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High frequency subtidal-peritidal cycles of the Callovian Calabozo Formation (Neuquén Basin, Western Argentina): Preliminary approach

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ABSTRACT

The Calabozo Formation (Cuyo Mesosequence, Neuquén Basin) is made up by a thin, up to 30-m thick Middle Jurassic carbonate-dominated sequence. The minor, thin siliciclastic facies in this formation (i.e. lowermost granule-pebble shoreface conglomerate and fine-grained sandstones interbedded among the lower carbonates) record early transgressive shoreline and shallow lagoonal-subtidal sedimentation, respectively. The major carbonate deposits have been split into six facies and seven microfacies on the base of macroscopic field observation and petrological analysis. The carbonate facies have been grouped into three major assemblages: 1) Tidal flat facies assemblage (including the planar laminated algal boundstone facies; 2) Inner platform facies assemblage (including peloidal and bioclastic wackestone, coral floatstone and bioclastic and intraclastic packstone facies; and 3) Platform margin assemblage (including oolitic-peloidal packstone-grainstone facies)**.** A fossil algal record made up by dasycladacean species (*Salpingoporella annulata, Cylindroporella* sp. and *Heteroporella* sp.) and blue-green algae (*Cayeuxia* (*Rivularia*) *piae,* and *Cayeuxia* (*Rivularia*) *kurdistanensis)* has been reported for the first time in this unit. The analysis of the intracycle facies and microfacies arrangements, as well as the nature of the cycle bounding surfaces, enabled one to identify two kinds of cycles. 1) Widespread subtidal cycles capped by shallow to intermediate subtidal facies, with no evidence of subaerial exposure at cycle tops; and 2) a minor subtidal cycle with similar shallowing-upward trend but capped by peritidal facies. The stacking pattern and thickness trend of these cycles was studied to determine possible allocyclic and autocyclic controls on their evolution. The Fischer plots reveal that the deposition of the Calabozo Formation subtidal-peritidal cycles took place under upward decreasing accommodation space conditions which may be related to eustatic lowering.

KEYWORDS **Subtidal-Peritidal Cyclicity. Carbonate facies and microfacies. Jurassic.**

INTRODUCTION

Much work has been carried out providing the regional framework and general stratigraphy of the Neuquén basin (e.g. Legarreta and Gulisano, 1989; Legarreta et al., 1993). However, little research has been focused on the lithofacies, microfacies and stacking patterns of the carbonate units deposited in this basin. The up to 30-m thick

Calabozo Formation (Neuquén Basin, Argentina) consists of a variety of carbonate facies bearing a deal of marine fauna and flora and associated with a variable siliciclastic content (Palma et al., 2000a). This paper deals with the description of the carbonate facies and microfacies of the Calabozo Formation, and also with the interpretation of its environmental evolution and of the possible mechanisms that forced the deposition of the observed shallowing-upward subtidal-peritidal cycles.

GEOLOGICAL SETTING

In west central Argentina, an at least 7 km thick Upper Triassic – Lower Tertiary sedimentary succession fills up the Neuquén Basin (Fig. 1). This is a back-arc basin whose sedimentary infill not only records rifting and thermal sag deposition, but also some of the synorogenic processes related to the Andean fold and thrust belt upbuilding (Legarreta and Gulisano, 1989; Manceda and Figueroa, 1995).

The sedimentary infill of the Neuquén Basin can be split into several mesosequences on the basis of regional stratigraphic discontinuities, which were influenced largely by eustatic events (Legarreta et al., 1993). In Mendoza Province, the Cuyo Mesosequence is equivalent to the so-called Cuyo Cycle or "Cuyano" (Gulisano et al., 1984a; Fig. 2). This mesosequence is bounded by intra-Liassic (Gulisano et al., 1984b) and intra-Callovian (Dellapé et al., 1979) regional discontinuities and includes alluvial-fan clastic deposits (El Freno Formation), marine inner shelf deposits (Puesto Araya Formation), and offshore shelf black mudstones (Tres Esquinas Formation). These deposits are overlain by fluvial-marine siliciclastics (Lajas Formation) and carbonate dominated deposits

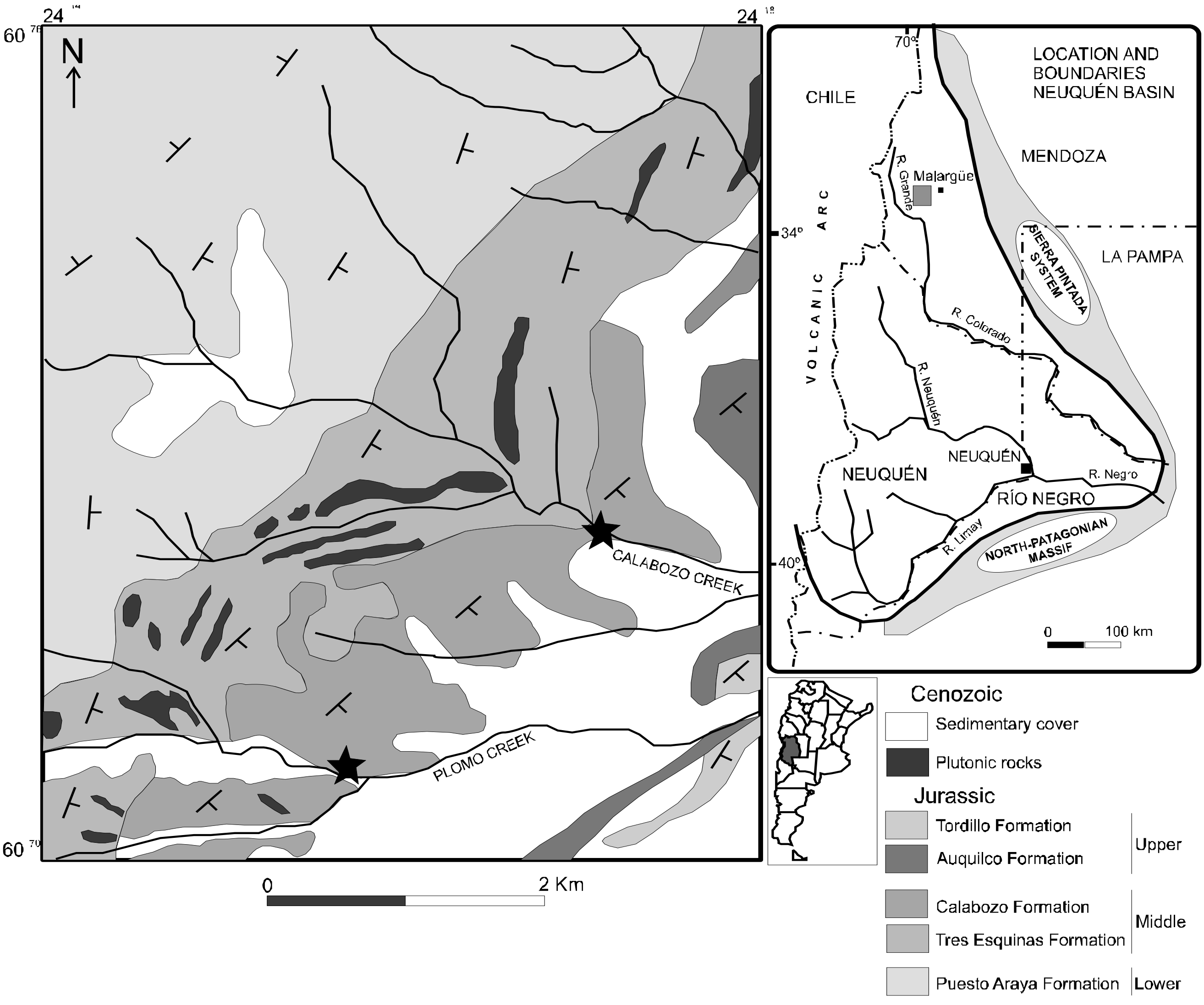

FIGURE 1 **Location maps and geological sketch of the studied area. Stars indicate the location of the sections analyzed.**

