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## **A triple junction in the Gulf of Mexico: Implications for deep petroleum exploration**

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### **RESUMEN**

Las secuencias mesozoicas de lechos rojos y sal representan el basamento económico de las subcuencas petroleras mexicanas del Golfo de México, así como el inicio de la transgresión marina tethisiana que formó los sistemas petroleros. Los análisis palinoestratigráficos (1969-1993) de estas secuencias permitieron obtener datos lito-, bio- y cronoestratigráficos del Alogrupo Los San Pedros y del Grupo Huayacocotla (edad Raetho-Liásica en la Cuenca Huayacocotla-El Alamar), de las formaciones del Jurásico Medio La Joya (subcuenca Chihuahua-Sabinas-Burgos), Rosario, Cahuasas (Subcuenca Tampico-Misantla) y Todos Santos (subcuencas de Veracruz y Sureste). Estos datos y los obtenidos del "caprock" del Challenger Knoll del Golfo de México, por Kirkland y Gerhardt, han permitido entender el origen y la evolución tectónica del Golfo de México. De estos datos se deduce la existencia de una discordancia entre las rocas metamórficas e ígneas del basamento y los lechos rojos del Jurásico Medio en las subcuencas del Golfo de México y que se continúa sobre las rocas fluvio-lacustres-marinas liásicas de las cuencas de Huayacocotla-El Alamar, Tlaxiaco y Huamuxtitlán. El modelo tectónico de la Unión Triple incluye tres periodos: (1) la formación de la Cuenca Rhaeto-liásica Huayacocotla-El Alamar, (2) el origen de la subcuenca Tampico-Misantla durante el Liásico Tardío y (3) el origen del Golfo de México y de sus subcuencas de Chihuahua-Sabinas, Veracruz y Sureste, durante el Jurásico Medio Temprano. Esta Triple Unión permitió el desplazamiento hacia el NW del Bloque Texas-Luisiana y de la parte occidental de México por medio de las megacizallas Vancouver-Bahamas, Texas-Sabinas y Pico de Orizaba-Laguna Inferior, al permanecer unido el Bloque Chiapas-Yucatán a Suramérica.

Este modelo y los datos geoquímicos permiten delimitar nuevas provincias potencialmente productoras de gas y petróleo hacia el centro del Golfo de México. Se trata de las rampas de las subcuencas de Chihuahua-Sabinas-Burgos, Tampico-Misantla y Sureste, ya que estuvieron muy próximas a la unión triple durante la subsidencia de sus bordes y fueron las primeras en recibir las aguas oceánicas tethisianas, donde el fitoplancton marino se desarrolló en condiciones físico-químicas ideales. Además, sus rocas ricas en materia orgánica fueron las primeras en alcanzar la temperatura de generación de petróleo y gas y éstos los primeros en migrar hacia las partes altas de las rampas.

**PALABRAS CLAVES:** Golfo de México, palinoestratigrafía, sal y lechos rojos, subcuencas petroleras mexicanas, exploración profunda de hidrocarburos.

### **ABSTRACT**

Mesozoic redbed and salt sequences have recently been dated using a palynostratigraphical method developed at the Mexican Petroleum Institute (IMP) since 1975. They represent the early Mesozoic marine transgression which formed the petroleum systems. The information from 1969 to 1993 for the Rhaeto-Liassic redbed Los San Pedros Allogroup and Huayacocotla Group (Huayacocotla-El Alamar Basin), Middle Jurassic La Joya Formation (Chihuahua Sabinas Sub-basin), Middle Jurassic Rosario and Cahuasas formations (Tampico-Misantla Sub-basin) and Middle Jurassic Todos Santos Formation (Veracruz and Southeastern sub-basins) and Middle Jurassic salt units (Southeastern sub-basins) and the caprock of the Challenger Knoll, drilled in the Gulf of Mexico, are reviewed.

After these data an unconformity between the igneous-metamorphic basement and the Middle Jurassic redbeds in some sub-basins of the Gulf of Mexico, and between the Liassic sedimentary rocks and the Middle Jurassic redbeds in the Huayacocotla-El Alamar, Tlaxiaco and Huamuxtitlán basins is proposed. The Triple Junction Model includes three different periods: (1) the formation of one or two Rhaeto-Early Liassic wrench or shear basins (Huayacocotla-El Alamar); (2) formation of the Tampico-Misantla Sub-basin during Late Liassic, and (3), the origin of the Gulf of Mexico Basin and the Chihuahua-Sabinas, Veracruz and Southeastern sub-basins during the Early Middle Jurassic. A triple junction system allowed the northwestward displacement of the Texas-Louisiana Block and the western region of Mexico away from the stable Chiapas-Yucatán Block along the Vancouver-Bahamas and Texas-Sabinas alignments and the Pico de Orizaba-Laguna Inferior Megasear.

From geochemical data oil and gas-producing provinces are predicted in continuation of the Chihuahua-Sabinas, Tampico-Misantla and southeastern sub-basins.

**KEY WORDS:** Gulf of Mexico, palynostratigraphy, salt and redbeds, mexican oil subbasins, deep hydrocarbons exploration.

## INTRODUCTION

A review of the Triple Junction Model for the origin of the Gulf of Mexico and its oil bearing sub-basins is presented (Rueda-Gaxiola, 2003). We summarize several models to explain the origin of the Gulf of Mexico (Rueda-Gaxiola, 1998). Some authors consider that the Gulf of Mexico has always existed as it is, while others hold that it was formed by lithospheric subsidence. After reconstruction of Pangea (Bullard *et al.*, 1965; Dietz and Holden, 1970; Seyfert and Sirkin, 1973), some authors found it difficult to fit Mexico, Central America and the Gulf of Mexico into plate because of overlap with South America. Later tensional models included right-hand (e.g. Freeland and Dietz, 1971), left-hand (e.g. Carey, 1958) and lateral movements of the Yucatán península based on paleomagnetic data (Urrutia, 1984; Urrutia *et al.*, 1987; Molina *et al.*, 1992). Lithospheric blocks such as Chortis, Honduras and Oaxaca have also been involved (Bocanegra *et al.* 1999).

The tectonic and palynological data in this paper are

based on the papers by Rueda-Gaxiola (2003) and the books by Rueda-Gaxiola (2001, 2002 unpublished).

### Redbed formations and salt sequences

Redbed data are very useful to determine the tectonic and sedimentary evolution of the Gulf of Mexico and its petroleum sub-basins in Mexico (Figure 1). Few models proposed to explain the formation and evolution of the Gulf of Mexico are based on stratigraphic data related to the initial breakup of the crust. The precise age of the rifting period is very difficult to establish because radiometric and paleomagnetic methods require samples of igneous rocks which are deep under the Gulf of Mexico.

Thus, the only means to determine the age of rifting are from continental fossils in redbeds from lacustrine and fluvial sediments deposited in grabens above sea level. The marine transgression occurred later, during the drifting period when the blocks subsided below sea level, and salt was deposited on top of the redbeds. The salt beds covered by

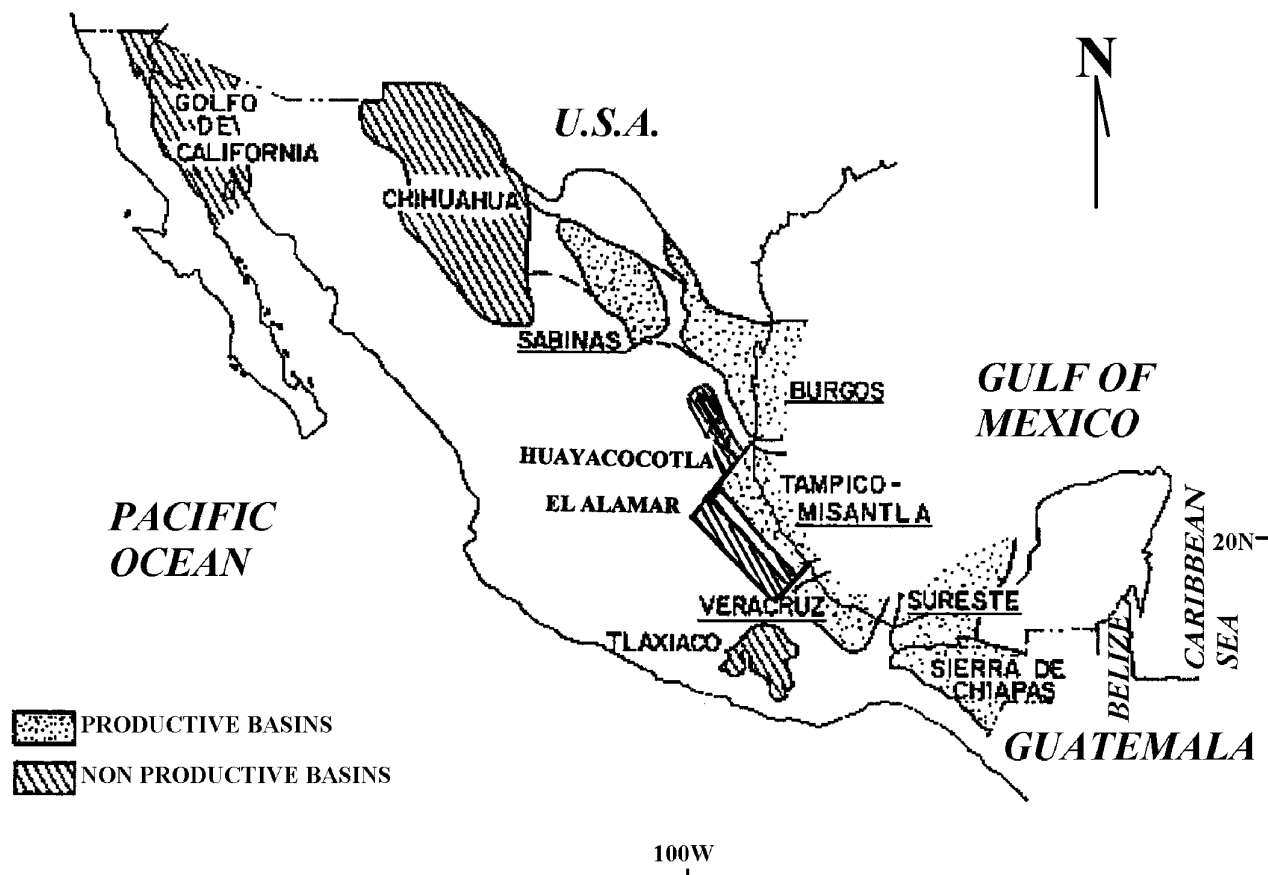


Fig. 1. Productive and non productive oil basins of Mexico. Only the non productive Huayacocotla-El Alamar and Tlaxiaco basins are not directly related to the origin of the Gulf of Mexico. Based on González-García and Holguín-Quinónez, 1992.

transgressive calcareous marine rocks, forming the Evans Triade [redbeds from epicontinental paralic environments (continental regime), transitional evaporites from restricted seas (intermediate environment) and marine marls (marine environment)] (Evans, 1978). Rocks with macro- and microfossils were deposited only during the drifting period. In transitional rocks, fossils that can be used for geochronology and paleogeography are rare. Palynostratigraphy is used, because can provide dates and correlations in continental, transitional and marine rocks, even using halite and gypsum which may contain few fossils.

