The evolution of Middle America and the Gulf of Mexico–Caribbean Sea region during Mesozoic time

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ABSTRACT

A plate-tectonic model for the evolution of Middle America and the Gulf of Mexico–Caribbean Sea region is presented. The model, which is based upon the existence of the Mojave-Sonora megashear, incorporates into the Triassic Pangea reconstruction three microplates between North and South America, thus avoiding the overlap of the Bullard fit. These plates are the Yaqui, bounded on the north by the Mojave-Sonora megashear; the east and west Maya plates, bounded on the north by the Mexican volcanic zone and on the south by a predecessor of the Motagua fault zone; and the Chortis plate (parts of Guatemala and Honduras). During Late Jurassic time, as North America split away from Europe, Africa, and South America, shear, with left-lateral sense of displacement, occurred along the transform faults that bounded the microplates.

If ~800 km of left-lateral displacement along the Mojave-Sonora megashear, ~300 km along the Mexican volcanic belt, and ~1,300 km along a proto-Motagua megashear are restored, and if Yucatan and Cuba are rotated to fit against northern South America, then (1) a curvilinear belt of late Paleozoic rocks that show lithologic as well as paleontologic similarities extends across the reconstruction and links outcrops in Texas, eastern Mexico, nuclear Central America, and Colombia; (2) a Mediterranean-like sea is delineated that was a precursor of most of the present Gulf of Mexico; (3) correlation is implied between the distinctive quartzose San Cayetano Formation of Cuba and the Caracas and Juan Griego Groups of Venezuela.

Geometric constraints suggest that probably shear initially occurred along the Mexican volcanic zone near the end of the Middle Jurassic. Subsequently, probably about 160 m.y. ago, displacements that total ~800 km began along the Mojave-Sonora megashear. Contemporaneously, Yucatan and fragments of pre-Cretaceous rocks that compose parts of central and western Cuba migrated northward toward their present positions. Rotation of Yucatan was facilitated by considerable displacement along the proto-Motagua zone and along a zone that is probably coincident with the modern Salina Cruz fault. Accumulation of widespread major salt units of Late Jurassic (Callovian to early Oxfordian) age in the Gulf Basin probably occurred contemporaneously with the arrival of these blocks at their present positions. Clastic units that interfinger with some of the youngest salt units and rim the Gulf of Mexico have not recorded major recognized translations since their accumulation.

Clockwise rotation of South America and the Chortis plate occurred during Early Cretaceous time. This movement, which was manifested by subduction of Jurassic ocean floor against the previously rifted precursor of the island of Cuba and under parts of Hispaniola and Puerto Rico, is recorded by circum-Caribbean orogeny.

Abrupt changes in the relative motions between North and South America during Late Cretaceous time may have resulted in extension and outpourings of basalt upon the Jurassic rocks of the ocean floor of the Venezuelan Basin. West of Beata Ridge, sea-floor spreading formed the Colombian Basin. Related subduction occurred as the Chortis plate (including part of Central America, the Nicaraguan Rise, and southeastern Cuba) was sutured against the Maya East plate along the present Motagua fault and Cayman Trench.

Our model is constrained by published geologic data, the relative positions of North and South America from Atlantic sea-floor magnetic anomalies, and the requirement that the major transform faults be compatible with the poles of rotation for the appropriate relative motions between North and South America. Paleomagnetic data from Middle America are sparse but do not conflict with the predicted motions of some of the microplates, especially Chortis.

INTRODUCTION

The Mojave-Sonora megashear, whose existence is suggested by interruption of northeasterly striking Precambrian tectonic belts, was defined by Silver and Anderson (1974) as a zone of major apparent left-lateral offset. This zone of disruption appears to extend S50°E from the southern Inyo Mountains, California, across the Mojave, Colorado, and Sonoran Deserts, into the Sierra Madre Occidental of Sonora, northeast of Hermosillo (Fig. 1). Examination of the regional distribution of overlying late Precambrian and Paleozoic rocks resulted in recognition of truncation of depositional trends offset in a sense compatible with the megashear. Provocative similarities between stratigraphic columns in the Inyo Mountains–Death Valley region and the area around Caborca, Mexico, on opposite sides of the dislocation zone, suggest 700 to 800 km of left-lateral offset. Arguments based upon: (1) the tectonic and stratigraphic history

Supplementary data (Appendix) for this article are available upon request from the GSA Documents Secretary. Ask for Supplementary Data 83-13.

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along the continental margin of western North America, (2) extensive U-Pb isotopic age data from Mesozoic rocks near the shear zone collected in large part by L. T. Silver, and (3) stratigraphic relationships in eastern Mexico suggest that this inferred structure developed during the Callovian and Oxfordian Stages about 150 m.y. ago. (Note: The assignment of absolute ages to stages is based upon the time scales published by Van Hinte, 1976a, 1976b).

At the National Meeting of the Geological Society of America in 1974, L. T. Silver initially pointed out that sinistral translation along the Mojave-Sonora megashear offers an intriguing partial solution to the seemingly intractable problem of the overlap of southern Mexico across northern South America encountered with the Pangea reconstruction for early Mesozoic time (Bullard and others, 1965). Silver also recognized that viable plate-tectonic models of the evolution of the Gulf of Mexico would be a product of translation along the Mojave-Sonora megashear. Our model, although distinct from Silver's suggested plate geometries, is a direct outgrowth of his discussions.

OBJECTIVE

We propose the existence of an easterly extension of the megashear as well as complementary fractures to the south and suggest an early Mesozoic configuration for the part of Pangea that includes Middle America and the Gulf of Mexico–Caribbean Sea region. The second half of this article presents a hypothetical post-Triassic geotectonic evolution for the same area that relies upon the motions suggested by Ladd (1976) as applied to our proposed reconstruction. We strive to show that the model and its subsequent evolution are strikingly compatible with available geologic data as summarized by Lopez-Ramos (1969, 1974), de Cserna (1960, 1971a), Dengo (1975) and P. O. Banks (1975).

The hypothesized configuration leads to a viable model for the evolution of the Gulf of Mexico and the Caribbean region during post-Triassic time. The timing and style of the orogenic events in this region reflect the relative motion of South America with respect to North America (Ladd, 1976). An overview of the relationship of plate motion to North and Central American tectonism was initially presented by Coney (1972), who recognized some of the motions described by Ladd (1976) and who emphasized their role in evolution of the North American cordillera. The timing and sequence of most of the major evolutionary events of the formation of the Gulf of Mexico as we view its development are similar to the model presented by Salvador and Green (1980), although our directions of approach to the problem were very different.

DEFINITION AND CONSTRAINTS OF PROPOSED CRUSTAL BLOCKS

From the segment defined by Silver and Anderson (1974) in northwestern Mexico, the Mojave-Sonora megashear is projected northwest as suggested by L. T. Silver (1974, personal commun.). Additionally, an eastward extension of the megashear that occupies a zone defined by the disturbed patterns of distribution of Precambrian, Paleozoic, and Mesozoic rocks across Mexico is proposed (Fig. 1).

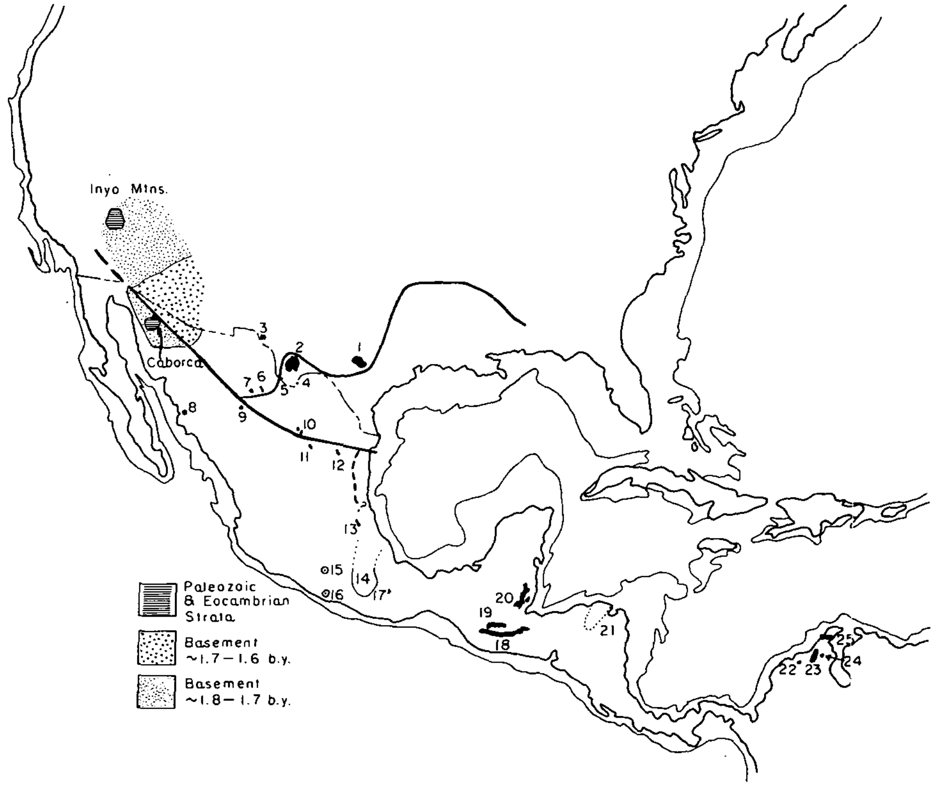

Figure 1. Index map showing the distribution of outcrops of some crystalline and sedimentary rocks mentioned in the text, as well as other relevant places and geologic and physiographic features. Basement configuration in southwestern North America based upon radiometric studies by L. T. Silver (1968; Anderson and others, 1971; Anderson and Silver, 1976; Silver and Anderson, 1974). Mojave-Sonora megashear is northwesterly trending heavy line. Probable western margin of sheets of Paleozoic rocks thrust toward the craton in the southern United States and eastern Mexico is represented by heavy solid line (Flawn and others, 1961) or inferred by heavy dashed line (de Cserna, 1971b). Horizontally ruled areas indicate regions where comparable sections of late Precambrian and Cambrian strata are known (Eells, 1972). 1. Llano uplift. 2. Marathon basin. 3. Van Horn region, west Texas. 4. Sierra del Carmen. 5. Solitario uplift. 6. Mina Plomosas–Placer de Guadalupe. 7. Sierra del Cuervo. 8. Sonobari complex. 9. Sierra Magistral. 10. Las Delicias, Acatita. 11. Apizolaya quadrangle, Zacatecas. 12. Ciudad Victoria; Peregrina and Huizachal uplifts. 13. Huayacocotla uplift. 14. Triassic basins. 15. Taxco. 16. Acapulco. 17. Nochistlan. 18. Permian rocks, Guatemala. 19. Eastern Chiapas, Mexico. 20. Maya Mountains, Belize. 21. El Plan Formation. 22. Chandua Group, Santa Marta block. 23. Cesar Basin. 24. Sierra de Perijá. 25. Cocinas trough.

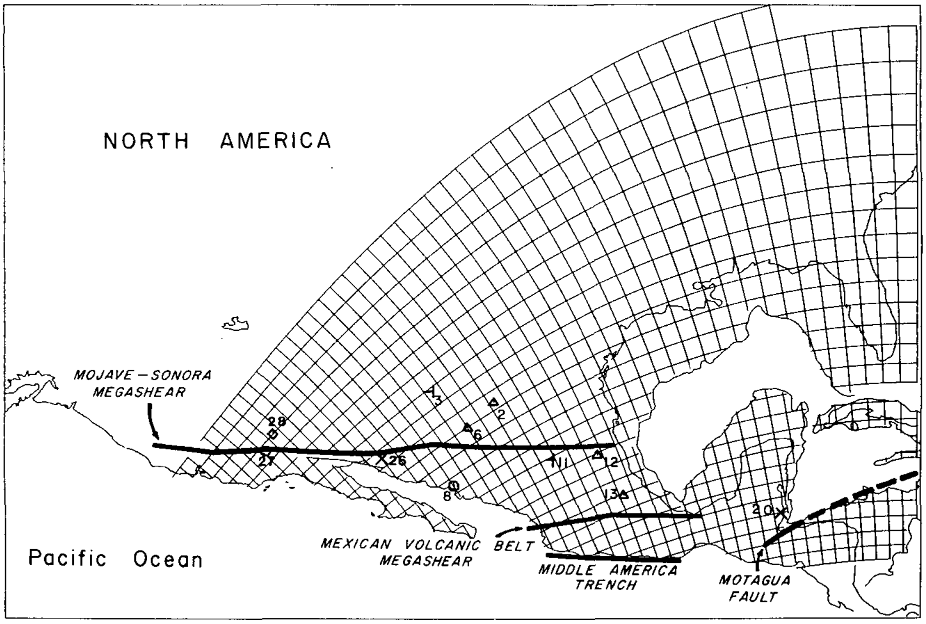

Figure 2. Oblique Mercator projection of Mexico, Middle America, and the Gulf of Mexico from the pole of rotation defined by the Mojave-Sonora megashear at lat. 52° N; long. 79° W.

2 - Δ - Marathon Basin
3 - ⊣ - Van Horn region
6 - Δ - Mina Plomosas–Placer de Guadalupe
11 - ⊣ - Apizolaya, Zacatecas
12 - Δ - Ciudad Victoria region
13 - Δ - Huayacocotla uplift
20 - X - Maya Mountains uplift
8 - ○ - Sonobari complex
26 - X - Caborca
27 - ○ - El Paso Mountains
28 - ◇ - White Mountains–Death Valley region

Utilizing this postulated trace for the megashear, a pole of rotation was determined from the orientation and curvature of the fault and was found to lie near lat. 52°N, long. 79°W. All transform faults related to this early Mesozoic pole of rotation fall along latitudinal lines for an oblique Mercator projection using this pole (Fig. 2). Examination of the plot resulted in the identification of two additional linear tectonic zones that are approximately parallel to the megashear. These are: (1) the Mexican volcanic belt and (2) a zone made up of the great faults traversing Guatemala and Honduras and including the part of the Middle American Trench that lies off southern Mexico. These former transform zones delineate three crustal blocks, composed largely of pre-Mesozoic sialic basement overlain by younger cover, between North and South America (Figs. 2 and 3).

Our goal in this report is to follow the evolution of these crustal blocks from a Pangea configuration based upon the Bullard and others (1965) assemblage for Late Triassic time to the present distribution of sialic crust in the Gulf of Mexico–Caribbean Sea region. We have limited discussion as best we could to the blocks of crust that existed by the Jurassic. Younger crust (for example, Panama), the existence of which results from either formation at a convergent margin or any type of tectonic accretion, is not treated unless its evolution played a key role in understanding the history of the pre-Jurassic blocks.

For the purpose of the discussion presented herein, we have designated the plates and microplates (or blocks) as follows:

Apache plate: that part of North America north of the Mojave-Sonora megashear.

Yaqui block: that part of Mexico bounded on the north by the Mojave-Sonora megashear and bounded on the south by the Mexican volcanic belt.

Maya block: that part of Mexico which lies south of the Mexican volcanic belt and north of the Acapulco-Guatemala megashear and Cuba. The Maya block is broken into two microplates along a proposed structure that may have been the predecessor of the Salina Cruz fault, which traverses the Isthmus of Tehuantepec.

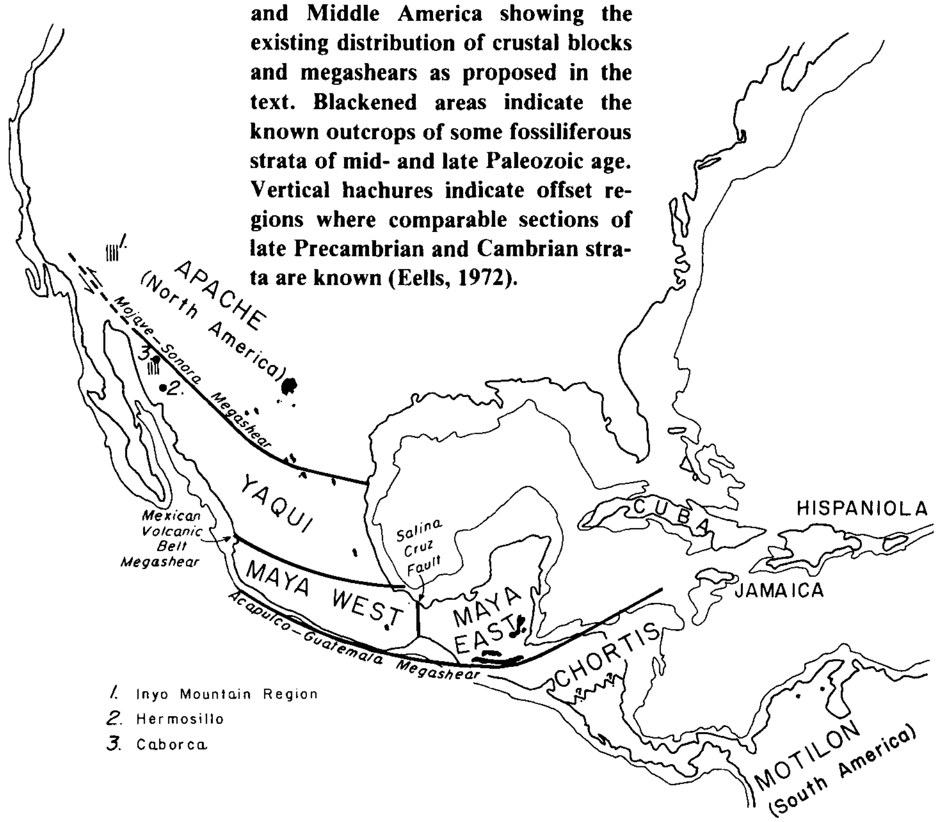

Figure 3. Sketch map of Mexico and Middle America showing the existing distribution of crustal blocks and megashears as proposed in the text. Blackened areas indicate the known outcrops of some fossiliferous strata of mid- and late Paleozoic age. Vertical hachures indicate offset regions where comparable sections of late Precambrian and Cambrian strata are known (Eells, 1972).