(Calabozo Formation). The stratigraphic succession of this cycle ends with the evaporite deposits of the Tábanos Formation that developed mainly in the center of the basin and records a strong restriction of the Neuquen basin coeval with a global sea-level fall (Riccardi et al., 2000).

The Cuyo Cycle includes the first Mesozoic marine strata recorded in the Neuquén Basin. The Calabozo Formation unconformably overlies the Bathonian – Callovian fluvial-marine sandstones of the Lajas Formation and is in turn overlain by the evaporites of the Tábanos Formation (Fig. 2). The biostratigraphic dating of the Calabozo Formation is based on the ammonite fauna represented by *Rehmannia* sp., *Choffatia* sp., and *Glossouvira* sp., which characterize the Lower-Middle Callovian (Riccardi et al., 2000).

The study area is located 50 km west of Malargüe, in southern Mendoza Province, Western Argentina. The detailed facies and microfacies studies were carried out in Calabozo Creek, the type section of the Calabozo Formation, but a similar trend in facies evolution has been recognized in the nearby Plomo Creek succession, close to Chuquichenque mine, five kilometers to the south of Calabozo Creek (Fig. 1).

METHODOLOGY

In order to document changes during the evolution of the Calabozo Formation carbonate platform, two outcrop sections were studied. The field survey was carried out at a centimetre scale using a 20 x hand lens to obtain an adequate data set, paying particular attention to thickness, facies associations, stacking patterns and paleontological content. Field differentiation of skeletal and non-skeletal components was carefully made. Samples were taken systematically from the base, middle and top of each bed and wherever it appeared necessary. Sixty thin sections were studied, allowing the qualitative determination of the recorded allochems. Recognition of field facies was confirmed by petrographic work, which allowed the recognition of seven microfacies types. Fischer plots (Fischer, 1964) were made on the basis of the data base obtained from the section studied (Calabozo Creek). Although the section was too short to make statistically significant Fischer plots (Sadler et al., 1993), they were used as a preliminary step to detect possible changes in depositional conditions.

GENERAL CHARACTERISTICS OF THE CALABOZO FORMATION

The Calabozo Formation (Figs. 1 to 3A) consists mainly of shallow water carbonate platform deposits (Palma et al., 2000a). The Calabozo Formation base is erosional on the underlying Lajas Formation and normally irregular, starting with a granule-pebble grained conglomerate. The contact of the Calabozo Formation with the overlying evaporites of the Tábanos Formation is sharp.

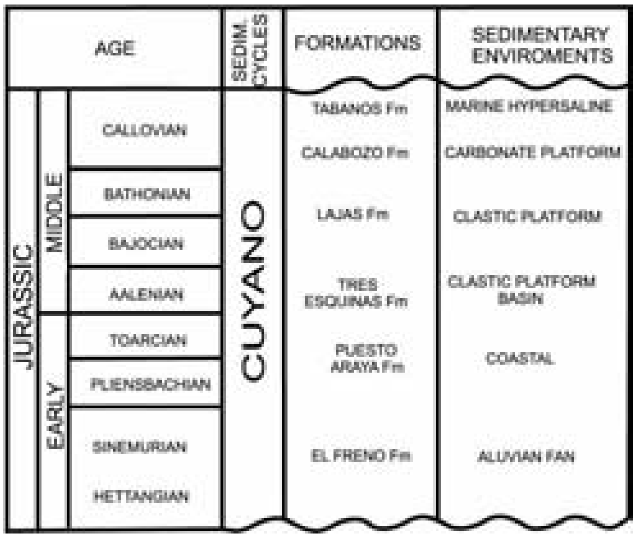

FIGURE 2 **Stratigraphic chart for the Cuyano Cycle in the Neuquén Basin (Modified from Legarreta and Gulisano, 1989).**

The predominant lithologies in the Calabozo Formation are dark-gray medium-to thick-bedded peloidal to bioclastic wackestones to packstones interbedded with minor oolitic-bioclastic grainstone/packstones and coral floatstones. Some sandstone beds appear interbedded with the wackestone/packstones close to the base of the unit. An abundant marine biota occurs in this unit including mainly bivalves, echinoderms, corals, foraminifers, green algae (dasycladacean) and cyanophite remains; calcispheres, scattered sponge spicules, and bryozoa also occur (Palma et al., 2000a). Terrigenous silicilastic grains occur sporadically in the carbonate facies, which are organized into decimetre-to meter-scale, fining- or coarsening-upward cycles interpreted as shallowing-upward cycles (Palma et al., 2000; Figs. 3B and C).

SILICICLASTIC FACIES. ENVIRONMENTAL INTERPRETATION

Two siliciclastic facies (beach conglomerate and lagoon to shallow subtidal sandstone facies) were identified in the Calabozo Formation on the basis of texture, sedimentary structures and fossil content (Table 1; Fig. 3A).

Conglomerate beach facies

This facies consists of light olive gray granule-pebble grained conglomerate. Bed thickness ranges between 0.80

and 1.10 m, and typically comprises a mixture of subrounded volcaniclastic pebbles (5 cm diameter), quartz grains, and re-worked Lajas Formation fragments containing bivalves and scleractinian corals. This conglomerate displays erosive base and lenticular geometry and obscure or lacking internal stratification, although discrete normal grading was observed locally. Field observations reveal that the basal conglomerate overlies the