Redbed and salt sequences (Figure 2 A) have often been placed geochronologically based on their stratigraphical position, including the economic basement of the Mexican Gulf of Mexico petroleum sub-basins. They represent the sedimentary basement of the Mesozoic marine transgression which formed the petroleum systems. Some of them, in the central part of the Gulf were dated by Kirkland and Gerhard (1971), others (Figures 2 B-D and 3 E-H), have been recently

dated by means of the palynostratigraphic method, originated in 1975 by the Mexican Petroleum Institute (Rueda-Gaxiola, 1999).

The Palynostratigraphy (Rueda-Gaxiola, 2000) aims to understand the organic and inorganic composition of the palynological residue of sedimentary rocks, from the macro- and microscopical analysis of thousands of palynological residues of Mesozoic and Cenozoic basal redbed and lacustrine rocks from the Mexican oil sub-basins. It is a practical method for salt and redbed sequences (Rueda-Gaxiola, 1999 and Rueda-Gaxiola *et al.* 1999). Macroscopic analysis of palynological residues allows us to determine their color and abundance and the color of the glycerinated alcohol in which they are preserved. The color and abundance of palynological residues depend on the mineral and organic constituents of rocks, in order to determine the lithological units in a sedimentary sequence. The color of the glycerinated alcohol shows the occurrence of hydrocarbons in the residue. Microscopic analysis of palynological residue offers a wide

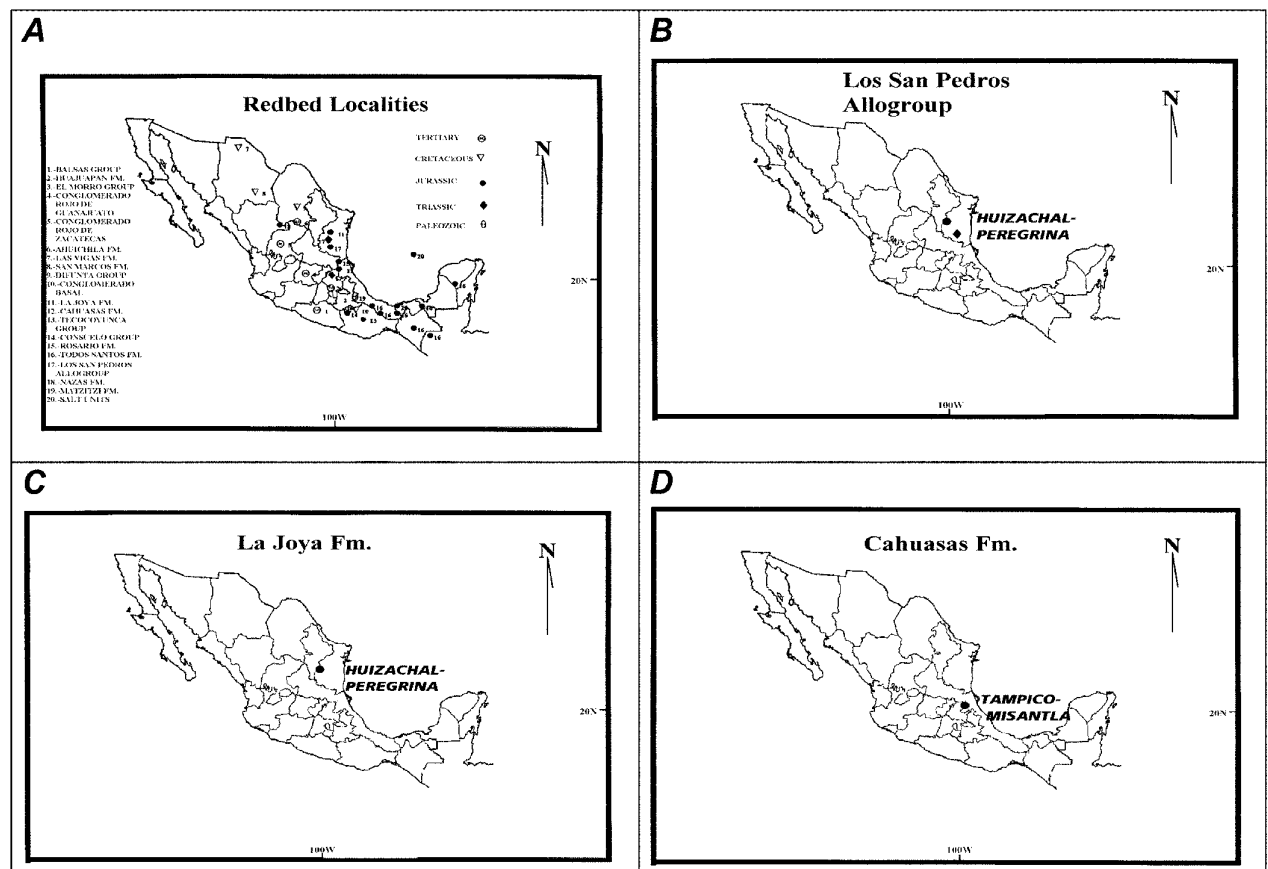


Fig. 2. A. Mexican redbed and salt localities. After Del Valle-Reyes, A., 1997. B-D. Redbed localities cited in Tables 1 and 2, dated by palynological analyses.

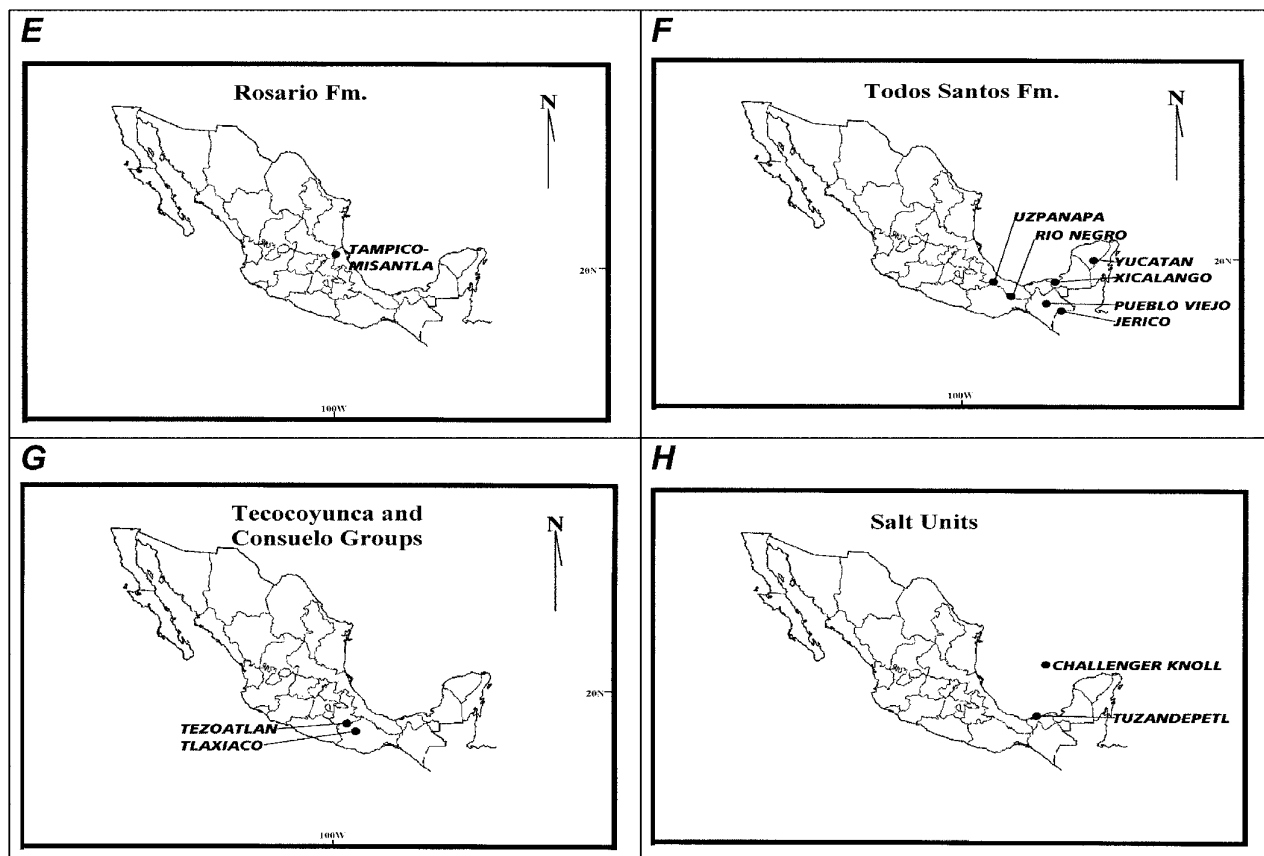


Fig. 3. E-H. Redbed and salt localities cited in Tables 1 and 2, dated by palynological analyses.

range of stratigraphical applications, because it contains microscopic allocthonous (e.g. heavy minerals) and authothonous (e.g. pyrite) remains from the original rock as well as new minerals formed when acids attack the mineral components of rock. Thus, it is possible to identify the parent rocks of redbeds and their sedimentary conditions by means of the size and type of residual minerals. The organic constituents of the residue are microscopic cells, tissues, organs and aquatic and terrestrial plants and animals. They are useful to identify sedimentary environments. Organic matter is the raw material for the production of coal, oil and gas during diagenetic processes in sediments and rocks; and fossils are very useful to determine the age of the rocks and sediments as well as their paleoecological and paleogeographical conditions. Thermal evolution of organic matter in the subsurface of a basin is shown by the color of the residual organic particles.

