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The Origin of the Gulf of Mexico Basin and its Petroleum Subbasins in Mexico, Based on Red Bed and Salt Palynostratigraphy

Jaime Rueda-Gaxiola

Escuela Superior de Ingeniería y Arquitectura, Instituto Politécnico Nacional, Unidad de Ciencias de la Tierra, Calzada Ticomán No. 600, 07340 México, D.F., Mexico

ABSTRACT

The most important red-bed and salt sequences in Mexico are Jurassic and are located in eastern Mexico in or around the Gulf of Mexico. Most of these rocks are Middle Jurassic, and they are overlain almost always by evaporitic sequences that mark the beginning of the Middle Jurassic transgressive sequence. In some places, they overlie pre-Jurassic rocks. Mesozoic red-bed sequences have recently been dated with organic and inorganic components of palynological residues.

Information from red-bed sequences in the Los San Pedros Allogroup and Huayacocotla Group (Rhaetic-Liassic age in the Huayacocotla–El Alamar Basin), La Joya Formation (Middle Jurassic age in the Sabinas Subbasin), Rosario and Cahuasas Formations (Middle Jurassic age in the Tampico-Misantla Subbasin), and Todos Santos Formation (Middle Jurassic age in the Veracruz and Tabasco-Chiapas-Campeche Subbasins) allows us to construct a model for the origin and evolution of the Gulf of Mexico. The model includes three different stages: (1) the formation of one (or two?) Rhaetic-Early Liassic wrench or shear basin(s) (Huayacocotla–El Alamar Basin) related to the evolution of the Pacific convergent system; (2) formation of the Tampico-Misantla Subbasin during the late Liassic as a result of the southwest displacement of the Huayacocotla and Tlaxiaco Blocks along the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears; and (3), the origin during the Middle Jurassic of the Gulf of Mexico Basin and the Sabinas, Veracruz, and Tabasco-Chiapas-Campeche Mexican petroleum subbasins as a result of the development of a triple junction. This triple junction allowed the northwestward displacement of the Texas-Louisiana block and the western region of Mexico from the stable Chiapas-Tabasco-Campeche-Yucatán block along the Lewis Clark–Bahamas and Texas-Boquillas-Sabinas lineaments and the Pico de Orizaba–Laguna Inferior Megashear.

RECENT GULF OF MEXICO TECTONIC MODELS

Table 1 shows the principal tectonic processes considered by several authors from 1958 to 1993. These models were created to explain the origin of the Gulf of Mexico as it relates to tensional movements of lithospheric plates. Some of these tensional models explain the clockwise (CM), counterclockwise (CCM) or lateral (LaM) movements of the Yucatán (Yu) Peninsula based on paleomagnetic data. Lithospheric blocks such as the Chortis (Ch), Honduras (Ho), and Oaxaca (Oa) blocks are included to provide an understanding of the geological history of the Gulf of Mexico.

NEW PALYNOSTRATIGRAPHIC DATA FROM MEXICAN OIL BASINS

Red-bed and salt sequences in general comprise the economic basement of the Mexican Gulf of Mexico petroleum subbasins (Figure 1), and they represent the initial Mesozoic transgressive deposits in the petroleum systems.

The following red-bed formations have been dated with continental and marine palynomorphs (Rueda-Gaxiola, 1999) at the Mexican Petroleum Institute: Cahuasas and Rosario Formations, Tampico-Misantla Subbasin, Todos Santos Formation, Southeastern Subbasin and the western Veracruz Subbasin and La Boca Alloformation in the Huayacocotla–El Alamar Basin. These are the most important red-bed and salt sequences in Mexico, and they are located in or around the Gulf of Mexico. Most belong to the Middle Jurassic, and they are overlain almost always by evaporitic sequences that mark the beginning of the characteristic Middle Jurassic transgressive marine sequence (Iturralde-Vinent, 1988). Locally, they were unconformably deposited on pre-Jurassic rocks. The relationships between all these units are shown in Table 2.

Table 2 shows the important unconformity that separates basement rocks from Middle Jurassic rocks (La Joya and Todos Santos Formations) in the Sabinas and Southeastern Subbasins (Figure 1) of the Gulf of Mexico. This unconformity also separates Liassic rocks (La Boca Alloformation and Huayacocotla Formation) from Middle Jurassic red beds (La Joya and Cahuasas Formations) in the Huayacocotla–El Alamar Basin. Nevertheless, in some localities in the Tlaxiaco Basin and in the northern part of the Tampico-Misantla Basin, the Rosario Formation red beds gradually change to the Cualac and Cahuasas Formations, which are the base of the Upper Jurassic–middle Cretaceous transgressive sequence. Above this unconformity, Middle Jurassic red beds are slightly older than the evaporitic rocks deposited along the margins of the Gulf of Mexico. These subbasins are slightly younger than the Gulf of Mexico Basin; their red beds are related to the marine transgression that occurred during the drifting stage. This conclusion is supported by marine palynomorphs present in the salt and marginal red beds. From this evidence, it is possible to establish that the rifting stage is older than the red beds and is possibly related to the Lázaro Cárdenas and Teziutlán-Acapulco Megashears (Toarcian-Aalenian). These structures allowed the Huayacocotla and Tlaxiaco Blocks (Figure 2) to shift southwestward, opening the Tampico-Misantla and the Tlaxiaco basins.

Table 2 also differentiates the ages of formation of the Huayacocotla–El Alamar Basin and the Gulf of Mexico, with its Mexican petroleum subbasins; the oldest red beds belong to the Late Triassic Huizachal Alloformation, and the Todos Santos red beds could be pre-Bajocian, an age related to the dextral displacement of the Huayacocotla and Tlaxiaco Blocks along the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears (Figure 2). This displacement broke the Huayacocotla–El Alamar Basin into three segments (Rueda-Gaxiola, 1999). This suggests that the Huayacocotla–El Alamar Basin is, in time and space, a different basin from the petroleum subbasins in the Mexican part of the Gulf of Mexico. A careful analysis of geologic and tectonic maps of Mexico lets us deduce the southwestward shift of the Huayacocotla and Tlaxiaco Blocks by considering the geographical positions of the Huizachal-Peregrina, Huayacocotla, and Tlaxiaco Blocks (Figure 2).

This information, obtained from the basal red-bed and evaporitic units of the Huayacocotla–El Alamar Basin and the Gulf of Mexico petroleum subbasins in Mexico, allows us to propose a simple tectonic model of the origin and evolution of these basins.

THE TRIPLE-JUNCTION MODEL FOR THE GULF OF MEXICO

The triple-junction model proposed in this paper is based on the age of the red-bed and salt units and on the tectonic information deduced from palynostratigraphic analysis of the Los San Pedros Allogroup

(Rueda-Gaxiola et al., 1993, 1994, 1997a, b, 1999), which can be summarized as follows:

- From northwest to southeast, the Huayacocotla–El Alamar Basin (Rueda-Gaxiola et al., 1993) is continuous to the Pánuco River, where the boundary between the Huizachal-Peregrina and Huayacocotla Blocks is found. At this boundary, the Los San Pedros Allogroup disappears, and the Rosario Formation, the oldest lake-marine sedimentary unit of the Tampico-Misantla Basin, begins.
- Toward the south, a continuation of the continental Los San Pedros Allogroup is found in the Huayacocotla Anticlinorium (Figure 2), where it changes to the equivalent marine Huayacocotla Group (Schmidt-Effing, 1980).
- The Pánuco River flows along the dextral megashear Tampico–Lázaro Cárdenas, which allowed a late Liassic southwestward displacement of the Huayacocotla Block. This is the northwestern boundary of the Tampico-Misantla Basin; the southeastern boundary is formed by a similar and contemporaneous megashear (Teziutlán-Acapulco). Both megashears were identified in 1987 by Aguayo-Camargo and Marín-Córdova but were considered to be post-Cretaceous and left lateral.

Original Position of the Chortis Block, Chiapas Batholith, and Yucatán Peninsula

The triple-junction model involves a late Paleozoic and early Mesozoic paleogeographic reconstruction that includes a time-space relationship between Precambrian, Paleozoic, and Mesozoic rocks from southeastern Mexico and Central America. This paleogeographic reconstruction, based on studies by López-Ramos (1974, 1979a, b) and Dengo (1973, 1983; Figure 3) and the model proposed by Moore and Del Castillo-García (1974), allows us to determine the original position of the Chortis Block, the Chiapas Batholith of the Chiapas Massif (Rueda-Gaxiola et al., 1993), and the Yucatán Peninsula. The Chortis Block was a continental sliver joined to southeastern Mexico from Cabo Corrientes, in the state of Jalisco, to the Tehuantepec Isthmus, in the state of Oaxaca. During the early Tertiary (possibly before the late Eocene), this block migrated southeastward and subsequently northeastward along the Polochic-Motagua fault system (Figure 3) to form the northwestern part of Central America (Karig et al., 1978; Shipley et al., 1980; Sandoval-Ochoa, 1988).

The original position of the Chortis Block is uncertain. Nevertheless, its northern limit may be the 1,000-m isobath in the Caribbean Sea. In order to interpret the size and configuration of this block, we envision a southern continuation of Triassic-Cretaceous strata of the Mexican Tectonic Belt (de Cserna, 1960) down to Costa Rica (Figure 3). A correlation of Middle Jurassic rocks from Honduras with the Mexican Tecocoyunca Group (Sabanero-Sosa, 1990) and with continental and marine Liassic rocks in Guatemala and Honduras can be made with rocks of the Huayacocotla Group, as well as with those from Coyula and Cualac in the state of Guerrero, Tezoatlán in the state of Mixtepec, Tlaxiaco in the state of Oaxaca, and Zoquitlán in the state of Puebla (López-Ramos, 1974). Metamorphic basement in northwestern Central America (Dengo, 1973) can be correlated with similar rocks in the states of Guerrero and Oaxaca (López-Ramos, 1974).

Original Position of the Chiapas Batholith and the Yucatán Peninsula

For a long time, the Chiapas batholith was considered an isolated feature separated from the intrusive rocks of the basement of the Gulf of Mexico subbasins. To find its original position, it is necessary to note that its dimensions are the same (Figure 4), as those of the Veracruz Subbasin (Figures 1 and 2). This depression is filled by as much as 8800 m of Tertiary terrigenous rocks. Meneses-Rocha et al., (1997) suggested that in the deepest part of this subbasin, upper Eocene and upper Miocene rocks alone may reach as much as 8900 m. Geophysical surveys suggest that the igneous basement could be more than 10,000 m deep, similar to the depth of the Gulf of Mexico sea floor (Guzmán-Vega, 1991).

One explanation for the origin of this depression is the southeastward displacement of the Yucatán-Campeche-Tabasco-Chiapas Block (Figure 4) along the Pico de Orizaba–Laguna Inferior Megashear (Figure 5), which extends into the Gulf of Tehuantepec and parallels the coast down to the Mexico-Guatemala border, near the Tacaná Volcano (Figures 2 and 4), where the Polochic-Motagua fault system begins (Figure 3). The Pico de Orizaba–Laguna Inferior Megashear, which is identified in Figure 6 (Medina-Martínez, 1997) as a series of seismic epicenters, is the southwestern limit of the Yucatán-Campeche-Tabasco-Chiapas block in the Polochic-Motagua fault system.

The alignment of epicenters of earthquakes from 1974 to 1983 (Figure 6) along the Chiapas coastline

Table 1. **Tectonic processes related to the origin of the Gulf of Mexico.**

Author	*Proposition*	*Classification*								
		LaM	*CCM*	*CM*	*Su*	*Pe.*	*Ch*	*Ho*	*Oa*	*Yu*
Carey, 1958	The Yucatán Block underwent a counterclockwise movement of about 135° during the Jurassic. The Honduras block rotated 65° in the same direction.		X					X		X
de Cserna, 1960; King, 1969; Malfait and Dinkelman, 1972 ; Karig et al., 1978; Dengo, 1983; Ross and Scotese, 1988	The Eastern Pacific Plate extends from the island of Cuba to the North American western subduction trench. Guatemala, Honduras, and Nicaragua form the Chortis Block of southwestern Mexico, which underwent a 32° counterclockwise movement along a fault placed at the Acapulco trench.		X				X			
Van der Voo and French, 1974; Seyfert and Sirkin, 1973	Central America and part of Mexico do not appear between North and South America in the reconstruction maps nor do they appear superimposed over the South American continent.									
Freeland and Dietz, 1971	During the Late Triassic, the Oaxaca Block was located in the Pacific; the Yucatán and Honduras Blocks were located in the Gulf of Mexico and underwent a clockwise movement of between 100° and 180° during the Early Jurassic.			X				X	X	X
Viniegra, 1971	The Gulf of Mexico was formed by subsidence.				X					
Meyerhoff and Meyerhoff, 1972	The Gulf of Mexico has always existed, without noteworthy morphologic changes.					X				
Walper and Rowett, 1972; Helwing, 1975	The Yucatán Block underwent a counterclockwise movement.		X							X
Uchupi, 1973	The Honduras Block was fixed in its present position and moved the Yucatán peninsula 40° sinistrally during the late Mesozoic and Cenozoic.		X					X		X
Moore and del Castillo, 1974, Humphris, 1979	Intracontinental break-up and sea-floor spreading occurred from Texas and Louisiana.	X						X	X	X
Gose and Swartz, 1977	The Honduras block was placed in the Pacific off Mexico during the Cretaceous.	X						X		
Karig et al., 1978	Movement of the Chortis Block occurred before the Miocene, as there is no evidence of Miocene sediments involved in the subduction process in the Acapulco trench.						X			
Pilger, 1978	The Gulf of Mexico was formed 198 m.y. ago by separation of North America from South America caused by left-lateral movement.	X								
Tardy, 1980	The Yucatán Peninsula underwent a clockwise movement.			X						

Table 1. Tectonic processes related to the origin of the Gulf of Mexico (cont.).

Author	*Proposition*	*Classification*								
		LaM	*CCM*	*CM*	*Su*	*Pe.*	*Ch*	*Ho*	*Oa*	*Yu*
Dickinson and Coney, 1980; Buffler et al., 1980; Klitgord and Schouten, 1986	The Yucatán Peninsula was placed to the northwest of and in contact with the South American Plate during the Triassic.	X								
Salvador and Green, 1980	Sea-floor spreading and southwestern Yucatán peninsula displacement occurred by means of a fault through the Tehuantepec strait.	X								
Walper, 1980	The Yucatán Peninsula is a portion of the oceanic crust that moved eastward, up to Cuba.	X								X
Schmidt-Effing, 1980	The Gulf of Mexico was formed from a triple junction, and the Huayacocotla Aulacogen was one of the Hettangian rifts, similar to the Newark grabens on the Atlantic margin of North America.	X								
Dengo, 1983	The Chortis Block was joined to Oaxaca during the Late Permian–Early Jurassic and moved southeastward during the Late Jurassic. The Gulf of Mexico was occupied by the Yucatán Block, which moved southeastward during the Late Cretaceous and Miocene.	X					X			X
Carfantan, 1983	The Gulf of Mexico was formed by oceanic spreading caused by block displacement along the Caltam (California-Tamaulipas) alignment during the Oxfordian.	X								
Charleston et al., 1984	The Yucatán Block moved southwestward during the middle Miocene, and the Sierra de Chiapas was folded.	X								X
Castro-Mora, 1985	The Gulf of Mexico oceanic spreading was caused by a left-lateral movement along the Sonora-Monterrey transform fault during the Late Jurassic.									
Longoria, 1985	A transpression process was the origin of Mexican structural features, and a northwest-southeastward sea spreading was the origin of the Gulf of Mexico.	X								
Aguayo and Marin, 1987	In agreement with the Charleston Model, except that movement of the Yucatan Block occurred during the Late Cretaceous and early Tertiary.	X								X
Pindell, 1985; Salvador, 1987; Dunbar and Sawyer, 1987; Herrera and Villaseñor, 1991	The Yucatán Block moved southeastward from Pangea with a 40° counterclockwise movement. Rifting process gave origin to the oceanic floor in the central Gulf of Mexico. A dextral transform margin with northwest-southeast movement of the Yucatán Block southeastward during the Late Triassic to Late Jurassic compressed the Todos Santos Formation and Upper Jurassic Formations.		X							X

changes its orientation to an east-to-northeast arch. Based on the frequency of seismic activity, as shown in Figure 6, it is possible to observe two different seismic regions in Mexico, which are bounded by the northwest and southwest borders of the Tampico–Lázaro Cárdenas Megashear.

The Pico de Orizaba–Laguna Inferior Megashear is a deep and active system forming the southwestern boundary of the Veracruz Subbasin and the northeastern border of the Sierra de Juárez (Mapas de Hipsometría y Batimetría: Atlas de México, 1991). This megashear coincides with high-magnitude seismic events during the 20th century; for instance, the Ciudad Cerdán–Orizaba earthquake in 1973 (Singh and Wyss, 1976) as well as three earthquakes greater than magnitude 7 on the Richter scale between 1800 and 1995 (Medina-Martínez, 1997; Figure 7). This megashear follows the Laramie tectonic front (Zozaya-Saynes et al., 1997), the Miguel Alemán dam, and the northwest-southeast alignments of some secondary rivers between the Papaloapan River to the northwest and the Coatzacoalcos River to the southeast. In the Gulf of Tehuantepec, this megashear is located on the narrow platform at the southwestern end of the Sierra de Chiapas, along the 100-m isobath contour. It also can be identified by the belt of earthquake epicenters along the Chiapas coast. (Figure 6; Medina-Martínez, 1997). Dextral movement along this megashear apparently explains the 150-km displacement of the Guichicovi batholith from its initial position in Oaxaca, where it correlates with Grenvillian rocks (Murillo-Muñetón, 1994; Figure 8).

This southeastward right-lateral motion explains the lack of rotation between the Oaxaca and Chiapas massifs (Figure 2) during the last 13 m.y. as well as the gravity anomalies observed in the Tehuantepec Isthmus. These anomalies, flanked by minimum gravity values, correspond to the Oaxaca and Chiapas massifs (Ligorria and Ponce, 1993). The Pico de Orizaba–Laguna Inferior Megashear (Figure 9) might be related to the southern part of the Tamaulipas-Oaxaca dextral transcurrent fault proposed by Padilla y Sánchez (1986). This megashear also is useful to explain the southeastward separation of the Yucatán block from North America and the volcanic differences between basaltic-andesitic-dacitic volcanism in the Mexican volcanic belt (Figure 2) and alkaline-hyperalkaline volcanics in the Gulf coastal plain (Negendank et al., 1985). This megashear also could be related to the oblique fault through the Tehuantepec Isthmus proposed by Salvador (1987, 1991b), which explains the southeastward movement of the

Table 1. Tectonic processes related to the origin of the Gulf of Mexico (cont.).

