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POST-PALEOZOIC TECTONICS OF NORTHEAST MEXICO AND ITS ROLE IN THE EVOLUTION OF THE GULF OF MEXICO

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RESUMEN

Se muestra la evolución sedimentaria mesozoica del noreste de México a través de varios mapas paleogeográficos regionales. También, con base en diferentes estilos de plegamiento, se propone un modelo alternativo para la deformación del Terciario Temprano del noreste de México, así como una serie de paleorreconstrucciones de tectónica de placas, basados principalmente en la existencia de varias fallas sinistrales de transcurrencia, orientadas al noroeste y una falla dextral transcurrente (Falla Tamaulipas-Oaxaca) orientada al nor-noroeste, a lo largo de la cual el bloque de Yucatán se movió hacia el Sur (Jurásico Tardío) desde su antigua posición en el sitio que hoy ocupa el Golfo de México.

ABSTRACT

The Mesozoic sedimentary evolution of northeastern Mexico is shown by means of several regional paleogeographic maps. Also, on the basis of different styles of folding, an alternative model for the Early Tertiary deformation of northeast Mexico is proposed, as well as a plate tectonics set of paleo-reconstructions, based mainly upon the existence of several NW trending sinistral transcurrent faults and one NNW dextral transcurrent fault (Tamaulipas-Oaxaca Fault), along which the Yucatan block moved southward (Late Jurassic) from its former position at the present site of the Gulf of Mexico.

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INTRODUCTION

The structural trends present in northeastern Mexico are the result of the Early Tertiary (Late Paleocene - Early Eocene) Laramide Orogeny. Their different styles of folding permit one to infer where ancient stable or basinal areas were located. Also based on structural styles, one can distinguish areas of structures due to gravity gliding *(décollements),* diapirism, structures associated with compression and basement shortening, and linear features (lineaments) that often have been interpreted either as crustal fracture zones, megashears, strike-slip faults, or normal faults.

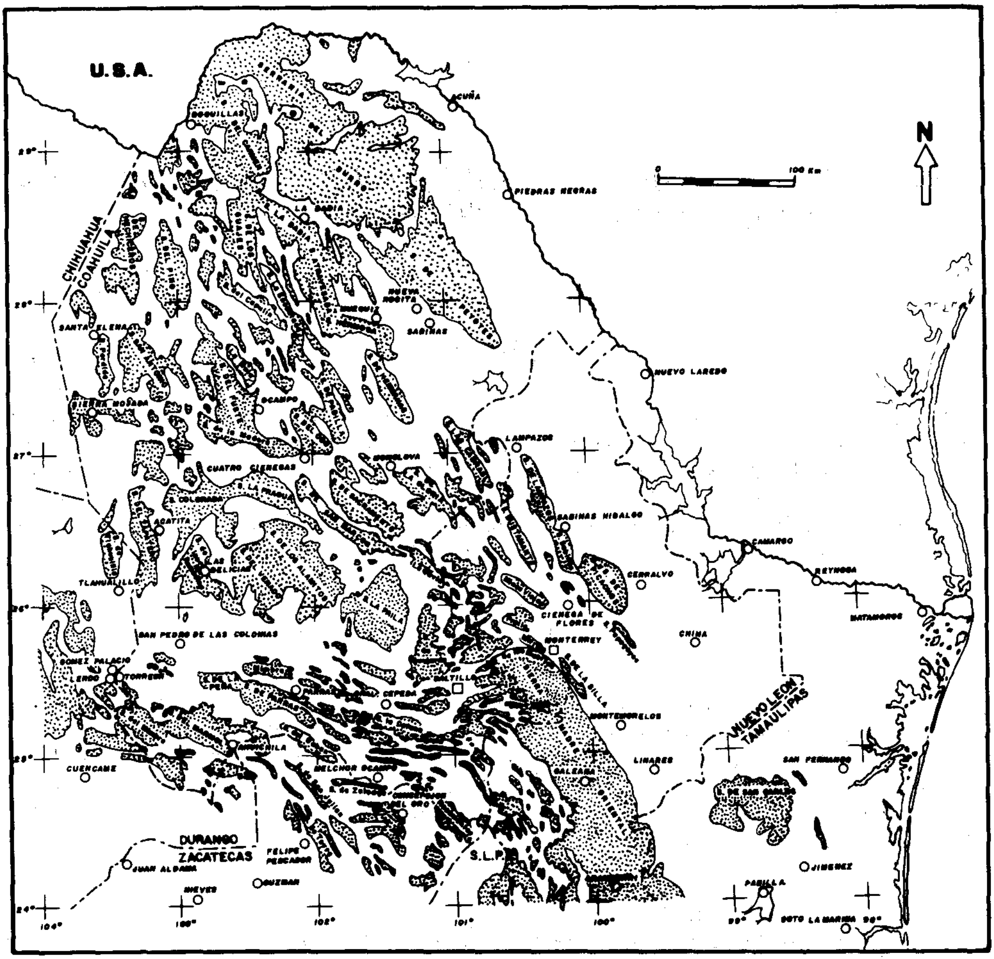


Fig. 1. Physiography of northeastern Mexico.

The principal purpose of this paper is to explain the post-Paleozoic tectonic evolution of northeastern Mexico and its relation with the Mesozoic and Cenozoic development of the Gulf of Mexico. To do so, the following sources have been considered: the information available in the literature, unpublished studies by the writer, the information derived from the interpretation of an ERTS satellite photographic composite map (scale 1:2 000 000, unpublished), LANDSAT images, and a photograph taken by the second mission of the space shuttle COLUMBIA.

The area of this paper includes the states of Coahuila, Nuevo León, and parts of the states of Tamaulipas, San Luis Potosí and Zacatecas. The limits are the Río Grande on the north, the Gulf of Mexico on the east, 24° N parallel on the South, and the 104° W meridian on the west (Fig. 1).

SUMMARY OF MESOZOIC AND CENOZOIC PALEOGEOGRAPHY OF NE MEXICO

Present day geomorphology of northeastern Mexico shows the distribution of different structural patterns that are closely related to the fundamental landforms of early Late Jurassic paleogeography. Since early in this century Böse (1923) suggested that an ancient continental mass, or masses, was present in northeast Mexico. He based his ideas primarily on different structural styles and stratigraphic observations. Later workers continued to determine other paleocontinental areas, also based on distinct structural styles, a large number of lithologic descriptions, and considerable paleontologic data (Kellum *et al.*, 1936; Imlay, 1936, 1937, 1938a; Humphrey, 1956; González, 1976; Charleston, 1971, 1981; Belcher, 1979; López-Ramos, 1980; Moor, 1980). The Mesozoic and Cenozoic paleogeographic history of northeastern Mexico is also closely related to the origin of the Gulf of Mexico (Salvador and Green, 1980), which began opening in the Late Triassic, when the North American plate began to separate from the South American and African plates. The breakup and separation of these plates allowed the formation of grabens and horsts that would determine the distribution of lands and seas, and consequently, the sedimentary patterns of northeast Mexico for the reminder of the Mesozoic and Cenozoic eras (Padilla y Sánchez, 1982).

Because of the regional scope of this paper, and because of the complexity of the stratigraphic nomenclature of northeast Mexico, the use of formational names is here restricted to a minimum in order to make more clear the presentation of the paleogeographic reconstructions (Fig. 2).

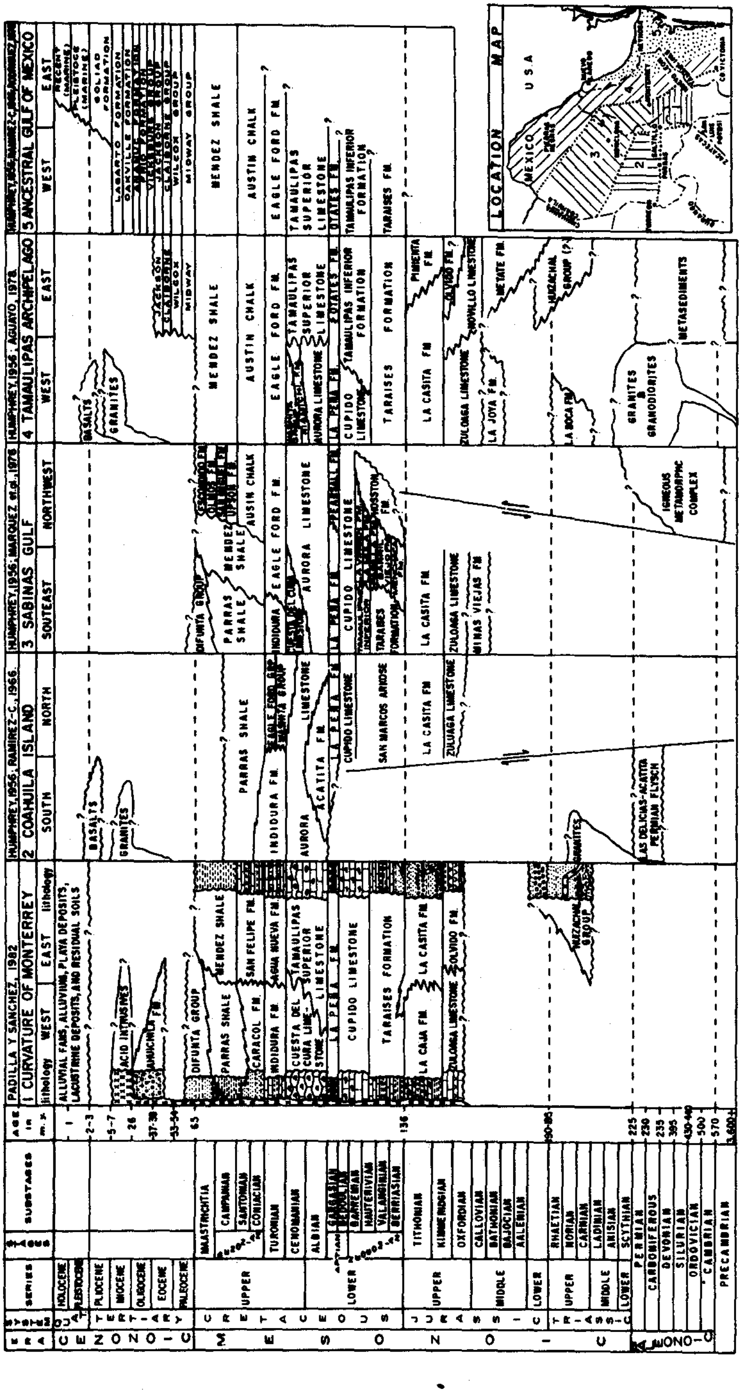


Fig. 2. Generalized stratigraphic sequences of northeast Mexico.

Lower Mesozoic rocks of northeast Mexico rest unconformably over older marine sediments, metasediments, and igneous complexes of uncertain age. Localities where the pre-Mesozoic basement is exposed are limited, and little has been deduced from them about the nature and extent of the Early Mesozoic lands. However, today's known distribution of paleocontinental and basinal areas for the Early Mesozoic has been largely inferred from the sedimentary patterns and structural styles of the later Mesozoic rocks (Fig. 3).

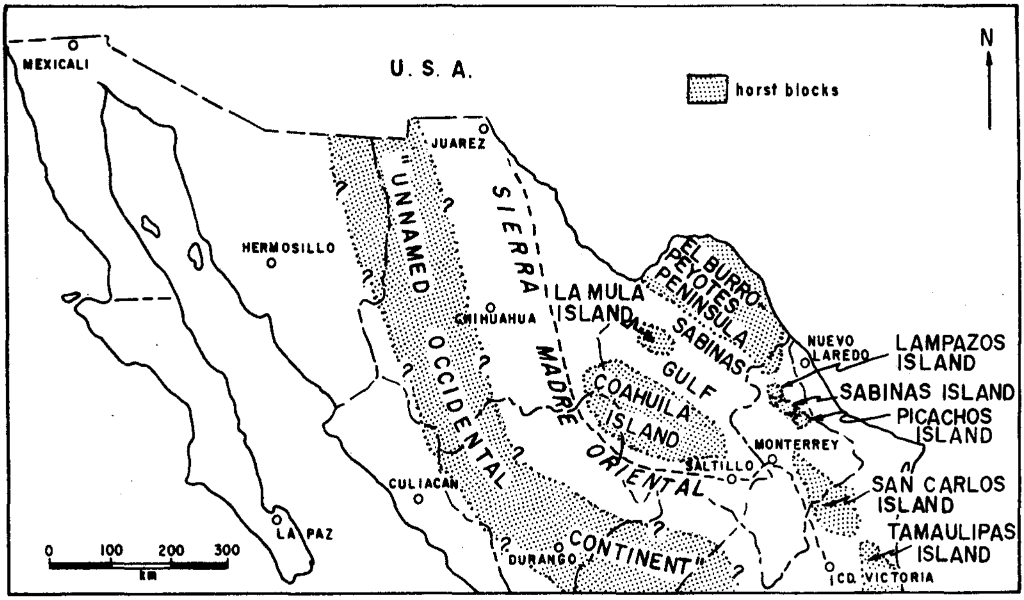


Fig. 3. Major Late Jurassic paleocontinental areas of northwestern Mexico. The Sierra Madre Oriental is a younger feature developed during the Early Tertiary Laramide Orogeny. After Humphrey (1949), González (1976), and López-Ramos (1980).

Late Triassic - Middle Jurassic

The oldest Mesozoic rocks known in the area of this paper are redbeds of uncertain age that are believed to be Late Triassic (López-Ramos, 1980), or Early to Middle Jurassic (González, 1976) (Fig. 4). The best surface exposure of these rocks is located in the Galeana area (Padilla y Sánchez, 1978a, 1982), whereas several subsurface locations are well known in the eastern part of the Tamaulipas Archipelago (Aguayo, 1978). Subcrops of redbeds west of this archipelago are less well defined, but their presence could be expected to the north and west. Farther west, in the

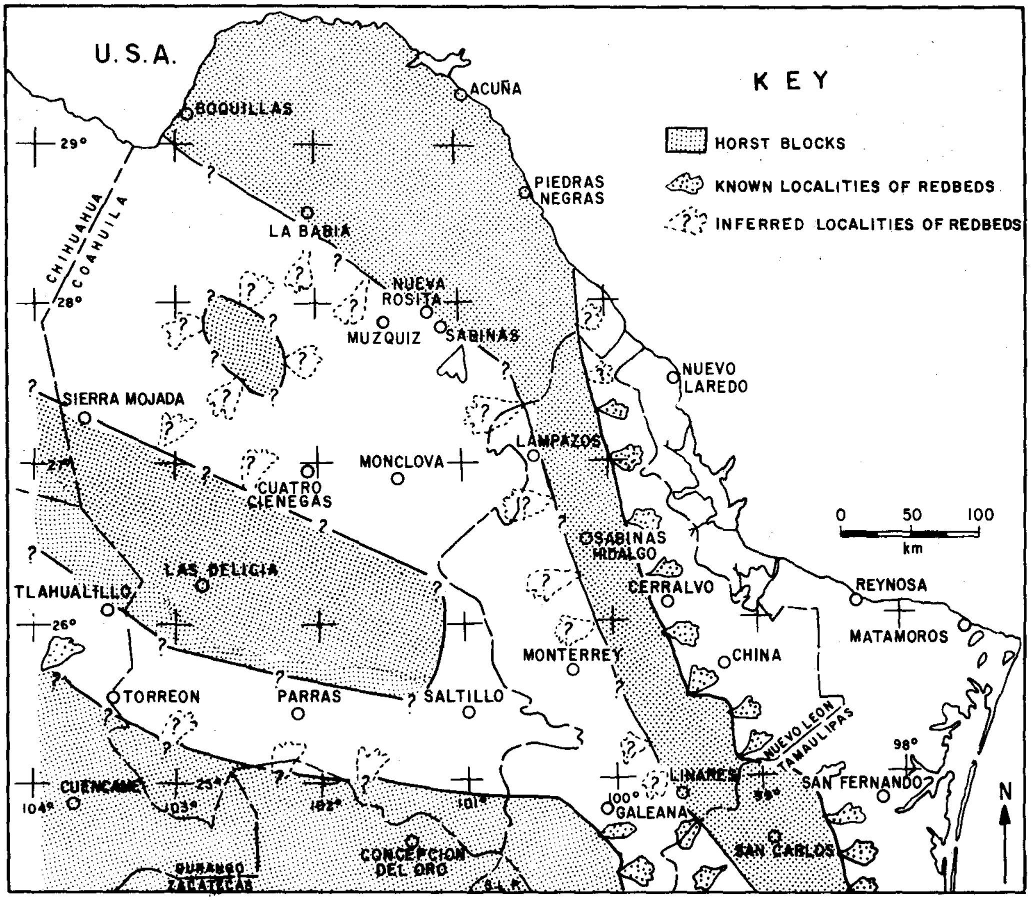


Fig. 4. Late Triassic-Middle Jurassic paleogeography of northeast Mexico.

vicinity of Caopas and Rodeo, Zacatecas, a series of volcaniclastic rocks and conglomerates have been placed as correlatives to the eastern Galeana redbeds (de Cserna, 1956) and to those near Torreón (McLeroy and Clemons, 1965).

