Late Cretaceous Anoxia and Lateral Microfacies Changes in the Tres Esquinas Member, La Luna Formation, Western Venezuela

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The Tres Esquinas Member of the La Luna Formation is a glauconite-rich phosphorite unit associated with changes that took place in depositional environments in the Maracaibo Basin at the end of the Late Cretaceous. The unit marks the end of La Luna Formation sedimentary cycle. This paper presents results of petrographic studies of samples from two sections, one outcrop (Río Guaruries), and one well core (Perijá), and from seismic profiles across the Perijá and Colón areas in the Maracaibo Basin.

The Tres Esquinas Member is three meters thick in both locations. In the Río Guaruries outcrop, it contains an abundant foraminiferal fauna in addition to common allochemical material. Perijá core samples contain voluminous carbonate matrix, scarce allochemical materials, rare foraminifera, and poor definition of mineral facies, which may reflect higher-energy conditions on the sea floor.

The deposition of the Tres Esquinas Member resulted from altered sea-floor topography during an episode of intense tectonic activity in the eastern part of the Maracaibo Basin. The modified shelf configuration ended anoxic conditions on the sea floor and led to increased erosion characteristic of the Tres Esquinas Member.

INTRODUCTION

The Tres Esquinas Member of the La Luna Formation is a glauconite-rich phosphorite unit that represents a profoundly different depositional environment in the Maracaibo Basin from the underlying units of La Luna Formation (Gosh, 1984; de Romero, 1991; de Romero and Alvarez, 1995; Erlich et al., 1997). This investigation concerns the petrography and paleontology of the unit in two localities (Fig. 1) and their significance in terms of depositional environment.

Tomalin (1938) first described this unit as a distinctive horizon at the top of La Luna Formation in Mérida State. Stainforth (1962) formally described the unit as green layers of sandy, calcareous, fossiliferous glauconite. Equivalent horizons have been identified in other Andean states and in the Perijá foothills (Renz, 1959; Ford and Houbolt, 1963; Carmona, 1971; Van Hinte, 1976; Gosh, 1984) (Fig. 2). This phosphatic unit has been mined commercially and is a key marker for petroleum exploration in the Maracaibo Basin. Although numerous studies have been carried out in relation to the origin and paleoenvironment of the Tres Esquinas Member, the unit is not yet entirely understood.

GEOLOGICAL SETTING

Stratigraphic Framework

The Tres Esquinas Member is the uppermost member of La Luna Formation (Galea, 1989) (Fig. 2), the main petro-

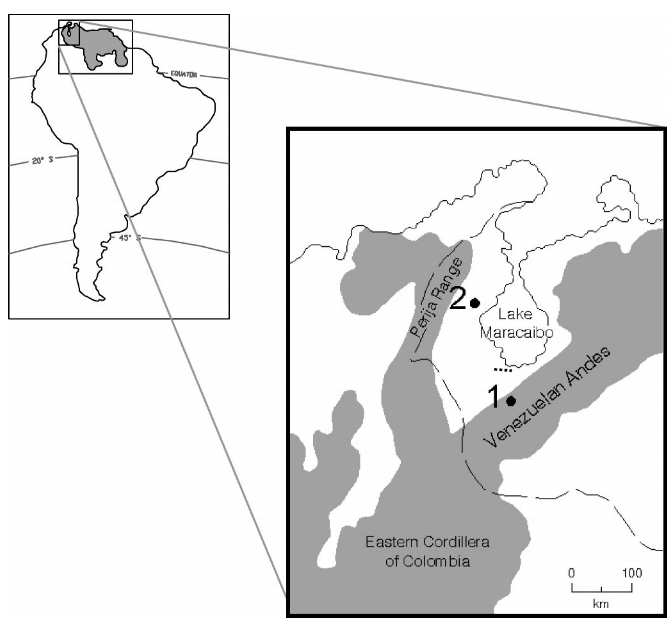

FIGURE 1—Location of the study area showing outcrop section (1), well (2), and seismic profiles (dotted lines).

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FORMATION	GENERAL DESCRIPTION
MITO JUAN	Gray and black shales, thin limestones and sandstones to the top.
COLÓN	Dark gray to black, microfosiliferous, hard shales, thin limestones.
TRES ESQUINAS MEMBER	Glauconitic, calcareous and fossiliferous sandstones. Phosphatic pelloids are very common.
LA LUNA	Calcareous shales and limestones, with abundant organic matter. Nodules and thin chert layers are common, as well as, elipsoidal or discoidal calcareous concretions. Ammonoids are very common.
CAPACHO	Gray, hard, fossiliferous (mainly mollusks) limestones. Black, hard, occasional laminated shales.

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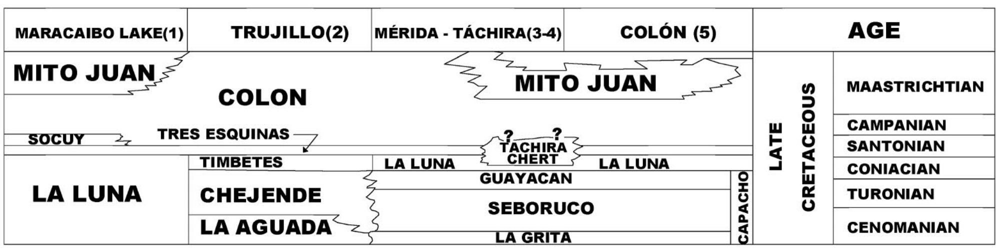

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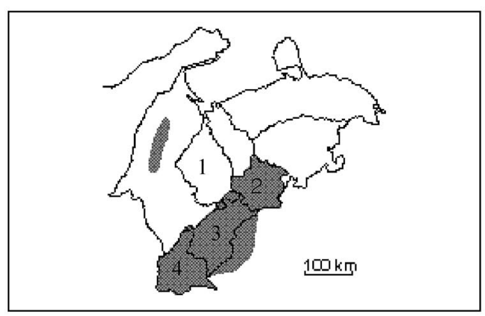

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FIGURE 2—Late Cretaceous stratigraphic units of Western Venezuelan Basin. (A) General lithologic characteristics of Late Cretaceous units in Western Venezuela. (B) Stratigraphy of Late Cretaceous in the Western Venezuelan Basin. (C) Distribution of outcrops of the Tres Esquinas Member in western Venezuela. Modified from III Léxico Estratigráfico Venezolano (http://www.pdv.com/lexico/lexicoh.htm).

leum source rock in the Maracaibo Basin. At the type section in Río Guaruríes, Mérida State described by de Romero (1991), the Tres Esquinas Member overlies black, laminated shales of La Luna Formation and underlies gray, slightly glauconitic shales of the Colón Formation. The Member is three meters thick and is composed of highly bioturbated, dark-gray, phosphatic, calcareous rocks. An early Campanian age for this unit based on foraminiferal biostratigraphy was determined by de Romero and Galea (1995).

Organic carbon-rich rocks of the La Luna Formation were deposited in anoxic bottom-water conditions during high eustatic sea levels in the Late Cretaceous. However, the presence of planktic foraminifera, bioturbation (*Planolites*), radiolarians, fish remains, and ammonites (Gonzalez de Juan et al., 1980; de Romero and Galea, 1995) suggests that oxygenated conditions occurred in the overlying water column and locally in deep waters.