Author	*Proposition*	*Classification*								
		LaM	*CCM*	*CM*	*Su*	*Pe.*	*Ch*	*Ho*	*Oa*	*Yu*
Stephan and Mercier de Lepinay, 1990	Oceanic spreading was a result of a north-northwest–south-southeast movement along the Texas-Boquillas-Sabinas, the Caltam, and the Lewis Clark–Bahamas alignments.	X								
Guzmán-Vega, 1991	Adapted Buffler et al., Stephan and Mercier de Lepinay, and Michaud models with a lateral displacement of the Yucatán Block along a fault on the northeast margin of the Chiapas massif.	X	X							
Marton and Buffler, 1993	Applied the "lithospheric simple shear" model to interpret Gulf of Mexico conjugate passive margins, using lateral movement of the Yucatán Block along a "detachment fault" toward the distal margin.	X								

Legend: LaM = lateral movement; CCM = counterclockwise movement; Cm = clockwise movement; Su = subsidence; Pe = Permanent (always existed); Ch = Chortis Block; Ho = Honduras Block; Oa = Oaxaca Block; Yu = Yucatan peninsula.

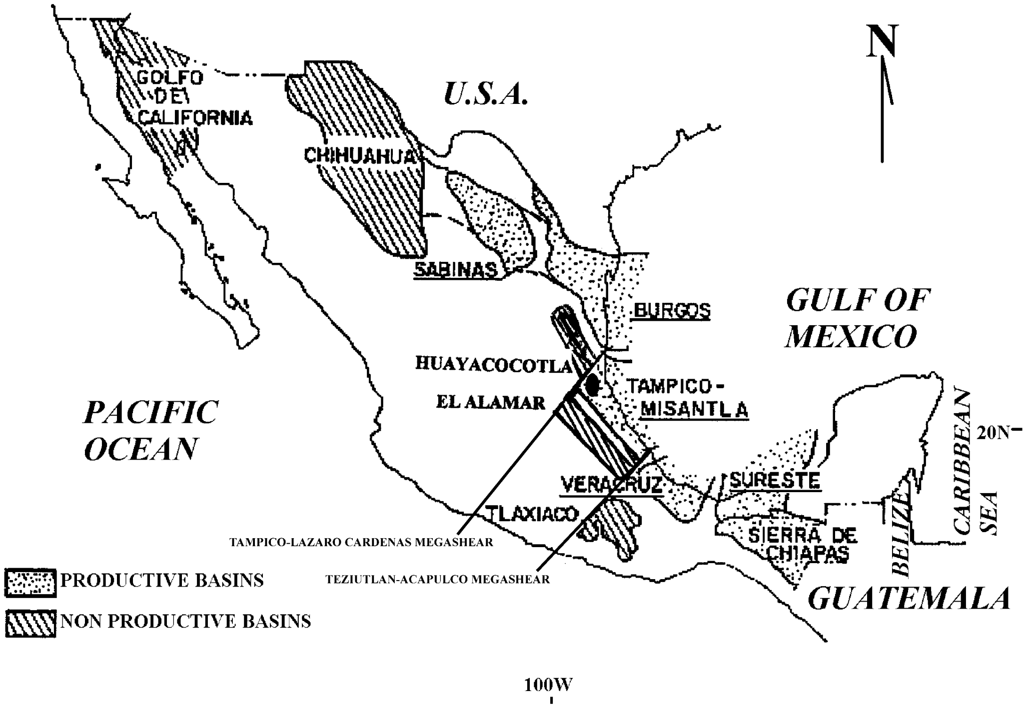


Figure 1. **Productive and nonproductive oil basins of Mexico. The black point in the Tampico-Misantla basin shows the position of the late Liassic Rosario Formation basin. (Modified after González-García and Holguín-Quiñonez, 1992).**

trend of young volcanoes along the northwest margin (north and northeast of Veracruz; Figure 2).

This trend begins at Pico de Orizaba and continues northward through Jalapa and Nautla, plunging northeast to the Gulf of Mexico along the 21° parallel. Northeast of Tampico, the Mexican Ridges (Cordillera de Ordoñez) change their direction of folding (Geología Marina and Tectónica: Atlas de México, 1991). The north-northeast–south-southwest Nautla–Pico de Orizaba trend (Figure 9) represents (1) the eastern topographic limit between the Teziutlán massif (Figure 2) and the coastal plain of the Veracruz Subbasin (Hipsometría and Batimetría del Territorio Nacional: Atlas de México, 1991), (2) the limit between maximum and minimum gravity values that represent the subbasin and the Teziutlán massif, (3) the crust-mantle interface alignment shown in Figure 9, and (4) the limit between the massif rocks and the subbasin sedimentary rocks (Negendank et al., 1985).

On the southeast margin of the Veracruz Subbasin is another north-northeast–south-southwest trend

Yucatán Block. This scenario would permit elimination of the perpendicular [Tehuantepec?] isthmus fault proposed by Viniegra-Osorio (1971).

The relative southeastward displacement of the Yucatán-Campeche-Tabasco-Chiapas Block (Figure 5) began in a crustal tensional zone as suggested by geographical, geophysical, and geological evidence found at the northwest and southeast margins of the Veracruz Subbasin. These margins are well defined by Fe, Mn, and opal mineral accumulation alignments (Salas et al., 1975) and a north-northeast–south-southwest

Table 2. **Stratigraphic correlations of red beds and evaporitic rocks from some Mexican localities (see Figures 1 and 28).**

Age	*Sabinas Subbasin*	*Huizachal-Peregrina Anticlinorium*	*Huayacocotla Anticlinorium*	*Tlaxiaco Anticlinorium*	*Tampico-Misantla Subbasin*	*Southeastern Subbasin*
Middle Jurassic	Minas Viejas				Huehuetepec	Salt Todos Santos*
	La Joya *	La Joya *	Cahuasas *	Cualac	Cahuasas	*
Lower Jurassic	*Basement*	La Boca	Huayacocotla	Rosario	Rosario	*Basement*
		Huayacocotla–El Alamar Basin?				

**Unconformity*

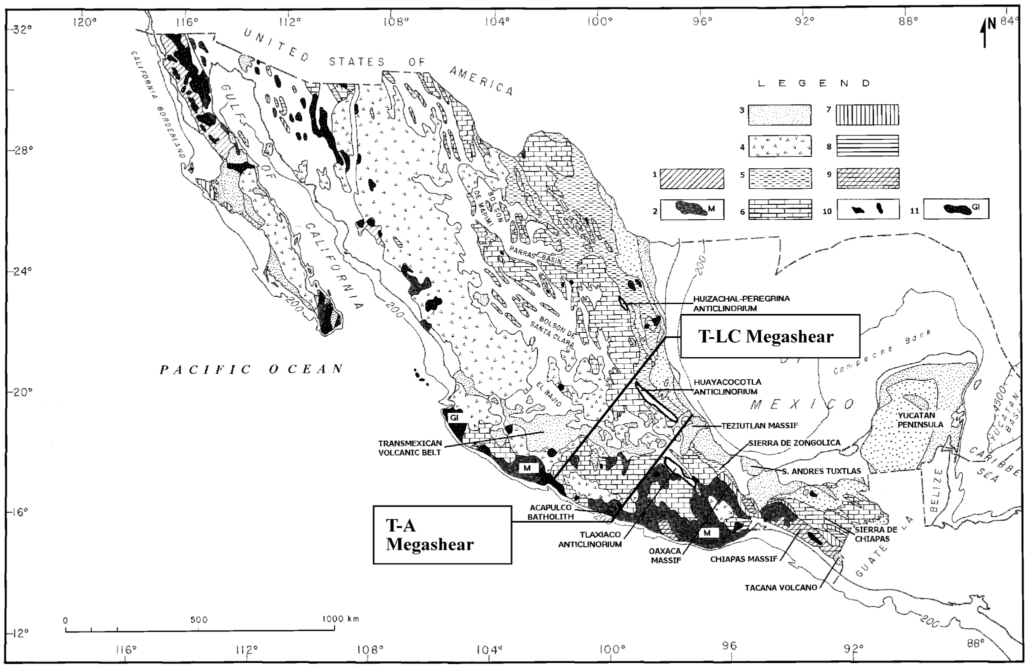


Figure 2. Simplified geologic map of Mexico showing principal locations of several geologic structures and places cited in text (de Cserna, 1989). Blank areas correspond to Pliocene-Quaternary terrestrial clastic deposits. 1 = Upper Jurassic–Lower Cretaceous eugeoclinal deposits. 2 = Precambrian and Paleozoic metamorphics and associated minor plutonic bodies. 3 = Pliocene-Quaternary volcanics. 4 = Tertiary volcanics. 5 = Upper Cretaceous–Paleocene clastic wedge. 6 = Upper Jurassic–Lower Cretaceous miogeoclinal deposits. 7 = Upper Triassic–Lower Jurassic red beds and eugeoclinal deposits. 8 = Paleozoic marine deposits. 9 = Paleozoic intrusives. 10 = Ophiolites in Cedros Island, Vizcaino Peninsula, Santa Margarita Island, and in northern Sinaloa; elsewhere, ultrabasic intrusives and serpentinites. 11 = Upper Cretaceous to Tertiary granitoids.

representing the border with the Salina del Istmo and the Southeastern Subbasin boundary. This trend begins in the Cuauhtémoc seismic station (Figure 10) where the Pico de Orizaba–Laguna Inferior Megashear (Figure 9) crosses the central part of the Istmo de Tehuantepec. From this point, the fault continues north-northeast toward San Andrés Tuxtlas (Figure 9), forming a crustal boundary where deep earthquakes (as much as 182 km) of high-magnitude (greater than 7 on the Richter scale; Medina-Martínez 1997; see also Figure 7) have been generated in the last century. This trend extends through the San Andrés Tuxtlas caldera and continues north into the Gulf of Mexico as the western limit of the salt intrusions found along axes of depressions (Mapa de Geomorphologia: Atlas de México, 1991) until it joins with the southwestern end of the Campeche escarpment (Figure 9) near the 3000-m isobath. In the Veracruz Subbasin, this southeast boundary is defined by the change in orientation of folding of Tertiary rocks, from northwest-southeast to north-northeast–south-southwest, which occurs southeast of the San Andrés Tuxtlas (Zozaya-Saynes et al., 1997). This folding, also known as the Catemaco folded belt, is in lateral contact with the Shallow Salt folded belt, which is the western limit of the Southeastern Subbasin. This structural feature is probably the product of compression since the middle Miocene, caused by the northeastward movement of the Chortis Block after passing south of the Chiapas massif (Aranda-García, 1998; Prost and Aranda, 2001). The San Andrés Tuxtlas volcanic transtensional system (Garduño-Monroy and Jacobo-Albarrán, 1995) probably is the result of seismic activity on this border of the Veracruz Subbasin.

The El Pico de Orizaba–Laguna Inferior northwest-southeast megashear and the Cuauhtémoc–Los Tuxtlas fault join at the Cuauhtémoc Seismic Station (Figure 10). The Tehuantepec Isthmus is the most seismically active region of Mexico (Figure 6; Medina-Martínez, 1997; also Figure 1, Yamamoto and Mota, 1991). Ligorria and Ponce (1993) show the position of 40 earthquake epicenters between 16° and18° N and 94° and 98° W, detected from April to May, 1986 (Figure 10). Seismic data permit an estimate of thickness of the continental crust of 37 to 38 km in the Tehuantepec Isthmus at the La Ciruela (CIR), Tres Islas (TIO), and La Ventosa (VEN) stations; 33 to 37 km along the Pacific Coast at the Huilotopec (HUI) and San Francisco del Mar (SFM) stations; and 29 km at the El Azufre (EZO) station. On the other hand, earthquakes produced along the El Pico de Orizaba–Laguna Inferior Megashear had hypocenters at depths of 87 and 119 km, and those produced along the Cuauhtémoc–Los Tuxtlas fault had hypocenters at depths of 113 and 182 km, showing a

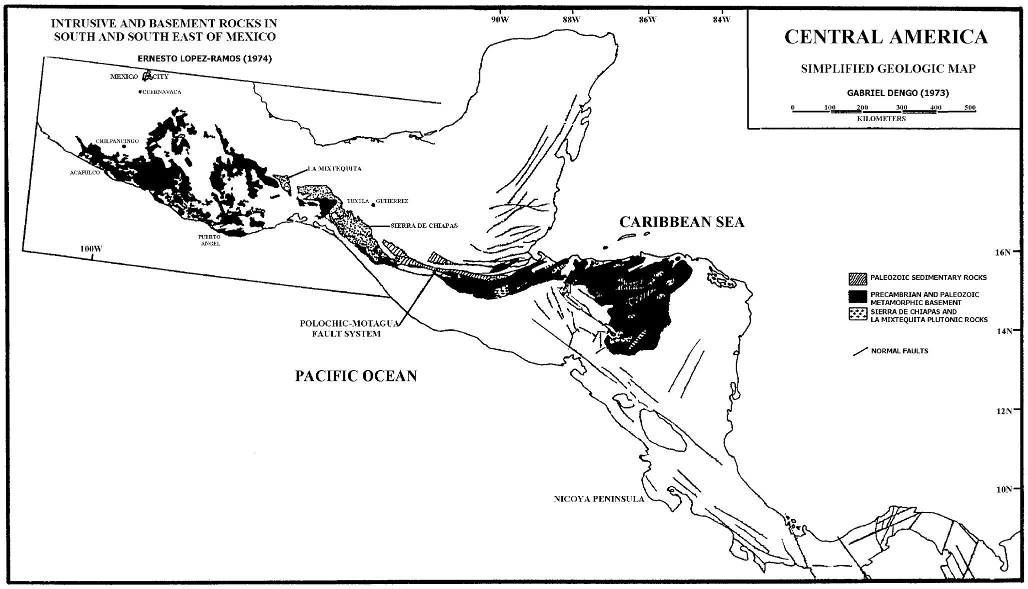


Figure 3. Precambrian and Paleozoic metamorphic rocks in southern Mexico and Central America (López-Ramos, 1974, and Dengo, 1973).

complete rupture of the earth crust. Vázquez-Meneses et al. (1992) showed hypocenters maps of 0 to 220 km that reveal trends along the El Pico de Orizaba–Laguna Inferior Megashear and the Cuauhtémoc–Los Tuxtlas fault up to the Veracruz Canyon, where the earthquake foci reach depths of 170 and 220 km. It is clear that these deep earthquakes located between 14° and 16° N, close to the subduction zone, were produced by processes other than subduction.

Once these megashears and faults are identified, it is possible to reconstruct the Late Triassic paleogeography, before the origin of the Gulf of Mexico, by placing the Chortis and the Yucatán-Campeche-Tabasco-Chiapas Blocks (Figure 12) in their original positions. In order to close "the possible zone of transtension" (Salvador, 1987, 1991a) between the Florida and Yucatán peninsulas, it is necessary to place the Huayacocotla Block in its position prior to the time it was displaced toward the southwest by the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears.

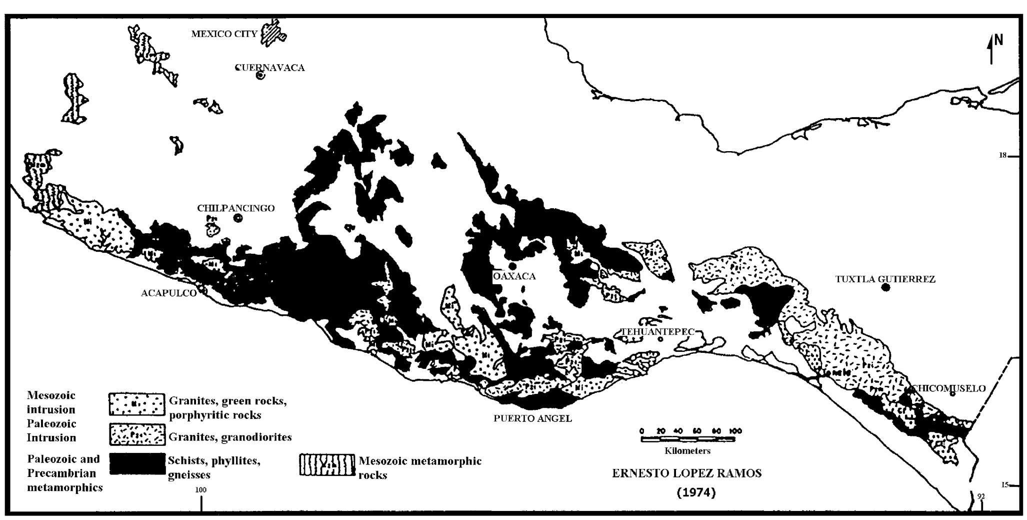


Figure 4. Generalized map of metamorphic and intrusive rocks in southeastern Mexico (López-Ramos, 1974).

Figure 11 shows the present distribution of Triassic marine rocks and the location of these megashears. This configuration (López-Ramos, 1974; Carrillo-Bravo, 1982; Romero-Espejel, 1985; Gómez-Luna et al., 1997) suggests the existence of an epicontinental sea in central and western Mexico (the states of Sonora, Zacatecas, and San Luis Potosí). Only continental Triassic rocks are located southeast of this limit. This distribution indicates that the megashear divided this part of North America into two blocks: one topographically lower, toward the northwest, and a higher one toward the southeast containing continental sediments only.

Late Triassic–early Jurassic Paleogeography

Late Triassic paleogeography makes possible the recognition of three tectonic events that explain the origin of the Huayacocotla–El Alamar Basin and the Gulf of Mexico subbasins in Mexico.

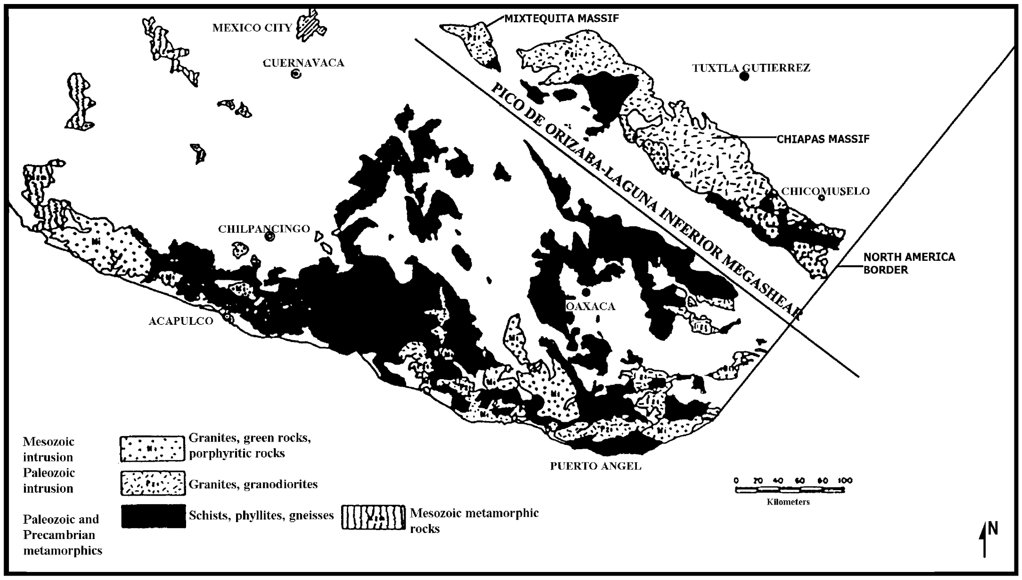


Figure 5. Paleogeographic position of the Chiapas massif during the Triassic (Rueda-Gaxiola, 1993), based on the distribution of intrusive and metamorphic rocks (López-Ramos, 1974) and on seismic, tectonic, and geographic evidence.