#### DATA

Data from palynological analyses of Mexican redbed formations (Rueda-Gaxiola, 2000) are shown in Table 1.

There are four ages related to salt structures in the Chiapas-Tabasco-Campeche region, known as the southeastern Sub-basin. Palynological analyses (Rueda Gaxiola, 2000) are shown in Table 2.

#### (a) Mesozoic redbeds and evaporitic rocks

It is important to establish the relationships between all these dated stratigraphic units, based on palynostratigraphical analyses (Rueda-Gaxiola, 2001).

In Table 3, an important unconformity separates the basement rocks from the Middle Jurassic rocks (La Joya, and Todos Santos formations) in the Sabinas and southeastern sub-basins (see Figures 1, 2 B-D and 3 E-H), and the Liassic rocks (La Boca Alloformation, and Huayacocotla Formation) from the Middle Jurassic redbeds (La Joya, and Cahuasas formations) in the Huayacocotla-El Alamar Basin. This basin was probably related to the southeastern Tlaxiaco and Huamuxtitlán basins (Figures 1 and 4), as suggested by Salvador (1987). However, in the Tlaxiaco Basin and in the

Table 1

Redbed formations in Mexico dated by palynological analyses

Formation	Year	Basin	Age	Publication
Cahuasas	1969	Tampico-Misantla Sub-basin	Middle Jurassic <u>Bathonian-Callovian?</u>	Rueda-Gaxiola, J. (1972)
Rosario	1975	Tampico-Misantla Sub-basin	Liassic-Middle Jurassic <u>Toarcian-Bajocian?</u>	Rueda-Gaxiola, J. (1975, 1977)
Todos Santos	1982	Western of the Chiapas-Tabasco-Campeche Sub-basin	Upper Jurassic <u>Kimmeridgian</u>	Gutiérrez-Galicia, L. (1984)
Todos Santos	1986	Eastern of the Chiapas-Tabasco-Campeche Sub-basin	Middle Jurassic <u>Bajocian-Bathonian</u>	Rueda-Gaxiola, J. and Dueñas, M.A. (1990)
Todos Santos	1987	Western border of the Veracruz Sub-basin	Middle to Upper Jurassic <u>Bathonian-Oxfordian</u>	Dueñas, M.A. <i>in</i> Herrera <i>et al.</i> (1990)
La Boca Alloformation. (Los San Pedros Allogroup)	1990	Huayacocotla-ElAlamar Basin	Liassic <u>Sinemurian-Pliensbachian</u>	Rueda-Gaxiola, J., López-Ocampo, E., Dueñas, M.A. and Rodríguez, J.L. (1993)
Rosario (Grupo Consuelo)	1996 (?)	Tlaxiaco Basin	Liassic	Rueda-Gaxiola, J. and Jiménez-Rentería, J. (1996)

northern part of the Tampico-Misantla Basin, the Rosario Formation redbeds may gradually change into the Cualac and Cahuasas formations, which are the base of the transgressive marine Upper Jurassic-Middle Cretaceous sequence. Above the unconformity, the redbeds are of Middle Jurassic age and are slightly older than the evaporitic rocks deposited over the Gulf of Mexico marginal sub-basins (Sabinas, Tampico-Misantla and southeastern sub-basins). Therefore, the age of these sub-basins is slightly younger than that of the Gulf of Mexico, because the redbeds are related to the marine transgression occurred during the drifting stage as represented by marine palynomorphs in the salt and marginal redbeds. From this evidence, the rifting stage may be

older than the redbeds and may be related to the Tampico-Lázaro Cárdenas (see Figure 5-B) and Teziutlán-Acapulco megashears (Toarcian-Aalenian) which allowed the Huayacocotla (see Figure 5-B) and Tlaxiaco blocks to shift southwestward, giving origin to the Tampico Misantla and the Tlaxiaco basins. The evidence of origin, age, and motion of blocks limited by these megashears is examined and discussed in Rueda-Gaxiola (2001) and Rueda-Gaxiola (2002, 2003).

In Table 3, is possible to differentiate the ages of the Huayacocotla-El Alamar Basin and the Gulf of Mexico from its Mexican petroleum sub-basins, because:

**Table 2**

Palynological ages of salt and caprock in the southeastern sub-basin

Material	Year	Site	Age	Publication
Caprock	1967	Challenger Knoll <u>Center of the Gulf of Mexico</u>	Bajocian- Kimmeridgian	Kirkland, D.W. and Gerhard, J.E. (1971)
Salt	1970	Trinitaria Well <u>Southeastern Sub-basin</u>	Middle Jurassic	Rueda-Gaxiola, J. Unpublished report
SALT	1970	Soledad 102 Well <u>Southeastern Sub-basin</u>	Middle Jurassic	Data from Rueda- Gaxiola, J. cited <i>in</i> Viniegra, 1971)
Salt	1993	Tuzandepetl Salt dome <u>Southeastern Sub-basin</u>	Middle Jurassic	Dueñas, M.A. Unpublished report

**Table 3**

Stratigraphic relationships of redbeds and evaporitic rocks

AGE	SABINAS SUB-BASIN	HUIZACHAL- PEREGRINA ANTICLINO- RIUM	HUAYACO- COTLA ANTICLINO- RIUM	TLAXIACO ANTICLINO- RIUM	TAMPICO- MISANTLA SUB-BASIN	SOUTH EASTERN SUB-BASIN
	MINAS VIEJAS				HUEHUE- TEPEC	
MIDDLE JURASSIC	LA JOYA	LA JOYA	CAHUASAS	CUALAC	CAHUASAS	SALT TODOS SANTOS
	*	*	*			*
LOWER JURASSIC		LA BOCA	HUAYACO- COTLA	ROSARIO	ROSARIO	
	<u>BASEMENT</u>					<u>BASEMENT</u>
		HUAYACOCOTLA-EL ALAMAR BASIN?				

- the oldest redbeds belong to the Late Triassic Huizachal Alloformation, and

- the redbed Todos Santos Formation could be pre-Bajocian which is related to the dextral displacement of the Huayacocotla and Tlaxiaco blocks through the Tampico-Lázaro Cárdenas and Teziutlán-Acapulco megashears (see Figure 5 B). Based on this displacement the Huayacocotla-

El Alamar Basin may have been divided into two three blocks rather than two.

Hence, the Huayacocotla-El Alamar Basin is, in time and space, very different basin from the Petroleum Sub-basins in the Mexican part of the Gulf of Mexico. A careful analysis of the geologic and tectonic maps of Mexico suggests southwestward shift of the Huayacocotla and Tlaxiaco