Several second-order sea-level cycles have been identified within the La Luna Formation. Parnaud et al. (1995) identified three cycles in the Maracaibo Basin, with the third maximum flooding surface located within the Tres Esquinas Member. The Late Cretaceous transgression was followed by a regression that is represented by the shaly facies of the overlying Colón and Mito Juan Formations (Parnaud et al., 1995).

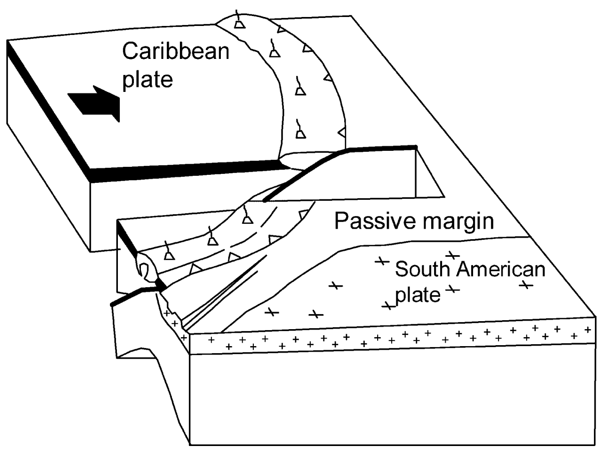

FIGURE 3—Tectonic framework of the Late Cretaceous in northwestern South America. Modified from Audemard (1998).

TABLE 2—Compositional estimates in percentages of the Tres Esquinas Member and the Colón Formation in the Río Guaruries section. TR = Trace Amounts.

Components/ Microfacies	Tres Esquinas Member OBW	OBPG	OBPGG	Colón Fm. GCS
Extraclasts	5	4	5	TR
Calcitic Cement	17	25		
Dolomite			20	
Siliceous Cement		5	5	
Micritic Matrix	20	3		
Clay Matrix				50
Fossils	35	27	15	10
Ooids		14	12	
Pelloids	5	10	3	
Glauconite		3	35	25
Pyrite		2		10
Porosity	3	7	5	
Organic Matter	15			

Tectonic Framework

Convergence and collision between the Pacific, South American, and Proto-Caribbean plates during the Late Cretaceous led to accretion of the Western Colombian Cordillera and the San Jacinto Belts on the magmatic arc of the Central Colombian Cordillera (Pindell and Barrett, 1990; Fig. 3). This activity changed the Maracaibo Basin from a passive to an active margin (Parnaud et al., 1995; Lugo and Mann, 1995). Parnaud et al. (1995) identified an early Cenomanian hiatus that could be associated with the collision, and suggested that the Cenomanian–Campanian transgressive pulse was related to tectonic subsidence in western Perijá (Fig. 4).

METHODS

Samples from the type section of Tres Esquinas Member were obtained from PDVSA, the Venezuelan Petroleum Company. The other section studied was a cored proprietary well from the Perijá area in the western part of the Maracaibo Basin (Fig. 1). All samples were observed in thin section. Petrographic analysis included the identification of fossils, authigenic phases, and clastic grains. The relative abundance of the different components was determined by modal grain counts. The diagenetic history of samples was inferred by observing textural relationships of authigenic phases and cements.

Foraminifera were identified at the generic level to help establish depositional environment and determine the age of samples. Thin-section foraminiferal identification was based on compilations of Sliter (1995) and Premoli Silva et al. (1999), with assistance from Irene Truskowski. Seventeen different genera were identified in the Guaruries section (Table 1). Poor preservation in the Perijá core prevented identification of genera. Finally, microfacies were defined for each locality based on petrography and foraminiferal assemblages. These microfacies were interpreted in terms of depositional environment.

TABLE 1—Foraminiferal occurrence in the Río Guaruríes section.

Microfacies/Genus	Tres Esquinas Member OBW	OBPG	OBPGG	Colón Formation GCS
Bolivinoides		X	X	X
Contusotruncana	X	X		X
Dorothia				X
Gaudrina		X	X	X
Gavelinella		X	X	X
Globotruncana				X
Guembelitria		X		
Hedbergella		X	X	X
Heterohelix	X	X	X	X
Lenticulina		X		
Orthokarstenia	X	X	X	X
Praebulimina		X	X	X
Pseudonodosaria		X		
Pyramidina		X	X	
Rugoglobigerina		X	X	
Siphogenerinoides	X		X	X
Svenia		X	X	

RESULTS

Tres Esquinas Member in the Río Guaruries Section

Phosphatic pellets, fish debris, angular phosphatic nodules, and glauconite grains are observed in thin section. Glauconite is common in the lower part of the unit and becomes more abundant towards the top. Pyrite also is observed near the top of the unit. The Tres Esquinas Member is characterized by abundant benthic and planktic foraminifera (Table 1) with variable preservation in individual samples. Finally, abundant shallow-water carbonate material, including ooids and peloids (Table 2 and Fig. 5), is observed. The matrix of samples is largely micritic. Four microfacies are defined (Figs. 6–8).

Orthokarstenia and Bolivinoides Wackestone Microfacies (OBW): The OBW microfacies is characterized by the benthic foraminifera *Orthokarstenia* and *Bolivinoides* and is present in the lowermost 60 centimeters of the Tres Esquinas Member in the Río Guaruries section. This micro-

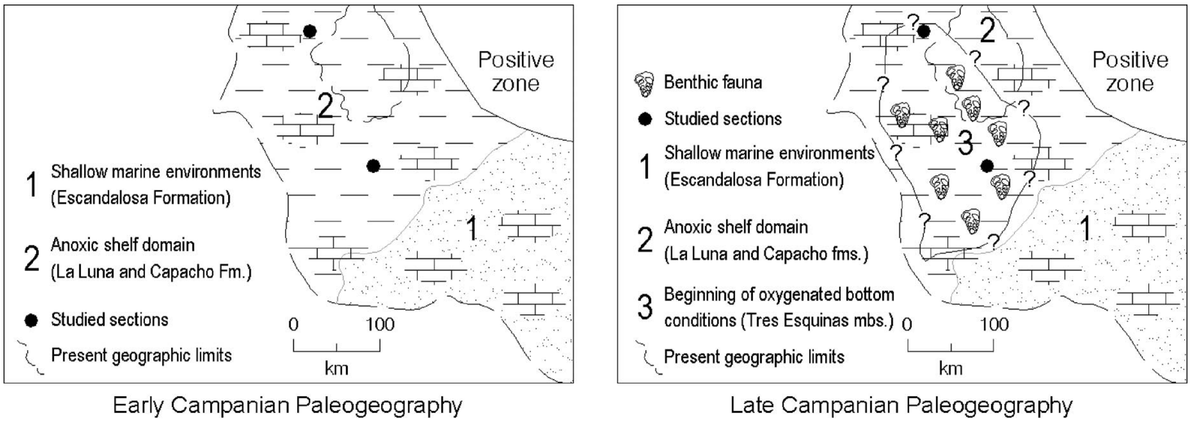

FIGURE 4—Foreland basin created in western Venezuela during the Late Cretaceous and resulting facies distribution. Modified from Parnaud et al. (1995).

facies has the least diverse foraminiferal assemblage and highly variable fossil preservation. The best-preserved foraminifera include *Contusotruncana*, *Heterohelix*, *Siphogenerinoides*, *Bolivinoides*, and *Orthokarstenia*. Other unidentifiable planktic foraminifera are observed. Shell material is heavily recrystallized, with chambers filled by sparry cement. A few fossils show evidence of phosphatization and dissolution. Shells are embedded in a micritic matrix with opaque material filling sub-parallel cracks. Fine quartz grains are a minor component (Fig. 7A). Although this microfacies lacks glauconite, the occurrence of phosphate indicates that it is part of the Tres Esquinas Member.