The information available about the pre-Late Jurassic redbeds is scanty, as well as the areas of exposure. Little is known about this part of the Mesozoic, except that extensive areas were exposed to conditions of semi-aridity, which could partly explain the absence of fossil remains. However, some poorly preserved fossil plants were found in the Huizachal Valley (off the area of this study) by Mixon *et al.* (1959), which permitted them to separate the Huizachal Group into two formations, La Boca and La Joya, that are considered to be Late Triassic and Early to Middle Jurassic, respectively.

All of these rocks were probably deposited by alluvial fans into grabens, along the edges between the grabens and horsts produced during the Late Triassic by the separation of the North American, African, and South American plates (Salvador and Green, 1980). These rocks had been considered in this paper as Late Triassic-Early Jurassic merely on the basis of their stratigraphic position; little other evidence permits assignment to this age.

Late Jurassic

At the beginning of the Late Jurassic an extensive transgression started in most of northern Mexico and continued until Late Cretaceous. During this time sea-water moved into the graben areas and defined the limits of islands and peninsulas (Fig. 5). Through Late Oxfordian-Early Kimmeridgian terrigenous sediments (La Gloria Fm.) were deposited at the western part of the Sabinas Gulf and along the borders of El Burro-Peyotes Peninsula, La Mula and Coahuila Islands, and the Tamaulipas Archipelago (González, 1976). Shallow-water carbonates (Zuloaga and Novillo Limestones) and evaporites (Olvido and Minas Viejas Formations) were deposited over extensive platforms southward of El Burro-Peyotes Peninsula and the Coahuila Island, and on the eastern part of the Tamaulipas Archipelago. A belt of oolitic banks restricted the water circulation and allowed the deposition of evaporites along the eastern part of the Tamaulipas Archipelago (Aguayo, 1978). It is possible that the oolitic banks between Saltillo and Monterrey caused the restricted circulation of the waters at the Sabinas Gulf, allowing the deposition of evaporites in this area (Padilla y Sánchez, 1982) (Fig. 5).

By the Late Kimmeridgian-Tithonian only El Burro-Peyotes Peninsula and the Coahuila and La Mula Islands were emergent, whereas the Tamaulipas Archipelago was completely covered by the seas by Late Tithonian (Fig. 6). Conglomerate, conglomeratic sandstone, and sandstone bordered the emergent lands, whereas shalier sediments were deposited on the eastern part of the Sabinas Gulf and over the former Tamaulipas Archipelago. All these terrigenous sediments were included by Humphrey (1956) into La Casita Group. Shallow-water carbonate and shale (Pimienta Fm.) were deposited on the eastern part of the Sabinas Gulf and eastward of the former Tamaulipas Archipelago. La Caja Formation south of the Coahuila Island contains phosphatic limestone and shale of an offshore environment.

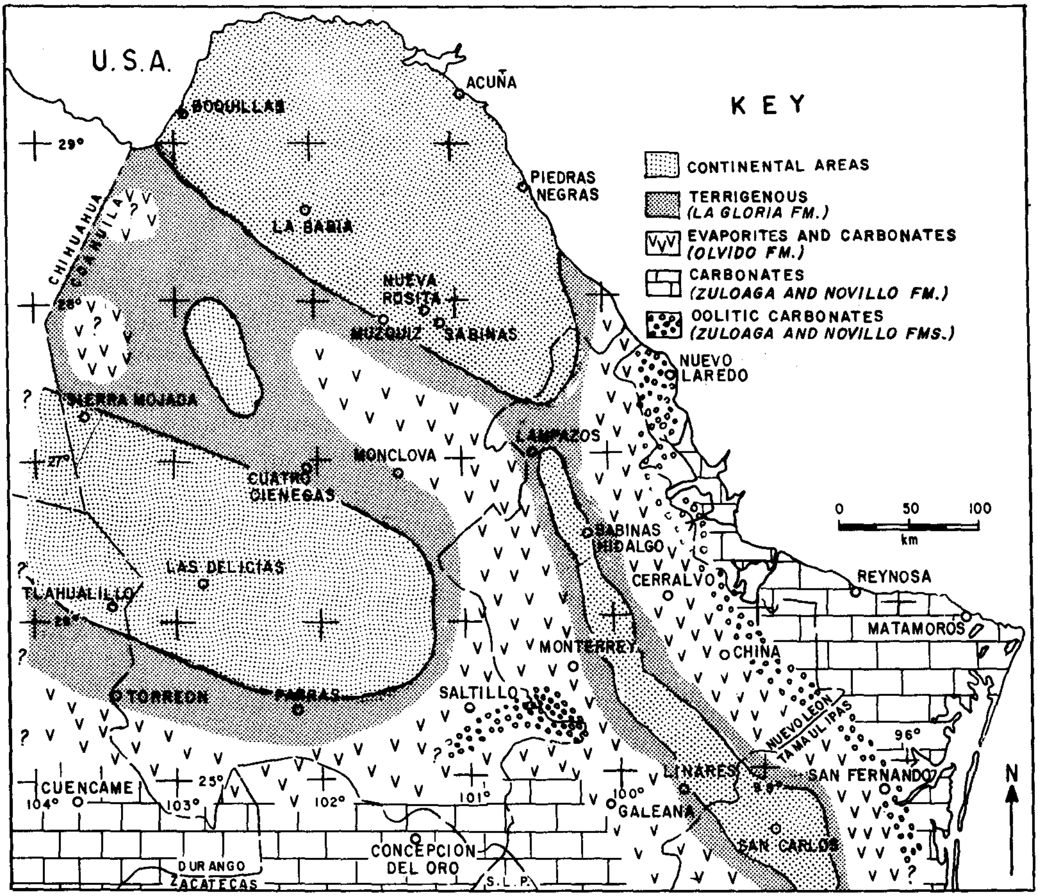


Fig. 5. Late Oxfordian - Early Kimmeridgian paleogeography of northeast Mexico.

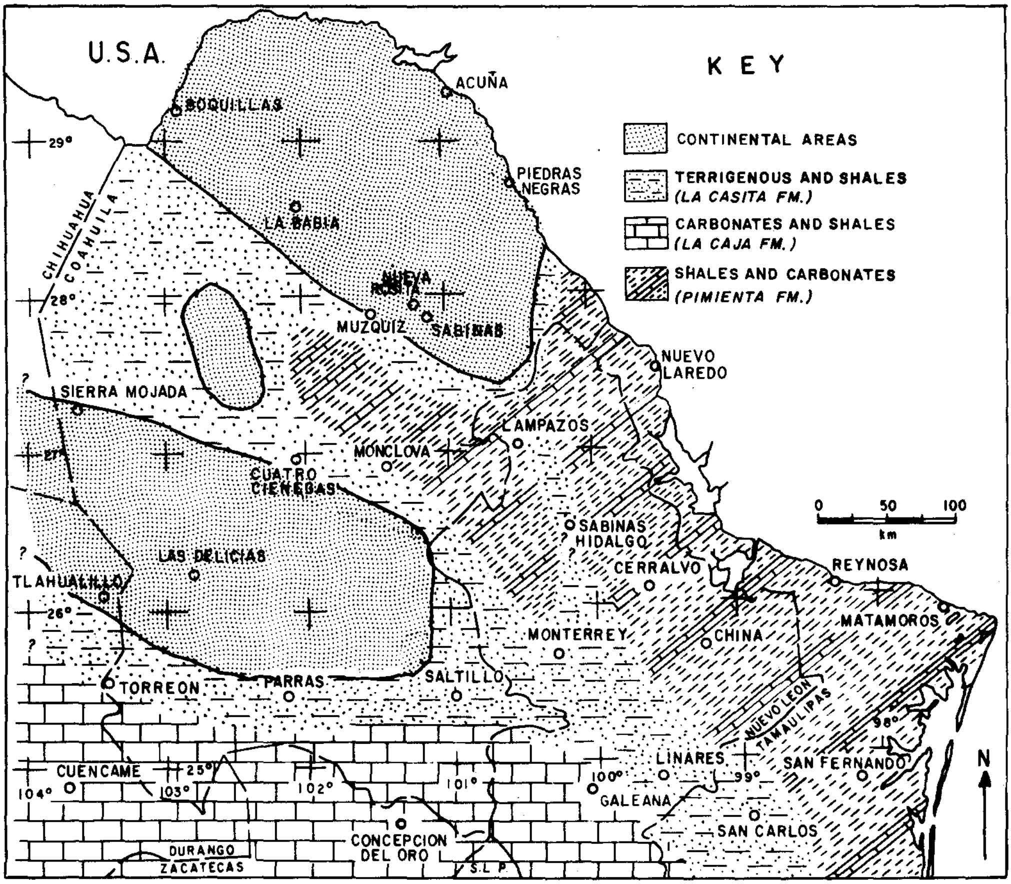


Fig. 6. Late Kimmeridgian - Tithonian paleogeography of northeast Mexico.

Cretaceous

At the beginning of the Cretaceous a monotonously thick sequence of carbonates started to develop, while the subsidence of this area continued and the seas also continued their advance over the lands. The El Burro-Peyotes Peninsula and the Coahuila and La Mula Islands were still emergent, bordered by terrigenous sedimentation (San Marcos Arkose and Hosston Fm.), whereas in the area of the Sabinas Gulf, shale and carbonate (Menchaca Fm.) and limy shale (Barril Viejo Fm.) were deposited. Contemporaneously, a sequence of carbonate with intercalated shale (Taraises

Fm.) was deposited toward the south and east, and farther east-south-eastward beyond the reach of terrigenous clastics a sequence of carbonates with chert nodules (Tamaulipas Inferior Fm.) (Humphrey, 1956) was also deposited during the Berriasian-Valanginian (Fig. 7).

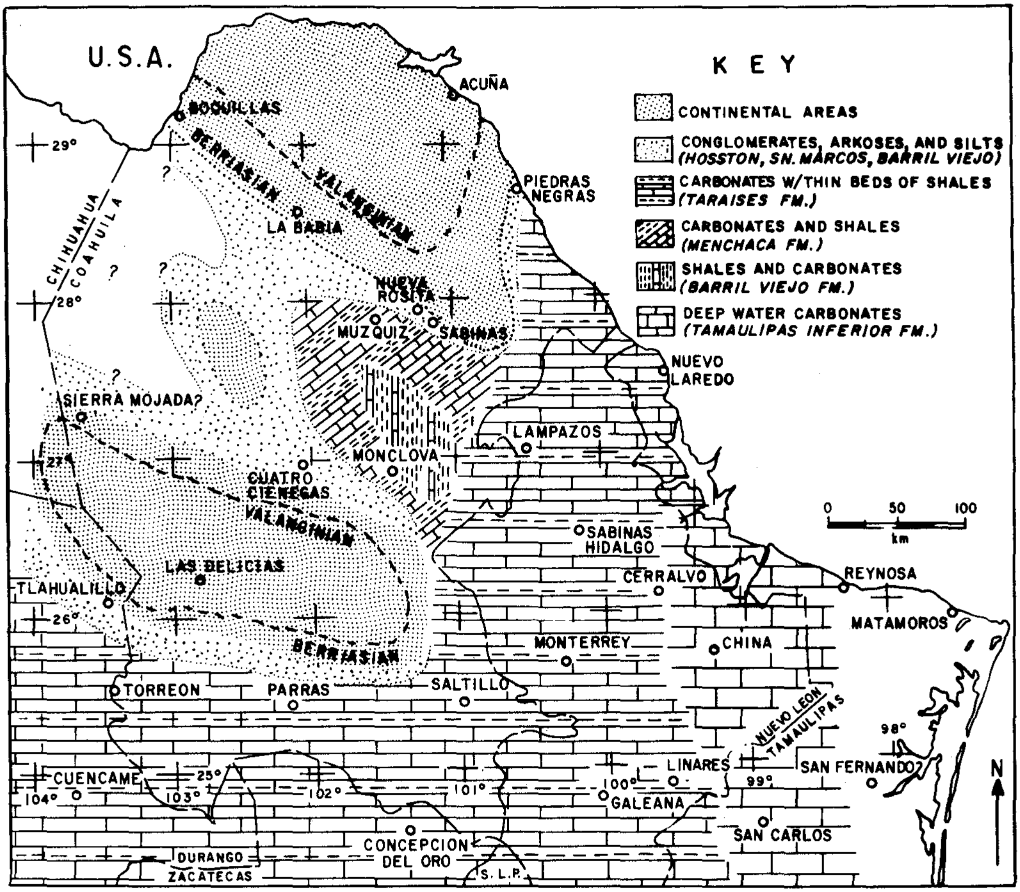


Fig. 7. Berriasian - Valanginian paleogeography of northeast Mexico.

During the Hauterivian to Early Aptian, the emergent El Burro-Peyotes Peninsula and the Coahuila Island continued their influence on the sedimentation, whereas La Mula Island was covered by shale (La Mula Fm.), and later on by carbonates (Padilla Limestone)(Fig. 8). The El Burro-Peyotes Peninsula and the Coahuila Island were still partially emerged, and were bordered by terrigenous (Patula Arkose) and clastics (La Mula Fm.). In most areas of the Sabinas Gulf and southern Coahuila Island an extensive deposit of limestone, shale, and evaporites (La Virgen Fm.) took place behind an almost continuous trend of barrier and patch reefs (Cupido "Reefal Member"), that extended from Nuevo Laredo, Tamaulipas, southward to Monterrey,

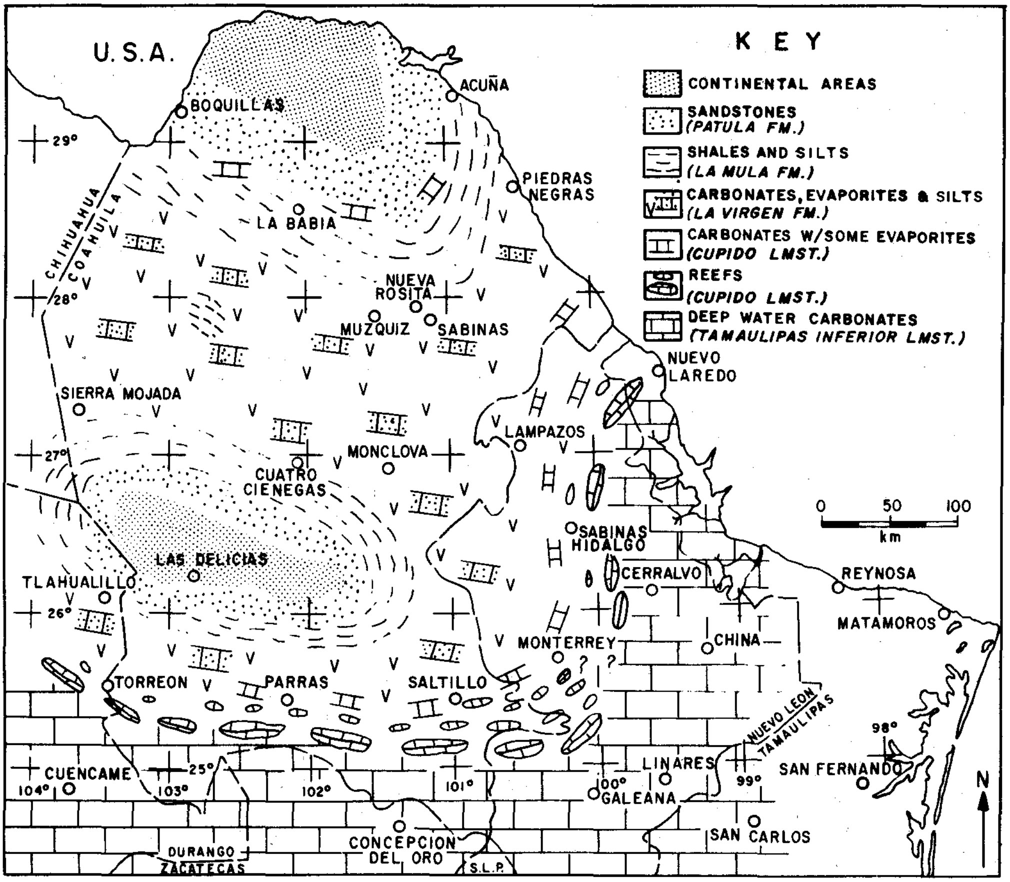


Fig. 8. Late Neocomian paleogeography of northeast Mexico.