Chortis block: that part of Central America which lies south of the Acalpulco-Guatemala megashear and is underlain by pre-Mesozoic rocks.

Motilon plate: northwestern South America.

The Maya and Chortis blocks are named in accordance with Dengo's (1969) designation of major tectonic units of Central America.

The positions of these blocks are keys to the solution of the problem, associated with the reconstruction of Bullard and others (1965), of the overlap of northern South America across parts of Central America and southern Mexico, which are composed of Paleozoic and older rocks (Guzman and de Cserna, 1963; Dengo and Bohnenberger, 1969; McBirney and Bass, 1969). As noted by Le Pichon and Fox (1971), when North America, South America, and Africa are assembled into a prerift configuration, the Caribbean Basin is closed and a basin comparable in size to the present Gulf of Mexico remains. Early Mesozoic and older components of the Greater Antilles must fit into this area unless they can be shown to be exotic. The region of overlap must be translated either to the east, into the primordial, prerift basin between North and South America (Carey, 1958; Dietz and Holden, 1970), or to the west (Walper and Rowett, 1972; Pilger, 1978). We have chosen the latter of these alternative configurations because the model (1) can be generated in a straightforward way from a postulated plate-tectonic evolution suggested by the displacement on the Mojave-Sonora megashear; (2) permits the accommodation of the crustal blocks delineated above into the Bullard and others (1965) configuration by means of a simple series of motions that do not result in crustal overlap or necessitate leapfrogging of one block over another; and (3) consistently results in the juxtaposition of rock sequences that show strong lithologic and paleontologic similarities and that are probable time equivalents.

The juxtapositions of strata that have similar characteristics result when blocks (small plates), the positions of which are constrained primarily by their crustal geometry, are assembled into a reconstruction that satisfies the Bullard and others (1965) reconstruction. We acknowledge that geologic correlations that stem from our model are not unique. However, we believe that existing tectonostratigraphic relationships must be carefully considered and incorporated into a logical, if nonunique, interpretation. We assume that blocks underlain by sialic basement may not overlap similarly composed blocks, and we have tried hard to avoid this type of overlap. On account of this assumption, we have been forced to consider the pre-Mesozoic history as well as later evolution. Description of pertinent pre-Mesozoic geologic settings and rocks, as reported in published studies, may be acquired from the Data Bank.[1] Although these supporting descriptions of Paleozoic and Precambrian units make rather dry reading, we hope that interested readers can gain insight into why we chose the particular configurations presented here.

Individual blocks that constitute the reconstruction for Triassic time (Figs. 4A and 4B) are also subject to the following specific geometric and geologic constraints:

Yaqui block: the pole of rotation with respect to North America is determined from the orientation and curvature of the Mojave-Sonora megashear. Angle of rotation is derived from the match of offset belts of Precambrian and Paleozoic rocks (Fig. 1). Baja California is rotated to close deeper parts of the Gulf of California.

Maya West block: the pole of rotation with respect to the Yaqui plate is approximated from the orientation and curvature of the Mexican volcanic zone. The angle of rotation is sufficient to make room for the Maya East block after it has been juxtaposed against the pre-Jurassic parts of South America.

Maya East block: the Maya Mountains should fit against South America so that late Paleozoic beds are approximately juxtaposed against units of similar age at Chandua and Sierra de Perija in northwestern South America. The block is fit so that the continental shelf of Yucatan does not overlap North America across the easternmost extension of the Mojave-Sonora megashear and so that Cuba lies snugly against northern South America.

Chortis block: the Chortis block is loosely constrained by crustal geometry. It is fit against Maya East and Maya West with overlaps of South America restricted to the minimum and its western margin crudely aligned with the western coasts of Maya West and Yaqui blocks.

Four essential geometric constraints were imposed in addition to the geological considerations: (1) As North America begins to split away from Pangea, moving to the northwest with respect to South America, the Maya, Yaqui, and Chortis microplates are successively left behind via long left-lateral transform faults. In each case, the pole of rotation for adjoining microplates is that of the transform fault that forms the common boundary. (2) "Ball-bearing" rotation of the Maya East microplate is counterclockwise, consistent with and presumably driven by the above-mentioned shearing motion. (3) So long as continental crust predominates, the long transform faults take up the shear; when extensive oceanic basins are opened, ball-bearing motion can set in. (4) Ladd's (1976) relative motions for North and South America are adhered to with only minor differences in timing for the period 180 to 127 m.y. B.P. Finite rotations for our reconstruction as well as for later evolutionary stages are presented in Table 1.

These constraints produce a simple and sensible model for the motions of the microplates. They still leave some latitude for alternative models, especially for the later stages of motion of the Chortis plate. In all such cases, we have chosen the simplest possible motion consistent with available geological and geophysical evidence. We regard this simplicity as a strength of the model, in that all motions arise in a very natural way from the relative motions of North and South America plus the eastward pressure of the line of subduction along the western margin of the microplates.

PROPOSED MEGASHEARS

Introduction

The oblique Mercator projection (Fig. 2) based upon a pole of rotation defined by the Mojave-Sonora megashear can be used as a key to the identification of former transform faults. In addition to the Mojave-Sonora megashear, the Mexican volcanic belt and the hypothetical Acapulco-Guatemala megashear are considered to be the traces of relict transform faults. We

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[1] A complete descriptive Appendix is available free of charge from the GSA Data Bank. Request Supplementary Data 83-13 from the Documents Secretary.

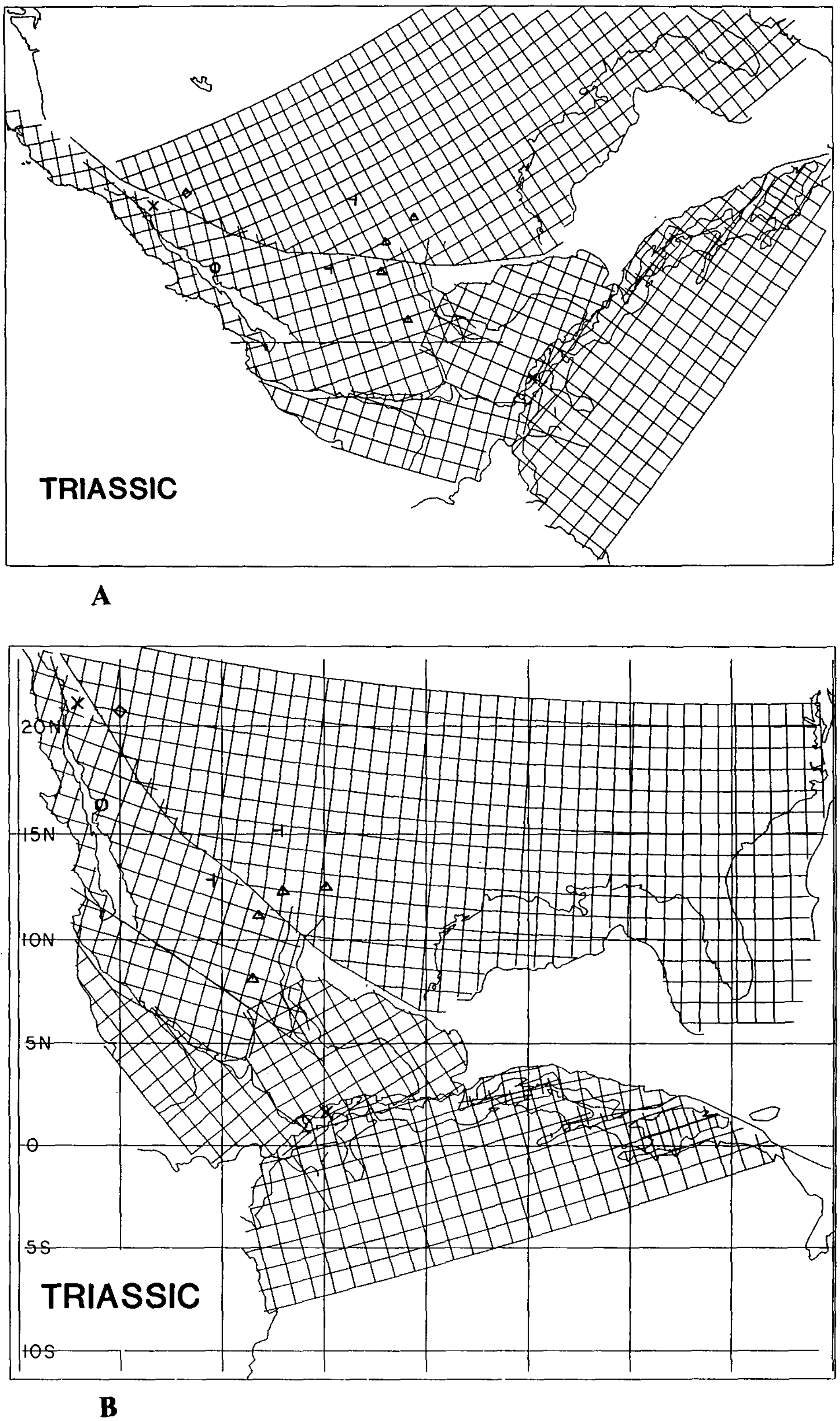

Figure 4. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during Triassic time. Latitude-longitude intervals are 2°. A. The pole of the projection is that of the pole of rotation defined by the Mexican volcanic belt megashear. B. The pole of projection is the paleomagnetic pole for Triassic time at lat. 72°N, long 98°E. Symbols are identified in Figure 2.

have striven to elucidate the nature of these possible ruptures of Mesozoic age, although we recognize that their characteristics have been highly modified by younger events. We evaluate proposed displacements along the shear zones in light of geometric and plate-tectonic constraints as well as geologic data, such as disrupted linear stratigraphic and structural trends and juxtaposed terranes that currently display geologic contrasts.

The Mojave-Sonora Megashear in Eastern Mexico

In northwestern Mexico, regional geologic relationships delineate a zone that must coincide with a fault, along which regional patterns of crystalline basement and pre–Late Jurassic cover are disrupted (Anderson and Silver, 1979). Displacement of 700 to 800 km is proposed (Silver and Anderson, 1974).

East of Sonora, in western Chihuahua, Cenozoic volcanics cover most of the older rocks and outcrops of the megashear are unknown. However, in central Chihuahua, apparent truncation of Paleozoic tectonic and lithostratigraphic trends has been a nagging problem for many years (Flawn and Diaz G., 1959). Postulated faults and paleogeographic reconstructions, which provide viable solutions to the observed disruption (de Cserna, 1970), agree both in sense and magnitude with the dislocation proposed for the Mojave-Sonora megashear in northwestern Mexico and the southwestern United States.

In northeastern Mexico, the postulated trace of the Mojave-Sonora megashear passes just south of the apparently truncated Paleozoic belt and follows a southeasterly trending course that extends to a point north of Ciudad Victoria, where Paleozoic rocks comparable to those of the Ouachita system crop out (Fig. 1). The covered fault zone generally coincides with the great swing of the fold belt developed in the Mexican geosyncline in northeastern Mexico. This distinct change in the trends of regional structures may mark the boundary between contrasting basement provinces that were juxtaposed during displacement along the Mojave-Sonora megashear.

Murray (1956, 1961) suggested that pre-Cretaceous displacement along an easterly trending, hypothetical, Saltillo-Torreon fracture zone (Fig. 5) was the solution to the disappearance of the Paleozoic rocks. Later, de Cserna (1970, p. 100) argued for the existence of a similar Early Triassic structure, the Torreon-Monterrey fault, the existence of which is based upon regional gravimetric work (Woollard and others, 1969) that revealed an 80 mgal change in anomaly values across a line between the cities of Torreon and Monterrey.

The Saltillo-Torreon and Torreon-Monterrey structures are essentially coincident, as shown by Murray (1961, Figs. 3.1 and 3.2) and de Cserna (1970). The Mojave-Sonora megashear is not coincident with these fractures as shown but rather cuts across them at a low angle (Fig. 5). De Cserna (1970) believed that regional stratigraphic and structural relationships of Mesozoic rocks indicate about 400 km of left-lateral displacement along the Torreon-Monterrey fault.

Coincidentally, it was pointed out by Burckhardt (1930) and re-emphasized by Kellum and others (1936) that a narrow seaway, the presence of which is implied by studies of stratigraphy and paleontology, extended across northern Mexico from Late Jurassic to Early Cretaceous time.

P. B. King (1975) implied the existence of a northwest-trending transform fault to explain his southernmost discontinuity in the Paleozoic orogenic pattern in the southern United States.

Van der Voo and others (1976) presented a generalized model for a Permo-triassic continental configuration that requires the existence of major left-lateral translation of most of Mexico in order to open the Gulf of Mexico.

Our reconstruction for Triassic time (Fig. 4), which results from clockwise rotation of the Maya East block (Uchupi, 1973) and displacements along the proposed megashears, indicates that the easternmost extension of the Mojave-Sonora megashear coincided approximately with the Campeche escarpment. East of the escarpment, we propose that the fault terminated at a spreading center.

Mexican Volcanic Belt Megashear

The geometric requirement that Maya West block be positioned so as to avoid overlap of pre-Mesozoic crust after the rotation of Maya East (Fig. 4) suggests that approximately 300 km of left-lateral displacement has occurred along a fault coincident with the Mexican volcanic belt.

TABLE I. RELATIVE MOTIONS OF BLOCKS (MICROPLATES) AND PLATES WITH RESPECT TO NORTH AMERICA

Stage	Age range	Blocks	Rotation N lat.	Pole E long	Angle (deg.)
Rotate from present locations to Triassic Pangea	Triassic	Africa	67.6	-14.0	-74.8
		South America	48.14	76.88	-32.35
		Yaqui	52.0	-79.0	-15.0
		Maya West	59.0	-67.72	-16.52
		Maya East	29.9	-93.71	-58.08
		Chortis	41.7	-91.33	-55.87
		Cuba	21.61	99.87	-14.0
		Hispaniola	22.93	102.76	-18.42
Stage 1: Mexican Volcanic Zone active	Early to Middle Jurassic	South America, Africa, Maya West, Maya East, Chortis, Cuba, Hispaniola	47.0	31.0	3.0
Stage 2: Sonora-Mojave Megashear active, Caribbean sea begins to open	Middle to Late Jurassic	Yaqui, Maya West	52.0	-79.0	10.0
		South Amerca, Africa	70.82	-45.5	12.03
		Maya East	30.59	-92.41	33.85
		Chortis	55.17	-70.29	14.11
		Cuba, Hispaniola	56.24	116.74	6.53
Stage 3: Cuba plus all north of Motagua Fault reaches present position	Latest Jurassic earliest Cretaceous	Maya East	21.34	-93.1	24.4
		Cuba, Hispaniola	14.51	-70.01	-9.06
		Yaqui, Maya West	52.0	-79.0	5.0
		South America, Africa	36.88	94.76	12.31
		Chortis	51.51	-82.98	15.35
Stage 4: Further opening of Caribbean, Hispaniola detaches from Cuba	Early to Late Cretaceous	South America	28.0	111.4	8.96
		Hispaniola, Chortis	28.0	111.4	4.5
Stage 5: More opening in southern Caribbean	Late Cretaceous early Tertiary	South America	23.53	0.32	4.85
Stage 6: Rotation of Chortis, opening of Colombian Basin	Early Tertiary	Chortis	14.91	-87.55	31.67
		South America	18.11	-52.75	-6.31

Note: Rotation angles are positive for counterclockwise rotations. The number of significant digits given allows other workers to precisely reconstruct our diagrams but is not intended to indicate high precision in the actual determination of the poles.

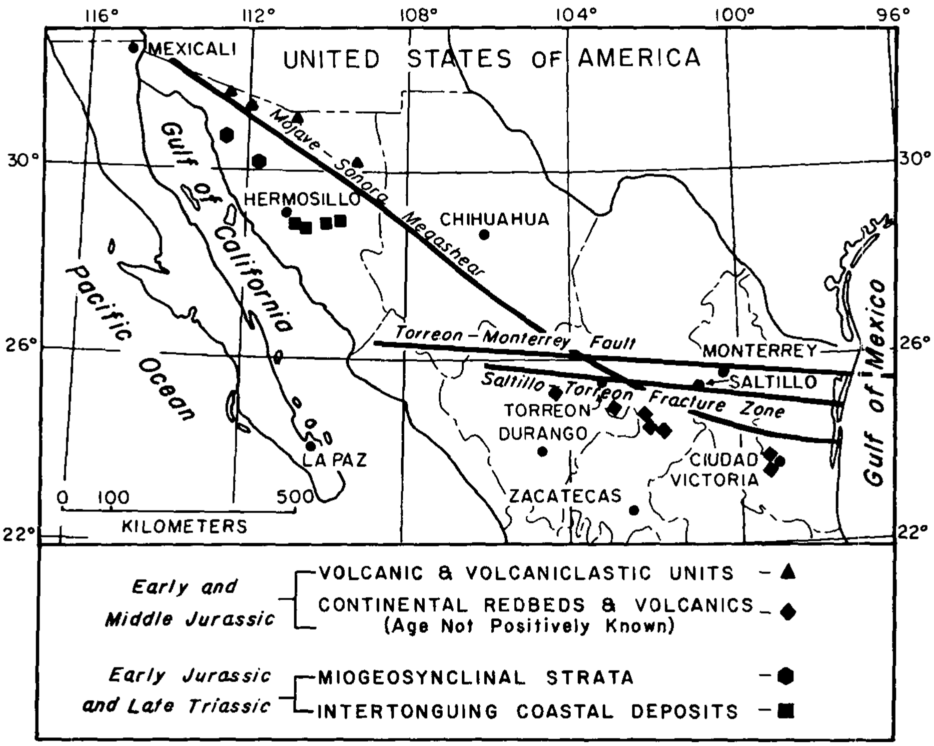

Figure 5. Sketch map of northern Mexico showing the location of hypothetical faults discussed in the text and their relation relative to strata of Late Triassic and Early to Middle Jurassic age (modified from de Cserna, 1970). ***Triangle.*** **Unnamed beds, northern Sonora, Mexico.** ***Diamond.*** **Nazas Formation (near Torreon) and La Joya (near Ciudad Victoria).** ***Square and hexagon.*** **Barranca Group, Sonora.**

This impressive belt is distinguished by the distribution of Holocene volcanoes, forming a zone 20 to 70 km wide that crosses the country in a west-northwest–east-southeast direction. Although the postulated fault appears to be young, as it transects formations of Upper Cretaceous–lower Tertiary age, its sinuosity and the existence of several branches that extend from it suggest the possibility that the volcanic activity may indicate the presence of a major, older, crustal fracture (Mooser, 1969).

