Microfacies analysis and paleoenvironmental dynamic of the Barremian-Albian interval in Sierra del Rosario, eastern Durango state, Mexico

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ABSTRACT

The detailed microfacies analysis on a stratigraphic section located in eastern Durango contribute to the paleoenvironmental and paleogeographic understanding of the Cupido and Coahuila carbonate platforms in the southern part of the Coahuila basement block, a poorly investigated area. The stratigraphic section herein studied spans the Barremian-Albian interval and is composed of the upper Cupido, La Peña and Upper Tamaulipas formations. The recognition of this latter unit in the eastern part of the Durango state is a significant contribution to the stratigraphic scheme of the southern part of the Sierra del Rosario.

The studied interval of the Cupido Formation is represented by different microfacies associations: 1) peritidal and subtidal facies deposited in a shallow lagoon. In these facies, an important microbial contribution and high energy events are recognized; 2) sand bars facies accumulated on the platform margin. Interaction of these facies with sea level fluctuations caused different levels of restriction and periodic flooding in the platform interior; 3) platform margin and fore-reef facies. The microfacies associations of the La Peña Formation were deposited on the periplatform zone in an outer neritic to upper bathyal environment. The microfacies associations of the upper part of the La Peña Formation and those belonging to the Upper Tamaulipas Formation are typical of open marine and relatively deep-water conditions.

The microfacies have been divided according to their relation with the different phases of the Cupido Platform drowning. The definitive drowning phase began in the early Aptian when the sea level rose over the sand shoals on the platform margin. An increase in the crinoid content and a mixture of lagoonal and open marine biota are characteristics of the drowning phase at the end of the Cupido Formation deposition. The microfacies associations within the lower part of the La Peña Formation recorded the definitive drowning of the platform and an environmental stress that accentuated this event. Post-drowning facies in the upper part of the La Peña Formation and throughout the Upper Tamaulipas Formation are represented by pelagic facies deposited in an open marine environment with significant oxygen variations in the water-sediment interface. The sand shoals facies described in the Cupido Formation correspond to the western continuation of the Barremian-Aptian Cupido Platform margin.

Key words: microfacies, platform drowning, Barremian-Albian, Durango, Mexico.

RESUMEN

El análisis detallado de microfacies de una sección estratigráfica localizada en el este del estado de Durango aporta importante información paleoambiental y paleogeográfica sobre las plataformas

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carbonatadas Cupido y Coahuila en la porción meridional del bloque de Coahuila, un área pobremente estudiada. La sección estratigráfica comprende el lapso Barremiano-Albiano y está compuesta por la parte superior de la Formación Cupido y las formaciones La Peña y Tamaulipas Superior. El reconocimiento de esta última unidad en el este del estado de Durango es una contribución significativa al esquema estratigráfico de la porción sur de la Sierra del Rosario.

El intervalo analizado de la Formación Cupido comprende diferentes asociaciones de microfacies: 1) facies lagunares perimareales y submareales, en algunas de las cuales se reconoce un importante aporte microbiano y facies relacionadas con eventos de alta energía; 2) facies de barras arenosas en la margen de la plataforma, cuya interacción con las fluctuaciones del nivel del mar causaron diferentes niveles de restricción en el interior de la plataforma e inundaciones periódicas; 3) facies de margen de plataforma y del frente arrecifal. Las asociaciones de microfacies de la Formación La Peña fueron depositadas en una posición de periplataforma en la zona nerítica externa a batial superior. Las asociaciones de microfacies de la parte superior de la Formación La Peña y las correspondientes a la Formación Tamaulipas Superior son propias de ambientes marinos abiertos relativamente profundos.

A partir de los rasgos de las microfacies se discriminaron las asociaciones relacionadas con cada fase del ahogamiento de la Plataforma Cupido. El ahogamiento definitivo ocurrió a inicios del Aptiano cuando el nivel del mar superó las barras arenosas en la margen de la plataforma. El aumento de crinoideos y la mezcla de biota lagunar y de condiciones marinas abiertas caracterizan la fase de ahogamiento al término del depósito de la Formación Cupido. Las asociaciones de microfacies de la parte inferior de la Formación La Peña denotan el ahogamiento definitivo de la plataforma y registran un estrés ambiental que terminó de acentuar este evento. Las facies posteriores al ahogamiento, en la parte superior de la Formación La Peña y en la Formación Tamaulipas Superior, son facies pelágicas depositadas en una zona con circulación libre al océano abierto y variaciones significativas en el contenido de oxígeno en la interfase sedimento-agua. Las facies de barras arenosas descritas en la Formación Cupido corresponden a la prolongación más al oeste de la margen sur de la Plataforma Cupido durante el Barremiano-Aptiano.

Palabras claves: microfacies, ahogamiento de plataforma, Barremiano-Albiano, Durango, México.

INTRODUCTION

The Barremian-Albian interval of northeastern Mexico was characterized by the development of widely extended carbonate platforms, when those paleogeographic elements reached their maximum extent around the Gulf of Mexico coast (Scott, 1990; Wilson and Ward, 1993). The platforms that developed during this interval correspond to the Cupido and Coahuila and they grew around and on top of the Coahuila basement block (Wilson, 1987). Important researches have documented the composition and paleogeographic situation of these platforms in the Sierra Madre Oriental near Monterrey and Saltillo (Conklin and Moore, 1977; Wilson and Pialli, 1977; Padilla y Sánchez, 1982; Goldhammer *et al.*, 1991; Wilson and Ward, 1993) and in the Sierra de Parras (Lehmann *et al.*, 1998, 1999, 2000).

Our work focused on a stratigraphic section located in eastern Durango state (lat 25°16'N - long 103°46'W) (Figure 1), because it provides crucial paleoenvironmental information about the Cupido and Coahuila Platforms in the southwestern part of the Coahuila block, a poorly studied area. Furthermore, this paper sheds new light to the understanding of the paleogeographic and stratigraphic configuration of the area and to the drowning of the Cupido Platform.

Based on stratigraphic and paleontological data, (Araujo and Martinez, 1981, *in* Araujo-Mendieta, 1993) recognized in the stratigraphic section herein studied from bottom to top: the upper part of the Cupido Formation (Imlay, 1937; Humphrey, 1949), the whole La Peña Formation (Imlay, 1936; Humphrey, 1949), and the lower part of the Aurora Formation (Burrows, 1910). A previously detailed petrographic analysis integrated with geochemical and paleontogical information of the Cupido and La Peña formations by Barragán (2001) provided useful data to the understanding of the environmental changes indicative of the transgressive episode that apparently drowned the Cupido Platform. A recent research of Barragán-Manzo and Díaz-Otero (2004) provided additional biostratigraphic data to this stratigraphic section, and defined the Barremian-Aptian transition by the first stratigraphic appearance of the benthic foraminifer *Palorbitolina* cf. *lenticularis* (Figure 2).

The research presented in this work consisted of a new interpretation of this stratigraphic section based on a more detailed microfacies analysis in a more expanded stratigraphic succession and a higher resolution sampling for petrographic study.

GEOLOGICAL SETTING

Early Cretaceous time was marked by the development of extensive Peri-Tethyan carbonate platforms in