Nuevo León, and westward to Torreón, Coahuila (Márquez et al., 1976). Most of these carbonate buildups developed over the site of the buried islands of the Tamaulipas Archipelago (Lampazos, Sabinas, and Picachos Islands), that even when they were covered since the Late Tithonian by marine deposits, still continued a partial influence over the sedimentary patterns to the Early Aptian. A deeper-water carbonate sequence (Tamaulipas Inferior Fm.) continued to be deposited east and southeastward of the mentioned reef trend. It is possible that salt anticlines and diapirs on the eastern part of the Sabinas Gulf allowed the development of reefs during the Early Cretaceous (Humphrey, 1956). However, Stabler and Márquez (1977) have suggested that upwelling shale of the thick shale sequence at the top of the Jurassic (La Casita Group) and the base of the Cretaceous (Menchaca Fm.) could be the cause for local uplifts, where reefs could have developed. By the Late Aptian the entire area was covered by deeper seas and a thin horizon of limestone, shale, and volcaniclastic material (generated somewhere at the west-southwest) was deposited (La Peña and Otates Formations).

During the Early Albian-Late Cenomanian (Fig. 9), the development of reefs was restricted to the borders of the submerged Coahuila Island (Aurora and Paila Formations), and a reef trend was developed westward of Cd. Acuña and Nuevo Laredo,

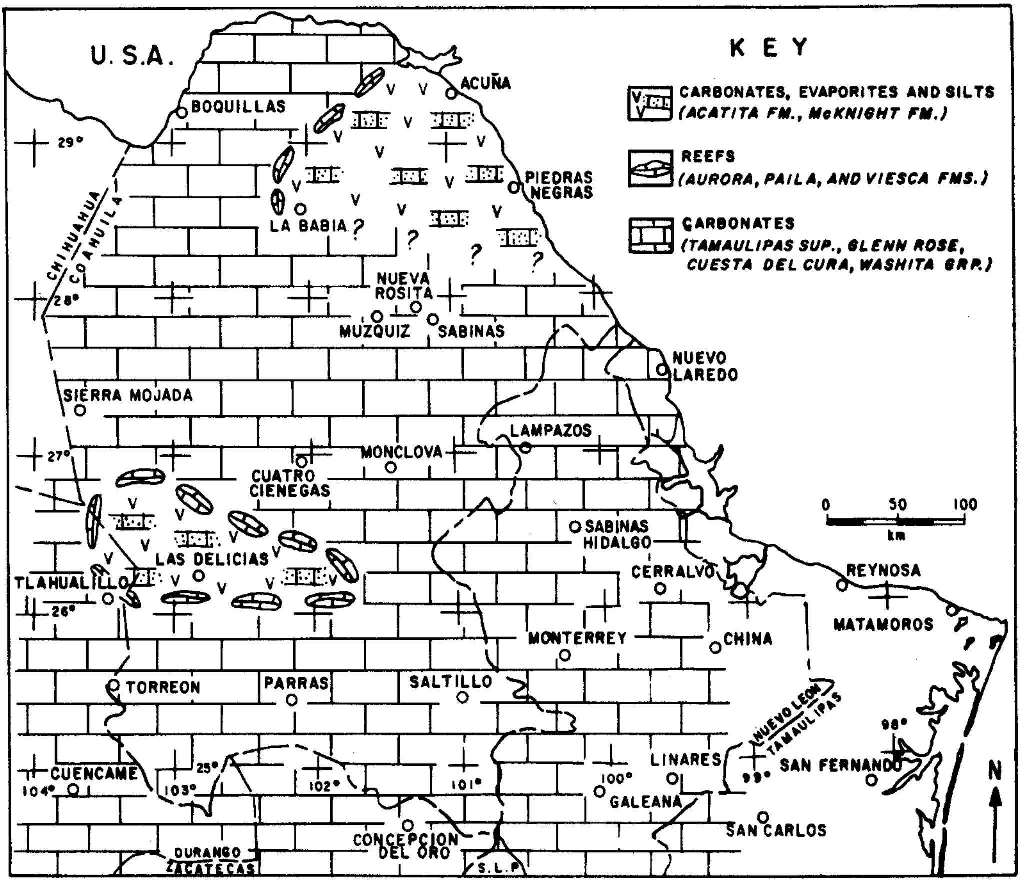


Fig. 9. Albian - Cenomanian paleogeography of northeast Mexico.

over the former El Burro-Peyotes Peninsula. Behind the reef trends, the restricted circulation of the waters allowed the deposit of evaporites (Acatita Fm.) on the former Coahuila Island (González, 1976), whereas in the El Burro-Peyotes Peninsula similar conditions probably existed, but this has not been demonstrated. The rest of northeast Mexico was covered by shallow-water carbonate (Sabinas Gulf) and by deeper-water carbonate with chert nodules (Tamaulipas Superior Limestone) and chert layers (Cuesta del Cura Limestone).

By the Turonian (Fig. 10) the entire area was covered by marine water, but the development of the characteristic thick sequences of carbonates decreased sharply.

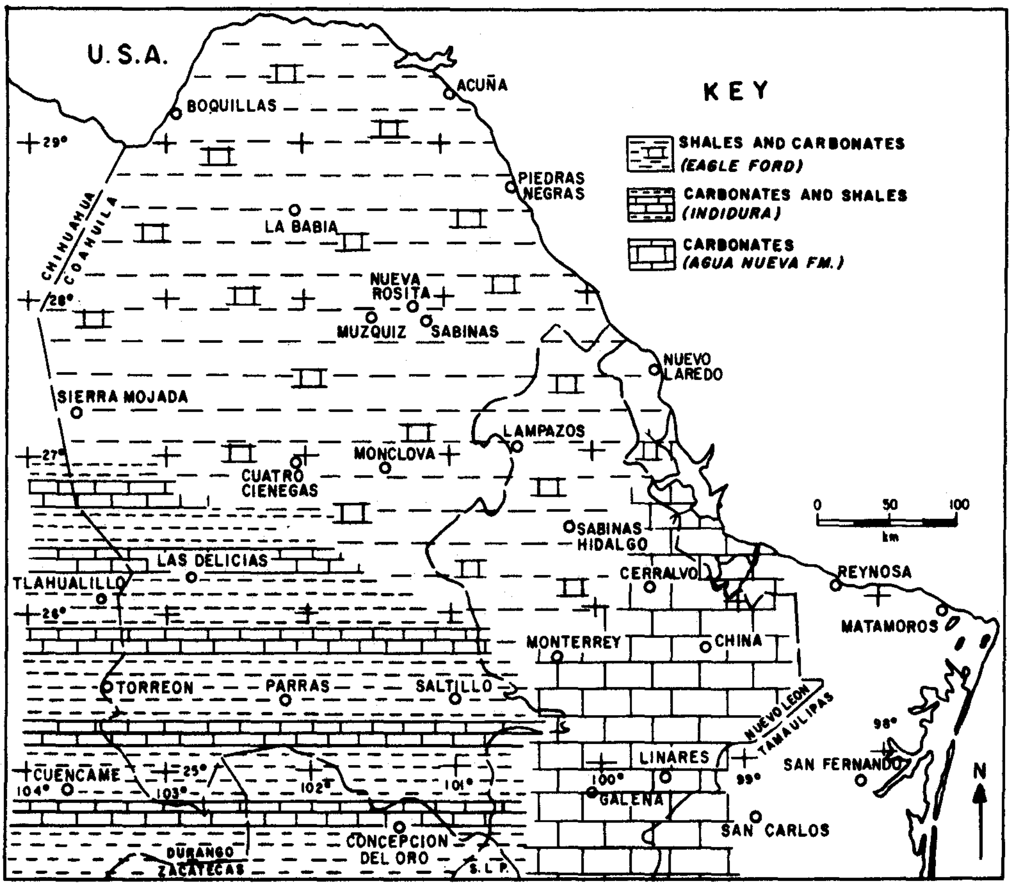


Fig. 10. Turonian paleogeography of northeast Mexico.

In general, a shalier sequence with minor amounts of carbonate was deposited in the northern part of this area covering almost the entire State of Coahuila. López-Ramos (1980) has considered these rocks to be the southward extension of the equivalent Eagle Ford Formation of Texas. Southward, a thin sequence of carbonate and shale (Indidura Fm.) was deposited, while eastward, a carbonate sequence (Agua Nueva Fm.) was also deposited.

During the Coniacian to the Santonian the sedimentary pattern had change slightly (Fig. 11). Most of the northern part of this area was covered by shallow-water carbonate and shale, which have been considered as equivalent to the Austin Group (López-Ramos, 1980), whereas the southern part was covered by sandstone and

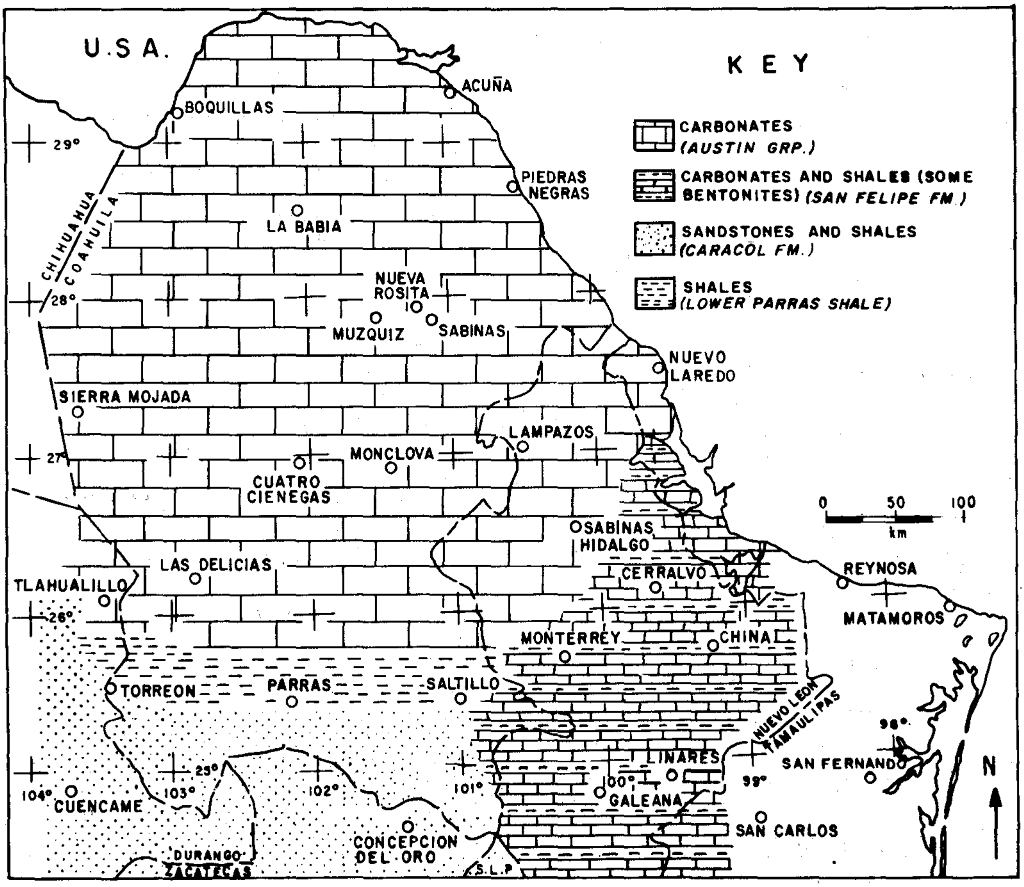


Fig. 11. Coniacian - Santonian paleogeography of northeast Mexico.

shale (Caracol Fm.), and between Torreón and Monterrey, the deposition of shalier sediments (lower Parras Shale) took place (Padilla y Sánchez, 1982). Eastward, the deposition of a thicker sequence of thinly-bedded carbonate and shale with bentonite horizons (San Felipe Fm.) covered an extensive area.

By the Late Cretaceous, Campanian to Maastrichtian, the entire area was covered by terrigenous and clastic sediments originated by fluvial streams that flowed from the west, which allowed the development of extensive coal deposits (Sabinas Coal "Basin"). The foredeep Parras Basin was half-filled by the Parras Shale during the Campanian and completely filled by the Difunta Group by Late Maastrichtian time (Padilla y Sánchez, 1978a, 1982) (Fig. 12).

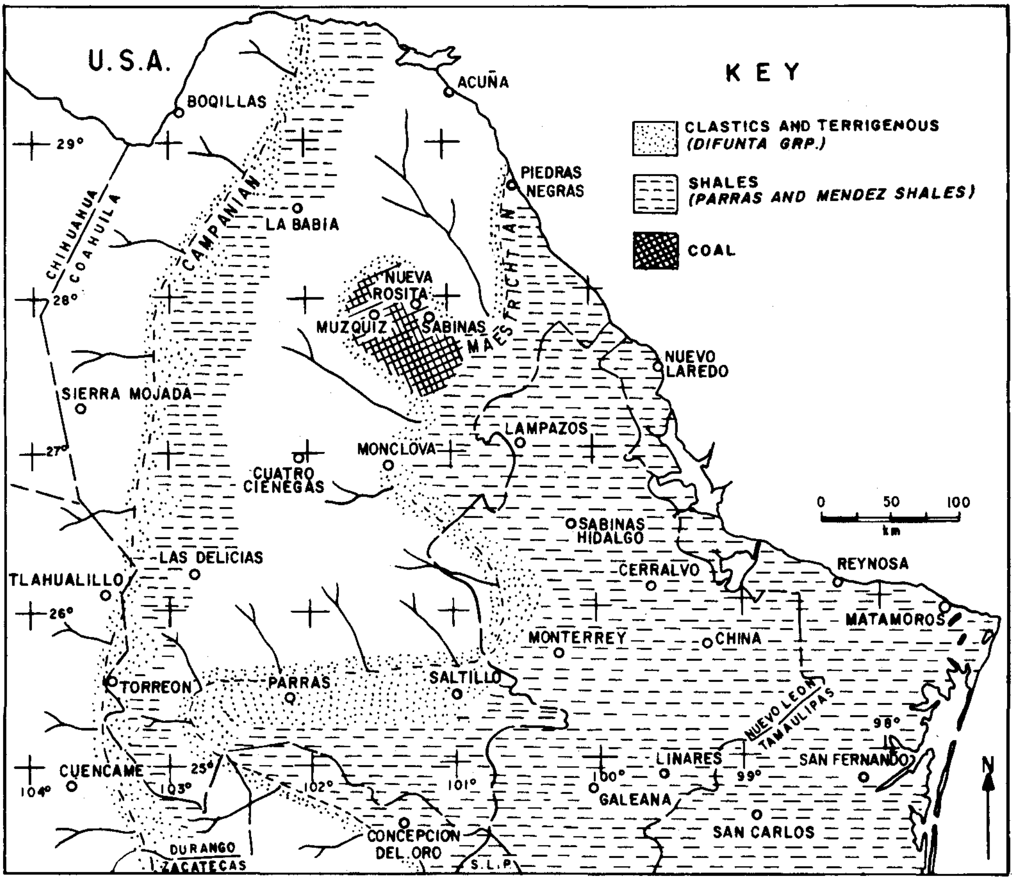


Fig. 12. Campanian - Maastrichtian paleogeography of northeast Mexico.

Tertiary

Early in the Tertiary the Mesozoic sequence deposited in northeast Mexico was deformed by the Laramide Orogeny, and the Cenozoic seas retreated eastward, leaving behind them a thick sequence of sandstone and shale (Fig. 13). The Tertiary Burgos Basin was formed after the Laramide and is considered to be the southern continuation of the Rio Grande Embayment. This basin then started to be filled with terrigenous and clastic sediments of the Midway and Wilcox Groups (Paleocene-Early Eocene), deposited in a complex system of barrier bars and deltas which allowed the development of thick sequences of shale and sand. This bar-deltaic complex prograded eastward through the entire Cenozoic era, thus favoring the development of numerous growth faults that formed favorable traps for the accumulation of gas (Echánove, 1976).