No apparent transcurrent offsets have been reported along the Mexican volcanic belt, although Le Pichon and Fox (1971) suggested that it may delineate a paleoshear zone. The orientation of the volcanic belt is not obviously related to Holocene subduction along the southwestern coast of Mexico, which supports its interpretation as an ancient zone of weakness currently exploited by rising magma.

The presence of a trough along this zone during Callovian time is suggested by the narrow belt of marine deposits, the distribution and age of which are reported by Imlay (1980).

The Acapulco-Guatemala Megashear

It is suggested that the Acapulco-Guatemala megashear is composed of three segments: (1) a northwestern segment coincident with the northern one-half of the Middle American trench; (2) a central segment defined by the arcuate faults of Guatemala; and (3) an eastern segment defined by the northern flank of the Nicaraguan Rise (Fig. 3). A displacement of ~1,300 km along this zone is proposed to have taken place during Jurassic and Cretaceous time. Displacement is determined by the geometric requirement that the eastern part of the Chortis block (that is, the Nicaraguan Rise) be positioned so as to avoid overlap with the Motilon block (northwestern South America) (Fig. 4). We have assumed that the rocks that make up the Nicaraguan Rise are mainly Jurassic. However, we have no evidence to corroborate our assumption and, in view of the facts that the Santa Marta block is bounded by faults and may have been displaced and that the age of the basement of the Nicaraguan Rise is unknown, the proposed displacement along the Acapulco-Guatemala megashear is poorly constrained.

Although seismic data (Molnar and Sykes, 1969) indicate that subduction is currently occurring along the Middle American trench, the abrupt termination of crystalline basement at the coast and the presence of structures that trend at a high angle to the coast suggest prior truncation (Kesler and Heath, 1970; de Cserna, 1969). Both de Cserna (1969) and Mooser (1968) discussed this apparent truncation and presented models invoking post-Cretaceous displacements of hundreds of kilometres, as did Freeland and Dietz (1971), Malfait and Dinkelman (1972), and Moore and Del Castillo (1974).

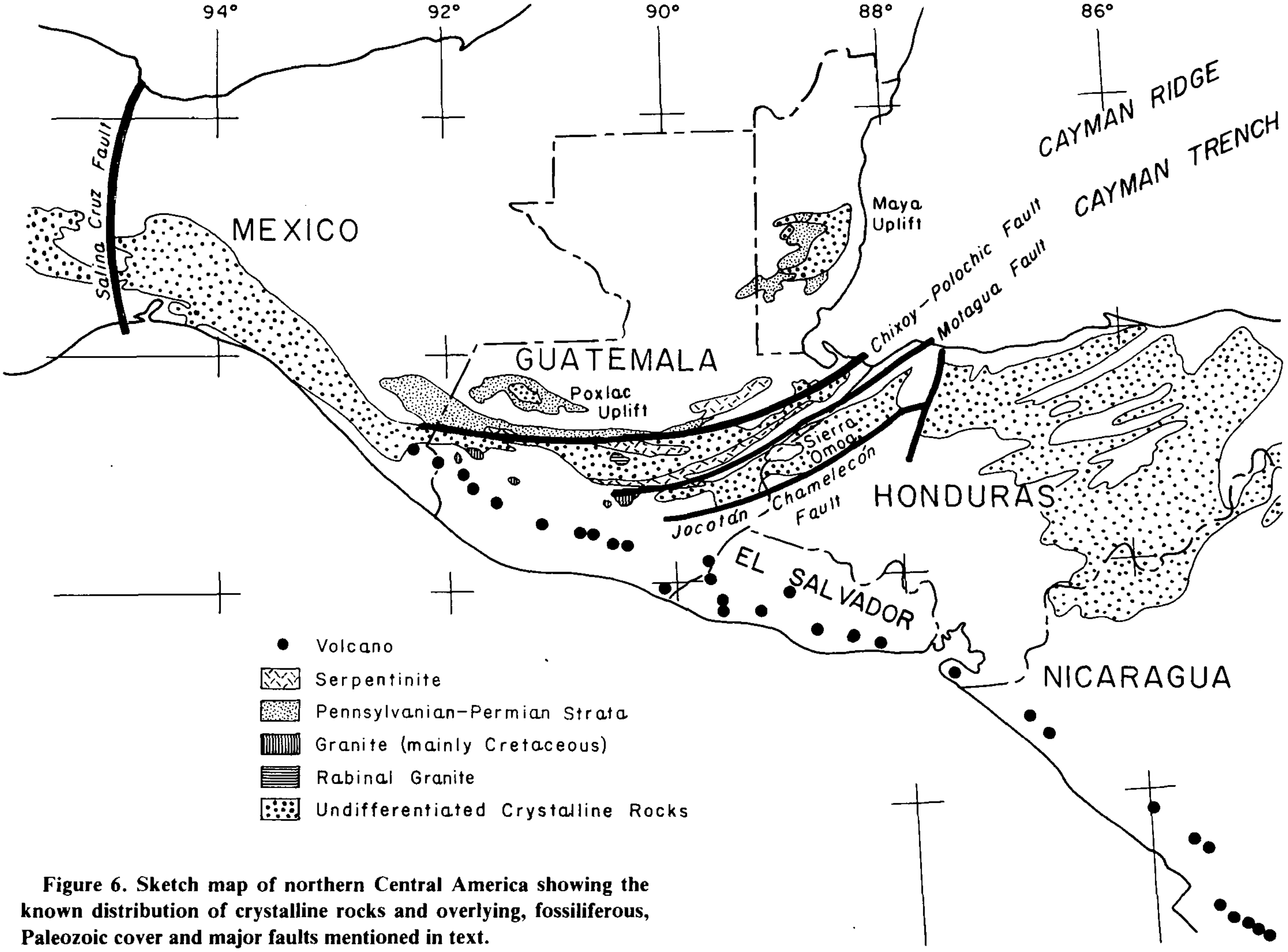

Figure 6. Sketch map of northern Central America showing the known distribution of crystalline rocks and overlying, fossiliferous, Paleozoic cover and major faults mentioned in text.

To the east, the physiographically and geologically prominent Motagua fault system delineates an east-west arc that is convex to the south and traverses Guatemala (Fig. 6). From north to south, this system consists of three major fractures. The Chixoy-Polochic fault, the trace of which is occupied by a series of deep river valleys from the Gulf of Honduras to the border between Guatemala and Mexico, is the most physiographically striking. The Motagua fault appears to separate two distinctive basement terranes (Dengo, 1969), although Horne and others (1976) pointed out that generalizations about the basement may be too simple, particularly in those regions bounded by the individual faults. Southeast of the Motagua fault, the Jocotán-Chamelecón fault extends into Honduras, where it is broken by cross faults but probably continues offshore. For more than two decades, the strong physiographic expression of the over-all fault system, coupled with the distinctive geology of fault-bounded blocks and the apparent alignment of the system with the Cayman trough, has prompted speculation that post-Cretaceous displacements of great magnitude have occurred along this zone (Hess and Maxwell, 1953). Khudoley and Meyerhoff (1971) and Dengo and Bohnenberger (1969) presented arguments against large displacements and concluded that the fault system probably delineates an old weakness zone the history of which extends as far back as Paleozoic time (Meyerhoff, 1966). Field studies of segments of Jocotán-Chamelecón (Dengo and Bohnenberger, 1969), Motagua (McBirney, 1963), and Chixoy-Polochic (Anderson and others, 1973) indicate small separations that consistently show left-lateral movement. The fact that the faults are overlapped by Tertiary and Cenozoic deposits certainly restricts interpretations that necessitate large post-Cretaceous displacements.

The south flank of the Bartlett (Cayman) fault system is the apparent present offshore equivalent of the Motagua system, as is suggested by bathymetry (Banks and Richards, 1969). Topography, defined by north-south–oriented ridges and valleys in part of the Cayman (Bartlett) trough, was cited by Holcombe and others (1973) as evidence for sea-floor spreading, which they believed was initiated at least by middle Miocene. However, these structures of the Bartlett (Cayman) system developed after Jurassic time and are not incorporated into the pre-Cretaceous model.

A SUMMARY OF THE PROPOSED CONFIGURATION OF CONTINENTAL CRUST IN THE GULF OF MEXICO REGION AT THE END OF THE TRIASSIC PERIOD

The assemblage of small plates at the end of the Triassic (Fig. 4) is based upon:

1. ~800 km of left-lateral displacement restored along the Mojave-Sonora megashear. Displacement is determined by offset terranes of Precambrian crystalline rocks and overlying late Precambrian and Paleozoic strata in northwestern Mexico (Silver and Anderson, 1974) and by offset segments of the Ouachita orogenic belt, which record comparable apparent displacement in both sense and magnitude.
2. ~300 km of left-lateral displacement restored along the Mexican volcanic belt. Displacement is determined by the geometric requirement that the Maya West block be positioned so as to avoid overlap of pre-Mesozoic crust after the rotation of Maya East (Fig. 4).
3. ~1,300 km of left-lateral displacement restored along the Acapulco-Guatemala megashear. Displacement is determined by the geometric requirement that the eastern part of the Chortis block (that is, the Nicaraguan Rise) be positioned so as to avoid overlap with the Motilon block (northwestern South America).
4. Rotation of Yucatan and Cuba (Dillon and Vedder, 1973; Uchupi, 1973) such that the eastern flank of Yucatan and southern flank of Cuba are juxtaposed against the northern margin of South America.

Restoration of ~800 km of left-lateral displacement along the Mojave-Sonora megashear (Silver and Anderson, 1974); ~300 km along the Mexican volcanic belt, and ~1,300 km along a proto-Motagua megashear (Freeland and Dietz, 1971; Malfait and Dinkelman, 1972; Moore and Del Castillo, 1974) avoids overlap encountered with the Bullard and others (1965) reconstruction. Furthermore, if Yucatan and Cuba are rotated, as suggested by Dillon and Vedder (1973) and Uchupi (1973), to fit against northern South America (Fig. 4), then a sinuous belt of correlative upper Paleozoic rocks (C. A. Ross, 1979) extends across the reconstruction and links outcrops in Texas, eastern Mexico, northern Central America, and Colombia (Fig. 7). This belt is composed of formerly segregated stratigraphic sequences mainly of Paleozoic age. The similarities of these juxtaposed sequences are evaluated in light of discussions of regional correlations in Mexico and Central America (de Cserna, 1967, 1971a, 1971b; Lopez-Ramos, 1969, 1972; Dengo, 1969, 1975; Dengo and Bohnenberger, 1969; Walper and Rowett, 1972) and with regard to proposed tectonic configurations based upon regional paleontological analyses (Rowett, 1974; C. A. Ross, 1979).

The most widespread Paleozoic units within this belt are predominantly clastic beds of Pennsylvanian and Permian(?) age that in places overlie strata that include distinctive novaculite (Fig. 8). In northern and east-central Mexico, Pennsylvanian-age beds crop out in the cores of structural uplifts at Sierra del Cuervo (Bridges, 1964a), Ciudad Victoria (Carillo-Bravo, 1961), and Huayacocotla (Carillo-Bravo, 1965) (Fig. 7). To the south, in the Mexican states of Puebla and Oaxaca, Carboniferous plant-bearing units (Silva-Pineda, 1970) are similar to those described from western Guatemala by Litke (1975) that are correlative with strata of the Maya Mountains in Belize (Bateson and Hall, 1971; Bateson, 1972). In northern Mexico, these rocks are considered to belong to the orogenic phase of the Ouachita system (Flawn and others, 1961), whereas to the south they form the Huastecan structural belt that, according to de Cserna (1967), continues across northern Guatemala and underlies much of Yucatan.

Upper Paleozoic beds extend eastward under the coastal plain of eastern Mexico, as indicated by well data (Carillo-Bravo, 1961; Lopez-Ramos, 1969).

Metamorphosed equivalents of upper Paleozoic beds may be greenschist-grade pelitic units with intercalations of marble and quartzite that constitute the basement in Honduras (Fakundiny, 1970) and similar beds of phyllite, schist, quartzite, and marble that crop out in the states of Oaxaca and Chiapas, southern Mexico (Lopez-Ramos, 1969). However, our model suggests that the Honduran rocks have been displaced eastward more than 1,000 km from the western margin of Mexico where they accumulated.

In northern South America, Carboniferous(?) and Permian beds that crop out in Sierra de Perijá (Trumpy, 1953) and the slightly metamorphosed Chandua Group

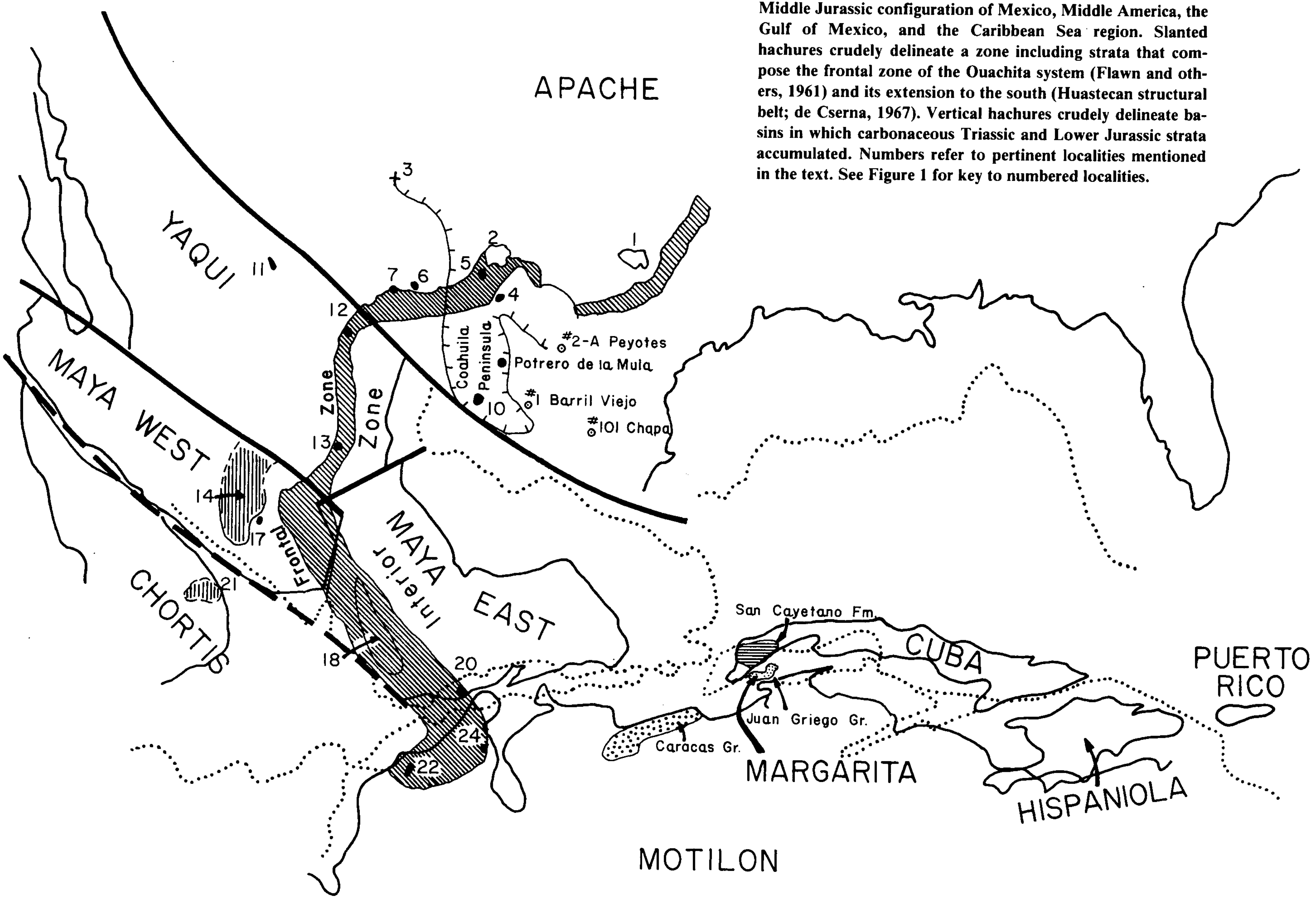

Figure 7. Sketch map of the proposed post-Paleozoic–pre-Middle Jurassic configuration of Mexico, Middle America, the Gulf of Mexico, and the Caribbean Sea region. Slanted hachures crudely delineate a zone including strata that compose the frontal zone of the Ouachita system (Flawn and others, 1961) and its extension to the south (Huastecan structural belt; de Cserna, 1967). Vertical hachures crudely delineate basins in which carbonaceous Triassic and Lower Jurassic strata accumulated. Numbers refer to pertinent localities mentioned in the text. See Figure 1 for key to numbered localities.