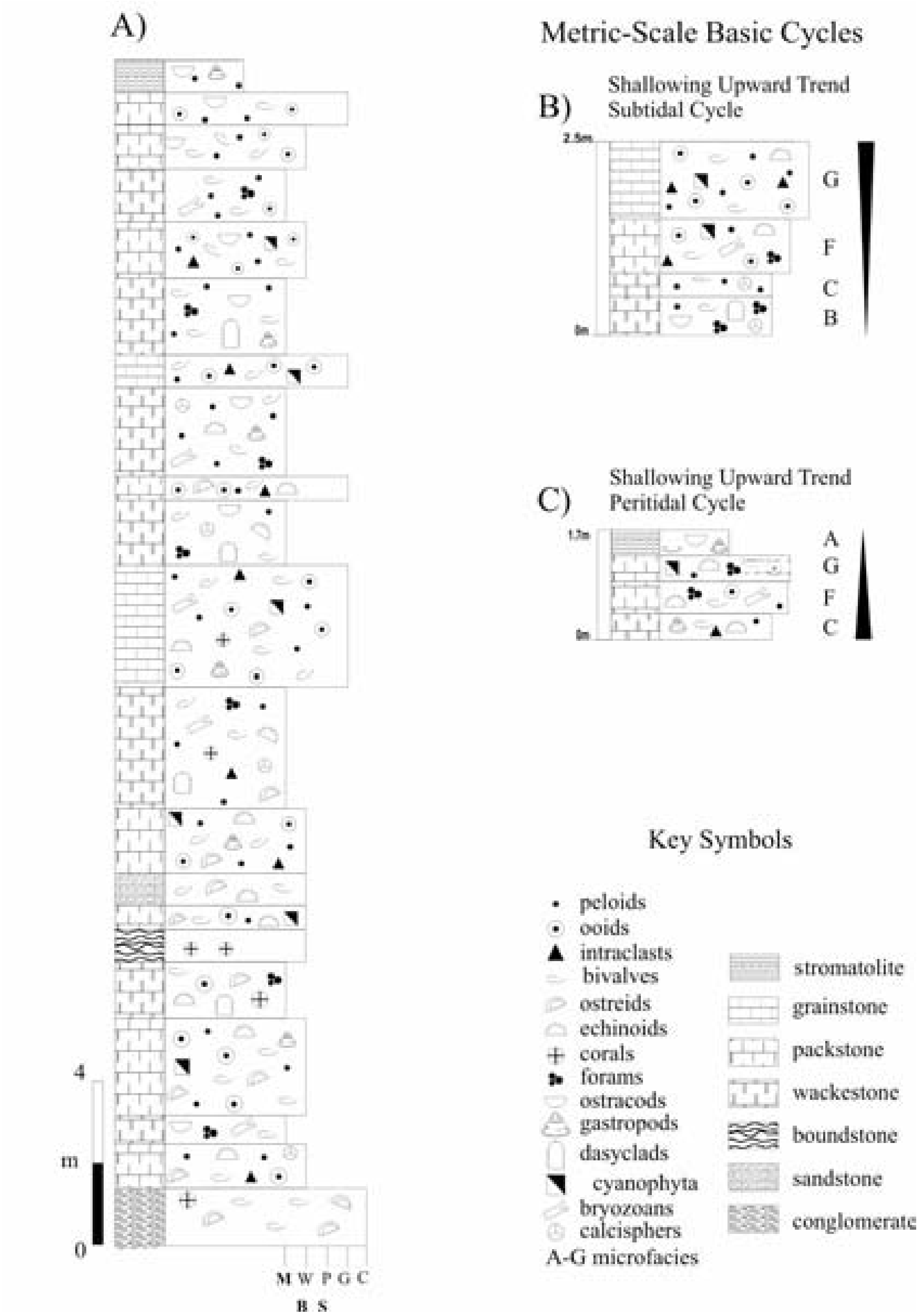

FIGURE 3 **A) Simplified lithological log of the Calabozo Formation showing the textural evolution, fossil contents and stacking patterns of platform cycles and the common cycles in the study section. B) Subtidal cycle. C) Peritidal cycle.**

shoreface deposits of the Lajas Formation. In its turn the conglomerate is overlain abruptly by the wackestone-packstone facies that yielded fossil marine biota. This basal conglomerate records a beach face environment related to a marine transgressive succession. Clast composition indicates a volcanic source, whereas allochem particles reflect contribution from the underlying Lajas Formation.

Lagoon to shallow subtidal sandstone facies

This facies is massive to horizontally bedded, with a thickness of just around 40 cm and a lateral extension of a few tens of meters. These sandstone beds occur interbedded with the carbonate facies (wackestone/packstones) in the lower part of the unit, and are poorly to moderately well sorted. Beside molluscs, oysters, echinoderms and coral fragments, a few benthonic foraminifera, green algae (dasycladacean) and bryozoa occur. Thalassinoides-type burrows are widespread. These fine-grained sandstones were deposited in marine, lagoonal to shallow subtidal environments in an inner platform setting.

CARBONATE FACIES AND MICROFACIES. ENVIRONMENTAL INTERPRETATION

Six carbonate facies and seven related microfacies were defined in the Calabozo Formation on the basis of texture, sedimentary structures and fossil content (Table 1). Considering their distinctive paleoenvironmental significance, these deposits were grouped into three main interpretative facies assemblages: Tidal Flat (intertidal-lower supratidal), Inner Platform and Platform Margin assemblages.

Tidal- flat (intertidal-lower supratidal) facies assemblage

Planar laminated stromatolite boundstone facies

The tidal flat assemblage includes gastropod and ostracode bearing laminated to undulatory stromatolite boundstones. Laminae are frequently discontinuous. Fenestrae, micro-tepee structures and desiccation cracks were observed. This facies is medium to light gray in color and its bed thickness ranges from 20 to 35 cm. These deposits occur on the top of a complete subtidal cycle, just on the top of the Calabozo sedimentary succession. This facies includes a single algal boundstone microfacies.

Microfacies A. Algal boundstone

This microfacies is characterized by smooth and crinkled millimetre thick laminae, and alternating micrite and microsparite laminae, containing peloids, gastropods and scattered ostracods. Micrite-sparite laminae are irregular and exhibit centimetric lateral continuity; they present abundant irregular-spar and micrite-filled voids (fenestrae), which are generally aligned parallel to stratification (Fig. 4A). Lamination is disturbed by mollusc borings. Stromatolitic lamination becomes increasingly undulate towards the top of the facies and displays development of micro-tepee structures (Fig. 4B).

Trapping and binding of fine grained carbonate particles by cyanobacteria generate the wavy and flat laminated stromatolite boundstone in the upper intertidal zone. The planar fenestrae are thought to form either by the decay of algal films or by shrinkage of sediments due to alternate periods of wetting and drying (Shinn, 1968). Micro-tepee structures and mud cracks suggest repeated periods of emergence and subaerial exposure. In recent sedimentary environments they most commonly occur in the upper part of tidal-flat (Shinn, 1968).

Inner platform facies assemblage

A broad spectrum of facies and depositional textures occur in this environmental setting. The inner platform sediments are characterized by: 1) Bioclastic-peloidal-terrigenous wackestones; 2) Coral floatstones; 3) Bioclastic-peloidal-oolitic-intraclastic packstones.

Bioclastic peloidal-terrigenous wackestone facies

This is one of the most widespread facies in the Calabozo Creek section and includes interbedded medium gray, medium - to fine-bedded wackestones and bioclastic-peloidal-intraclastic packstones. Beds are 50-90 cm thick and their composition is quite variable. On the basis of allochem types and particle size, three microfacies (B, C and D) are recognized.

Microfacies B. Peloidal-bioclastic wackestone

This microfacies contains a distinctive open marine fauna. Disarticulated bivalve shells and echinoderms are the most abundant bioclasts (Fig. 4C). Minor foraminifers (in particular miliolids and rotalids), calcispheres and sponge spicules occur. Most skeletal carbonate grains are affected by intensive micritization and some of them (e.g. echinoderms and mollusc fragments) show microboring holes. This microfacies also includes a matrix of fine-to-medium grained skeletal fragments and silt-size peloids with heterogeneous texture. This microfacies is organic-matter rich and shows scattered pyrite crystals.