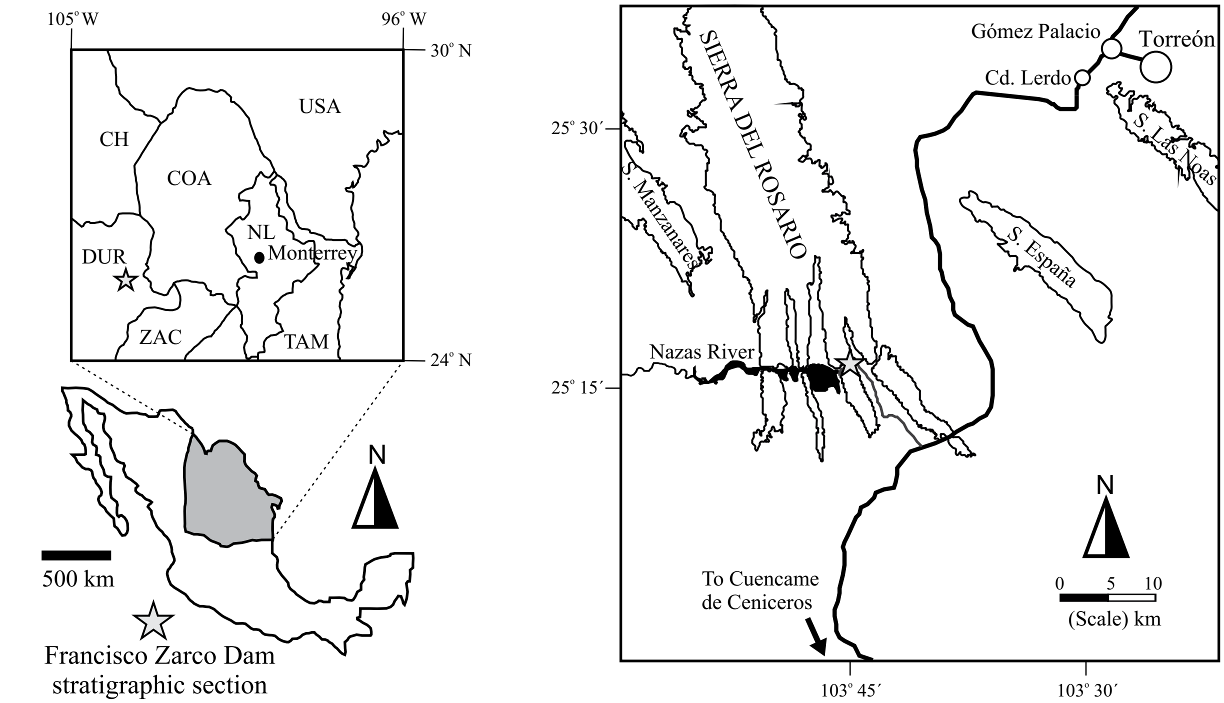

Figure 1. Map of northeast Mexico showing the geographic location of the Franciso Zarco dam stratigraphic section. CH= Chihuahua, COA= Coahuila, DUR= Durango, ZAC= Zacatecas, NL= Nuevo León, TAM= Tamaulipas.

different climatic and tectonic settings, and with an oceanographic dynamic ruled by the transgressive conditions that prevailed on that period. In northern Mexico, the Cupido carbonate Platform represents one of those paleogeographic elements developed during the Barremian-Aptian transition, and whose sediments piled out between the Coahuila basement block and a coral-rudist reefal margin (Conklin and Moore, 1977; Wilson and Pialli, 1977; Alfonso-Zwanziger, 1978; Selvius and Wilson, 1985; Goldhammer *et al*., 1991; Murillo-Muñetón and Dorobek, 2003). The drowning phase of this platform occurred about the middle to late Aptian and is recorded in the Cupidito facies. This informal unit was introduced by Wilson and Pialli (1977) as a transgressive unit on the topmost of the Cupido Formation that indicates a gradual upward deepening, event that prevails through the facies of the La Peña Formation (Lehmann *et al.*, 1999).

This transgressive pulse coincides with the episode of major demise of carbonate platforms in the peri-Tethys area (Föllmi *et al*., 1994) and it is informally known as the "Gargas" event in Mexico (Barragán-Manzo and Díaz-Otero, 2004). The deposition of pelagic limestones and shales during the middle to almost all throughout late Aptian of the La Peña Formation represents the record of this event in our study area (Trejo, 1975; Tinker, 1982; Goldhammer *et al.*, 1991).

A second major episode of carbonate platform development took place near the Aptian-Albian boundary and is represented by the shallow water deposits of the Aurora Formation accumulated on top of the Coahuila Block. In deep water environments the lateral equivalent deposits of this platform are recorded by facies of the Upper Tamaulipas Formation (Stephenson, 1922). The margin of this second platform exhibits a significant backstep northward from the preceding Cupido margin; in consequence, the identification of facies of the Aurora Formation in the stratigraphic section here studied made by Araujo-Mendieta (1993), is not consistent with current paleogeographic reconstructions.

The stratigraphic section discussed in this work is constituted by the aforementioned lithostratigraphic units and is located at the Francisco Zarco dam in Durango state (Figure 1), along the western exposed limb of an open anticline at the southern end of the Sierra del Rosario.

MATERIAL AND METHODS

A detailed analysis of the microfacies succession on the stratigraphic section was the main tool used in this research for the paleoenvironmental interpretations. It consisted in the study of paleontological and petrographic components of 390 thin-sections, following the guidelines of Dunham's (1962) classification of carbonate rocks. Grain assemblages were the main criteria to differentiate Microfacies Associations (MA) that represent a peculiar site of deposition with defined environmental conditions.

The material studied was obtained during several field seasons which allowed the recognition of initial formational characteristics. The section was measured on a bed-by-bed scale, up to a total thickness of 265.9 m, from which the lower 118.76 m correspond to facies of the

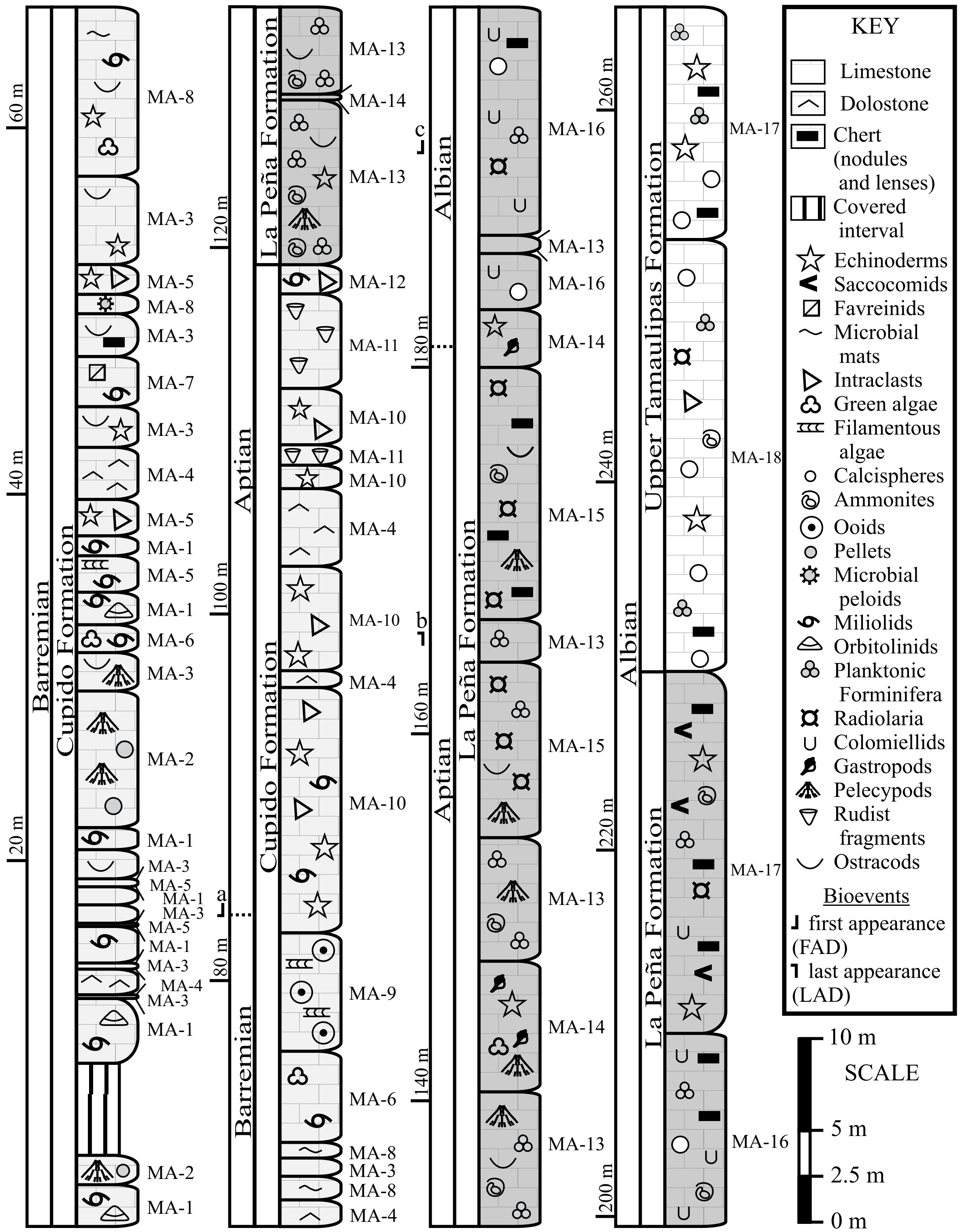

Figure 2. Stratigraphic column showing lithological changes within the stratigraphic section of this study. MA-1 to MA-18 were defined based on the vertical variation of microfacies. Bioevents: a. FAD of *Palorbitolina* cf. *lenticularis* (level PFZ 202) (*in* Barragán-Manzo and Díaz-Otero, 2004), b. LAD of *Hypacanthoplites* cf. *leanzae* (level PFZ 348) (*in* Barragán, 2000; Barragán-Manzo and Méndez-Franco, 2005), c. FAD of *Colomiella recta* Bonet, 1956 (level PFZ 440).

