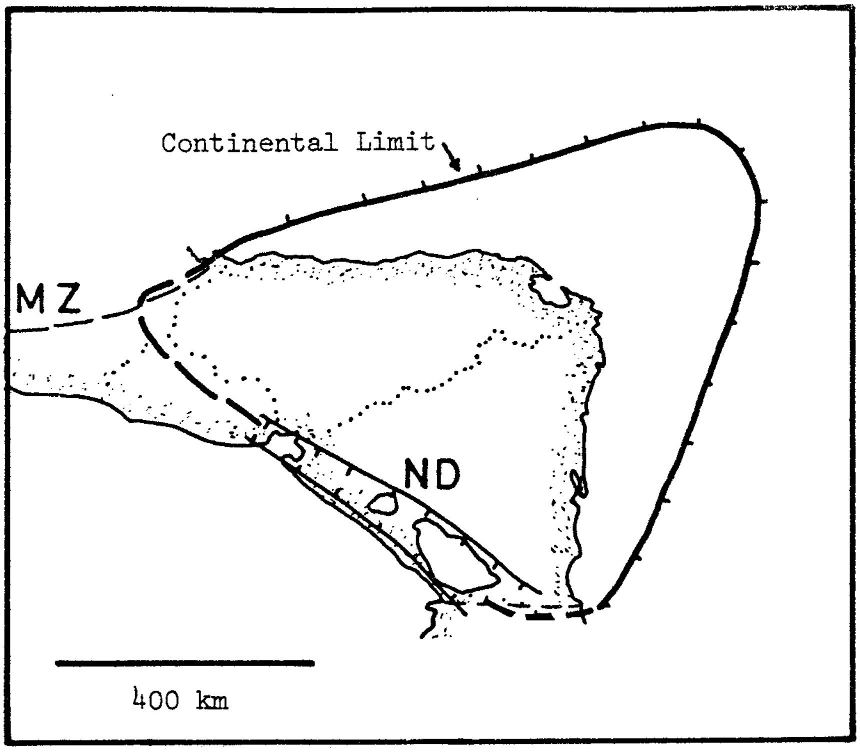


Figure 13. Limit of pre-Mesozoic continental crust of the Chortis block. Offshore position of boundary is approximately the 200 fathom depth contour. MZ = Motagua Fault Zone; ND = Nicaragua Depression.

basement along the Nicaraguan Rise.

Reconstruction of western Pangea:

Figure 14 is the final Permo-Triassic reconstruction of western Pangea that considers all of the points made in the preceding pages. The major aspects that characterize this reconstruction are 1) the North Atlantic fit is that defined by the marginal offsets along the opposing shores (LePichon and Fox, 1971), 2) the South Atlantic fit achieves complete closure of the Amazon gap by treating Africa as two plates in the Cretaceous, 3) complete closure of the Proto-Atlantic ocean is accomplished by placing Yucatan between the Ouachita Mountains and Venezuela, 4) the proposed Hercynian suture zone separates zones of foreland thrusting from zones of arc-related magmatic activity[1], and 5) paleomagnetic data (Van der Voo and French, 1974) are satisfied because South America and southern Africa are essentially in the same position relative to North America as that described by Van der Voo and French (1974). This reconstruction is used as the initial configuration for the North America-South America relative motion vector suggested in this paper (see chapter 2).

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[1] Geologic studies in western Africa have not identified a Late Paleozoic arc terrain. It may be that arc-related material is present beneath the continental margins of North America and/or Africa.

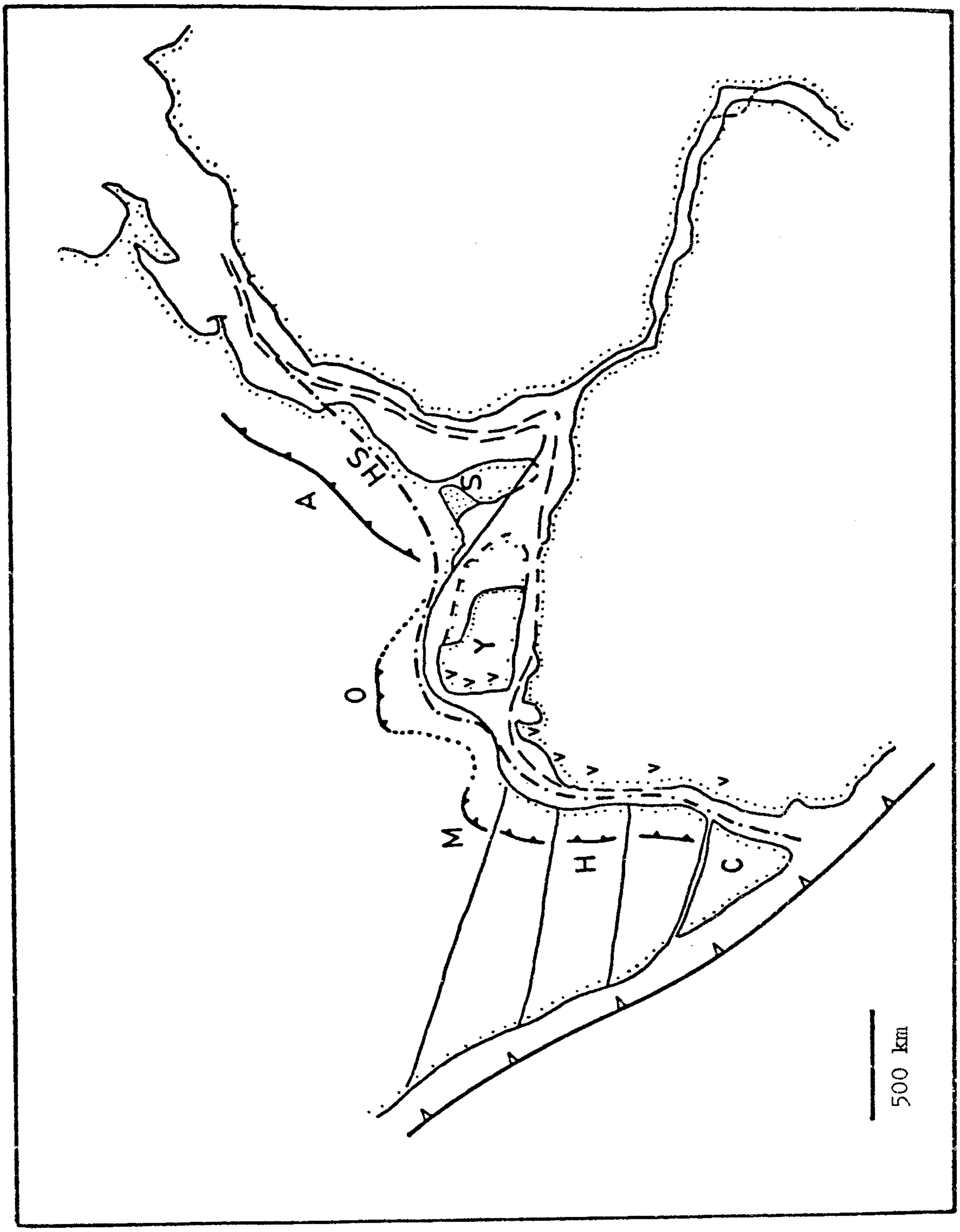

Figure 14. Sketch map showing revised Permo-Triassic continental reconstruction of western Pangea. Note that Proto-Atlantic Ocean is closed, and that zones of foreland thrusting (H = Huastecan, M = Marathon, O = Ouachita, A = Appalachian) are separated from Andean Arc terrains by the proposed Hercynian Suture (HS). S = Suwannee Basin with Gondwana faunal affinity, Y = Yucatan Block, C = Chortis Block.

CHAPTER II

ATLANTIC OPENING POLES AND RELATIVE MOTION VECTORS BETWEEN NORTH AND SOUTH AMERICA

Several sources of finite difference pole data have been incorporated to produce a new set of opening poles and rotations for the circum-Atlantic continents that most satisfactorily accomodates the criteria discussed in Chapter 1.

Africa with respect to North America:

In the North Atlantic (between eastern North America and Africa) the poles and rotations of Sclater _et al_. (1977) have been adopted and are summarized in Table I. These poles are based upon the work of LePichon and Fox (1971) for the early motions, 165-80 ma, and upon Francheteau . (1973) for the remainder. The use of these motions is justified in that the initial geometry of closure and timing of rifting are in accord with the preferences outlined in Chapter 1 whereas other sources of poles (e.g. Pitman and Talwani, 1972) deviate significantly. Following Sclater _et al_. (1977), the time scales of Sclater _et al_.(1974) and Van Hinte (1976 a,b) are used for the Cenozoic and Mesozoic, respectively.

South America with respect to Africa:

In the South Atlantic, the fact that the Bullard _et al_. (1965) initial fit is not used requires the incorporation of several data sources. The initial Jurassic fit used here is that presented by Rabinowitz and LaBrecque (1979) for the time of anomaly MO (110 ma). The additional rotation of the "southern plate" of Africa that is required to close the southern South Atlantic Ocean is defined in this study (see chapter 3) and occurred from the Valanginian (125 ma) to 110 ma. The motion of South America with respect to Africa during the interval 110 ma to 80 ma (Cretaceous Quiet Zone) is that defined by Rabinowitz and LaBrecque (1979), whose 80 ma position is taken from Ladd (1974,1976). From 80 ma to the present, the poles and rotations of Sibuet and Mascle (1978) are used. They too have taken Ladd's (1974, 1976) 80 ma position of South America with respect to Africa, and have recognized one minor change in the spreading history at 36 ma (anomaly 13). This provides additional control over the analysis of Sclater _et al_. (1977) for the South Atlantic, who assumes a single pole to have existed from 80 ma to the present, after Francheteau (1973). Table II summarizes the above mentioned poles and rotations used in this study for the opening of the South Atlantic.

South America with respect to North America:

Using the finite difference method, the relative motion poles of South America with respect to North America have been calculated with computer assistance. Table III summarizes these poles, both the total finite difference and the stage poles, and it is from this data that the relative motion vector (figure 15) has been plotted. The relative motion vector is plotted with respect to present-day North American coordinates.

TABLE I

RELATIVE MOTION POLES, AFRICA wrt NORTH AMERICA

TIME	MAG	FINITE DIFFERENCE			STAGE POLES		
(m.a.)	ANOM.	lat.	long.	angle	lat.	long.	angle
165	CM	66.0	-12.0	-74.8			
					55.9	-17.3	11.3
150	interp.	67.8	-13.8	-63.7			
					57.9	-21.7	5.4
140	M-22	68.8	-14.2	-58.4			
					60.9	-29.5	7.2
125	M-6	70.2	-12.9	-51.3			
					58.1	-22.0	7.2
110	interp.	72.3	-13.3	-44.3			
					58.4	-21.9	7.3
95	interp.	75.1	-14.0	-37.3			
					58.5	-21.7	7.3
80	34	79.1	-15.7	-30.4			
					82.9	153.7	9.9
65	29	70.9	-10.9	-21.2			
					70.3	-3.8	4.8
53	22	70.9	-13.1	-16.4			
					70.7	-3.2	6.0
36	13	70.5	-18.7	-10.4			
					70.5	-18.7	4.7
21	6	70.5	-18.7	-5.7			
					70.5	-18.7	3.00
10	5	70.5	-18.7	-2.7			
					70.5	-18.7	1.35
5	interp.	70.5	-18.7	-1.35			
					70.5	-18.7	1.35
0	----	----	----	0.0			

TABLE II

RELATIVE MOTION POLES, SOUTH AMERICA wrt AFRICA

TIME (ma)	MAG. ANOM.	FINITE DIFFERENCE		
		lat.	long.	angle
165-110	MO	55.1	-35.7	50.9
95	interp.	58.3	-35.8	42.3
80	34	63.0	-36.0	33.8
65	29	62.0	-36.3	26.8
53	22	60.8	-36.6	21.3
36	13	57.4	-37.5	13.4
21	6	57.4	-37.5	7.8
10	5	57.4	-37.5	3.7
5	interp.	57.4	-37.5	1.9
0	----	----	----	0.0

EARLY MOTION OF SOUTHERN AFRICA wrt NORTH AFRICA

TIME (ma)	MAG. ANOM.	lat.	long.	angle
125-110	M11-MO	19°N	2°E	8°

TABLE III

RELATIVE MOTION POLES, SOUTH AMERICA wrt NORTH AMERICA

TIME	MAG.	FINITE DIFFERENCE			STAGE POLES		
(ma)	ANOM.	lat.	long.	angle	lat.	long.	angle
165	--	52.1	37.6	-28.8			
					55.9	-17.3	11.3
150	--	45.2	61.6	-20.1			
					57.9	-21.7	5.4
140	--	35.9	75.5	-17.1			
					60.9	-29.5	7.2
125	--	15.4	91.8	-15.6			
					58.1	-22.0	7.2
110	--	5.0	-73.5	17.0			
					5.2	-92.7	-3.6
95	--	4.1	-68.5	13.6			
					2.4	-85.3	-3.8
80	--	3.9	-62.1	10.0			
					41.9	138.7	4.8
65	--	30.6	-70.3	7.8			
					28.2	-98.9	-1.4
53	--	30.0	-64.6	6.6			
					43.5	-81.1	-2.5
36	--	21.1	-57.7	4.3			
					11.1	-63.3	-1.5
21	--	26.4	-54.1	2.8			
					26.5	-55.1	-1.5
10	--	26.2	-52.9	1.3			
					23.8	-54.2	-0.6
5	--	28.2	-51.7	0.7			
					28.2	-51.7	-0.7
0	--	--	--	0.0			

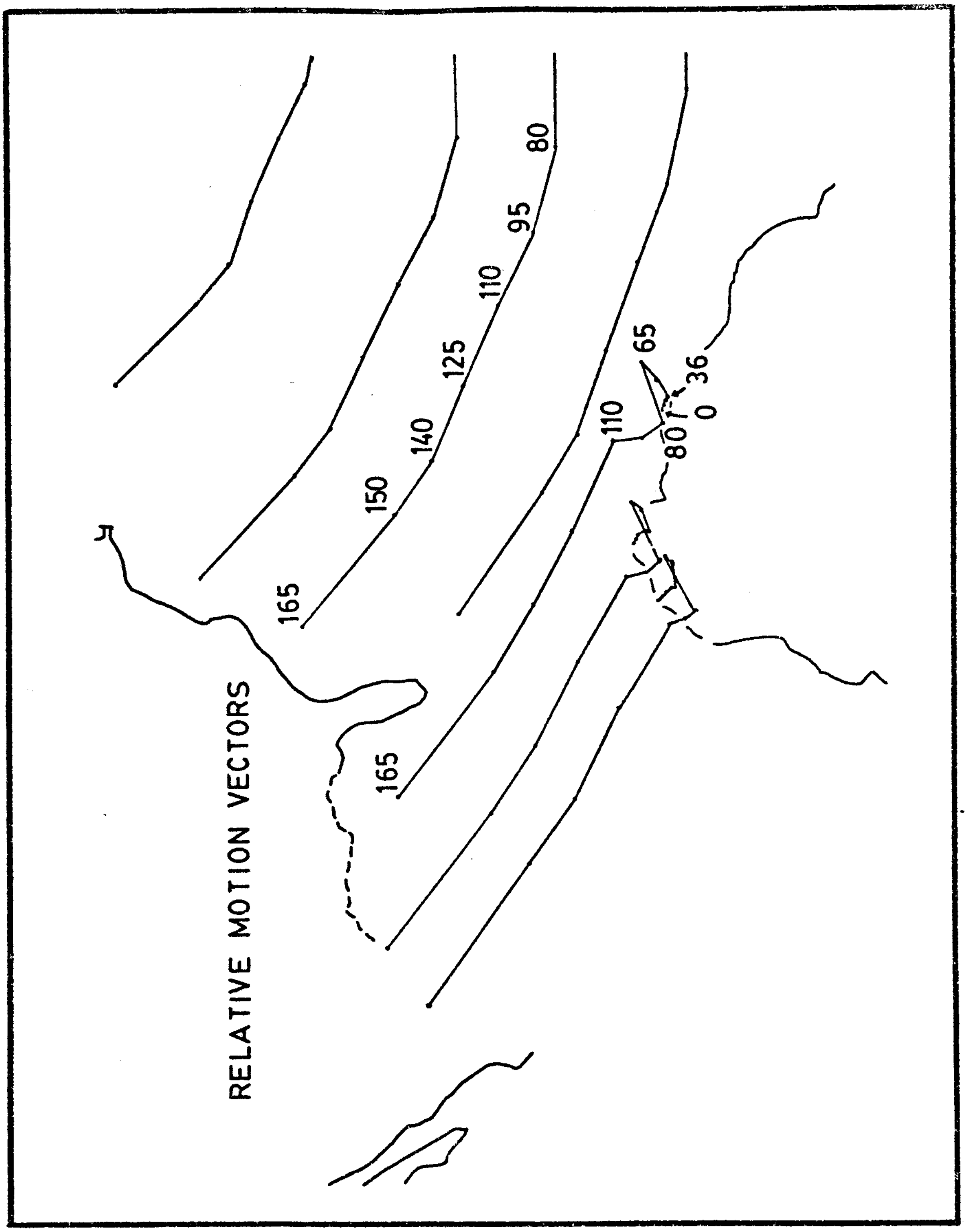

Figure 15. Relative motion histories of three points along northern South America with respect to North America. Early relative motion of Africa is shown as well. These provide the relative positions of the three continents at various times and thus provide a framework in which to base Caribbean/Gulf evolution. Vectors are the result of data in tables I, II and III.

CHAPTER III

INITIAL BREAKUP OF PANGEA

This chapter outlines the rifting and early spreading histories of the Atlantic Ocean basins. A model for the opening of the Gulf of Mexico and "Proto-Caribbean" Sea during the period from initial breakup to 125 ma is presented which includes the post-rifting development of Mexico and the Bahamas and which sets the stage for the evolution of the Caribbean plate. In addition, a model for the early opening of the South Atlantic Ocean is proposed that embodies the concept of Africa acting as two plates during Cretaceous times.