The predominance of mud-supported textures as well as the faunal association suggests deposition in a shallow subtidal environment. The peloidal wackestone, as well as the presence of disarticulated but not abraded skeletal elements, and the high matrix content reflect the low energy conditions prevailing on the subtidal sea floor. Peloids are

TABLE 1 | **Facies synthetic chart with interpretation of depositional environment.**

	Facies	Lithology/ Microfacies (MF)	Sedimentary structures	Biota	Interpretation
TIDAL FLAT FACIES	Planar laminated boundstone	Alternating micrite and microsparite laminae MF - A	Millimetre-scale planar or smooth to ondulate laminae. Fenestrae, tepee and bioturbation	Gastropods, ostracods	Upper intertidal to lower supratidal
INNER PLATFORM FACIES ASSEMBLAGE	(1a) Peloidal wackestone	Peloidal wackestone to packstones with peloids and bioclasts MF - B	Thin –to medium-bedded, nodular bedding locally. Disarticulated and micritized bioclasts	Bivalves, echinoderms, sponge spicules, forams, calcispheres	Shallow subtidal
	(1b) Bioclastic wackestone	Bioclastic to intraclastic wackestone MF – C - D	Medium –to fine bedded, planar laminae and graded lenses	Bivalves, echinoderms, forams and green algae. Ooids	Shallow subtidal
	(2) Coral floatstone	Small and domal coral packstone MF - E	Massive	Scleractinian, bivalves, gastropods, echinoderms, Cyanophyta, and serpulids	Subtidal, not wave resistant structure
	(3) Bioclastic and Intraclastic packstone	Intraclastic -skeletal wackestone-packstone MF - F	Medium bedded	Bivalves, echinoderms, and small bioclasts. Green algae and cyanophyta	Subtidal near or below fair-weather wave base
PLATFORM MARGIN FACIES	Oolitic pelloidal packstone - grainstone	Oolitic packstone-grainstone with peloids and intraclasts MF - G	Lenticular to through cross-bedding	Bivalves, echinoderms, gastropods, oncoids, forams, ostracods, and Cyanophyta	High energy subtidal
INNER PLATFORM SILICLASTIC FACIES	Sandstone	Fine sandstone	Massive	Bioturbation	Lagoon subtidal
	Conglomerate	Granule – pebble conglomerate	Massive to discrete normal gradation	Bivalves, corals	Beach

interpreted as mainly derived from shell fragments and some of them display micrite envelopes.

Microfacies C. Bioclastic-intraclastic wackestone

In this microfacies the allochems consist of thin walled, broken shells of bivalves and echinoderms (Fig. 4D). Accessory allochems are calcispheres, ooids (type 2 of Strasser, 1986) and foraminifera (Fig. 4E). The algal content is represented mainly by the dasyclad *Salpingoporella annulata* (Fig. 5A). All components are included in a peloidal micritic matrix where fine-grained bioclasts appear. Peloids are rounded and well sorted. Some subangular intraclasts have the same composition, but others consist of peloidal or bioclastic packstones. Bioclasts appear coated (cortoids of Flügel, 1982) showing a strong micritization.

As indicated by the fossil assemblage of echinoderms, bivalves, forams and algae, this microfacies was deposited under moderate-energy conditions in the subtidal zone of a shallow marine platform landward of the shelf margin shoal. The allochems in this microfacies reflect the alternation of low to intermediate and episodic high-energy conditions. Algal specimens are incomplete, and they appear both as broken and unbroken fragments which were transported by currents.

Peloid lime mud, calcispheres and miliolids were deposited during low and intermediate energy conditions. Scour during intermittent storms broke the weakly consolidated substrate into intraclasts, which were re-deposited together with peloids and bioclasts. The scattered ooids suggest that they were transported into this environment during