Cupido Formation, and the overlying 110.92 m are facies of the La Peña Formation (Figure 2). The upper 36.23 m are traditionally assigned to deposits of the Aurora Formation (Araujo-Mendieta, 1993).

The number of samples taken in each bed was a function of the stratum thickness. For example, rock samples were collected at the base, middle part and at the top of thick beds, whereas only one sample was required if the stratum was relatively thin. Within the Cupido Formation and the capping Aurora Formation in the stratigraphic section, all beds were sampled, while for the interval belonging to the La Peña Formation, the rock samples were taken only from beds with significant lithological features.

RESULTS

Lithostratigraphy

A description of the lithostratigraphic characteristics of the Cupido and La Peña formations in the stratigraphic section can be found in Barragán (2001). In this paper only the main features of the upper unit assumed as the Aurora Formation by other authors, as mentioned before, are discussed.

This unit is composed of bedded gray to blue limestones varying in thickness from 4 to 500 cm, with common pelecypod shells and fine, parallel lamination. The contacts between beds are irregular and rarely stylolitic. Its lower part is marked by very thick and thick limestone beds containing scarce chert nodules. In the middle and upper parts, the limestone beds alternate with thin beds of shale and marl. In the upper part, chert arranged in nodules and lenses are abundant; they reach 20 cm in length and are not aligned.

Although these stratigraphic attributes are not diagnostic of any lithostratigraphic unit, the microfacies analysis herein exposed, reveal that the uppermost lithostratigraphic unit of the stratigraphic section studied is instead part of the Upper Tamaulipas Formation.

Microfacies

The microfacies of the stratigraphic section of this study were grouped into eighteen characteristic microfacies associations (MA) (Figure 2) which are briefly described as follows, from bottom to top:

Cupido Formation
(Microfacies associations MA-1 to MA-12)

MA-1. Wackestone-mudstone with abundant to common miliolids and orbitolinids (Figure 3a). They usually contain pellets, and fragments of echinoderms and ostracods. An increase in the content of pelecypod fragments, as well as in the size of the orbitolinids originates a floatstone microfacies type (Figure 3b). Autochthonous worm tubes are peculiar components of this microfacies association.

MA-2. Floatstone with fragments of ostreids, pellets, peloids and common miliolids (Figure 3c).

MA-3. Dark, organic-rich mudstone with ostracods, echinoids, echinoderms and mollusk fragments. A peculiar feature of facies of this microfacies association is the presence of laminoid, fenestral fabrics and peloidal matrix (Figure 3d).

MA-4. Dolostone showing idiotopic, inequigranular mosaic of dolomite crystals. The intercrystalline pores are infilled with organic matter and silt. Poikilotopic dolomite is not so abundant (Figure 3e).

MA-5. This association is conformed by two facies: (A) packstone and rudstone with abundant imbricated filamentous algae, abundant mollusks, angular peloids, scarce echinoderms with syntaxial overgrowth, miliolids and worm tube fragments. These facies display low-angle, micro-cross-lamination (Figure 4a); and (B) grainstone and floatstone with abundant angular-subangular intraclasts and echinoderms with syntaxial overgrowth and abundant echinoids. Filamentous algae and miliolids are rare components (Figure 4b).

MA-6. Bioturbated wackestone and floatstone with abundant, well-preserved dasyclad algae and miliolids. Sponges, pelecypod fragments, cortoids, intraclasts and worm tubes are components of minor importance (Figure 4c).

MA-7. Wackestone with common to abundant favreinids, miliolids and cortoids. In minor proportion they contain worm tubes, intraclasts, mollusk fragments and green algae (Figure 4d).

MA-8. This association is made of the following facies: (A) microbial-peloidal packstone with a few miliolids, intraclasts, mollusks and echinoids (Figure 4e); and (B) wackestone-floatstone exhibiting incipient microbial laminated mats (Figure 4f) and dasyclad algae fragments. Miliolids are scarce, and sponges, intraclasts, ostracods and worm tubes are present in different proportions. Bioturbated fabric is common in both facies; however, non-depositional surfaces occur only in the latter.

MA-9. Grainstone and rudstone with superficial and well-sorted ooids, filamentous algae and intraclasts. The cortices of ooids exhibit radial, tangential and micritic microfabrics. Miliolids, pellets and mollusk fragments are common grains and they can occur as ooid nuclei. At the base, cortoids are typical grains and at the top normal ooids are the dominant grains (Figure 5a-5b).

MA-10. Grainstone and packstone characterized by the concentration of crinoids plates with syntaxial rim cements. Other grains comprise abundant to common peloids, intraclasts, miliolids and mollusk fragments. Algae fragments and monoaxial spicules are present as isolated grains (Figure 5c).

MA-11. Wackestone and floatstone containing randomly orientated rudists with algal incrustations. Most grains are echinoderms, echinoids, peloids, brachiopods,