Rifts of the eastern North American continental margin, southern Grand Banks to the Yucatan Peninsula:

In the middle Jurassic, true oceanic crust of the Central Atlantic Ocean and the Gulf of Mexico began to form as a result of continental rupture that separated Africa-South America from North America-Greenland-Eurasia. Complex development of grabens, failed-arms and domal uplifts preceded the oceanic phase during late Triassic-early Jurassic time within a broad, imprecisely defined belt that encompassed the eventual line of Atlantic spreading. The true plate boundary (where actual mid-ocean spreading and transform motion occurred) entered the Pangean super-continent from the Pacific Ocean between Mexico and South America and grossly followed the Hercynian suture zone (see Chapter 1). In southern Alabama, the developing plate boundary deviated from the Hercynian suture zone and continued to the southeast along a long transform-short ridge network (Klitgord, Popenoe and Schouten, in press), and this deviation was responsible for the Florida block (Suwannee Basin) becoming a permanent addition to North America (the Suwannee Basin was part of Gondwanaland in the Paleozoic, as shown by its faunal assemblages). From a poorly defined point east of Florida (somewhere beneath the Bahama Bank) the final plate boundary to emerge propagated northward between eastern North America and Africa to the Grand Banks. From here another long transform-short ridge network developed between Morocco (northern Africa) and the Iberian Peninsula, and the plate boundary system continued eastward into the Tethyan domain (Dewey, et al., 1973; Sclater, et al., 1977).

Burke (1976) points out that most of the continental ruptures that failed to become incorporated into the final plate boundary systems are found on the North American side of the Atlantic Ocean. The ruptures can grossly be classified into two groups. Members of the first group typically trend at relatively high angles to the rifted margins and are formed by failure of plate boundary propagation (failed arms). Members of the second group (marginal grabens trend approximately parallel to the rifted margin, are located between stranded horsts (outer marginal highs) and the continent, and are formed by simple extension within the zone of incipient rifting during the "East African Rift Stage".

Rifts of eastern North America associated with the opening of the Central Atlantic are listed and referenced below and are classified as failed arms or marginal grabens. Each rift is shown in figure 16.

Failed Arms

1. Grand Banks Troughs (Amoco and Imperial, 1973, 1974; Sheridan, 1974; Ayrton, et al., 1973; Burke, 1976).
    - 1a. Carson Subbasin
    - 1b. Jeanne D'arc Subbasin
    - 1c. Horseshoe Subbasin
    - 1d. Whale Subbasin
2. Fundy Graben (Bain, 1957).
3. Connecticut-Northfield-Deersfield Graben (Grimm, 1970; Sanders, 1960; King, 1977; Bain, 1957).
4. Southeast Georgia Embayment (Suwannee Channel) (inferred by Dillon, et al., 1979; Klitgord and Behrendt, 1979, page 109, there called the "Triassic embayment").
5. Mississippi Embayment (Ervin and McGinnis, 1975).

Figure 16. Rifts of eastern North America, Grand Banks to Yucatan, associated with Triassic-Jurassic breakup of Pangea. Numbers refer to rifts mentioned in text. a = Sabine Uplift, b = Lasalle Arch, c = Wiggins Arch, d = San Marcos Arch.

6. Chihuahua Trough (Cordoba, et al., 1971; Gries, 1979; Gries and Haenggi, 1971).

7. Huayacocotla "Aulocogen" (Schmidt-Effing, 1980).

Marginal Grabens

Emergent marginal grabens:

8. Newark Graben (King, 1977; van Houten, 1969; Manspeizer, 1980; Sanders, 1962; Bain, 1957).

9. Gettysburg Graben (Manspeizer, 1980; Sumner, 1978; Sanders, 1962; Bain, 1957)

10. Culpepper Graben (Roberts, 1928; Lindholm, 1979; Cornet, 1977; Lee, 1977; Lindholm, 1978).

11. Danville Graben (Cornet, 1977; Bain, 1957).

12. Richmond Graben (Cornet, 1977; Bain, 1957).

13. Deep River Graben (Bain, 1957).

14. Durham Graben (Cornet, 1977).

15. Sanford Graben (Cornet, 1977).

16. Wadesboro Graben (Cornet, 1977).

17. Dan River Graben (Cornet, 1977).

18. Balcones Fault Zone (Halbouty, 1967, page 15; Hager and Burnett, 1960; Walthall and Walper, 1967).

    18a. Mexia-Talco
    18b. South Arkansas
    18c. Pickens, Gilbertown
    18d. Luling

Submerged grabens:

19. South Whale Subbasin (Amoco and Imperial, 1973; Sheridan, 1974; Ayrton et al., 1973; Burke, 1976).

20. Nova Scotia Shelf Basin (McIver, 1973; Emergy and Uchupi, 1972; Sheridan, 1974).

21. Georges Bank Basin (Mattick, et al., 1974; Schultz and Grover, 1974; Schlee, et al., 1976; Sheridan, 1974; Klitgord and Behrendt, 1979).

22. Baltimore Canyon Trough (Mattick, et al., 1974; Sheridan, 1974; Drake, et al., 1968; Emery, et al., 1970; Schlee, et al., 1976; Klitgord and Behrendt, 1979).

23. Carolina Trough (Dillon and Paull, 1978; Klitgord and Behrendt, 1979).

24. Blake Plateau Basin (Sheridan, et al., 1966; Sheridan, 1974; Klitgord and Behrendt, 1979; Emergy and Uchupi, 1972; Hersey, et al., 1959).

In addition to these major submerged rifts, the platform areas (continental shelf) of the east coast contain several smaller grabens (not shown on figure 16), which have also been interpreted as Triassic in age, that are associated with the continental rifting (Klitgord and Behrendt, 1979; Ballard and Uchupi, 1972; Minard, et al., 1974; Popenoe and Zietz, 1977).

Field study of the basal sections of the presently subaerial failed arms and marginal grabens indicate that the timing of rifting and the character of deposition (and igneous activity) were very similar for each rift. Thick sections of sandy to conglomeratic redbeds interlayered with basaltic flows and intruded by diabasic dikes consistently date at Late Triassic. Redbeds generally become coarser (talus and boulders) toward the normal fault-boundary walls of the grabens, although several discontinuous bounding faults often exist for a given graben so that facies patterns are complex. The mafic intrusions indicate that continental foundering had begun during the Late Triassic, but apparently no single plate boundary had developed at this time to produce true oceanic crust. A general fining upward trend exists in most grabens but faunal evidence suggests that rift-related sedimentation in most of the basins continued into the early Jurassic, at which time marine incursion occurred in some of the basins (Connecticut, for example). Following Sclater et al. (1977), it is believed that true oceanic crust production did not begin until the Middle Jurassic (Bathonian) and thus the incipient rifting phase spanned about 40 million years (Burke, 1976).

Knowledge of the basal sections of the submerged marginal basins and failed arms is largely conjectural because published drill tests and seismic records do not yet provide a confident understanding. However, most authors extrapolate the land-based graben models to the offshore basins and assume very similar sedimentation patterns, igneous activity and ages of rifting. Since the early rift formation and sedimentation, thick Cretaceous and Tertiary sections of sands, shales and carbonates have been deposited upon the rift-facies rocks as a result of general subsidence of the thinned, rifted margins of the developing Atlantic Ocean (Watts and Steckler, 1979).

The presence of extensive salt and evaporites within and overlying the Late Triassic-early Jurassic rift facies of several of the submerged marginal grabens and failed arms records early attempts of the circum-Pangean oceans to invade the broad belt of incipient rifting. Burke (1975) has equated areas of Late Triassic-early Jurassic salt deposition on the margins of the circum-Atlantic continents to spills which entered from the Tethyan and Pacific Oceans. Apparently, Tethyan spills (Grand Banks-Nova Scotia Shelf area) slightly preceded the Pacific spills (Louann Salt of the Gulf of Mexico area), the reason for which is probably that the Pacific was more distal from the early Gulf of Mexico than was the Tethys from the Grand Bank-Nova Scotia area, so that tectonic barriers may have been more prominent in the Pacific-Gulf system. Similar spills from an austral ocean produced evaporitic sequences during the Cretaceous along the developing margins of eastern South America and southwestern Africa.

Grabens of the northern Gulf Coastal Plain

The chain of grabens (Luling, Mexia, Talco, South Arkansas, Pickens, Gilbertown) collectively known as the Balcones Fault Zone apparently contains Triassic-early Jurassic salt and separates continental crust of

North America from several stranded basement blocks beneath the Gulf Coastal Plain (Sabine Uplift, Wiggins Arch, Lasalle Arch, San Marcos Arch; see figure 16). Drilling has recovered Mississippian volcaniclastics from the Sabine Uplift (Dewey, personal communication) that may represent remains of the Late Paleozoic Andean arc prior to collision between North America and South America-Africa. If this is so then a likely position of the Hercynian Suture zone, the orogeny associated with which produced the Ouachita deformation (see chapter 1), lies between the above mentioned stranded basement blocks and the Ouachita Mountain system. Triassic-Jurassic rifting apparently tried to pass to the north of the blocks but failed, leaving them stranded as permanent additions to North America.

Rifts of the northern margin of South America, Colombia to Surinam:

Evidence that would allow a detailed understanding of the rifting that defined the northern margin of South America during the dispersal of Pangea has been largely obscured by later tectonic development of the margin. This margin has since suffered an arc-continent collision (late Cretaceous-early Tertiary) followed by later Cenozoic right-lateral strike-slip offset with respect to the Caribbean Plate totalling more than 1400 km within a complex plate boundary zone (see chapter 5).

However, conditions prior to the late Cretaceous orogenic episode were more stable. The northern South American rift margin was characterized by an Atlantic type thermally subsiding stable shelf from latest Jurassic to late Cretaceous time (Maresch, 1974; Gealey, 1980). Rifting associated with the breakup of Pangea is evidenced by extensive clastic redbeds, with volcanics in the lower sections, of the Giron and LaQuinta Formations that are mainly of Jurassic (but apparently late Triassic to early Cretaceous) age. These units unconformably overlie with variable thickness the crystalline and schistose rocks related to the Pennsylvanian-Permian continental collision with southern North America. The basal redbeds are difficult to date because they are largely of non-marine nature and little isotopic work has been done on the volcanics. Schubert (1980) suggests a Jurassic age for the rift facies based on plant remains. Marine transgression had definitely occurred onto at least some portions of the juvenile shelf by earliest Cretaceous time as evidenced by a gradual transition into Lower Cretaceous shales and limestones (Hargraves and Shagam, 1969). Farther southward transgression of the sea heralded widespread carbonate deposition across the shelf throughout the Cretaceous.

It seems as though continental rupture between South America and North America (and Yucatan) was a drawn out, complex process that occurred from late Triassic through latest Jurassic time. Of general consensus, though, is that marine incursion and margin subsidence had begun by the earliest Cretaceous, and therefore actual continental separation by development of intervening oceanic crust probably occurred in late Jurassic time (Maresch, 1974; Gealey, 1980; Hargraves and Shagam, 1969).

Isolated failed arms or marginal grabens associated with this continental rupture are rare. However, descriptions of a "geosynclinal trough" called the East Andean Miogeosyncline (figure 17) by Campbell (1974) in the region of the present-day Eastern Cordillera of Colombia to Lake Maracaibo suggest that crustal stretching with local subsidence occurred behind the Late Paleozoic arc complex of northwest Colombia (chapter 1) in latest Jurassic time (Tithonian). Cyclical deposition of sands, limestones and then shales (Burgl, 1961; Campbell and Burgl, 1965) produced a total section of some 12,000 meters in a trough whose axis followed the western margin of the Eastern Andes (Campbell, 1974) from Tithonian to late Cretaceous time. Superimposed upon this trough was an east-trending

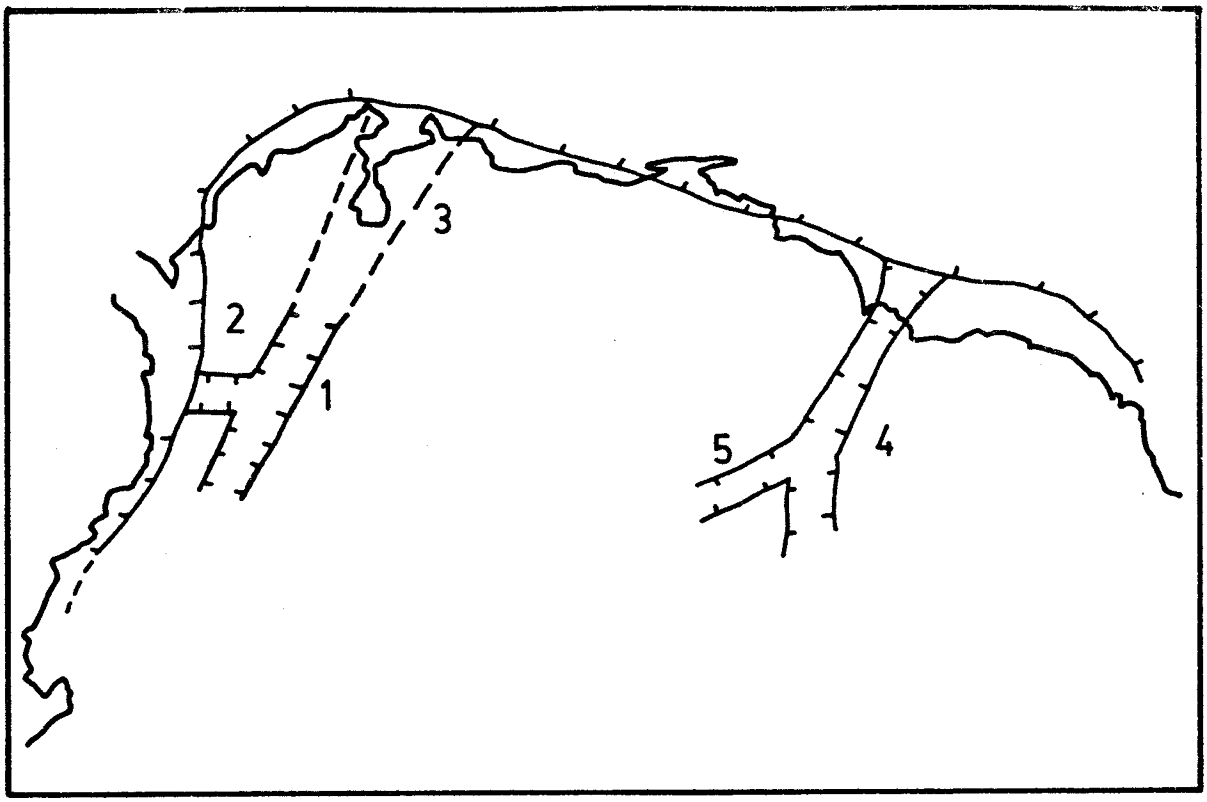

Figure 17. Rifts and the rifted margin of northern South America, associated with Jurassic breakup of Pangea.

1. East-Andean Miogeosynclinal Trough
2. Bogota Trough, providing open circulation with ocean
3. Maracaibo Platform
4. Takatu-Apoteri Rift System
5. Apoteri Rift

trough north of Bogota, Colombia (figure 17), where the maximum amount of subsidence occurred (Campbell, 1974). This latter trough apparently dissected the Late Paleozoic arc terrain and allowed open marine circulation between the Pacific Ocean and the inland trough. To the northeast, the stable carbonate shelf of the rifted continental margin was developed at this time and attained its greatest development on the Maracaibo Platform. Thus, subsidence was greater in the Maracaibo area than in adjacent areas to the west and east, indicating slightly greater crustal stretching that was perhaps associated with development of a very minor failed arm during the late Jurassic. However, the well defined, structurally controlled Maracaibo Basin (rift) did not come into existence until the end of the Eocene (Bucher, 1952; page 8). This Eocene rifting event probably was associated with complex, dominantly strike-slip motion between the South American and Caribbean plates (chapter 5).

To the east along this margin lies the Takatu-Apoteri rift system (figure 17). It has been suggested (Burke, Dessauvagie and Whiteman, 1971; Burke and Whiteman, 1973; Burke and Dewey, 1973) that the Takatu-Apoteri rift system is a failed arm of the Georgetown triple junction located off the coast of Guyana. The Apoteri rift (figure 17) may represent yet another juncture (Berrange and Dearnley, 1975; McConnell, et al., 1969) or a bifurcated extension of the rift system into the Guyana Shield. While the system was clearly active during the Jurassic breakup of Pangea, it may have reactivated older, perhaps Precambrian structures. On the whole, the system is better known within the continent than closer to the coast where we would expect the greatest influence of Jurassic activity.

Origin of the Bahamas Platform:

Jurassic reconstructions of the circum-Atlantic continents, including that of this study, show that most, if not all of the Bahamas Platform is underlain by oceanic basement. Assuming that the Bahamas basement is oceanic, substantial uplift to the photic zone must have occurred after or during middle to late Jurassic generation of this crust in order to allow the initiation of early Cretaceous evaporite and carbonate reef sedimentation. The parallelism of the Bahamas trend with fracture zones mapped immediately to the north of the Bahamas strongly implies that uplift of basement to near sea level was related to sea floor spreading processes. Two possible mechanisms seem plausible: 1) uplift of oceanic crustal blocks bounded by transforms or fracture zones, as suggested by Uchupi et al. (1971); or 2) the tracking of a short-lived hot spot (Dietz, 1973) similar to the Kelvin seamount chain (Emery and Uchupi, 1972). Consideration of 1) plate boundary geometries required to rift Gondwanaland from North America, 2) recently mapped fracture zone patterns immediately to the north of the Bahamas, and 3) subsidence rates obtained from Bahamian wells further indicates that the early Cretaceous uplift of the Bahamas Platform was related to transpression at a long transform-short ridge regime, similar to that seen in the present equatorial Atlantic.

Plate boundaries during initial rifting in the Bahamas area

Figure 18 shows the Jurassic continental reconstruction with a plate boundary geometry that is consistent with early opening data. A series of short ridge segments and transforms developed along the eastern U.S. seaboard. Because of the pre-rift position of South America, however, it is evident that one or more long left-lateral transforms and associated major fracture zones must have existed across the southern tip of Florida in order to connect the Atlantic ridge system with a complex ridge system in the Gulf of Mexico involving the Yucatan Block. The long transform/

fracture zone system must have been maintained until northwest South America had cleared Florida (130 ma, figures 18, 19 and 20). Estimates regarding when the Bahamas Platform originated typically suggest latest Jurassic-earliest Cretaceous (Uchupi, et al., 1972; Dietz, 1973) which is coeval with the existence of the long transforms.