Orthokarstenia and Bolivinoides Phosphatized Grainstone with Ooids Microfacies (OBPG): This microfacies is present in the 1.5-meter interval above the OBW microfacies. It differs from the OBW microfacies by having more abundant shallow-water material, including fossils, ooids, and peloids that lack internal structure. The foraminiferal assemblage is the most diverse of any microfacies. *Orthokarstenia* and *Bolivinoides* are the most abundant genera. Also present are *Contusotruncana*, *Gavelinella*, *Gaudrina*, *Guembelitria*, *Hedbergella*, *Heterohelix*, *Lenticulina*, *Praebulimina*, *Pseudonodosaria*, *Pyramidina*, *Rugoglobigerina*, and *Svenia*. Quartz and rounded glauconite grains are rare. Phosphatization of the shell material is pervasive. Cements include calcitic spar, microspar, and chalcedony (Fig. 7B).

Orthokarstenia and Bolivinoides Phosphatized Grainstone with Glauconite and Dolomite Microfacies (OBPGG): This microfacies is present in a 70-cm interval above OBPG. Glauconite is the most abundant component and occurs as rounded, sand-sized grains. The foraminiferal assemblage is diverse and dominated by *Orthokarstenia* and *Bolivinoides*. Shallow-water carbonate components are similar to the OBW and OBPG microfacies. Dolomite is the most important authigenic mineral, replacing matrix as well as detrital quartz, feldspar, and glauconite grains. Quartz cement rings are observed around grains and filling foraminiferal chambers (Fig. 8A).

Glauconite Calcareous Shale Microfacies (GCS): This microfacies lies above OBPGG in the uppermost meter of the measured section. It represents a marked change in sedimentation, and is considered part of the Colón Formation (Fig. 8B). The sparse faunal assemblage is low in diversity, dominated by *Bolivinoides*, *Contusotruncana*, *Dorotia*, *Gaudrina*, *Gavelinella*, *Globotruncana*, *Praebulimina*, and *Siphogenerinoides*. Glauconite grains and pyrite are present and embedded in the clay matrix.

TABLE 3—Compositional estimates in percentages of the Tres Esquinas member compared to the underlying members of the La Luna Formation in the Perijá well core.

Components/ Microfacies	La Luna Formation PFW	Tres Esquinas Member GPD	Tres Esquinas Member GW	Tres Esquinas Member PFWG
Intraclasts	15			
Calcitic Cement	30	10	15	
Dolomite		20		
Micritic Matrix	20	20	50	60
Fossils	20	10	15	20
Phosphatic Pelloids	10	10	5	TR
Glauconite		20	15	10
Pyrite		10	TR	10
Organic Matter	5			

Tres Esquinas Member in the Perijá Core

The Tres Esquinas Member is 3 m thick and composed of gray to brown oolitic limestones with glauconite, phosphate, and dolomite. This unit is post-Campanian, based on the age of the top of the underlying La Luna Formation (Peralta, 1993). Foraminifera are very rare and largely recrystallized. The carbonate matrix is abundant, with dolomite, glauconite, and pyrite less abundant than in the Río Guaruríes section (Table 3). Three microfacies are defined (Figs. 6, 9, 10).

Planktic Foraminifera Wackestone Microfacies (PFW): This microfacies belongs to the top of the La Luna Formation, *sensu lato,* and was not analyzed at Río Guaruríes. The limestones contain a micritic matrix with abundant planktic foraminifera and micritic intraclasts. *Globigeri-*

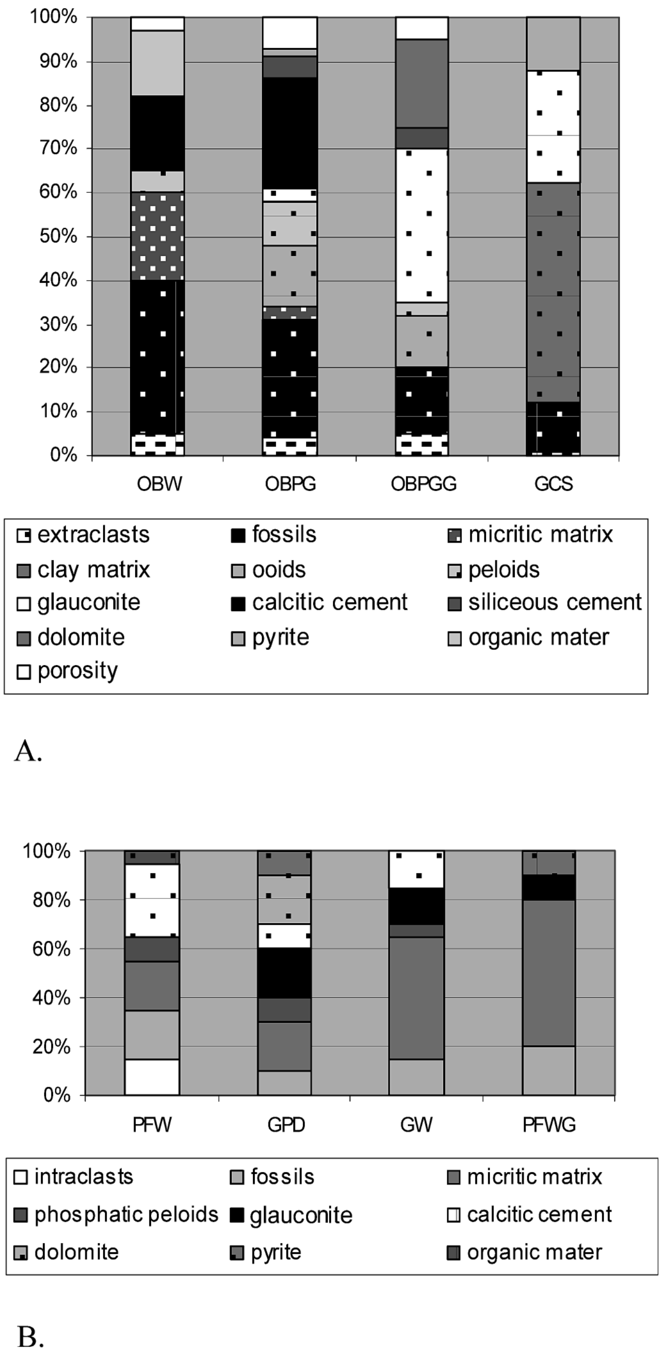

FIGURE 5—Microfacies components distribution in (A) Río Guaruries section (Table 2), and (B) Perijá well core (Table 3).

noides and *Heterohelix* are the most abundant foraminiferal genera present. Shell fragments are recrystallized and have been filled by sparry cement (Fig. 9A).

Glauconite Packstone with Dolomite Microfacies (GPD): This 60-cm thick microfacies lies at the base of the Tres Esquinas Member in the Perijá section. The shallow-water carbonate fraction is rare and is mainly composed of unidentifiable foraminifera, phosphatized ooids and peloids, and rounded glauconite grains that occasionally are associated with pyrite and phosphate particles. Dolomite often replaces the matrix and the glauconite. Pyrite replaces glauconite grains, dolomite, phosphates, and the matrix (Fig. 9B).