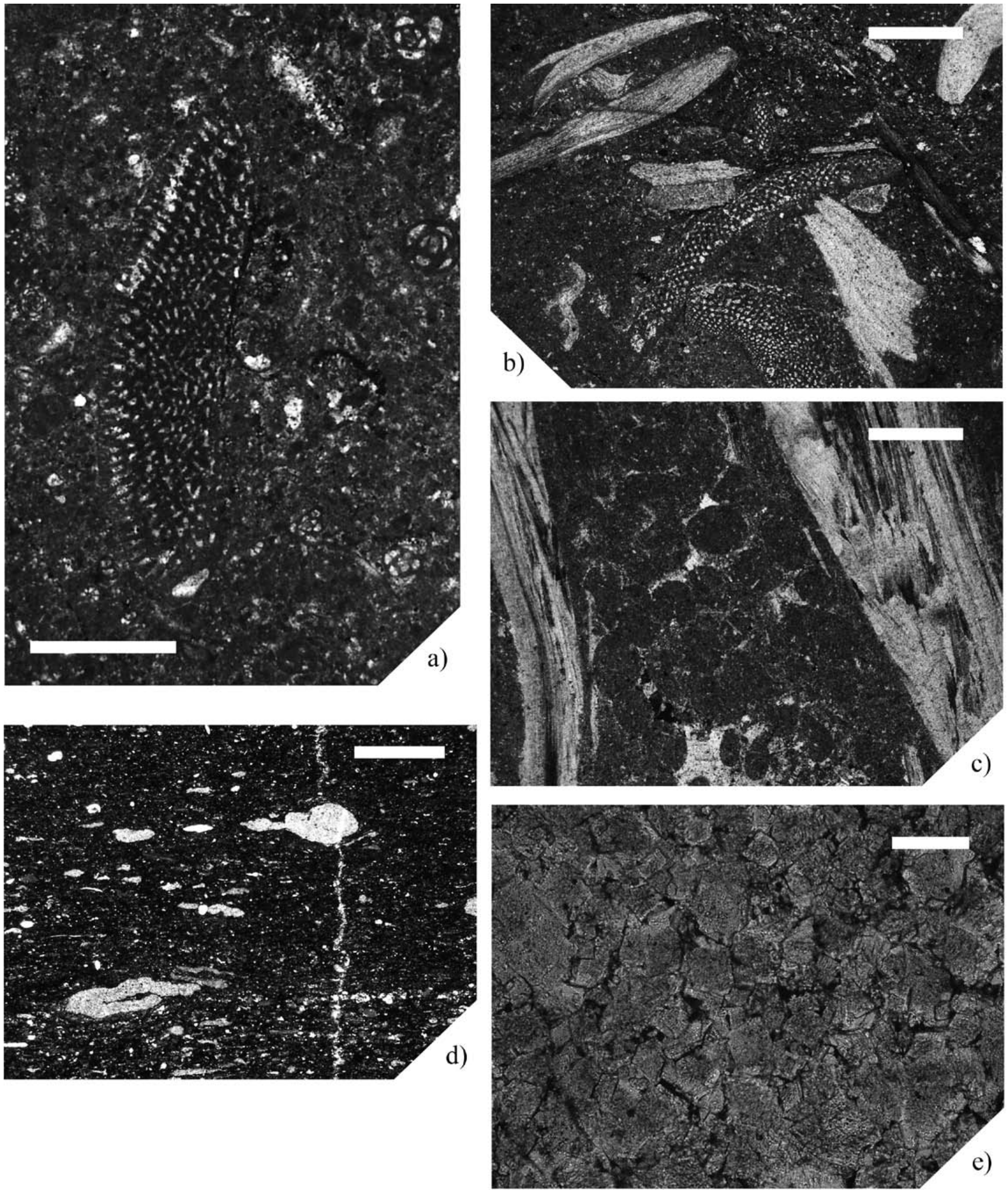

Figure 3. Microfacies of the Cupido Formation (MA-1 to MA-4). MA-1: (a) Wackestone with orbitolinids and miliolids; sample PFZ 100b, (b) Floatstone with pelecypod fragments and orbitolinids; sample PFZ 135b. MA-2: (c) Floatstone with ostreid fragments and pellets; sample PFZ 102. MA-3: (d) Laminoid fenestral mudstone showing plant root structures; sample PFZ 168. MA-4: (e) Dolostone with an idiotopic inequigranular mosaic of dolomite crystals; sample PFZ 210C. Scale bar: (a-d) = 1.0 mm, (e) = 0.1 mm.

and mollusk fragments. Grapestones, miliolids and intraclasts are common grains inside some of the rudists shells (Figure 5d).

MA-12. Wackestone and grainstone rich in miliolids, peloids and intraclasts. These facies contain common mollusk and brachiopod fragments and rare monoaxial spicules. Benthic agglutinated foraminifera, planktonic foraminifera and coral fragments are exceptionally present (Figure 5e-5g).

La Peña Formation
(Microfacies associations MA-13 to MA-16)

MA-13. Dark, organic-rich wackestone and mudstone with sulphur minerals. Frequent planktonic foraminifera and common echinoids, pelecypod fragments, ostracods and filaments are present. Benthic foraminifera are rare (Figure 6a).

MA-14. Wackestone with well-preserved gastropods, echinoids, crinoids and green algae fragments. Ostracods

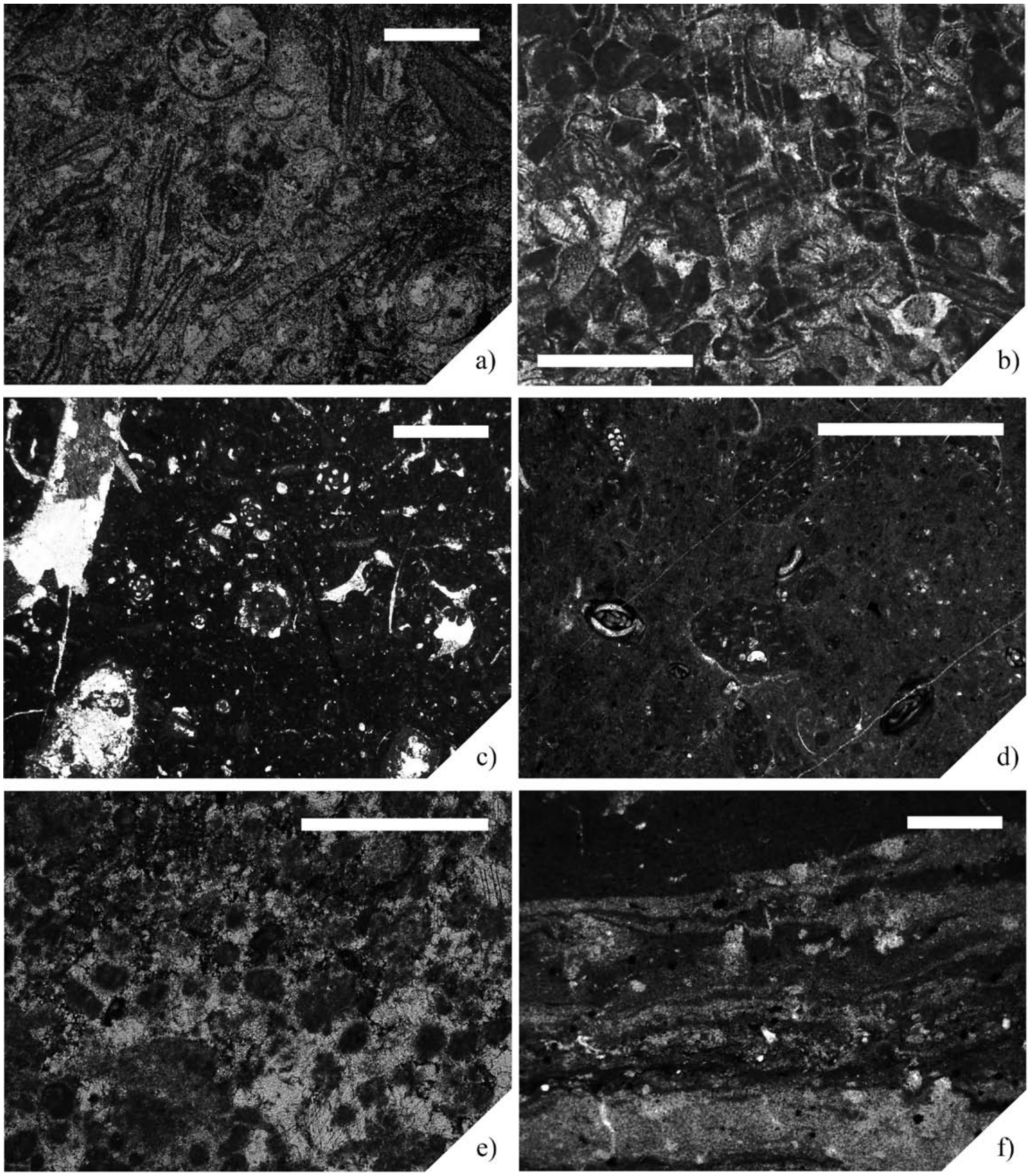

Figure 4. Microfacies of the Cupido Formation (MA-5 to MA-8). MA-5: (a) Rudstone with abundant filamentous algae and frequent gastropods; sample PFZ 141t, (b) Grainstone with intraclasts and echinoderms; sample PFZ 149. MA-6: (c) Wackestone with green algae and miliolids; sample 195m. MA-7: (d) Wackestone with miliolids and favreinids; sample PFZ 163. MA-8: (e) Microbial-peloidal Packstone; sample 201t, (f) Laminated microbial mat; sample PFZ 191. Scale bar: (a-d, f) = 1.0 mm, (e) = 0.5 mm.

are abundant while planktonic foraminifera are common to rare components. Calcispheres, radiolaria and ammonites are scarcely represented (Figure 6b).

MA-15. Wackestone and packstone with extremely abundant radiolaria, common planktonic foraminifera, and ostracods, and rare pelecypods and ammonites fragments. Inoceramid fragments are poorly represented. The matrix contains high concentrations of organic matter (Figure 6c).

MA-16. Wackestone and mudstone with common colomiellids and different proportions of calcispheres, planktonic foraminifera and radiolaria. Hyaline benthic foraminifera and ammonite fragments are trace components (Figure 6d-6e).