The existence of long transforms and fracture zones alone does not require the crust between the ridge segments to be at or near sea level, which is necessary for evaporite and carbonate reef deposition. It has been argued by Bonatti (1978) and Bonatti et al. (1977) that a compressional component across major transform zones may lead to uplift of blocks of oceanic crust along the transform zones to elevations "one or more kilometers above similar crust of equal age". A case in point is the Romanche Fracture Zone in the equatorial Atlantic. At the Miocene-Pliocene boundary, uplift was sufficient to initiate shallow water carbonate deposition (Bonatti, et al., 1977). The chief cause of the uplift was most probably compression of a long transform zone (Bonatti, 1978). Seismic reflection profiles show the presence of a thrust fault within the Romanche Transform, further documenting transpression (Beck and Lehner, 1975). Since the early Pliocene, the compressive stress has been relieved and the carbonates have subsided to approximately 1 km below sea level at rates 20 times faster (0.2 mm per year) than normal thermal subsidence (Bonatti, et al., 1977).

Returning to the Bahamas, Klitgord (personal communication, 1980) has traced fracture zone trends just to the north of the Bahamas escarpment that show a consistent kink of the sense that would produce transpression during left-lateral transform motion. This kink does not clearly appear at the scale of the relative motion vector contained herein (chapter 2), but it is suggested that a minor transient pole shift was responsible for the fracture zone offsets and that long transform faults in the Bahamas area were probably subjected to substantial compression with resultant uplift. Required uplift of normal oceanic crust of the age present at that time in the Bahamas area (0-20 million years old) to reach present-day sea level is approximately 2.5 to 3 km. Examination of sea level curves (Vail, et al., 1977) indicates that sea level was about 100 meters below that of the present in early Valangininan time. This addition is minor in relation to the proposed compressional uplift, but it may have aided in the progradation of isolated reefs during the uplift period.

Platform Subsidence

The fact that the Bahamas are at sea level today testifies that carbonate production has matched subsidence rates since the initial uplift. Cretaceous sedimentation rates obtained from several Bahamian wells indicate that subsidence rates in the Bahamas greatly exceeded rates typically associated with normal thermal subsidence. Cay Sal 1, for example, displays 3 km of early Cretaceous carbonates and anhydrites without entering the Jurassic (about 30 million years) (Paulus, 1972). The subsidence rate obtained (0.1 mm per year) exceeds thermal rates by a factor of 10. It is apparent, therefore, that a tectonic factor as well as thermal contraction must have contributed to the Bahamian subsidence, just as has occurred since the Pliocene at the Romanche Fracture Zone (Bonatti, et al., 1977). It is suggested that the transpressional regime ended at about 130 ma, when fracture zone traces (Klitgord, personal communication) indicate that the pole of opening for the Atlantic returned to a position more similar to its initial position. The relaxation of compressive stress at 130 ma would have allowed uplifted blocks in the Bahamas area to return to normal isostatically balanced levels at a fast rate in the middle- and late- Early Cretaceous, followed by rates more typical of thermal contraction and sediment loading thereafter.

The assertion that a tectonic factor dominated thermal subsidence in the early Cretaceous suggests that the hot-spot mechanism for initial uplift is inadequate. Today we see hot-spot volcanic edifices subsiding at rates compatible with thermal contraction.

Early opening phase of the South Atlantic Ocean:

The period during which intra-continental rifting and deformation occurred in north-central Africa is Valanginian to Albian (130-108 ma). This period corresponds very well to the initial rifting and early spreading period of the southern South Atlantic Ocean. Both Rabinowitz and LaBrecque (1979) and Sibuet and Mascle (1978) describe the early phase of opening of the South Atlantic by counterclockwise rotation of all of Africa with respect to South America, thereby producing compression (Rabinowitz and LaBrecque, 1979) or strike-slip (Sibuet and Mascle, 1978) between Africa and South America in the equatorial zone. I suggest, rather, that the early rifting in the southern South Atlantic extended into the African interior via the Benue Trough and that motion was distributed over the broad zone of structural features (figure 4) that were developing in north-central Africa at that time. Relative motions between northern Brazil and northwest Africa are regarded as minimal until the time of anomaly MO (110 ma), after which time rifting with a large component of strike-slip separated South America from northwest Africa. Relative motions between South America and Africa from 110 ma to 80 ma cannot be accurately determined as they happened during the Cretaceous quiet period. Fortunately, deformation of the African interior had ceased by 80 ma and thus the relative motion between South America and Africa (in its present shape) can be fairly well traced thereafter.

A pole of rotation that defines the early motion of southeastern Africa with respect to northwestern Africa-South America must satisfy fracture zone trends and magnetic anomalies associated with the early opening phase of the southern South Atlantic Ocean (M11-M0, or 125 ma-110 ma). The pole used by Rabinowitz and LaBrecque (1979) lies at 2.5°S, 45.0°W with an angular rotation of +11.0°, all with respect to South America. This rotation is based upon alignment of the ocean/continent boundaries, the seaward edge of salt boundaries, the trend of marginal fracture zones, particularly the Agulhas-Falkland fracture zone, and other geophysical measurements. I propose an additional constraint that requires minor adjustment of the pole position and angular rotation of Rabinowitz and LaBrecque (1979); the early South Atlantic pole must be located such that left-lateral motion across the Benue Trough must be accompanied by an extensional component in order to account for the rift-like nature of the trough. This requires that the pole be located at a more northerly position, and according to LaBrecque (written communication, 1981) the play in the data allows such a northward adjustment. The pole suggested here that seems to satisfy all constraining data lies at 19°N, 2°E with respect to present-day Africa, with an angular rotation of about 8°. It is assumed here that Africa had attained approximately its present shape by 110 ma. Any further opening in the Benue area followed by significant closure cannot be recognized in the ocean spreading data because of the Cretaceous quiet period from 110 ma to 80 ma. Thus, all post-110 ma rotations regard Africa as a rigid plate.

Plate boundary scenario between North America and Gondwana, 165 ma to 125 ma:

Figures 18 through 21 depict the proposed early spreading history of the Atlantic/Gulf/Caribbean region. Relative motions of the continents are based on figure 15. In each figure, motion vectors are shown that indicate the movement of the Gondwanide continents during the time interval leading to the next figure. Proposed plate boundaries satisfy these motions in the most simplistic manner.

Figure 18 shows the initial rift system that severed the Pangean continent. The rift system of the North Atlantic is that portrayed by Klitgord, Popenoe and Schouten (in press). A long transform across southern Florida connects this system to a complex system in the Gulf of Mexico region. The Yucatan block must have rotated away from North America and have undergone left-lateral strike-slip motion with South America in order to obtain its present position. These motions are shown in figures 18-21. The motion of Yucatan with respect to South America is nearly identical to the motion of Iberia with respect to Africa during the early Cretaceous. The emplacement of the Mexican blocks is also achieved during the period covered by these figures. Chortis is considered as a southern extension of Mexico that later undergoes major eastward migration to achieve its present position southeast of Yucatan (see chapter 5).

Figure 19 shows formation of the Sabine Uplift (S), Wiggins Arch (W), Chihuahua Trough (CT) and Louann Salts (cross-pattern). The Sabine Uplift and Wiggins Arch are considered as stranded horsts that were ripped away from North America during the rifting process. The Chihuahua Trough is an extensional transform fault, the motion upon which was responsible for much of Mexico's movement into the "overlap position". The Louann Salts were formed in the very restricted seaway between the Yucatan block and North America. The long transform in the Bahamas area (B of figures 19 and 20) underwent compression during imperfect strike-slip motion from about 145 to 130 ma.

By about 140 ma (figure 20), formation of the Gulf of Mexico is considered complete. Lack of data is responsible for the poor control over its evolution. Continued spreading between North America and Gondwana produced an oceanic seaway between North and South America (figure 21), into which entered crust of Pacific provenance. This was accomplished via southward subduction of Proto-Caribbean crust beneath Pacific crust at the oceanic gap. Since the Pacific crust was the overriding plate, it entered the Caribbean area whilst its westward and southward extensions were consumed beneath the Andean margins of North and South America. The volcanics that were formed on the leading edge of the Pacific crust would become the Greater Antilles Island Arc. This is treated further in chapter 5, which outlines the evolution of the Caribbean Plate. Thus, by 125 ma (figure 21), the stage was set for the development of the Caribbean Plate.