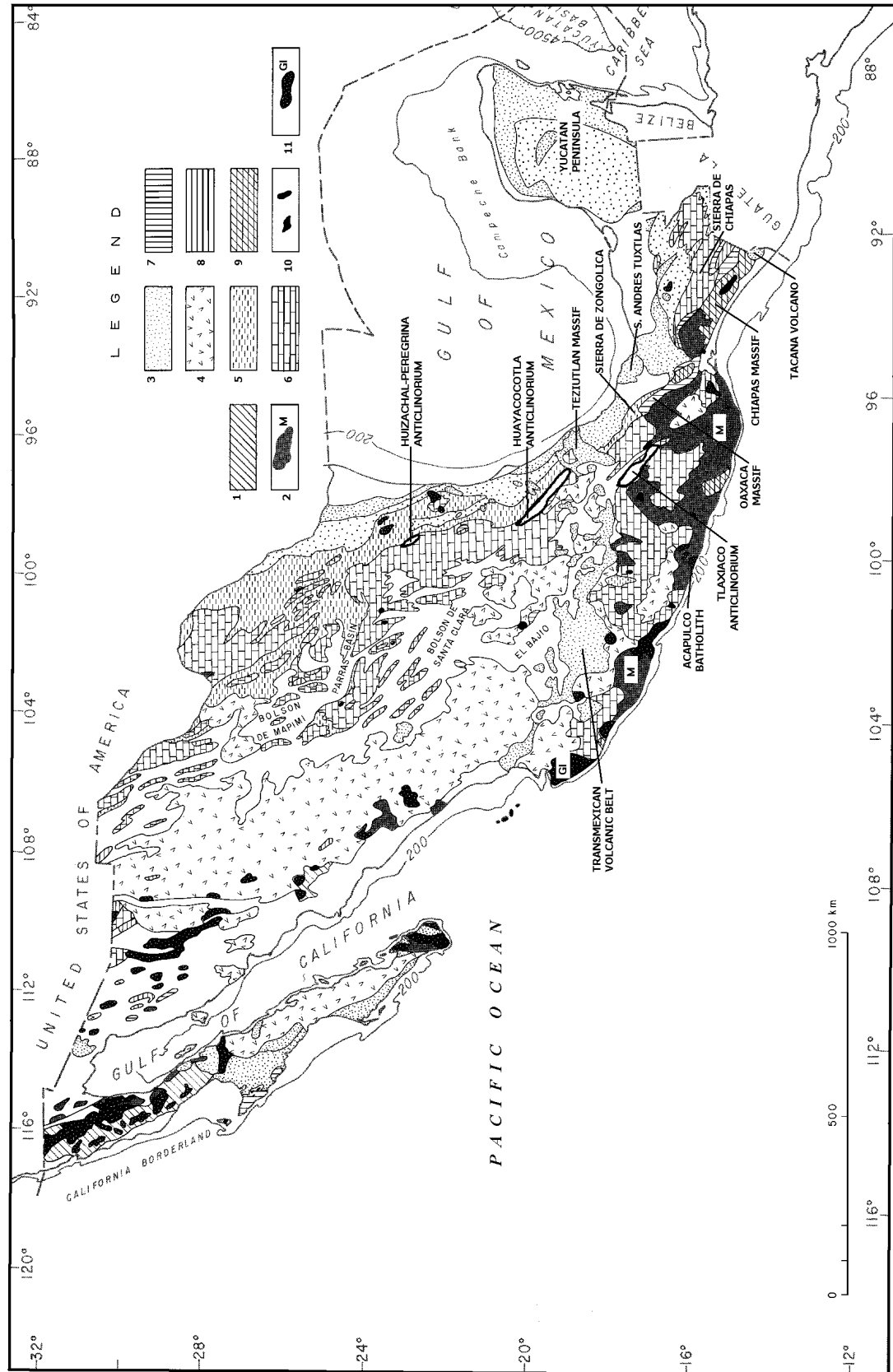


Fig. 4. Simplified geologic map of Mexico showing principal location of several geologic structures and places cited in text (de Cserna, 1989). Blank areas correspond to Plio-Quaternary terrestrial clastic deposits. 1, Upper Jurassic-Lower Cretaceous eugeoclinal deposits. 2, Precambrian and Paleozoic metamorphics and associated minor plutonic bodies. 3, Plio-Quaternary volcanics. 4, Tertiary volcanics. 5, Upper Cretaceous-Paleocene clastic wedge. 6, Upper Jurassic-Lower Cretaceous miogeoclinal deposits. 7, Upper Triassic-Lower Jurassic redbeds 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.

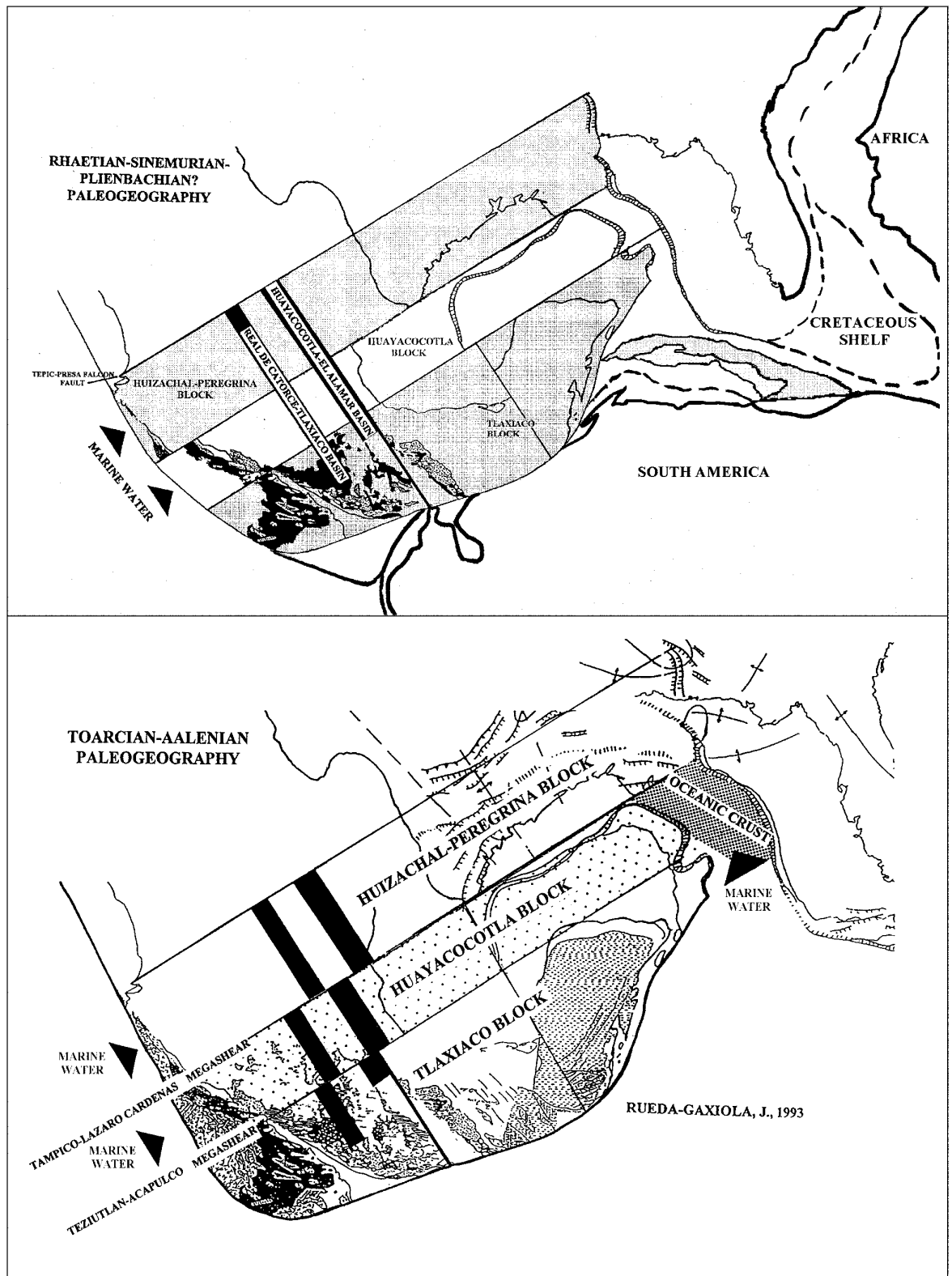


Fig. 5 A-B. These figures summarize Raethian-Aalenian stages of evolution, before formation of the Gulf of Mexico and its petroleum sub-basins in Mexico.

blocks by taking into account the positions of the Huizachal-Peregrina, Huayacocotla and Tlaxiaco anticlinoria (see Figures 4 and 5 B).

All this information was obtained from the basal redbed and evaporitic units of the sedimentary sequences of the Huayacocotla-El Alamar Basin and the Gulf of Mexico petroleum sub-basins in Mexico. Let us propose a simple tectonic model of the origin and evolution of this basin and these sub-basins (Rueda-Gaxiola, 1998, 2001, 2003). (1) Formation of one or two Rhaeto-Early Liassic wrench or shear basins (Huayacocotla-El Alamar Basin and Real de Catorce-Tlaxiaco), related to the evolution of the Pacific Plate convergent system (see Figures 1 and 5-A); (2) formation of the Tampico-Misantla sub-basin during the Late Liassic as a result of the southwestward displacement of the Huayacocotla and Tlaxiaco blocks along the Tampico-Lázaro Cárdenas and Teziutlán-Acapulco megashears (see Figures 1 and 5-B), and; (3) origin of the Gulf of Mexico Basin and the Sabinas, Veracruz and southeastern Mexican petroleum sub-basins in the Middle Jurassic, related to a triple junction system which allowed the northwestward displacement of the Texas-Louisiana Block and the western region of Mexico from the stable Chiapas-Tabasco-Campeche-Yucatán Block following the Vancouver-Lewis Clark-Bahamas (Figure 5-D) and Texas-Boquillas Sabinas lineaments and the Pico de Orizaba-Laguna Inferior Megashear (see Figures 1 and 5-C E). This block is stable because it was, during Jurassic, joined to South America (see Figure 5 A). There is no evidence (as a subduction zone and its related magmatic, metamorphic processes and an orogenic belt) of its motion to the SE as stated by some authors. If this block remained stable, only the Texas-Louisiana Block and the western region of Mexico moved toward the NW, where a subduction zone existed (Oldow *et al.*, 1989, Ducea, 2001).

## CONCLUSIONS

Figures 5, 6 and 7 summarize the proposed stages of Gulf of Mexico evolution, based on this triple junction model (Rueda-Gaxiola *et al.*, 2003, Rueda-Gaxiola, 1998, 2001, 2003). Figure 7-E shows the tectonic relationship between the petroleum sub-basins in the Gulf of Mexico during the Campanian. This information allows us to reconstruct a broad geological history of each sub-basin up to the Tertiary according to Kingston *et al.* (1983). It can be used to determine and predict sedimentary styles, organic matter, thermal evolution and tectonic deformation. These important factors may determine the occurrence of petroleum systems. Figure 7-F shows the oil producing sub-basins in their present position.

Oil and gas accumulations are the result of 6 independent events during the geological history of a sedimentary

basin (Sallé and Debyser, 1976; Welte *et al.*, 1997): Production, deposition, conservation and transformation of organic matter into petroleum and/or gas; migration, entrapment and accumulation. More concisely: Petroleum and/or gas formation, migration, entrapment and conservation. These steps imply the presence of 3, source rock, carrier reservoir rock and seal rock and trap formation and heating due to tectonic processes as subsidence (Rueda-Gaxiola, 2001); Perrodon, 1980; Demaison and Huizinga, 1991; Magoon and Dow, 1994, Demaison and Huizinga, 1991, divide petroleum systems in generative and migration entrapment subsystems.

Subsystem characteristics depend on charge factor, migration drainage style and entrapment style, depending on the tectonic style of the basin. Thus it is necessary to classify the basins in order to know their sedimentary and tectonic histories. Figure 8 shows the tectonic geographic relationship between productive Mexican sub-basins, as described by Guzmán Vega *et al.* (2001), and the Triple Junction Model. According to Kingston *et al.* (1983) classification, based on Plate Tectonics, the oil-producing petroleum sub-basins in Mexico may be classified as follows (Rueda-Gaxiola, 2001).