Upper Tamaulipas Formation (Microfacies associations MA-17 to MA-18):

MA-17. Wackestone and packstone with abundant saccocomids and plates of crinoids, as well as rare inoceramid fragments and hyaline benthic foraminifera (Figure

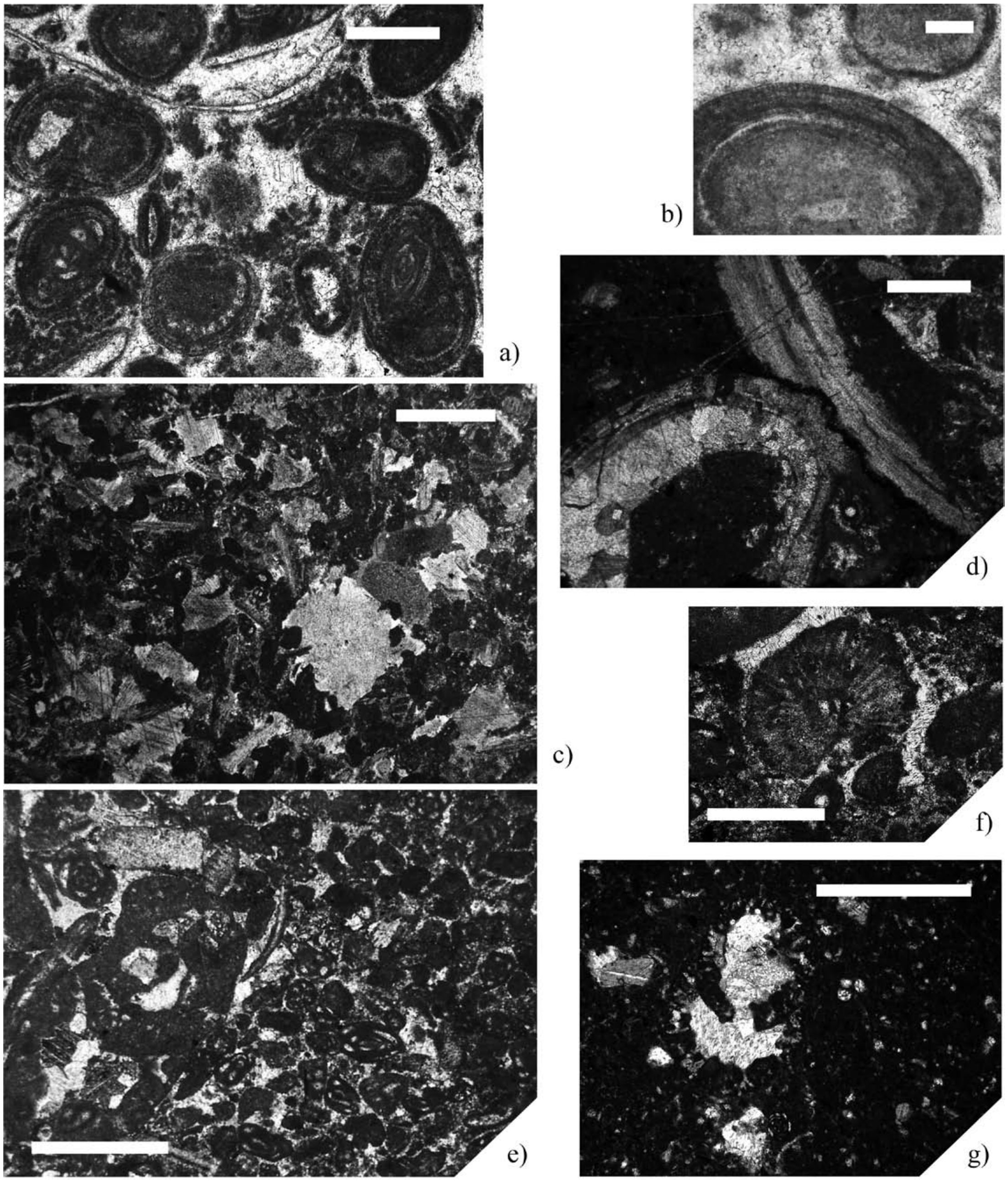

Figure 5. Microfacies of the Cupido Formation (MA-9 to MA-12). MA-9: (a) Rudstone composed of ooids and pelletoids. This picture shows miliolids an aggregate grains as ooid nuclei; sample 201b, (b) Radial and tangential microfabric of ooid cortex; sample 201b. MA-10: (c) Grainstone with crinoids, intraclasts and benthic foraminifera; sample 204b. MA-11: (d) Floatstone with rudist fragments; sample 213A. MA-12: (e) Grainstone with miliolids, peloids, intraclasts, mollusk fragments and echinoderms; sample PFZ 218m, (f) Coral fragment; sample PFZ 218m, (g) Agglutinated benthic and planktonic foraminifera; sample PFZ 218t. Scale bar: (a-e, g) = 1.0 mm, (f) = 0.5 mm.

7a). The components are commonly aligned. These facies appear at the upper part of the La Peña Formation but are more typical of the Upper Tamaulipas Formation. In the La Peña Formation these facies contain abundant planktonic foraminifera and common colomiellids, radiolaria and microcalamoids. In the Upper Tamaulipas Formation the crinoids are the dominant grains, planktonic foraminifera are common grains and thick-walled calcispheres are frequent at the base of the association. The microfacies of this association contain rare microcalamoids (Figure 7b-7c).

MA-18. Wackestone and mudstone with abundant thick-walled calcispheres and common planktonic foraminifera, microcalamoids and pelagic crinoids. Radiolaria, benthic foraminifera and ammonites are rare. Locally, intraclasts are abundant grains in wackestone and floatstone textures (Figure 7d-7e).

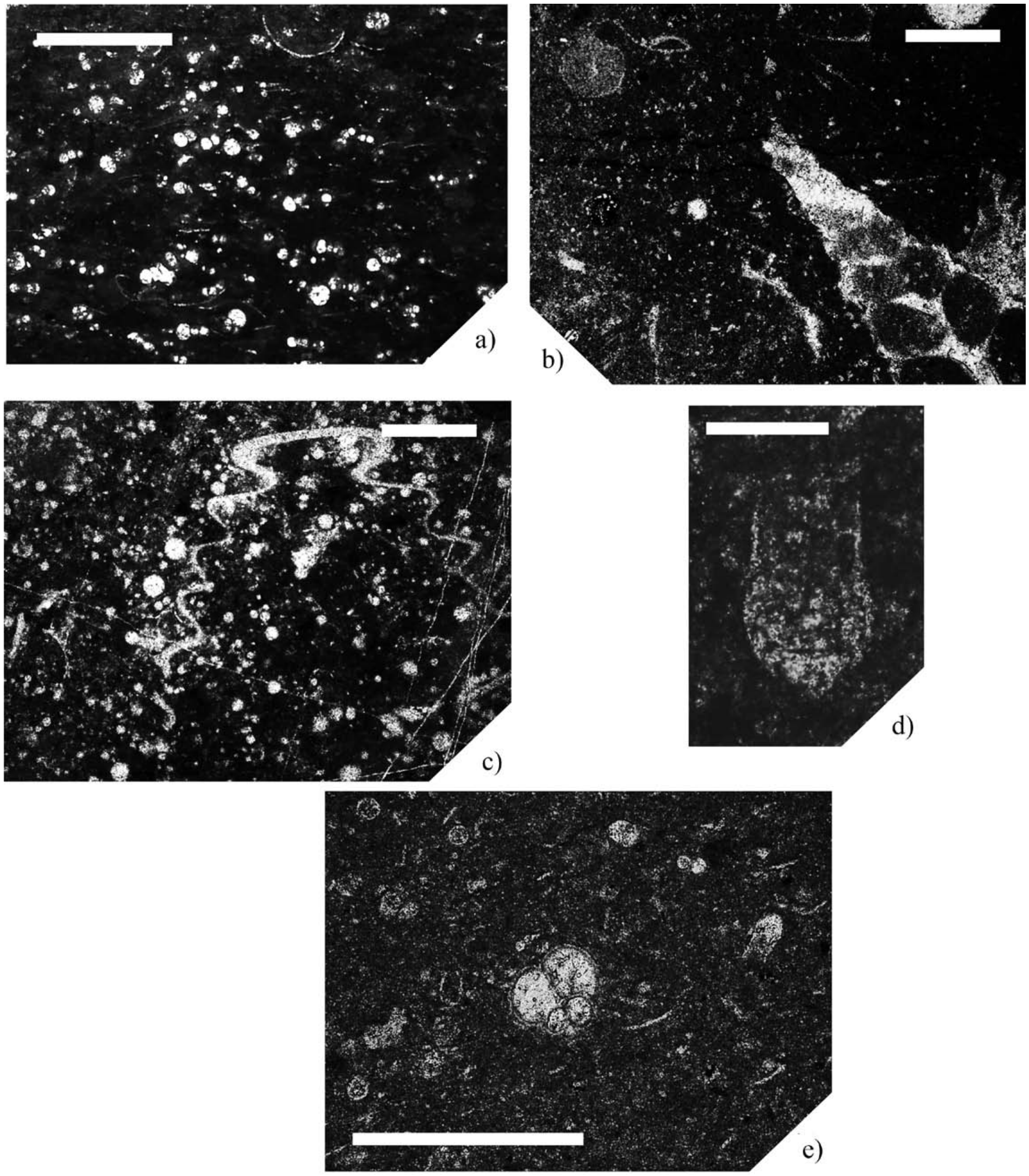

Figure 6. Microfacies of the La Peña Formation (MA-13 to MA-16). MA-13: (a) Wackestone with planktonic foraminifera, ostracods and filaments; sample PFZ 385. MA-14: (b) Wackestone with gastropods and mollusk fragments; sample PFZ 298. MA-15: (c) Wackestone with abundant radiolaria exhibiting an ammonoid fragment; sample PFZ 374. MA-16: (d) *Colomiella recta* Bonet; 1956; sample PFZ 440, (e) Wackestone with abundant colomiellids and planktonic foraminifera; sample PFZ 471. Scale bar: (a-c) = 1.0 mm, (d) = 0.05 mm, (e) = 0.5 mm.