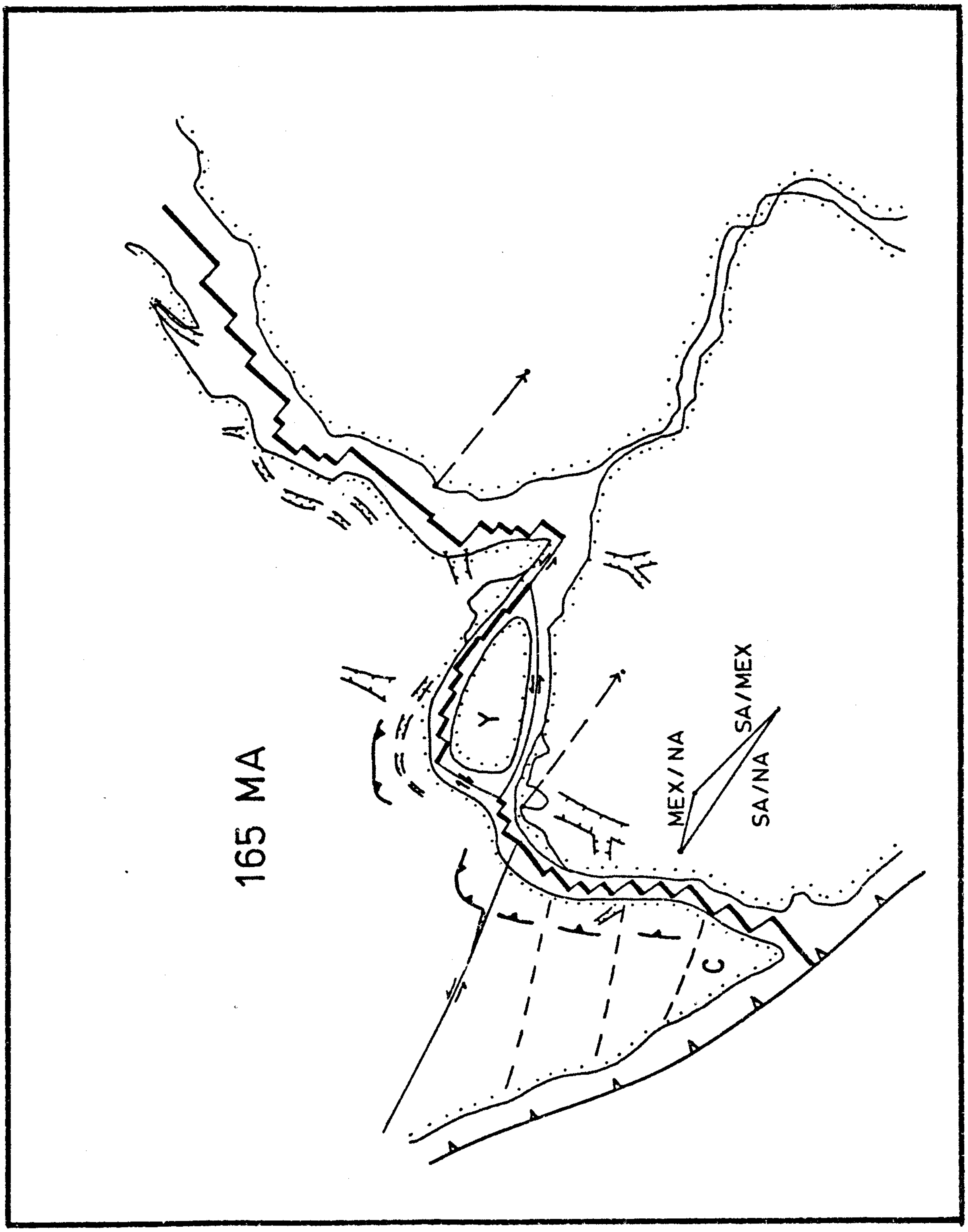

Figure 18

Plate boundaries at 165 ma, breakup of Pangea

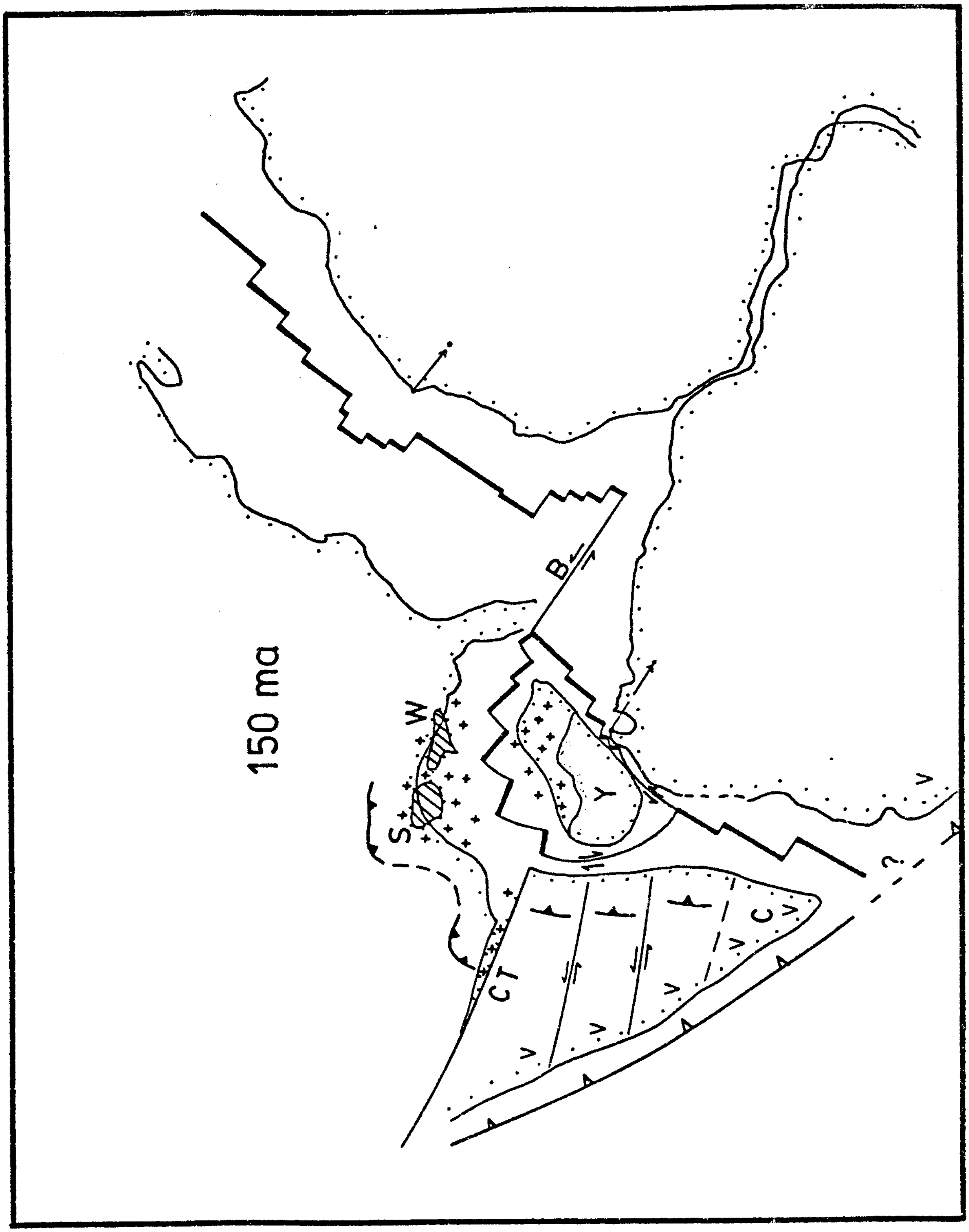

Figure 19

Plate boundaries at 150 ma

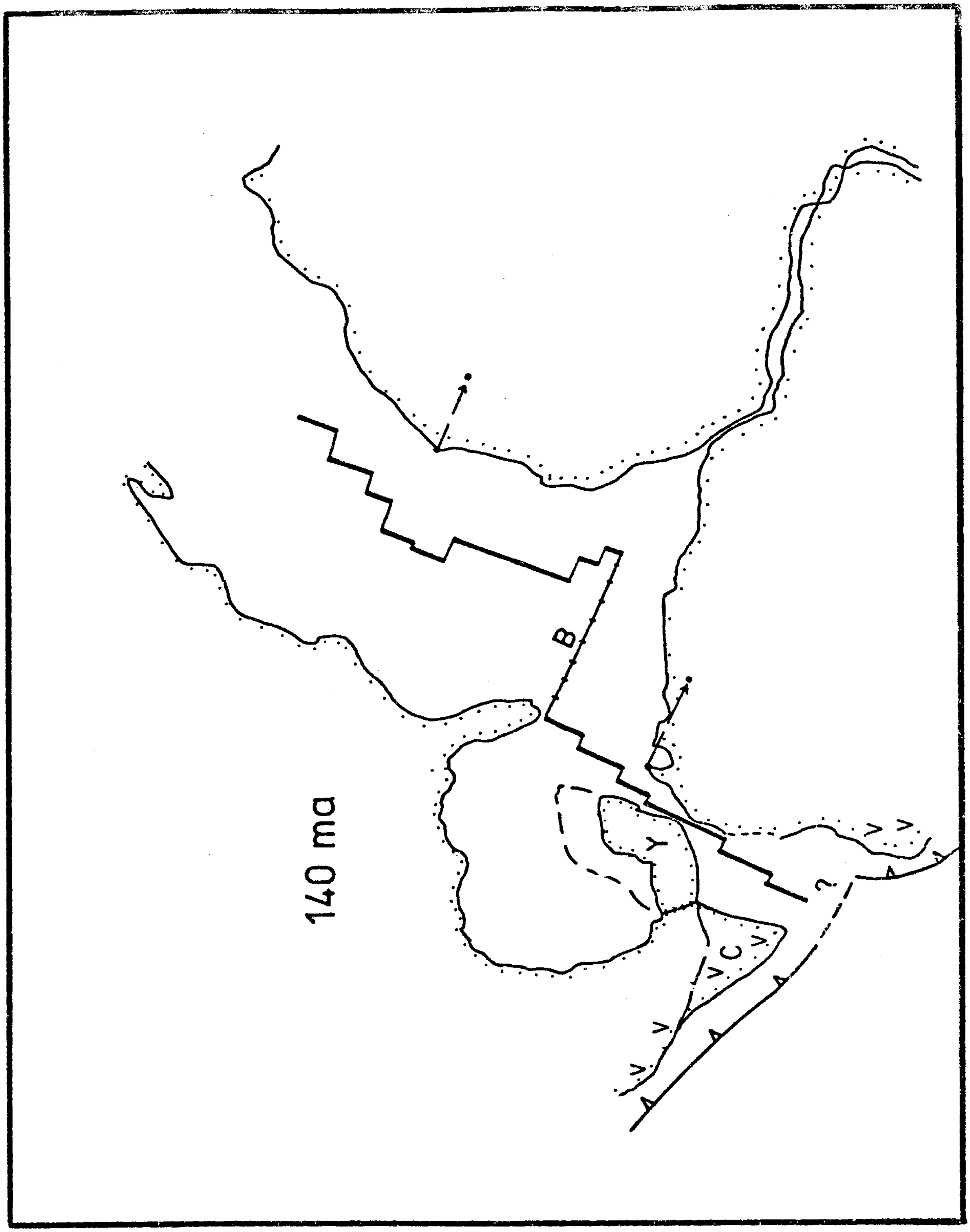

Figure 20

Plate boundaries at 140 ma

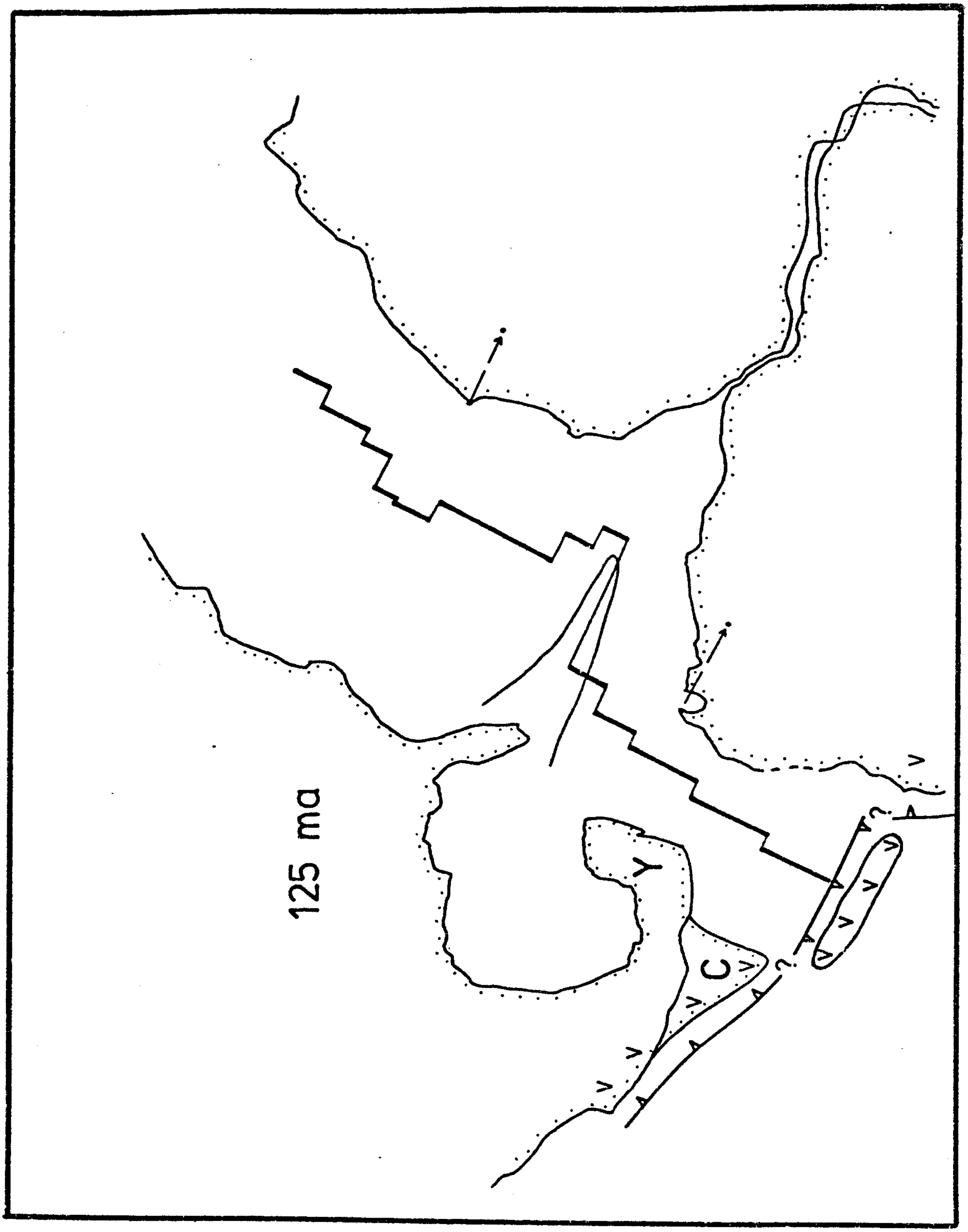

Figure 21

Plate boundaries at 125 ma

CHAPTER IV

ARCS AND OBDUCTED OPHIOLITES BORDERING THE CARIBBEAN: EVIDENCE FOR TECTONIC EVOLUTION OF THE CARIBBEAN PLATE

The extent of island-arc type terrain throughout the Caribbean region indicates that convergence between plates by subduction has played a vital role in Caribbean evolution. Fortunately, the geology of most of the arcs involved is clear enough to allow fairly accurate statements on 1) the period of subduction, 2) the polarity of subduction, and 3) the timing of collision where collision has occurred. Collision zones are very well marked by the occurrence of obducted ophiolites (see figure 22) in association with the island-arc complexes. Key elements of Caribbean geology such as these and other aspects are summarized below. The evolutionary model of chapter 5 is built within the framework of the relative motions of the continents and incorporates the major aspects of Caribbean geology as well.

Northern Greater Antilles Island Arc:

The Northern Greater Antilles island-arc includes Cuba, northern Hispaniola and Puerto Rico (and the Virgin Islands) and was once a continuous complex before Eocene development of the North Caribbean plate boundary zone. Convergence between the Bahamas and the northern Greater Antilles was accomplished by southward dipping subduction beneath the Greater Antilles (Khudoley and Meyerhoff, 1971), therby consuming a "proto-Caribbean" Sea. Since the Greater Antilles arc is of intra-oceanic character (Bowin, 1975), the age range of the volcanics on the islands is indicative of the period of active subduction. The period of arc-related vulcanism and therefore of subduction lasted from earliest Cretaceous to Eocene (Pardo, 1975; Mattson, 1979; Dickinson and Coney, 1980), when collision with the Bahama Platform marked the death of the "proto-Caribbean" Sea.[1]

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[1] It is felt here that an early phase of northward dipping subduction followed by middle Cretaceous flipping of polarity as suggested in Mattson (1979), though possible, is not well substantiated by Greater Antilles geology. Therefore, southward subduction is considered here to have occurred from early Cretaceous to Eocene time.

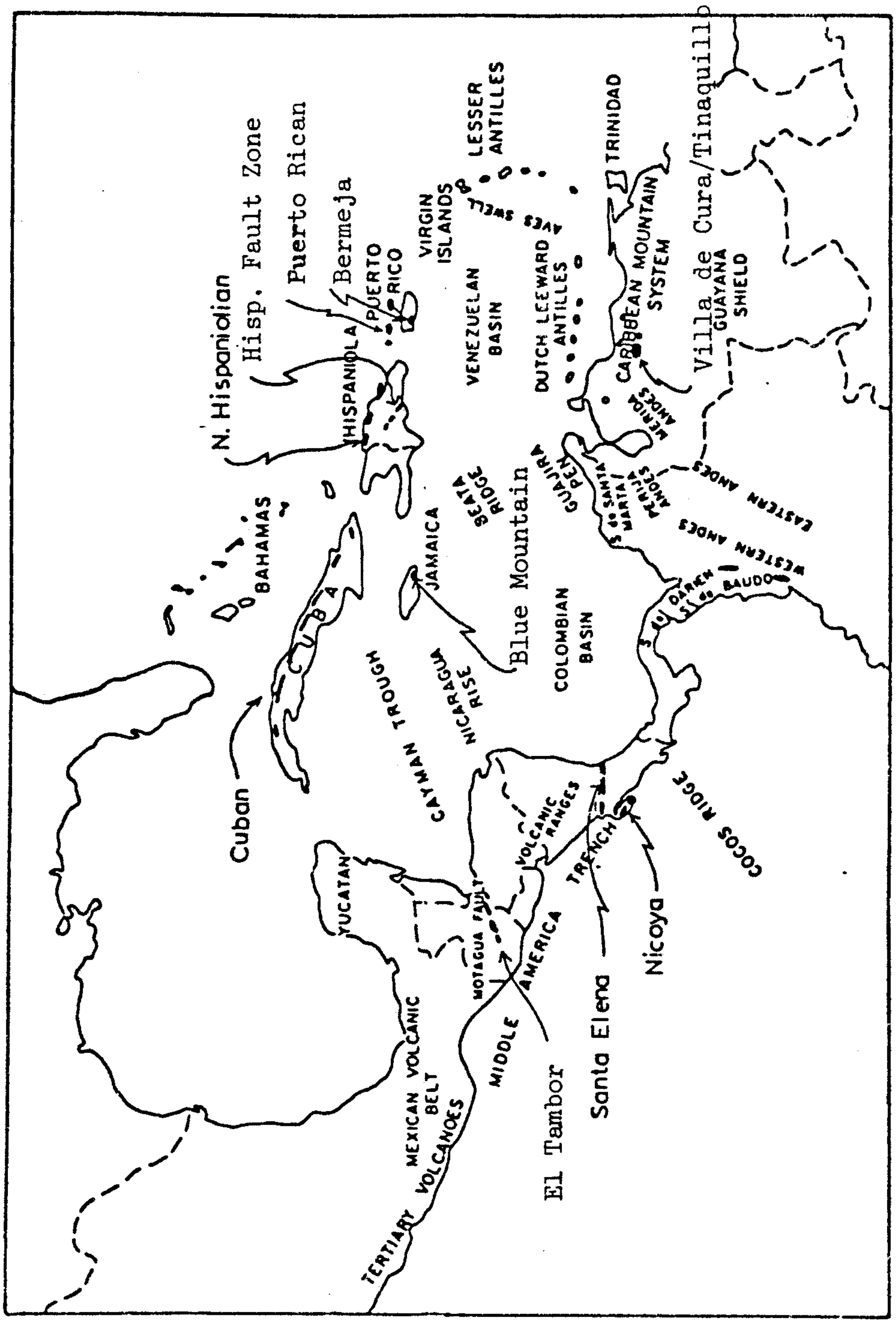


Figure 22. Obducted ophiolites (blackened areas) and physiography of the Caribbean Region.

Suturing between the Bahamas Platform and the northern Greater Antilles island-arc occurred during the Middle to Late Eocene (Wassal, 1956; Gealey, 1980; Dickinson and Coney, 1980), after which time the tectonic character of Cuba changed from island-arc to carbonate platform (Burke, et al., 1980; Brezsnyanszky and Iturralde-Vinent, 1978), while that of Hispaniola and Puerto Rico became dominated by strike-slip activity of the North Caribbean PBZ. The suture is marked by a chain of ophiolites and blueschists (figure 22) that lies along the northern coast of Cuba (Wassal, 1956; Khudoley and Meyerhoff, 1971) and Hispaniola (Nagle, 1974; Bowin, 1975) and offshore northern Puerto Rico (Heezen, et al., 1975; Mattson, 1979).

Southern Greater Antilles Arc and the Yucatan Basin:

The southern Greater Antilles arc includes the Nicaragua Rise, Jamaica and southern Hispaniola (south of the Cul de Sac-Enriquillo Graben). All are composed predominantly of Cretaceous arc-related volcano-plutonic rocks overlying an oceanic basement. Burke et al. (1978) suggests that the complex was a south-facing active arc during Cretaceous time as evidenced by "ophiolites" along the southern shores of Haiti, Dominican Republic and Jamaica. The mafic complexes (basalts and gabbros) are not complete ophiolites, however, and may be simply related to arc vulcanism.

Consideration of the Yucatan Basin, to the north, leads to a different hypothesis for the formation of the southern Greater Antilles arc complex. The Yucatan Basin is here considered as a back-arc basin active during Paleocene to Early Eocene time that was produced by extension of a north-facing Greater Antilles island-arc prior to the Late Eocene collision between the frontal arc (Cuba, northern Hispaniola, Puerto Rico) and the Bahamas Platform. Only the Cuban segment of the Greater Antilles arc underwent back-arc spreading, and the remnant arc (Karig, 1972) from which the frontal arc (Cuba) was rifted is now seen as the Cayman Ridge and Nicaragua Rise-Jamaica-southern Hispaniola arc complexes. Post-Eocene development of the Cayman Trough has dissected the remnant arc into its two components (Perfit and Heezen, 1978), so that the original Greater Antilles arc has been dissected twice, thereby producing three distinct arc complexes.

The first dissection of the Greater Antilles arc, Paleocene to Early Eocene back-arc spreading, produced rifted margins and other related rifts along the south side of the frontal arc and north side of the remnant arc that are filled with Paleocene to Early Eocene rift-type sediments (see figure 34). A similar age for the Yucatan Basin is indicated by subsidence analysis of the floor of the Yucatan Basin. Assuming the basin is underlain by normal oceanic crust, its depth (4500 meters) and sediment cover (1.5-2.0 km, Rosencrantz, personal communication, 1981) suggest an early Tertiary age.

Deformation within this proposed remnant arc that has been attributed to accretionary tectonics (Pindell, et al., 1981) is currently being reexamined in light of this new hypothesis.

Netherlands-Venezuelan Antilles Island Arc:

Arc-continent collision began between the Netherlands-Venezuelan Antilles island-arc and the South American craton in the latest Cretaceous (Gealey, 1980; Maresch, 1974; Beets, 1975) and continued into the early Tertiary (Gealey, 1980). Collision is indicated by blueschists occurring in ophiolites (Villa de Cura Complex, see figure 22) and deep water sediments which have been thrust southward onto the Late Jurassic to Cretaceous aged north-facing, stable shelf platform (and Early Paleocene sediments also) of northern Venezuela. The Netherlands-Venezuelan Antilles are composed of a sequence of Cretaceous volcanic rocks that may be divided into two stages, an early tholeiitic stage and a later calc-alkaline stage (Beets, 1975). If the entire sequence represents island-arc vulcanism, as is inferred by Maresch (1974) then subduction probably occurred throughout the Cretaceous. However, some question exists as to whether the early tholeiitic stage represents early island-arc or mid-ocean ridge vulcanism. If the latter is the case, subduction probably occurred only during Late Cretaceous time.

Maresch (1974) proposed that north-dipping subduction occurred south of the island-arc during the earlier part of the Cretaceous to explain the volcanic sequence of the islands but that the polarity of subduction flipped prior to collision so that collision occurred about a south-dipping subduction zone, thereby producing obduction of the Villa de Cura Complex onto the South American shelf. More recent accounts in other similar areas of arc-continent collision with emplacement of thrust sheets (Gealey, 1980; Rowley and Kidd, 1981; Mitchell, 1978; and others) indicate that the relationships are readily explained by subduction away from the continent, and thus the proposed pre-collision flipping event is unnecessary. It is felt here that north-dipping subduction beneath the Netherlands Antilles occurred during late Cretaceous time, after which arc-continent collision caused obduction of ophiolites and deep water maring sediments only the shelf platform of South America. Preserved evidence for this suture zone extends from the Guajira Peninsula of Colombia to northern Trinidad, where recumbent folding of deep water sediments occurs, and in Tobago, where there are blueschists (Maxwell, 1948).

It should be noted that earliest Tertiary calc-alkaline volcanics found in the Venezuelan Andes (Maresch, 1974; Beets, 1975) may have been produced by short-lived south-dipping subduction at a trench located to the north of the Netherlands Antilles.

Motagua Fault Zone:

The east-trending ophiolite complex (El Tambor formation, figure 22) in Central Guatemala and its likely equivalent in Bay Islands marks a suture between the Yucatan and Chortis blocks (Lawrence, 1976; McBirney and Bass, 1969; Donnelly, 1977). The El Tambor contains minerals in the blueschist metamorphic facies and is bounded and cross-cut by southward-dipping thrust faults of Late Cretaceous age. The thrusting occurred during either continental collision between the Chortis and Yucatan blocks or arc-continent collision between the Yucatan block and a Cretaceous westward extension of Cuba (see chapter 5). The collision caused obduction of the ophiolites onto the middle Cretaceous southward-facing carbonate shelf sequence of the southern part of the Yucatan block. These relations indicate southward dipping subduction as an oceanic basin of unknown size was consumed. Considerable left-lateral strike-slip motion has occurred across the zone since the time of collision, probably from Late Eocene to the present.

Isthmus of Panama-Costa Rica Arc:

In Panama and Costa Rica, an ophiolitic basement complex is overlain by andesites and granodiorites, typical of most intra-oceanic arcs. The age of the basement is Early Cretaceous, as suggested by faunal evidence, and the unconformably overlying vulcano-plutonic rocks of Campanian age indicate the initiation of subduction at this time (Galli-Olivier, 1979). Subduction has been maintained to the present, with no apparent breaks in activity.

The Santa Elena Peridotite (see figure 22) defines the boundary between continental crust of the Chortis block and oceanic crust overlain by arc material of the Panama-Costa Rica island-arc (de Boer, 1979). Juxtaposition of the two masses occurred in latest Cretaceous time, but it is uncertain as to whether this was accomplished by subduction between the two or by strike-slip motion or by both. An interesting aspect of the Santa Elena peridotite is that it is co-linear with the Hess Escarpment (figure 22), upon which Late Cretaceous strike-slip motion may have occurred (Dewey, personal communication, 1980). Since the Panama-Costa Rican arc is part of the Caribbean plate, any motion on the Hess Escarpment would have occurred along the Santa Elena Peridotite zone as well.