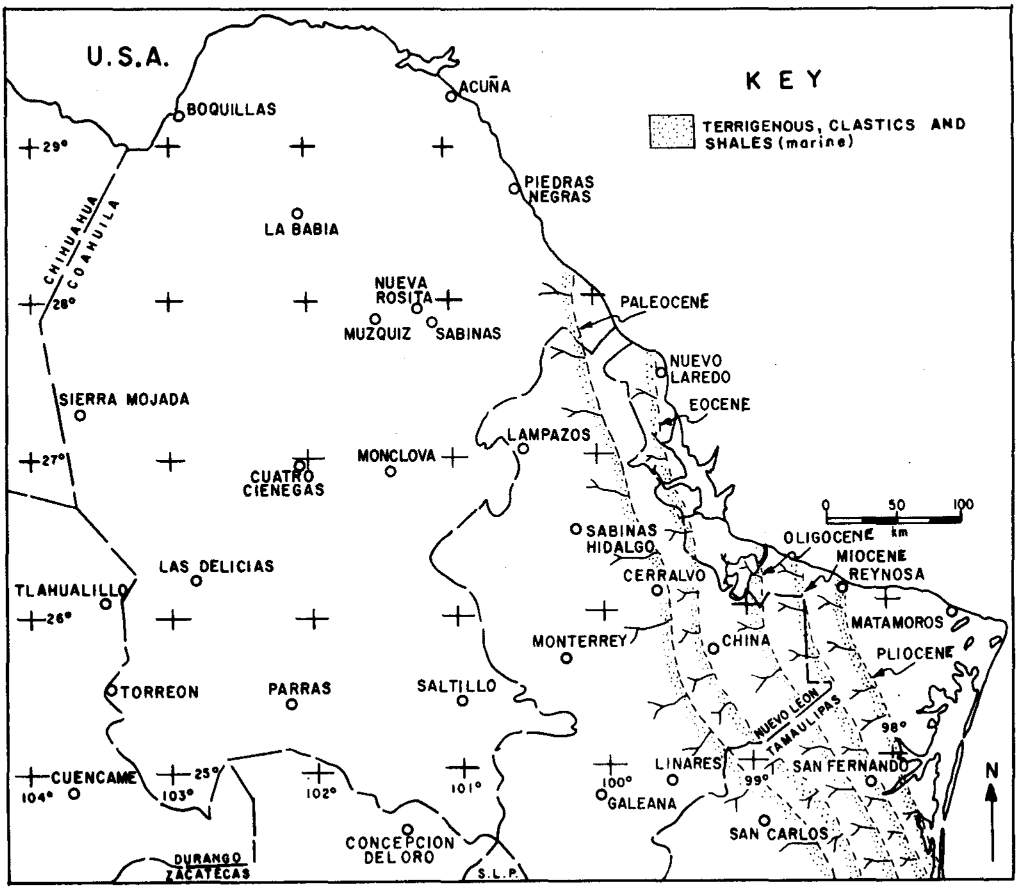


Fig. 13. Tertiary paleogeography of northeast Mexico.

TECTONICS AND STYLES OF FOLDING IN NORTHEAST MEXICO

Present day geomorphology of northeast Mexico represents the distribution of different structural patterns that are closely related to the fundamental landforms of early Late Jurassic paleogeography. Thus, from the observation of satellite photographs one can distinguish several groups of mountains that directly correlate with areas of different styles of folding and with ancient landmasses, as well as large-scale linear features that coincide with the boundaries of known Late Jurassic continental areas (Figs. 14 and 15). In the following pages the correlation between different styles of folding and paleogeographic elements is analyzed. In order to explain the

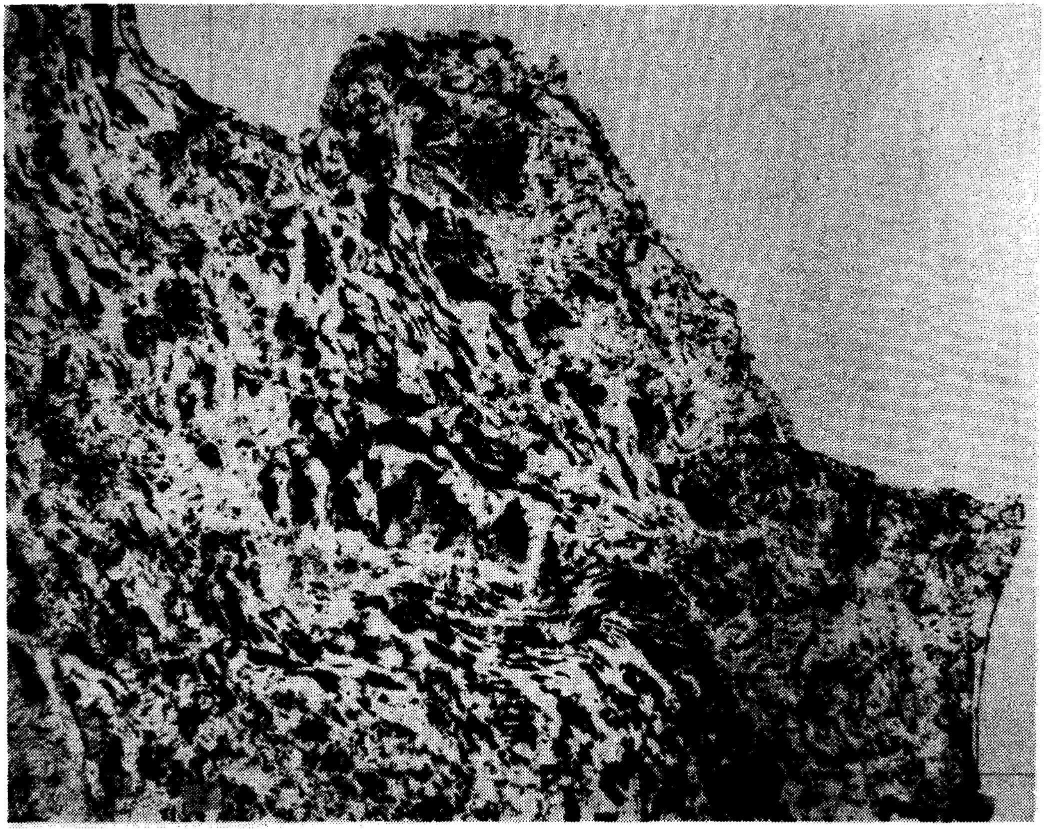


Fig. 14. ERTS photographic composite map of northeast Mexico. The original photographs were over-contrasted in order to emphasize the structures.

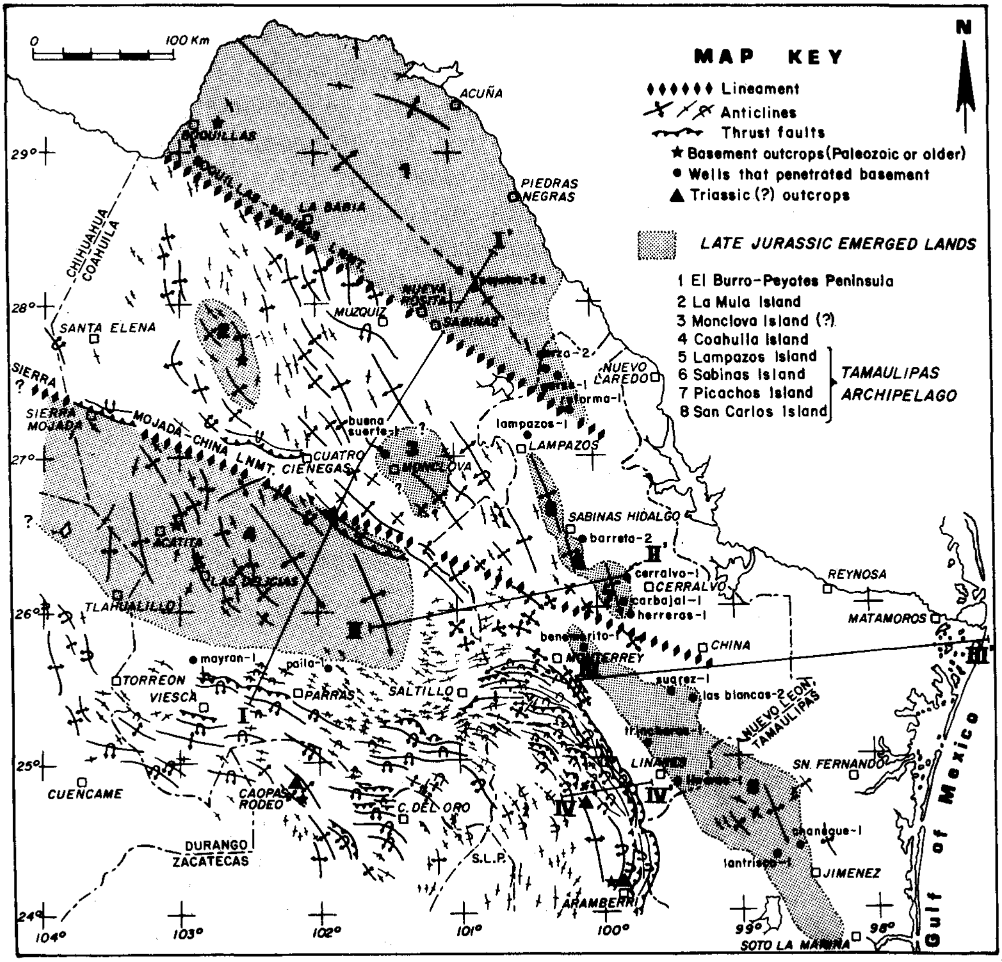


Fig. 15. Structural map of northeast Mexico showing the approximate location of Late Jurassic continental areas. The location of wells is approximate. The lines of sections shown in this map correspond to those of Figure 17.

structural and tectonic evolution of northeast Mexico since the beginning of the Mesozoic, the area of this study has been divided according to structural styles into two major groups; structures over ancient continental areas, and structures developed on ancient basinal areas.

A. *Areas of basement highs (horsts)*

Today in northeast Mexico five blocks of ancient continental areas have been recognized (Fig. 15), which are named here El Burro-Peyotes Peninsula, La Mula, Monclova, and Coahuila Islands, and the Tamaulipas Archipelago, which is formed by the Lampazos, Sabinas, Picachos, and San Carlos islands. These areas were covered by marine water at different times during the Mesozoic, but they continued to influence sedimentary patterns and structural styles until the Tertiary. The structures over these areas are broad, often breached, and symmetric anticlines, called by some Mexican geologists "Tortugones", that contrast sharply with the tighter folds of basinal areas (Figs. 14 and 15).

1) *El Burro-Peyotes Peninsula*

This peninsula is limited to the south by the Boquillas-Sabinas Lineament, which will be described latter, and may be the southern continuation of the Solitario and Marathon areas (Flawn *et al.*, 1961; González, 1976). Its eastern and southeastern limits are less well defined, but subsurface information has shown that its southeastern end is located somewhere near the well Reforma - 1 (Fig. 15), and it is separated from the Lampazos Island by what has been called the "Portal de Anáhuac" (Alfonso, 1976).

The oldest rocks known in this area (Sierra del Carmen) are Paleozoic (Flawn *et al.*, 1961), and possibly Precambrian (Garrison *et al.*, 1980) (Fig. 16); they are overlain by Lower Cretaceous (Albien) rocks of the Glen Rose Limestone, whereas in the well Peyotes - 2A Berriasian rocks unconformably overlie gneisses and quartzites (González, 1976). In contrast, redbeds (Triassic?) and Upper Jurassic Limestone and terrigenous rocks have been reported in the Potrero de Oballos, located in the Sierra de Las Hermanas (Humphrey, 1956).

El Burro-Peyotes Peninsula was progressively covered by Cretaceous seas and entirely submerged by the Maastrichtian. This peninsula was considered by Humphrey (1956) as the northwestern part of what he termed the "Tamaulipas Peninsula".

The most important structures over this paleopeninsula are the anticlines of El Burro, Peyotes, and El Carmen (Figs. 1 and 15). These folds are broad anticlines, of which, El Carmen is the smallest. El Burro and Peyotes are large folds that appear to

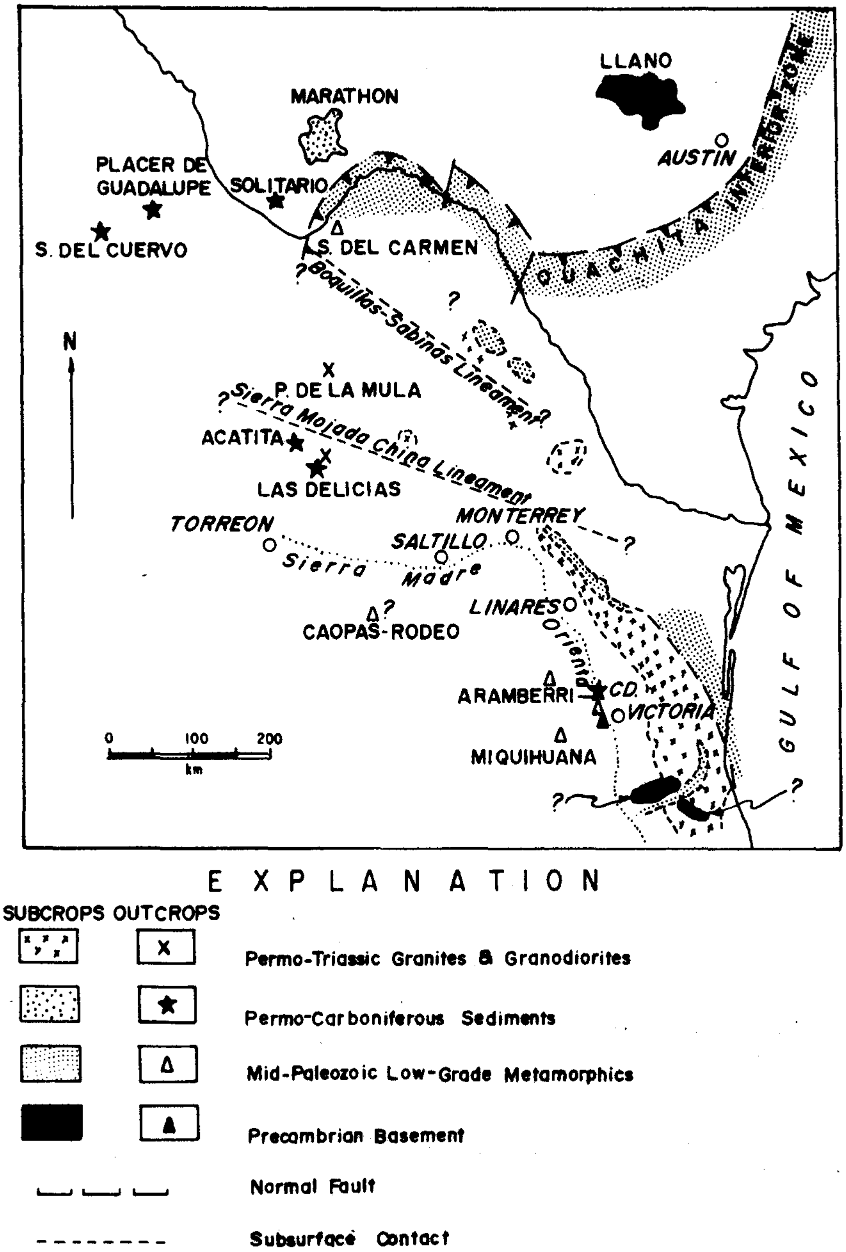


Fig. 16. Generalized geologic map of southern United States and northeast Mexico showing the surface and subsurface occurrences of pre-Mesozoic rocks. Modified from Garrison *et al.* (1980), after Flawn *et al.* (1961), López-Ramos (1972), and unpublished sources.