Huayacocotla–El Alamar Basin and Related Basins

The Huayacocotla–El Alamar Basin was formed during the Late Triassic as a product of tensional stresses related to the Pacific Plate convergent system in this part of North American. This basin is filled with the red-bed Huizachal and La Boca Alloformations and with the red-bed and marine Huayacocotla Group in the southern Huayacocotla Block (Figure 12; Rueda-Gaxiola et al., 1999). Its southeast extension is found at the Ajalpan Basin in the state of Puebla and Teotitlán, in the state of Oaxaca, and in the Tlaxiaco Block, on the eastern side of the Tehuacán Graben. Liassic strata at Sierras Internas del Cinturón Plegado de Zongolica (Meneses-Rocha et al., 1997) are part of the same belt (Figure 2). The Zongolica Basin was initially filled with red beds and marine early Liassic (Sinemurian) rocks (Echánove-Echánove, 1963; López-Ramos, 1974). These data indicate that the Huizachal-Peregrina Block was higher than the Huayacocotla Block during the Liassic.

Nevertheless, it is necessary to point out that the oldest known sedimentary rocks are Toarcian (late Liassic) in the Tlaxiaco Basin and Bajocian (early Middle Jurassic) in the Huamuxtitlán Basin. Thus, the Tlaxiaco and Huamuxtitlán Basins may be the product of tensional stresses during southwestward displacement of the Tlaxiaco Block along the Teziutlán-Acapulco Megashear during the late Liassic.

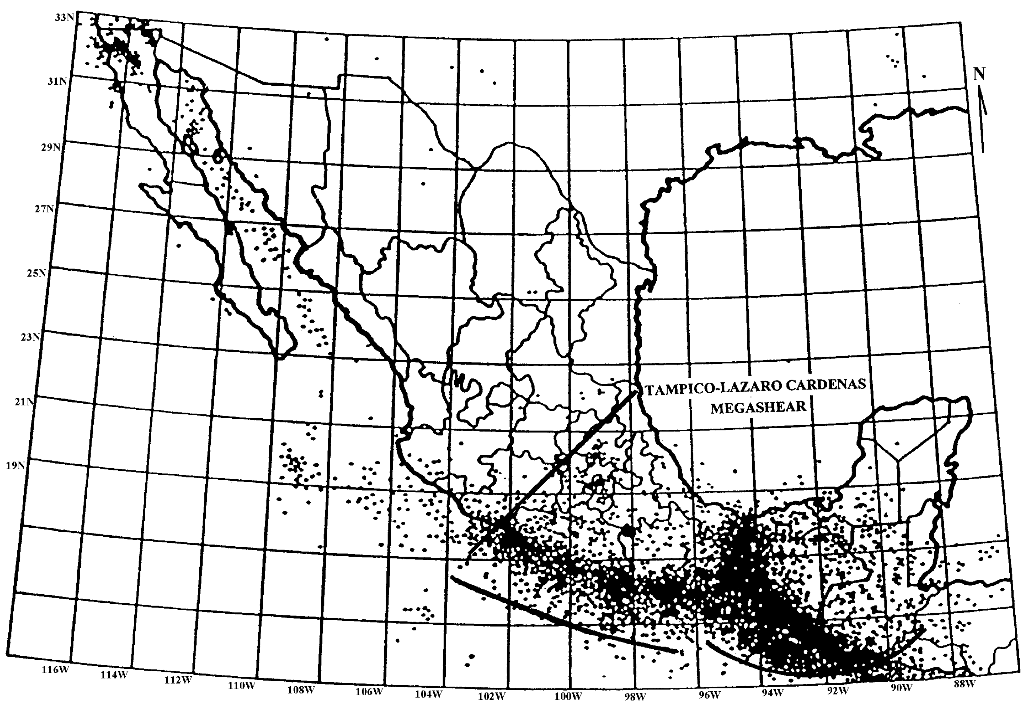


Figure 6. Principal zones of seismicity in Mexico from 1974 to 1983. The Tampico–Lázaro Cárdenas Megashear forms the northwestern boundary of seismic zones of different intensity (Medina-Martínez, 1997).

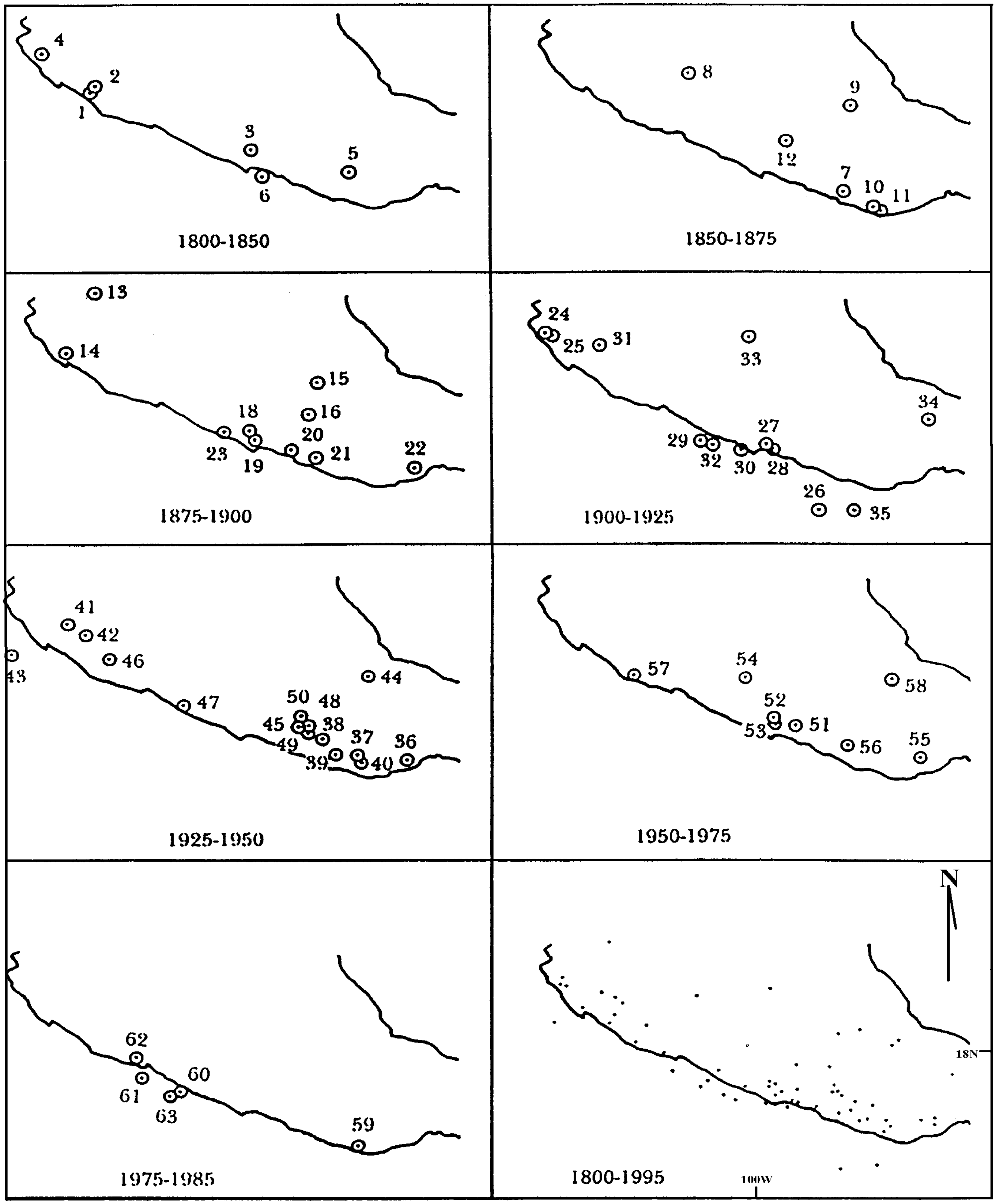


Figure 7. Location of earthquakes greater than magnitude 7 on the Richter scale in southern Mexico from 1800 to 1995 (Medina-Martínez, 1977).

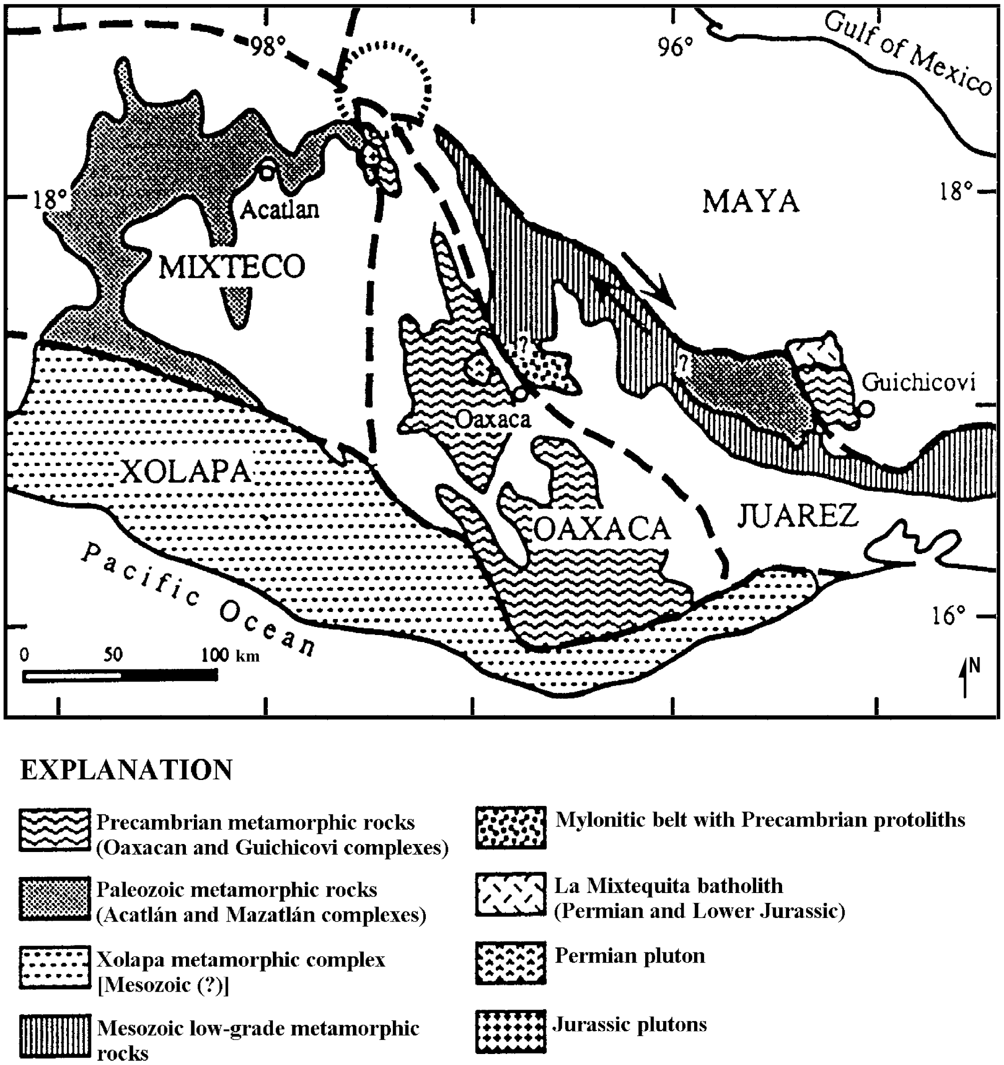


Figure 8. Translation of the Precambrian Guichicovi complex and the La Mixtequita batholith as a single block, along the boundary between the Maya and Juárez terranes. Circle indicates the possible original position of the block, and dashed lines are terrane boundaries (Murillo-Muñetón, 1994).

Chortis Block. The latter has shown evidence of Liassic marine paleontology in Guatemala and Honduras.

Paleontological data obtained from Schmidt-Effing (1980) and palynostratigraphic data from Rueda-Gaxiola et al. (1999) indicate that this epicontinental sea advanced from south to north in the Huayacocotla–El Alamar Basin during red-bed deposition of the upper part of the Huizachal Formation, probably since the late Hettangian. At least two transgressions reached the northern part of this basin during the Sinemurian. However, only the eastern boundary of this peribatholithic basin is well known, possibly because it is in actuality a half graben eroded in the west and deeper to the east, where the Los San Pedros Allogroup was deposited over the Permian Guacamaya Formation.

Evolution of the Liassic Epicontinental Sea

Paleontological evidence (Imlay, 1980; Cantú-Chapa, 1997) shows that Pacific marine waters were restricted during the early Sinemurian to Sonora and central Mexico (Figure 13). To the south, these regions were connected to the Pacific Ocean by "Portal del Balsas" (López-Ramos, 1974; Carrillo-Bravo, 1982), forming an epicontinental sea (Salvador, 1987, 1991a, b) that reached the Paleobahía de Huayacocotla (Erben, 1954a, b), presently known as the southern part of the Huayacocotla–El Alamar Basin. The distribution of Liassic marine rocks indicates that this epicontinental sea was widespread (Figure 13), extending from the Huizachal-Peregrina Block to the

In the Real de Catorce Anticlinorium (Figures 12 and 14), Reaser et al. (1989) found the red-bed Huizachal Group (*sensu* Carrillo-Bravo, 1961) in contact by décollement with the Zuloaga Formation. Bartolini (1997) reported a Liassic a Ar^{40}/Ar^{39}age (195 + 5.5 m.y.) for rhyolite of the Nazas Formation in Cañada Villa Juárez, in the state of Coahuila, where the Nazas is unconformably overlain by the La Gloria Formation. This age allows a correlation with Liassic rocks at Real de Catorce. In the Sierra de San Julián, in Zacatecas, the Nazas Formation is pre-Oxfordian in age (Blickwede, 1997). Eguiluz de Antuñano (1997) proposed a Middle Jurassic age for the Nazas, suggesting that it was deposited in rift basins of central Mexico. These rift basins probably are related to the previously mentioned Mesozoic marine volcanic arc located in the Huayacocotla Block.

Late Liassic–early-middle Jurassic Paleogeography

The second Mesozoic tectonic stage involves the conversion during the Toarcian-Aalenian of the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco normal faults into dextral megashears. The dextral displacement of the Huayacocotla and Tlaxiaco Blocks divided the Huayacocotla–El Alamar Basin into three fragments, producing the possible zone of transtension proposed by Salvador (1987, 1991a, b), between the Florida and Yucatán peninsulas. It also caused subsidence of the northwestern portion of the Huayacocotla Block and compressed the fill in the Huayacocotla–El Alamar Basin. The main geological events that resulted from this displacement were (see Figure 21):

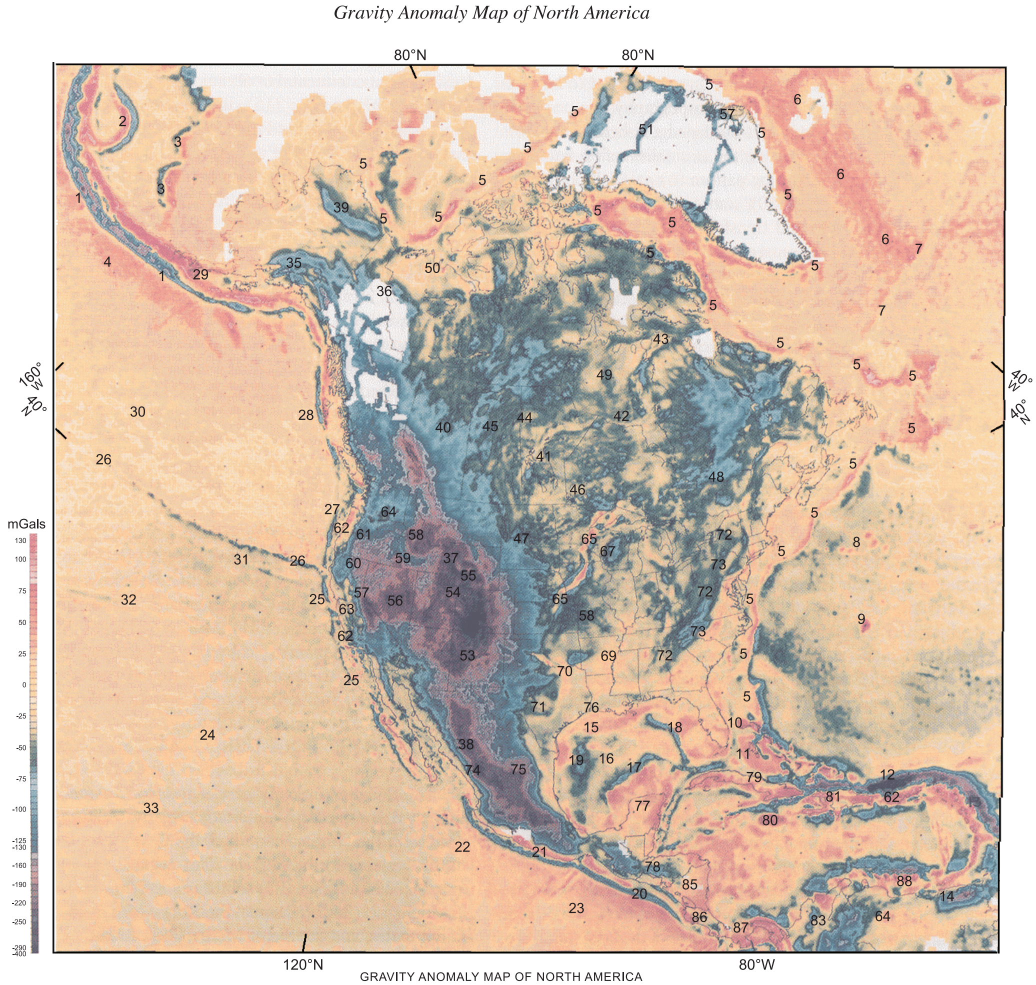


Figure 9. **The Nautla–Pico de Orizaba fault (north-south) is the limit between minimum and maximum gravity values representing the Veracruz Subbasin (−75 mGals = light blue color) to the east and the Teziutlán massif (−190 mGals = violet color) to the west in this fragment of the Gravity Anomaly Map of North America taken from Hanna et al., 1989. The Pico de Orizaba–Laguna Inferior Megashear (northwest-southeast) limits this subbasin to the southwest, continues through the Tehuantepec Isthmus, and ends near the beginning of the Motagua-Polochic fault system in Guatemala. Numbers keyed to features are noted in the text of Hanna et al., 1989.**

1) The origin of the Tampico-Misantla Subbasin caused by dextral displacement of the Huayacocotla Block and initial deposition of fluvial-lacustrine sediments during the late Early Jurassic in the subbasin's deeper, northwestern depression, as a result of northwest tilting. Based on palynostratigraphic, organic, and inorganic data (Rueda-Gaxiola, 1975; Rueda-Gaxiola et al., 1982a,b; Rueda-Gaxiola et al., 1997a, b), this part of the subbasin began to fill (Figure 1) with red-bed fluvial-lacustrine sediments followed by marine sediments derived from the epicontinental late Liassic sea.
2) Uplift and erosion of Liassic strata deposited in the Huayacocotla–El Alamar Basin produced the Cahuasas Formation red beds. Red beds were deposited on the Rosario Formation in the northern portion of the Tampico-Misantla Subbasin and at the base of small grabens formed by normal faults parallel to the Tampico–Lázaro Cárdenas Megashear in the central and southern parts of the basin. The Rosario Formation was covered by a Middle and Late Jurassic transgressive marine sequence that began with the

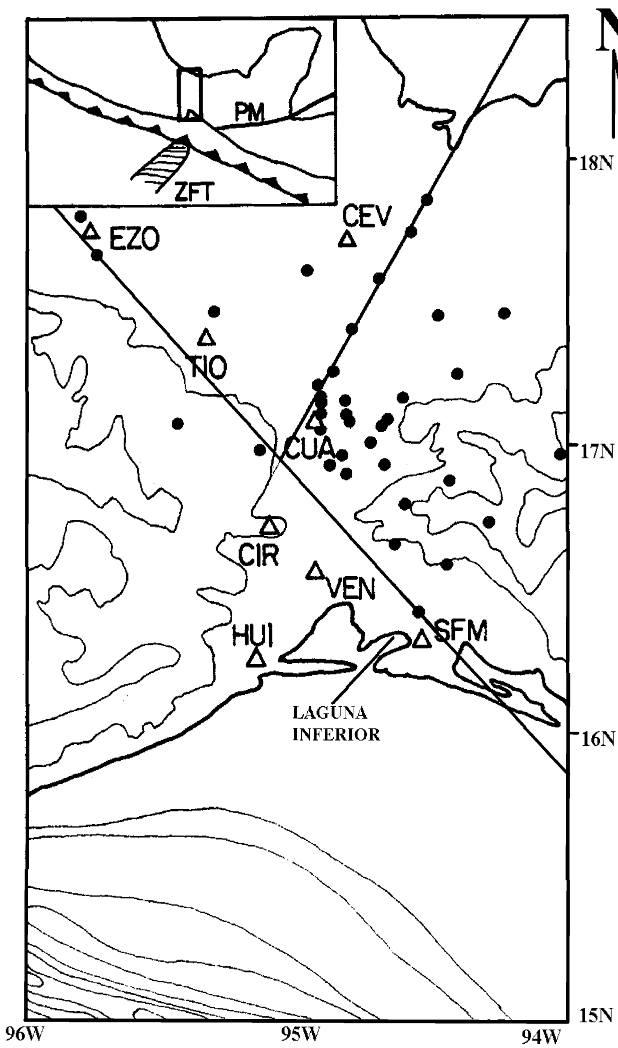


Figure 10. Position of 40 earthquake epicenters in the Tehuantepec Isthmus, detected from April to May, 1986. CUA = Cuauhtemoc Seismic Station. EZO = El Azufre Seismic Station. TIO = Tres Islas Seismic Station. CEV = Cerro Encantado Seismic Station. CIR = La Ciruela Seismic Station. HUI = Huilotepec Seismic Station. VEN = La Ventosa Seismic Station. SFM = San Francisco del Mar Seismic Station. PM = Polochi-Motagua transform faults system. ZFT = Tehuantepec fractured zone (Ligorria and Ponce, 1993).