Throughout the Cenozoic, the juxtaposed complexes have apparently defined the western edge of the Caribbean Plate. Eastward movement of the Caribbean Plate with respect to North and South American has led to the Panama-Colombia collisional event, or Andean Orogeny of northern Colombia, following eastward dipping subduction of intervening oceanic crust beneath northern Colombia, as evidenced by Tertiary vulcanism in the Central Cordillera (Irving, 1975; Campbell, 1974). Suturing between the Panama-Costa Rica island-arc and northwestern Colombia (cratonic South America) began during the Miocene and oceanic circulation between the Pacific and Caribbean seas was tectonically interrupted by the Pliocene, about 5 million years ago (Keigwin, 1978). The exact suture is poorly defined as yet, but intense folding and eastward dipping thrust faulting in the area of the western Cordillera has developed in response to closure since the Miocene (Irving, 1975). Throughout the early and middle Tertiary, a transform fault is inferred to have connected the southern end of the Panamanian arc to a convergent plate boundary that ran up and down the entire western South American coastline. The sense of motion on this fault was probably left-lateral (see Chapter 5).

Aves Ridge and the Lesser Antilles Island Arc:

The Aves Ridge is an extinct island-arc (Fox and Heezen, 1975) that was active in latest Cretaceous to Paleocene (?) time. Since then, subsidence has allowed deposition of Eocene and Miocene limestones to occur, but more recently the ridge has become too deep in most areas for shelf-type limestones to develop. Construction of the Lesser Antilles began in the Eocene (Tomblin, 1975), immediately after extinction of the Aves Ridge, and has continued to the present. The present trench associated with the Lesser Antilles arc lies to the east and dips to the west beneath the Caribbean Plate. The Grenada Basin separates the Aves Ridge from the Lesser Antilles and was perhaps formed either by back-arc spreading or by the eastward shift of the subduction zone in the Early Tertiary (Tomblin, 1975; Montadert, *et al*., 1979).

CHAPTER V

PLATE TECTONIC EVOLUTION OF THE CARIBBEAN PLATE, 125 MA TO THE PRESENT

This chapter presents the continuation of the plate tectonic evolution of the Caribbean Plate that was begun in Chapter III. A series of figures summarizes the plate boundary scenario from 125 ma to the present, constructed within the framework of the relative motion vectors proposed in Chapter II.

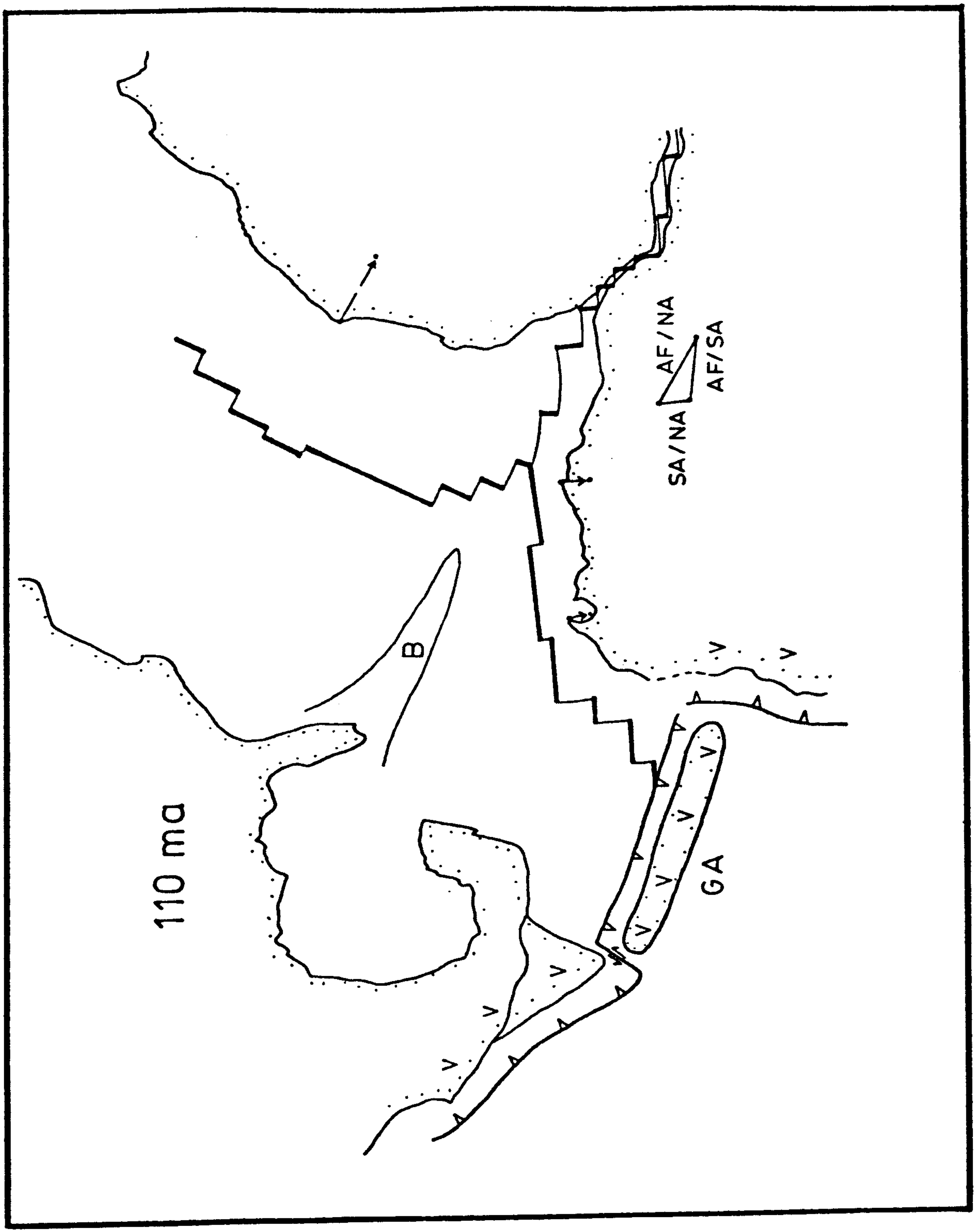


Figure 23. At 110 ma, rifting between South America and Africa began, thus producing a 3-plate system. The independent motion of South America requires a new orientation for the ridge between north and South America. It is suggested that the ridge jumped from its Bahamian postion to that shown; at 80 ma this new ridge position will be the site of a subduction zone (Venezuelan Antilles), following the principle that subduction often is initiated at zones of weakness. The Greater Antilles Arc (GA) begins migrating towards the Bahamian Platform.

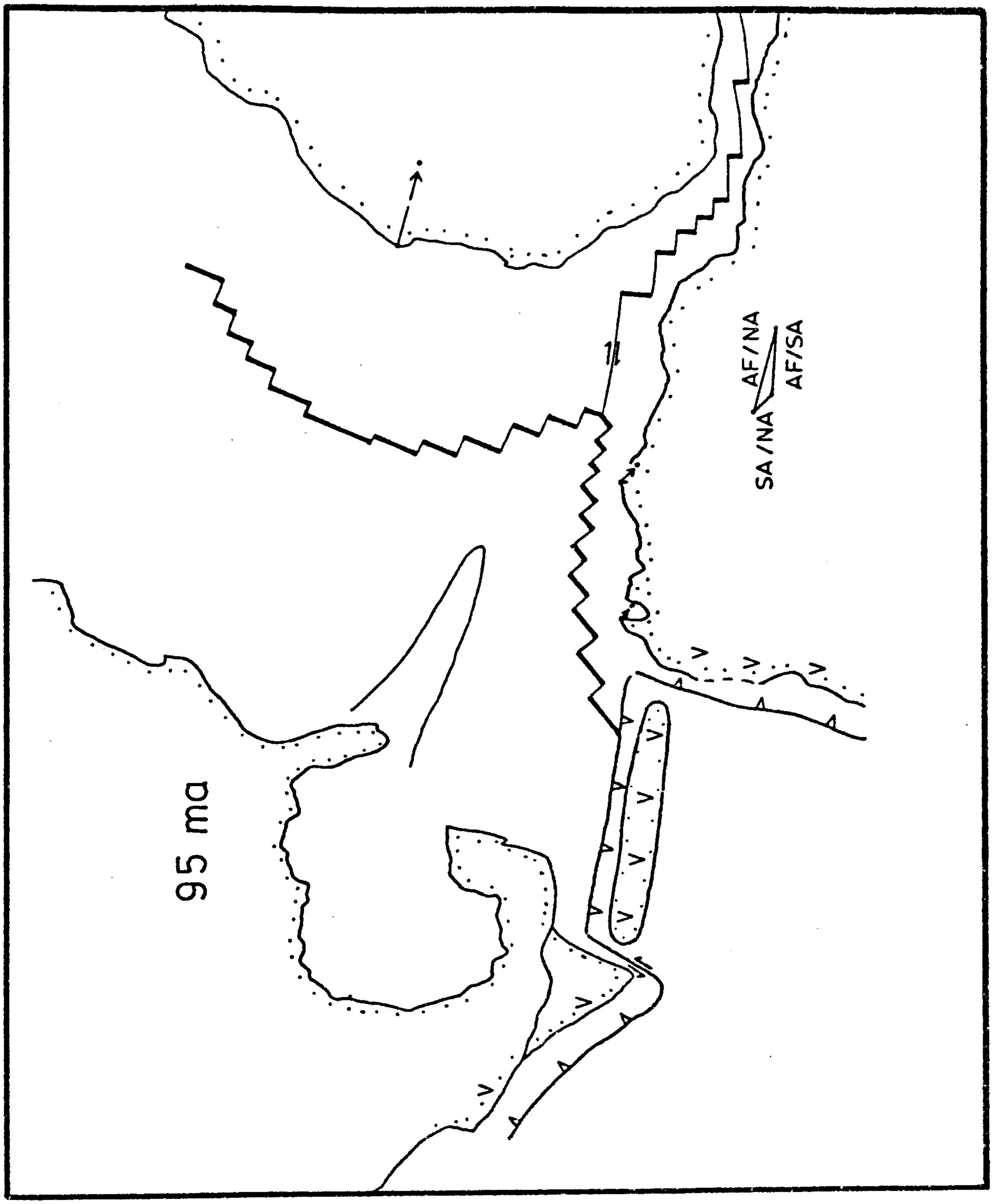


Figure 24. At 95 ma, opening of the equatorial Atlantic continues, and the Greater Antilles arc continues to migrate into the North-South American gap. By 80 ma, the western portion of the arc will have collided with the Yucatan Platform. This position is preferred over a Chortis-Yucatan collision due to the lack of evidence of collision in the Late Cretaceous stratigraphy of northern Chortis.

Figure 25. 80 ma. The Late Cretaceous seems to be a time of great complexity. The Greater Antilles arc collided with the Yucatan block, sending thrust sheets northward onto the shelf bank. Eruption of B" basalts and gabbros by this time (80-90 ma) puts a maximum on the age of motion upon the Hess escarpment. An igneous event capable of doubling the thickness of normal oceanic crust would surely destroy any pre-existing topographic or magnetic features. The presence of B" basalts in accretionary complexes of southern Hispaniola suggests that a short-lived north dipping subduction episode occurred to the south of the Greater Antilles arc. A Late Cretaceous unconformity in southwest Dominican Republic further supports this view. It is suggested that motion upon the Hess Escarpment occurred in the Late Cretaceous, after erpution of the B" basalts, and that their motion was associated with the northward dipping subduction. Subduction was also initiated at the Panama-Costa Rican arc during the 80-70 ma period, further complicating matters. The presence of B" basalts in the accretionary prism at Nicoya, Costa Rica indicates that this subduction zone was initiated within the area affected by B" event. The presence of sediments underlying the basalts in the Caribbean Sea suggests that the vulcanism was off-axis, similar to that in the Hawaiian chain.

To the east, northward dipping subduction was initiated at the Netherland-Venezuelan Antilles arc (NVA) at this time; approach by the South American plate led to collision by 65 ma. The geometry of the intersection of the convergent boundaries cannot be specified at this time. Better understanding of the convergence along the Southern Greater Antilles Arc is required.

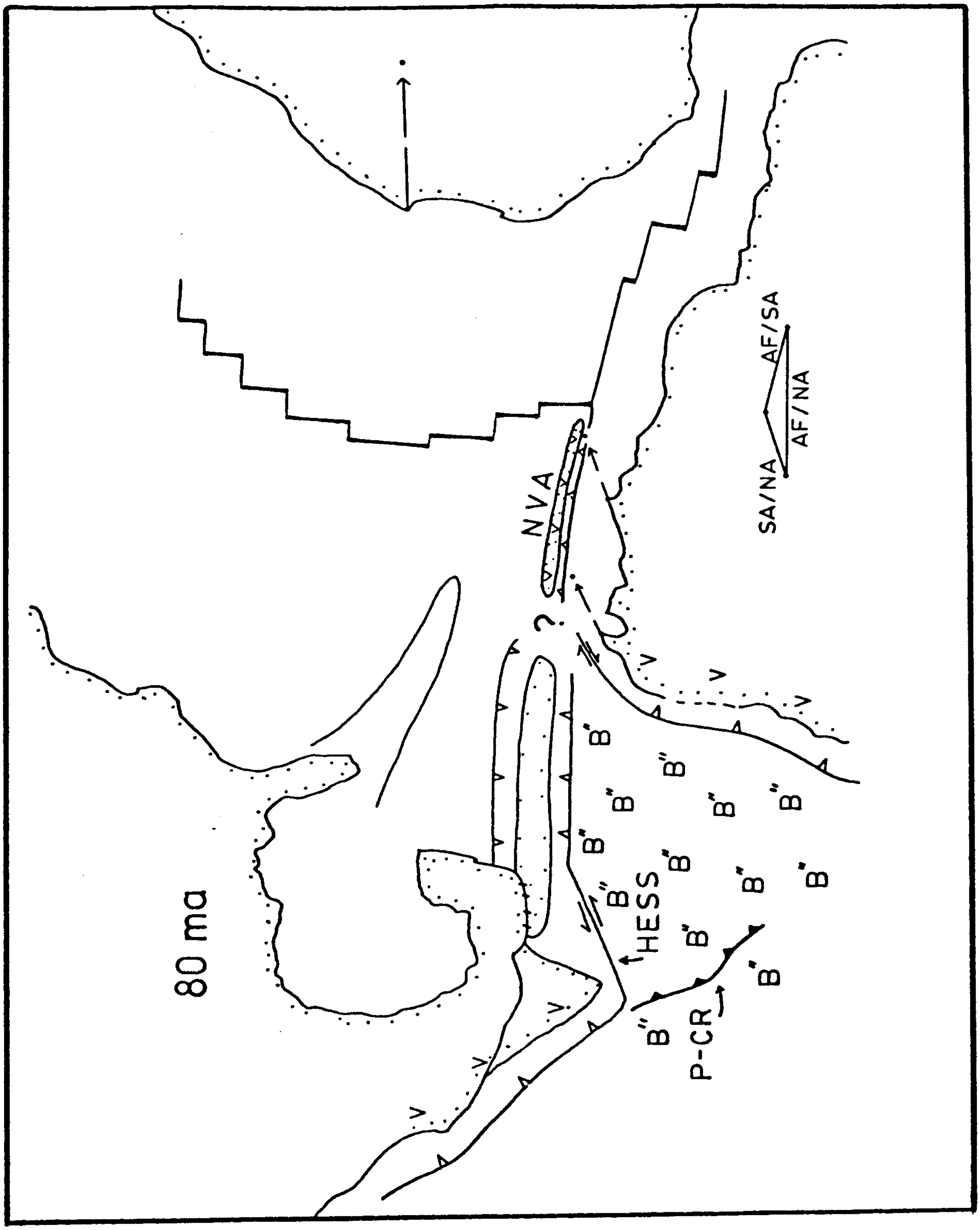


Figure 25. Plate boundary configuration at 80 ma.

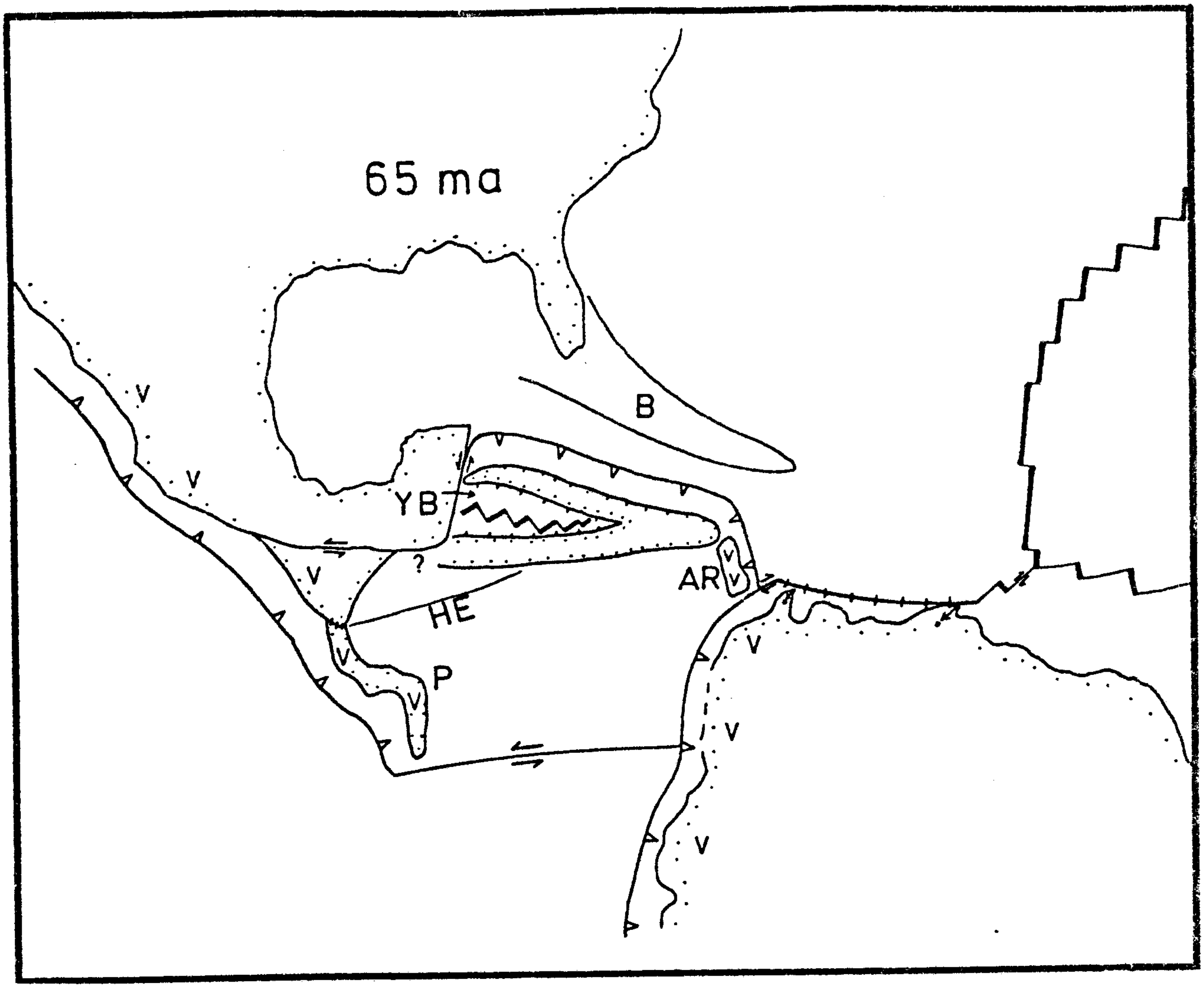


Figure 26. At 65 ma, back-arc spreading was initiated within the Greater Antilles arc, thereby producing the Yucatan Basin (YB). Cuba migrated northwards (frontal arc) while the Nicaragua Rise, Jamaica and south Hispaniola (remnant arc) were left behind. The arc may have gone into extension as a result of subduction at the Panama-Costa Rica arc (P) and to the south of the Greater Antilles arc (Figure 25), thereby reducing the convergence rate of the subduction zone north of the Greater Antilles.