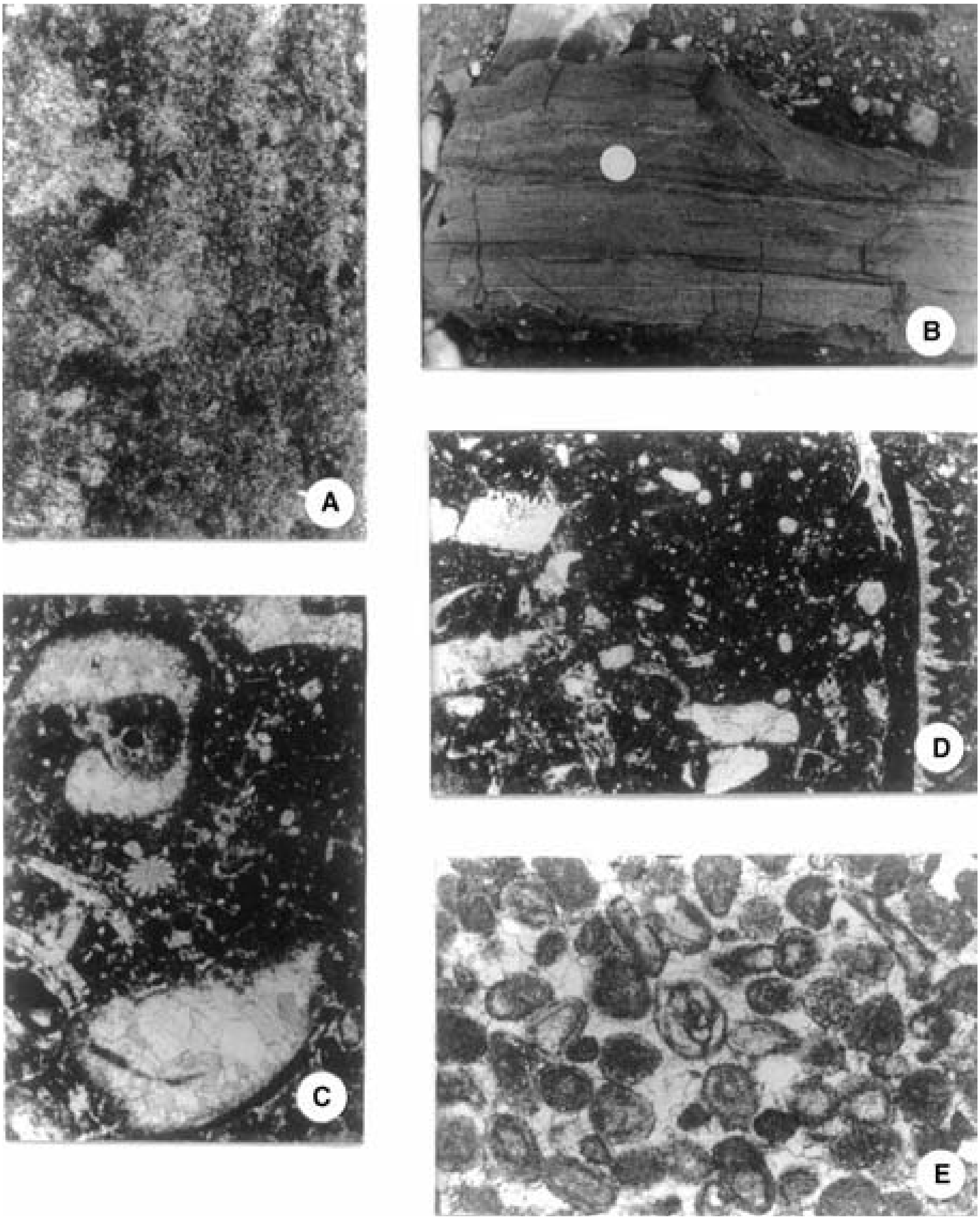

FIGURE 4 | **Characteristic microfacies in the peritidal and subtidal cycles of the Calabozo Formation. A) Microfacies A. Horizontal to crinkled laminated planar stromatolite showing laminar to irregular fenestrae filled with spar calcite. x18. B) Microfacies A. Tidal-flat laminated cycle top. Horizontal to vertical desiccation cracks and development of micro-tepee structure. Coin is 2 cm in diameter. C) Microfacies B. Peloidal-bioclastic wackestone rich in bivalve and echinoderm fragments. Calcispheres are also present. x10. D) Microfacies C. Bioclastic-intraclastic wackestone with broken bivalve shells and echinoderm fragments. Intraclasts. Micritic matrix is peloidal. x10. E) Microfacies C. Peloids, micritic ooids and foraminifera. Note the intense micritization. x20.**

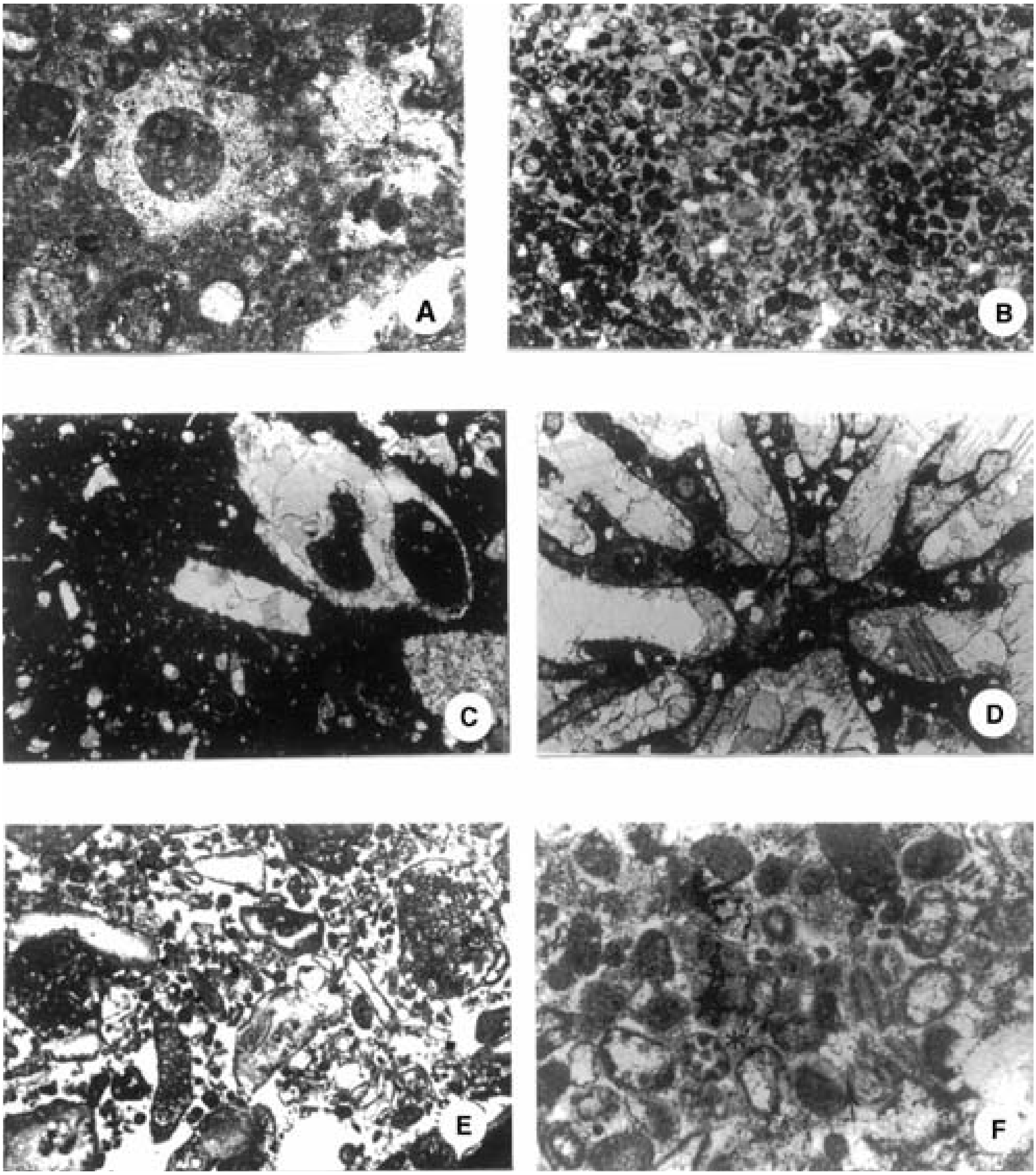

FIGURE 5 **Characteristic microfacies in the subtidal cycles of the Calabozo Formation. A) Microfacies C. *Salpingoporella annulata* CAROZZI. x20. B) Microfacies D. Rather well sorted bioclastic-peloidal wackestone. Debris of molluscs, calcispheres and micritic ooids are also present. Subangular to angular terrigenous grains are characteristics. x10. C) Microfacies D. Longitudinal section of gastropod shell after a strong recrystallization, and fragment of dissolved bivalve shells. x20. D) Microfacies E. Strong recrystallized scleractinian coral filled by blocky cement. x20. E) Microfacies F. Thin section of peloidal-bioclastic-intraclastic packstone. Ooids, peloids, intraclasts and fragments of cyanobacteria. x10. F) Microfacies F. *Cylindroporella annulata* CAROZZI (*) and *Salpingoporella annulata* CAROZZI (arrow). x20.**

storms. In fact, the facies association suggests a possible oolite shoal adjacent to this wackestone microfacies.

Microfacies D. Bioclastic-peloidal-terrigeneous wackestone

This microfacies is quite similar to the peloidal and bioclastic wackestones microfacies (microfacies B and C, respectively) except for a relatively high concentration (15%) of terrigenous material (Fig. 5B). Non-carbonate components are represented by subangular to angular fine-grained quartz, feldspars and volcanic clasts.

Strongly recrystallized bivalves, gastropods (Fig. 5C), echinoderms and calcispheres are present in the matrix, together with intraclasts and scattered ooids, peloids and terrigenous material. The peloids are spherical in shape, subrounded and very well sorted; some of them have an irregular shape suggesting that they are fragments of micritized allochems (Tucker and Wright, 1990). Matrix appears recrystallized and shows a gradual transition to peloid components.

This microfacies is interpreted as a subtidal facies based on the presence of the marine biota and the absence of features indicative of emergent conditions. Low energy conditions below fair-weather-wave base predominated during the deposition of the peloidal wackestones, but the presence of terrigeneous material is possibly related to storm erosion of nearby siliciclastic deposits.