Glauconite Wackestone Microfacies (GW): This two-meter thick microfacies lies above GPD. Its principal component is a micritic matrix with few unidentifiable foraminifera, fish fragments, and rounded glauconite grains. The shallow-water carbonate fraction is rare compared to the Río Guaruries section. Foraminiferal chambers are sparand pyrite-filled (Fig. 10A).

Planktic Foraminifera Wackstone with Glauconite Microfacies (PFWG): This microfacies is located in the uppermost 40 cm of the Tres Esquinas Member, just below the Colón Formation (Figs. 6 and 10B). Clay matrix is the dominant component and benthic foraminifers are not abundant. Glauconite grains are less abundant than in other microfacies.

Seismic Expression of the Top of the La Luna Formation

Seismic data show that the top of the La Luna Formation is associated with a very pronounced reflector throughout the Western Venezuelan Basin. The La Luna Formation and underlying units often show structures that are not present in the overlying Colon Formation (see examples in Figures 11 and 12 ; other examples can be found in Cooney and Lorente, 1997 and Gallango et al., 2002). Significant changes in the thickness of the Colon Formation occur laterally as this unit onlaps underlying formations. These structures are evidence for a Late Cretaceous (Campanian–Maastrichtian) compressional phase in Western Venezuela, prior to deposition of the Colon Formation (Cooney and Lorente, 1997; Gallango et al., 2000). This event was associated with the collision between the Pacific–proto-Caribbean and South American plates.

DISCUSSION

Paleoenvironment and Tectonics

The La Luna Formation was deposited in anoxic bottom conditions in a hemipelagic setting at depths of 300 to 500 m (De Romero and Galea Alvarez, 1995). Conditions became slightly oxygenated during the Campanian when the Tres Esquinas Member was deposited. Increasing oxygen levels are indicated by abundant benthic foraminifera (*Bolivinoides*, *Orthokarstenia*, *Lenticulina*, *Praebulimina*), trace fossils (*Thalassionoides* and *Planolites*), significantly lower organic carbon contents, and the abundance of phosphate and glauconite (Burnett, 1974; de Romero and Galea, 1995).

The Tres Esquinas Member shows lateral lithologic variation as a consequence of variable bottom-water oxygenation across the basin (Table 2, Fig. 6). Oxygen levels were higher and increased at an earlier time at Río Guaruríes. The Perijá core shows scarce and poorly preserved benthic foraminifera and little phosphate, suggesting lower oxygen levels.

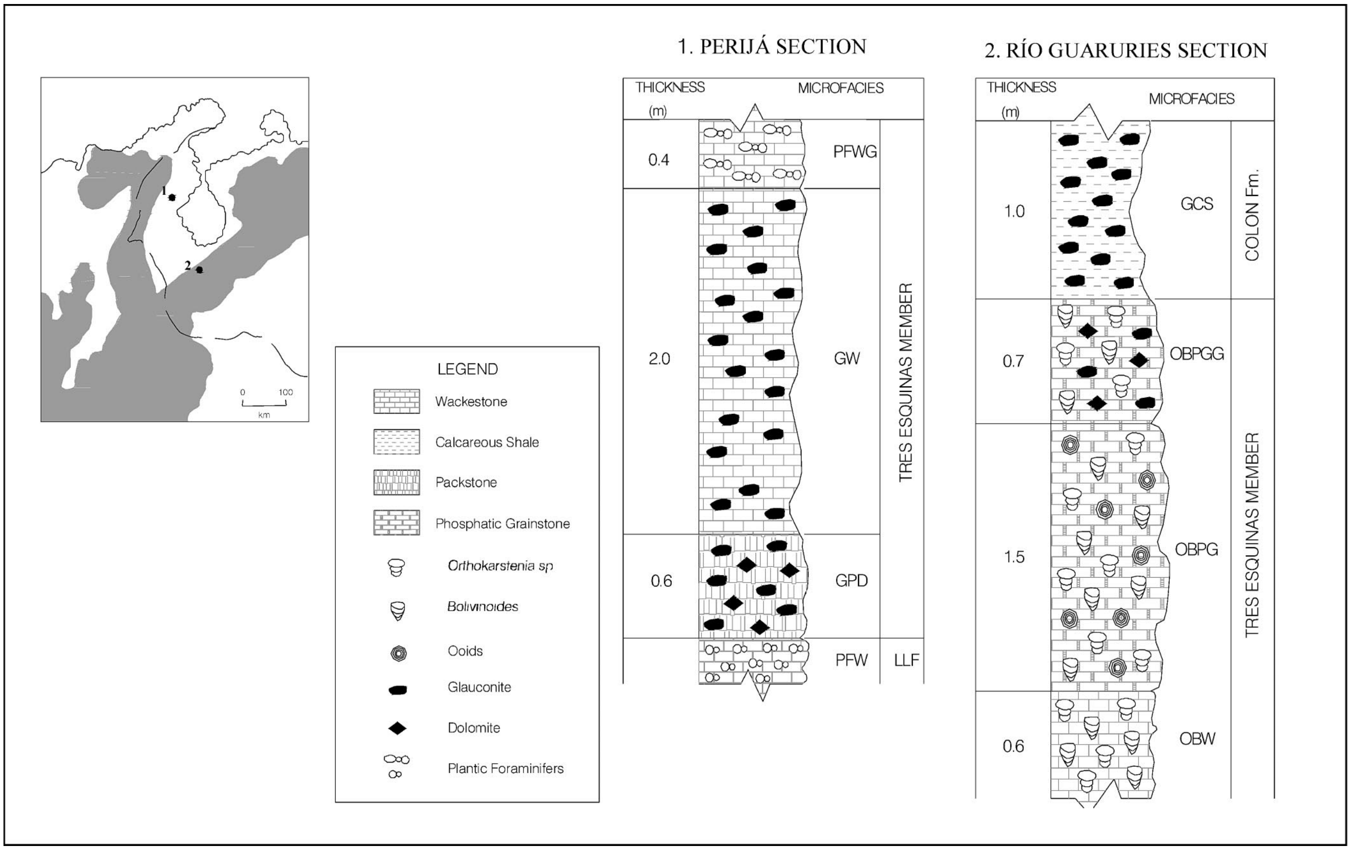

FIGURE 6—Stratigraphy of the Tres Esquinas Member in the studied locations.

Deposition of the Tres Esquinas was affected by bottom currents. Rounded glauconite and phosphate grains are evidence of reworking. According to Burnett (1974), after precipitation in interstitial waters, phosphates must be concentrated into indurated pellets, concretions, and nodules by winnowing and reworking. Currents and storms also may be responsible for the mixture of fossils with variable degrees of preservation, as well as the higher oxygenation of bottom waters. Paleobathymetric estimates suggest that this increase in energy was not controlled by sea-level fluctuation (Galea, 1989).

Based on stratigraphy and structure, changes in depositional environments between the La Luna Formation *sensu lato* and the Tres Esquinas Member may have been controlled by a compressional event. Deformation likely generated uneven sea-floor topography, which controlled the distribution of bottom currents and caused local erosion and redeposition (Fig. 13). Moreover, seismicity may have triggered turbidity currents that concentrated phosphate in a similar fashion to the modern Peru and Chile shelves where sediments similar to those of the Tres Esquinas Member are deposited (Burnett, 1974).