Vulcanism at the Aves Ridge indicates subduction at this time, possibly related to eastward motion of the Caribbean Plate wrt the North American Plate.

Collision between the Netherlands-Venezuelan Antilles arc and South America had occurred by 65 ma. Relative motions between the North and South American Plates from 65 to 53 ma is slightly extensional; this extension may be seen in the development of early Eocene rifts of northern South America.

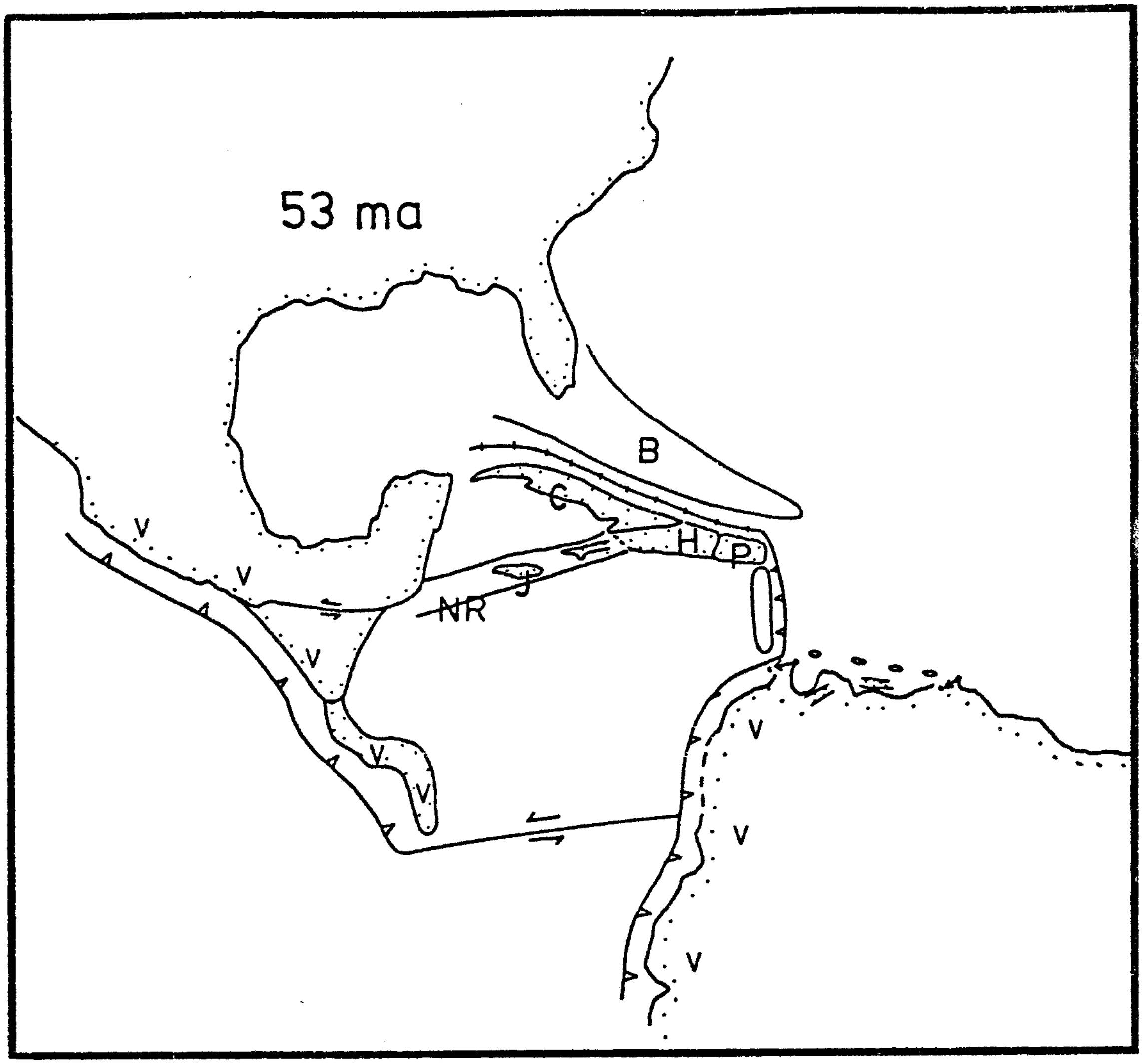


Figure 27. At 53 ma, collision between the Northern Greater Antilles Arc and Bahamas Platform marked the closure of the Proto-Caribbean Sea, the formation of which was associated with the opening of the Atlantic Ocean. By this time, no original crust remained between North and South America. Since the Eocene, eastward migration of the Caribbean Plate relative to both North and South America has produced the North and South Caribbean Plate Boundary Zones. During the interval 53 to 36 ma, vulcanism along the eastern margin of the Caribbean Plate migrated from the Aves Ridge to the Lesser Antilles.

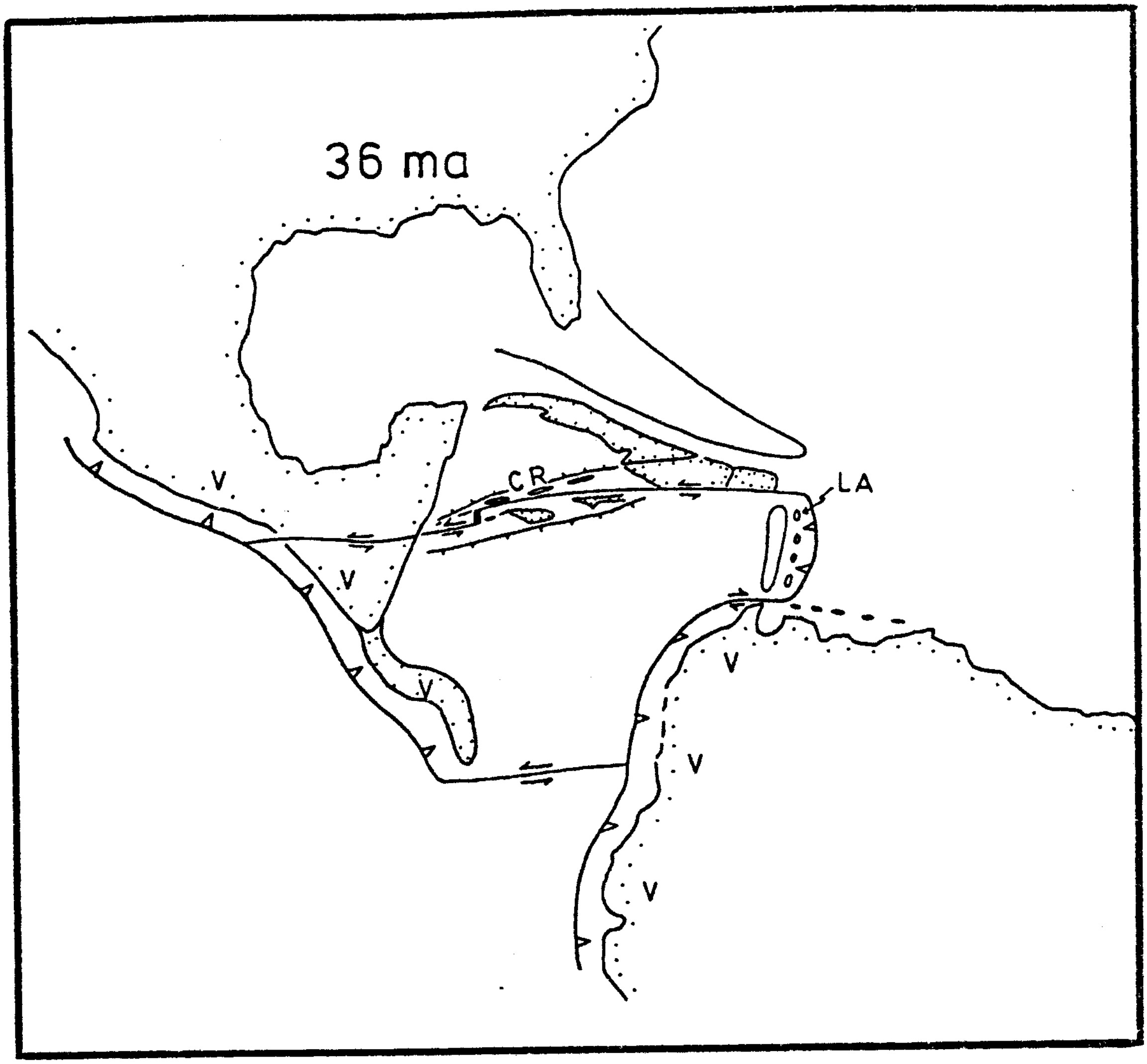


Figure 28. At 36 ma, strike-slip faulting and basin development (pull-aparts) had begun with the Northern Caribbean PBZ. The Mid-Cayman Spreading Center was developed at about this time, the transforms associated with which bisected the Cayman Ridge (CR) from the remainder of the remnant arc. Grandiose eastward migration of the Caribbean Plate relative to North and South America was underway at this time.

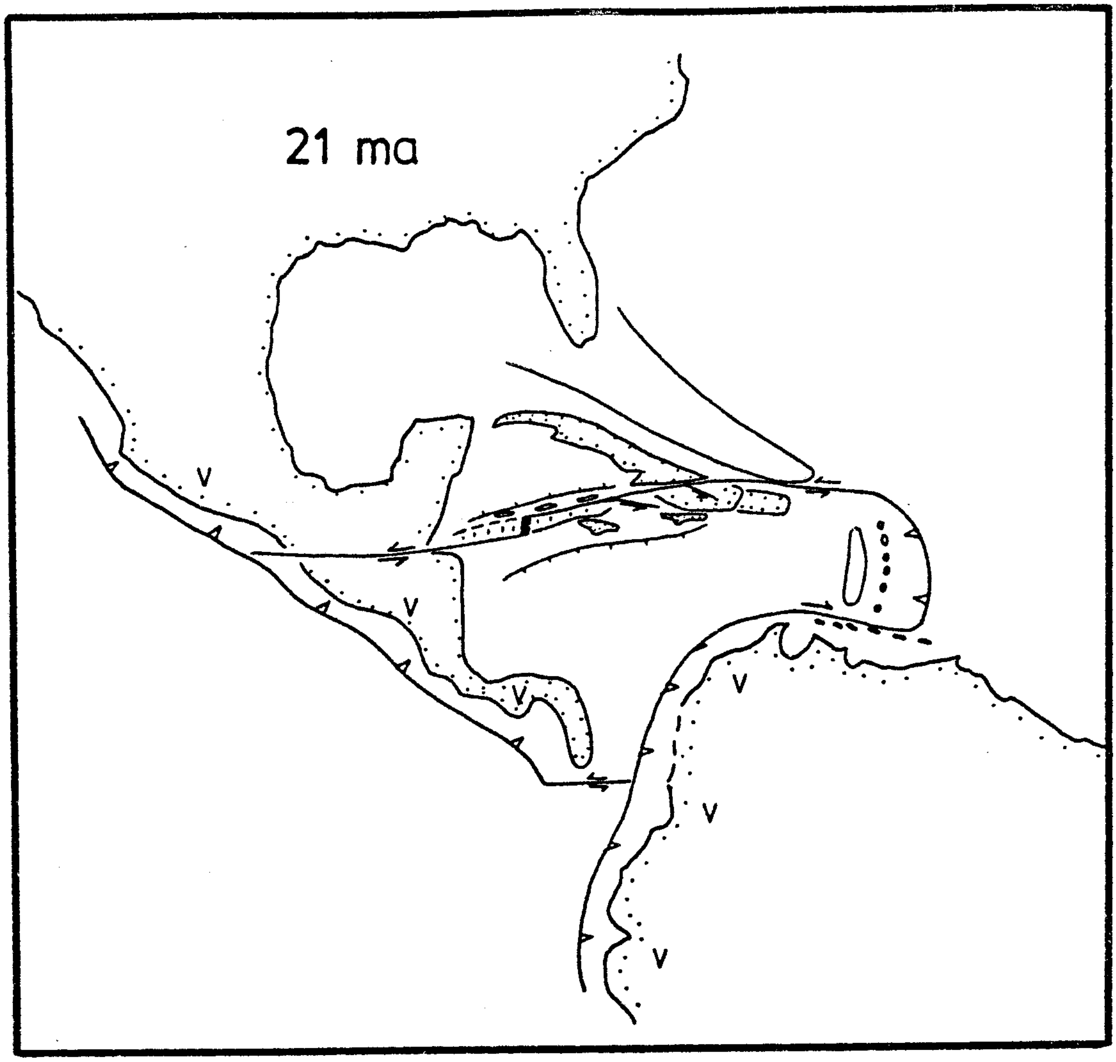


Figure 29. At 21 ma, eastward migration was continuing, but the main through-going fault of the North PBZ had shifted northward to bisect Hispaniola from southeastern Cuba. Panama was approaching western Colombia, and basin development (pull-aparts) was underway in the South Caribbean PBZ.

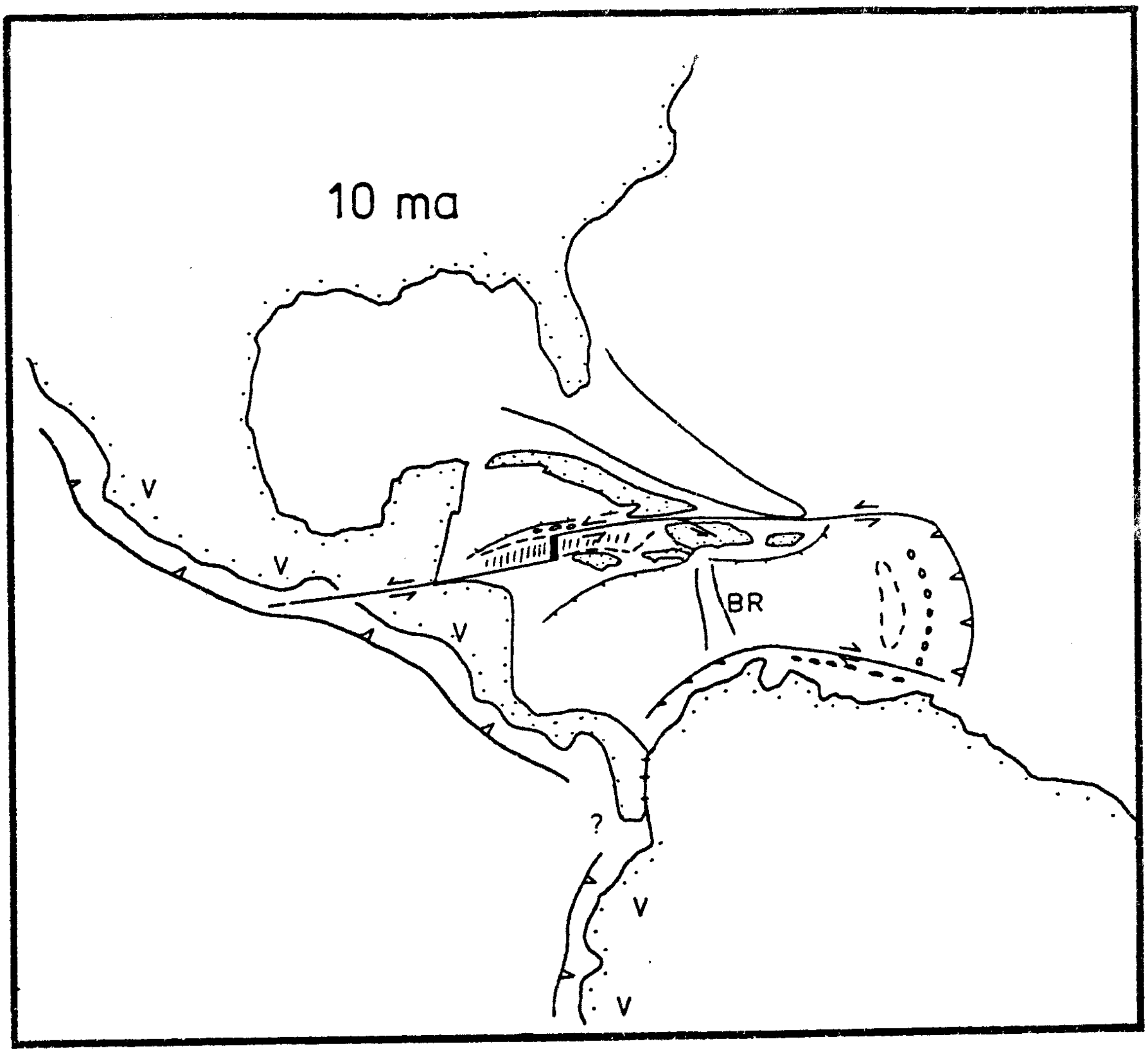


Figure 30. At 10 ma, collision between the Panamanian arc and Colombia was underway. Hispaniola had been separated from Cuba, and the juncture between southern and northern Hispaniola was achieved by strike-slip faulting, with extension deposition of evaporites in a closing basin (Cul de Sac/Enriquillo). The development of many miocene grabens along the PBZs and uplift of the Beatta Ridge (BR) may indicate a tectonic disturbance to the Caribbean Plate. It is suggested that the Panama-Colombia collision produced these far-reaching effects. Also, a slight convergent component between the North and South American Plates has probably led to deformation of the Caribbean Plate as well.