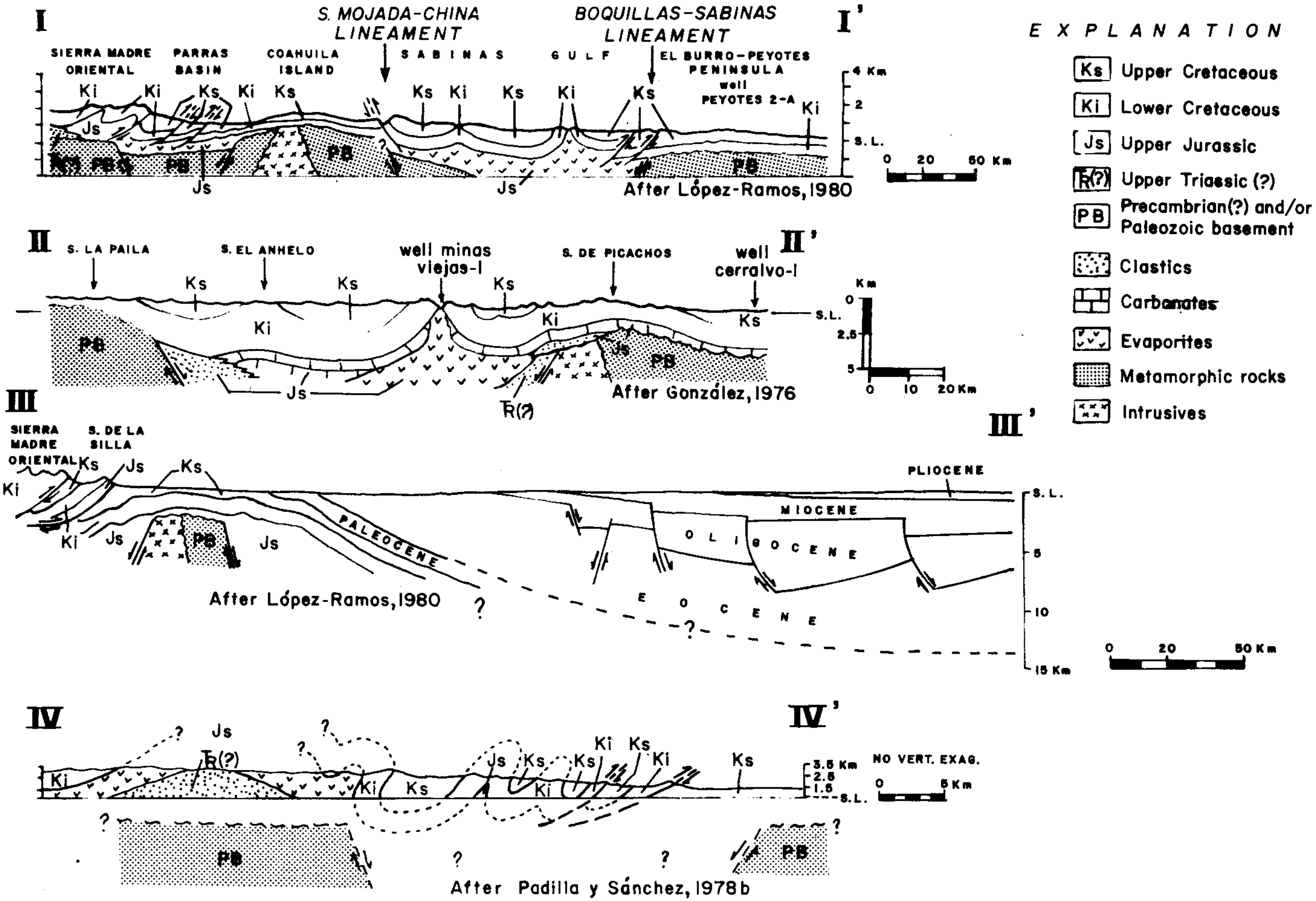


Fig. 17. Schematic cross-sections showing the different styles of folding in northeast Mexico. All four cross-sections have been slightly modified by the writer, but their vertical and horizontal scales are the same used in the original sources. For location of sections see Figure 15.

be the northwestern continuation of the Salado Arch of Murray (1959). These anticlines contrast sharply with the tighter structures of the Sabinas Gulf to the south, as is shown in section I-I' of Fig. 17.

2) *La Mula Island*

This basement high was first considered by Kellum *et al.*, (1936) as the western limit of the Sabinas Gulf, and as part of the so-called "Coahuila Peninsula". It is uncertain who was the first to postulate this island, but it is probable that the original definition is in some unpublished report in the files of Petróleos Mexicanos. However, Alfonso (1976) claims to be the one who first postulated this island in the unpublished report (1968) NE-M-1089 of PEMEX.

Nevertheless, it is very interesting to speculate if the boundaries of this island can be deduced from the shape of the folds that cover it, because there is no accurate information in the literature about its limits. From the observation of satellite photographs it can be seen that there are three large amplitude anticlines, apparently symmetric, that correspond to the Sierra de La Mula and to the Sierra del Fuste (Figs. 1, 14 and 15). On the basis of these data and knowing that in the Potrero de La Mula granitic Early Mesozoic rocks underlie the Padilla Limestone (Humphrey, 1956), the boundaries of La Mula Island were sketched (Fig. 15). This island was emergent during the Late Jurassic and was covered by marine water during the Hauterivian (Alfonso, 1976).

3) *Monclova Island* (?)

It is unknown who first described this island and when, but it is mentioned frequently in recent publications (Márquez *et al.*, 1976; González, 1976; Alfonso, 1976). Its boundaries are unknown and they were sketched in Fig. 15 only on the basis of the information presented by the above authors. According to them this island was emergent from the Berriasian until the very beginning of the Hauterivian, when it was covered by the Padilla Limestone. No other information is available, but it is possible that this "island" (?) could be related to diapiric mobilization (piercement folds) of Jurassic evaporites in the Sabinas Gulf. If this is the case, then it should not be interpreted as a basement high, as has been done by Alfonso (1976, p. 147, Fig. 17).

4) *Coahuila Island*

This paleogeographic unit was first described by Kellum *et al.* (1936) as the "Coahuila Peninsula", a Late Jurassic continental area that was believed to extend northward from the Acatita-Las Delicias-Paila-San Marcos area to connect with El Burro-Peyotes Peninsula, including La Mula Island. But recent subsurface data and studies done by PEMEX's geologists (Márquez *et al.*, 1976) have shown that this area was emergent since the Late Jurassic, and that it was an island, at least, since the very beginning of the Cretaceous (Berriasian), but possibly also during the Late Jurassic, until it was finally covered by marine water during the Late Aptian. However, it is still unclear whether this landmass was a peninsula or an island during the Late Jurassic (González, 1976), but it seems probable that it was an island (Alfonso, 1976), and that the Sabinas Gulf was a sea connected with the Chihuahua Mesozoic Trough. Smith (1970) first suggested the possibility of an island in the southern part of the "Coahuila Peninsula" for the Late Aptian, but stated that his interpretation was only a guess, because no subsurface data were available in the literature by that time.

Northward of the cities of Torreón and Saltillo there is a group of large amplitude structures very different from the tighter structures that form the ranges of the Sierra Madre Oriental (Figs. 14 and 15). This is where the approximate southern limit of the Coahuila Island has been placed (González, 1976). The northern limit of this island is determined by a very linear feature that seems to continue southeastwardly, passing between the San Carlos and the Picachos Islands (Fig. 15) and disappearing in the surroundings of China, Nuevo León. This linear feature has been named Sierra Mojada - China Lineament (Padilla y Sánchez, 1982), and will be discussed later in this paper. The western limit of this island is uncertain but it possibly is located somewhere west of Tlahualillo and Sierra Mojada.

The structures over the Coahuila Island are broad anticlines that trend generally northwestward. The most important are La Paila, Alamitos, El Venado, Los Remedios, El Zapatero, and Tlahualillo (Figs. 1 and 15), which are relatively simple and symmetric folds (Fig. 17, sections I-I' and II-II').

5. *Tamaulipas Archipelago*

This archipelago was first postulated as a paleogeographic element by Alvarez (1958), but it was not until the last decade that its existence was demonstrated by wells that penetrated Paleozoic rocks, as for example the Lampazos-1, Barreta-2, Cerralvo-1, Carbajal-1, Herreras-1, Benemérito-1, Suárez-1, Las Blancas-2A, Trincheras-1, Linares-1, Chaneque-1, Lantrisco-1, and several others (Fig. 15). All wells that penetrated Paleozoic metasediments are located on the eastern side of the Tamaulipas Archipelago (Fig. 15), which makes one wonder whether these metasediments are similar to the interior zone of the Ouachita System. On the other hand, all the wells drilled in the western part of these islands penetrated granitic rocks that had radiometric ages that vary from 138±9 to 234 m.y. (Rivera-J., 1976).

The Tamaulipas Archipelago was considered by Humphrey (1956) to form a continuous continental mass during the Late Jurassic which bordered the western part of the ancestral Gulf of Mexico. He named this land "Tamaulipas Peninsula", whereas other authors called it "Tamaulipas Platform" (López-Ramos, 1980), as well as "Tamaulipas Arch" for its southern end (Murray, 1959).

The Tamaulipas Archipelago includes, from northwest to southeast, the Lampazos*, Sabinas*, Picachos*, and San Carlos islands (Fig. 15). It is bounded to the north by the "Portal de Anáhuac" (a depression between the El Burro-Peyotes Peninsula and the Lampazos Island), to the east by the Gulf Coastal Plain, and to the south by the Soto la Marina River. However, the southern end of this archipelago is located in the Tampico region (Tamaulipas Island), southward of the area of this paper.

Each island of this archipelago is characterized by broad anticlines that at the surface form low-relief, elongate mountains (Fig. 17, section II-II'), but the San Carlos Island has been complicated by Miocene (?) granitic (?) intrusions at its southern end (López-Ramos, 1980).

Marine water covered this archipelago during the Late Jurassic (Aguayo, 1978), and it continued to subside through the entire Cretaceous until it was deformed and uplifted by the Laramide Orogeny.

B. *Areas of basement lows*

Since the beginning of the Mesozoic Era the continental blocks described before, controlled the deposition of redbeds (Late Triassic?); evaporites, carbonates, and ter-

* In this study the Lampazos, Sabinas, and Picachos islands are considered to be isolated positive areas, but they possibly once formed (in the Late Triassic) a continuous block.

rigenous rocks (Late Jurassic); thick sequences of carbonates, clastics, and evaporites (Early Cretaceous); and mainly terrigenous and clastics (Late Cretaceous), over extensive shallow-water platforms, and in some areas deeper basins. All these sedimentary rocks were folded later during the Laramide Orogeny (Late Paleocene-Early Eocene), and are characterized by very tight folds, sometimes overturned and thrust-faulted, and sometimes diapiric. One can distinguish three areas of different styles of folding: the Sabinas Gulf, the Sierra Madre Oriental, and the Foredeep Parras Basin (Figs. 3, 14, and 15).

1. *Sabinas Gulf*

This region of northeast Mexico was defined by Humphrey (1956) as the Sabinas Gulf, which he considered to coincide with the geomorphologic province of the Coahuila Ridges and Basins. In this paper the name Sabinas Gulf is assigned to the same region, but its area and boundaries have been modified. The Sabinas Gulf is limited to the north by El Burro-Peyotes Peninsula to the east by the Tamaulipas Archipelago; to the south by the front ranges of the Sierra Madre Oriental and the Coahuila Island; and to the west by the Chihuahua trough (Fig. 3). Its western limit is uncertain because of the presence of Middle Tertiary Plutonic rocks, and Late Tertiary - Early Quaternary volcanic rocks.

The structures at the Sabinas Gulf are large, elongate, tight, *en échelon* folds, often breached, that can be easily differentiated from those structures over the more stable paleocontinental areas (Figs. 14 and 15). However, toward the boundaries with these stable areas, the folds are often overturned and thrust-faulted with a vergence toward the more stable paleoelements, as is the case of the Sierra Hermosa, Sierra Mojada, Sierra de la Fragua, and Sierra de San Marcos (Figs. 1, 15, and 17, section I-I'). Toward its southern end there is a distinct area where the folds are dome-like, an area that had been considered by Wall *et al.* (1961) to be the result of diapirism of Upper Jurassic evaporites in the Sierra de Minas Viejas and Sierra del Fraile (Fig. 17, section II-II').

2) *Sierra Madre Oriental*

The Sierra Madre Oriental is that area of northeast Mexico that has the highest relief of this region. Relative relief between low hills and peaks is on the order of 800 to 1 900 m. It occupies the southern part of the area of this paper and is limited to the east by the Tamaulipas Archipelago and to the north by the foredeep Parras Basin (Figs. 3 and 15). It was considered by Humphrey (1956) as the "Mexican Geosyncline", but this term is no longer used.

The oldest rocks known in this area are Paleozoic rocks at Caopas-Rodeo and Aramberri, Upper Triassic (?) redbeds at Galeana and Aramberri, and Upper Triassic (?) metavolcanics and sediments at Caopas - Rodeo (Fig. 15). Covering these rocks there are evaporites, terrigenous, clastic, and carbonate rocks (Upper Jurassic); carbonate rocks (Lower Cretaceous); and terrigenous and clastic rocks (Upper Cretaceous).

The structures of this region are very distinct from those of the rest of the area. They are characterized by very tight overturned folds, sometimes isoclinal, which often are thrust-faulted. Its eastern limit is a large thrust fault that extends from Aramberri to Monterrey, where the mountain belt curves sharply westward and southwestward to the vicinity of Saltillo. There, the ranges trend westward to the city of Torreón, where they curve again northwestward into the State of Chihuahua (Fig. 15). An example of the style of folding in the Sierra Madre Oriental is shown in Fig. 17, section IV-IV'.

3) *Foredeep Parras Basin*

This basin is located between the cities of Torreón, Saltillo, and Monterrey. It is limited to the north by the Coahuila Peninsula, to the west, south, and southeast by the front ranges of the Sierra Madre Oriental, and to the northeast by the Sabinas Gulf (Figs. 3 and 15). The structures in this basin are easily differentiated from those of other areas, and have been divided by Weidie (1961) into three zones of different structural styles; an area of mild deformation to the northeast, a zone of greater deformation in the southeast, and an area of intensely deformed strata in the narrow western part of the basin.

The structures in this basin are the result of Laramide stresses over Upper Cretaceous deltaic sediments of the Difunta Group, which has a thickness that varies from 1 000 to 3 500 m (González, 1976). Subsurface data obtained from the wells Paila-1A and Mayrán-1, have shown that the Difunta sandstones and shales are underlain by a thin sequence of Lower Cretaceous carbonates and terrigenous rocks, that have a combined thickness of no more than 500 m (Fig. 17, section I-I') (López-Ramos, 1980).

C. *Lineaments*

There are several linear features in northeastern Mexico, from which two are the most prominent because of their regional extent, and because they coincide and define the boundaries of major paleocontinental areas. These two lineaments are the Boquillas-Sabinas and the Sierra Mojada-China (Figs. 14 and 15).

1) *Boquillas - Sabinas Lineament*

The Boquillas-Sabinas Lineament is defined here as that linear feature observable on satellite photographs in northeastern Mexico that trends S 55° E from the vicinity of the town of Boquillas, Coahuila, passing near Sabinas, Coahuila, and becoming unrecognizable southeastward, in the vicinity of Lampazos, Nuevo León. It has a width of about 10 km, and it coincides with the sharp structural discontinuity present between the tight folds of the Sabinas Gulf and the broad, gentle folds of the El Burro-Peyotes Peninsula (Fig. 15). It is also the southern boundary of the Texas Lineament of Muehlberger (1965, 1980).

The Boquillas-Sabinas Lineament has been previously described by Tardy (1980) as the northern limit of what he called the *"décollement du bassin de Sabinas"**, and parallel to the Texas Lineament and to the "Caltam Lineament"*. This structure has been also called the "Babia Lineament" by Charleston (1981).

Whether the Boquillas-Sabinas Lineament represents a strike-split fault, a normal fault, or a crustal discontinuity, will be discussed later in this paper.

2) *Sierra Mojada - China Lineament*

The Sierra Mojada-China Lineament is here defined as that linear feature observable in satellite photographs in northeast Mexico that trends S 67° E from the village of Sierra Mojada, Coahuila, southeastward to the vicinity of the town of China, Nuevo León. This lineament approximately coincides with the northern boundary of the Coahuila Peninsula and the southern limit of the Sabinas Gulf, more or less following the axes of the Sierra Mojada, Sierra de la Madera, Sierra de San Marcos, and Sierra de la Gavia, passing near the northern end of the Sierra de Minas Viejas, and fin-

* These terms are used by Tardy (1980) in his thesis, but he does not explain the source where they were first described.

ally through the depression between the Picachos and San Carlos islands toward the site of the town of China, Nuevo León (Figs. 1 and 15).

The Sierra Mojada-China Lineament has been mentioned before by Charleston (1981) as the "San Marcos strike-slip fault", but ignoring the trusts at the Sierras Mojada, La Madera, and San Marcos, which are wrongly interpreted by him as a sinistral strike-slip fault. However, this lineament appears to continue northwestward passing near the town of Villaldama, Chihuahua, and beyond that town. For this reason and because of its trend, it could be possibly related with the so-called "Mojave-Sonora Megashear" proposed by Silver and Anderson (1974). Whether the Sierra Mojada-China Lineament is a strike-slip fault or not, will be discussed later in this paper.