Callovian Tepéxic Formation (Pacific affinity), followed by Late Jurassic rocks of Atlantic affinity that represent the origin of the Gulf of Mexico.

3) The Tlaxiaco Basin was filled with late Liassic fluvio-marine rocks of the Consuelo Group. The Tlaxiaco Block was also tilted toward the northwest as a consequence of its dextral displacement along the Teziutlán-Acapulco Megashear. Therefore, this basin's origin is similar to that of the northern part of the Tampico-Misantla Subbasin. It also was filled by an epicontinental sea of Pacific affinity. Block motion continued during the Middle Jurassic and produced uplift and erosion of the Tlaxiaco Block, and resulted in the molassic sediments of the Cualac Formation. The Cualac Formation was deposited over the Consuelo Group to the southwest (Rueda-Gaxiola and Jiménez-Rentería, 1996) and over the Huamuxtitlán Basin basement rock (Williams-Rojas et al., 1997). The Cualac Formation was covered by the Middle–Upper Jurassic Tecocoyunca Group, which is well defined by the Bajocian Taberna Formation.

Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears

Late Liassic paleogeography was controlled by the position and displacement of the Huayacocotla and Tlaxiaco Blocks along the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears, which are still active.

- **The Tampico–Lázaro Cárdenas Megashear** follows the Pánuco and Moctezuma Rivers in northeastern Mexico. It forms a well-defined geologic boundary along which the Mesozoic lithostratigraphic units of the Huayacocotla Block were displaced to the southeast with respect to the Huizachal-Peregrina Block. In this region, there is a depression to the south of this boundary and a high rim to the north. South of the megashear, the Huayacocotla Anticlinorium and the younger volcanic rocks in the Transmexican volcanic belt occur at the highest elevations in Mexico. Toward the southwest, this megashear continues through Acámbaro in the state of Michoacán, west of the Caldera de Pathé in the state of Hidalgo, and through Zitácuaro in the state of Michoacán. It finally reaches the Pacific Ocean at the mouth of the Balsas River.
- **The Teziutlán-Acapulco Megashear** is clear on Mexican geologic and tectonic maps; it forms the northwestern border of the Tlaxiaco Block and has a high topographic expression. This block is bounded on the southeast by the Huayacocotla Block. The Teziutlán-Acapulco Megashear begins northeast of Teziutlán, continues toward the southwest through the Los Humeros Caldera and the Atoyac River, passes east of Chilpancingo, and reaches the Pacific Ocean east of Acapulco.

Because the Balsas River is born in the Teziutlán-Acapulco Megashear and ends in the Tampico–Lázaro Cárdenas Megashear, and because the Pánuco-Moctezuma River flows northwest, it is possible to consider the Huayacocotla Block as being tilted presently toward the northwest (Figure 15).

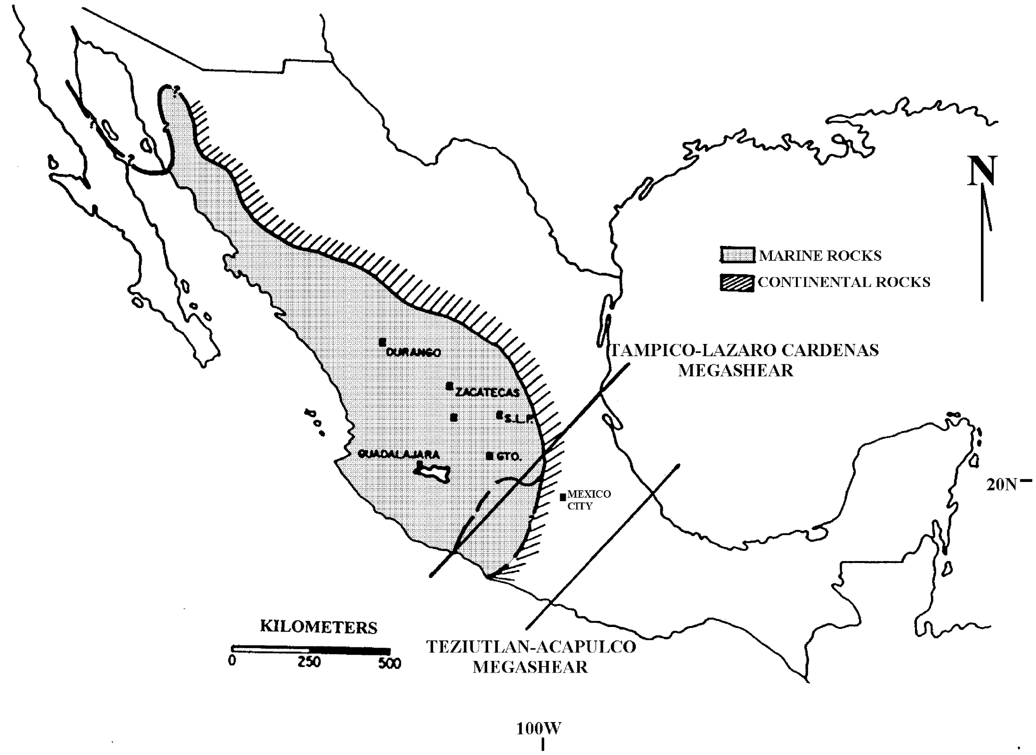


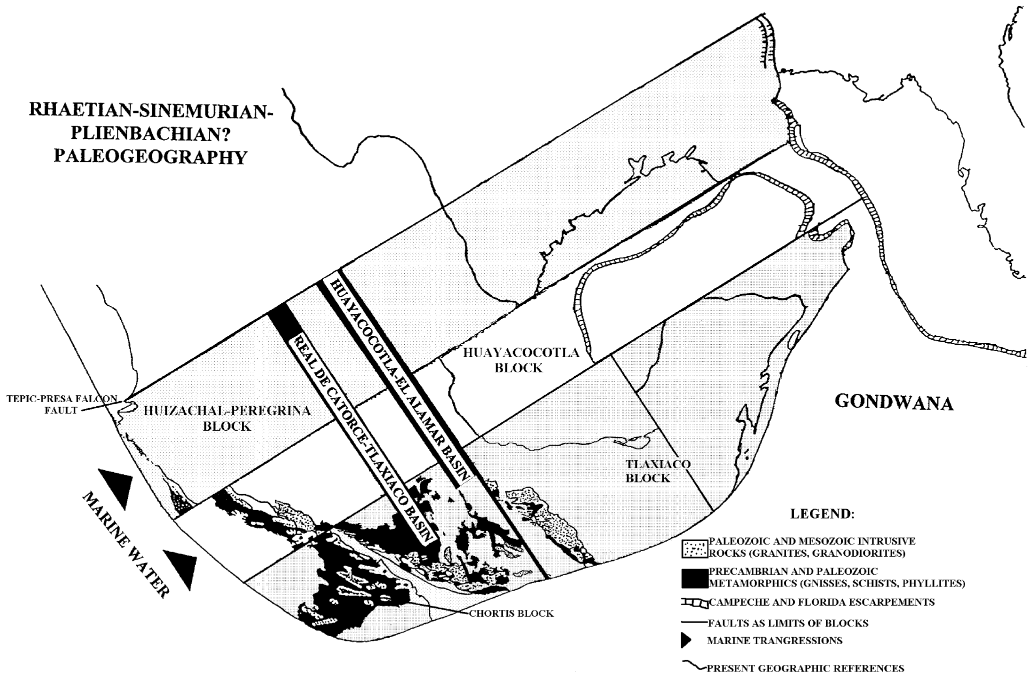
Figure 11. Present distribution of Triassic marine rocks (López-Ramos, 1974; Carrillo-Bravo, 1982; Romero-Espejel, 1985; Gómez-Luna et al., 1997).

The Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears are well represented in the Pacific Ocean and Gulf of Mexico continental shelves. In the Pacific continental shelf, the Teziutlán-Acapulco Megashear appears to be the limit of the uplifted Tlaxiaco Block, expressed in bathymetry and in surface morphological features of the Acapulco Trench and abyssal plain. The Tampico–Lázaro Cárdenas Megashear is better represented in the Gulf of Mexico continental shelf than on the Pacific shelf, as its continuity to the northeast is shown by a change in orientation of folding of the Zona de Crestas Mexicanas, as shown in the Carta Tectónica de México, Universidad Nacional Autónoma de México-Instituto Nacional de Estadistica Geografía e Informática (1994), and in the Carta de Geología Marina IV. 1.1., in the Atlas Nacional de México, 1991. Both megashears represent fault systems that allowed lava extrusions in the Tampico-Misantla Subbasin during the Tertiary; that control the flow of the Tuxpan, Cazones, and Tecolutla Rivers; and that contain northeast-southwest mineralized alignments (Salas et al., 1975).

At present, the boundaries of the Huayacocotla Block show important seismic activity. Some earthquakes of more than 7 on the Richter scale have occurred along the Teziutlán-Acapulco Megashear. Historical seismicity in the state of Guerrero from 1900 to 1982 (Rosas-Jurado, 1990, and Figure 1 from Singh et al., 1980), shows that the Teziutlán-Acapulco Megashear system has produced at least 12 earthquakes since 1875, and the Tampico–Lázaro-Cárdenas system has produced only a few. The September 19 and 21, 1985, earthquakes that affected Mexico City were produced by movement of the Cocos Plate at a depth of 17 km. Foci were located on both sides of the Tampico–Lázaro Cárdenas Megashear, about 100 km apart (Eissler et al., 1995). Figure 16 is an isoseismic map (Ortega-Gutiérrez, 1985) that shows the distribution of isoseismic lines in both the Huizachal-Peregrina and Huayacocotla Blocks. The distribution on the latter is more uniform between the Balsas and Moctezuma Rivers, showing an exponential diminishing of the wave propagation pattern as it approaches Mexico City. At Mexico City, the waves were amplified (intensity IX) by the subsoil materials.

The Brecha de Guerrero (Guerrero gap) is bounded by both megashears (Figure 17); here, subduction processes of the Orozco and Cocos Plates produce only low-magnitude earthquakes. Because the Huayacocotla Block has been deeper since the Late Triassic than the Huizachal-Peregrina and Tlaxiaco Blocks, the slope of the subduction zone (Figure 18A and Geología Marina map IV. 9.5: Atlas Nacional de México, 1991) under these three blocks is not

Figure 12. Late Triassic–early Liassic paleogeography. The Chortis Block and the Mixtequita and Chiapas massifs have been placed at their original position. Huayacocotla–El Alamar and Real de Catorce–Tlaxiaco graben basins formed as a result of the western subduction system.



uniform. This could explain why the subducting oceanic plate reaches a depth of approximately 100 km under the Huizachal-Peregrina and Tlaxiaco Blocks, whereas it reaches a depth of 150 km under the Huayacocotla Block (Hanus and Vanek, 1978). It also seems to explain why the upper part of the Wadati-Benioff zone has different slopes under these three blocks (Figures 18 and 19). The zone is steep under the Huizachal-Peregrina Block (sections i–l, Figure 3, Pardo and Suárez, 1995), gentle under the Huayacocotla Block (sections e–h, Figure 3, Pardo and Suárez, 1995), and steep under the Tlaxiaco Block (sections a–d, Figure 3, Pardo and Suárez, 1995). Subduction depths and angles of subduction also explain the change in direction of tension axes of the earthquake focal mechanisms (Figure 19; Pardo and Suárez, 1995) in southern Mexico, as well as present volcanic activity that is more distant from the coastline in the Huayacocotla Block than in the Huizachal-Peregrina Block (Figure 17). Varying subduction depths and angles also may explain the relationship of volcanic provinces (Figure 20) to the

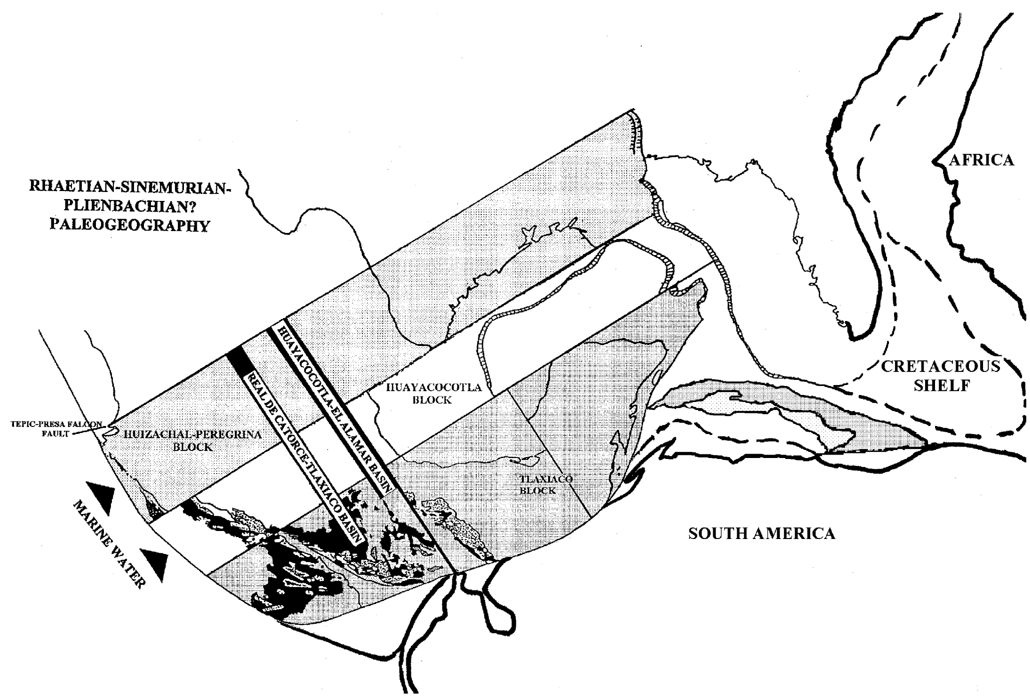


Figure 13. Geographic relationship between North and South America and Africa during the Late Triassic–early Liassic. Continental margins of eastern North America, Africa, and South America are based on Hall (1990). The Tlaxiaco Block and South America remained joined until the latest Jurassic–Early Cretaceous.

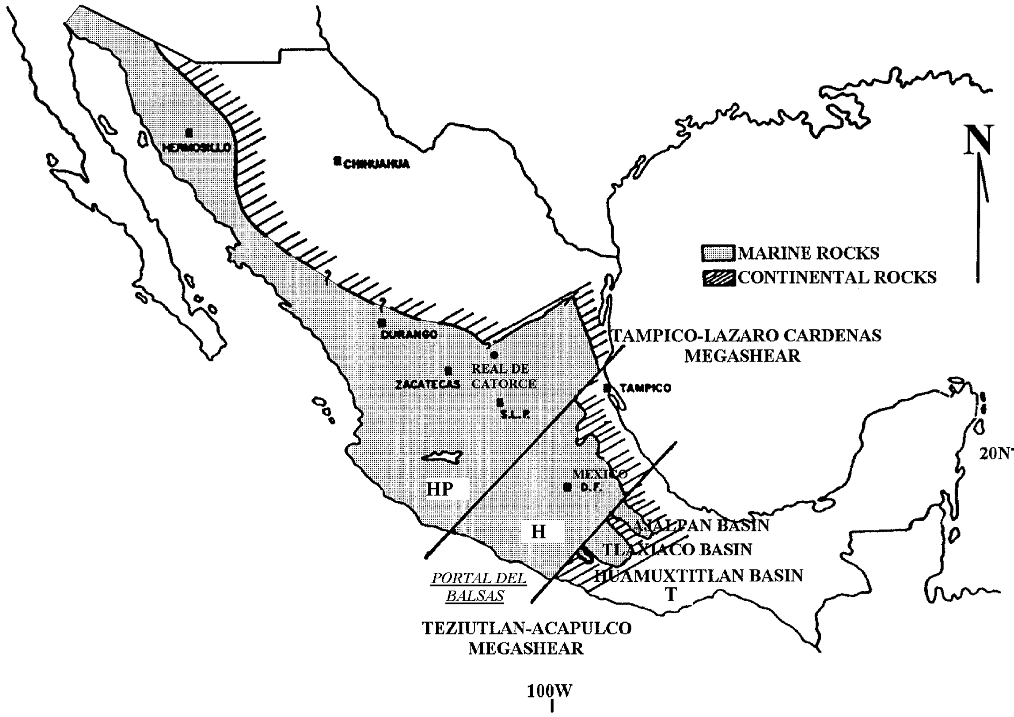


Figure 14. Present distribution of Liassic marine rocks in the Huizachal-Peregrina (HP), Huayacocotla (H), and Tlaxiaco (T) Blocks. These rocks were displaced to the southwest at the end of the Liassic.

position of Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears (Pasquaré et al., 1991).