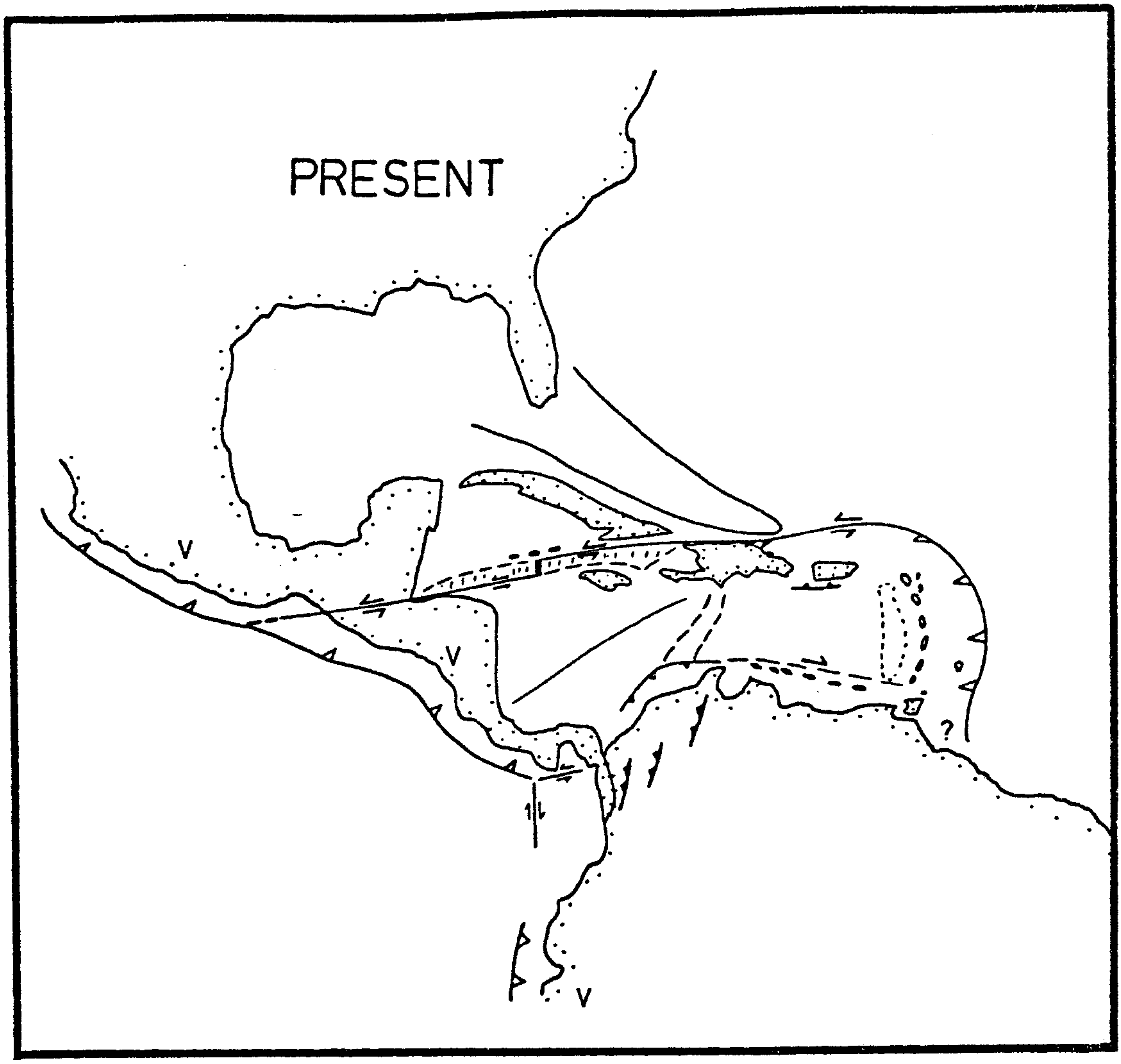


Figure 31. At present, intense deformation is occurring in Colombia in response to continental compression of the collision. Eastward migration of the Caribbean Plate, and associated deformation in the North and South Caribbean PBZs continues. The total offset along the North Caribbean PBZ is at least 1400 km, as evidenced by the crust created at the Mid-Cayman Spreading Center.

CHAPTER VI

RIFTS AND SUTURES OF THE CENTRAL AMERICA-CARIBBEAN REGION

RIFTS

ACTIVE AND POST-EOCENE RIFTS

The Caribbean plate, outlined in figure 32, is bordered on the north and south by complex plate boundary zones (PBZ), within which many small active rifts occur as products of internal deformation of the Caribbean plate (Burke, et al., 1980). The plate boundary zones have developed since the Late Eocene as a response to eastward migration of the Caribbean Plate with respect to North and South America. The eastern and western plate boundaries, on the other hand, are defined by subduction zones whose overriding plate is the Caribbean plate in both cases. The western plate margin presently exhibits extensional rifts of the kind described in Molnar and Atwater (1978, Appendix), which are capable of developing into marginal basins. Likewise, proponents of the idea that the Grenada Basin formed by back-arc spreading between the Lesser Antilles and Aves Ridge (as considered in Tomblin, 1975) would suggest that the eastern margin may have undergone similar extensional behavior during the Paleocene to Eocene time. I, however, do not here consider the Grenada Basin as a rift.

North Caribbean Plate Boundary Zone

Sinistral shear totalling about 1400 km offset, as indicated by the apparent length of the Cayman Trough, has characterized and modified the northern margin of the Caribbean plate since the Late Eocene. Much of this offset, but not all, has occurred along the Motagua-Swan-Oriente-Puerto Rico Trench transform system. The remainder has been taken up by fault-splay systems distributed within the northern 200 km of the Caribbean plate in the Greater Antilles (Burke, et al., 1980). The Greater

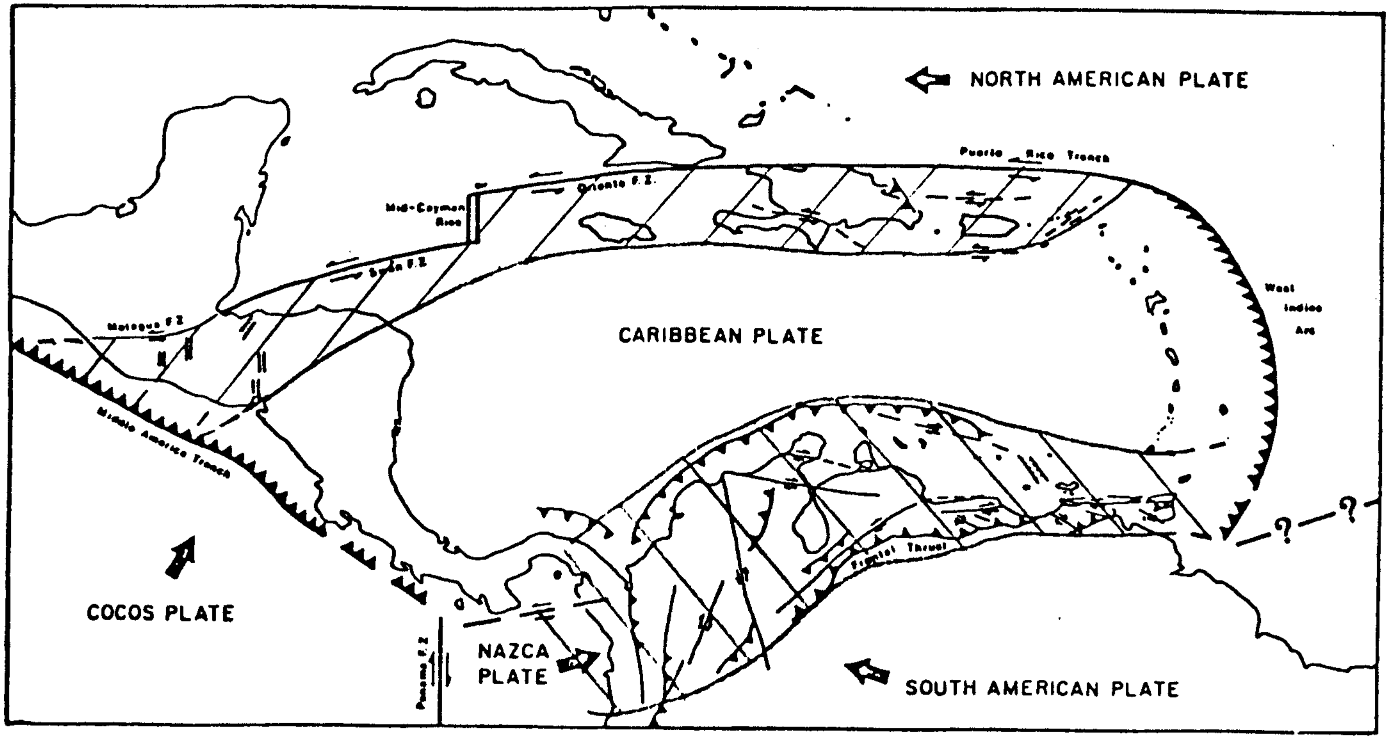


Figure 32. A schematic tectonic map of the Caribbean region showing plate boundaries and Late Cenozoic tectonic features. Hypothetical or inferred structures are represented by broken lines. Bold arrows give the direction of plate motions with respect to the Caribbean Plate. North and South Caribbean Plate Boundary Zones are shown by diagonal patterns. (modified after Jordan, 1975.)

Antilles are largely composed of Cretaceous-early Tertiary arc-related igneous rocks that lie on a highly modified oceanic basement.

The arc-related material in the left-lateral North Caribbean PBZ, although not homogenous in nature, has behaved to a large extent like the material in the simple shear zone experiments of Tchalenko (1970). Since the late Eocene there has been NE-SW compression and NW-SE extension, so that faults oriented NW-SE experience extension (rifts). Uplift typically accompanies compression while depression accompanies extension; thus, emergent areas in the North Caribbean PBZ (Jamaica, Hispaniola, Puerto Rico) are presently dominated by thrusting along NW-SE trending faults. The thrusting has produced several Miocene to present ramp valleys in these areas (for example, the San Juan, Cibao and Enriquillo Basins of Hispaniola), but these and other basins may have had an earlier history of rifting. Most active rifts in the North Caribbean PBZ occur in offshore portions of the Greater Antilles and in the northern portion of the Chortis block, which is underlain by continental crust. Post-Eocene rifts of the North Caribbean PBZ are shown in figure 33.

Most rifts in the Greater Antillean portion of the North Caribbean PBZ are pull-apart grabens (at releasing bends) where the trend of various left-lateral strike-slip faults veers to the left, thereby opening deep cavities as strike-slip motion continues. The cavities are typically 0.5 to 4 km in depth and are filled primarily by Miocene-present sediments. Active, named rifts that satisfy this classification are the *Yallahs Basin* [1] (Burke, 1967), the *West Navassa* [2] (Burke, *et al*., 1980), the *Central and East Navassa* [3, 4] (Mann and Burke, 1981), the *Southern Haitian grabens* [5, 6, 7] (Butterlin, 1960; Burke and Mann, 1981), the *Port au Prince* [8] (Woodring, *et al*., 1924), the *Low Layton* [9] (Mann and Burke, 1980; Wadge, 1981), the *Windward Passage* graben [10] (Goreau, 1980) and

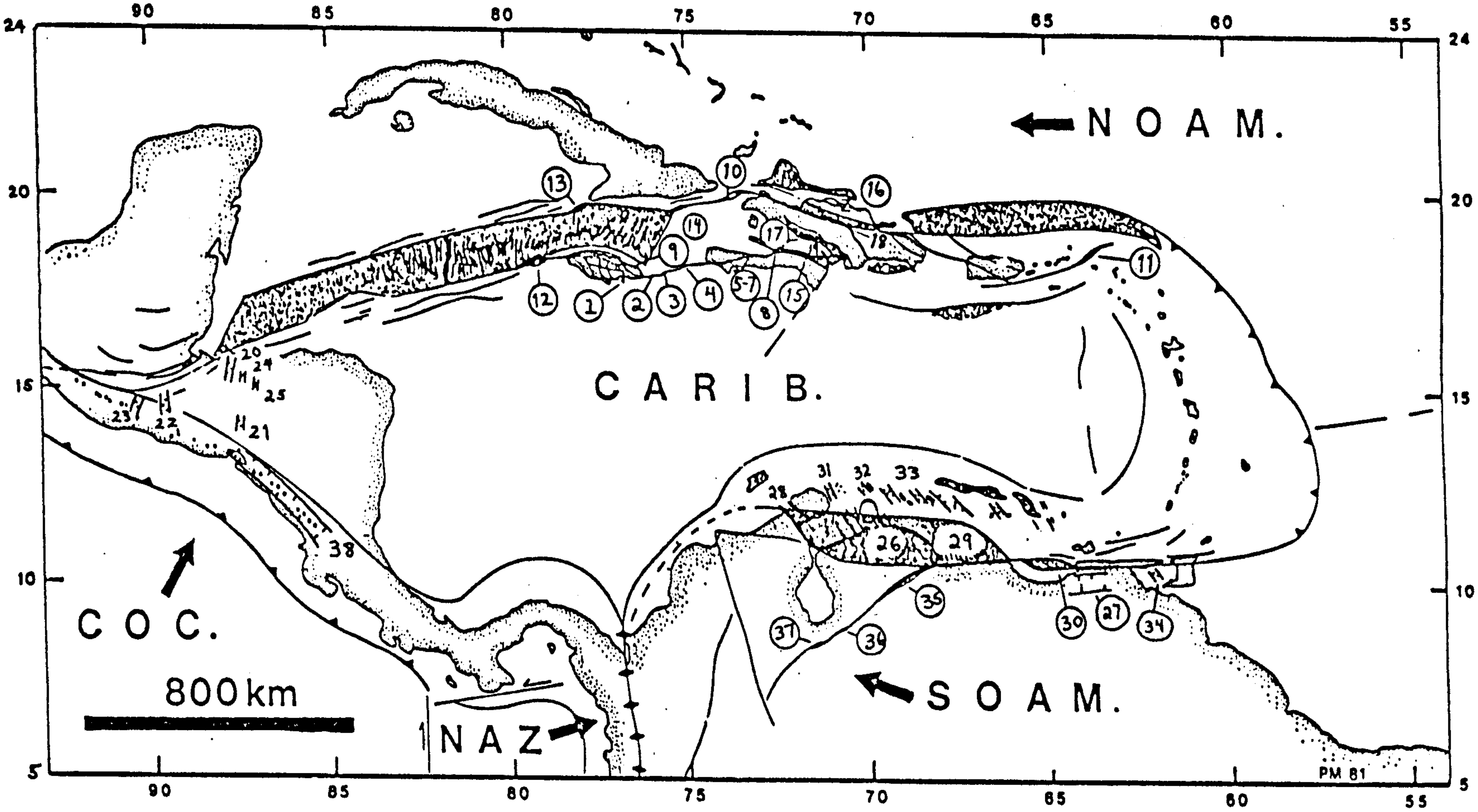


Figure 33. Post-Eocene rifts of the Central American-Caribbean region. Numbers refer to rifts described and named in text. Modified after Paul Mann, 1981.

the Anegada graben [11] (Donnelly,1963). Other rifts occur at 79°W 18°20'N [12] (Holcombe, 1981), 78°W20°N [13] (Case and Holcombe, 1980), and 76°W19°30'N [14] (Case and Holcombe, 1980). Basins that are presently in compression but that may have had an earlier history of rifting (Oligocene?) are the Cul de Sac-Enriquillo [15] (Bowin, 1975), the Cibao [16] (Bowin, 1975; Biju-Duval, et al., 1980), the San Juan [17] (Michael and Millar, 1977), the Tavera [18] (Palmer, 1979; Mann and Burke, 1981), and the Fondo Negro [19] (Cooper, in prep.).

In northern Chortis, rifts of the sort under consideration are so numerous that Mann (personal communication, 1981) has applied a Prandtl cell model to the area in order to interpret the current deformation of the crust. All are considered to be Neogene and presently active due to the sharp topography associated with them (Muehlberger, 1976). The Honduras Depression (Muehlberger, 1976) is composed of several discontinuous grabens known as the Ulua [20] (Dengo, 1968), Comayagua [21] (Everett, 1970; Fakundiny, 1970) and others that more or less cross central Honduras from the Gulf of Honduras to the Pacific Ocean (Gulf of Fonseca). Downdrop in most of these is about 2000 meters, and the maximum horizontal extension proven on any one graben is about 2 km (Muehlberger, 1976). Other similar, representative grabens of northern Chortis are the Ipala [22] (which may have undergone a small amount of counterclockwise rotation during the predominantly left-lateral shear), the Mixco [23], the El Nigrito [24] and the Morazon [25] (Muehlberger, 1976). All are roughly oriented north to northeast and are truncated at their southern and northern ends by strike-slip faults with a typical trend of N60W, which are associated with the left-lateral shear of the North Caribbean PBZ.

South Caribbean Plate Boundary Zone

Considerable right-lateral offset has occurred between the South

American and Caribbean plates since the Eocene. During this period South America has moved westward with respect to North America (see figure 15), and the left-lateral offset between the North American and Caribbean plates is about 1400 km. Therefore, dextral motion across the South Caribbean PBZ totals at least 1400 km. The plate boundary zone itself (see figure 32) is 200-400 km wide and the rock types situated within the PBZ are 1) continental crust of northern South America and 2) island arc-related igneous rocks resting on oceanic basment (Netherlands and Venezuelan Antilles). It is likely that the trench along the outer wall of the Curacao Ridge (and its poorly defined extensions) has been predominantly strike-slip in nature and has taken up much of the total offset, but fault-splay systems and the differential motion between the South American and Caribbean plates have produced the South Caribbean PBZ. For these reasons, the South Caribbean PBZ may be considered as a mirror image of the North Caribbean PBZ (Bucher, 1948), especially to the east of Golfo de Venezuela and Lago de Maracaibo. Several northwest trending extensional grabens may be interpreted as having developed in a late Cenozoic dextral shear zone (Case, 1974) in which NW-SE extension occurred. To the west of the Maracaibo area, compression has been the dominant mode since the Miocene as a result of nearly head-on convergence between northwestern South America and southwest portions of the Caribbean plate. There is also evidence for northward extension (several east-west trending rifts) throughout the Middle Tertiary (Silver, et al., 1975). Because of the structural complexities of the Venezuelan Borderland, a credible, all-inclusive model has not yet been constructed (but see Vierbuchen, 1978).