- Chihuahua-Sabinas-Burgos Sub-basin (Figures 1, 6, 7, 8 and 9): **IF and IS types** (formed on continental crust; sediments can overlap onto oceanic crust adjacent to continent; divergent plate movements; continental interior fractures and sag). This was initially a ramp deepening toward the SE as a graben, overlapped by transgressive Tethys waters since middle Jurassic. It includes three provinces, Chihuahua, Sabinas and Burgos. The Chihuahua province has only superficial evidences of hydrocarbons. This Mesozoic and Tertiary sub-basin produces **dry gas** in the Sabinas province, but toward the border with the Burgos Basin the production is mainly **gas and condensates** in regressive Tertiary rocks and sediments. In Burgos province, the generative subsystem may be found in a sequence more than 8000 m thick of Mesozoic and Tertiary rocks (more than 6000 m) deposited in a ramp with rapid subsidence and high thermal gradient (more than 26°C at present, and about 100°C during Mesozoic in the Sabinas province). Due to NW motion of the Texas-Louisiana Block, during Late Mesozoic and Paleogene this sub-basin had a transpressive tectonic deformation process.
- Tampico-Misantla Sub-basin (Figures 1, 6, 7, 8 and 10): **MS type** (formed on continental crust; sediments can overlap onto oceanic crust adjacent to continent; divergent plate movements; margin of plate; continental margin sag). In this sub-basin it is possible to differentiate 3 productive zones: the Mesozoic western region produces mainly oil and the Faja de Oro atoll produces **oil and gas**, while the Tertiary Chicontepec Paleocanal produces mainly **very**

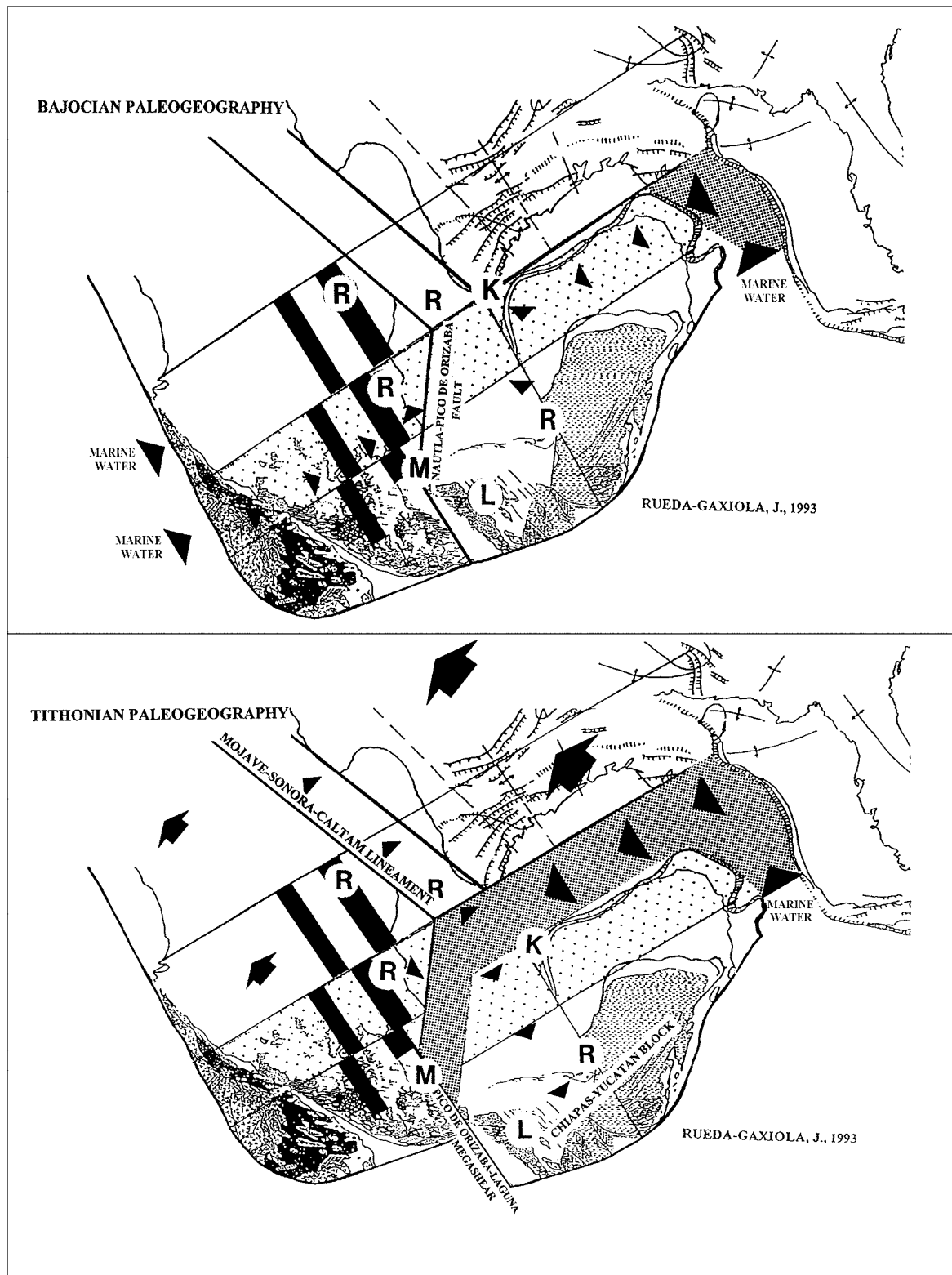


Fig. 6 C-D. These figures summarize Bajocian-Tithonian stages of evolution, during formation of the Gulf of Mexico and its petroleum sub-basins in Mexico. Letters K-L-M- and R show places of samples dated by Kirkland and Gerhard, 1971=K, Gutiérrez-Galicia, 1989=L, Dueñas, 1993=M, and Rueda-Gaxiola, 1972, 1977; Rueda-Gaxiola *et al.* 1993 a-b, 1996=R (see Table II).

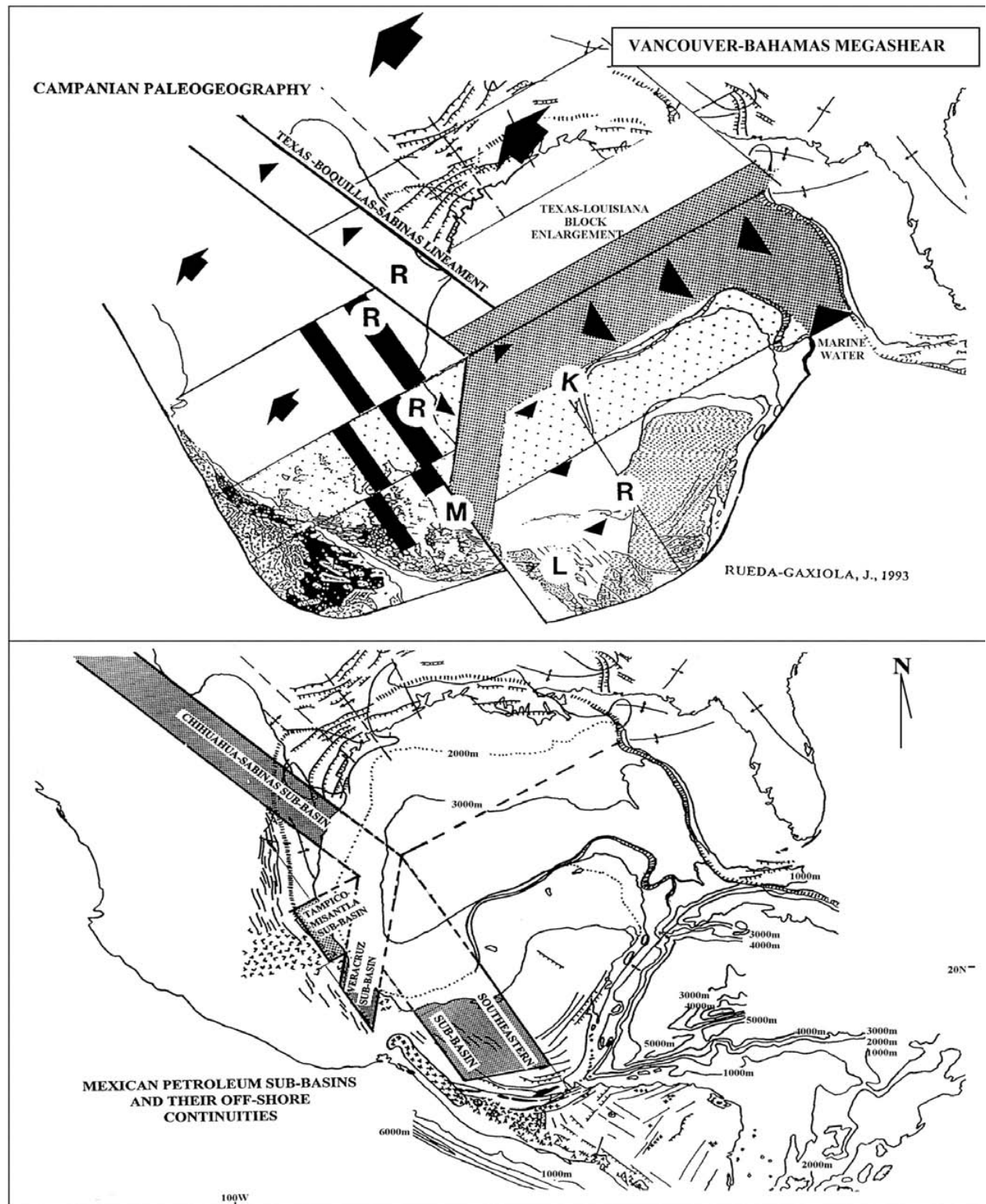


Fig. 7 E. This figure summarizes Campanian stage of evolution, during formation of the Gulf of Mexico and its petroleum sub-basins in Mexico. Letters K-L-M- and R show places of samples dated by Kirkland and Gerhard, 1971=K, Gutiérrez-Galicia, 1989=L, Dueñas, 1993=M, and Rueda-Gaxiola, 1972, 1977; Rueda-Gaxiola *et al.* 1993 a-b, 1996=R (see Table II). Figure 7 F shows the Mexican petroleum sub-basins and their off-shore continuities toward the center of the Gulf of Mexico Basin.