Figure 21 shows late Liassic paleogeography in which mountains formed at the Huayacocotla Anticlinorium (see Figure 2) as a result of southwestward displacement of the Huayacocotla Block and compression of the aulacogen. The triple junction northeast of Tampico may have been initiated during this time, with rifting occurring above sea level and producing the basal red-bed fluvial-lacustrine deltaic sediments deposited in the southeastern part of the "Cuenca de la Formación Rosario," located north of the Tampico-Misantla Subbasin (see Figure 1).

The Tlaxiaco Basin and the northern part of the Tampico-Misantla Subbasin (Rueda-Gaxiola, 1975; Rueda-Gaxiola et al., 1982a,b) were part of the same sea in which marine rocks were deposited on fluvial-lacustrine deltaic rocks and were, in turn, covered by the Cahuasas Formation red beds derived from the west.

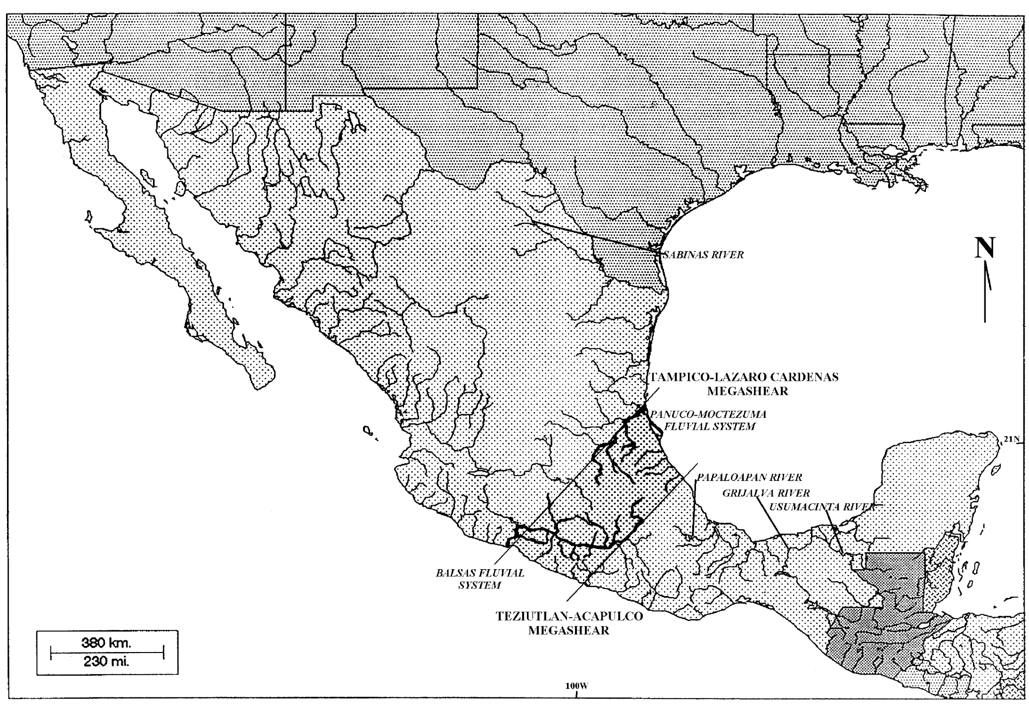


Figure 15. The principal rivers of Mexico. The location of the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears shows that the deltas and mouths of the Pánuco-Moctezuma and Balsas Rivers are controlled by these tectonic features.

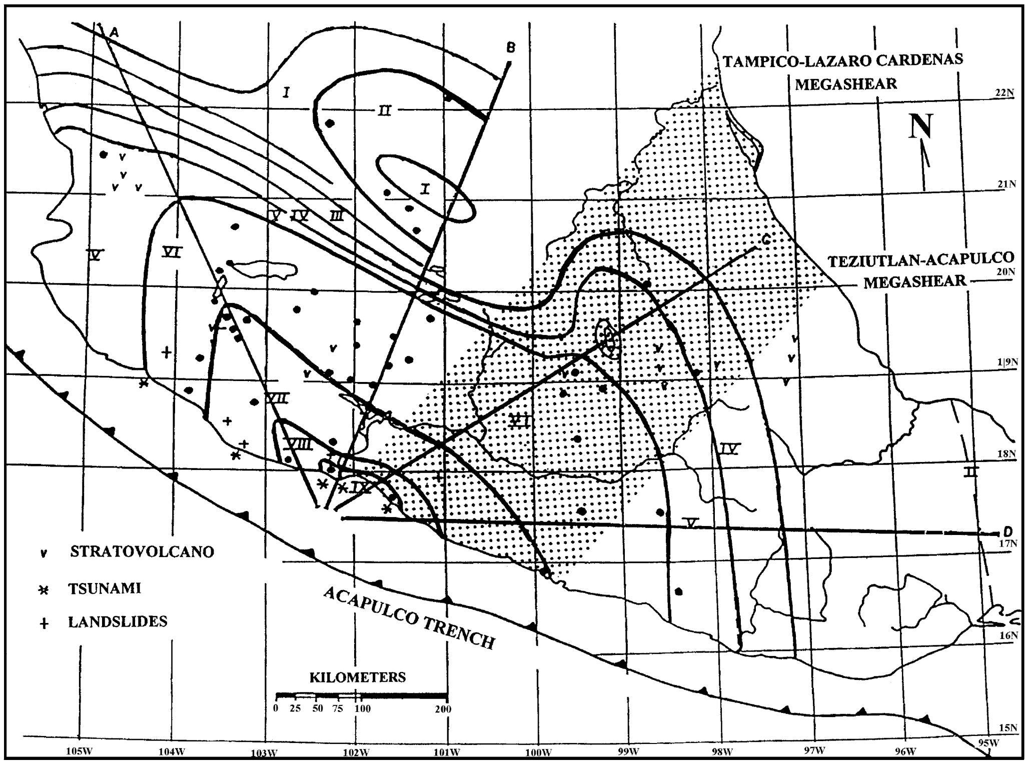


Figure 16. Isoseismic map after the 8.1-degree earthquake on September 19th, 1985. Propagation of seismic waves was controlled by the megashears at the limits of tectonic blocks. The Guerrero gap (see Figure 22) at the subduction zone is also bounded by the same megashears. Shading depicts the Huayacocotla Block (Ortega-Gutiérrez, 1985, internal report).

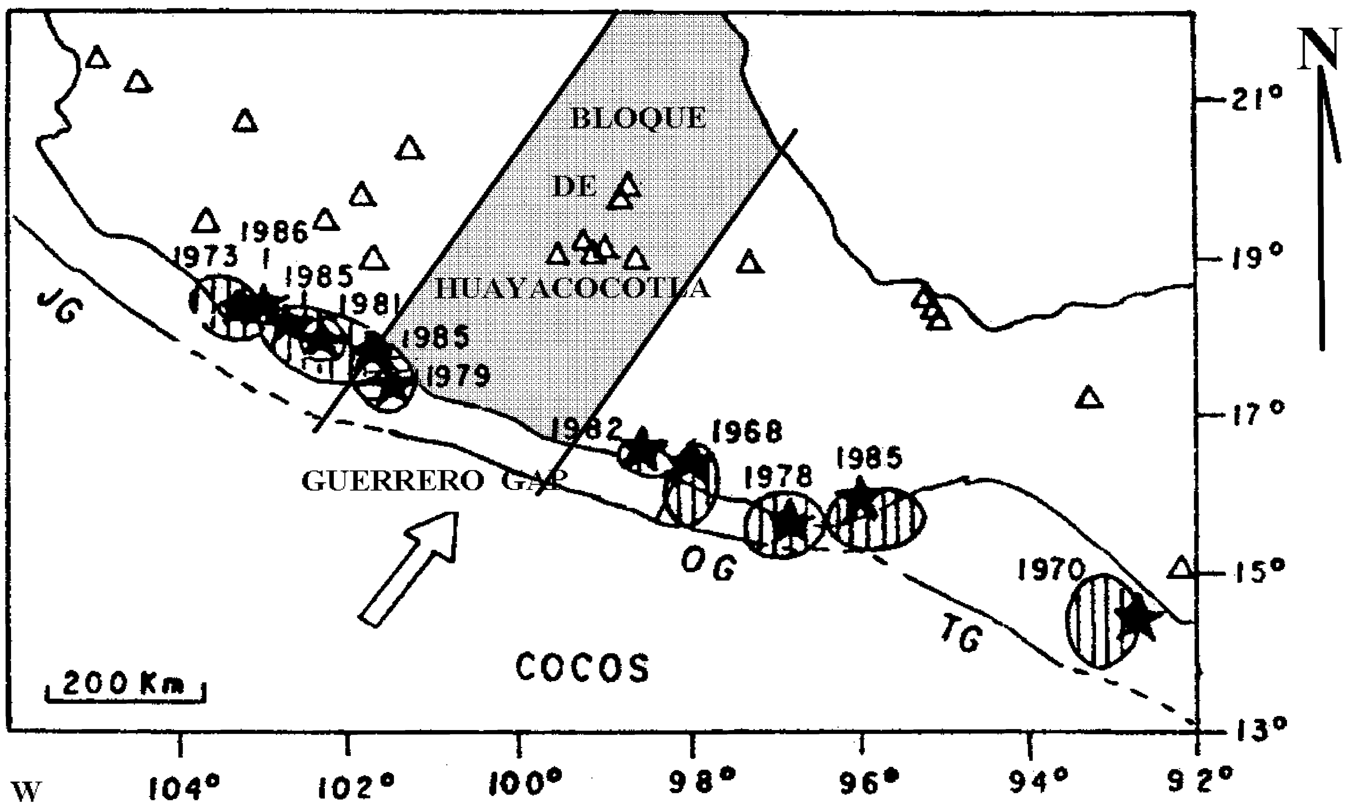


Figure 17. The Guerrero seismic gap is bounded by the Tampico–Lázaro Cárdenas and Teziutlán Megashears. No earthquakes of magnitude greater than 7 degrees have been reported since 1979. JG = Jalisco gap; OG = Oaxaca gap; and TG = Tehuantepec gap. Triangles represent volcanoes (modified after Rosas-Jurado, 1990).

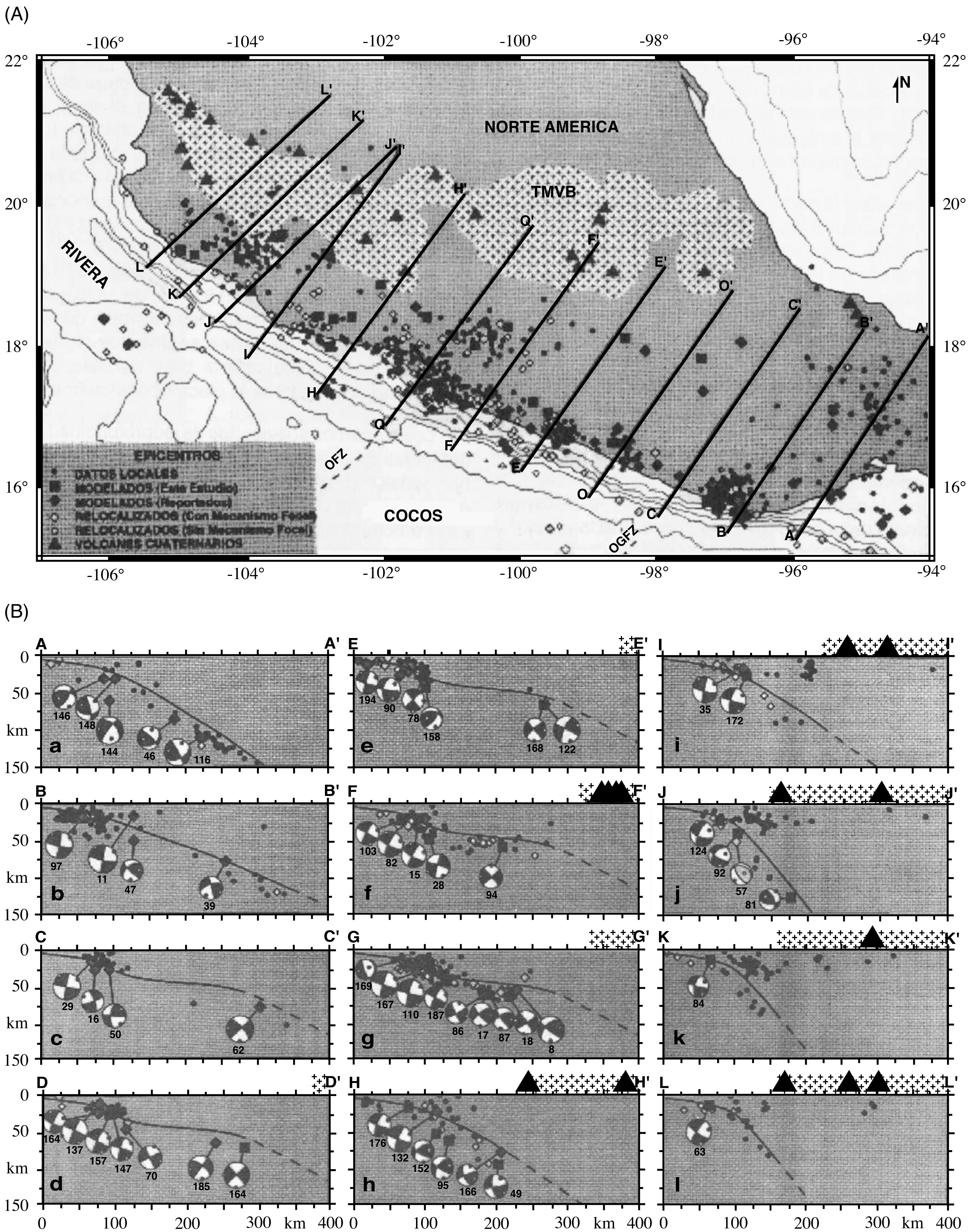


Figure 18. (A) Location of epicenters used to define the subduction geometry of the Rivera and Cocos Plates; presented in 12 sections (B). Orozco subplate is located between the Rivera subplate and the Cocos Plate. TMVB = transMexican volcanic belt (modified after Pardo and Suárez, 1995).

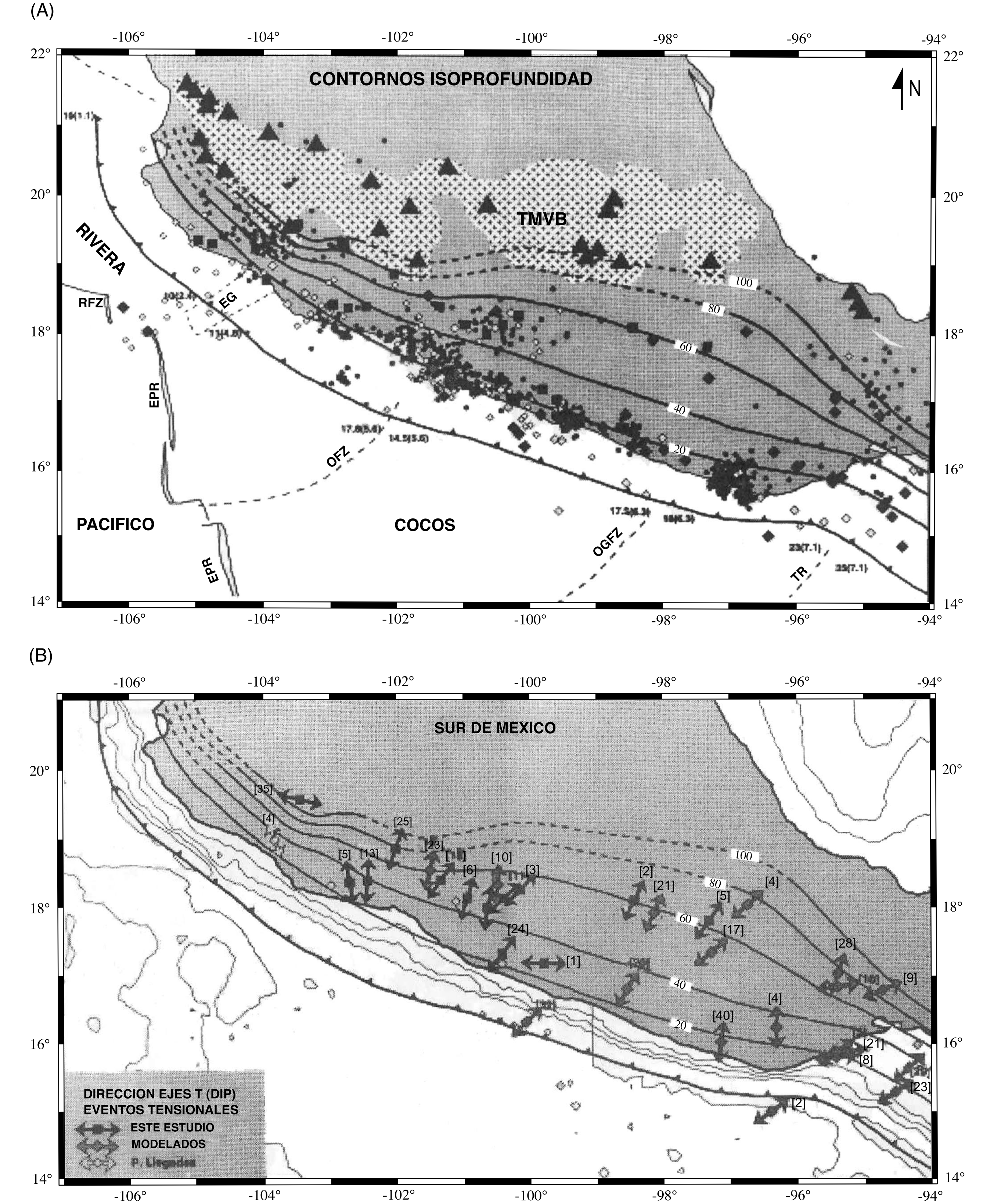


Figure 19. Pardo and Suárez (1995) show lines of the same depth, each 20 km from the upper limit of the Wadati-Benioff zone. In (A) it is possible to see the relationship between epicenters, the position of principal volcanoes, and the tectonic blocks limited by the Tampico–Lázaro Cárdenas (A-Á), Teziutlán-Acapulco (B-B́), and Pico de Orizaba–Laguna Inferior (C-Ć) Megashears. (B) shows the changes of direction of tension axes of the focal mechanisms of earthquakes reported in the tectonic blocks.