Coral floatstone facies

This facies consists principally of fragments of corals along with small corals in growth position (scleractinian patch reef). The spaces among the corals are filled up with mud containing coral fragments, bivalve shells, echinoderm debris and peloids. The rock is dark-gray and is massive to poorly bedded ranging from 0.30 to 0.40 m in thickness. This facies includes a single microfacies type:

Microfacies E. Coral packstone

This microfacies principally consists of fragments of corals (scleractinians) affected by strong recrystallization. Micrite envelopes coat the septae and the sclerites are filled with micrite and peloids (Fig. 5D). Some scattered small domal colonies in life position are recognized. The colony diameters are about 8 cm. Other associated allochems include bivalves, gastropods, echinoids and Cyanophyta. The interstitial sediments are composed of either wackestones or packstones. Bivalves and echinoid fragments lack physical abrasion; nevertheless, they are usually bored by marine organisms (bivalves, worms or sponges, probably).

The fragmentation of most of the fossils and the poor sorting of the matrix suggests moderate turbulence and reasonably shallow deposition, close to a patch reef environment. The original skeletal structure of the coral and mollusc allochems is obscured by synsedimentary destruction of corals by the action of bioeroders, diagenetic dissolution of original skeleton microstructures (Palma et al., 2000b) and different internal sediments filling up the internal cavities product of dissolution (Oklavi and Amini, 1998).

Packstone-grainstone facies

This facies includes bioclastic-peloidal-oolitic-intraclastic packstone/grainstone beds. Bed thickness varies from 0.80 – 1.00 m. Packstone beds are well bedded, dominated by large recrystallized bivalves, oysters and *Gryphaea* fragments, as well as intraclasts showing a composition quite similar to those of the wackestone facies. Some small oncoids and fragments of patch reef corals are recognized. Packstone facies are characterized by Microfacies F.

Microfacies F: Peloidal-bioclastic-intraclastic packstones

This microfacies is characteristically composed of micritic ooids, peloids, echinoderms (plates and spines), coral and bivalve shell fragments, together with green algae and Cyanophyta, gastropods and intraclasts (Fig. 5E). The intraclasts are generally rounded to subangular and consist of reworked peloidal or bioclastic wackestone/packstones or peloidal-bioclastic-oolitic packstones/grainstones and less abundant algal intraclasts. Some aggregate grains and intense micritization are observed.

Fossil algae are represented by fragments of dasycladacean algae, particularly *Cylindroporella* sp. (Fig. 5F). Different forms of the blue-green algae *Cayeuxia* were found. They are represented by *Cayeuxia* (*Rivularia*) *piae* (Fig. 6A) and *Cayeuxia* (*Rivularia*) *kurdistanensis*. Peloids are well rounded and show good sorting. Allochems are accumulated in patches and show no abrasion, and appear immerse in a peloidal matrix which was partly washed out in place.

The composition of this microfacies suggests a shallow subtidal environment influenced by moderately high-energy conditions. Deposits were generated by erosion and reworking of other microfacies in a shallow water environment. Rounded and subangular intraclasts and aggregate grains are interpreted as being deposited in a shallow lagoon. Wave action and bottom currents led to winnowing and agitation also resulted in the formation of algal coatings around the grains. The abundance of micritic ooids and the regular micritization of others particles suggest a low sedimentation rate. This microfacies lacks subaerial exposure features. Similar forms of green dasyclads to those reported from the Jurassic and Cretaceous of Lebanon and Europe (Basson

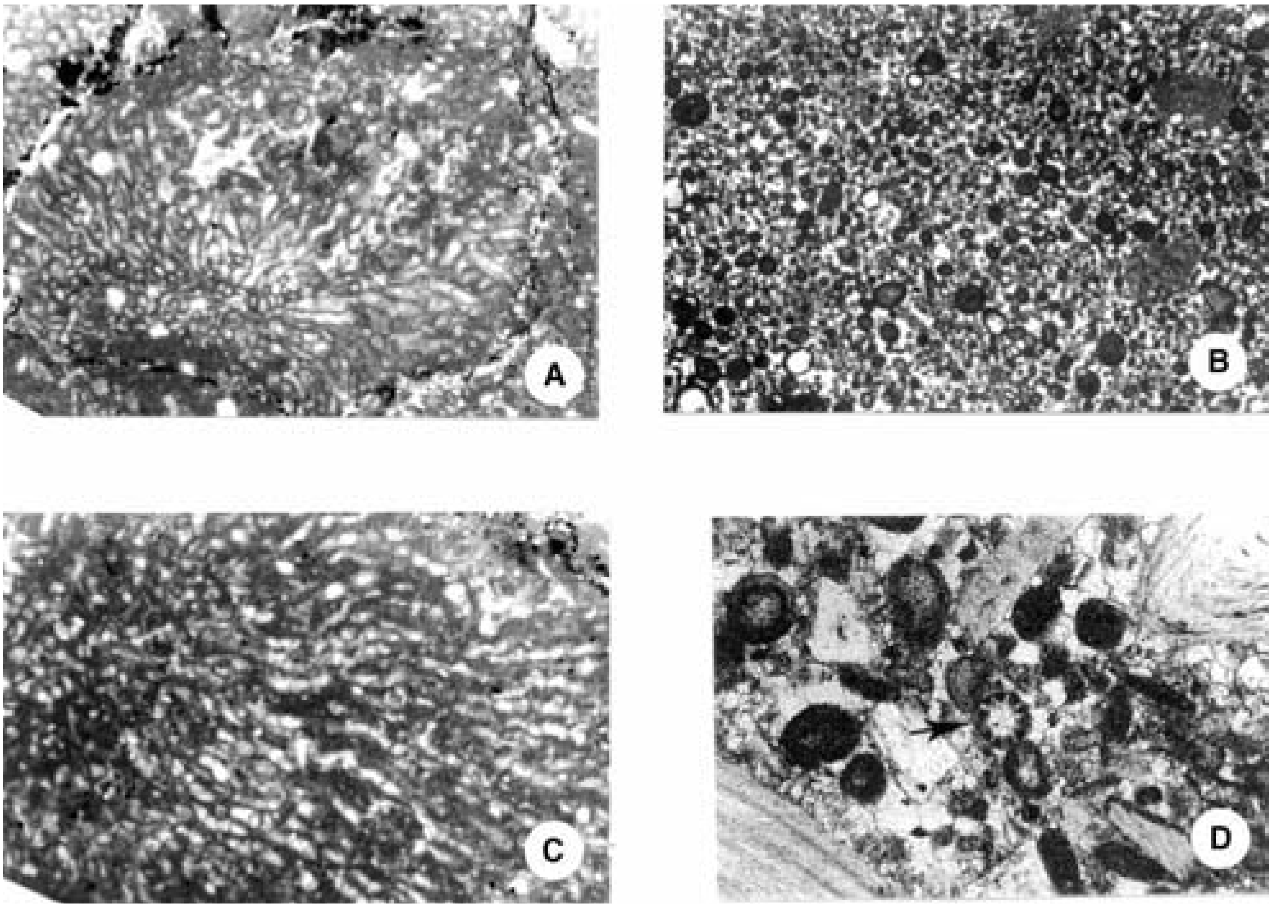

FIGURE 6 **Characteristic microfacies in the subtidal cycles of the Calabozo Formation. A) Microfacies G. *Cayeuxia* (*Rivularia*) *piae* RECH-FROLLO. x20. B) Microfacies G. Well sorted medium-grained oolitic-bioclastic-peloidal packstone/grainstone. Most ooids are strong affected by micritization and mixed with intraclasts and peloids. x10. C) Microfacies G. *Cayeuxia* (*Rivularia*) *kurdistanensis* ELLIOT. x20. D) Microfacies G. *Heteroporella* sp. (arrow). x20.**

and Edgell, 1971) indicate deposition in a warm shallow protected marine environment.