**heavy oil.** There may be three different productive sub-systems: one (mainly Upper Jurassic rocks) in the Mesozoic western region in a very short sequence (about 3000 m thick) that produces **oil and gas** mainly in the western reef rock of the atoll, and a second one (Mesozoic and Tertiary) toward the east of the atoll in a very thick sequence of 10 000 m of Mesozoic-Tertiary rocks and sediments, that produces **gas and light oil** entrapped in the eastern reef rocks of the atoll. The third one is found in a Tertiary paleocanal where the production is only of **very heavy oil**. Due to the very short Mesozoic and Tertiary sequences and a thermal gradient of 25°-30°C at present, the western region of the sub-basin produces oil and heavy oil. The eastern region produced **gas and light oil** because of the very thick sedimentary sequence and the higher thermal gradient at the vicinity of the rifting zone of the center of the Gulf.

- Veracruz Sub-basin (Figures 1, 6, 7, 8 and 11): **OS type** (formed on oceanic crust; area of divergent plate move-

ments; oceanic sag). In this sub-basin there is a very thick sedimentary sequence composed by Mesozoic (Upper Jurassic-Maestrichtian) and Tertiary rocks and sediments. The former are dominantly calcareous (Albian-Cenomanian) and marl (Turonian Maestrichtian) **oil** producing rocks, outcropping in the western province (Córdoba Platform); toward the East province (Veracruz Tertiary Basin), this calcareous sequence overlaps the sea floor, is folded, faulted, and thrust and covered by a Tertiary **condensates and gas** productive siliciclastic sequence about 9000 m thick. Hydrocarbon source rocks are considered Upper Jurassic, Upper Cretaceous and Miocene highly organic rocks. Nevertheless, only in the Córdoba Platform they are in part productive (16°-20°C is the present thermal gradient). They are overmature in the Veracruz Tertiary province (20°-24°C at present). Thus hydrocarbon migration, due to the structural position of source and accumulation rocks and the early high heat flow, must be from East to West during basin subsidence; i. e., from the center of the Gulf toward the border of the sub-basin.

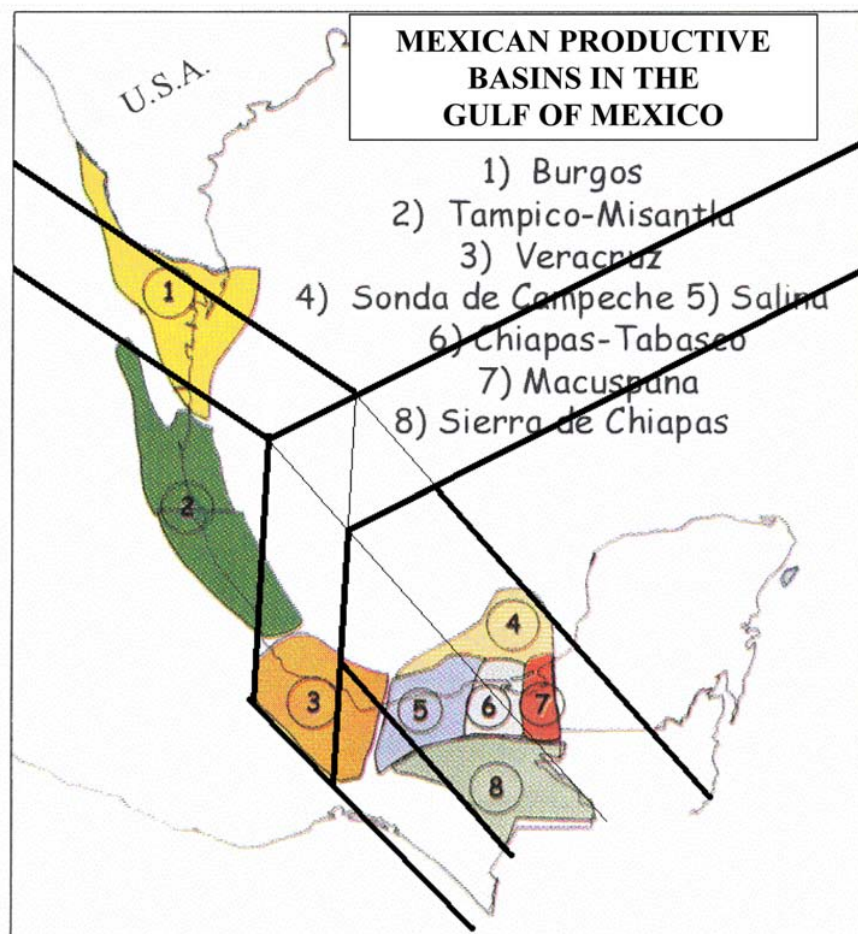


Fig. 8. Relationship between Triple Junction Model and the producers oil and gas Mexican Gulf sub-basins. Based on Mario Guzmán-Vega *et al.*, 2001.

- Southeastern Sub-basin (Figures 1, 6, 7, 8 and 12): **IF and MS type** (formed on continental crust; sediments can overlap onto oceanic crust adjacent to continent; divergent plate movements; continental interior fractures and sag; continental margin sag). This is the most recent (since 1972) and most important **oil and gas** discovery in Mexico. It produces more than 95% of Mexican hydrocarbon. It is composed by three continental provinces (Comalcalco, Villahermosa Uplift and Macuspana) and one marine province (Sonda de Campeche). It was initially a ramp deepening toward the NW into a huge graben, overlapped by transgressive Tethysian waters since Middle Jurassic. In general, over Mid Jurassic redbeds, the transgressive marine sedimentary sequence is composed by Mid Jurassic salt, Upper Jurassic-Mid Cretaceous calcareous rocks and Upper Cretaceous-Tertiary regressive siliciclastic rocks and sediments. Mesozoic calcareous rocks are thicker in the Sierra de Chiapas province, but Tertiary siliciclastic sequence is very thick toward the center of the Gulf in Comalcalco and Macuspana provinces. Source rocks are considered rich organic sedimentary units from transgressive Tithonian (brown-black) limestones, and regressive Middle Eocene (calcareous) shales, Lower Oligocene shales and Middle Miocene shales. The mean thermal gradient is 23°C but it is lower (<20°C) toward the E and SE, far from the center of the Gulf. Thus there are oil accumulations in very deep (> 6000 m) Upper Jurassic rocks. The presence of oil near the center of the Gulf of Mexico, in the Challenger Knoll, is evidence of very long range lateral and vertical migration.

This genetic classification of Mexican sub-basins shows that the evolution of the initial RRR triple junction (Figures 6 and 7 C-F) generated sub-basins of different tectonic and sedimentary characteristics. This is evident from the thermal gradient and the production of different quantities and types of hydrocarbons. Mexican sub-basins must have been connected toward the center of the Gulf of Mexico, and probably an important quantity of hydrocarbons in deep Mesozoic sequences was produced in “kitchens” far the accumulation places. Vertical and lateral long-range migration and entrapment occurred toward marginal sequences.

Geochemical data obtained since 1978 (Table 4) in the Institut Français du Pétrole, in the Mexican Petroleum Institute, and elsewhere (Guzmán-Vera and Holguín-Quinónez, 2001), from lithological sequences drilled by PEMEX in the Gulf of Mexico sub-basins and their off-shore continuation toward the center of the Gulf, show that oil and gas extracted from Mexican sub-basins has not always generated in the continental regions. Hydrocarbon family types were produced since the Mesozoic in almost symmetrical Gulf of Mexico sub-basins, as shown in Figure 13 and Table 4.

Thus hydrocarbons from the Burgos and Macuspana provinces contain geochemical evidences of migrated constituents from overheated zones toward the center of the Gulf. The accumulation of Lankahuasa non associated gas in the border of the Tampico-Misantla and Veracruz sub-basins has a similar origin. Some hydrocarbons may have been lost by overheating, but the rest may have migrated toward the con-

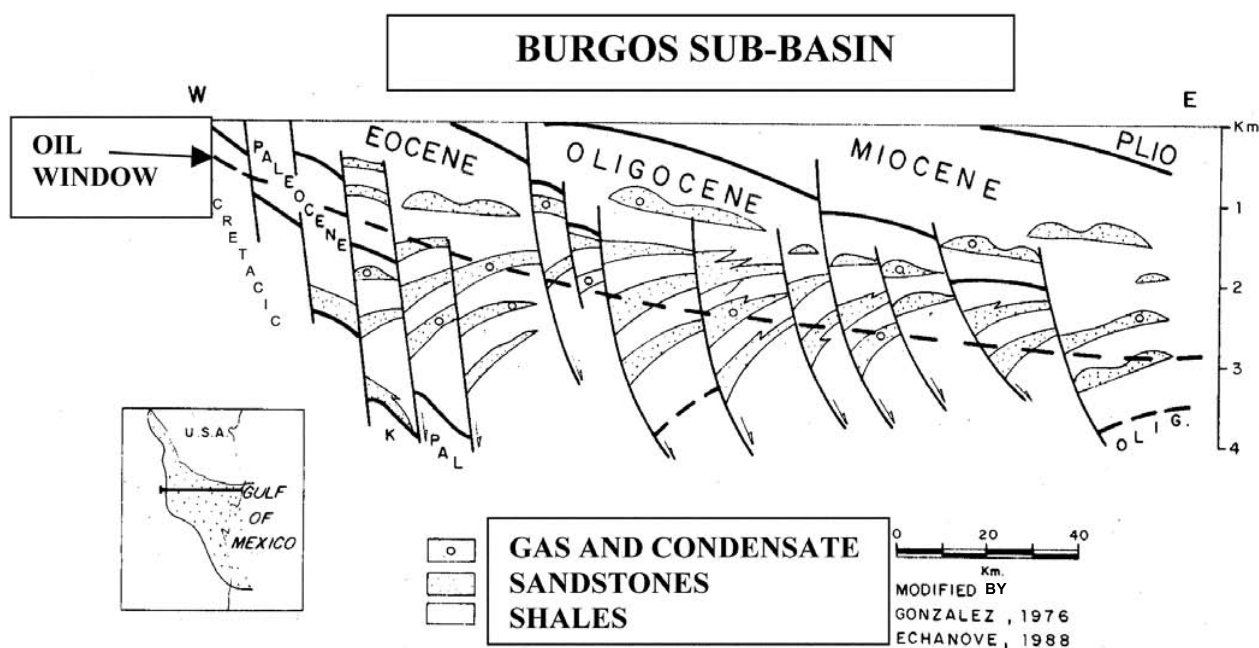


Fig. 2. Stratigraphic section of the Burgos province in Chiapas, México. Burgos sub-basin, showing the beginning of the oil window. Taken from González-García, and Holguín Quinónez, 1991.

tinental margins of the sub-basins. Migration in the sub-basins can be deduced from the tectonic and sedimentary history of sequences, registered by seismic data and related to deep and marine bottom geochemical data interpretation. It is necessary to establish the true limits of sub-basins following a tectonic model. The proposed Triple Junction Model could be a basis for delimiting and selecting the best regions for deep exploration.