Whether it is tectonically significant to distinguish between east trending and southeast trending rifts is debatable. All are shown in figure 33. East trending rifting probably associated with Tertiary north-south extension, whether orthogonal or accompanied by a strike-slip component, is evidenced by the *Maracaibo* (reactivated in the Eocene), *Falcon*, *Baja-Guajira*, *Bonaire*, *East-Venezuelan* and Cariaco (?) Basins. These rifts crudely form a semi-continuous belt of extension across the northern Venezuelan borderland. The *Falcon Basin* [26] (Silver, *et al*., 1975; Muessig, 1978; Wheeler, 1963; Case, 1974) shows continuous sedimentation from Eocene to Miocene time, with deposition of 6,000 meters of Oligocene to Early Miocene shales, sandstones, limestones and conglomerates during primary basin subsidence. Likewise, the *East Venezuelan Basin* [27] (Hedberg, 1950: Silver, *et al*., 1975) contains 6,000 to 10,000 meters of Oligocene to Miocene shales, with limestones, sandstones and conglomerates around the basin edges. The *Baja Guajira Basin* [28] (Irving, 1971, Case 1974) contains at least 3 km of Tertiary sediments that were deposited during north-south extension (but see Case and MacDonald, 1973 for strike-slip origin), while similar extension between the Venezuelan coastline and Venezuelan Antilles has been suggested to have produced the *Bonaire Basin* [29] (Ball, *et al*., 1971; Silver, *et al*., 1975). The very recent *Cariaco Basin* [30] (Peter, 1971; Ball, *et al*., 1971; Harrison and Ball, 1973) is most likely a complex pull-apart basin bounded by the San Sebastian and El Pilar right-lateral faults (Silver, *et al*., 1975) and therefore not strictly a north-south extensional rift.

Northwest-southeast trending rifting, which fits well into the right-lateral shear zone model, is seen to be occurring today within the Guajira Peninsula and between each of the islands of the Netherlands and Venezuelan Antilles (see figure 33)in a belt that lies just north of the extensional belt described above. The *Chichibacoa Basin* [31] (Thomas, 1972; Case, 1974) contains 4 km of later Tertiary sediments between the uplifted blocks of the Guajira Peninsula and Los Monjes islands. Between the Peninsula de Paraguana and the island of Aruba, a similar basin [32] contains 1.5 km of recent sediments (Feo-Codecido, 1971). Within the island chain itself, very deep sedimentary basins [33] (up to 10 km, Edgar, et al. 1971) exist between Aruba and Curacao and Curacao and Bonaire, while less well developed northwest trending rifts occupy the gaps between Islas de Avez, Islas de Roques, Isla Orchila and LaBlanquilla (Silver, et al., 1975). Northwest trending Los Roques Canyon may be a fault-controlled feature as well. Another southeast trending Miocene pull-apart is the Soldado graben [34] beneath the Gulf of Paria (Salvador and Stainforth, 1965; Ablewhite and Higgins, 1965).

In summary, it is apparent that two rift belts of differing character occupy the South Caribbean PBZ. The relationships between the two belts, if any, are as yet unclear, but it is likely that the southern belt of east-west trending rifts pre-dates development of the northern belt. Three other rifts not related to these belts are found along the Bocono Fault and have developed since the Pliocene. These are the Yaracuy [35], the Mucuchies [36] and the Gonzalez [37] grabens (Schubert, 1980).

Western Caribbean Plate Boundary (Central America)

Oceanic crust of the Cocos plate has been subducted beneath the Caribbean plate at least since the Cretaceous (Schmidt-Effing, 1979; Krushensky, et al., 1976; Karig, et al., 1978). There is evidence, however, that the arc system has recently become somehwat extensional in nature. Several grabens have developed with their long axes roughly parallel to the Central American Trench which collectively form the Nicaragua Depression [38] (see figure 33) (Muehlberger, 1976). The Nicaragua Depression potentially may develop into a back-arc basin but at present is still quite immature.

PALEOCENE TO EOCENE RIFTS

The Yucatan Basin is treated as a back-arc basin of Paleocene to Early Eocene age that was produced by extension of the north-facing Greater Antilles island-arc prior to the Late Eocene collision between the frontal arc (Cuba, northern Hispaniola, Puerto Rico) and the Bahamas Platform. Only the Cuban segment of the Greater Antilles arc underwent back-arc spreading, and the remnant arc (Karig, 1972) from which the frontal arc (Cuba) was rifted is now seen as the Cayman Ridge and Nicaragua Rise-Jamaica-southern Hispaniola arc complexes. Post-Eocene development of the Cayman Trough has dissected the remnant arc into its two components (Perfit and Heezen,1978), so that the original Greater Antilles arc has been dissected twice, thereby producing three distinct arc complexes.

The first dissection of the Greater Antilles arc, Paleocene to Early Eocene back-arc spreading, produced rifted margins and other related rifts along the south side of the frontal arc and north side of the remnant arc that are filled with Paleocene to Early Eocene rift-type sediments (see figure 34). A similar age for the Yucatan Basin is indicated by subsidence analysis of the floor of the Yucatan Basin. Assuming the Basin is underlain by normal oceanic crust, its depth (4500 meters) and sediment cover (1.5-2.0 km, Rosencrantz, personal communication, 1981) suggest an early Tertiary age.

The Cauto rift [39] of southeastern Cuba probably formed in a manner similar to the North Island, or Taupo Volcanic zone of New Zealand (described by Karig, 1970; Dewey, 1980). That is, it represents the hinge of an opening back-arc basin. The stratigraphic section (Breznyansky and Iturralde-Vinent, 1978; Iturralde-Vinent, 1978) includes Paleocene and Lower Eocene volcano-sedimentary deposits that are succeeded by Middle Eocene transgressive carbonates and Upper Eocene to Middle Oligocene carbonate-

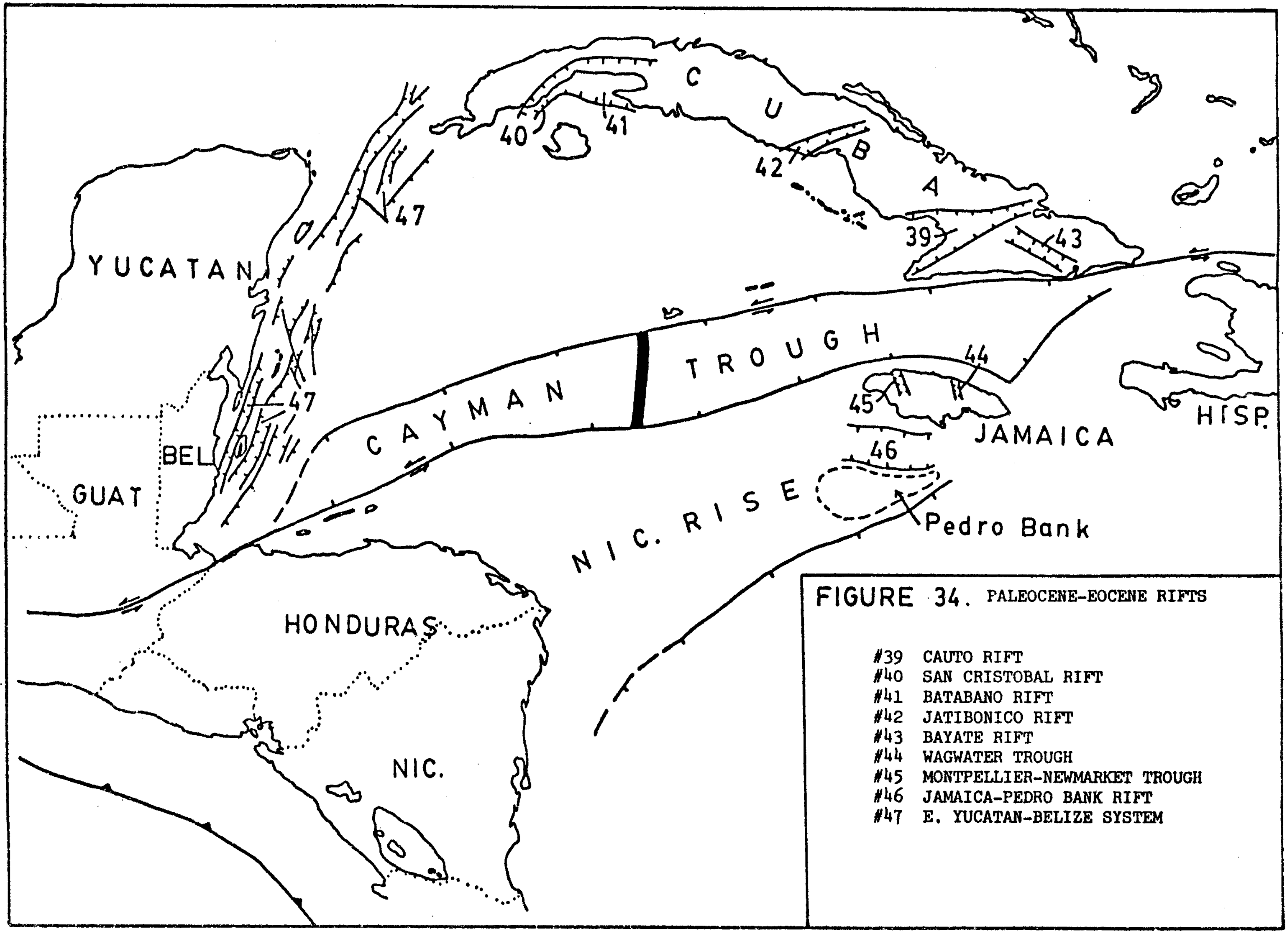


FIGURE 34. PALEOCENE-EOCENE RIFTS

#39 CAUTO RIFT
#40 SAN CRISTOBAL RIFT
#41 BATABANO RIFT
#42 JATIBONICO RIFT
#43 BAYATE RIFT
#44 WAGWATER TROUGH
#45 MONTPELLIER-NEWMARKET TROUGH
#46 JAMAICA-PEDRO BANK RIFT
#47 E. YUCATAN-BELIZE SYSTEM

terrigenous deposits. Carbonate deposition continued until Lower Miocene times when strike-slip activity began to lift the region.

A similar depositional pattern is found in the *San Cristobal* [40], *Batabano* [41], *Jatibonico* [42] and *Bayate* [43] grabens of Cuba. The *Batabano* is interpreted as the rifted margin that formed as Cuba was rifted from the Cayman Ridge-Nicaragua Rise complex. The *San Cristobal* and *Jatibonica* Basins may represent small-scale failed arms during the rifting episode or they may represent zones of extensional differential movement as Cuba migrated northward away from the remnant arc. The *Bayate* graben and its relation to the *Cauto* rift is poorly understood, although its orientation is similar to the *Enriquillo* [15] and *San Juan* [17] basins of Hispaniola which, during pre-Cayman Trough time, may have been directly aligned with *Bayate*. A confident assessment of pre-Cayman Trough Antillean paleogeography awaits more data.

Turning to the north side of the remnant arc, and restoring post-Eocene movement on the Cayman Trough system, two rifts are known in Jamaica with the same age as those in Cuba. The *Wagwater Trough* [44] and the *Montpellier-Newmarket Trough* [45] (see figure 34) were extensional rifts of Paleocene to Early Eocene age (Green, 1977; Mann, in prep.) which have since gone into compression during post-Eocene deformation. Mann has also suggested (personal communication) a rift-related origin of this age for the channel separating the Pedro Bank from Jamaica [46].

Another consequence of Early Tertiary back-arc spreading was the left-lateral transform passage of westernmost Cuba along the eastern Yucatan-Belize margin. This passage occurred in latest Cretaceous to Paleocene time. During the lower Cretaceous, stable carbonate and evaporite platform deposition predominated across the eastern Yucatan Peninsula, but the uppermost Cretaceous strata contain many layers of angular to rounded limestone conglomerates through several hundred meters of section that are suggestive of uplift and faulting (Weidie, et al., 1976). Vedder et al. (1971) suggests that the faulting occurred as early as Paleocene time. The present-day basement morphology of the offshore margin is composed of several ridges or horsts that are separated by intervening grabens (Uchupi, 1973; Dillon and Vedder, 1973). Subsidence of the margin to its present depth has occurred since the passage of the Cuban arc and is associated with the natural thermal subsidence of the newly emplaced back-arc basin crustal material. The intervening grabens are here named the East Yucatan-Belize marginal graben system [47]. Similar grabens between submerged ridges are reported from the Yucatan Channel on strike to the north (Pyle, et al., 1973).

SUTURES

Most of the sutures of the Caribbean region were discussed in Chapter 4 and thus discussion is not repeated here. These are:

Panama-Colombia Suture [1]
Northern Greater Antilles-Bahama Suture [2]
Motagua Suture Zone [3]
Netherlands-Venezuelan Antilles-South American Suture [4]
Chortis-Costa Rica Suture: Santa Elena Peridotite [5]

The existence of two additional sutures has been proposed, however, and these are briefly described below. These and all other known sutures are shown in figure 35.

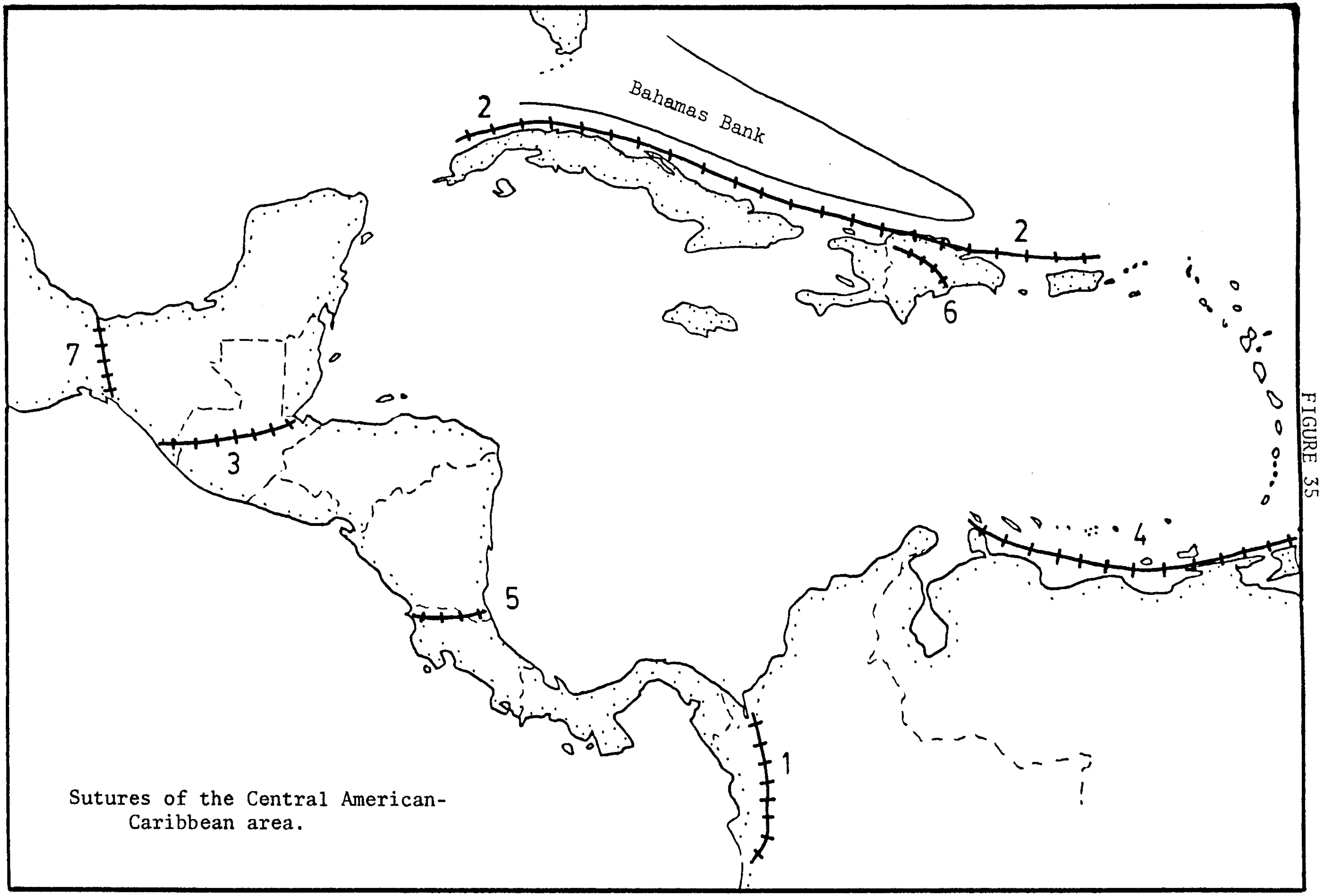
Hispaniola Fault Zone of Hispaniola [6]

It has been suggested (Draper and Lewis, 1980) that the peridotite belt adjacent to the Cordillera Central (Hispaniola Fault Zone) may

Figure 35. Sutures of the Central American-Caribbean area.

1. Panama-Colombia Suture
2. Northern Greater Antilles-Bahamas Suture
3. Motagua Suture Zone
4. Netherlands-Venezuelan Antilles--South America Suture
5. Santa Elena Peridotite
6. Hispaniolan Fault Zone (?)
7. Isthmus of Tehuantepec Suture (?)

FIGURE 35



Sutures of the Central American-Caribbean area.

represent the remains of an ancient subduction zone. Present knowledge is insufficient to substantiate this view as the only possibility and therefore the peridotites do not necessarily represent a genuine suture, although additional field work may strengthen the case. Because the island of Hispaniola is an intra-oceanic arc where calc-alkaline igneous rocks rest upon an ocenic basement, the peridotite occurrence along the Hispaniola Fault Zone may simply be related to the uplift of slivers of oceanic basement within the fault zone during Neogene transform motion.

Isthmus of Tehuantepec Suture [7]

Several authors have proposed the possible existence of a Late Jurassic suture between the Yucatan block and the rest of Mexico in the area of the Isthmus of Tehuantepec (White, 1980; Freeland and Dietz, 1972).

The proposals are based on geometric constraints required to dispose of the South America-Central America overlap encountered in most Pangea reconstructions. Jurassic geology is deeply buried by younger sediments and little subsurface data is available to the public; therefore, a definite statement cannot be made as to whether a true suture exists across the Isthmus of Tehuantepec nor whether the juxtaposition was achieved by strike-slip motion or convergence via subduction.

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