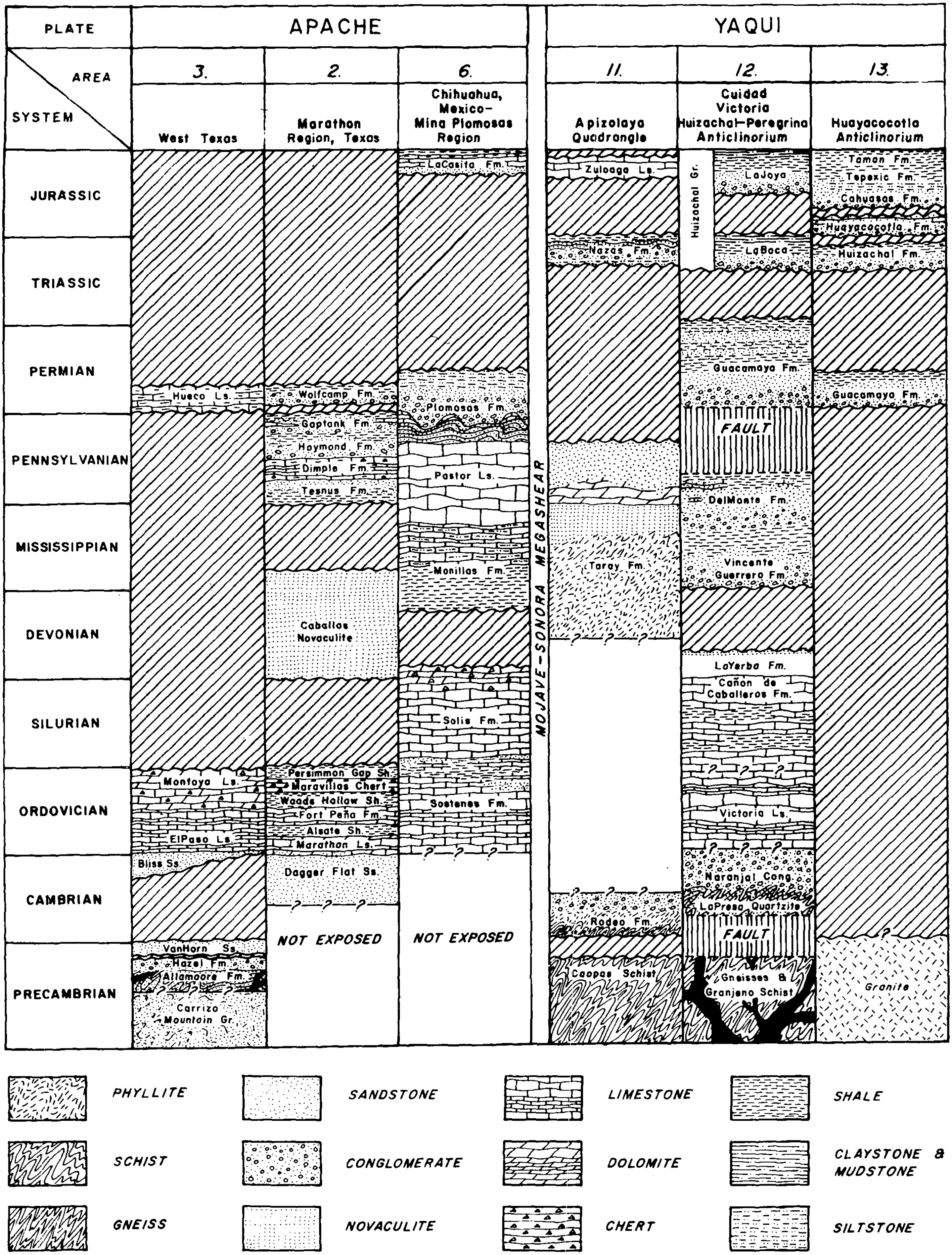
PLATE
APACHE
YAQUI
AREA
SYSTEM
3.
2.
6.
11.
12.
13.
West Texas
Marathon Region, Texas
Chihuahua, Mexico–Mina Plomosas Region
Apizolaya Quadrangle
Cuidad Victoria Huizachal–Peregrina Anticlinorium
Huayacocotla Anticlinorium
JURASSIC
TRIASSIC
PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
Hueco Ls.
Montoya Ls.
ElPaso Ls.
Bliss Ss.
VanHorn Ss.
Hazel Fm.
Allamoore Fm.
Carrizo Mountain Gr.
Wolfcamp Fm.
Gaptank Fm.
Haymond Fm.
Dimple Fm.
Tesnus Fm.
Caballos Novaculite
Persimmon Gap Sh.
Maravillas Chert
Woods Hollow Sh.
Fort Peña Fm.
Alsate Sh.
Marathon Ls.
Dagger Flat Ss.
NOT EXPOSED
LaCasita Fm.
Plomosas Fm.
Pastor Ls.
Monillas Fm.
Solis Fm.
Sostenes Fm.
NOT EXPOSED
MOJAVE–SONORA MEGASHEAR
Zuloaga Ls.
Nazas Fm.
Taray Fm.
Rodeo Fm.
Caopas Schist
Huizachal Gr.
LaJoya
LaBoca
Guacamaya Fm.
FAULT
DelMonte Fm.
Vincente Guerrero Fm.
LaYerba Fm.
Cañon de Caballeros Fm.
Victoria Ls.
Naranjal Cong.
LaPresa Quartzite
FAULT
Gneisses & Granjeno Schist
Tamon Fm.
Tepexic Fm.
Cahuasas Fm.
Huayacocotla Fm.
Huizachal Fm.
Guacamaya Fm.
Granite
?
PHYLLITE
SANDSTONE
LIMESTONE
SHALE
SCHIST
CONGLOMERATE
DOLOMITE
CLAYSTONE & MUDSTONE
GNEISS
NOVACULITE
CHERT
SILTSTONE

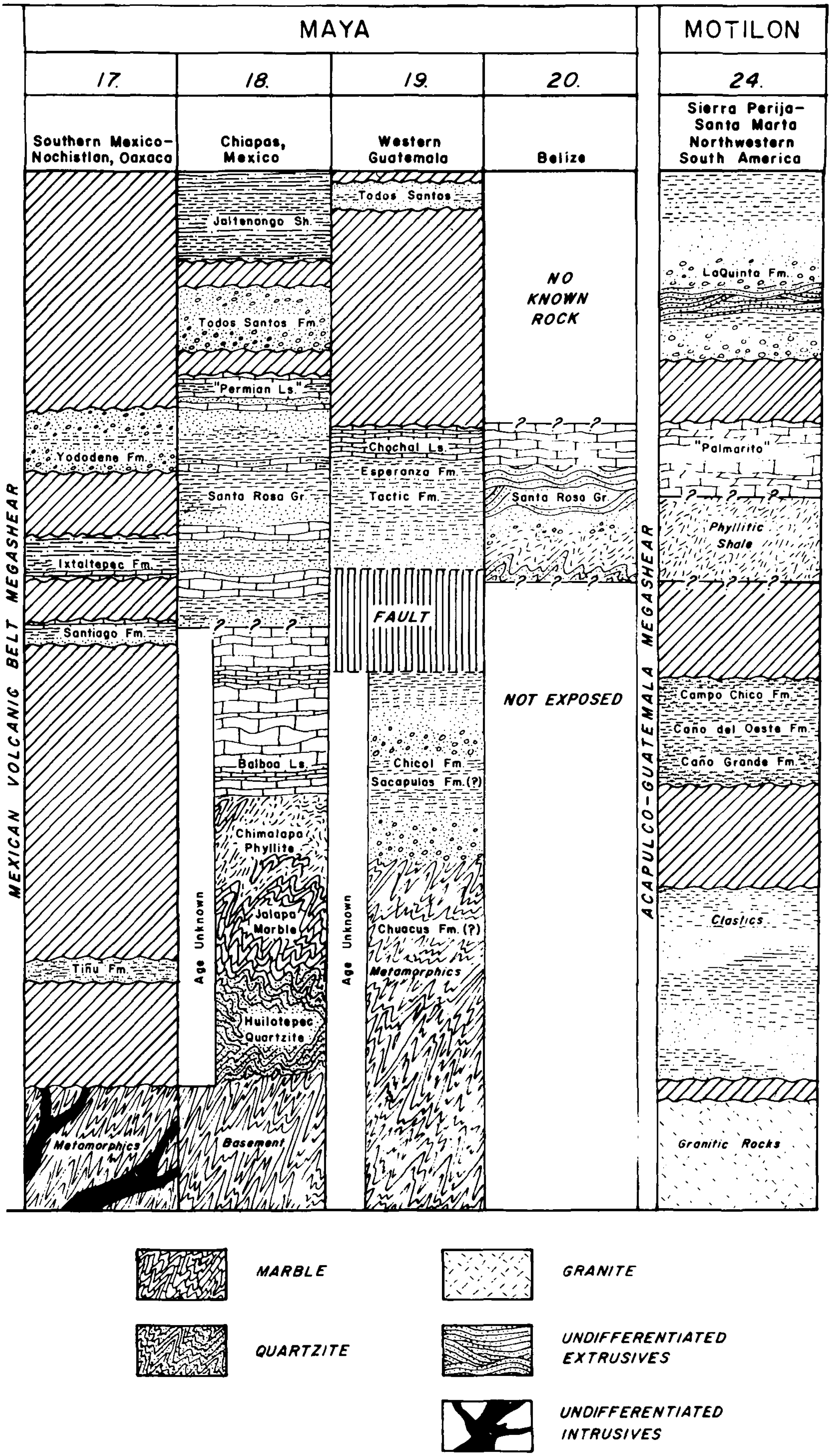

Figure 8. Representative stratigraphic columns from some localities within blocks bounded on one or both sides by megashears (transform faults). Numbers refer to localities indexed in Figure 1. *Southern margin of Apache block:* 3. Van Horn region, west Texas (adapted from King and Flawn, 1953). 2. Marathon region, Texas (adapted from Flawn and others, 1961). 6. Mina Plomosas–Placer de Guadalupe area (adapted from Bridges, 1964a). *Yaqui block:* 11. Apizolaya quadrangle, northern Zacatecas (adapted from Cordoba, 1964). 12. Ciudad Victoria-Huizachal-Peregrina anticlinorium (adapted from Carillo-Bravo, 1961, and Mixon and others, 1959). 13. Huayacocotla anticlinorium (adapted from Carillo-Bravo, 1965). *Maya block:* 17. Nochistlán, Oaxaca, southern Mexico (adapted from Pantoja-Alor, 1970). 18. Chiapas, Mexico (adapted from Webber and Ojeda-Rivera, 1957). 19. Western Guatemala (adapted from Anderson and others, 1973). 20. Belize (adapted from Bateson and Hall, 1971). *Motilon block:* 21. Sierra de Perijá, northwestern South America (adapted from J. B. Miller, 1962, and Irving, 1975).

(Gansser, 1955) make up likely equivalents to the late Paleozoic rocks of Central America.

In contrast to the predominantly clastic rocks of Carboniferous age, many of the Permian sections are characterized by carbonate beds. The distribution of the Early Permian mid-continent–Andean fusulinacean fauna realm is suggestive of a preexisting cohesive belt (C. A. Ross, 1979). This rich assemblage of offshore, shallow-water fauna is reported from rocks in Texas (Miller and Furnish, 1940), Coahuila (northern Mexico) (King and others, 1944), Chiapas (southern Mexico) (Mullerried and others, 1941), adjacent parts of western Guatemala (Kling, 1960; Stehli and Grant, 1970), Belize (C. A. Ross, 1962; Dixon, 1957), and northern Colombia (Thompson and Miller, 1949; Miller and Williams, 1945). Late Paleozoic corals also define a province within this region (Rowett, 1974).

In places beneath the widespread late Paleozoic strata, there are nearshore sediments of early and middle Paleozoic age that accumulated along the eastern margin of an elongate arm of cratonic basement that extended under eastern Mexico from Texas to Oaxaca. Lithologies and ages of the overlying mid-Paleozoic sedimentary beds from Chihuahua (Placer de Guadalupe; Bridges, 1964a, 1964b), Zacatecas (Apizolaya Quadrangle; Cordoba, 1964), and Tamaulipas (Ciudad Victoria; Carillo-Bravo, 1961) are comparable to strata of the frontal zone of the Ouachita system as defined by Flawn and others (1961) (Fig. 7). To the southeast, R. J. Ross (1976) did not emphasize the continuity of the Ouachita belt with the outcrop of lower Paleozoic strata in eastern Mexico that include beds of Cambrian and Ordovician age (Robison and Pantoja-Alor, 1968). Although the Lower Ordovician faunas were interpreted by Yochelson (1968) as belonging to the North American outer shelf, Palmer (1974) noted that the affinities of Late Cambrian fauna from the Oaxaca locality are closer to faunas of northwestern Europe and Bolivia than to those of North America. Furthermore, additional stratigraphic contrasts among some of the early to middle Paleozoic sections between Puebla and Oaxaca and possible equivalents in Chiapas and Guatemala led Dengo (1975) to conclude that the two regions were distinct basins during most of their evolution. These complications in rocks from southern Mexico reduce the effectiveness of the pre-Pennsylvanian sedimentary sequences as tools for identification of pre-existing configurations in this region.

The basement for the Paleozoic strata of the frontal zone in Texas and northeastern Mexico is composed of gneiss and schist with less abundant marble and quartzite. Radiometric ages of the crystalline rocks called the Grenvillian orogenic belt (P. B. King, 1975) consistently fall between 900 and 1,200 m.y. (Wasserburg and others, 1962; Fries and others, 1962a, 1962b; Denison and others, 1969; Ortega-Gutierrez, 1978a). In southern Mexico, basement rocks commonly exhibit mineral assemblages indicative of upper amphibolite and granulite facies and geochronological studies indicate a metamorphic culmination at about 1,050 m.y. ago (Anderson and Silver, 1971). This terrane has been called the Oaxacan structural belt (de Cserna, 1967) and its associated metamorphic event, the Oaxacan orogeny (Fries and others, 1962a). Outcrops of crystalline rocks that are exposed in structural highs (Huayacocotla and Ciudad Victoria) north of Oaxaca are characterized by lithologies and radiometric ages that Fries and others (1962b) correlated to the southern province. Data from wells drilled within the coastal plain between these highs indicate that likely correlative basement exists in the subsurface (Lopez-Ramos, 1972). Northwest of this region, in Zacatecas, less strongly metamorphosed rocks may represent a western facies that is lithologically comparable to Precambrian rocks at Van Horn, Texas, according to Cordoba (1964).

The southernmost extent of this elongate belt of correlative Precambrian basement is unknown. Hints of its existence have been reported from Central America (Gomberg and others, 1968) and, although very little data are available, the 940-m.y.-old event recorded by rocks in northern South America and mentioned by Tschanz and others (1974) may be related.

The interior zone of the Ouachita belt, which is composed of metamorphosed and penetratively deformed sedimentary and much less abundant igneous rocks, is less well known than the frontal zone because rocks that characterize this zone rarely crop out. Well cores provide the majority of data pertaining to these rocks. The interior zone that lies east of the frontal zone has been identified in the subsurface south of the Llano uplift (Flawn and others, 1961, Pl. 2). In this area, two lithologies may be discerned: (1) abundant fine-grained schist-phyllite-slate-metaquarzite-marble and (2) less common black graphitic slate. The zone continues west as far as the Río Grande, where it swings northwest and trends approximately parallel to the present river course. Just south of the Río Grande in Coahuila, Mexico, rocks that crop out in Sierra del Carmen have been interpreted as being part of the interior zone (Fig. 1, no. 4) (Flawn and Diaz G., 1959). Extension of the interior zone in the subsurface toward the southeast is suggested by the presence of highly sheared slate and metagraywacke (well No. 2-A Peyotes) and granodiorite (well No. 1 Barril Viejo) in wells (Flawn and Diaz G., 1959) (Fig. 7).

Near the southern margin of the Coahuila Peninsula, in the Valle de Las Delicias, a section more than 3,000 m (9,840 ft) thick, which ranges in age from at least Wolfcampian to possibly Ochoan, is composed of mafic and intermediate flows and intrusives interlayered with graywacke, conglomerate, sandstone, fossiliferous limestone, minor quartzite, and shale (King and others, 1944). These beds, the faunas of which are correlative with those of the Permian basin of Texas and New Mexico (King and others, 1944), are relicts of a volcanic belt (Rowett and Hawkins, 1975) that probably constituted part of the interior zone of the Ouachita system.

Toward the east, across the Mojave-Sonora megashear (Fig. 1), schist that crops out at Ciudad Victoria and Aramberri may also be a part of the sequence composing the interior zone. De Cserna (1971b) argued that the schist is in tectonically emplaced slices that define a belt of thrusts of Ordovician age throughout eastern Mexico. However, muscovite from schist, graphitic schist, and pegmatite yields apparent K-Ar ages from 320 to 270 m.y. (Denison and others, 1971). This area has been the focus of vigorous discussion (Garrison, 1978; Ramirez-Ramirez, 1978; de Cserna and Ortega-Gutierrez, 1978; de Cserna and others, 1977) and, in light of unresolved problems, the general conclusions of Denison and others (1971) are perhaps most applicable. They concluded the following: (1) the schist is a product of low-rank metamorphic processes and is distinct from associated gneisses of upper amphibolite to granulite grade, (2) the schist was metamorphosed in Permian-Pennsylvanian time and the age of its accumulation is uncertain, and (3) the schist records a history different from the older gneiss and fossiliferous Paleozoic sequence and may have been emplaced tectonically. South of Ciudad Victoria, information from more than 150 wells drilled into the coastal plain clearly shows that strongly metamorphosed rocks, fossiliferous beds of Paleozoic age, and intrusive masses constitute a major part of the terrane that underlies the coastal plain (Lopez-Ramos, 1972). Some of these units are probably equivalent to the "interior zone" of the Ouachita system.