New provinces (Figures 7-F, 13 and 14) toward the Central Gulf of Mexico may have high prospects as potential petroleum and gas producers. These provinces are basically the off-shore continuation of the Chihuahua-Sabinas-Burgos, Tampico-Misantla and Southeast sub-basins. They were closer to, but not above, the triple junction during subsidence. Also, (1) they were the first to receive ocean waters, where marine organisms developed in ideal physico-chemical conditions, (2) their rich organic sedimentary rocks were the first to reach the adequate subsurface temperatures for generating oil and gas, and (3) they were the earliest to migrate toward the highest parts of the ramps.

Because of sedimentation above the ocean floor, the deep Mesozoic sedimentary sequence of the Veracruz sub-basin is considered to have matured since long time ago, due to its very high thermal gradient. Thus produced hydrocarbons could have migrated and accumulated a very long time

ago. Hydrocarbons that accumulated early in marginal sequences of the Veracruz sub-basin, and the neighboring Tampico-Misantla sub-basin and Comalcalco province may still be found as very light oil, condensates and non-associated gas accumulations.

The salt intrusions define the probable limits of the initial transgression and deposition of organic marine matter, because at present there is evidence of oil and gas migrations along the borders of these salt structures that have pierced the upper sedimentary sequences.

Oil accumulations in submarine platforms in the Gulf of Mexico could also be detected from bottom marine evidence, such as the presence of bacterial carpets on the sea floor fed by hydrocarbons from migration or dismigration processes in the deeper sedimentary sequences where they were produced. Migrated and dismigrated oil and gas may be detected, characterized and measured from sediments on the ocean floor by means of geochemical analysis of sediments, rocks and organic matter: gasometry, bitumen extraction, gas phase chromatography, isotopy, fluorescence, biomarkers. Thus one may detect (1) mappable geochemical anomalies that would allow us to delimit possible plays, (2) geographic distribution of oil families, (3) possible depths of accumulations, and, (4) possible volumes of oil and gas accumulations.

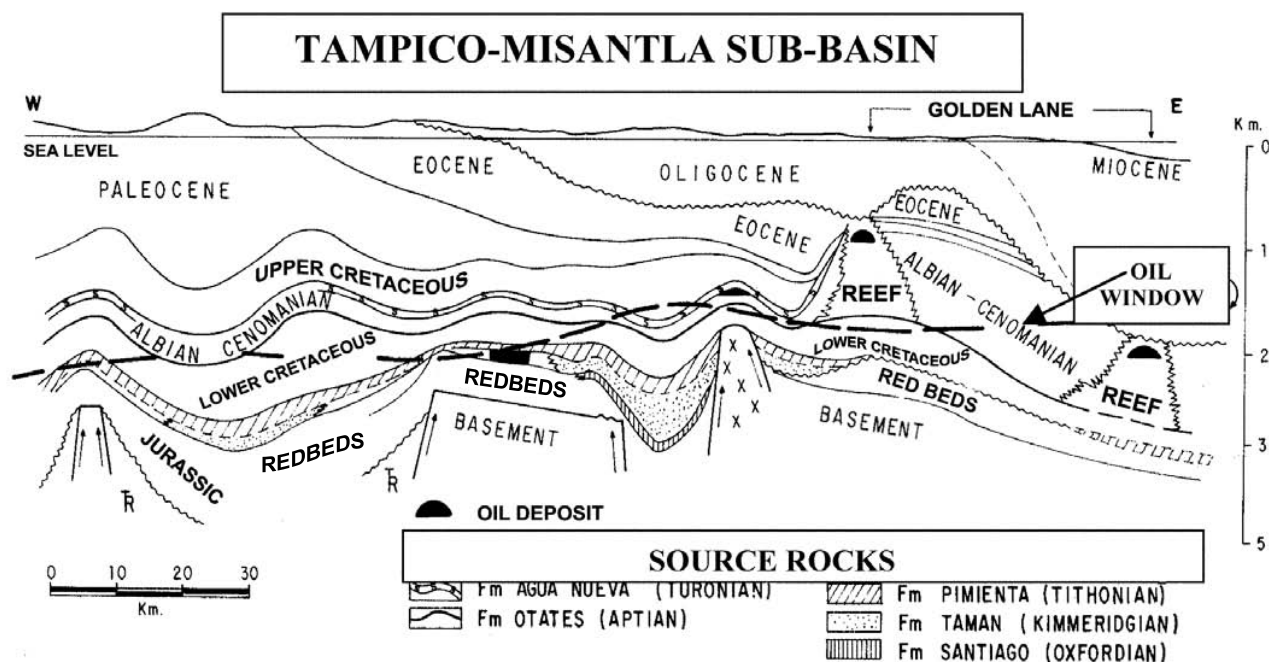


Fig.10. Transversal section of the Tampico-Misantla sub-basin, showing the Faja de Oro, the western and eastern provinces and the beginning of the oil window. Taken from González-García, and Holguín-Quinónez, 1991.

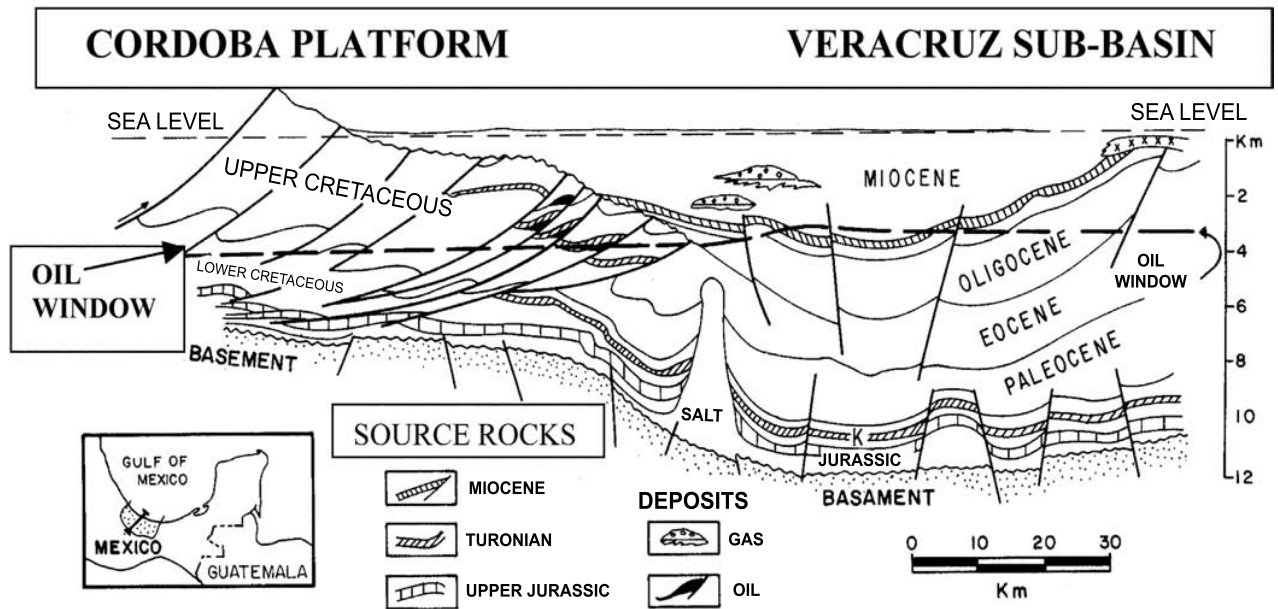


Fig. 11. Transversal section of the Veracruz sub-basin, showing the Córdoba Platform and the Tertiary Veracruz provinces, and the beginning of the oil window. Taken from González García, and Holguín-Quirón, 1991.