Platform margin facies assemblage

Oolitic-peloidal packstone-grainstone facies

The platform margin assemblage includes a variety of oolitic-peloidal packstone-grainstone beds, which are lenticular beds and locally cross-bedded, with bed thickness ranging from 50 to 90 cm. Commonly, this facies together with the bioclastic-intraclastic packstones form the upper part of subtidal cycles. This facies is characterized by Microfacies G.

Microfacies G: Oolitic-bioclastic-peloidal packstones/grainstones

This microfacies interfingers with peloidal-bioclastic wackestone-packstones. Particles are coarse grained and mainly composed of ooids, peloids (Fig. 6B), abundant fragments of recrystallized bivalves, echinoderms (plates and spines) and oncoids. They occur together with gastropods, intraclasts and large pieces of the thallus of *Cayeuxia* (*Rivularia*) *kurdistanensis* (Fig. 6C). Another type of algal remains was also found probably belonging to *Heterporella* sp. (Fig. 6D). Some of the algal specimens are incomplete, broken and abraded fragments. The oncoids range in shape from spherical to elongate, and their diameters vary from 2 to 10 mm. The cores of these oncoids are small rounded shell fragments, intraclasts or fragments of *Cayeuxia* sp.

Scattered benthonic foraminifera and ostracods were recognized. The matrix is peloidal and was washed out in some places. Ooids have spherical to elliptical shapes, and three types of ooids were distinguished. They include micritic ooids, multilayered ooids and ooids with a radial-fibrous fabric. The nuclei of all of the ooids consist of peloids or skeletal debris. The thicker laminae show a concentric fabric, but some ooids are commonly strongly micritized. Intraclasts are subrounded and derived from the interbedded wackestone/packstone microfacies. Ooids and intraclasts mostly occur within microfacies coinciding with an increase in grain size. All fossil remains exhibit micrite rims or abundant coating.

This microfacies suggests deposition in a high-energy shallow-water deposit. The high degree of sphericity of the ooids and the well developed, concentric laminae of some ooids indicate that they may have been formed in a relatively continuously agitated environment, similar to modern oolite shoals (Loreau and Purser, 1973). Nevertheless, the presence of ooids with radial-fibrous structure could indicate calm water. However, their presence in this microfacies as part of intraclasts, suggests that they derived from another microfacies. In fact, the origin of the intraformational intraclasts of subtidal origin may reflect reworking by storm action. Oncoid formation suggests, at least periodically turbulent environment which causes overturning (Tucker and Wright, 1990).

The peloids are inferred to have formed due to recrystallization of ooids, shell fragments or small intraclasts. Micritization is interpreted to be caused by microbial boring activity during sedimentation (Kobluk and Rist, 1977). The dasycladacean algae fragments present in this microfacies are reworked, despite their environmental preference, which suggests a low energy setting below wave agitation or a protected area (Wray, 1977).

SUBTIDAL AND PERITIDAL CYCLES

Considering the vertical evolution of facies and microfacies, the studied section is arranged into decimeter to meter-scale shallowing-upward cycles ranging between 0.40 and 1.70 m in thickness (Fig. 3A).

Types of cycles

On the basis of the intracycle facies and microfacies arrangement and of the characteristics of the bounding surfaces, two kinds of subtidal cycles have been identified: 1) Cycles capped by shallow to intermediate subtidal facies; and 2) cycles with a similar shallowing-upward trend but capped by peritidal facies. In general, the succession in the Calabozo Formation consists of incomplete subtidal cycles of the first type that never include intertidal o supratidal facies. Only one exception has been recorded on the top of the succession, where a Type 2 subtidal cycle (which shows subaerial features and represents a break in sedimentation) occurs below the overlying Tábanos evaporites (Fig. 2; Palma et al., 2000a).

Deepening-shallowing successions that never reach intertidal or supratidal facies have been termed “subtidal cycles” by Osleger (1991). In the Calabozo Formation these subtidal cycles are generally made up by peloidal or bioclastic wackestones that evolve upwards through gradational contacts into bioclastic or oolitic packstone-grainstone facies that lack emersion features. The increasing abundance of ooids, allochems and intraclasts indicate that the depositional environment shallowed upwards (Fig. 3B). The characteristic faunal association, the occurrence of calcareous algae remains and the lack of traces of subaerial exposure suggest that these peloidal or bioclastic wackestones and the bioclastic or oolitic packstone-grainstones were deposited in shallow subtidal shelf lagoon environments, in well oxygenated waters. There are sites of mud and peloid deposition in many modern carbonate environments like Bahamas or Persian Gulf (Loreau and Purser, 1973). Modern ooid deposits also accumulate at or above wave base, under high-energy conditions as shallow shoals in the Bahamas (Hine, 1977) and in the Persian Gulf. The presence of micro-oncoids suggests a very shallow subtidal environment (Gebelein, 1976). Thin intercalations of shell concentration layers with local erosional base and rapid lateral wedging out are interpreted as resulting from the action of storm currents, suggesting that deposition took place above the storm-wave base (Aigner, 1985).

The complete subtidal cycle (Type 2) is composed of peloidal or bioclastic wackestone passing upwards through gradational contacts into bioclastic or oolitic packstone-grainstone lithofacies that are overlain by stromatolitic limestones with laminar fenestrae and micro-tepee structures (Fig. 3C). Taking into account the vertical evolution of facies and microfacies, their arrangement indicates an inner-carbonate platform environment, showing a regressive trend from subtidal lagoonal to tidal-flat conditions.

Analysis of cyclicity

Fischer plots (Fischer, 1964) were constructed from the major outcrop section studied (Calabozo Creek). The outcrop section was too short to make statistically significant Fischer plots (Sadler et al., 1993), but they were used as a preliminary guide to detect possible changes in accommodation space. Fischer plots were conventionally drawn by cumulative departure from mean cycle thickness against cycle numbers (Sadler et al., 1993). The Fischer plots revealed three distinctive parts in the stratigraphic section that show different accommodation space trends (Fig. 7)

The thickest beds of the lower part of the section show a relatively high accommodation space where carbonate productivity was high enough to fill the available space (cf. Strasser et al., 1999). The general succession of microfacies within this section characterizes a shallow inner platform, with peloidal-bioclastic-intraclastic wackestone (microfacies B and C) and bioclasts-peloidal packstones (microfacies F), followed by oolitic-bioclastic-peloidal packstones-grainstones (microfacies G). These successions indicate shallowing-upward trends.