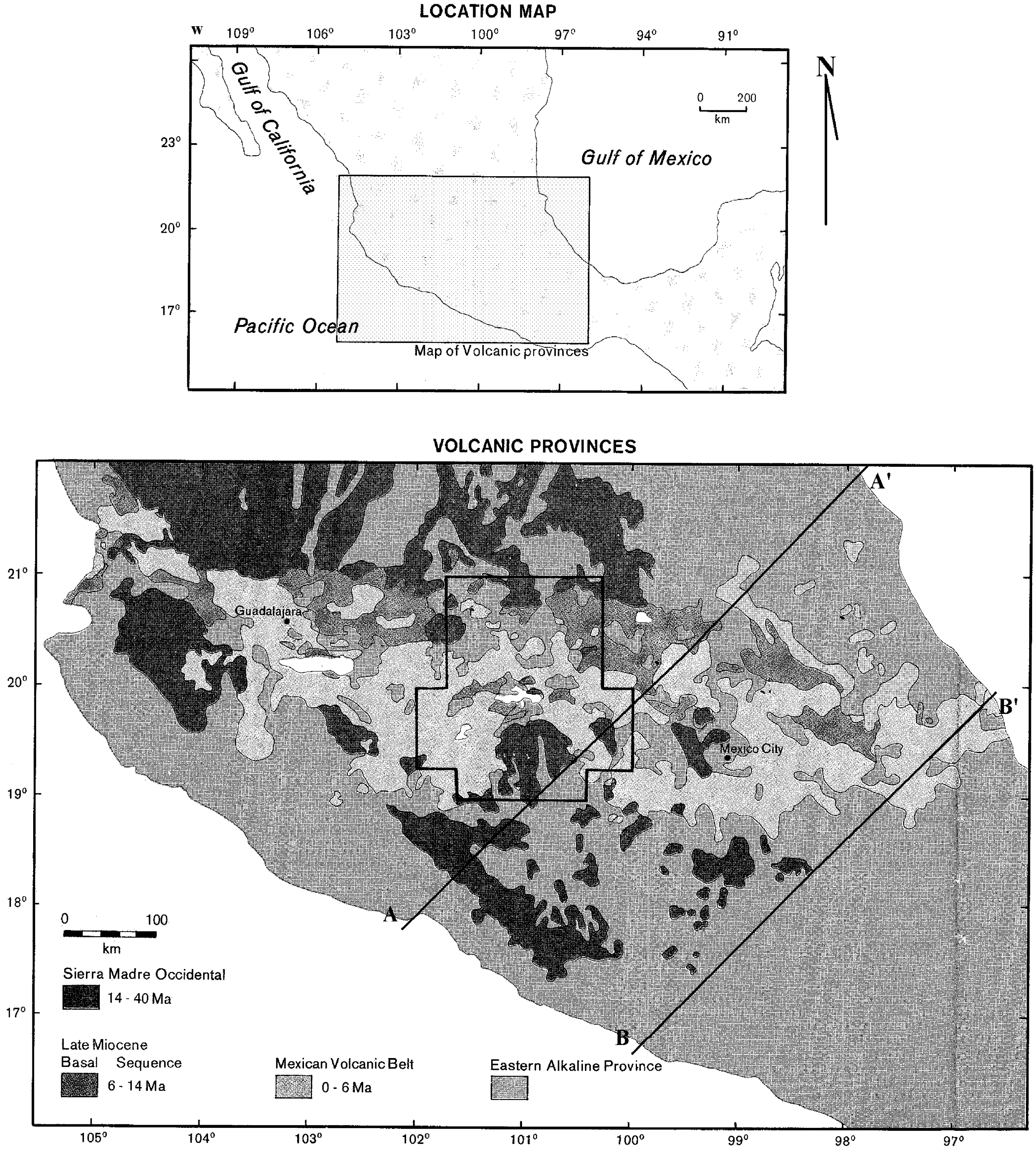


Figure 20. Central Mexico volcanic provinces (modified after Pasquaré et al., 1991). Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears are shown in order to reveal their relationship to the geology of the region.

Middle–late Jurassic to Late Cretaceous Paleogeography

The last stage in the evolution of the Gulf of Mexico involved a tensional Late Jurassic episode, followed by development of Cretaceous carbonate platforms. This stage began during the Bajocian, when a triple junction developed northeast of Tampico. Bajocian rifting processes gave origin to the Gulf of

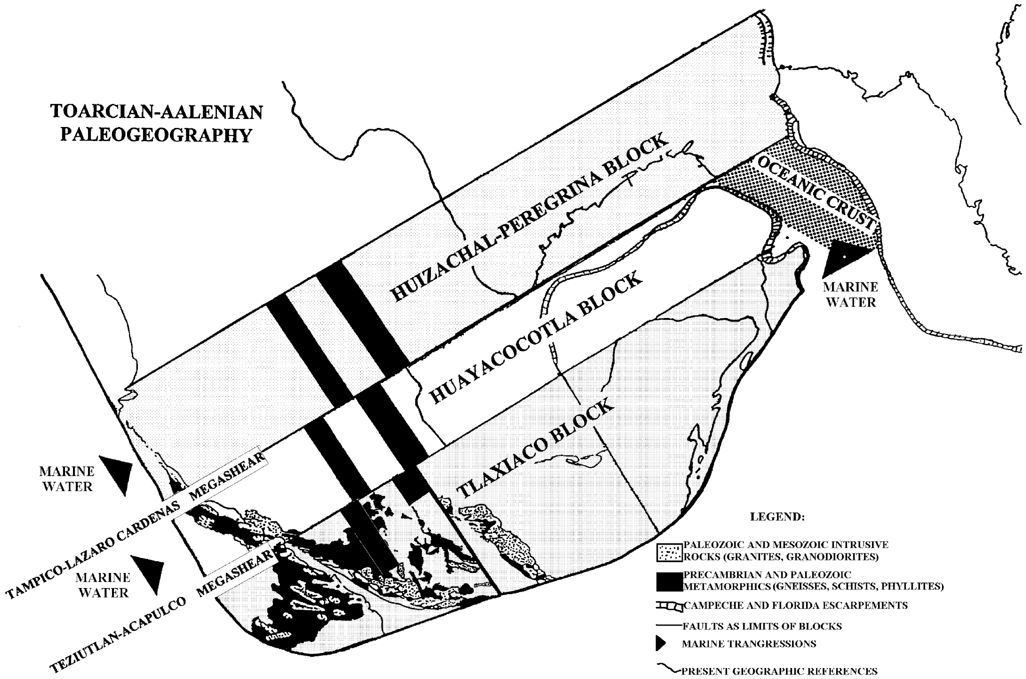


Figure 21. **Late Liassic paleogeography following the southwestward displacement of the Huayacocotla and Tlaxiaco Blocks along the Tampico–Lázaro Cárdenas and Teziutlán-Acapulco Megashears.**

Mexico and its Veracruz, Southeastern (Tabasco-Chiapas-Campeche), and Sabinas Subbasins, which were filled by Gulf waters that entered through the Campeche escarpment arm (Figure 9) of the triple junction. Palynostratigraphic studies confirm that the oldest marine rocks found in the Southeastern Subbasin are Bathonian (Rueda-Gaxiola and Dueñas, 1990; Xicalango 101 well) and are younger in the southeastern margin of the Veracruz Subbasin (Todos Santos Formation), as shown by dinoflagellate cysts.

Subsidence of the Huizachal-Peregrina, Huayacocotla, and Tlaxiaco Blocks formed three different types of carbonate platforms (Figure 22). The Morelos platform (Ortega-Gutiérrez et al., 1992) formed over the eastern portion of the Huayacocotla Block; it had a slower subsidence rate than the western portion and was bounded by a fault immediately to the west of the Tlaxiaco Block (Hernández-Romano, 1995). The Valles–San Luís Potosí (Carrillo-Bravo, 1982) and Tuxpan platforms, both of which contained large reef structures, developed over the subsiding Huizachal-Peregrina Block, and the Córdoba platform developed over the Tlaxiaco Block.

Figures 23 and 24 show the paleogeography of the Gulf of Mexico during the Middle–Late Jurassic based on tectonic, red-bed, and salt palynostratigraphic information. Figure 25 shows Middle–Late Cretaceous paleogeography after the platform stage and before displacement of the Chortis block.

THE MEXICAN OIL SUBBASINS OF THE GULF OF MEXICO

Tampico-Misantla Subbasin

The basement of the Tampico-Misantla Subbasin is formed by Permian-Triassic granitoids and overlying metamorphic rocks. It is bounded to the northwest by the Huizachal-Peregrina Block and the Tampico–Lázaro Cárdenas Megashear and to the southeast by the Teziutlán massif and the Teziutlán-Acapulco Megashear (Figure 1). The subbasin originated by dextral displacement of the Huayacocotla Block, in the late Liassic. This displacement tilted the block to the northwest and northeast, creating a depression that was filled with strata of the Rosario Formation. The base of this formation contains red-bed fluvial-lacustrine rocks, sourced from the east, followed by marine sediments deposited in an epicontinental sea connected to the Pacific Ocean through the Portal del Balsas. The Rosario Formation is overlain by red beds of the Cahuasas Formation, which prograded from the west as a result of uplift and erosion of the early Liassic Huayacocotla Group. Rocks of the Bajocian-Bathonian Cahuasas Formation consist of a syntectonic alluvial fan, piedmont, and flood-plain strata deposited in depressions formed during Late Jurassic flexure between the highlands to the east and the Huayacocotla Group uplift to the west. Locally, some grabens were filled with more than 1000 m of this unit (Soledad 101 Well). The Cahuasas Formation records compression, uplift, and erosion of the Huayacocotla Group, which was deposited during the aulacogen stage of the Huayacocotla–El Alamar Basin (Huayacocotla orogeny).

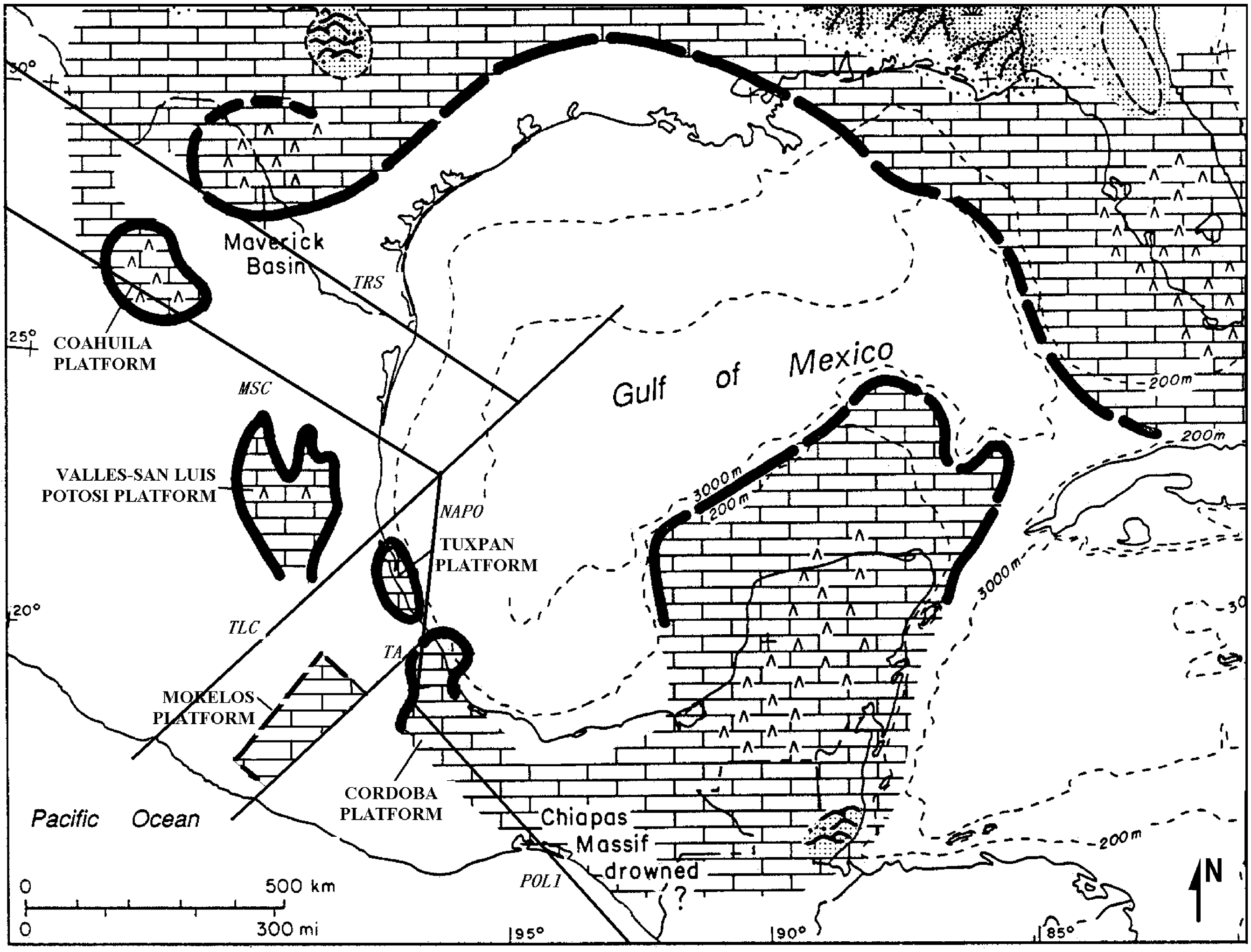


Figure 22. **Distribution of principal carbonate platforms and basins formed by displacement of the Mesozoic Tampico–Lázaro Cárdenas (TLC), Teziutlán-Acapulco (TA), Pico de Orizaba–Laguna Inferior (POLI), Mojave-Sonora-Caltam (MSC), and Texas–Río Sabinas (TRS) Megashears and the Nautla–Pico de Orizaba (NAPO) fault (modified after Salvador, 1991).**

These are small grabens parallel to both megashears and filled with Cahuasas Formation (red beds), oolitic Tepéxic Formation (Callovian–early Oxfordian), or the evaporites of the Huehuetepec Formation (Callovian).

Middle–Upper Jurassic strata of marine transgression from the Gulf of Mexico were deposited over the Tepéxic and Huehuetepec Formations. Sedimentation occurred in relative anoxic environments that were rich in organic matter and pyrite crystals in laminated calcareous rocks. This sequence overlapped the initially faulted Liassic rocks at the Huayacocotla Anticlinorium (Hernández-Treviño et al., 1996) to the west, the Topila-Pasarones uplifts to the east (Guzmán-Vega, 1991), and also part of the basement of the Faja de Oro (Golden Lane) atoll (Figure 26). These rocks record a transgression caused by cooling of this part of the crust after the triple junction rifted and after considerable southeastward displacement of the Yucatán-Campeche-Tabasco-Chiapas Block. This displacement slowed during the late Tithonian–Berriasian. Subsidence of carbonate platforms are contemporaneous to the Tampico–Lázaro Cárdenas Megashear. During the early Tertiary, both mechanisms gave birth to the Bejuco–La Laja Canyon in the Tampico-Misantla Subbasin (Figure 26). This subbasin is an MS (continental margin sag) type (Kingston et al., 1983), and corresponds to a marginal plate basin in a divergent system formed in continental crust.

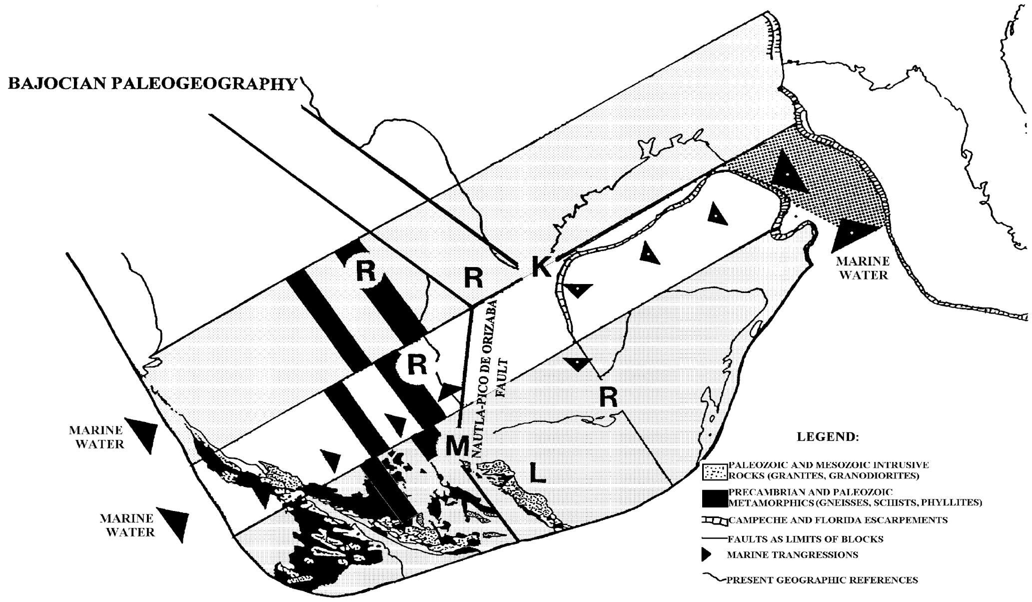


Figure 23. Bajocian triple junction, initial displacement of blocks, and marine transgression from Pacific and Tethys seas above the Huayacocotla and Tlaxiaco Blocks. K, L, M, and R are areas studied by the cited authors. (K = Kirkland and Gerhard, 1971; L = Gutiérrez-Galicia, 1984; M = Dueñas, 1990; and R = Rueda-Gaxiola, 1967, 1977, 1999, and Rueda-Gaxiola et al., 1982a,b, 1990, 1993, 1994, 1996, 1197a,b, 1999).

Veracruz Subbasin

By the end of the Early Jurassic, the Tlaxiaco Block had started to break up along the El Pico de Orizaba–Laguna Inferior Megashear (Figures 24 and 26). This break-up was a result of the opening of two branches of the triple junction that caused relative southeast displacement of the northeast portion of the Tlaxiaco Block during the Middle–Late Jurassic. The triple junction is defined by the southwest-northeast Escarpe de Campeche (see Figure 9), the north-south Nautla–Jalapa–Pico de Orizaba fault (see Figure 23), and the southeast-northwest Mohave-Sonora-Caltam Megashear (Figures 24 and 27). This displacement formed the Veracruz Subbasin, which is bordered on the southwest by the El Pico de Orizaba–Laguna Inferior Megashear. To the northwest, this basin is bounded by the north-northeast–south-southwest Nautla–Jalapa–Pico de Orizaba fault (Figure 23), which is the southeastern boundary of the Teziutlán massif; to the southeast, the Veracruz Subbasin is bounded by the

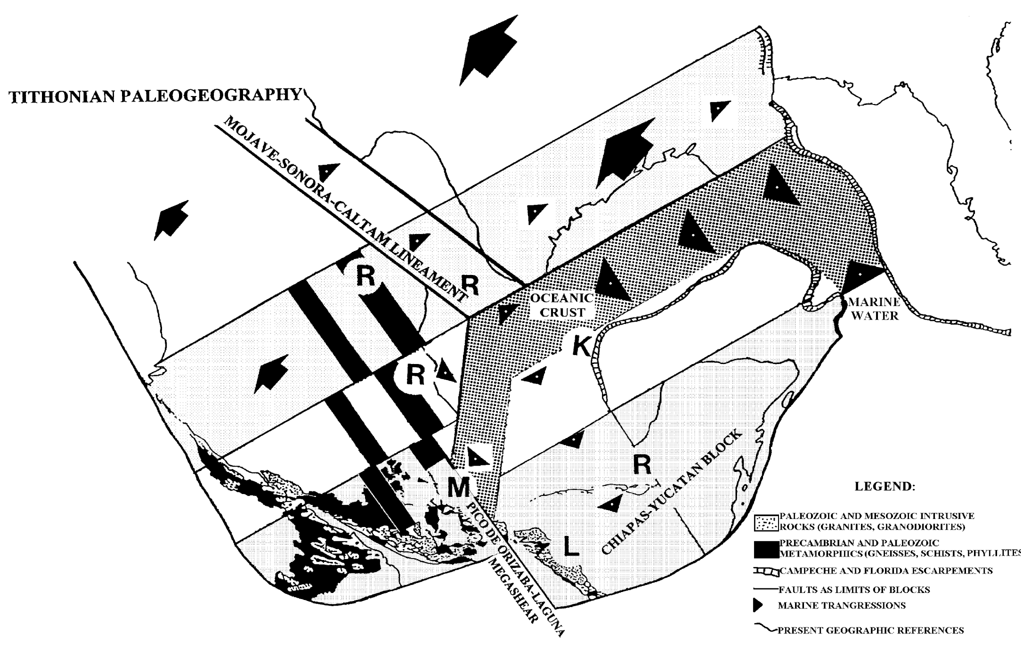


Figure 24. Evolution of the triple junction in the Tithonian showing the northwestward displacement of the Texas-Louisiana and Western Blocks from the static Chiapas-Yucatán Block. The Gulf of Mexico marine transgression covered all the petroleum subbasins, and the Tehuantepec Isthmus was formed. K, L, M, and R are areas studied by the cited authors. (K = Kirkland and Gerhard, 1971; L = Gutiérrez-Galicia, 1984; M = Dueñas, 1990; and R = Rueda-Gaxiola, 1967, 1977, 1999, and Rueda-Gaxiola et al., 1982a,b, 1990, 1993, 1994, 1996, 1197a,b, 1999).