MODEL FOR THE MECHANISM OF DEFORMATION OF NE MEXICO

The origin of the structures of northeastern Mexico has been a matter of conjecture since the early years of this century, and today it is still an open question. Several authors have suggested that these structures are the result of coaxial compressive forces that acted from the southwest and "squeezed" the Mesozoic sediments against pre-Mesozoic stable continental areas during the Laramide Orogeny (Imlay, 1938b; Humphrey, 1956; González, 1976; and several others). The relatively "weak" deformation shown by the Mesozoic sedimentary cover that overlies paleocontinental areas was considered to be the result of the major resistence of these basement highs, which absorbed the Laramide stresses. On the other hand, another group of authors (Haarman, 1917; de Cserna, 1956; Tardy, 1980) have also supported the idea of coaxial compressive forces acting from the southwest toward the northeast, and postulated that the folds of the Sierra Madre Oriental were the result of a *décollement* in the Torreón-Monterrey area. A third group of authors have suggested that the structures of northeast Mexico could be the result of sinistral shear (east-west) stresses (Murray, 1961; Krutak, 1967; Mullan, 1978).

In this study it is proposed that the structures of northeast Mexico are the result of a sinistral relative movement of southern United States (westward) with respect to northern Mexico (eastward) during the Late Paleocene - Early Eocene, contemporaneously with a regional *décollement* that was produced by the tilting toward the northeast of the so-called "Unnamed Occidental Continent" (Humphrey, 1956), or "Geoanticlinal Occidental" (Alfonso, 1976) (Fig. 3). Thus, the following pages are dedicated to explain what is the evidence that supports this idea, even though in the model presented here, no attempt is made to explain the pre-Mesozoic tectonics of northeast Mexico.

To analyse the mechanism, or mechanisms, that deformed the Mesozoic rocks of northeast Mexico, the model presented here is compared to the "classical" model suggested by earlier authors (Haarman, 1917; Imlay, 1938b; Humphrey, 1956: de Cserna, 1956; Murray, 1961; Krutak, 1967; Alfonso, 1976; González, 1976; Mullan, 1978; Tardy, 1980). In both models it is assumed that the genesis of basins, platforms, and positive areas during the Early Mesozoic was produced by block-faulting tectonics (Figs. 18 and 19). However, it has to be considered that the origin of these

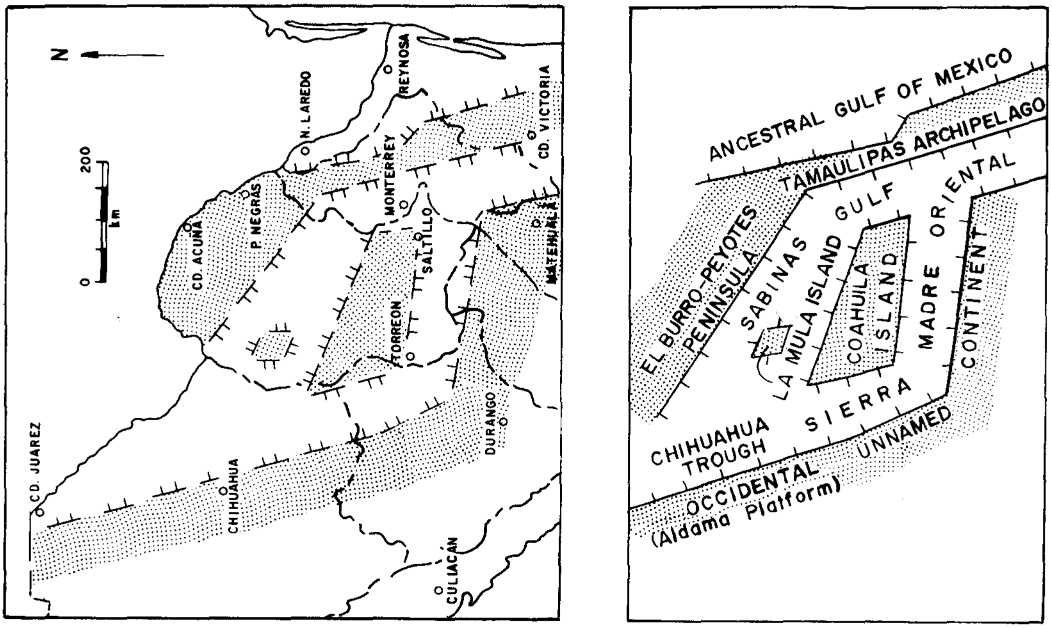


Fig. 18. Diagrammatic distribution of Early Mesozoic horsts and grabens in northeast Mexico.

basins could have been the result of a shear regime, which consequently would allow the formation of pull-apart basins during the Early Mesozoic, but no evidence known until today supports this idea.

If it is assumed that the structures of northeastern Mexico were originated by coaxial compressive forces acting in a southwest-northeast direction ("classical" model), and that the distribution of grabens and horsts was that shown in Figs. 18 and 19,

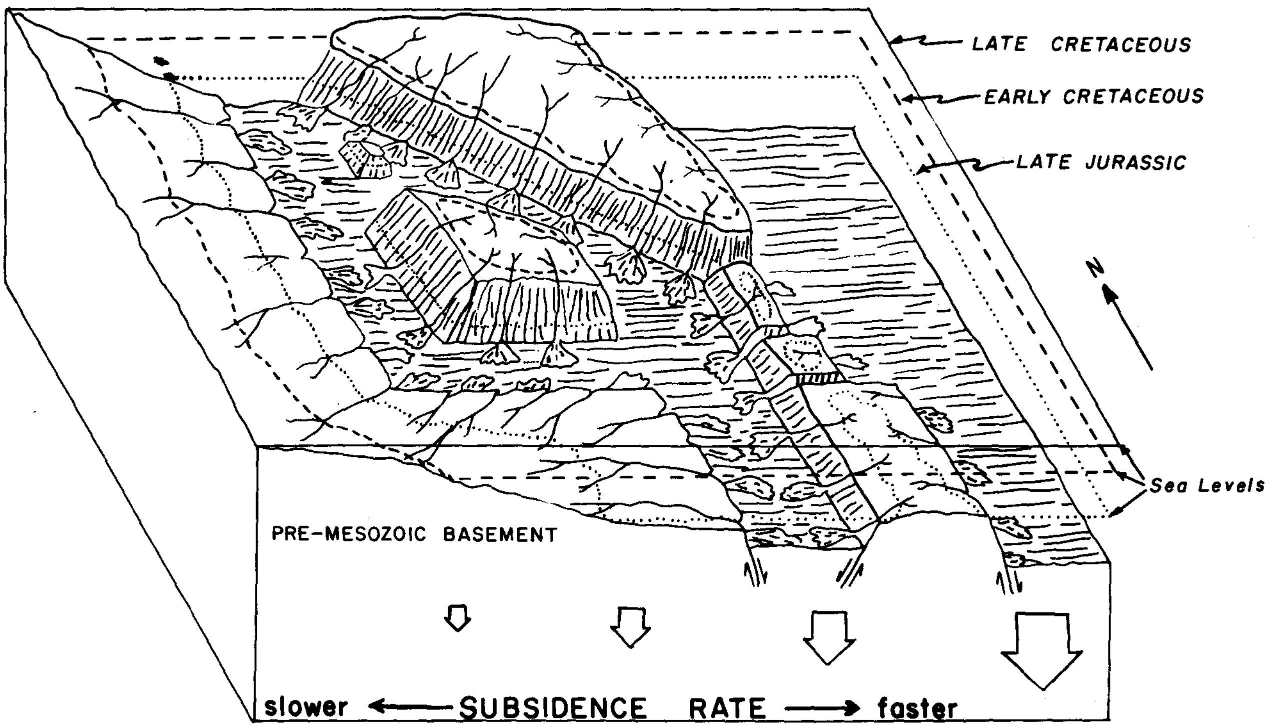


Fig. 19. Idealized block-diagram showing the major Early Mesozoic grabens and horsts in northeastern Mexico, and the inferred transgression of the sea over continental areas during the Late Jurassic (dotted line), Early Cretaceous (dashed line), and Late Cretaceous (solid line).

then one could expect fold axis essentially parallel to the basement highs (Fig. 20a). Overturned folds and thrust faults would show a vergence toward the stable areas. Besides, if a simultaneous, regional, northeastward tilting of the western "unnamed continent" is assumed, then a *décollement* zone would develop causing the sliding downward (to the northeast) of the sediments of the Sierra Madre Oriental, with tight, overturned folds and thrust faults with a vergence toward the basement highs (*i.e.*, Coahuila and San Carlos Islands). Also, it would be reasonable to expect that the evaporites in the lower part of the Mesozoic sedimentary sequence would not only allow the sliding of the rocks over them, but also to be "squeezed" and "dragged-out" (between the allochthon and the authocthon) toward the front of the *décollement* zone, thus producing some diapiric structures along the outer edge of the front ranges of the Sierra Madre Oriental, in the southeastern end of the Sabinas Gulf. Finally, potential SW-NE strike-slip faults could develop at the narrow areas of the Pre-Mesozoic basement, whereas low amplitude folds would be created over the relatively more stable basement highs (Fig. 20a).

On the other hand, in the model presented here a sinistral shear couple of forces (Fig. 20b) is assumed, instead of coaxial compressive forces; and exactly the same contemporaneous tectonic conditions are also assumed (*i.e.*, regional tilting of the western "unnamed continent", *décollement* of the Mesozoic sedimentary cover northeastwardly, and diapiric structures). Under such conditions, one would expect different fold patterns in the Sabinas Gulf and different directions of the potential strike-slip faults. In general, the structures over the relatively stable basement highs, the structures associated with the *décollement* zone, and the diapirs (*i.e.*, Sierra del Fraile and Sierra de Minas Viejas), would be essentially the same as those in the "classical model" of compressive forces. However, two significantly different structural features would be present: *a) en échelon* folds in the Sabinas Gulf, and *b)* a NW strike for the potential strike-slip faults across the narrow areas of basement highs, which would follow approximately the same strike of former normal faults and consequently, could also produce significant lineaments (Fig. 20b).

When a comparison is made between the two models (Fig. 20) and the real structures of northeast Mexico (Figs. 14 and 15), it can be concluded that the model presented here is a better explanation for the structural patterns and lineaments.

If it is assumed that a relative sinistral movement of southern United States (westward) respect to northern Mexico (eastward) during the Early Tertiary (Laramide

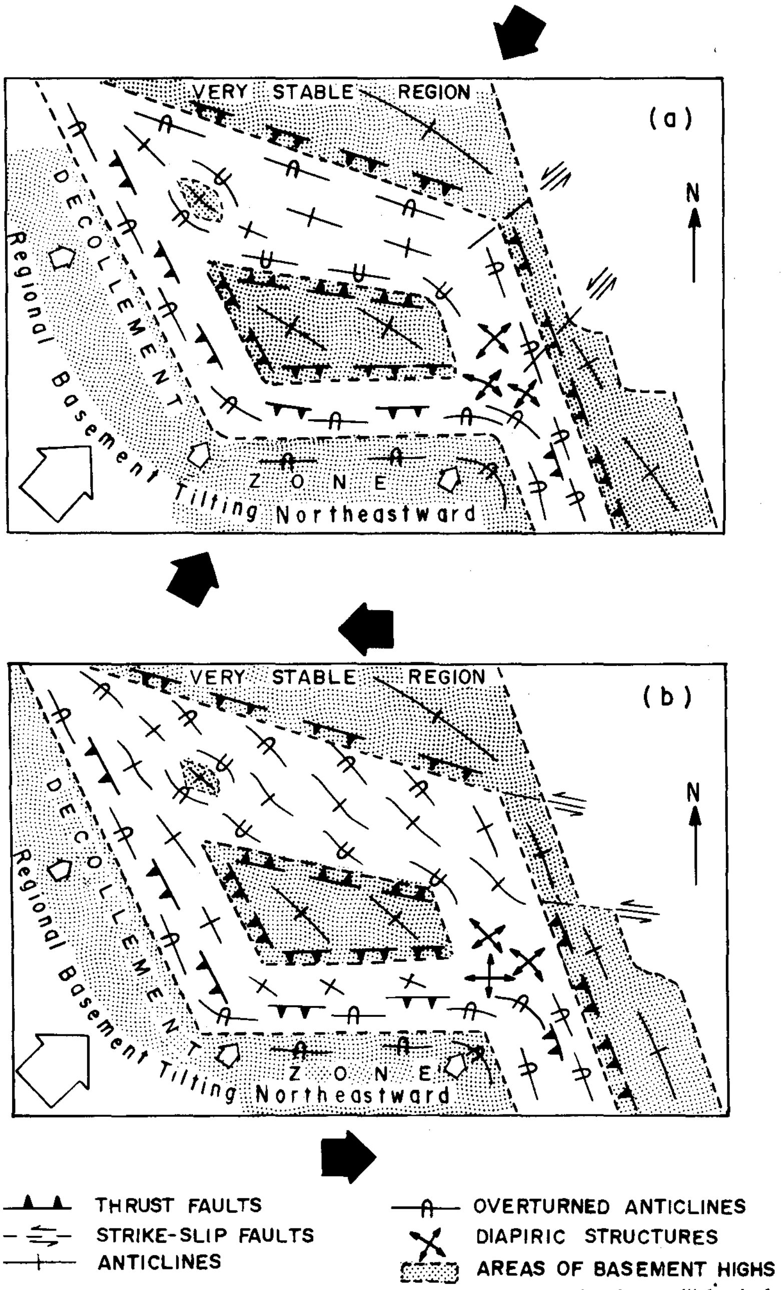


Fig. 20. Idealized distribution of structures if (a) SW-NE coaxial compressive forces ("classical model"), or (b) a sinistral E-W shear couple of forces were applied to a sedimentary post-Late Triassic-Late Cretaceous cover. See text for discussion.

Orogeny) is the mechanism that produced the structures of northeast Mexico, then it has to be assumed that the Boquillas - Sabinas and the Sierra Mojada - China Lineaments are, most probably, left-lateral strike-slip faults that in turn were originally normal faults.

The evidence that supports a sinistral absorbing regime during the Early Tertiary in northeast Mexico is the following:

- The left-lateral offset between the horsts of El Burro-Peyotes Peninsula, and the Tamaulipas Archipelago, as well as the same relationship between the islands of this archipelago (Fig. 15).

- The *en échelon* left relationship of the sigmoidal fold axes of the Sabinas Gulf (Figs. 15 and 20b).

- The oblique, abrupt, termination of the *en échelon* folds of the Sabinas Gulf, along the Boquillas - Sabinas and Sierra Mojada - China Lineaments (Fig. 15).

- The discontinuity of the Albian-Cenomanian reef trends across the Boquillas-Sabinas Lineament (*i.e.*, Serranía del Burro-Sierra Hermosa - Sierra de la Bahía) (Figs. 1 and 9).

- The stratigraphic evidence proposed by McKee *et al.* (1984) for a sinistral strike-slip fault (Sierra Mojada - China Lineament).

There are also some questions that are somewhat more difficult to explain, as for example, the apparent right-lateral offset between the Picachos and San Carlos islands (Fig. 15); but a reasonable answer would be that in a sinistral shearing regime, anticlockwise rotations would be common. Thus, if such tectonic events ever occurred, they could explain the puzzling rotations of 130° counterclockwise of Mexico relative to North America proposed by Gose *et al.* (1982).

Finally, it is referred in this paper that the shear movement along the Boquillas-Sabinas and Sierra Mojada-China Lineaments occurred during the maximum stresses of the Laramide Orogeny (Late Paleocene - Early Eocene), but it is also possible that this movement occurred throughout most of the Mesozoic and Early Tertiary, thus implying that the basins of northern Mexico (*i.e.*, Sabinas Gulf and Chihuahua Trough) could have been formed as pull-apart basins. These concepts agree quite well with the plate tectonics model proposed in the following pages.

PLATE TECTONICS MODEL FOR THE MESOZOIC-CENOZOIC EVOLUTION OF THE GULF OF MEXICO-CARIBBEAN REGION

Numerous plate tectonics models have been proposed to try to understand the post-Paleozoic evolution of this part of the Earth. The great amount of information dealing with this region is a direct consequence of the "lack of fitness" shown by Bullard *et al.* (1965) in their early Mesozoic reconstruction of the continents, where they juxtaposed most of Central America and southern Mexico over northern South America. Due to this juxtaposition most plate tectonics models are concerned mainly with the geometrical fit of plates and microplates in order to have the sufficient space to create the Gulf of Mexico and the Caribbean Sea regions (Dietz and Holden, 1970; Freeland and Dietz, 1971; Walper and Rowett, 1972; Malfait and Dinkelman, 1972; Moore and Del Castillo, 1974; Van der Voo *et al.*, 1976; Ladd, 1976; Salvador and Green, 1980; Pindell and Dewey, 1982; Wadge and Burke, 1983; Anderson and Schmidt, 1983; and several others). Besides the geometrical problem, most of the existing models have attempted to explain the evolution of the Gulf of Mexico-Caribbean Sea area by different lines of evidence, such as paleomagnetic data, magmatic events, or paleogeographic reconstructions.