An intermediate part of the section shows thinner cycles and an aggradational stacking pattern. In this section asymmetrical cycles composed of microfacies B, C and F, are capped by oolitic-peloidal packstone-grainstones (microfacies G), suggesting an increase of wave activity in response to shoaling, which represents a period when carbonate deposition kept pace with sea-level on the platform. These characteristics suggests that sedimentation rate on the platform was equivalent to the increase in accommodation space.

The upper part of the section shows an upward decreasing cycle thickness, while variations in the microfacies associations (microfacies C, G, F, from bottom to top) are capped by planar to wavy laminae with exposure features, suggesting decreasing accommodation space. This trend suggests an increasing importance of shallower depositional environments.

Factors controlling meter scale cycles

Stacked cycles in shallow-water carbonate platforms can result from either autocyclic or allocyclic mechanisms (Einsele et al., 1991; Strasser, 1991). Diverse mechanisms (autocyclic and allocyclic processes) have been proposed to explain the origin of such fourth to fifth order cycles, although there are not unambiguous criteria for distinguishing one from another (Goldhammer and Harris, 1989). Autocyclic processes involve progradation of tidal flats or lateral migration of tidal channels (Ginsburg, 1971; Pratt and James, 1986; Strasser, 1991). Allocyclic processes would include repeated fault movements ("jerky subsidence" of Cisne, 1986) and/or eustatic sea-level fluctuations (Koerschner and Read, 1989; Elrick and Read, 1991; Goodwin and Anderson, 1985; Balog et al., 1997) that are independent from the local depositional environment.

The correct interpretation of the cyclicity observed in the Calabozo Formation stacking pattern and its possible controlling factors is debatable due to the areally limited outcrops and the absence of an accurate chronostratigraphic control of the cycles. However, if the absence of peritidal facies with diagnostic criteria of sediment progradation capping the cycles (recording the reduction of the available space for the "carbonate factory") were confirmed, it would suggest an allocyclic control instead of an autocyclic progradation or lateral migration of the system in a context of homogeneous subsidence. Moreover, the observed lateral continuity of the cycles would also suggest an allocyclic control, if a similar number of them was recorded basin wide, ruling out the possibility of a local, exclusive influence of autocyclic processes.

The Fischer plots reflect changes in accommodation space driven by relative sea-level changes. In the Calabozo Formation these plots show an upward decrease in cycle thickness, and a thinning–upward trend of the bed thickness in the cycles (Fig. 7). These features are related to changing sea-level or accommodation (Elrick and Read, 1991). Taking into account the thinning-upwards tendency of the Calabozo succession, and the changes in accommodation space, a relative sea-level change would have probably controlled the deposition of the unit.

Assuming that an allocyclic mechanism were proved, the distinction between tectonic "jerky" subsidence and eustatic sea-level fluctuations would be difficult. The currently availabel data do not allow us to reach any reliable conclusion. The main regional fault-related tectonic activity was over during Callovian times in the considered basin area; there are no regional evidences of fault-related activity documented during the deposition of the Calabozo Formation, which took place during a thermal decay episode probably dominated by thermal subsidence (Manceda and Figueroa, 1995). Although these considerations do not completely exclude the tectonic "jerky"

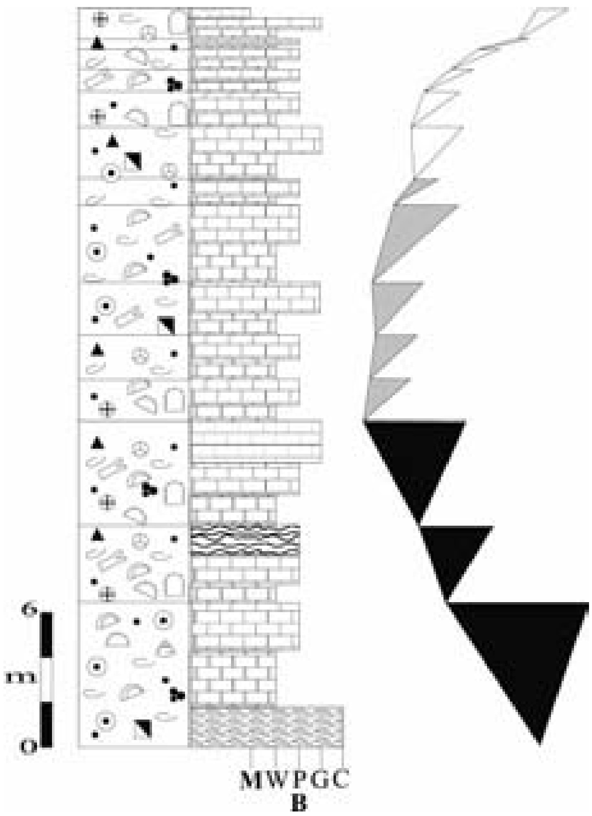

FIGURE 7 **Fischer plot scaled by the thickness of the cycles for Callovian Calabozo Formation. See legend in Figure 3.**

mechanism, it is considered that a strong tectonic forcing was not probable in the considered depositional setting.

The absence of a sufficiently accurate chronostratigraphic framework of the observed cycles does not enable one to closely compare their frequencies with those of the Milankovitch-derived mechanism stated for short term sea-level fluctuations during greenhouse periods. Nevertheless, although the available data do not allow to firmly state the controlling factors that have caused the cyclicity of the Calabozo Formation, relative sea-level changes appear like the more probable mechanism.

CONCLUDING REMARKS

The Callovian Calabozo Formation was deposited on a shallow-marine carbonate dominated platform, with minor siliciclastic deposition. The lowermost, early transgressive, coarse-grained siliciclastic facies were deposited in littoral beach environments. Thin lagoonal, shallow subtidal sandstones occur interbedded in the lower part of the formation.

The carbonate facies were deposited in tidal-flat, inner platform and platform margin environments that can be distinguished on the basis of their sedimentological and petrological characteristics. Detailed petrographic analysis have led to the recognition of seven carbonate microfacies related to diverse subenvironments. The intertidal-supratidal environments were characterized by deposition of planar algal boundstones (microfacies A). Shallow, low energy subtidal subenvironments (innner platform environments) were characterized by peloidal-bioclastic wackestones, bioclastic-intraclastic wackestone, bioclastic-peloidal-terrigenous wackestone , peloidal-bioclastic-intraclastic packstone and coral floatstone (microfacies B to F). Finally, high-energy subtidal environments developed in platform margin zones and resulted in the deposition of oolitic-bioclastic-peloidal packstone-grainstones (microfacies G).

Fossil algae are represented by some dasycladacean species, which include *Salpingoporella annulata*, *Cylindroporella* sp. and *Heterporella* sp. The blue green algae *Cayeuxia* (*Rivularia*) *piae* and *Cayeuxia* (*Rivularia*) *kurdistanensis* also occur. These algal assemblages indicate deposition in warm shallow protected marine environments and had not been previously reported from the Callovian carbonate platform of Argentina.

On the basis of the intra-cycle facies and microfacies arrangement and the cycle bounding surfaces, two kinds of subtidal cycles are recognized: a) widespread subtidal cycles capped by shallow subtidal facies that show no evidence of subaerial exposure; and b) a minor subtidal cycle capped by peritidal facies with subaerial exposure traces. The thickness of these cycles shows a thinning-upward tendency that indicates a decrease of accommodation space driven probably by relative sea-level lowering.

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