Diachroneity of the Tres Esquinas Member across the basin is also consistent with tectonic activity. The earlier return of oxygenated conditions in the area may be associated with the Mérida Arch, a structural high that led to shallow-water conditions over a wide area (Fig. 14). This structure may have been reactivated as a result of Late Cretaceous collisional tectonics.

Diagenetic Processes

Diagenesis of the Tres Esquinas Member began with the formation of phosphate and glauconite. These early-diagenetic phases and the scarce clastic fraction suggest a limited terrigenous supply to the basin. However, the presence of glauconite indicates enrichment of iron in sedimentary pore waters, possibly from intense weathering of the Guayana Shield.

The concentration of phosphorus could be related to waning anoxic conditions (de Romero, 1991). Phosphatization did not affect the other authigenic minerals that are present in this unit, suggesting that these minerals were formed after the phosphates. Silica (quartz or chalcedony) is present as rings around foraminiferal tests or within chambers. These minerals could have been produced by the dissolution of siliceous skeletal elements such as radiolarians. The space resulting from this dissolution was then filled by equigranular calcitic cement. Dolomite and pyrite, which replace all the other authigenic and fossil components, probably were formed later. Dolomitization

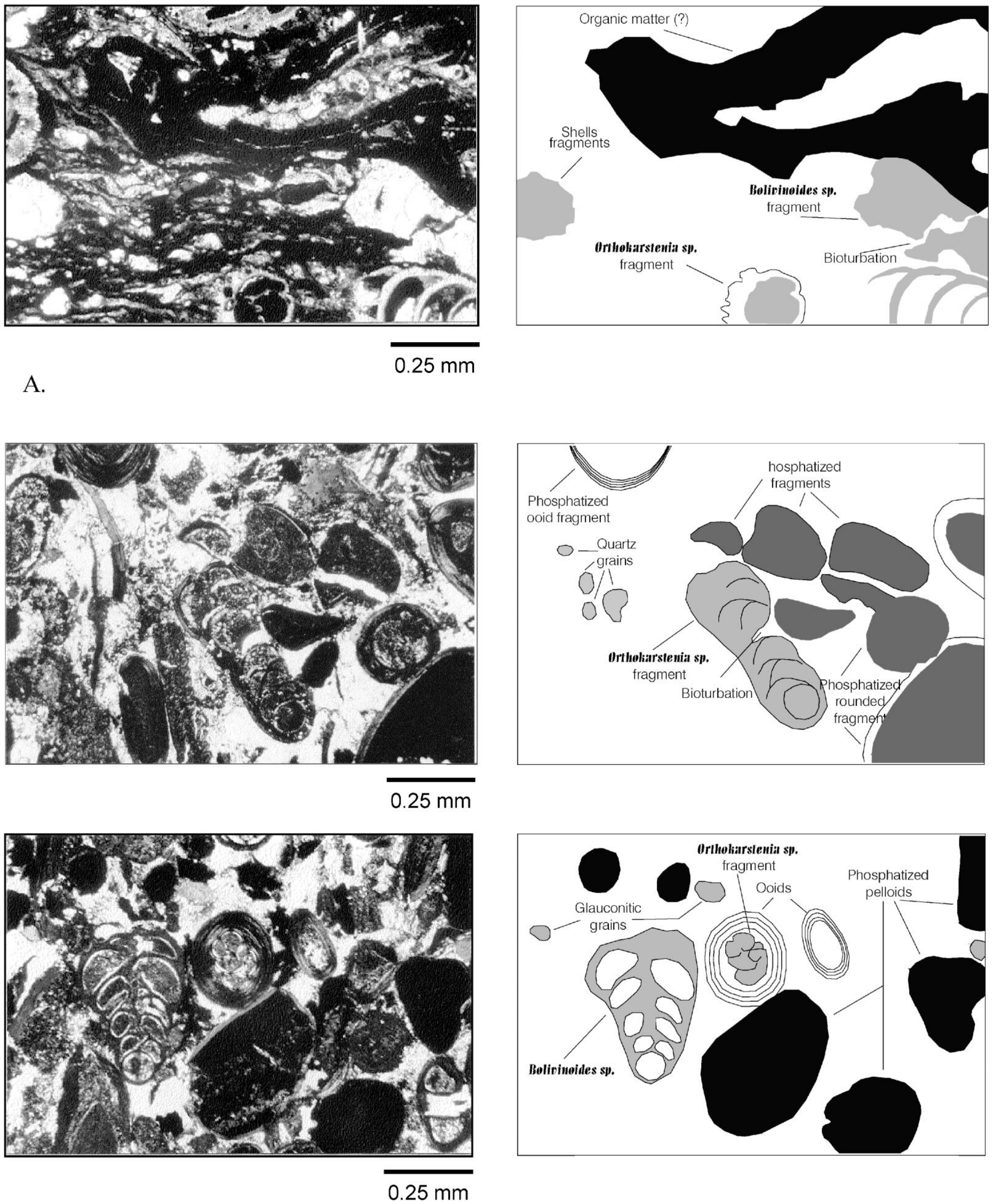

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FIGURE 7—Photomicrographs of Río Guaruries section microfacies. (A) *Orthokarstenia* and *Bolivinoides* wackestone (OBW). (B) *Orthokarstenia* and *Bolivinoides* phosphatized grainstone with ooids (OBPG).

must have taken place during later burial stages because the chemical conditions that favor the formation of phosphates do not usually favor dolomite (Gosh, 1984). The Tres Esquinas Member also has been subjected to burial compaction, causing flattening of grains and interpenetrating contacts between them.

CONCLUSIONS

The Tres Esquinas Member represents a significant event at the end of the La Luna Formation sedimentary cycle in the Maracaibo Basin. Abundant benthic foraminifera, trace fossils, low organic-carbon contents, and the occurrence of phosphate and glauconite indicate higher oxygen levels than during deposition of the underlying La Luna Formation. However, oxygenation and deep-water circulation intensity varied significantly between the two sections investigated, as shown by differences in the abundance and preservation of benthic foraminifera. Phosphate and glauconite also indicate reworking by bottom currents and active early-diagenetic processes favored by limited clastic supply. Increased bottom current activity