Outcrops of pre-Cretaceous intrusive rocks are rare, but available stratigraphic and radiometric data suggest that, at three localities, plutons that may be related to orogenesis within the interior zone are preserved. Granodiorite at Potrero de la Mula that is overlain by Cretaceous beds (Kellum and others, 1936) yielded a K-Ar hornblende age of 206 ± 4 m.y. (Denison and others, 1969) (Fig. 7). Similarly, on the flanks of the range between Acatita and Las Delicias (Fig. 1, no. 10), two distinct granitic masses were described as post-Permian by Kelly (1936) and by King and others (1944) on the basis of intrusive relationships with the Permian section and unconformable relations with overlying Cretaceous beds. One of these rocks, a granodiorite, similar to the one at Potrero de la Mula, yielded a K-Ar biotite age of 203 ± 4 m.y. (Denison and others, 1969).

Studies in the southern Mexican states of Oaxaca and Puebla (Rodríguez-Torres, 1970; Ruiz-Castellanos, 1970; Ortega-Gutierrez, 1978b) and Chiapas (Pantoja-Alor and others, 1974) and in western Guatemala (Kesler, 1971; Kesler and others, 1970; Anderson and others, 1973) and previous research (Webber and Ojeda-Rivera, 1957; McBirney, 1963) have established the existence of substantial terranes of pre-Pennsylvanian crystalline rocks. Metamorphic facies characteristic of these rocks are commonly greenschist or lower to middle amphibolite-grade, in contrast to the upper amphibolite or granulite facies rocks of the craton, which yield ages close to 1.0 b.y. These metamorphic rocks derived from sedimentary beds with intercalated volcanic units are cut by syntectonic and post-tectonic intrusives.

Dated plutonic rocks of mid-Paleozoic age include two from southern Puebla (Acatlan augen schist and Totoltepec granodiorite) that yield Rb-Sr ages of about 450 m.y. (Fries and others, 1966; Fries and others, 1974) and the Rabinal granite in Guatemala, the interpreted zircon age of which is about 350 m.y. (Gomberg and others, 1968). Large masses of granitic rocks that intrude Precambrian(?) rocks in Oaxaca have been mapped by de Cserna (1971a) as Paleozoic, as have been numerous plutons that intrude the metamorphic sequence in western Guatemala (Kesler and others, 1970; Anderson and others, 1973).

Plutons of late Paleozoic to Triassic age that intrude layered sequences have been dated from Belize and central and western Guatemala. Permotriassic granite is mentioned from western Guatemala by Marcus and others (1975). In central Guatemala, a stock that intrudes presumably early to middle Paleozoic metamorphic rocks yields a Rb-Sr age of 275 m.y. (Pushkar, 1968). Bateson (1972) reported Rb-Sr and K-Ar dates from three intrusives in Belize that range from 390 to 200 m.y. and that are associated with Late Pennsylvanian volcanic rocks (Hall and Bateson, 1972). Subsurface data indicate the presence of Carboniferous basement as far north as central Yucatan (Dengo, 1969).

In northwestern Colombia, rocks may also record the vestiges of latest Paleozoic orogeny that extended into the Triassic period. Although fossiliferous marine Permian sediments in Sierra de Perijá record little intense deformation or metamorphism, Irving (1975) pointed out that in the Guajira Peninsula stratigraphic and intrusive relationships suggest that the Uray Gneiss and the paraschist of the Macuira Formation are probably pre-Triassic in age (MacDonald, 1964; Lockwood, 1965; Alvarez, 1967).

Clockwise rotation of Yucatan and pre-Cretaceous parts of Cuba to fit against northern South America implies correlation between the distinctive quartzose San Cayetano Formation of Cuba and Caracas Group and Juan Griego Group of northern Venezuela and Margarita Island, respectively (Fig. 7). Crystalline rocks, considered to be of Paleozoic and/or Precambrian age (Khudoley and Meyerhoff, 1971; Tijomirov, 1968), in and south of Cuba could be relict fragments broken away from the South American craton during Late Jurassic rifting that accompanied rotation. Finally, the proposed configuration leads to the conclusion that a small basin, floored by oceanic crust, which was coincident with the northeastern part of the present Gulf of Mexico, existed at the end of Paleozoic time (Fig. 7). The nature and age of this basin are compatible with the geophysical data and interpretations of Ewing and others (1960, 1962) and Wilhelm and Ewing (1972).

STRATIGRAPHIC FRAMEWORK OF TRIASSIC AND JURASSIC ROCKS OF MIDDLE AMERICA AND THE GULF OF MEXICO–CARIBBEAN SEA REGION

Introduction

Proposed relative motions of the Maya, Chortis, and Motilon blocks during Middle to Late Jurassic time require that (1) Triassic and Early to Middle Jurassic sedimentary basins around the margin of the Caribbean be disrupted and (2) Middle to

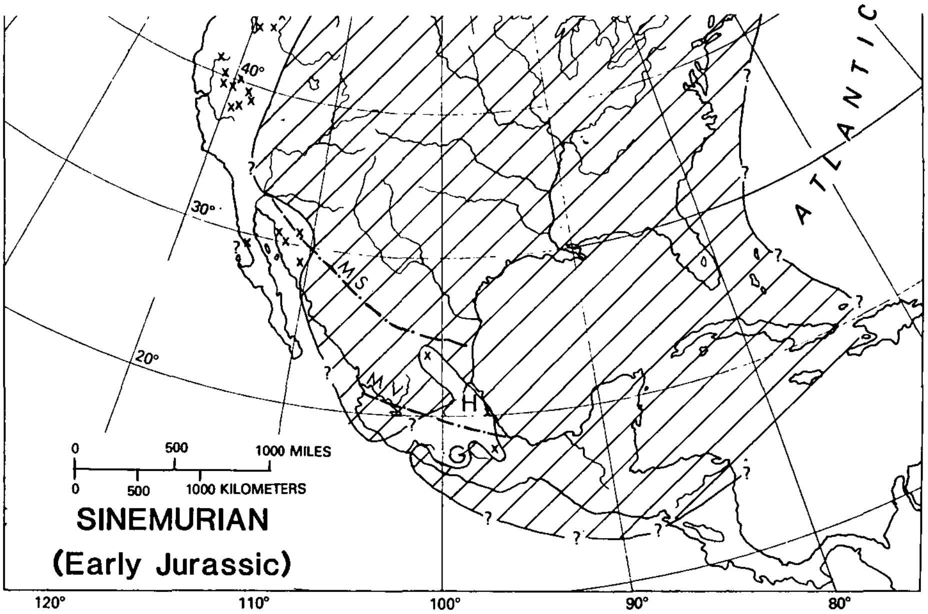

Figure 9. Distribution of Sinemurian ammonites (x) and inferred seas in southern North America. Land areas are ruled (adapted from Imlay, 1980, Fig. 3). H. Huayacocotla embayment. G. Guerrero embayment. MS. Mojave-Sonora megashear. MV. Mexican volcanic belt megashear. Megashears not yet active (compare Fig. 4).

Upper Jurassic beds *overlap* formerly active plate boundaries. For this reason, the relationships among Triassic and Early Jurassic units offer a variety of tests of the proposed model, as do younger overlapping units that should not record major translations. Are ages and lithologies compatible for our suggested correlations? Do Upper Jurassic formations extend across earlier plate boundaries?

Although stratigraphic relationships are complex for these sequences and the problems and pitfalls are considerable (see Wilson, 1974, p. 1351), we have attempted to provide a very brief overview of the ages and lithologies of relevant beds, in order to focus attention upon their characteristics and distribution. Regional description and distributions have been extracted from thorough reviews by Imlay (1943, 1980) as well as those of Cook and Bally (1975), Viniegra O. (1971), Wilson (1974), Khudoley and Meyerhoff (1971), Mills and others (1967), Erben (1956a, 1956b), and other sources, as cited below. Hypothetical stratigraphic correlations and speculations that result from our proposed model are based upon the descriptions by these authors but are not in every case in agreement with their interpretations.

Triassic Rocks

In Mexico, the distribution of strata bearing Triassic flora has been discussed most recently by Silva-Pineda (1979). The best-documented Triassic beds occur in northwestern Mexico in the state of Sonora and are restricted to the region south of the proposed Mojave-Sonora megashear (Fig. 5). In northeastern Mexico, Upper Triassic plant fossils have been reported from the Huizachal Formation at several localities from the states of Tamaulipas and Hidalgo. (Note: Silva-Pineda, 1979, pointed out that Huizachal Formation as defined by Imlay and others, 1948, and utilized by Carillo-Bravo, 1961, was raised to Group status by Mixon and others, 1959. Within this sequence, two formations were separated. The older formation, called La Boca, was distinguished by its degree of deformation and incipient metamorphism and by its unconformable relationship with the overlying beds mapped as La Joya Formation. Owing to problems surrounding the regional usage of the subdivision, it has not been accepted. Rather, according to Silva-Pineda, 1979, the name "Huizachal" should be used for a formation that includes all Upper Triassic red beds and the name "La Joya Formation" is restricted to red beds at the base of the Upper Jurassic.)

In north-central Mexico, in the region between the limits where Triassic beds are known, the Nazas Formation crops out. This unit was tentatively assigned to the Triassic on the basis of its stratigraphic position and lithology (Pantoja-Alor, 1963). Nazas Formation has been suggested to be stratigraphically equivalent with Huizachal Formation. According to Cordoba (1979, personal commun.), units of the Nazas bear resemblance to unnamed beds of probable Jurassic age mapped by Corona (1979) north of the Mojave-Sonora megashear in Sonora (Fig. 5).

Marine fossils of Late Triassic age have been reported from Sonora, San Luis Potosi, and Zacatecas (Burckhardt, 1930) and exposures of these fossiliferous units crudely define a band west of the plant-bearing sequences.

In the Santa Marta region of northern Colombia, Irving (1975) assigned Triassic age to parts of several formations. Los Indios Formation, which may be as old as Late Permian(?), is composed of a lower black shale about 180 m (600 ft) thick and an upper sandy member with some tuff and conglomerate that is about 300 m (1,000 ft) thick. Corual Formation, which may be in part correlative with Los Indios Formation, consists of siltstone, graywacke, shale, and chert with abundant mafic to silicic lava and tuff. These strata are overlain by a thick sequence of red tuffs called Guatapuri Formation. Unfortunately, the Santa Marta massif is fault-bounded and its role in the plate-tectonic evolution of northern South America is not tightly constrained.

Jurassic Rocks

For discussion of Jurassic rocks in Mexico and Central America, we have relied mainly upon the overviews of Imlay (1943, 1980) and Erben (1956a, 1956b).

In southern Mexico, Erben (1956a, 1956b) postulated the former existence of two marine embayments during Early Jurassic time (Fig. 9). Northeast of Mexico City, in the Huayacocotla embayment, a thick section of alternating marine and nonmarine clastic rocks accumulated between the beginning of Sinemurian and earliest Pliensbachian (Schmidt-Effing, 1980). The uppermost beds of this sequence contain plant remains. Southwest of Mexico City, existence of the Guerrero embayment is poorly documented, although it probably existed during Toarcian time. In some parts of the intervening area, northwest of the city of Oaxaca, mainly nonmarine, predominantly clastic beds that are commonly plant-bearing but contain some intercalations of marine units crop out. These units,

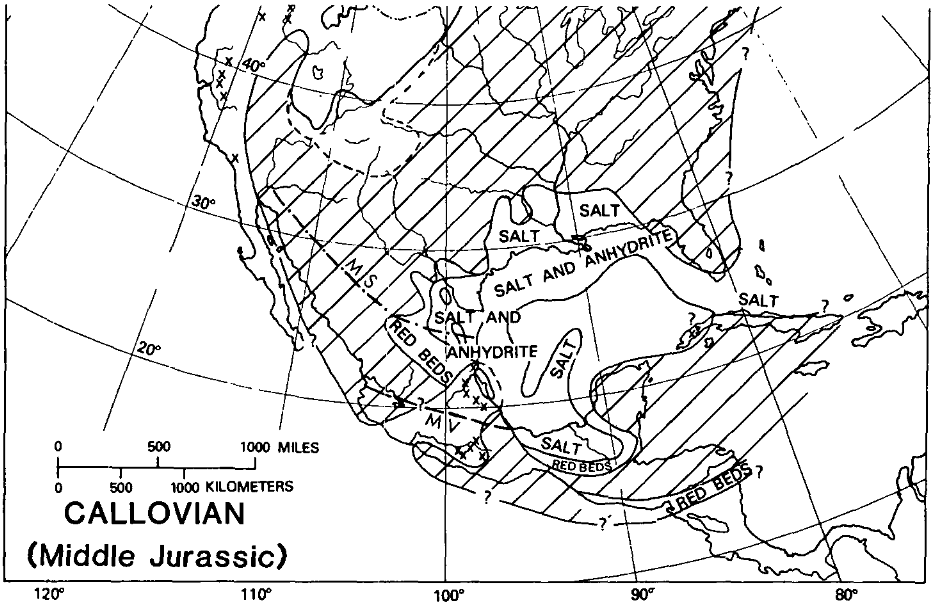

Figure 10. Distribution of Callovian fossils (x) and inferred seas in southern North America and Central America. Displacement along the proposed Mexican volcanic-belt megashear (MV) probably occurred about this time. Displacement along the Mojave-Sonora megashear (MS) possible, but major displacement is younger (adapted from Imlay, 1980, Fig. 8).

within the Consuelo Group, probably range in age from Toarcian through Aalenian time (Erben, 1956b).

Overlying the strata of Middle or Early Jurassic age, which represent marine and paludal environments, are more widespread units composed predominantly of red, nonmarine, clastic rocks (Fig. 10). In places, these red beds are associated with evaporite, mainly salt. In eastern Mexico, these beds are mapped as La Joya Formation, whereas, in southern Mexico and northern Central America, equivalent red beds are commonly mapped as Todos Santos Formation (Mixon and others, 1959; Imlay, 1943; Viniegra O., 1971; Richards, 1963; Mills and others, 1967). These formations commonly show a transition into marine strata of very Late Jurassic or Early Cretaceous age. Viniegra O. (1971) emphasized that in southeastern Mexico the oldest salt beds, which interfinger with and in places underlie these clastic units, were restricted to the post-Callovian–pre-Kimmeridgian interval because the humid environment of deposition suggested by the Middle Jurassic strata would not have been conducive to salt formation. Fossils from the upper part of Todos Santos Formation indicate Late Jurassic age.

Widespread beds of salt about 180 m (600 ft) to 300 m (1,000 ft) thick accumulated in the Gulf of Mexico Basin and on its margins in northern Central America, southern Mexico, the southern United States, and perhaps in northern Cuba concurrently with the red beds (Imlay, 1943, 1980). Kirkland and Gerhard (1971), who studied microfossils from a diapir in the central part of the Gulf of Mexico, reported ages within the interval Late-Middle Jurassic. They reviewed the published data and suggested that the major pre-Cretaceous evaporite suites, which include the Louann-Werner of the southeastern United States, the Minas Viejas and the Salina of Mexico, and the Punta Alegre of Cuba as well as the postulated Sigsbee salt, are correlative units of Middle or Late Jurassic age (Fig. 11).

In Central America, El Plan Formation, which crops out in Honduras, is considered to be at least Early to Middle Jurassic on the basis of the presence of cycad plant remains and may be as old as Triassic (Newberry, 1888) (Fig. 1, no. 21). Mills and others (1967, p. 1761) described the lithology of a representative section of El Plan as consisting of dark gray to black, thick-bedded shale interbedded with thin-bedded, fine-grained sandstone and rare dark gray beds of pebble conglomerate. The thickness of this unit, which is bounded by unconformities, may be as much as 914 m (3,000 ft).

Red conglomerate, sandstone, and shale with interbedded volcanic rocks that locally overlie El Plan Formation are widespread, although the thickness of these beds ranges from less than 30 m to several hundred metres (Mills and others, 1967; Burkart and others, 1973; Horne and others, 1976). Early Cretaceous limestone that overlies this clastic sequence provides a younger age limit. Many authors suggest correlation between Todos Santos Formation and these lithologically comparable beds that occupy a similar stratigraphic position; however, neither stratigraphic continuity nor paleontologic evidence is known that would establish equivalency (Wilson, 1974).

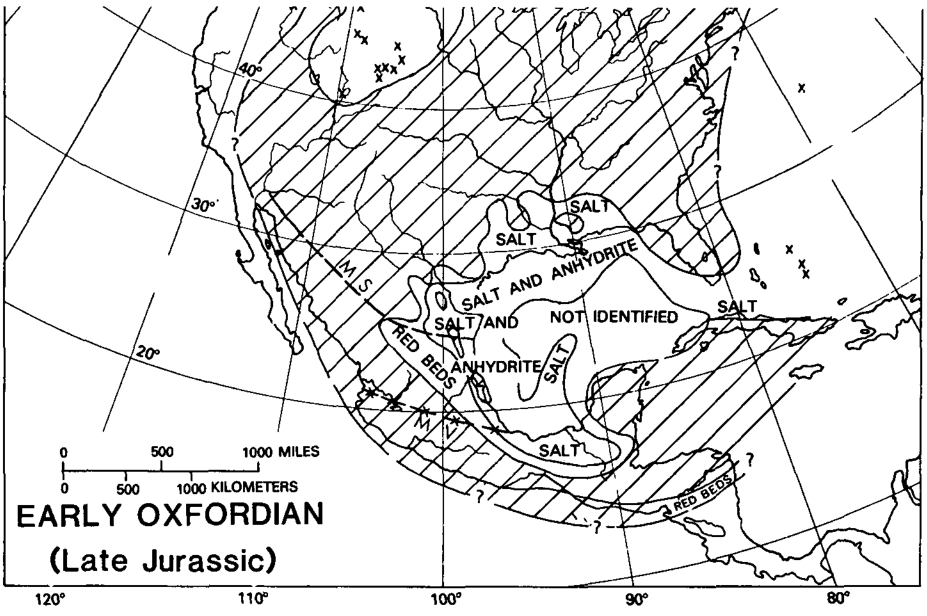

Figure 11. Distribution of early to early middle Oxfordian fossils (x) and inferred seas in southern North America and Central America. Land areas are ruled (adapted from Imlay, 1980, Fig. 9). MS. Mojave-Sonora megashear. MV. Mexican volcanic-belt megashear. Proposed Mexican volcanic belt now inactive. Mojave-Sonora megashear active (compare Fig. 9).