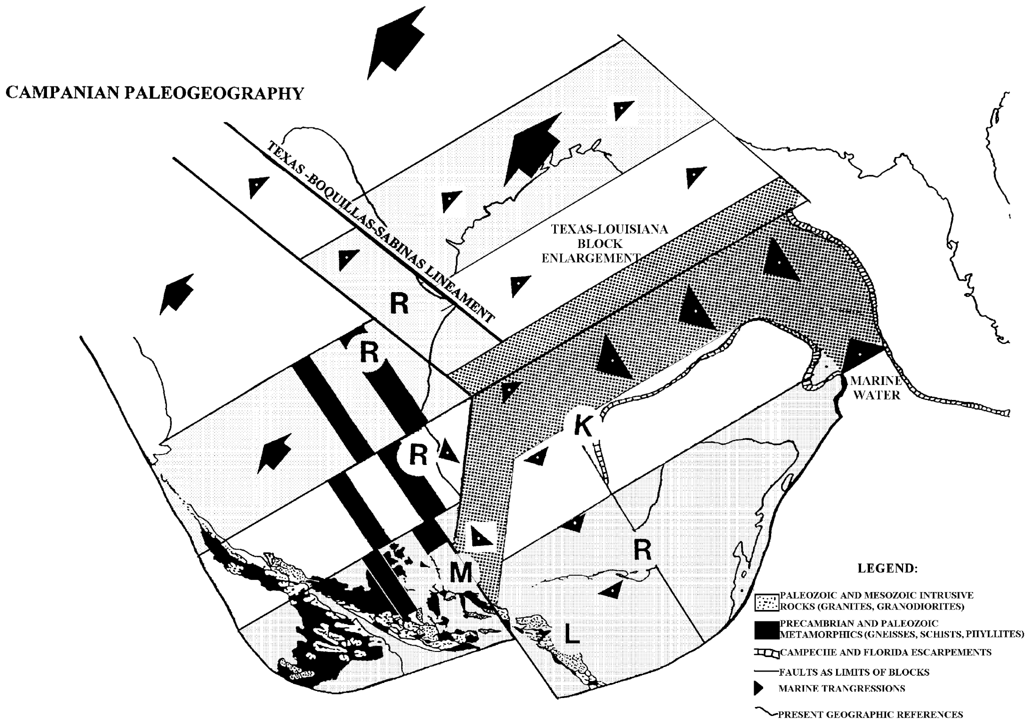


Figure 25. Paleogeographic map showing the stage of almost maximum displacement and extension of the Texas-Louisiana Block toward the northwest, just before initial displacement of the Chortis Block toward the southeast. The Gulf of Mexico subbasins began to fill with siliciclastic sediments coming from the west as a result of uplifting of the western region of the North American continent during the Late Cretaceous. K, L, M, and R are areas studied by the cited authors. (K = Kirkland and Gerhard, 1971; L = Gutiérrez-Galicia, 1984; M = Dueñas, 1990; and R = Rueda-Gaxiola, 1967, 1977, 1999, and Rueda-Gaxiola et al., 1982a,b, 1990, 1993, 1994, 1996, 1197a,b, 1999).

north-northeast–south-southwest Cuauhtémoc–San Andrés Tuxtla–Veracruz Canyon fault (Figures 9 and 10). The Veracruz Basin is a deep depression filled by more than 10,000 m of sediments. The red-bed Todos Santos Formation was deposited over the Tlaxiaco Block bordering the El Pico de Orizaba–Laguna Inferior megashear on the southwest (Figure 24 and 26). It was derived from the Sierra de Chiapas uplift (Vázquez-Meneses et al., 1992).

In the northwestern region of the Teziutlán massif (Figure 2), the basement is composed of schists and granites and is covered by the red-bed Huizachal Alloformation and marine Huayacocotla Formation. These units are unconformably overlain by red beds of the Cahuasas Formation. Locally, Cretaceous Tamaulipas Inferior, Horizonte Otates, Tamaulipas Superior, Agua Nueva, San Felipe, and Méndez Formations are present and the Cenozoic Chicontepec, Aragón, Guayabal, Chapapote, and Horcones Formations are exposed in a few localities. This sequence suggests that, to the northwest, the sedimentary history of the Teziutlán massif was directly related to the evolution of the Huayacocotla–El Alamar Basin and the Tampico-Misantla Subbasin.

Regional uplift was produced by Cenozoic granite and granodiorite intrusions that presently outcrop in the Tatatila–Las Minas region; east of the massif, Cenozoic volcanism occurred in a large number of volcanoes located along a north-northeast–south-southwest trend (Consejo de Recursos Minerales, 1994) extending from Nautla, through Jalapa, and ending at El Pico de Orizaba volcano. This is the most conspicuous northwestern boundary of the Veracruz Subbasin. Several large northeast-southwest faults cross these massifs; they are normal and strike-slip faults that cause deep ravines. The most important strike-slip fault is the Teziutlán-Acapulco Megashear that can be followed northeast in this region to the coast along a regional ultrabasic rock trend (Negendank et al., 1985) and southwest along the alignment of the Los Humeros caldera (Yañez-García and García-Durán, 1982) to Acapulco.

In the Veracruz Subbasin several wells have encountered a Tertiary clastic sedimentary sequence, thousands of meters thick, deposited over the Cretaceous platform strata located at more than 8,000 m. Northwest of the Mixtequita batholith, the Ixcatlán Well encountered Jurassic rocks at 6450 m (see Figure 8). Seismic sections show that the Cretaceous rocks are folded and thrusted, and that the Tertiary sequence is less deformed. This Tertiary clastic sequence is separated by an unconformity between the

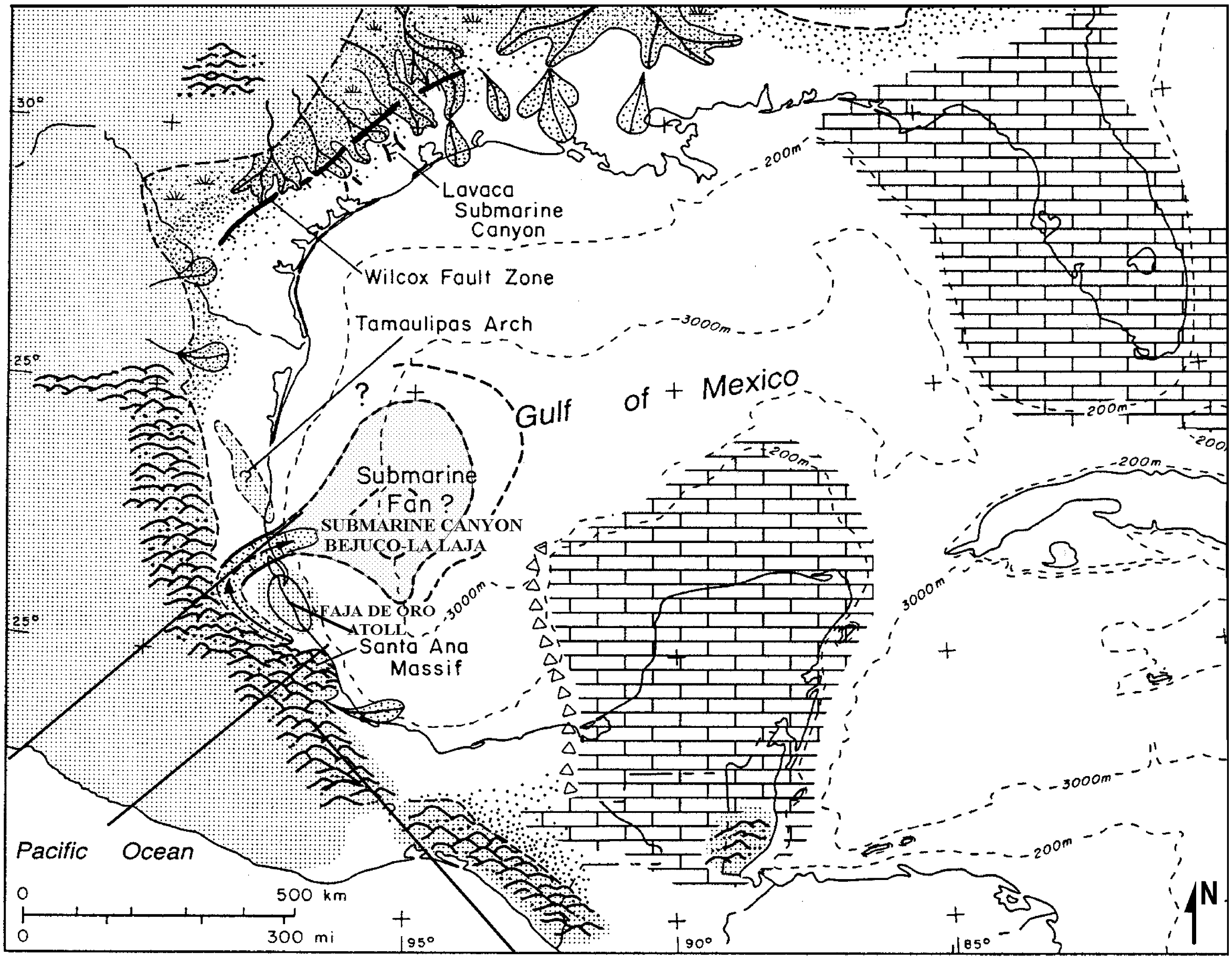


Figure 26. Relationship between the Tampico–Lázaro Cárdenas Megashear and the emplacement of the Bejuco–La Laja submarine canyon (Flores-Balboa, 1962). The three principal Megashears are shown. (Modified after Salvador, 1991b).

lower–middle Eocene and the upper Eocene–upper Miocene units. The latter (8900-m thick) overlaps the Cretaceous thrusted sequence to the west. Toward the northeast, seismic data show that the northwest-southeast Anegada uplift may have formed by lithospheric flexure or by a dextral fault related to the displacement of the Yucatán block to the southeast (Meneses-Rocha et al., 1997) followed by extrusion of alkaline magmas. This fault seems to be related to the Loma Bonita fault and also may be part of the El Pico de Orizaba–Laguna Inferior megashear system.

In explaining the origin of the Gulf of Mexico, it has been assumed that the Yucatán Block underwent a relative displacement toward the southeast (Salvador and Green, 1980; Dengo, 1983; Pindell, 1985; Dunbar and Sawyer, 1987; Herrera and Villaseñor, 1991; Guzmán, 1991). However, there is no evidence that displacement occurred in this direction, (Figure 13). There is no evidence of any subduction zone or other related evidences on the southeastern margin of the Yucatán peninsula that could have allowed movement in this direction; based on tectonic and volcanic evidence, the southeastern margin of the Veracruz Subbasin is the most active one. In fact, the southeastern margin of the Yucatán peninsula is a left-lateral margin produced by displacement of the Cuban continental block to the northeast. However, Marton and Buffler (1993) explain the evolution of the Gulf of Mexico as a conjugate passive margin where the Yucatán block moved southeastward by means of a detachment fault toward the distal margin.

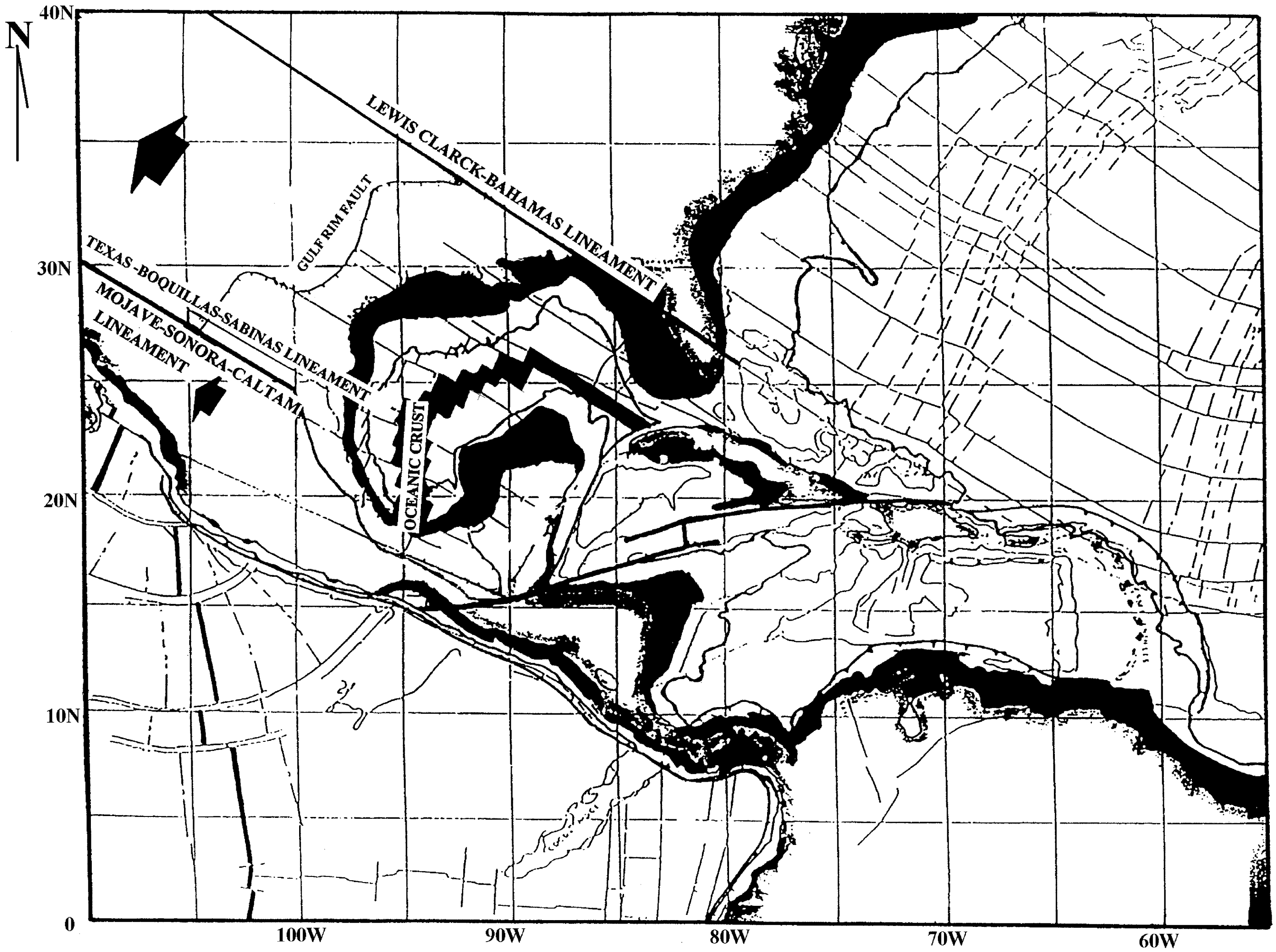


Figure 27. **Actual displacement and extension toward the northwest of the Texas-Louisiana Block along the Lewis Clark–Bahamas Megashear in the northeast, and the Texas lineament–Boquillas-Sabinas and Mohave-Sonora-Caltam Megashears in the southwest. The line of the Gulf Rim fault zone shows approximately the maximum displacement and lengthening of this block from the northwestern border of oceanic crust. Distribution of oceanic rocks in the center of the Gulf and continental shelves are marked in black. (Modified from Klitgord and Schouten, 1986).**

If the Chiapas-Tabasco-Campeche-Yucatán Block could not be displaced southeastward because during the Jurassic it was a fixed plate still joined to the South American continent, including Cuba (Figure 13), the rest of the continent might have been displaced northwestward. The origin of the Chihuahua-Sabinas Subbasin and the displacement of the Paleozoic Marathon-Washita system northwestward seems to support this concept. In this scenario, the Gulf of Mexico is not related to southeastern displacement of the Yucatán Block but to northwest displacement of the rest of North America (Figures 24, 25, and 27). This was possible because:

1) During the Mesozoic, there was a subduction zone on the western border of North America (Oldow et al., 1989).
2) The Veracruz Subbasin tilted to the northwest as a result of thermal cooling of the oceanic floor and compaction of overlying sediments.
3) The red beds of the Todos Santos Formation, bordering the Veracruz Subbasin, are older toward the northwest because they were initially deposited during northwestward displacement of the continent.
4) Volcanic and seismic events are much more active on the southeastern margin (San Andrés Tuxtlas volcanoes) than on the northwestern margin. In the latter, however, there still is thermal activity, as evidenced by hot water springs.

Based on these characteristics, the Veracruz Subbasin may be classified as type OS (oceanic sag), after Kingston et al. (1983); that is, the subbasin was formed over a cooling, rapidly subsiding ocean in a pull-apart setting (Prost and Aranda, 2001).

Southeastern Subbasin

The Southeastern Subbasin was named in 1992 by González-García and Holguín-Quiñonez (Figures 1 and 28). It was the product of displacement of the Texas-Louisiana Block to the northwest along the Texas lineament–Boquillas-Sabinas and Lewis Clark–Bahamas Megashears (Albritton and Smith, 1957; Zwanzinger, 1978a, b; Tardy, 1980) (Figures 25 and 27). During shorter northwestward displacement (approximately 800 km; Anderson, 1997) of the rest of Mexico along the Mojave-Sonora-Caltam Megashear (Anderson and Silver, 1974; Tardy, 1980) (Figure 24) the Chiapas-Tabasco-Campeche-Yucatán block remained static.