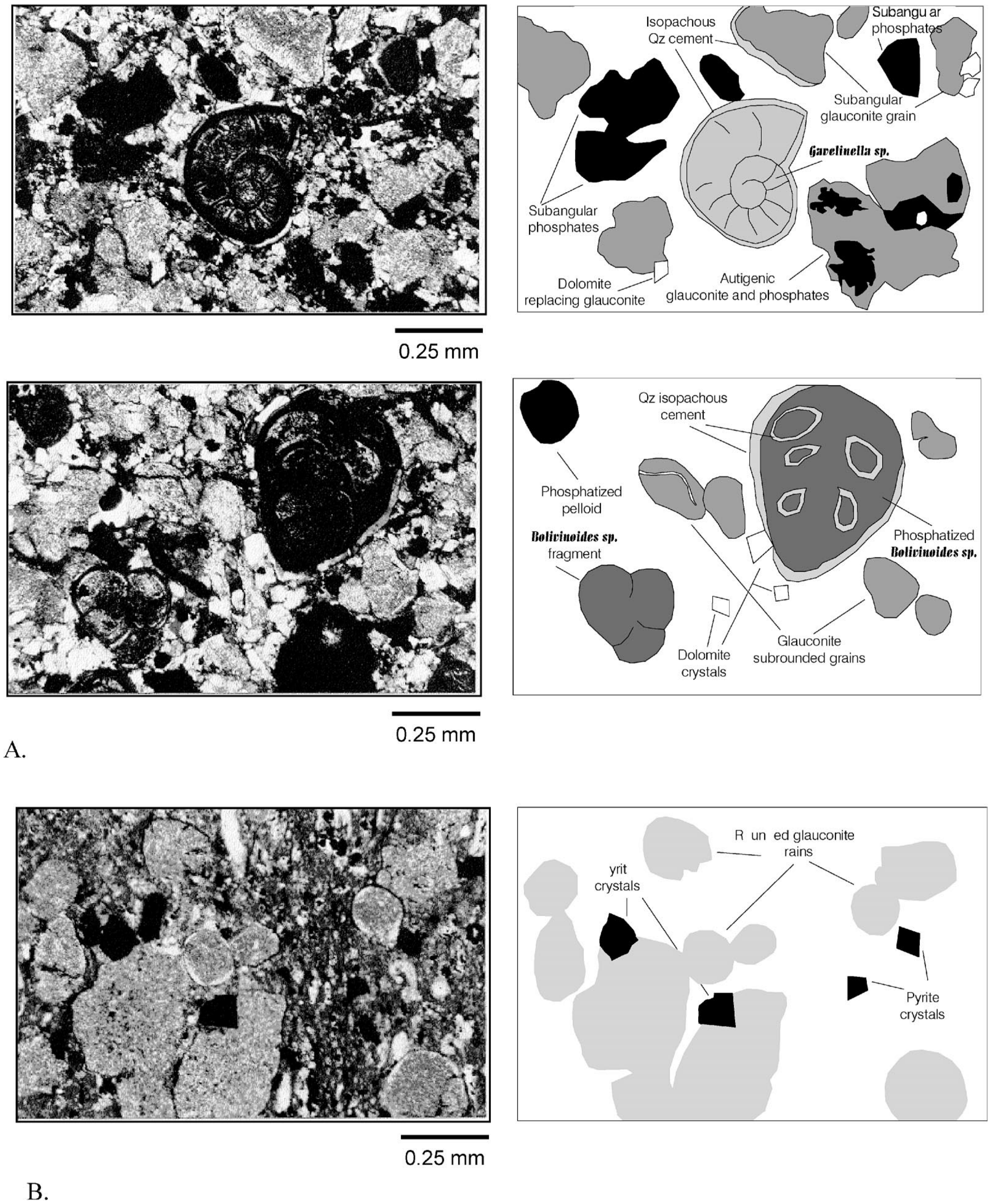

FIGURE 8—Photomicrographs of Río Guaruries section microfacies. (A) *Orthokarstenia* and *Bolivinoides* phosphatized grainstone with glauconite and dolomite microfacies (OBPGG). (B) Glauconite calcareous shale microfacies (GCS).

likely was associated with tectonic processes that led to shoaling of the sea floor over a large part of the Maracaibo basin. This tectonic event marks the initial deformation of the Western Venezuela passive margin associated with the convergence of the Pacific, Caribbean, and South America plates.

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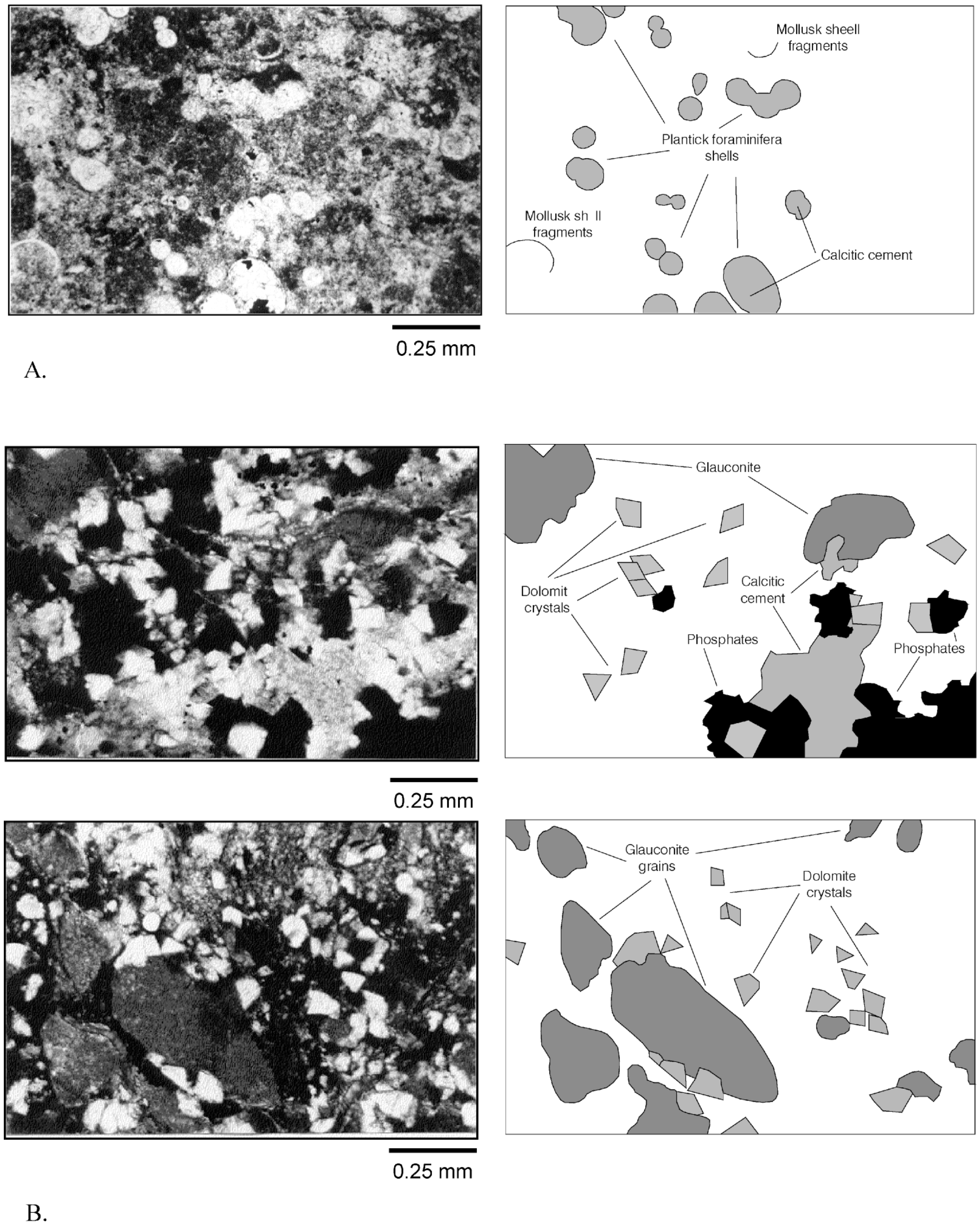

FIGURE 9—Photomicrographs of the Perijá well core microfacies. (A) Planktic foraminiferal wackestone (PFW, La Luna Formation, *sensu lato*). (B) Glauconite packstone with dolomite (GPD).