DISCUSSION

The temporality of the paleoenvironmental conditions defined for the stratigraphic section of this study is supported by the identification of two important transitions. The Barremian-Aptian transition was previously established in the study area, on the basis of the first stratigraphic appearance of *Palorbitolina* cf. *lenticularis* (Figure 2; Barragán-Manzo and Díaz-Otero, 2004, fig. 6N). The recognition in this investigation of the first stratigraphic appearance of *Colomiella recta* Bonet, 1956 in the level PFZ 440 (Figures 2 and 6d), and the identification of ammonites of late Aptian age in the level PFZ 348 (Figure 2; Barragán, 2000; Barragán-Manzo and Méndez-Franco, 2005), allow to define an interval within which occurs the Aptian-Albian transition.

The composition and general characteristics of the upper Barremian-lower Albian facies of the study stratigraphic section in Durango correspond to a complete shallow platform-to-basin transect. This paleoenvironmental change could be explained as a consequence of the relative sea-level rise during the Early Cretaceous (Vail *et al*., 1977). As argued by Barragán (2001), the Cupido Formation facies in the stratigraphic section here studied are typical of the "Cupidito" unit, and indicate deposition in a shallow lagoonal environment with intervals of relatively restricted conditions. Our results contribute to a better understanding of the paleoenvironmental dynamic in the lagoon.

The Cupido Formation deposited in peritidal and subtidal environments, in a shallow lagoon with different levels of restriction under fertility conditions. Lagoonal conditions into partially-restricted and very shallow water are indicated by the facies of MA-1 (Figure 3a), due to the abundance of miliolids and orbitolinids. These organisms are typical of muddy, soft bottom. Intermittent periods of agitation represented by the increase of skeletal fragments (especially pelecypods) and the floatstone microfacies (Figure 3b) are responsible of substrate stabilization and subsequent worm activity. Deposition from intertidal to shallow subtidal zone is suggested by the ostreid shell fragments of the MA-2 (Figure 3c). The alignment of these skeletal grains was probably caused by wave-induced bottom currents above the looseground substrate. Based on the pellets abundance, high eutrophic level of seawater can be proposed during the deposition time of MA-2 and MA-3.

MA-3 represents a shallow water environment with a low-energy regime and poorly oxygenated conditions. Although the laminoid, fenestral fabric is characteristic of supratidal and intertidal settings, the good state of preservation of this structure is more common in the former. Moreover, the presence of some structures which resemble plant root holes (Figure 3d) is in agreement with this assertion. According to the model of Flügel (1979) for Bahamas-type platforms, the facies type containing the aforementioned fabric is typical of the mud-dominated tidal flats. Contrasting with the previous microfacies association, the facies of MA-5 were deposited during high-energy episodes that occurred in the platform interior. Imbricate grains, cross-lamination and filamentous algae transported from the platform-margin are characteristics of the MA-5-A (Figure 4a) which support the existence of these events. MA-5-B (Figure 4b) represent periods of platform flooding which cause an increase in the echinoderms and intraclasts production as a result of more trophic and higher energy conditions.

The facies with dasyclads algae and miliolids of MA-6 (Figure 4c) are characteristics of shallow subtidal lagoonal environment with normal salinity into the photic zone. Peybernes (1979) described similar facies in intertidal to shallow subtidal settings for Early Cretaceous carbonate platforms. The bioturbation structures are the evidence of oxic and eutrophic substrate levels. The assemblage of cortoids, green algae and mollusks of MA-7 (Figure 4d) is indicative of a shallow subtidal zone with warm-water and photic to disphotic conditions. The sedimentation occurred to a depth of about few meters to tens of centimeters. The abundance of miliolids supports the existence of normal salinity and a muddy eutrophic bottom.

An important microbial contribution is indicated by the microbial peloids and microbialites of MA-8 (Figure 4e-4f). These facies suggest calcium carbonate saturation of seawater under warm temperature and highly restricted marine settings. Low oxygenated and hypersaline levels could explain the scarce of skeletal grains in the packstone microfacies. A low sedimentation rate allowed the formation of hard bottoms, worm activity, bioturbation and fixation of sponges.

The Cupido Platform margin corresponds to the sand bars facies of the MA-9 (Figure 5a-5b). They represent periods of more oxygenated, shallower waters and high environmental energy. The incipient gravitational cementation of this facies took place during relative subaerial exposure of the margin to the marine vadose zone. The variety of cortices microfabrics was the result of different agitation levels. The increase in cortoids at the base of the association can be used as a proxy for less agitated levels into the shallow submareal zone. This microfacies association favors the subtidal sedimentation within the restricted lagoon in the platform interior.

High energy settings, oxygenated and eutrophic conditions are inferred from the composition of MA-10 (Figure 5c) and MA-11 (Figure 5d). The accumulation of crinoid arms was produced by disarticulation of these organisms during agitated periods, while the wave action on the bottom resulted in the abundance of intraclasts. The presence of randomly oriented fragments of rudists in the MA-11 (Figure 5d) is typical of a fore-reef position which received large skeletal grains and wastes generated in the high energy zone of the reef margin (Tucker and Wright, 1990). The latter microfacies association suggests a period of a deepening of the site of sedimentation and a better circulation of water. These conditions are characteristic of an outer platform environment with a depth of 50-80 m (Wilson and Jordan, 1983). Barragán-Manzo and Díaz-Otero (2004) proposed that those facies at the top of the Cupido Formation must be interpreted as the recovery of the lagoonal restricted conditions. However, the presence of planktonic foraminifera and coral fragments in the MA-12 (Figure 5e-5g) is more representative of open marine settings in platform margin positions, an scenario adopted herein.

The beginning of deposition of the La Peña Formation represents a shift from a set of facies indicative of a shallow carbonate platform into facies representing a more open-marine environment, typical of an outer ramp or slope (Barragán, 2001). This situation is evidenced by the drastic decrease in benthic foraminifera and the proliferation of planktonic foraminifera in the MA-13 (Figure 6a), and is associated with stagnant bottom water and normal marine salinity in the upper part of the slope. Anoxic bottom conditions are further supported by the abundance of organic matter in MA-13 and MA-15. Deposition of MA-15 (Figure 6c) is characterized by the sudden abundant