The first northwestward displacement of the Texas-Louisiana Block occurred along two great megashears: the Texas lineament and the Lewis Clark–Bahamas lineament. The Texas lineament represents the northeastern margin of the Sabinas-Chihuahua Subbasin (Figures 1, 27, and 28) and includes the Sabinas River fault (Figure 15), in the state of Coahuila. The existence of both megashears permitted this displacement away from the southwest-northeast branch of the triple junction, stretching and lengthening of the southeast continental margin and oceanic floor, and forming the Veracruz Subbasin (Figure 25). The fault that forms the northeastern boundary of the Southeastern Subbasin starts at the triple junction and proceeds southeastward along the 200-m isobath bordering the northeast side of the saline intrusion zone (Carta Tectónica: Atlas Nacional de México, 1991), continuing through the Laguna de Términos in Guatemala, and paralleling to the Usumacinta River (Figure 15). This fault is also the southwestern border of the Yucatán peninsula and marks the change between folded and unfolded Mesozoic sedimentary sequences of the Yucatán peninsula (Chárleston-Avilés et al., 1984). The southwestern border of this subbasin is the northeastern limit of the Chiapas batholith (Michaud, 1987), and it is represented by a large fault (Rodríguez-Licea, 1983). The Southeastern Subbasin is a large graben that developed an extensive platform that gradually tilted toward the southwest and northwest.

Igneous intrusive (285 m.y granites), metamorphic (317 m.y schists), and sedimentary (late Paleozoic) rocks form the basement of the Southeastern Subbasin. This subbasin was initially filled by Middle Jurassic red beds of the Todos Santos Formation, followed by Bathonian marine sediments. Initially, it was a gentle, large sedimentary wedge, inclined toward the northwest and also the southeast as a result of cooling of the rift zone at the center of what was to become the Gulf of Mexico. As a consequence, the former centrifugal drainage became centripetal. This subbasin later received transgressive marine waters from the southeast and northeast. These waters are the source of thick Bathonian-Callovian salt. As cooling continued, this wedge gradually inclined northwestward,

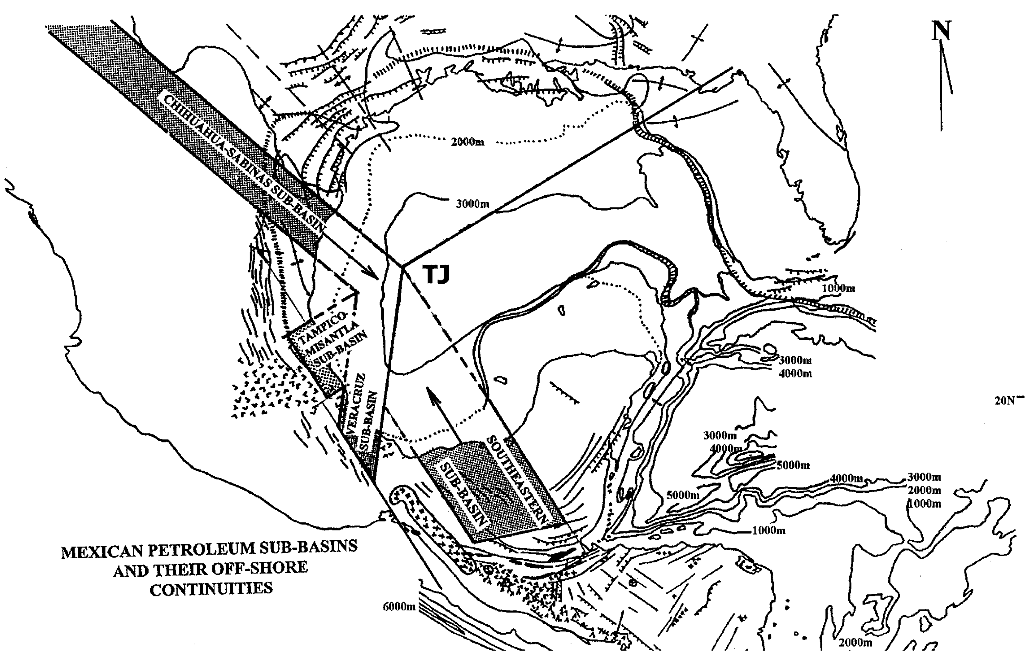


Figure 28. Location of Mexican oil subbasins and their relationship to the ancient position of the triple junction (TJ). Arrows show that Southeastern and Chihuahua-Sabinas Subbasins plunged toward that position.

and sea water deposited as much as 1200 m of salt on red beds in the Coatzacoalcos region. The salt later was covered by carbonates. The recessive motion of the coastline was well established by the Middle Jurassic–Early Cretaceous age of the red-bed Todos Santos Formation on the northeastern border of the Chiapas batholith. The most complete transgressive sequence on the northeastern border of the subbasin was drilled by the Xicalango 101 and Palomares 1 wells (Rueda-Gaxiola and Dueñas, 1990). This sequence is composed of reddish transitional rocks that are rich in pollen, spores, and Bathonian-Callovian dinoflagellate cysts; it was covered by Late Jurassic marine calcareous rocks and Early Cretaceous platform carbonates. During the Late Jurassic and Early Cretaceous, a northeast-southwest high toward the southwest, named the Artesa–Mundo Nuevo horst (Rodríguez-Licea, 1983), and the Reforma-Akal uplift toward the northeast began to form in this subbasin (Ortiz-Ubilla, 1996); an Early Cretaceous platform formed over this horst. Consequently, the subbasin was divided into three structural units (Williams-Rojas, 1995): (1) the Comalcalco and Salt Basin to the west, (2) the horst in the middle, and (3) the Macuspana Basin to the east. The limits of this horst are presently defined by salt domes and by the Uspanapa and Grijalva Rivers (Figure 15). This horst is the most important structural feature controlling Mesozoic and Cenozoic oil and gas generation, migration, and distribution in the Southeastern Subbasin. Erosion of the platform during the middle Cretaceous was followed by deposition of several thousands of meters of sediments over this platform and the Comalcalco and Salt and Macuspana Basins during the Late Cretaceous and the Tertiary.

By the late–middle Cretaceous, this subbasin had received volcanic sediments (evidenced by presence of bentonite) from the south and southeast, followed (in the Campanian) by terrigenous sedimentation following initial tectonic and volcanic events related to the southeastward displacement of the Chortis Block during the Paleogene. This motion was important in the development and evolution of the Veracruz and Southeastern Subbasins. During the Late Cretaceous, the western continental uplift generated huge volumes of terrigenous sediments that were transported by rivers originating in the Chortis Block and were deposited in northeastern deltas. This is the case in the Mexcala Formation deposited on the calcareous Morelos platform (Figure 22) during the Late Cretaceous (Hernández-Romano, 1995). At the same time, deposition of large volumes of terrigenous sediments in the Veracruz Subbasin are the result of erosion of the same blocks, which covered the rapidly subsiding Cretaceous platform carbonates. Sediments possibly were transported by the Papaloapan River (Figure 14) and other small rivers. In the Southeastern Subbasin, these processes produced the same sediments, although they were deposited some time later as the Chortis Block began to migrate to the southwest, passing the Chiapas-Tabasco-Campeche-Yucatán Block along its southeastern border. This depositional episode in the geological history of southeastern Mexico and Central America is recorded in the sedimentary sequences of the Salina Cruz 1, Salina Cruz 2, and Arista 1 wells (Pedrazzini et al., 1982; Figure 4). In the Salina Cruz 1, an unconformity between early Oligocene and late Miocene represents the time when the Chortis Block moved along the continental border of the Yucatán Block, causing erosion and deposition of deltaic terrigenous sediments in the Comalcalco and Macuspana Basins, where these sequences contain a shorter, almost equivalent unconformity from the late Oligocene to the middle Miocene. These deltaic deposits were transported by rivers that passed through the Chiapas fold and thrust belt, and that reached their present height at the time the Chortis Block began moving northeastward along the Polochic-Motagua fault system. At this time, compression switched to a northwest-southeast extension, forming little pull-apart basins in the Sierra de Chiapas (Meneses-Rocha, 1991) and folding of sediments along the southeastern border of the Veracruz Subbasin. Erosion of the Chiapas batholith and the folded Sierra de Chiapas (Figure 2) triggered sedimentation, progradation, and subsidence toward the central Gulf of Mexico.

Based on the above characteristics, this subbasin corresponds to IF (continental interior fracture) and MS (continental margin sag) basin types (Kingston et al., 1983), because it is a large graben formed between the Yucatán peninsula and the Chiapas batholith and also represents a composite basin characterized by diverging stresses, rapid subsidence, and seaward tilting.

Sabinas-Chihuahua Subbasin

The third branch of the triple junction pertains to another graben, the Sabinas-Chihuahua Subbasin (Figures 1 and 28). This subbasin plunges southeastward and was initially filled by Callovian red beds of the La Joya Formation in the southeastern Sabinas portion.

Transgressive marine sediments of the Zuloaga Group (Götte, 1990) were deposited over the red bed continental sediments. They had reached the northwestern Chihuahua portion by the late Kimmeridgian and Tithonian.

This subbasin was formed in the Middle Jurassic by rifting processes of the Gulf of Mexico. It is bordered on the northeast by the Texas lineament (Albritton and Smith, 1957), extends into the state of Coahuila, is bounded by the Boquillas-Salinas fault (Zwanzinger, 1978a, b) and is bounded to the southwest by the Mojave-Sonora (Anderson and Silver, 1974) and Caltam (California-Tamaulipas after Tardy, 1980) lineaments. This subbasin began as a high-subsidence intercontinental basin produced by a tensional and left-lateral displacement with initial red bed sedimentation. Later, the subbasin was converted to a wedge covered by Middle Jurassic–Cretaceous evaporitic and calcareous transgressive marine sediments. The northwestward displacement of the Texas-Louisiana Block during development of the Gulf of Mexico (Figure 27), Jurassic-Paleogene compression caused by convergent tectonics along the western margin of North America, and the displacement of the southern block of the Mohave-Sonora-Caltam Megashear combined to cause the characteristic transpressive deformation of rocks deposited in this subbasin (Zwanzinger, 1978a, b).

The southeastern portion of this graben is called the Sabinas Basin, and it begins at the triple-junction point in northeastern Tampico. The Sabinas Basin dips toward the central Gulf, where it contains several compressive structures consisting of folded red beds (La Joya Formation) and very thick evaporates equivalent to the Callovian Minas Viejas Formation (Götte, 1988, 1990) deposited in the Huizachal-Peregrina Anticlinorium and drilled by the Peregrina 1 Well. In the northwestern part of the Plataforma de Valles–San Luís Potosí (Valencia-Islas, 1993), the section above the Minas Viejas Formation consists of the Jurassic Zuloaga and La Casita Formations and the Cretaceous Taraises, Tamaulipas Inferior, Horizonte Otates (La Peña), Tamaulipas Superior, Agua Nueva, San Felipe, and Méndez Formations. To the northwest, in the Sabinas-Monclova region, Pemex wells encountered Jurassic Zuloaga and La Casita Formations; Cretaceous Cupido, La Peña, Aurora, Eagle Ford, Austin, Upson, San Miguel, and Olmos Formations; and Tertiary Sabinas conglomerate.

The northwestern portion of this graben is called the Chihuahua Basin. It is bounded on the northeast by the Paleozoic Sierra del Diablo and on the southwest by the Sierra de Aldama. Here, the red beds are covered by the clastic and clastic-calcareous rocks of the late Oxfordian–Tithonian La Casita Formation. This formation changes vertically and gradually to early Neocomian limestones and evaporitic rocks of the Navarrete Formation and then to the red beds of the Las Vigas Formation. These red beds represent an important uplift followed by a new period of subsidence, in turn represented by the early Aptian La Virgen (evaporites) and Cupido (limestones) Formations. The Cupido Formation represents the first stage of a calcareous platform that began with the clastic calcareous, organic-rich La Peña Formation and ended with the Middle Cretaceous Tamaulipas Superior Formation or its equivalent Albian Aurora Group. The Aurora Group consists of the Coyame, Benigno, El Bronce, and Finlay Formations. A regression began during the Turonian when the Aurora Group was covered by the Benavides, Loma de Plata, Del Río, Buda, Ojinaga, and San Carlos Formations. This Late Jurassic sedimentary sequence can be correlated (Ortuño-Arzate, 1985) with similar sequences deposited at the same time in the Mesogea (Tethys sea) domain. A detailed sedimentary analysis of this sequences shows that subsidence and transgression ended during the Berriasian with the establishment of a platform over the ramp margin (Eguiluz de Antuñano, 1997) similar to other subbasins of the Mexican Gulf coast. The regression that affected this and the other Gulf of Mexico subbasins in Mexico occurred because of continental uplift to the west during deposition of the Turonian Buda Formation. This regression became more evident during the deposition of paralic coal in the prograding delta system, which occurred from the Coniacian in Ojinaga to the Maastrichtian in Sabinas and Nueva Rosita localities, and by the deposition of the Ojinaga Formation flysch. Palynological analysis of coals and other rocks (Rueda-Gaxiola, 1967) suggest that at least 2000 m of rocks above this coal were lost by erosion because of uplift and folding in the west. The outcropping coal is bituminous (1.35–1.45 vitrinite reflectance values), indicating that it reached the final stage of the oil window and underwent a strong heating process during burial.

According to these geological characteristics, this Sabinas-Chihuahua Subbasin can be classified as an IF or MS type (Kingston et al., 1983). This corresponds to an interior fractured basin on continental crust— a basin formed by divergence and tension, development

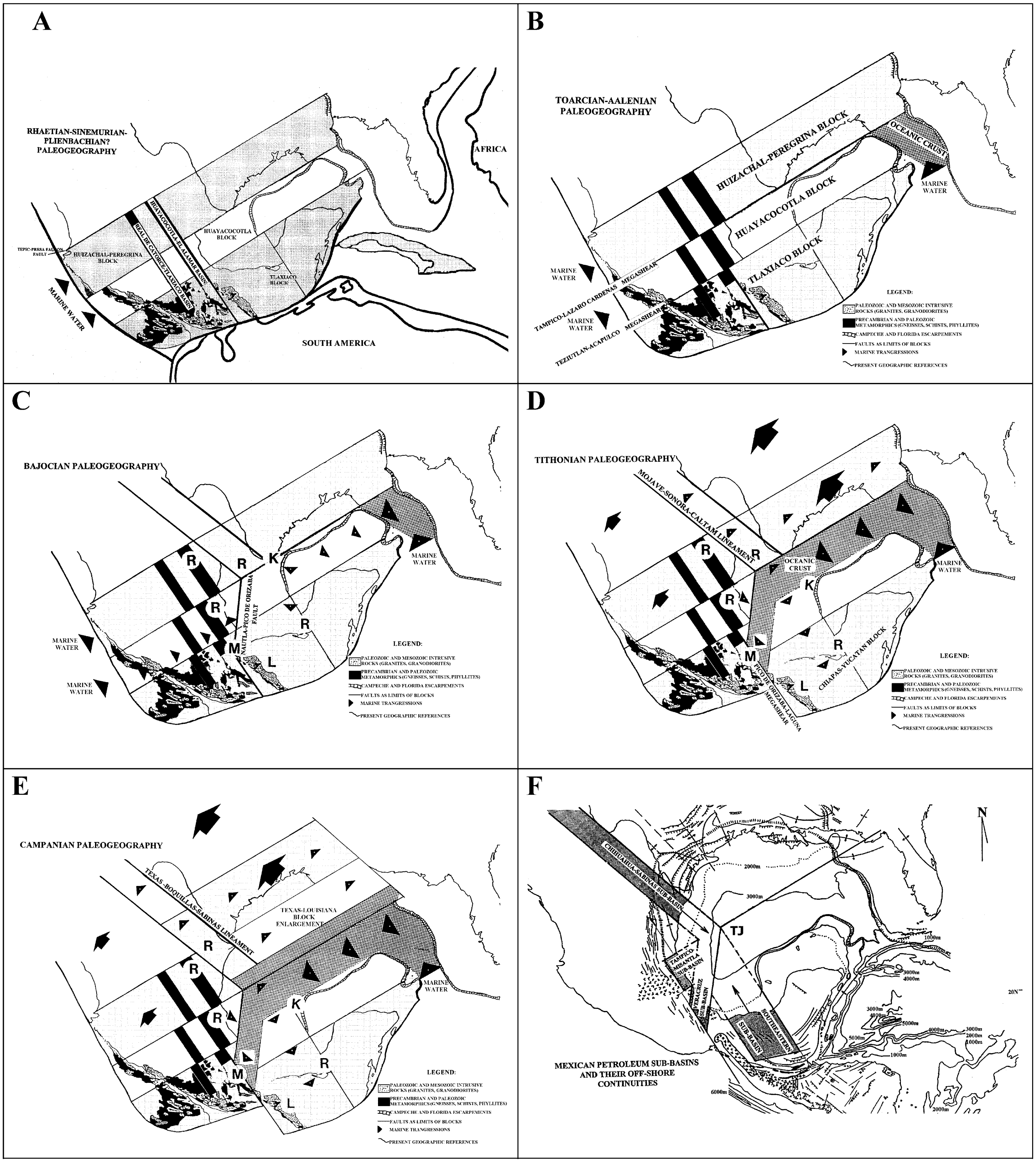


Figure 29. Different stages of evolution, before and during formation of the Gulf of Mexico and its petroleum subbasins in Mexico. Arrows indicate tectonic movement. Triangles indicate marine water movement. Size of arrows and triangles indicates magnitude of movement.

of horsts and grabens, and rapid subsidence. In the northwestern Gulf of Mexico, it extends to the external margin of the continental crust, where it plunges toward the sea (Figure 28).

Figure 29-E shows tectonic relationships between the petroleum subbasins in the Gulf of Mexico during the Campanian; Figure 29-F shows all these oil-productive subbasins in their present position.

CONCLUSIONS

This study can be used to determine and predict the sedimentary style, organic matter, thermal evolution, and tectonic deformation of the subbasins in the Gulf of Mexico. These are important factors needed to determine the occurrence of petroleum systems.

The triple-junction model for the origin of the Gulf of Mexico allows us to predict new provinces toward the central Gulf of Mexico that have high potential as petroleum and gas producers. These provinces are the offshore continuations of the Chihuahua-Sabinas, Tampico-Misantla, and Southeastern Subbasins. Because they were closer to the triple junction during subsidence, they were the first to receive oceanic waters, in which marine organisms developed in ideal physical-chemical conditions; their organic-rich sedimentary rocks were the first to reach an adequate temperature for generating oil and gas; and the hydrocarbons produced were the first to migrate toward the highest parts of the basins.

The distribution of salt intrusions reveals the probable limits of the initial transgression and deposition of marine organic matter, because evidence exists of oil and gas migration along the borders of these salt-piercing structures. The search for oil accumulations in submarine platforms in the Gulf of Mexico uses evidence such as the presence of bacterial carpets on the sea floor that are nourished by migrating hydrocarbons. Migrated and dismigrated oil and gas may be detected, characterized, and measured in sediments on the ocean floor by means of traditional geochemical analysis of sediments, rocks, and organic matter (gas analysis, bitumen extraction, gas phase chromatography, isotope analysis, fluorescence, biomarkers). Results would reveal geochemical anomalies that would allow us to geographically delimit possible plays, geographic distribution of oil families, possible depth of accumulations, and possible volume of oil and gas accumulations.

Successful oil and gas exploration on the Texas and Louisiana continental shelf shows that application of modern technology can be efficiently applied to oil exploration in the offshore Gulf of Mexico (Brooks et al., 1986a, b, 1990; Kennicutt II, 1988a, b; Kennicutt II et al., 1989, 1992; MacDonald et al., 1990a, b; Comet, 1992). Unfortunately, some of these hydrocarbon accumulations exist in deepwater reservoirs that require new technologies to exploit them.

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