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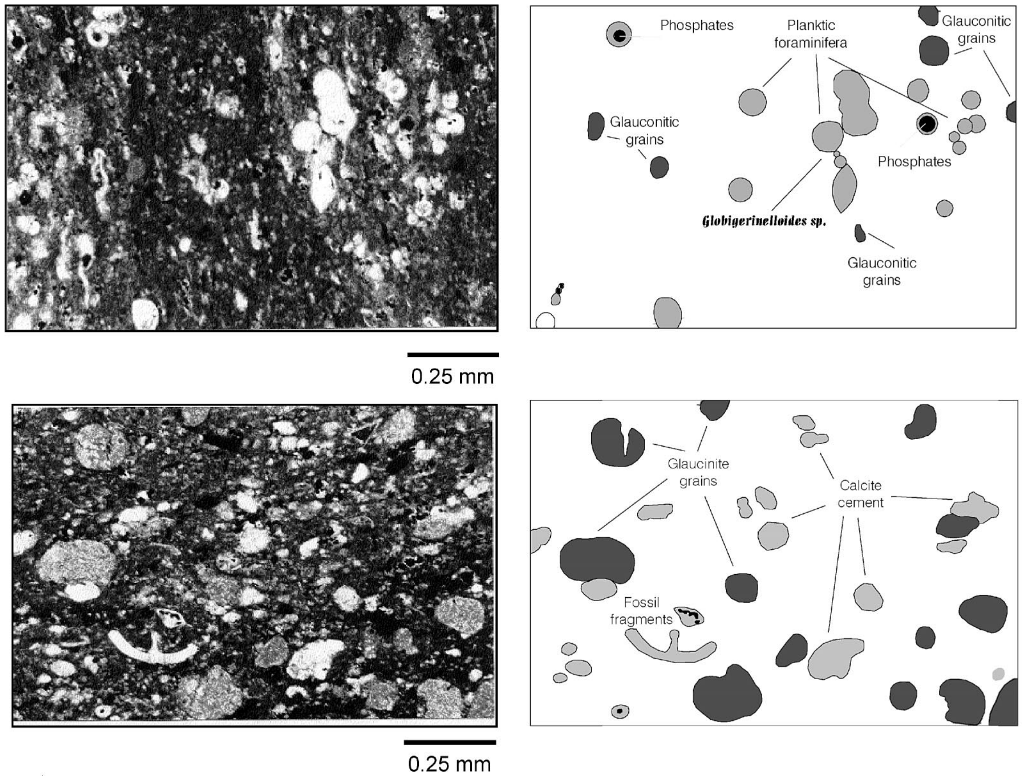

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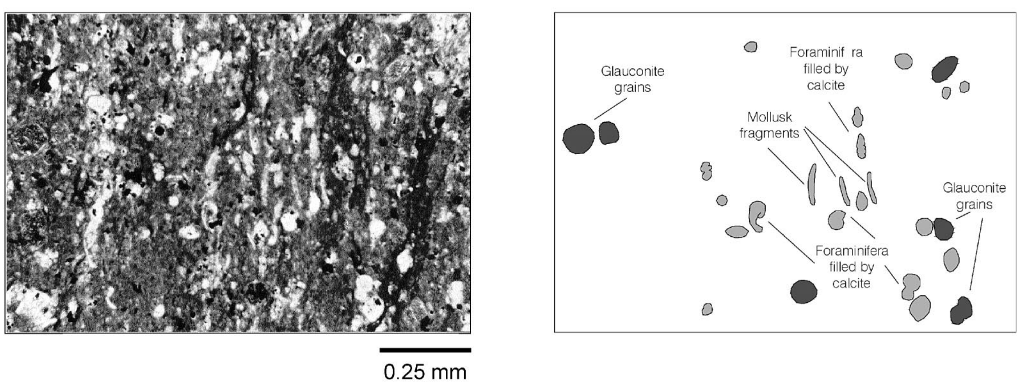

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FIGURE 10—Photomicrographs of the Perijá well core microfacies. (A) Glauconite Wackestone (GW). (B) Planktic foraminiferal wackestone with glauconite (PFWG).

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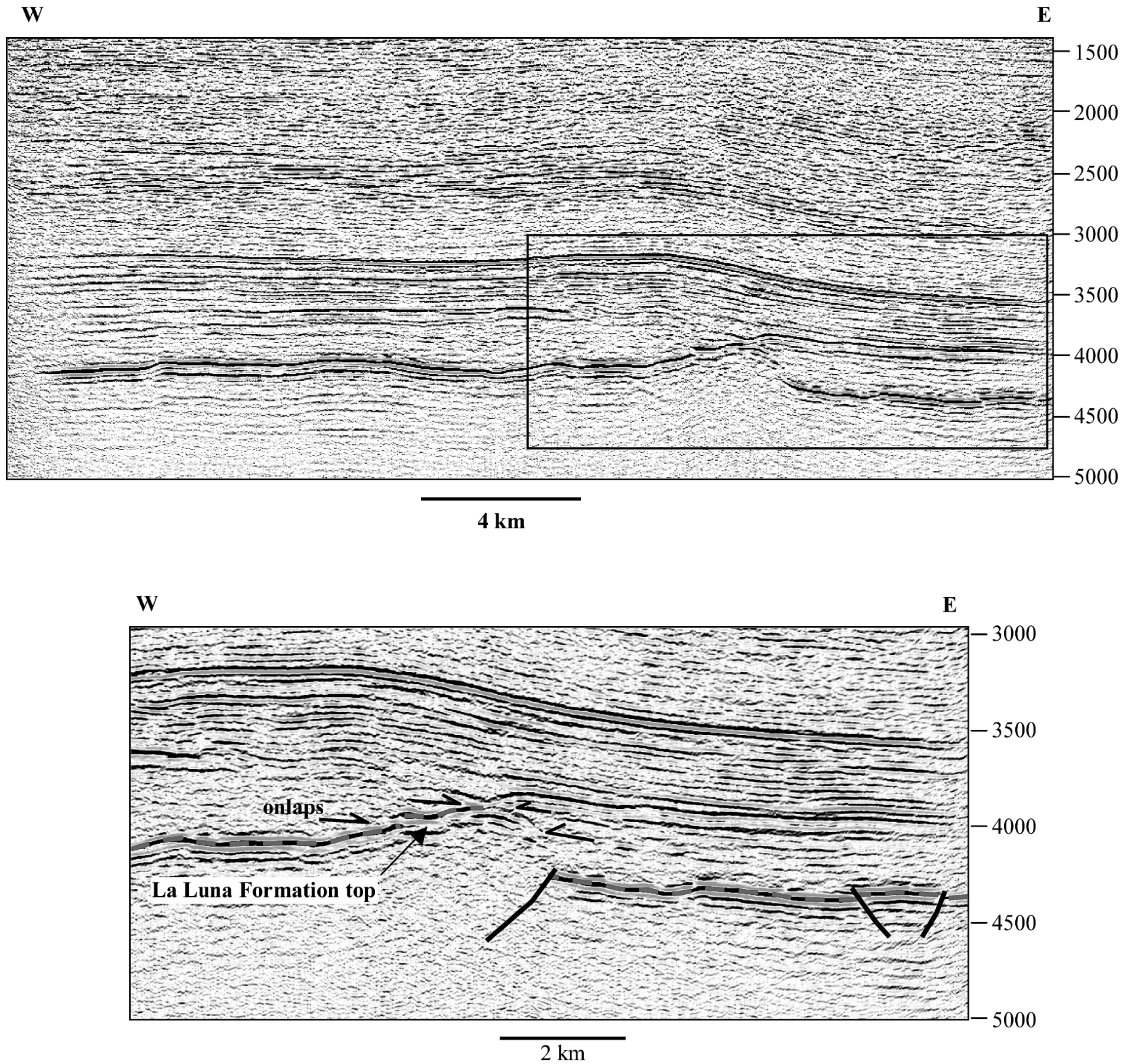

FIGURE 11—Seismic section of southern Lake Maracaibo, showing deformation of the top of the La Luna Formation prior to deposition of the overlying units. East–West section. A 400-millisecond-high anticline can be observed in the La Luna and underlying units.