San Cayetano Formation, which is known only from westernmost Cuba (Fig. 7), is a well-bedded monotonous sequence of black to dark gray, micaceous, quartzose, carbonaceous shale, sandy shale, siltstone, and fine-grained sandstone (Khudoley and Meyerhoff, 1971). These authors noted that the beds, which are 1 to 20 cm thick, contain abundant remains of plant stems and rare well-preserved plants. Marine beds are rare and indicate that accumulation of these units occurred in very shallow water under reducing conditions.

Haczewski (1976), who studied sedimentary features of San Cayetano Formation, noted the strong vertical and lateral lithologic variations and concluded, in agreement with the above authors, that the formation accumulated on a coastal alluvial plain. Detritus had been carried by rivers to the continental margin from a source a few hundred kilometres to the south. Transition from the San Cayetano Formation to overlying carbonate within a thin interval suggests an abrupt cessation of clastic supply.

Studies by Myczynski (1976) and Kutek and others (1976), which are summarized by Wierzbowski (1976), confirm the transition of predominantly clastic beds of the San Cayetano Formation into limestone, marl, siltstone, shale, and sandstone of the overlying, correlative Jagua and Francisco Formations of middle to late Oxfordian age. These beds are overlain by limestones of Tithonian age that compose the Guasasa and Artemisa Formations.

Marine pelecypods of Bajocian-Bathonian to middle Oxfordian ages have been reported from the San Cayetano Formation, as have plant remains that are assigned to the interval from Late Triassic to Late Jurassic. Most of the marine fossils probably occur near the top of the unit. However, both precise stratigraphic position and thickness that is approximated to be between 1,500 and 3,000 m (5,000–10,000 ft) are obscured by the effects of deformation.

South of Cuba, Jurassic rocks crop out on islands north of the coast of South America and in the Caribbean mountain system of northern South America (Maresch, 1972). On Margarita Island, La Rinconada Group is composed of at least 2,000 m (6,560 ft) of basic volcanic metasediments, associated flows, and intrusions (Maresch, 1971). Within an interval of about 100 m (328 ft), this sequence is transitional into quartzose metasediments of the Juan Griego Group (Maresch, 1972). On the mainland of South America, the Caracas Group, which lithologically resembles the Juan Griego Group, has been interpreted to represent a stable shelf sedimentary assemblage, 3,000 m (9,840 ft) to 4,000 m (13,120 ft) thick (Menéndez, 1967; Bell, 1971). The lower part of the Caracas Group, which rests unconformably upon granite, consists of quartzose metaclastics and metaconglomerates with lenses of marble of probable biohermal origin (Dengo, 1953; Smith, 1953). Beds higher in the section are graphitic and calcareous with numerous limestone lenses (Smith, 1953). These strata suggest the initiation of reducing conditions across much of the depositional shelf (Shagam, 1960).

The Juan Griego and Caracas Groups are inferred to be Late Jurassic to Early Cretaceous in age (Maresch, 1974) on the basis of rare fossil occurrences and lithologic correlation with unmetamorphosed sequences that crop out in eastern and western Venezuela and Trinidad (Menéndez, 1967; Furrer, 1968; Stainforth and others, 1970; Maresch, 1971; Potter, 1968). In view of this age interpretation, La Rinconada Group must be at least Late Jurassic (Maresch, 1974).

To the west, in the central part of the Guajira Peninsula, 3,250 m (10,660 ft) of mainly clastic rocks accumulated in the east-trending Cocinas trough probably during Jurassic time (Rollins, 1965). The Cocinas Group is composed of sandstone, silty shale, and red and green argillite (Cheterlo Formation); micaceous shale and siltstone with rare beds of limestone and sandstone (Caju Formation); sandstone and conglomerate with rare shale and limestone beds (Chinapa Formation); and micaceous shale with interbedded sandstone, siltstone, limestone, and bioherms (Cuisa Shale). Sparse fossils occur in the lower three formations, but unfortunately only the assemblage from Cuisa Shale has been suitable to firmly establishing its age as Late Jurassic (Kimmeridgian-Portlandian). The Jurassic rocks are conformably overlain by similar clastic beds with prominent limestone facies of Early Cretaceous age that are in turn transitional into a sequence of massive limestone.

South of the Guajira Peninsula in the Sierra de Perijá, continental red beds, called the Giron Group in Colombia and La Quinta Formation in Venezuela, contain abundant volcanic units in the lower parts of the sections. According to Irving (1975), Cediel (1968) subdivided the Giron Group at the type locality into a lower formation, called Jordon, composed of fine-grained clastic beds with interstratified ignimbrites. Above the Jordon Formation, quartzose clastic beds with a few intercalated volcanics have been designated Giron Formation. Although ages of these formations have not been determined directly, incorporated clasts of Early Jurassic granite led Irving (1975) to conclude that both Jordon and Giron are probably Middle to Late Jurassic in age near their type localities. An Early Cretaceous age for the uppermost beds cannot be precluded.

In the Venezuelan Andes, La Quinta Formation (Hargraves and Shagam, 1969) is composed primarily of purplish-red siltstone and sandstone with less abundant conglomerate and gray or green clastic interbeds. At some localities, tuff units crop out at the base of the section. The age of the lower part of La Quinta is based upon scarce fossils the ages of which fall within the interval between Late Triassic and Early Jurassic time. The basal volcanic beds may be as old as Permian. Commonly, La Quinta is transitional into shale and limestone of the Early Cretaceous (Hargraves and Shagam, 1969).

Northeast of the Perijá range, in the southern part of the Guajira Peninsula, nonfossiliferous units, very similar to Giron and La Quinta, crop out (Alvarez, 1971). These beds, which include dark red conglomerate, sandstone, and shale interbedded with rhyolite, rest upon crystalline basement and constitute the lower part of the Cojoro Group (Rollins, 1965). These continental rocks locally contain petrified logs and stumps and a few bivalves, although none of these fossils has yielded an age. Clean quartzose sandstone and pebbly conglomerate (Uipana Formation), which overlie the Rancho Grande Formation with a minor unconformity, indicate a probable marine transgression. The Cojoro Group is more than 850 m (2,800 ft) thick. Lithologically, the Rancho Grande Formation resembles La Quinta Formation of the Merida Andes, the Sierra de Perijá of Venezuela, and the Giron Group of eastern Colombia. Rollins (1965) suggested that the upper marine beds (Uipana) may be equivalent to La Quinta.

Thick accumulations of basic igneous rock of Jurassic and Early Cretaceous age also form the Nicaraguan Rise, and although a blanket of sediments overlies the mafic layer, its crustal thickness is only two-thirds the thickness of average continental crust, and Arden (1969) argued against its origin as part of a geosyncline.

PROPOSED EVOLUTION OF MIDDLE AMERICA AND THE CARIBBEAN REGION DURING EARLY JURASSIC TIME (195–175 m.y. B.P.)

The Early Jurassic, prior to displacement along the proposed transform faults, is roughly coincident with the rift phase of Buffler and others (1980). The interval was marked by the accumulation of dominantly clastic sediments in basins, commonly elongate and fault-bounded, developed largely in sialic crust near the margins of the present-day Gulf of Mexico (Salvador and Green, 1980; Schmidt-Effing, 1980). In eastern Mexico, at least 3,000 m of sediments accumulated in the Huayacocotla graben (Schmidt-Effing, 1980), which had limited access to open marine water (Erben, 1956a) (Fig. 1, no. 14). Alternating marine and nonmarine conditions, unfavorable for the accumulation of salt, are recorded by these Lower Jurassic beds. Deformation accompanied by weak metamorphism brought this interval to a close before accumulation of the Middle Jurassic Cahuasas Formation (Imlay, 1980).

El Plan Formation, which crops out in Honduras, probably accumulated during Early Jurassic time under conditions not dissimilar from those in southern Mexico. We suggest that El Plan has been displaced far eastward of where it formed. The basin in which the formation accumulated possibly could have been a southerly extension of the zone that includes the similar strata of southern Mexico (Fig. 7, nos. 14 and 21).

This speculative stratigraphic correlation is in contrast to the interpretation by Iturralde-Vinent (1975), who argued for equivalency between El Plan and the San Cayetano Formation of Cuba. Our model suggests that Cuba and Hispaniola lay against the northern margin of South America during Early and Middle Jurassic time (Fig. 7). This requires correlation between the San Cayetano Formation and the Caracas and Juan Griego Groups of Venezuela

(Dengo, 1953; R. J. Smith, 1953; Maresch, 1972).

Paleontologic data indicate that the uppermost part of the San Cayetano Formation is middle Oxfordian (Myczynski and Pszczolkowski, 1976), whereas the basal beds may be as old as Late Triassic (see summary in Khudoley and Meyerhoff, 1971). Although no firm age can be assigned to the Caracas and Juan Griego Groups, they are no younger than Late Jurassic to Early Cretaceous in age (Dengo, 1953; R. J. Smith, 1953; Maresch, 1974). The mineralogy of these clastic sequences is characterized by abundant quartz, mica, feldspar, and common carbonaceous material with scattered beds of quartzite and carbonate. The Caracas Group, the thickness of which is 3,000 m (9,840 ft) to 4,000 m (13, 120 ft), was derived largely from crystalline basement upon which it rests. The sequence represents beds that accumulated upon a stable shelf (Maresch, 1974). To the north, the Juan Griego Group is lithologically similar to the Caracas Group (Maresch, 1972) but overlies and interfingers with mafic volcanic metasediments and associated metamorphosed flows and intrusions of La Rinconada Group, which we speculate were generated during rifting.

Haczewski (1976) concluded that the San Cayetano Formation, the maximum thickness of which lies between 1,500 m (4,920 ft) and 3,000 m (9,840 ft), accumulated on a flood plain along the margin of a continental landmass composed of clastic terrigenous rocks and their metamorphic equivalents. His studies of paleocurrent directions and grain size of sediments suggest that detritus most likely was transported a few hundred kilometres from a source to the south.

Juxtaposition of the San Cayetano Formation against the Caracas and Juan Griego Groups does not result in incompatible stratigraphic relationships. In fact, the reconstruction provides a convenient source, the Guyana shield, for the sediment incorporated into the San Cayetano Formation (compare Khudoley and Meyerhoff, 1971). Quartzose metamorphic rocks, largely in southern Cuba and nearby islands, may be in part metamorphic equivalents of San Cayetano but may also contain elements (marble, metavolcanic units) derived from younger or possibly distant (La Rinconada, Juan Griego–Caracas Groups) rock units. If, in fact, the fragments of metamorphic terranes are older (that is, Paleozoic?), as suggested by Tijomirov (1968), they could have been rifted from the margin of South America. The possibility that equivalents of the San Cayetano Formation crop out on Hispaniola (Khudoley and Meyerhoff, 1971) suggests that it, too, was attached to South America.

Away from the margins of the Gulf, along some, if not most, of western Mexico, extensive magmatism characterized Early Jurassic time (Guerrero and others, 1978; Corona, 1979; Anderson and Silver, 1979). Eroded debris from this mountain belt spread eastward toward the continental interior. We propose that the strata of Nazas Formation, and possibly parts of La Joya Formation, are equivalents of Early Jurassic beds in northwestern Mexico. Nazas and the pre–Late Jurassic units of La Joya occupy their present positions because of displacement along the Mojave-Sonora megashear.

LATE-EARLY TO EARLY-LATE JURASSIC EVOLUTION (175–143 m.y. B.P.)

Between 175 and about 160 m.y. ago, initial displacement probably occurred along the transform coincident with the Mexican volcanic belt (Fig. 12). The pole of rotation we have chosen is compatible with both the Mexican volcanic-belt transform and the pole of early opening of the North Atlantic defined by Le Pichon and Fox (1971). If initial displacement occurs along this zone, then margins of North America and Africa separate cleanly and protuberances of continental crust, such as the Grand Banks, are not sheared off. We assume that displacements along the Mexican volcanic belt are roughly contemporaneous with active spreading that began in the Atlantic during the interval between 175 and 165 m.y. ago, as suggested by paleomagnetic results (Smith and Noltimier, 1979; Dalrymple and others, 1975). The inception of faulting is supported by the development of a marine connection coincident with the existing Mexican volcanic belt (Imlay, 1980). The existence of this narrow band of marine beds of Bathonian age is compatible with the postulation of major fault displacement and associated rifting along this proposed fault zone. Sclater and others (1977) concluded that the initial break between Africa and North America occurred 165 m.y. ago on the basis of their assumptions of spreading rates and ages of magnetic anomalies. If separation proceeded at the average rate of 4 cm/yr (Pitman and Talwani, 1972), then 300 km of displacement along the Mexican volcanic-belt transform would be completed in less

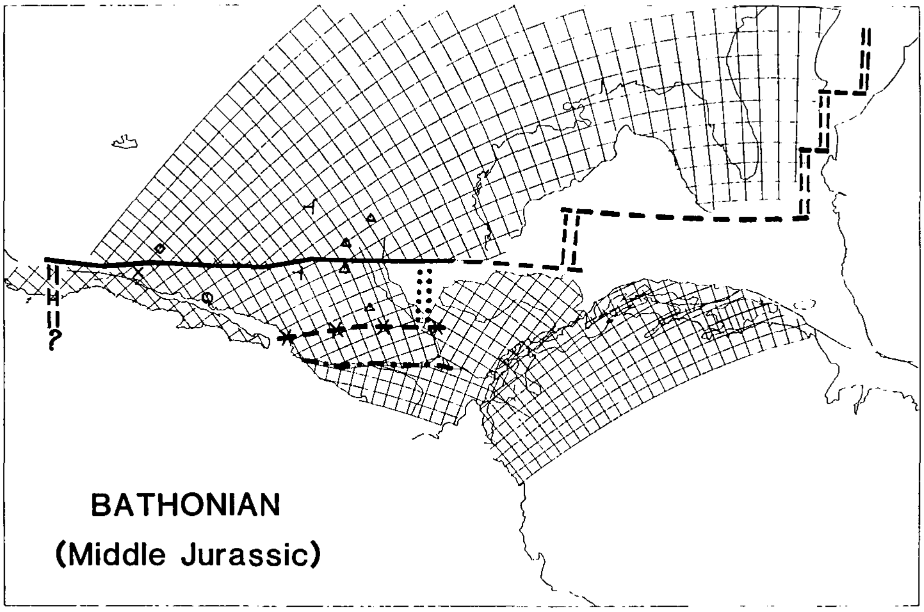

Figure 12. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during Middle Jurassic time (~ 160 m.y. ago) from a pole of rotation defined by the Mojave-Sonora megashear at lat. 52°N, long. 79°W. Transform fault, heavy line; inferred, broken line; future position, dash-dot; inactive, heavy line with crosses. Convergent zone, heavy line with teeth pointing toward the upper plate; inferred, broken line with teeth pointing toward the upper plate; inferred future position, dash-dot line with teeth.

than 10 m.y. As shown in Figure 12, motion along the Mexican volcanic-belt transform was completed before any motion occurred along the Mojave-Sonora megashear. Although contemporaneous displacements along these two faults are not precluded, major offset along the Mojave-Sonora megashear probably occurred after 160 m.y. ago.

Oceanic crust generated by spreading during this Middle Jurassic interval as well as oceanic crust generated when displacement took place along the Mojave-Sonora megashear should occupy the western part of the Gulf of Mexico. Deep seismic-reflection results were interpreted by Ladd and others (1976) as being suggestive of oceanic crust underlying Jurassic(?) salt in this region. A magnetic survey of this area (Moore and Del Castillo, 1974) revealed anomalies of an amplitude compatible with an origin by sea-floor spreading, but with an irregular pattern (obscured by overlying sediments) that is complex.

Approximately 155 to 145 m.y. B.P., the Mojave-Sonora megashear was active, with cumulative displacement of about 800 km (Fig. 13).

The Maya East block rotated in a counterclockwise sense (Uchupi, 1973) and probably parts of Cuba and Hispaniola, which maintained connection to Yucatan (Baie, 1970; Moore and others, 1971; Vedder and others, 1971, 1973; Pyle and others, 1973), separated from South America. The time of this separation from South America (158–145 m.y. ago) may be signaled by a change in the San Cayetano Formation from predominantly nonmarine beds to marine beds that occurred from Callovian(?) through Oxfordian time, according to Khudoley and Meyerhoff (1971). These authors noted that pre-Tithonian marine strata are known only from northwestern Cuba (coincident with the distribution of the San Cayetano Formation), whereas by early to middle Tithonian time, marine conditions were present in most of Cuba.

If Cuba separated from South America and moved approximately 10° of latitude toward the north, allowing 10 m.y. for passage, then the average rate would be about 7.0 cm/yr.

The rotation of Maya East (Yucatan) was suggested by Dillon and Vedder (1973) and Uchupi (1973). Their model is based mainly upon oceanographic data that imply the existence of a series of linear fault ridges that occur along the eastern Yucatan continental margin and in the rest of the western Caribbean. These faults, which merge southwestward toward Guatemala, may bound tilted blocks, formed as Yucatan separated from South America.

We speculate that to the west, from central Guatemala to Chiapas, a manifestation of this rotation may be recorded by the presence of pebble-, cobble-, and boulder-sized clasts of the Chóchal (Permian) limestone in conglomerate that constitutes the basal beds of the Todos Santos Formation. The upper beds of Todos Santos are Kimmeridgian or younger. The abundant limestone clasts suggest rapid erosion of uplifted Chóchal limestone possibly as a result of displacement along normal faults that formed due to extension as Yucatan rotated. According to Uchupi (1973), Yucatan was isolated from adjacent blocks by faults equivalent to the Acapulco-Guatemala megashear and the northerly-trending Salina Cruz fault, which cuts the Isthmus of Tehuantepec (Fig. 3).