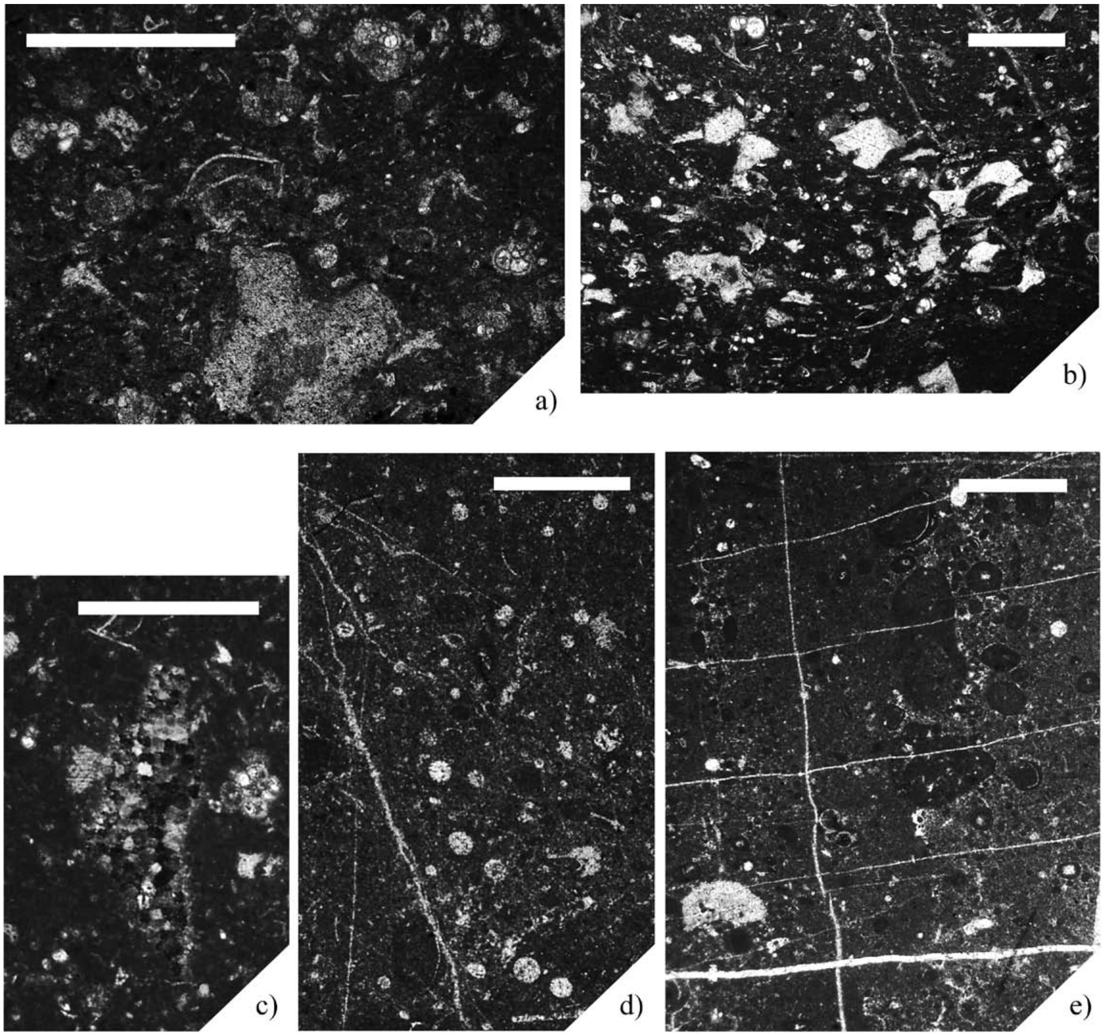

Figure 7. Microfacies of the La Peña and Upper Tamaulipas formations (MA-17 to MA-18). MA-17: (a) Wackestone with crinoids and planktonic foraminifera. The largest bioclast corresponds to a brachial element of *Saccocoma* sp.; sample PFZ 533, (b) Packstone with abundant aligned crinoid plates; sample PFZ 613, (c) Inoceramid fragment showing a well-defined honeycomb microstructure; sample PFZ 606. MA-18: (d) Wackestone with calcispheres and ostracods; sample PFZ 582, (e) Wackestone with calcispheres and local accumulation of rounded intraclasts; sample PFZ 579. Scale bar = 1.0 mm

appearance of radiolaria, which becomes dominant over planktonic foraminifera. Based on a significant increase in Total Organic Carbon (TOC) up to 18%, this microfacies association has been interpreted as the deposition under anoxic bottom conditions related to a local upwelling system and eutrophication of surface water (Barragán, 1999, 2001). The presence of inoceramid fragments could be related with those oxygen-depletion events as have been exposed in other Cretaceous facies (Sageman, 1989; Kauffman and Sageman, 1990; Duque-Botero and Maurrasse, 2004). The MA-14 (Figure 6b) is composed of reworked mollusks and algae fragments transported to the periplatform zone during reworking of material episodes. The high sedimentation rate of these events explains the low content of planktonic foraminifera of the microfacies association.

MA-16 (Figure 6d-6e) and MA-17 (Figure 7a-7c) are representative of a more open marine environment in a deep outer neritic to upper bathyal zone. This paleobathymetric inference is supported by the presence of a dominantly pelagic assemblage composed of abundant planktonic foraminifera; the presence of *Lenticulina* sp. in facies of the MA-16, and the presence of *Saccocoma* spp., colomiellids, *Favusella* sp. and radiolaria in MA-17. The variation of radiolaria and calcispheres content was determined by changes in the trophic and oxygen levels. Less fertile and poorly oxygenated seawater favor calcispheres proliferation, while the increase of trophic levels was related to the radiolaria deposition. Although these periods were alternated through the deposition of MA-16, aggressive conditions for the development of marine biota were more extended during the deposition of the MA-18 (Figure 7d-7e). Those conditions are consistent with the abundance of calcispheres in this microfacies association, which according to Urey *et al.* (1951) are characteristic of open marine environments with normal salinity and warm temperature. The local abundance of intraclasts in the latter microfacies association suggests the action of strong bottom currents above the substrate.

The global changes in the sea level for the studied interval (Haq *et al*., 1987) reflect a tendency which is not totally compatible with the complex environmental dynamic in the Cupido Platform interior, as it is evidenced by the described microfacies associations. Despite the influence of the sea-level rise in the environmental changes, the role of internal factors as tectonic subsidence or carbonate accumulation should not be underestimated. The balance of these parameters was responsible for different levels of restriction and energy in the lagoon and in the long term, as it is argued by Schlanger (1981), played an important role in the drowning of the Cupido Platform.

DROWNING INTERPRETATION OF THE CUPIDO PLATFORM

The drowning of the Cupido Platform has been studied in the stratigraphic section by Barragán (2001), who described intermittent vertical periods of organic-rich strata related to this event. Although the whole facies of the Cupidito unit recorded the drowning of the Cupido Platform (Conklin and Moore, 1977; Wilson and Pialli, 1977; Lehmann *et al.*, 1999), this investigation permits a refinement of the drowning history based on the new, collected microfacies data. The microfacies that represent the drowning phase must be understood as those that were deposited during the definitive drowning of the platform

Pre-drowning phase

During this phase, the platform interior was characterized by a marine, lagoonal environment protected by a barrier shoal margin (MA-9, Figure 5a-5b). The peritidal and subtidal sedimentation (MA-1 to MA-8, Figures 3 and 4) was determined by the sea level fluctuations and its interaction with the platform margin. As it is argued by Read (1985), during the drowning of carbonate platforms, short-term transgressive pulses of a few meters amplitude are followed by shallowing of sea level and peritidal deposition.

The presence of sand shoals in the platform margin is typically recognized during the second phase of the platform drowning, when sediment production often catches up with sea level (Read, 1985; Handford and Loucks, 1993). In this case, the pendant cement in the ooid of grainstone and floatstone microfacies (MA-9, Figure 5a-5b) suggests carbonate aggradation near the meteoric-vadose or meteoric-phreatic environments. Lehmman *et al.* (1999) have proposed a similar mechanism against the drowning, based on the isolated rudist pinnacle reef described by Conklin and Moore (1977) in the Cupidito unit. Before the definitive drowning of Cupido Platform, periodical flooding of the restricted lagoon produced reworked bottom intraclasts and an increase in the echinoderms abundance (MA-5-B, Figure 4b).

Drowning phase

This phase occurred at the beginning of the Aptian, when the sea level rose over the sand shoals on the platform margin. Typical signals of drowning events which are found in the microfacies related to this phase are the increase of suspension-feeders (Blomeier and Reijmer, 1999) (crinoids in MA-10, Figure 5c) and the occurrence of lagoonal biota associated with open marine and reef margin biota (MA-12, Figure 5e-5g). According to Flügel (2004), the former is a consequence of a better adaptation of this kind of organisms to the newly settled conditions. Although the latter signal is here described at the uppermost part of the Cupido Formation, it continues in the basal part of the La Peña Formation, where Barragán (2000) reported biocalcilutites and soft, marly horizons with ammonites, miliolids, and orbitolinids.