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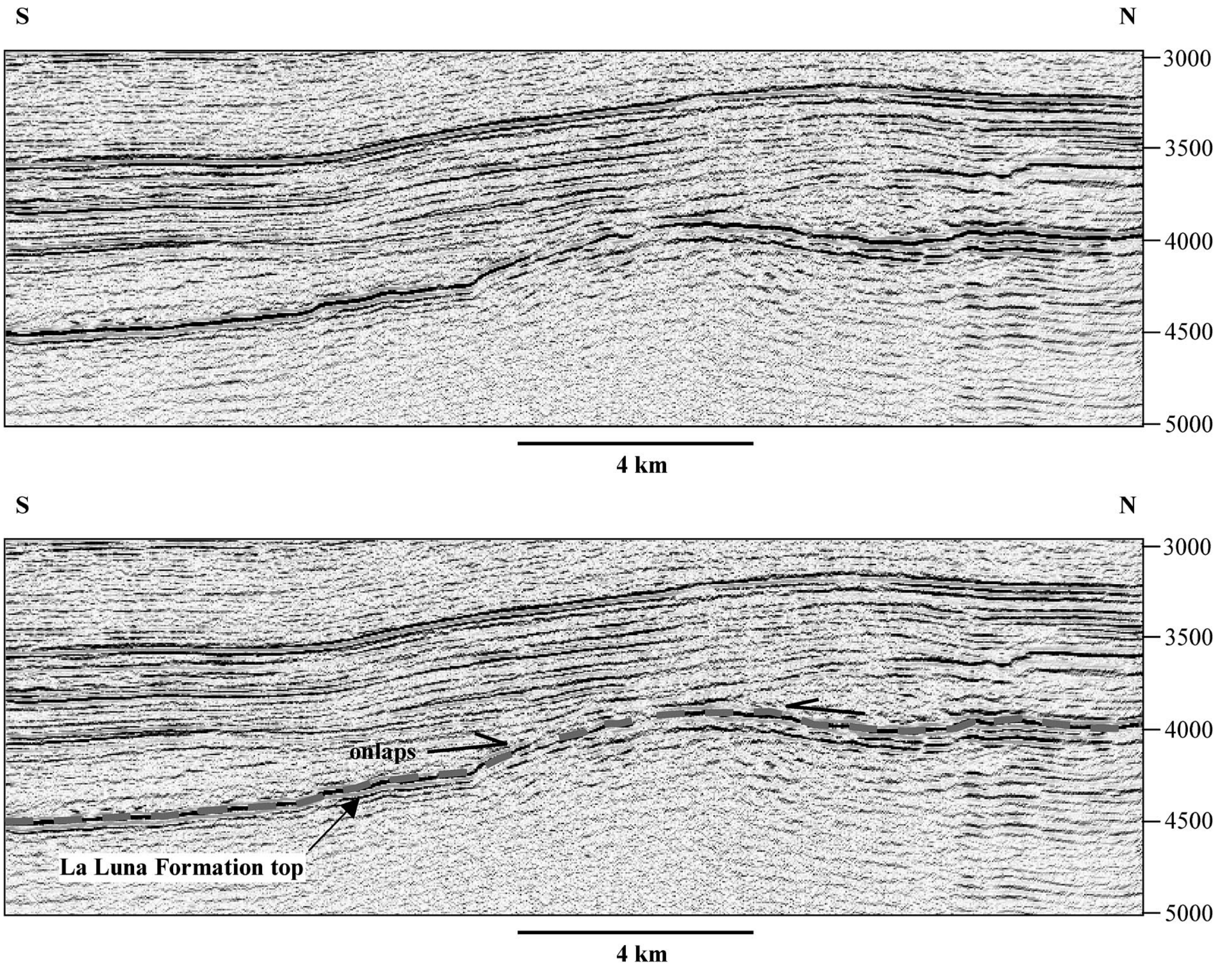

FIGURE 12—Seismic section of southern Lake Maracaibo, showing deformation of the top of the La Luna Formation prior to deposition of the overlying units. North–South section. A 400-millisecond-high anticline can be observed in the La Luna and underlying units.

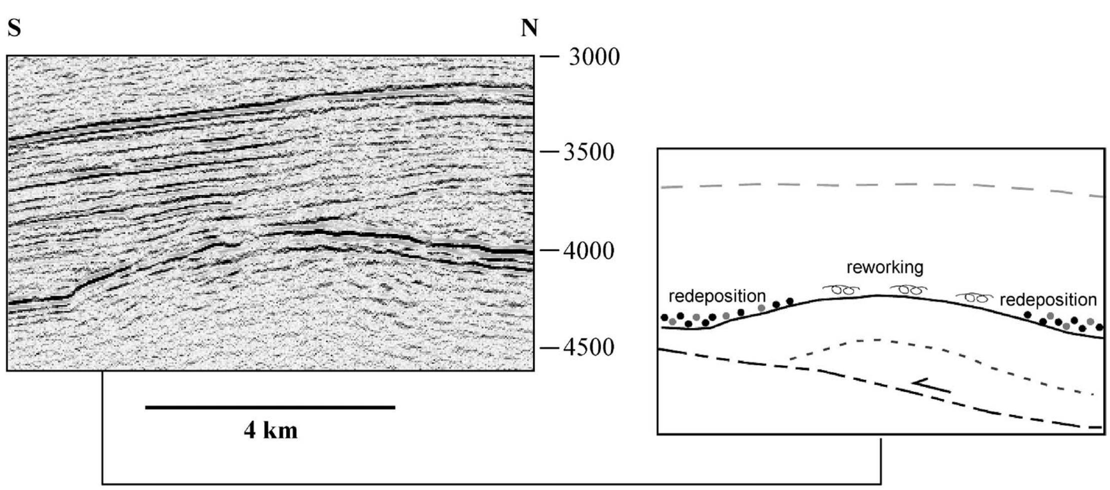

FIGURE 13—Tectonic control on sedimentation during the Late Cretaceous in the Maracaibo Basin.

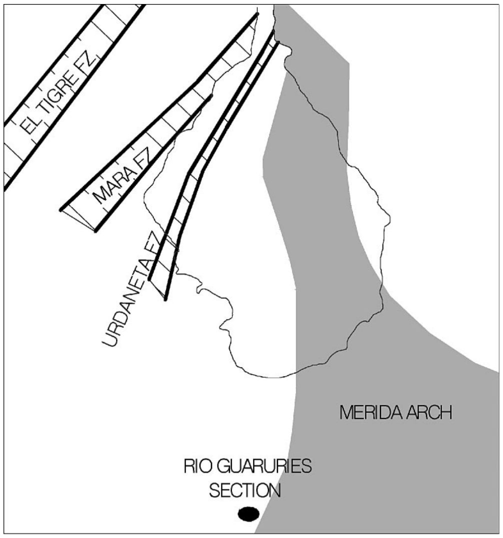

FIGURE 14—Structural elements in the Maracaibo basin at the beginning of Cretaceous. Modified from Lugo and Mann (1995).

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