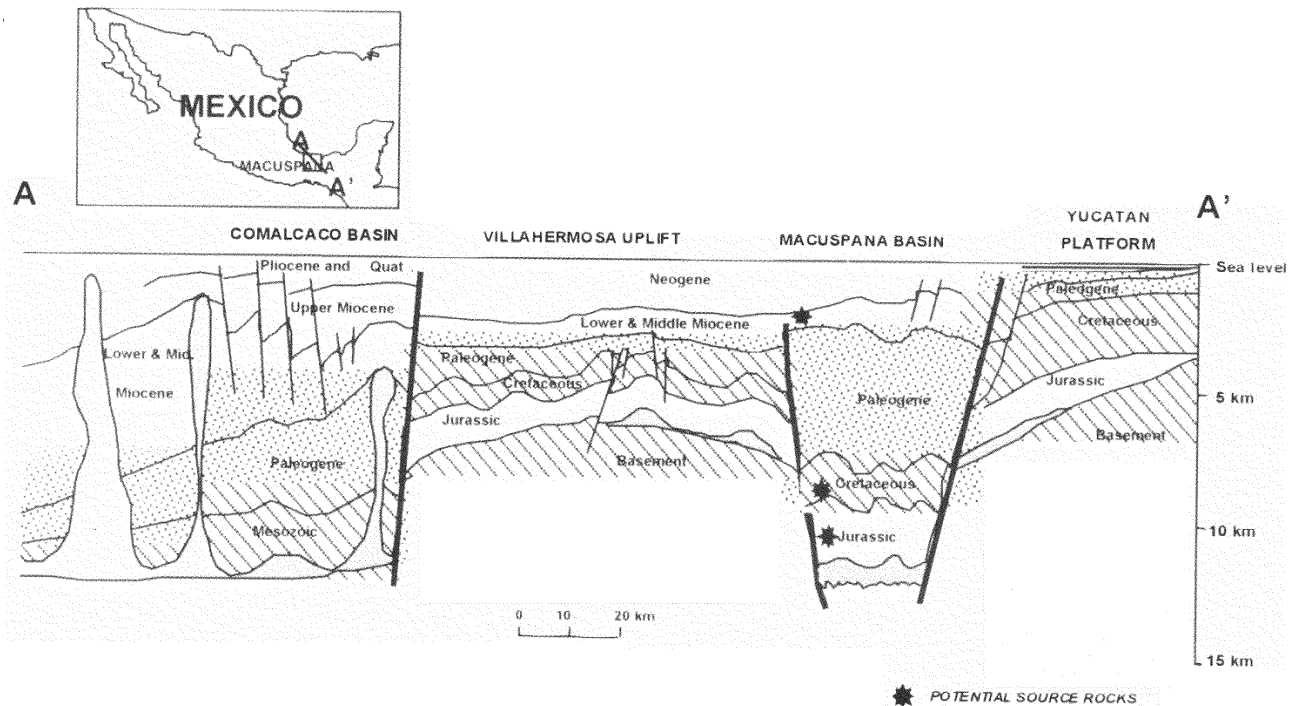


Fig. 12. General cross section of the southeastern Mexican sub-basin, showing the 3 main source rocks of Macuspana Province. Taken from Prinzhofer, A. and Guzmán-Vega, M., 2001.

Table 4

Genetic classification of Mexican Gulf of Mexico sub-basins and their hydrocarbon production

MEXICAN GULF SUB-BASINS	PROVINCES	PRESENT THERMAL GRADIENT	PRINCIPAL PRODUCTION			SEDIMENTARY THICKNESS	BASIN TYPE
CHIHUAHUA- SABINAS- BURGOS	CHIHUAHUA						IF and IS
	SABINAS				DRY GAS		
	BURGOS	26°C		CON DEN SATE	DRY GAS	8000 METERS	
TAMPICO- MISANTLA	WESTERN	25-30°C	OIL			3000 METERS	MS
	FAJA DE ORO (WEST)	25-30°C	OIL		ASSO CIA TED GAS	3000 METERS	
	FAJA DE ORO (EAST)		OIL	CON DEN SATE	DRY GAS	4000 TO 10000 METERS	
	CHICONTEPEC		HEA VY OIL				
VERACRUZ	CORDOBA PLATFORM	16-20°C	OIL				OS
	VERACRUZ TERTIARY	20-24°C	OIL	CON DEN SATE	DRY GAS	9000 METERS	
SURESTE (SOUTHEAST)	COMALCALCO		OIL		GAS		IF and MS
	SONDA DE CAMPECHE	23 TO <20°C	OIL	CON DEN SATE	ASSO CIA TED GAS	> 6000 METERS	
	VILLAHERMO- SA UPLIFT		OIL	CON DEN SATE	ASSO CIA TED GAS		
	MACUSPANA		OIL		DRY GAS		

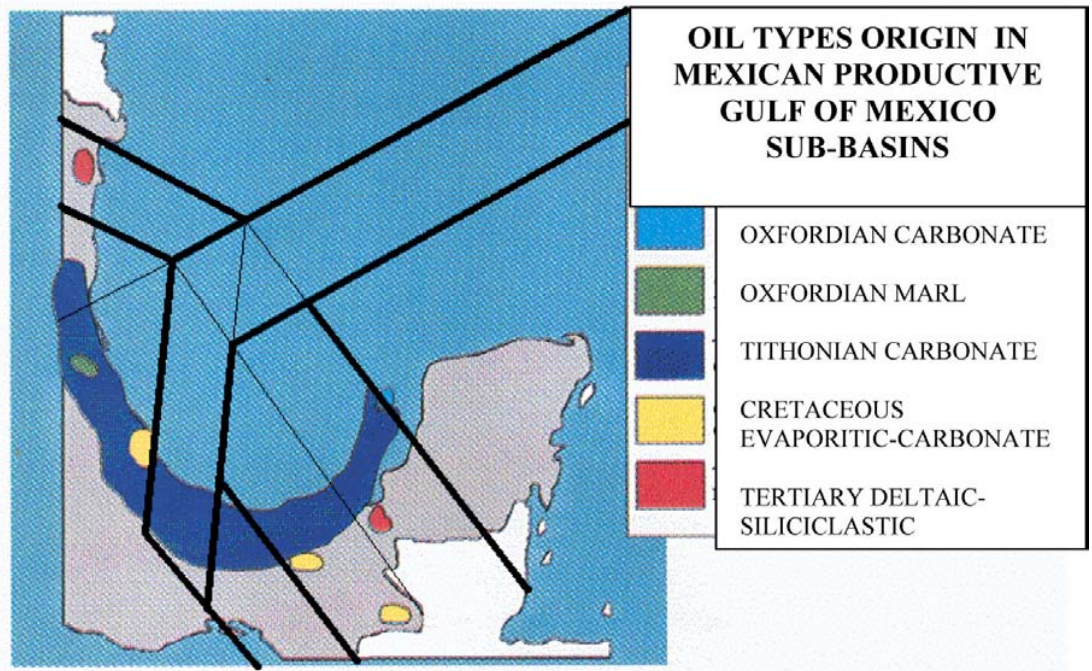


Fig. 13. Distribution of oil marine families produced in Mexican Gulf of Mexico oil sub-basins. Note the tectonic almost symmetrical distribution after the Triple Junction Model. Based on Mario Guzmán-Vega *et al.*, 2001. Pale blue: oxfordian carbonate origin. Red: Tertiary siliciclastic deltaic origin. Yellow: Cretaceous evaporitic-carbonate origin. Dark blue: Tithonian clayed limestone and marl origin. Green: Oxfordian marl origin.

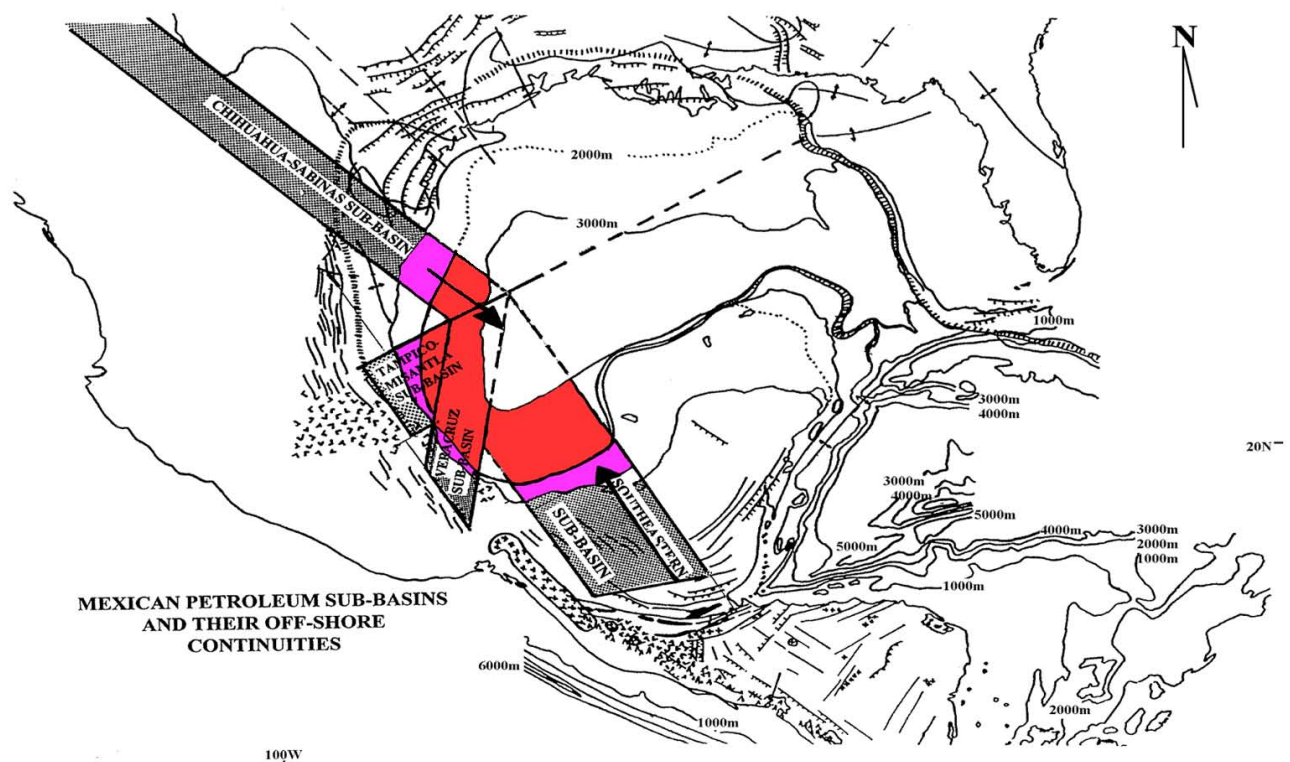


Fig. 14. Mexican petroleum Gulf of Mexico sub-basins and their off-shore continuity zones, limited by 2000 and 3000 meters deep. Arrows show that ramps become deeper toward the ancient triple junction.

Successful oil and gas exploration on the Texas and Louisiana continental shelf shows that modern technology could be efficiently applied to oil exploration in the Gulf of Mexico off shore (Brooks *et al.*, 1986 a and b; Brooks *et al.*, 1990; Kennicutt II, 1988 a and b; Kennicutt II *et al.*, 1989; Kennicutt *et al.*, 1992; MacDonald *et al.*, 1990 a and b; Comet, 1992). Many of these Gulf of Mexico oil and gas accumulations remain inaccessible due to the deep waters under which they are located (Figure 14).

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