Rifting of Yucatan from South America also may be recorded by the east-trending Cocinas trough, which lies across the Guajira Peninsula in northwestern Venezuela and northeastern Colombia (Fig. 1, nos. 25 and 10; Fig. 13, loc. E). This fault-bounded trough, which bounds part of the northern margin of the South American stable platform, was filled with 3,250 m (10,660 ft) of Jurassic strata, the uppermost beds of which yield fossils of Kimmeridgian and Portlandian age (Rollins, 1965). According to Rollins, this sequence and overlying Early Cretaceous strata record a transition from nearshore, locally terrestrial conditions, to a progressively more open marine environment in the youngest beds. Paleogeographic sketch maps constructed by Rollins (1965, Fig. 18) indicate a widening marine basin between bounding highlands to the north and south.

The tectonic effects of Cuba's passage as it separated from South America are minimal. Although the San Cayetano Formation is commonly somewhat metamorphosed, the age of metamorphism is unknown. Suffice it to say that Khudoley and Meyerhoff (1971, p. 52) agree to the existence of "mild disturbance recorded in the post-Oxfordian–pre-Kimmeridgian(?) interval." Callovian-Kimmeridgian clastic rocks that fringe northern Cuba are interpreted by Khudoley to represent the aftereffects of major orogeny probably associated with the emplacement of serpentinite masses and plutons. However, Wierzbowski (1976) confidently reported that a gradual transition exists between San Cayetano and younger beds, and Meyerhoff argued that the igneous rocks are more likely remnants of Paleozoic orogens that in places were remobilized during Cretaceous time.

Crustal shortening during this rotation was probably restricted to the eastern mar-

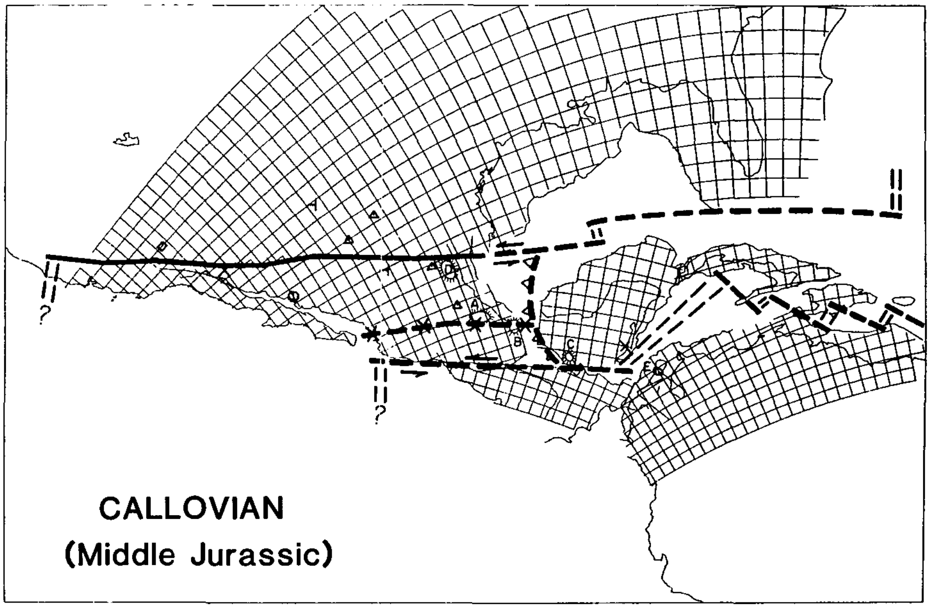

Figure 13. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during late Middle Jurassic time (~150 m.y. ago) from the pole of rotation defined by the Mojave-Sonora megashear at lat. 52°N, long. 79°W. A. Teziutlán uplift. B. San Andres Tuxtla uplift. C. Poxlac uplift. D. Tamaulipas uplift. E. Cocinas trough.

gin of the Yaqui block because the Apache block, which lay north of the Mojave-Sonora megashear, was moving relatively away from Yucatan at a similar velocity. Along the eastern margin of the Yaqui block, uplifted massifs include Tamaulipas, south of Ciudad Victoria, and Teziutlán and San Andres Tuxtla, which occur northwest and southeast of Veracruz, respectively (Fig. 13) (Viniegra O., 1971). In the Maya East block, the Poxlac uplift in western Guatemala (Anderson and others, 1973) and much of the Yucatan Peninsula (Viniegra O., 1971; Lopez-Ramos, 1975) were probably highlands that contributed detritus toward an intervening basin the axis of which trends northwesterly (Lopez-Ramos, 1979, Fig. XIV-3). Altered granitic rocks that intrude Middle Jurassic strata are overlain by Kimmeridgian beds near Teziutlán (Lopez-Ramos, 1979).

In Hispaniola, no unique history can be deciphered for the paired metamorphic belts of Cretaceous or older age that crop out on the northern margin of the island (Nagle, 1974). However, a possible interpretation of these metamorphic rocks and magmatic rocks of Jurassic age on Désirade (Mattinson and others, 1979), as well as correlative beds (Donnelly, 1975) on the Virgin Islands, is that they formed as oceanic crust was created in the wake of the rifted crustal fragments. Subsequently, the rocks of Jurassic age were modified during Cretaceous tectonism.

Broad constraints upon the timing of deformation that likely accompanied rotation may be provided by stratigraphic relationships of the Cahuasas Formation of Middle Jurassic age. This unit, which crops out on the Yaqui and Maya West blocks, unconformably overlies the Huayacocotla Formation, which has suffered both deformation and weak metamorphism (Imlay, 1980). Cahuasas is itself undeformed but is disconformably overlain by the Santiago Formation of early or middle Callovian to late Oxfordian age. On the basis of these stratigraphic relationships, and the arguments concerning the age of the various units by Imlay (1980), strongest deformation was younger than Pliensbachian and probably older than Bajocian.

As Yucatan rotated, contemporaneous translation must have taken place along the Acapulco-Guatemala fault. By this time, South America had been decoupled from all plates except Chortis, which was a very weak connection. As South America moved toward the 127-m.y. B.P. position defined by Ladd (1976), Chortis bent counterclockwise slightly about its attachment to South America in order to avoid overlapping with the Maya West plate (Fig. 13). This resulted in necessary left-lateral slip along the Acapulco-Guatemala fault and freed Maya East (Yucatan) along its southern margin, thus facilitating rotation.

Paleomagnetic evidence (Guerrero and Helsley, 1974) indicates that rotation of the Maya East microplate was completed by the late Oxfordian. These data also corroborate the Kimmeridgian age for red beds within the upper Todos Santos Formation and agree with the conclusion reached by Richards (1963) and Viniegra O. (1971), who argued that most of the formation was of Late Jurassic age with uppermost beds of Neocomian age. As a consequence of rotation of Maya East and limited displacement along the Acapulco-Guatemala transform, Jurassic(?) red beds on the Chortis plate would be juxtaposed against the Todos Santos Formation of Maya East. These strata were correlated by Mills and others (1967), but Wilson (1974) considered this correlation to be hazardous.

Rifting that probably accompanied the positioning of sialic crustal fragments during Late Jurassic time was essentially coeval with the initiation of major accumulation of salt, anhydrite, and intercalated red clastic beds around the Gulf of Mexico during the interval from late Callovian to middle Oxfordian. The salt beds have not been dated directly, aside from the study of Kirkland and Gerhard (1971), which suggests a Middle or Late Jurassic age. Arguments based upon stratigraphic relationships by Imlay (1943, 1980) and Viniegra O. (1971) leave little doubt of the validity of the assignment of Callovian to middle Oxfordian age. At this time, limited access to the Gulf was probably provided by one or more of the narrow seaways or straits (1) between Florida and Cuba, (2) between Cuba and Yucatan, (3) across the Isthmus of Tehuantepec (Viniegra O., 1971), and (4) across northern Mexico (Burckhardt, 1930; Kellum and others, 1936), possibly coincident with the Mojave-Sonora megashear. Older salt layers may exist, but certainly major accumulation occurred during the Late Jurassic.

EVOLUTION DURING KIMMERIDGIAN, PORTLANDIAN, AND EARLY NEOCOMIAN (143–130 m.y.)

By the late Oxfordian (145 ± m.y. ago), Maya East (Yucatan) and Cuba had reached their present positions (Guerrero and Helsley, 1974) (Fig. 14). Movement along the Mexican volcanic belt previously had concluded and displacement along the Mojave-Sonora megashear was terminating. Red clastic beds intercalated with evaporites, which probably accumulated almost contemporaneously with activity along the Mojave-Sonora megashear, are transitional to beds commonly bearing anhydrite (Imlay, 1943). This transition, which

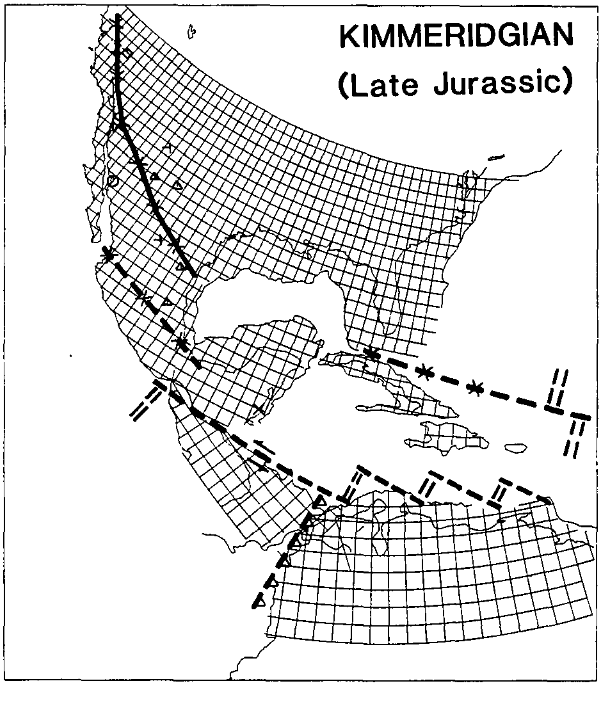

Figure 14. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during latest Jurassic time (~140 m.y. ago) from pole of rotation defined by Ladd's (1976) 127 to 84 m.y. pole at lat. 28°N, long. 111.4°E.

is recorded along the northern and northwestern margins of the Gulf, places a minimum age upon displacements along the megashear because late-middle Oxfordian strata are not known to be disrupted by major strike-slip fault displacement (Imlay, 1980) (Fig. 15). In southeastern Mexico, evaporites continued to accumulate during Cretaceous time as previously uplifted areas were gradually submerged by constantly encroaching marine water. Viniegra O. (1971) provided a detailed account of this fascinating history.

Meanwhile, as South America continued toward Ladd's (1976) 127-m.y. position, we suggest that Chortis remained attached but was bent strongly counterclockwise, which probably produced additional left-lateral slip between Maya East and Chortis and may have resulted in the slight unconformity between Todos Santos and Aptian-Albian(?) carbonate beds as well as the apparent absence of strata of Neocomian age (Wilson, 1974).

In Cuba, marine elements of San Cayetano record local transitions into latest Jurassic carbonate beds (Wierzbowski, 1976).

Along the margin of northern South America, latest Jurassic sedimentary sequences are transitional into lithologically similar beds of earliest Cretaceous age (Rollins, 1965; Maresch, 1974).

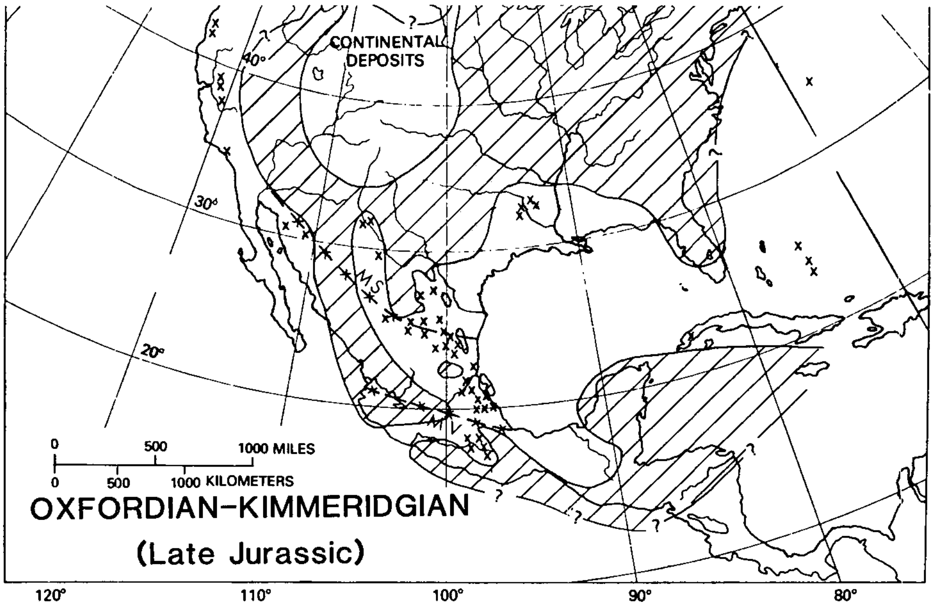

Figure 15. Distribution of late middle Oxfordian to early Kimmeridgian fossils (ammonites and buchia) (x) and inferred seas in southern North America and Central America. Land areas are ruled (adapted from Imlay, 1980, Fig. 10). Mojave-Sonora megashear and Mexican volcanic-belt megashear are inactive (compare cf. Fig. 14). MS. Mojave-Sonora megashear. MV. Mexican volcanic-belt megashear.

EVOLUTION DURING VALANGINIAN THROUGH CONIACIAN (130–85 m.y.)

A distinct change in plate motion from separation with a northwest-southeast trend to clockwise rotation of South America with respect to North America occurred during Valanginian time (Fig. 16). Ladd (1976) pointed out that the above change in plate motion was contemporaneous with north-south compression and lithospheric consumption along most of the Caribbean perimeter. He also noted that simple strike-slip motion of the major plates was not sufficient to generate the existing record.

Ladd (1976) further recognized that, if a plate extension existed to the north of Venezuela and Colombia, then, as rotation occurred, convergence could result in the Caribbean region. This necessary plate configuration is generated in a straightforward way in our proposed model (Figs. 14 and 16). The orientation of the Chortis block is constrained by the paleomagnetic data of Gose and Swartz (1977). If Chortis were to remain attached to South America during this interval of time, then clockwise rotation of these blocks and the ocean floor bounded by them on the west and south would drive the newly formed Late Jurassic ocean crust against Cuba, Hispaniola, and Puerto Rico, resulting in the convergence along the southern margin of Cuba (exclusive of southeasternmost Cuba, mainly Oriente Province, which was accreted at a later time) and under part of Hispaniola and Puerto Rico. Convergence in this region is compatible with: (1) the conclusion reached by Khudoley and Meyerhoff (1971) and Pardo (1975) that a eugeosyncline extended along this zone and (2) the distribution of Early to Middle Cretaceous volcanic rocks, as shown by the paleogeographic maps of Khudoley and Meyerhoff (1971), which suggest the existence of a former magmatic arc. Furthermore, in light of recent paleontologic data (Mattson and Pessagno, 1979) that indicate that the Bermeja ophiolite of Puerto Rico is pre-Late Jurassic, we consider it possible that this allochthonous complex is a remnant of Jurassic sea floor that was uplifted and emplaced in pre-Cenomanian time as the result of northward gravity sliding (Mattson, 1973). The paired metamorphic belts in Hispaniola (Nagle, 1974) as of yet cannot be assigned a unique age, but they would be compatible either as old fragments previously rifted from South America and modified by Cretaceous metamorphism or as belts formed and emplaced during Early Cretaceous subduction.

Volcanism, mafic plutonism, metamorphism, and uplift in Puerto Rico during this time period are suggested by the results of K-Ar isotopic studies (Cox and others, 1977). Donnelly (1975) concluded that, although scant evidence for polarity of Cretaceous subduction near the Virgin Islands exists, chemical data from a volcanic unit (Jolly, 1970) and results from structural study of the Bermeja complex (Mattson, 1973) are compatible with northward subduction under Puerto Rico. Chemistry from regionally distributed volcanic rocks in Puerto Rico (Lidiak, 1972) is inconclusive. Mattson (1979) also reached the conclusion that northward subduction had existed, based upon his analysis of the distribution, lithologies, and ages of metamorphic rocks in the northern Caribbean. However, he postulated that northward subduction ceased about 127 m.y. ago and was replaced by southward-directed subduction from 110 to 85 m.y. ago. Whether or not the subduction zone flipped, considerable geochronologic and geologic evidence leads to the conclusion that a major change in tectonic processes occurred about 85 m.y. ago (Ladd, 1976; Mattson, 1979).

The facies maps of Wilson (1974) for nuclear Central America are useful in attempting to understand the history of the

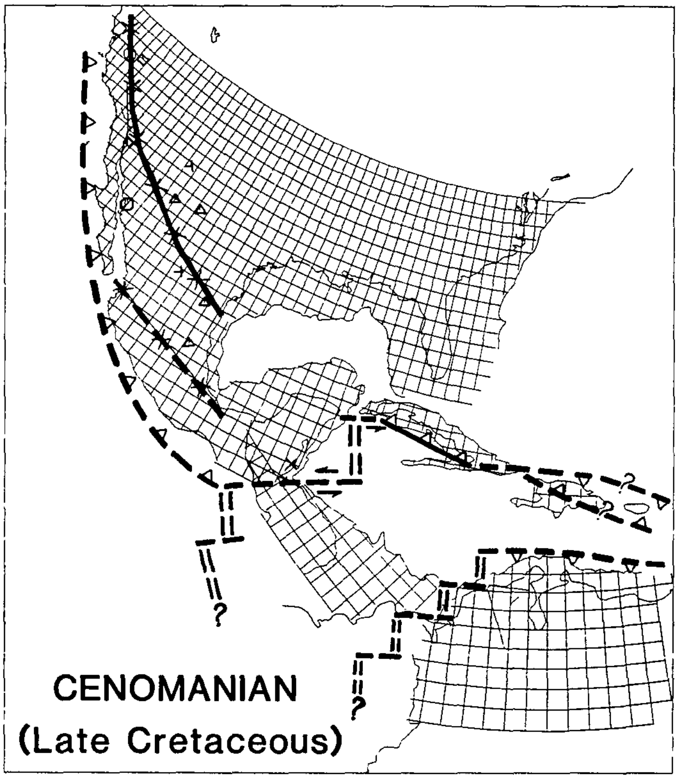

Figure 16. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during Late Cretaceous time (~95 m.y. ago) from the pole of rotation defined by Ladd's (1976) 127 to 84 m.y. pole at lat. 28°N, long. 111.4°E.