The model presented here is based mainly on geological and geophysical evidence, which have supplied the data required to define continental fault zones and paleocontinental areas that play a key role in the post-Paleozoic evolution of the Gulf of Mexico-Caribbean region.

Plate tectonics reconstructions for Mexico require several sinistral northwesterly trending shear zones in order to have the possibility to move continental blocks along them, thus avoiding the overlap shown by Bullard *et al.* (1965). Several authors have suggested the existence of this kind of structures transecting Mexico (Murray, 1956, 1961; Woollard *et al.*, 1968; de Cserna, 1971, 1976; Silver and Anderson, 1974).

Major faults and crustal discontinuities involved in this model

Deep crustal discontinuities in Mexico are represented at the surface by large shear zones closely associated with lineaments and boundaries that separate different geological provinces. The major shear zones considered in this paper are, from north to south, are the Texas, Boquillas-Sabinas, and Sierra Mojada-China lineaments, the Mojave-Sonora Megashear, the Tamaulipas-Oaxaca Fault, and the Motagua-Polochic Fault Zone (Fig. 21).

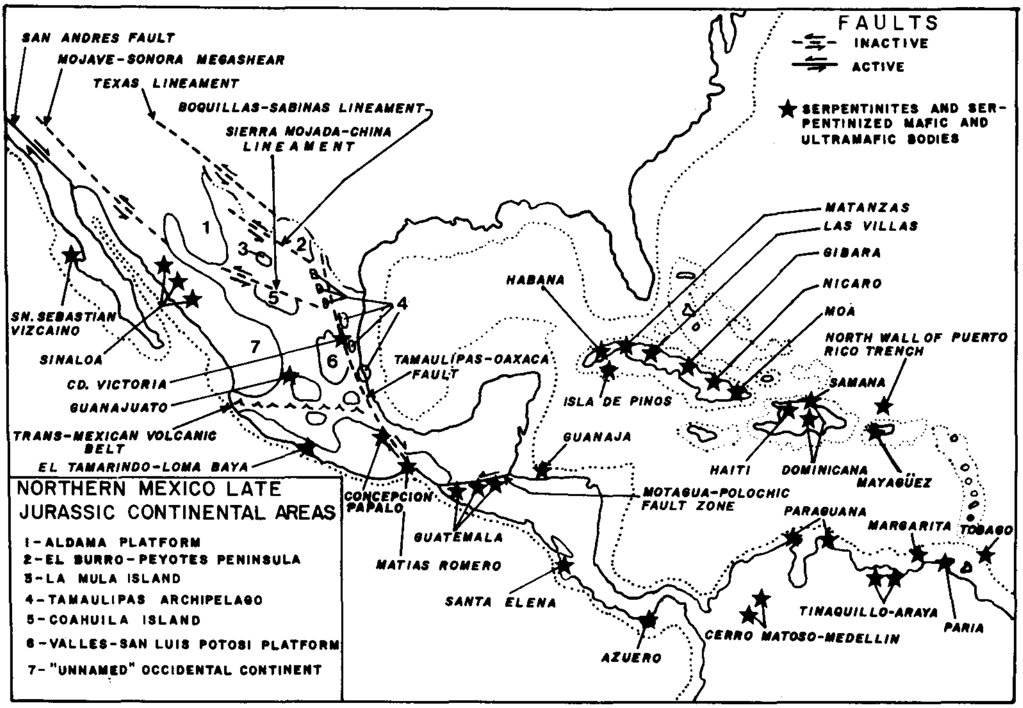


Fig. 21. Major tectonic features considered in this paper. From several sources, mainly Case (1980), Enos (1983), Urrutia-Fucugauchi (1984), Anderson and Schmidt (1983), Delgado and Morales (1984), Horne *et al.* (1976), and Dengo (1972). Note that most serpentinites and serpentinized mafic and ultramafic rocks are commonly related to transform fault zones.

The Texas Lineament had been largely discussed by Hill (1902), Albritton and Smith (1957), and Muehlberger (1965, 1980); the Boquillas-Sabinas and Sierra Mojada-China lineaments had been proposed by Padilla y Sánchez (1982, and in this paper); the Mojave-Sonora Megashear was proposed by Silver and Anderson (1974), and discussed by Anderson and Schmidt (1983); and the Motagua-Polochic Fault Zone has been studied and discussed by Hess and Maxwell (1953), McBirney (1963), Dengo (1969), Dengo and Bohnenberger (1969), Khudoley and Meyerhoff (1971); Anderson *et al.* (1973), Horne *et al.* (1976), and several others.

The Tamaulipas-Oaxaca Fault is named and defined here as that shear zone along which the Yucatan block drifted apart south-southeastwardly from Norteamerica during the Late Jurassic (Fig. 21). This fault was first suggested by Robin (1982) to explain the differences in volcanism between the Trans-Mexican Volcanic Belt (basalt-andesite-dacite suites), and the alkaline and hyperalkaline volcanism of the Gulf Coastal Plain (Fig. 22), and has also been interpreted by Ramírez (1984) as the boundary between true continental crust and rifted continental crust (transitional or attenuated crust) (Fig. 23).

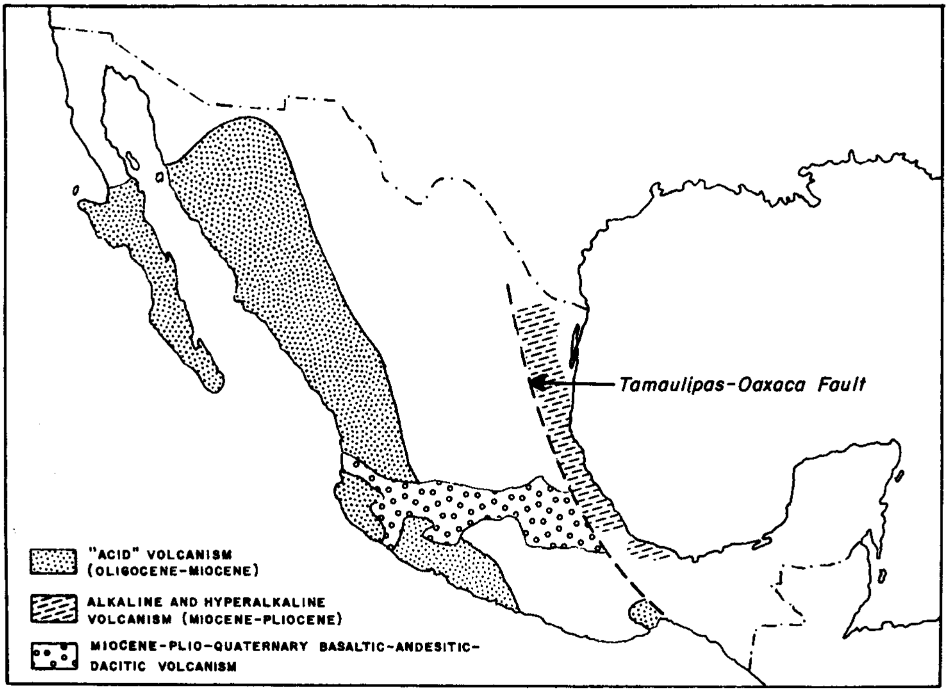
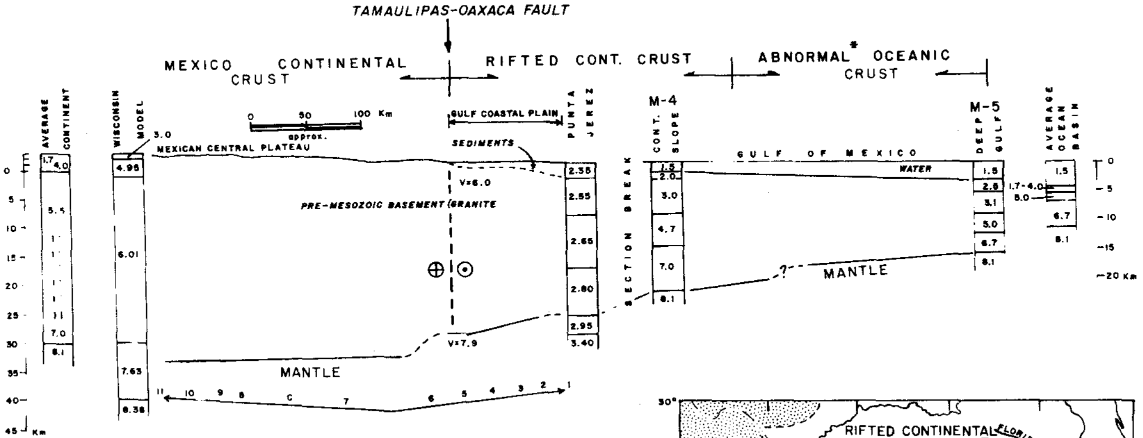


Fig. 22. Distribution of Cenozoic volcanism in Mexico. Modified from Robin (1982). El Chichonal volcanic area and several others have been omitted because they are irrelevant for this discussion.

Additional evidence supporting this fault is not conclusive, but it strongly suggests the presence of a major crustal discontinuity that coincides with the boundaries of extensive Early Mesozoic landmasses (*i.e.*, Tamaulipas Archipelago, Valles-San Luis Potosi Platform, etc.). Besides, the Tamaulipas-Oaxaca fault provides an alternative explanation for the emplacement of serpentinites in the basement of the Sierra Madre Oriental bordering the Gulf of Mexico (Cd. Victoria and Concepcion Pápalo areas) (Fig. 21), along a major shear zone. Also, the relation between the Paleozoic (or older) rocks of the Oaxaca region, and the Paleozoic (or older) rocks of the "Massif of Chiapas" is still unclear, but it seems probable that the latter could fit the former if they are moved northwestwardly along the Tamaulipas-Oaxaca Fault.



Numbers in Punta Jerez column indicate densities in g/cc, otherwise indicate Pwave velocities in Km/sec

*Abnormal means an oceanic crust covered by a thick package of sediments

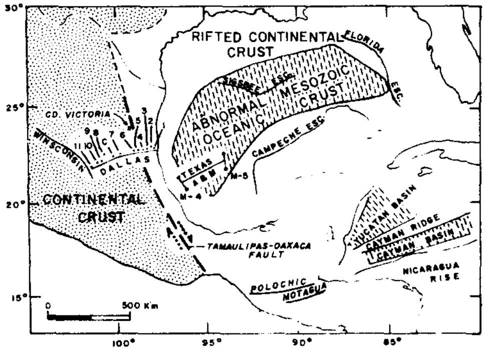


Fig. 23. Crustal model of eastern Mexico and adjoining areas. Modified from Ramírez (1984).

Plate Tectonics reconstructions

The following plate tectonic reconstructions are displayed from Fig. 24 to 30, in order to explain graphically the evolution of the Gulf of Mexico - Caribbean region, considering the major geological features of northeast Mexico, as well as paleomagnetic data (Van der Voo and French, 1974; Pindell and Dewey, 1982).

During the Late Triassic the western part of Pangea was subjected to tensional stresses produced by a widespread doming and rifting (Pindell and Dewey, 1982), which allowed the deposition of considerable amounts of continental terrigenous clastics along the edges of major grabens. The Honduras-Nicaragua block was by this time linked to southern Mexico, whereas the Yucatan block was attached to North America along the Texas-Louisiana region (Fig. 24).

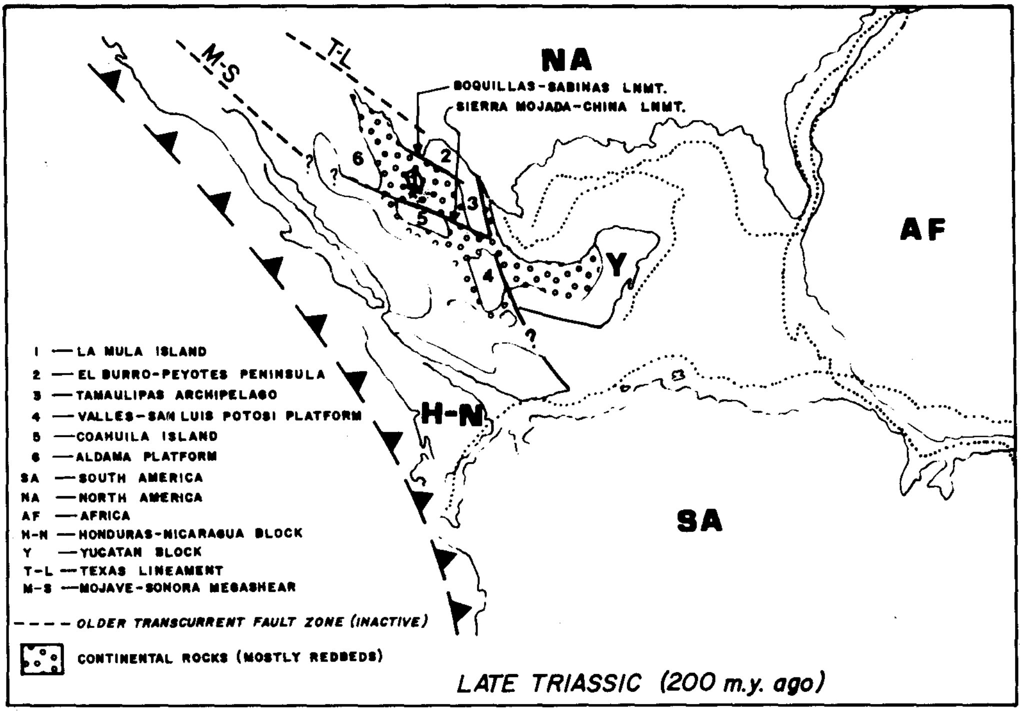


Fig. 24. Paleo-reconstruction at 200 Ma. Note in this and in subsequent figures that paleogeographic data are included only for Mexico, specifically the northeastern part.

These tectonic conditions set the scene for the early opening of the Gulf of Mexico basin, which received marine water from the proto-North Atlantic basin and from the Pacific Ocean (Salvador and Green, 1980) during the Callovian, when the African plate started to drift apart from the Northamerican plate along a mid-Atlantic spreading system (Klitgord *et al.,* 1982) (Fig. 25). The Yucatan block moved apart from Northamerica along the Tamaulipas - Oaxaca Fault, thus creating the oceanic crust actually present in the Gulf of Mexico which, in spite of the thick sequence of younger sediments that overlies it, actually shows positive Bouguer gravity anomalies of 250 milligals (Martin and Case, 1975). Over this oceanic crust a thick sequence of evaporites was deposited during the Late Callovian in the Texas, Louisiana, Sigsbee, and Tabasco - Campeche areas, whereas the evaporites of northeast Mexico were deposited later during the Oxfordian, as marine water advanced over the Sabinas Gulf. The Honduras - Nicaragua block continued attached to southern Mexico, but between it and South America a new spreading system started to be active (Pindell and Dewey, 1982). It is important to point-out that the Tamaulipas -

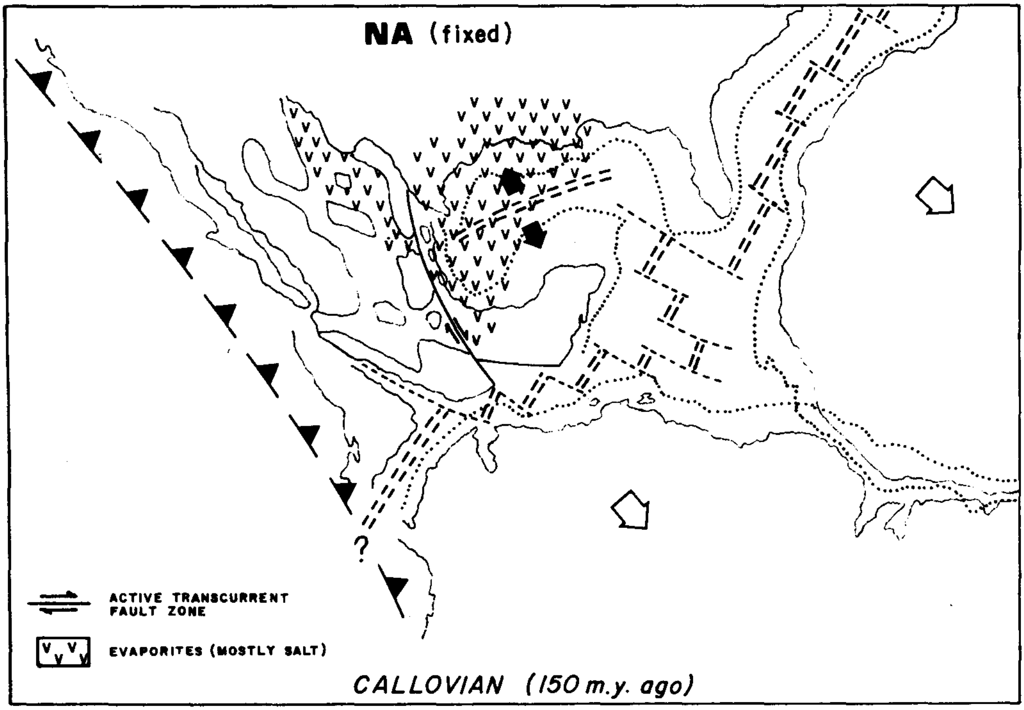


Fig. 25. Paleo-reconstruction at 150 Ma.