The accumulation of crinoid plates represents the switch to high-energy environments within the platform interior caused by the transgressive conditions. In this context, the abundance of intraclasts (MA-10, Figure 5c) is interpreted as an increase of the bottom current intensity, while the fore-reef facies (MA-11, Figure 5d) suggest the destruction of a relatively nearby rudist reef margin, which in fact could consist in an isolated rudist pinnacle reef as those described by Conklin and Moore (1977).

The flooding peak was completed after the establishment of a real, transgressive condition associated with a major sea level rise. Although the components of the microfacies associations which were deposited during this time (MA-13 and MA-15; Figure 6a and Figure 6c, respectively) are characteristic of pelagic environments, the intercalation of these microfacies associations with shallow platform derived material (MA-14, Figure 6b) suggests the persistent influence of the Cupido Platform during the drowning event. The reworking of lagoonal sediments due to the progression of sea level rise could be responsible of the deposition of these shallower facies in the periplatform zone. Deposition of facies of the association MA-16 (Figure 6d-6e) marked the final step of the drowning event associated with the deepest conditions of sedimentation. This is supported by the disappearance of reworked facies of the association MA-14 (Figure 6b) and the continuous decrease of shales and marly limestones beds intercalated with limestones in this part of the La Peña Formation.

According to Barragán (2001), the most characteristic feature of this stage is the abundance of organic matter related with stagnant bottom waters during the initial transgression, and with a local upwelling system in a basinal environment. The environmental stress caused by these oxygen-depleted conditions accentuated the Cupido Platform drowning.

Post-drowning phase

Open marine environments with minor influence of the shallow carbonate platform occurred in the late Aptian-early to middle Albian interval. They are represented by the microfacies association MA-17 (Figure 7a-7c) and MA-18 (Figure 7d-7e) deposited during an advanced stage of the transgression.

PALEOGEOGRAPHIC AND GEOLOGIC IMPLICATIONS

The position of the Cupido shelf margin has been widely documented for the Monterrey-Saltillo area; however, very little attention has been given to the southern position of this margin. According to Wilson and Ward (1993), from its position south of Saltillo, the margin apparently trends northeastward because the Cupido equivalent section in the Sierra Madre front, west and southwest of Saltillo, is composed only of pelagic mudstone. More recently, Lehmann *et al.* (1999) demonstrated that the margin was also present southwest of Saltillo based on an extensive study of exposures to the west and northwest in the Sierra de Parras and above the Coahuila basement block. They described this margin as composed of a narrow fringe of high-energy grainstone shoal deposits and reported it at the Viobora canyon in the northern of Sierra de Jimulco, about 125 km west of the stratigraphic section herein studied.

The presence of lagoonal facies in the stratigraphic section of this study suggests a more southern position of the platform margin than those displayed in the up to date paleogeographic reconstructions (González-García, 1976; Padilla y Sánchez, 1982; Morán-Zenteno, 1994; Eguiluz *et al*., 2000). Thus, the facies of grainstone and rudstone with abundant ooids presented in this work (MA-9, Figure 5a-5b) could be the western continuation of the Barremian-Aptian Cupido Platform (Figure 8).

On the other hand, the recognition of facies of the Upper Tamaulipas Formation in the uppermost part of the stratigraphic section presented in this work is in agreement with the paleogeographic schemes proposed for the Albian-

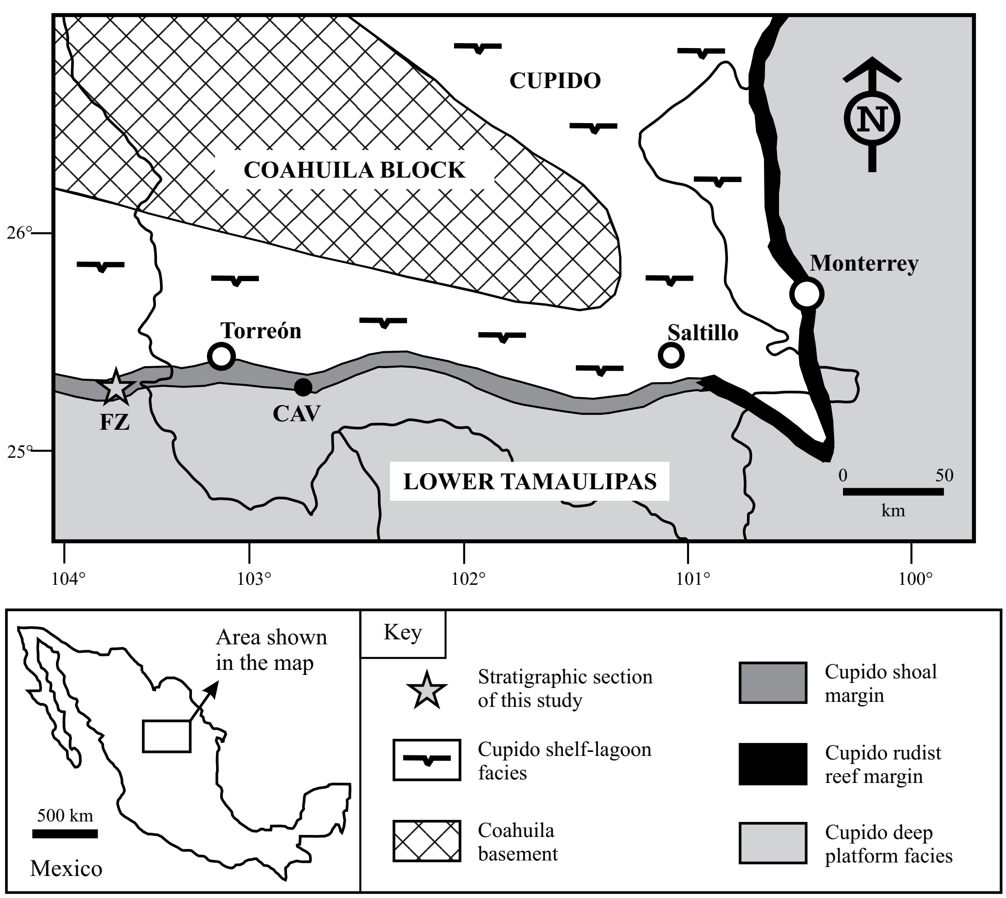

Figure 8. Paleogeographic map for upper Barremian carbonate Cupido Platform of northeastern Mexico (Modified from Lehmann *et al.*, 1998). Note that the Cupido shoal margin probably extends from the Viobora canyon (CAV) westward to the Francisco Zarco dam location (FZ).

Cenomanian of the region, and reflects the backstep of the Cupido Platform (Lehmann *et al*., 1999). In a regional context, this correction to the stratigraphic configuration of the southern Sierra del Rosario is coincident with previous changes to the nomenclature of the Albian strata in the Sierra de Parras (Lehmann *et al*., 1999), which also have proposed the Upper Tamaulipas Formation for this paleogeographic position.

CONCLUSIONS

The upper Barremian-lower Albian interval exposed at Sierra del Rosario in northern Mexico is representative of deposition during the transgressive episode that drowned the Cupido Platform and caused the subsequent periplatform and open marine deposition south of the Coahuila block. Three major microfacies associations were differentiated according to its relation with the drowning event:

1. The pre-drowning phase is characterized by peritidal and subtidal deposition in a lagoonal environment with fertile conditions for biota development and microbial contribution. These facies were protected by sand shoals in the platform margin whose interaction with sea-level fluctuations caused different levels of restriction and periodic flooding of the platform interior.

2. The definitive drowning phase occurred at the early Aptian when sea level rose over the platform margin. The beginning of the event is recorded in the upper part of the Cupido Formation, and the flooding peak was marked by an important environmental stress during the deposition of the La Peña Formation.

3. The upper part of the La Peña Formation represents the deepest conditions and together with the microfacies association of the overlying formation were accumulated during the post-drowning phase. These microfacies are typical of open marine environments with intercalated periods of different oxygenated conditions.

Additionally, important paleogeographic and geologic implications resulted of the microfacies data of this investigation. (1) The facies of grainstone and rudstone with abundant ooids correspond to the western continuation of the Barremian-Aptian Cupido Platform, west of Torreón. (2) The upper unit of the stratigraphic section studied represents deposits of the Upper Tamaulipas Formation, which reflects a change of the locus of shallow-marine sedimentation northward on the Coahuila block.

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