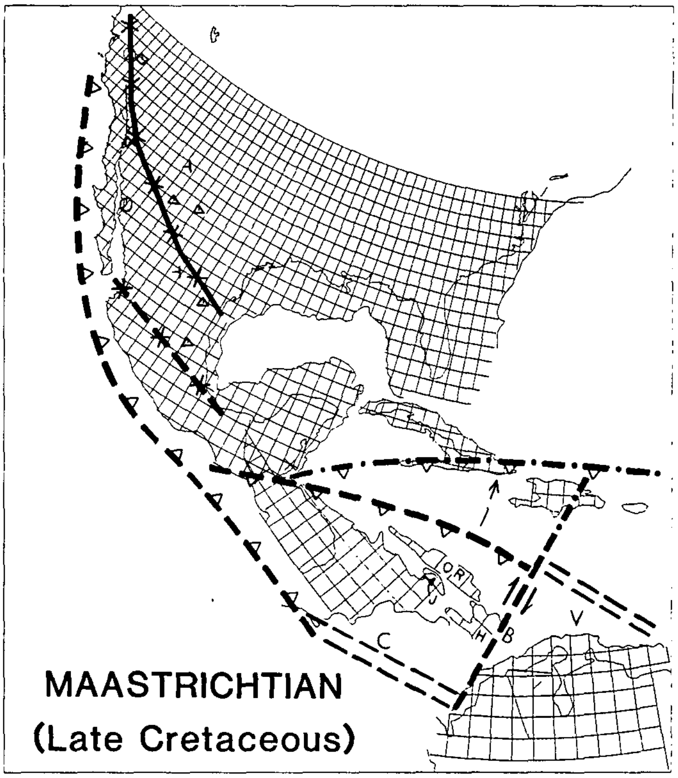

Figure 17. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico–Caribbean Sea region during latest Cretaceous time (~70 m.y. ago) from the pole of rotation defined by Ladd's (1976) 127 to 84 m.y. pole at lat. 28°N, long. 111.4°E. J. Jamaica. H. Hispaniola. OR. Oriente Province, southeastern Cuba. B. Beata transform. C. Colombian Basin. V. Venezuelan Basin.

northeasternmost part of the Chortis plate (southeastern Guatemala and western Honduras). By Aptian time, the whole of nuclear Central America had been submerged and carbonate beds with intercalated evaporite were accumulating. However, discontinuity along the hypothetical fundamental crustal break between the Chortis and Maya plates is indicated by the development of a "pelagic-basinal facies" in Albian time. These deep-water beds, which include volcaniclastic units, accumulated in an elongate basin, only several tens of kilometres wide (Wilson, 1974, Figs. 26 and 27) and may record the position of a trough, coincident with a major fault system. Left-lateral displacement along this zone, the precursor to the existing Motagua fault, probably had accumulated to about 1,000 km during latest Jurassic and Early Cretaceous time. This displacement is compatible in sense and magnitude with that suggested by Pinet (1972), on the basis of offset of diapirlike features, east of Honduras, presumably from latest Jurassic evaporites of the Chiapas Basin. Existing geological data do not permit us to evaluate all of the strong rotations of Chortis during Cretaceous time (Gose and Swartz, 1977).

Aves Ridge was described by Tomblin (1975) as an extinct volcanic arc of post-middle Cretaceous–pre-early Miocene age. We speculate that it may have formed when the easternmost protrusion of Late Jurassic-age oceanic crust, east and north of Chortis and South America, converged against adjacent sea floor. If our model is correct, then the Grenada trough may be underlain by a relict remnant of Jurassic ocean floor, the eastern limit of which is marked by the correlative rocks on Désirade, which has been uplifted during formation of the Lesser Antilles.

Along northern South America, during middle Cretaceous time, subduction toward the south was short-lived (Maresch, 1974) and may have been caused by the relatively small amount of northward motion of South America with respect to North America indicated by Ladd (1976, Fig. 2B).

The end of this period of left-lateral motion has been placed at 84 m.y. ago. This is the youngest date possible for the termination of the motion, although possibly it terminated earlier in the Coniacian or even late Turonian (Ladd, 1976).

EVOLUTION DURING CONIACIAN TO LATE EOCENE (84-40 m.y.)

Ladd (1976) suggested that during 80 to 40 m.y. ago North America separated from South America along a northwest-southeast trend. However, the possibility that extension could have begun as early as late Turonian, as noted by Ladd, is supported by geological evidence indicating that tectonic and stratigraphic changes occurred at this time. In northern and western Cuba, igneous activity largely ceased after Turonian time and, throughout much of Cuba, abundant Cretaceous volcanic rocks that were erupted until early Turonian time are disconformably overlain by sedimentary rocks of Campanian-Maastrichtian age (Khudoley and Meyerhoff, 1971). In fact, Khudoley and Meyerhoff noted that a major break, commonly represented by an angular unconformity between beds of Cenomanian or early Turonian age and overlying Campanian or Maastrichtian, exists throughout the Greater Antilles. Where rare Turonian-Santonian beds exist, they also commonly lie with an angular unconformity upon Early Cretaceous strata.

Separation of North America and South America may be manifested by extension that is compatible with the outpouring and intrusion of basalt and dolerite in the Venezuelan Basin between latest Turonian and Campanian (Edgar and others, 1973). Donnelly and others (1973) concluded that the geographic distribution of these rocks and their relationship to the pattern of linear magnetic anomalies (Donnelly, 1973) did not suggest an analogy to mid-ocean volcanism but rather represented a simultaneous series of eruptions throughout a widespread area. Perhaps these eruptions issued through a pre-Cretaceous ocean floor fragmented by contemporaneous extension.

West of the Venezuelan Basin, extension appears to have been manifested by ocean-floor spreading between 85 and 65 m.y. ago that resulted in the formation of the Colombian Basin (Christofferson, 1976). Northward spreading could have rotated Chortis in a counterclockwise sense (Gose and Swartz, 1977), such that a V-shaped fragment of Jurassic ocean floor was subducted under the Cayman Ridge (Fig. 17). The history and nature of this convergent margin have been described in some detail by Perfit and Heezen (1978), who concluded that parts of the Nicaraguan Plateau, Cayman Ridge, Jamaica, Oriente Province (southeastern Cuba), and Hispaniola formed as volcanic edifices above a southward-dipping subduction zone. This attractive, viable model is compatible with much existing geological data (Draper and others, 1976; see below).

We speculate that the northeasterly-trending Beata Ridge that separated the Colombian and Venezuelan Basins may have been a ridge-trench transform that permitted the Colombian Basin to evolve independently of the Venezuelan Basin, as suggested by Malfait and Dinkelman (1972). Studies by Fox and Heezen (1975) suggested that Beata Ridge was elevated in post-Late Cretaceous time but before mid-Eocene. This interval coincides with the timing suggested for rotation of Chortis.

Although the hypothesis that Beata Ridge is a transform fault that permits Chortis to rotate into its present position is attractive, it does not provide a unique solution to some of the tectonic features described in the vicinity of the Cayman Trench. In Guatemala, the western extension of the subduction zone proposed by Perfit and Heezen (1978) crops out within a zone delineated by Chixoy-Polochic, Motagua, and Chamelecón faults. The distribution of Cretaceous volcanic rocks (Wilson, 1974) and plutons south of the Motagua fault (Williams and McBirney, 1969; Clemons and Long, 1971; Horne and others, 1976) supports the recent studies of Schwartz (1972), Schwartz and Newcomb (1973), Lawrence (1976), and Donnelly (1977), who concluded that a crustal suture occurred along a south-dipping subduction zone coincident in places with the Motagua fault zone. Continent-continent collision is suggested by their interpretation and the tectonic effects of this event may have been recorded as far north as the Chixoy-Polochic fault zone, where mafic heavy-mineral detritus, which accumulated in Campanian-Maastrichtian and slightly older Late Cretaceous clastic units north of this fault (Blount, 1967; Bonis, 1967), and K-Ar cooling ages from the Chuacus Group (Sutter, 1979) record extensive uplift that exposed former ocean floor to erosion. The culmination of tectonism probably occurred as serpentinite was emplaced upon latest Cretaceous beds by gravity sliding (Wilson, 1974). Eastward in Cuba, extensive north-directed tectonic slide masses were emplaced (Pardo, 1975), probably following collision of the Cayman Ridge–Nicaraguan Rise terrane with the earlier-formed magmatic arc on and south of Cuba. Northward gravity sliding comparable to that described from north of the Cayman convergence zone has not been reported from areas to the south. However, thick sequences of coarse-grained clastic rocks suggest erosion of uplifted areas above a subduction zone. In Central America during Maastrichtian and early Tertiary time, debris was shed from the suture along the Motagua fault toward the south (Wilson and Meyerhoff, 1978, Fig. 3). Similarly, in eastern Jamaica, coarse sandstone and conglomerate, mainly of Eocene and Paleocene age, attest to comparable conditions (Arden, 1975), as do correlative suites in Hispaniola, although these contain more carbonate and volcanic units (Khudoley and Meyerhoff, 1971; Bowin, 1975). Probable northward displacement of a nappe in post-Maastrichtian time also occurred in Puerto Rico (Matt-

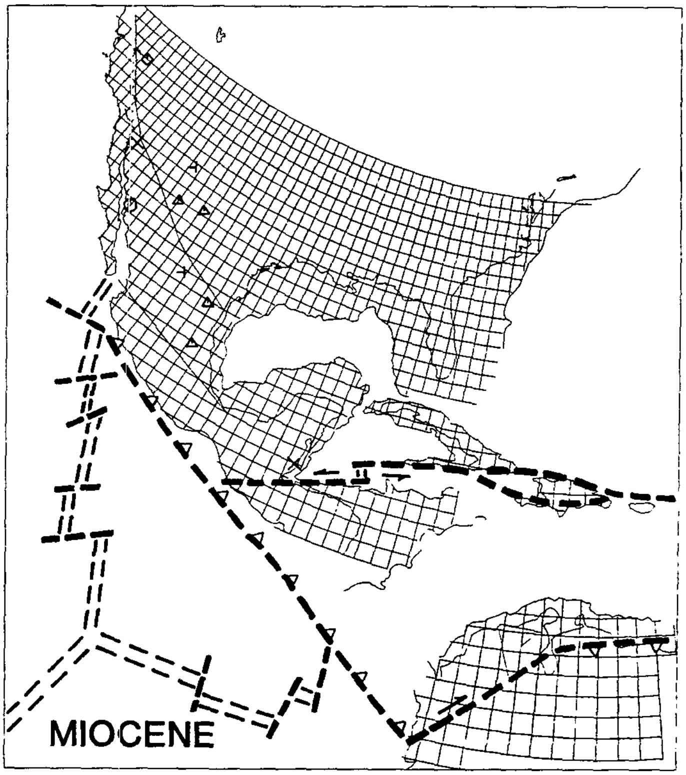

Figure 18. Oblique Mercator projection of a plate-tectonic reconstruction of Middle America and the Gulf of Mexico-Caribbean Sea region during Miocene time (~8 m.y. ago) from the pole of rotation defined by Ladd's (1976) 127 to 84 m.y. pole at lat. 28° N, long. 111.4° E.

son, 1973) east of Beata Ridge. If Beata Ridge was a transform, then the nappe was not formed as a result of collision at a convergent margin similar to that which occurred to the west.

Rocks of the Dutch Leeward Islands, the Venezuelan Islands, and the Coast Range tectonic belt record major magmatism and metamorphism of latest Cretaceous to Paleocene age that culminated in a late Eocene–Oligocene orogenic event that resulted in the existing structural framework of the margin of the Caribbean Mountain system of northern South America (see Maresch, 1974, and Santamaria and Schubert, 1974, for summaries and sources).

LATE EOCENE TO PRESENT (40–0 m.y.)

Ladd (1976) showed a small northward motion of South America relative to North America during this time but cited recent research on northern South America that suggests compression occurred along the north-northwest trend (Fig. 18). According to Meyerhoff and Meyerhoff (1972), east-northeast–trending structures that affect the early Eocene and older strata on the islands of Barbados, Trinidad, and Tobago may reflect these same forces.

In the Greater Antilles, the post-mid-Eocene section is distinguished by the lack of volcanic units (Nagle, 1971) and by its gentle folds. Paleogeographic models suggesting that Cuba migrated to its present position from the west (Malfait and Dinkelman, 1972; Dickinson and Coney, 1980) neglect the absence of igneous rocks and strong deformation in post-Eocene strata that is clearly noted by Iturralde-Vinent (1969, 1970, 1972). In contrast, the Lesser Antilles are underlain by volcanic strata, the oldest of which is mid-Eocene (Nagle, 1971). Possibly, compression resulted in extrusion of the present Caribbean plate toward the east, and along the Lesser Antilles this was manifested by subduction. However, to the north, where the Cayman trough and the Puerto Rico trench were aligned, a small amount of left-lateral displacement may have begun to occur. The problem of compression without attendant subduction during this interval was discussed by Burke and others (1978), who suggested that considerable internal deformation of the Caribbean plate has taken place. Nagle (1971) made it clear that, although the Puerto Rico trench, which first appeared in late Eocene or Oligocene time (Monroe, 1968), ends north of eastern Hispaniola and that it contrasts with the Cayman trough in crustal thickness, gravity, and magnetic patterns and probably in origin and age, these two features may be now experiencing similar tectonic forces. The change in tectonic regime, as deduced from Ladd's (1976) data, is compatible with the approximate estimate for the time of initial opening of the Cayman trough of about early Eocene, as suggested by Holcombe and others (1973). Both Holcombe and others (1973) and Meyerhoff (1966) concluded that the system acquired its present form by Miocene time.

If slip had occurred between the Caribbean and North American plates along the Cayman trough zone at a rate of about 3 cm/yr (Jordan, 1975) for ~15 m.y., then displacement would be about 300 km. The absence of evidence for large offsets along major fault zones in northern Central America indicates that (1) perhaps the contemporaneous slip rate is higher now than in the past or (2) displacements are distributed across many faults, including Chamelecón, Motagua, Chixoy-Polochic, and less conspicuous breaks in Chiapas, Mexico (Viniegra O., 1971).

Comparable complexities elucidated by Jordan (1975) and Silver and others (1975) are encountered along northern South America. These plate boundaries clearly illustrate the extremely complicated nature of response along these present zones that are formed by the coalescence of former trenches and transforms.

SUMMARY OF THE PROPOSED EVOLUTION OF MIDDLE AMERICA AND THE GULF OF MEXICO-CARIBBEAN SEA REGION DURING THE MESOZOIC ERA

We conclude that, during the Jurassic, as North America split away from Europe, Africa, and South America, Mexico and Middle America were sheared into microplates by three long, left-lateral transform faults: (1) the Mojave-Sonora megashear, (2) the Mexican volcanic-belt paleoshear, and (3) the Acapulco-Guatemala megashear.

Geometric constraints similar to those discussed by Le Pichon and Fox (1971) indicate that shear initially occurred along the Mexican volcanic zone prior to the Late Jurassic. As displacements followed along the Mojave-Sonora megashear, Yucatan, Cuba, and smaller fragments that now may be incorporated into the islands of Hispaniola, Puerto Rico, Virgin Islands, and Désirade migrated toward their present positions, leaving newly formed, Late Jurassic ocean crust in their wakes. Counterclockwise rotation was facilitated along the proto-Motagua zone and along a zone that is probably coincident with the modern Salina Cruz fault. Accumulation of major early Oxfordian salt units in the Gulf Basin was contemporaneous with the arrival of the large blocks to their present positions, which delineate the western and southern segments of the Gulf margin.

Clockwise rotation of South America and the Chortis plate during Early and middle Cretaceous time, which wedged the northern margin of the Jurassic ocean floor in the Caribbean against the previously rifted islands of Cuba, Hispaniola, and Puerto Rico and the southern edge against northern South America, was manifested by circum-Caribbean orogeny.

Abrupt changes in the relative motions between North and South America during Late Cretaceous time resulted in extension and outpourings of basalt upon the Jurassic ocean floor of the Venezuelan Basin, whereas to the west, a transform fault coincident with the Beata Ridge permitted sea-floor spreading that formed the Colombian Basin. The Chortis plate, with its eastern part composed of the Nicaraguan Rise and perhaps Jamaica and southwesternmost Hispaniola, was rotated into its present position during this spreading. Meanwhile, subduction occurred under southeastern Cuba and Cayman Ridge (Perfit and Heezen, 1978), whereas to the east, subduction occurred along a southward-dipping zone on the north side of Puerto Rico and the east side of the Lesser Antilles.

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The opportunity to work in Guatemala and Mexico in cooperation with the Geological Division of the Instituto Geográfico

Nacional of Guatemala, directed by Ign. Oscar Salazar, and with the Instituto de Geología, Universidad Nacional Autónoma de Mexico, formerly directed by Ign. Diego A. Cordoba, permitted Anderson to acquire an overview of the geology that was of fundamental importance in this research.

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