Oaxaca Fault played a vital role in this model, because it provided a logical direction of movement for the Yucatan block, which according to the paleomagnetic results of Guerrero (1975), has not suffered any significant rotations since the beginning of the Mesozoic. Other authors have moved the Yucatan block southeastwardly along the Salina Cruz fault of Viniegra (1971) (Dillon and Veeder, 1973; Uchupi, 1973; Anderson and Schmidt, 1983), but to make this movement they had to rotate Yucatan counterclockwise several degrees. However, the Salina Cruz fault has not been documented, nor it is recognizable from gravity maps or geological data.

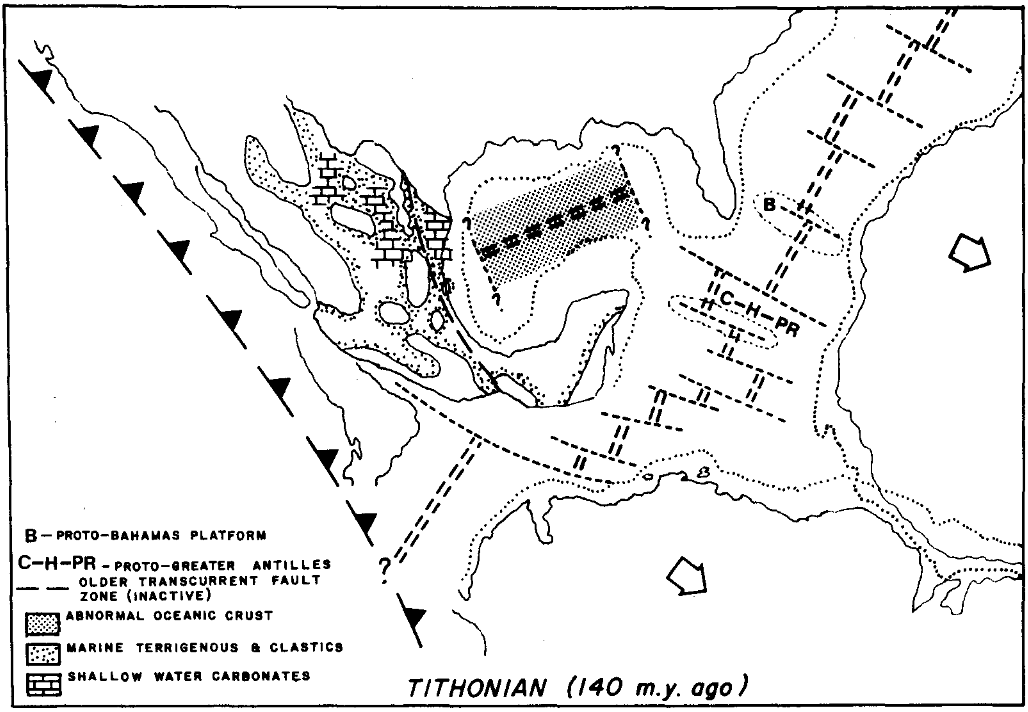


Fig. 26. Paleo-reconstruction at 140 Ma.

By the Tithonian the African and Southamerican plates continued their separation from North America. The Honduras - Nicaragua block was still attached to Mexico, and Yucatan has reached its present position. The Tamaulipas - Oaxaca fault ceased its activity as a transcurrent fault, and most probably started to act as the boundary between rifted crust (eastward) and true continental crust (westward) (Fig. 26). Most of Mexico was under subsidence and an extensive transgression took place, allowing the deposit of shallow-water sediments, with a predominance of terrigenous and clastics and minor amounts of carbonates. The Bahama area in its early stages was probably associated with a long transform, which caused uplift of the oceanic basement to the photic zone, thus allowing the initial deposition of carbonates (Pindell and Dewey, 1982). It seems probably that the Greater Antilles were developed under similar conditions, although Mattson and Pessagno (1979) have proposed a subduction regime instead of a transform. The Jurassic origin of the Greater Antilles and Cuba had been previously discussed and documented by several authors (Khudoley and Meyerhoff, 1971; Mattinson *et al.*, 1973; Ladd, 1976; Mattson, 1979).

During the Early Cretaceous the Honduras - Nicaragua block was still attached to southern Mexico, whereas separation of Northamerica with respect to Pangea continued, and South America and Africa started to drifted apart (Fig. 27). By that time extensive platform carbonates were deposited over most of Mexico, and long narrow belts of rudistid reefs were developed around and along continental areas. The growth of the Bahamas and Greater Antilles areas continued and a primitive island arc started to develop in the Central America region.

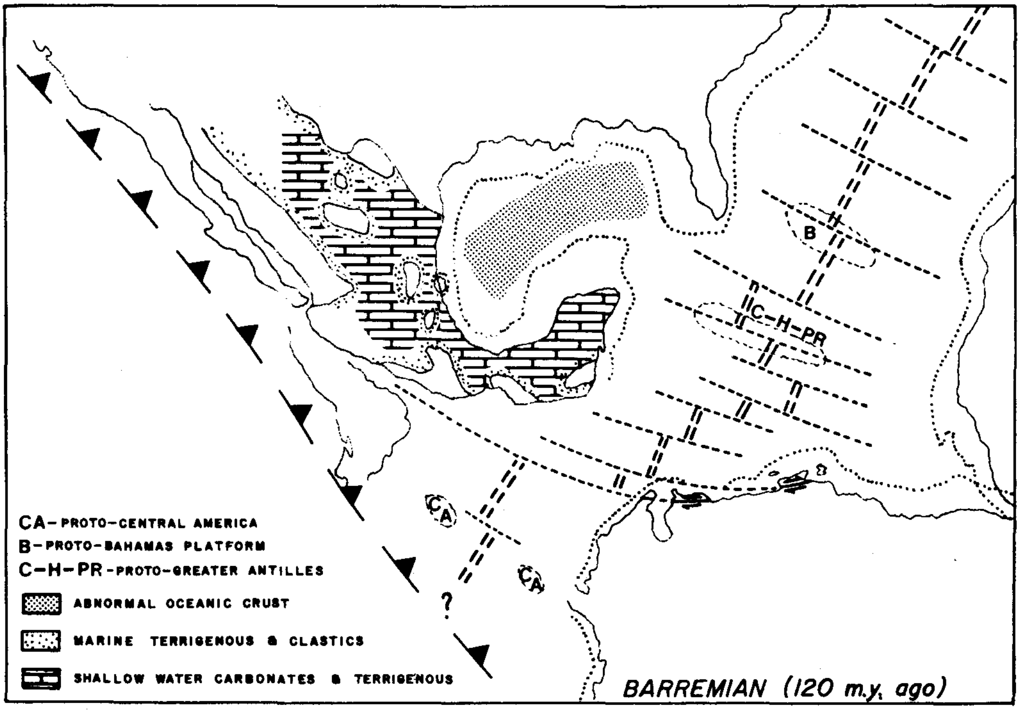


Fig. 27. Paleo-reconstruction at 120 Ma.

By the Campanian the Honduras - Nicaragua block initiated its eastward movement with respect to Mexico, along the Acapulco-Guatemala Megashear proposed by Anderson and Schmidt (1983) (Fig. 28). Most of eastern Mexico was covered by marine terrigenous and clastics derived from a regional uplift in western Mexico. The Bahamas, Central America arc, and Greater Antilles continued their development, whereas in the Cayman and Beatas areas new spreading systems started to be active, causing individualization of blocks in the Greater Antilles and the beginning of an island arc in the Lesser Antilles area.

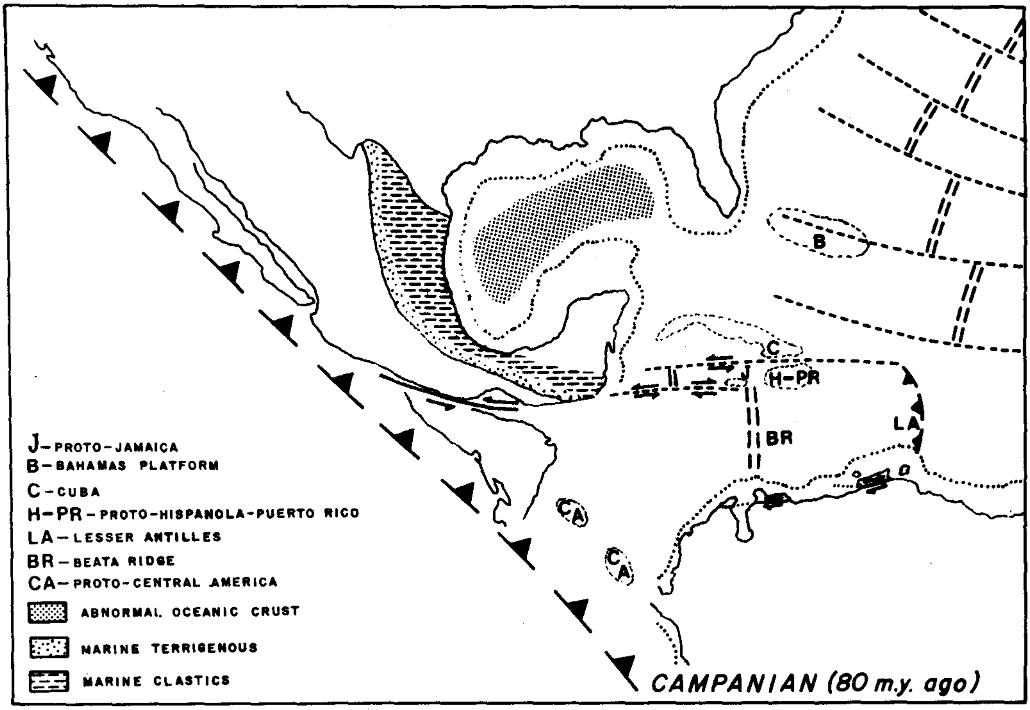


Fig. 28. Paleo-reconstruction at 80 Ma.

Most of Mexico was emerged by the Early Tertiary, when an intense deformation started (Laramide Orogeny). As North America continued its westward drift, Mexico was subjected to a sinistral shear regime, with NE-SW compressional components that caused recurrent movements along older normal faults (*i.e.*, Boquillas - Sabinas and Sierra Mojada - China Lineaments), *en échelon* folds in the Gulf of Sabinas areas, and large thrusts in the Sierra Madre Oriental area in combination with a regional northeastward *décollement* (Fig. 29). Under such shearing conditions, Mex-

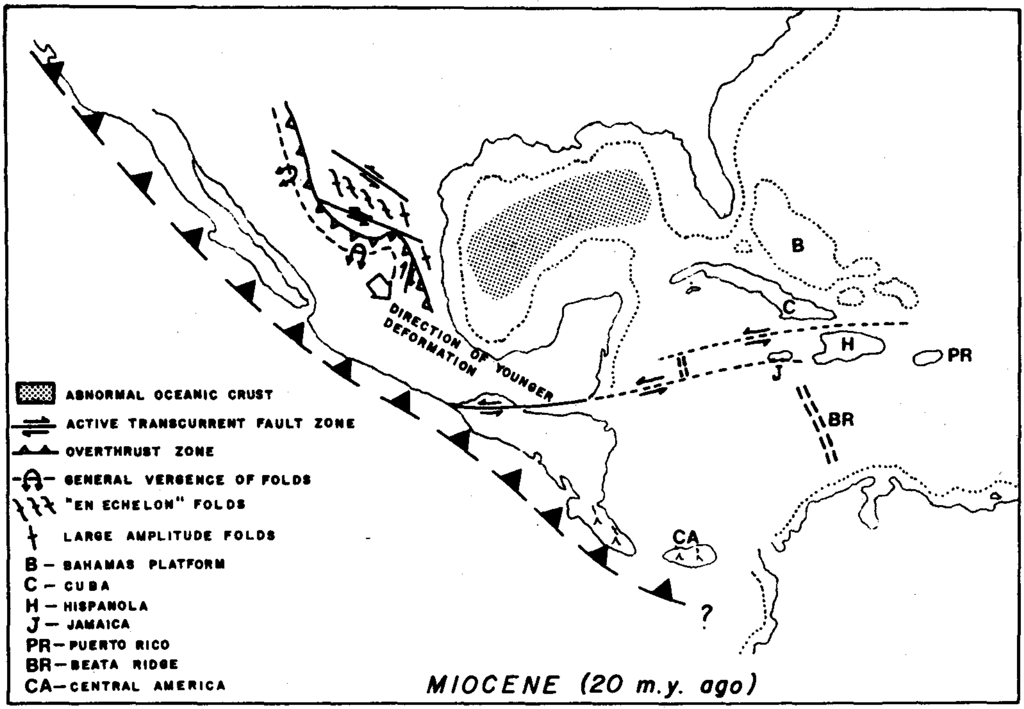


Fig. 29. Paleo-reconstruction at 20 Ma.

ico was strained and elongated from NW to SE, thus causing a migration of deformation in time and space, being such deformation older northwestwardly and younger southeastwardly. The Honduras - Nicaragua block continued to displace with respect to southern Mexico, Central America still was developing, and in the Greater Antilles Hispaniola was offset from Cuba (Wadge and Burke, 1983).

During the Plio-Pleistocene the position of the plates involved in this model was approximately the same as today, but an intense volcanic activity was present along the Trans-Mexican Volcanic Belt (Fig. 30). Such volcanism is most probably related to subduction in close association with the conditions of simple shear under which Mexico was subjected by the westward movement of the North American plate respect to the Caribbean and Cocos plates.

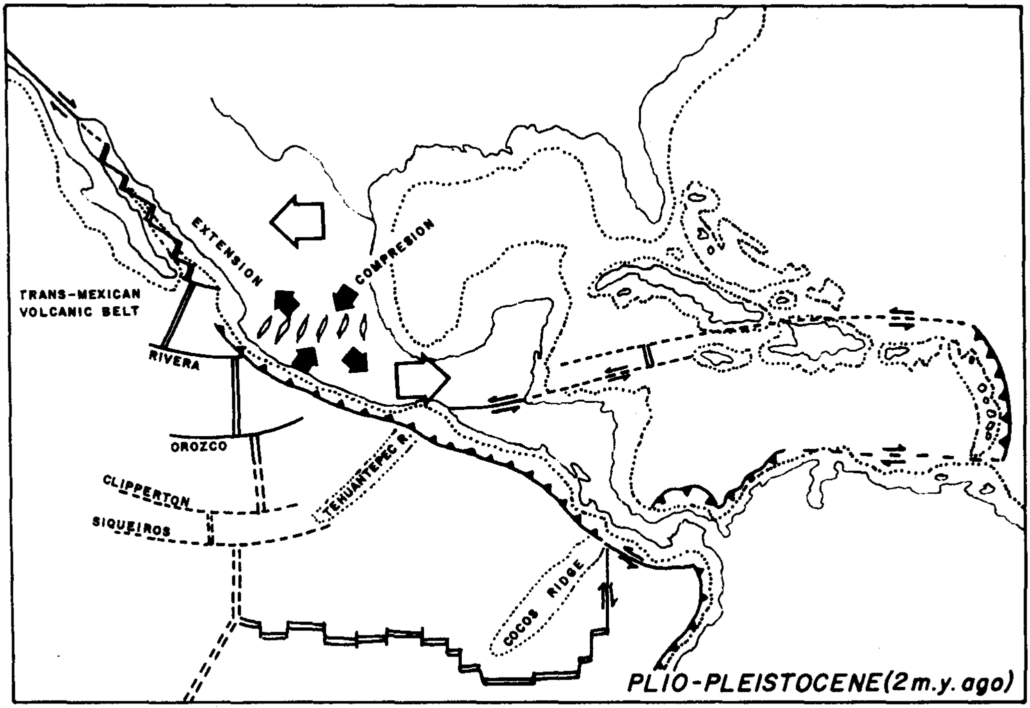


Fig. 30. Paleo-reconstruction at 2 Ma.

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