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Depositional, diagenetic and stratigraphic aspects of microfacies from Riachuelo Formation, Albian, Sergipe Basin, Brazil

Aspectos deposicionais, diagenéticos e estratigráficos de microfácies da Formação Riachuelo, Albiano, Bacia de Sergipe, Brasil

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Abstract

The rocks of the Riachuelo Formation, Sergipe Basin, Brazil, represent an example of carbonate sedimentation related to the drift phase during the opening of the South Atlantic Ocean. The Carapeba and Brejo quarries exhibit the best onshore outcrops of the drift carbonate section along the Brazilian continental edge. Field studies and microfacies analysis of the outcropped sedimentary section showed six sedimentary deposits related to the physiography of a carbonate shelf. Proximal mixed deposits are represented by the rich-terrigenous dolostone. Levels with alternate layers of fine grained sandstones and siltstones are here related to distal facies of submarine fans deposits. Mudstones with miliolids and textularids represent a lagoonal environment in a semi-restricted middle shelf. Packstones, grainstones and occasionally wackestones with oncoids, intraclasts and peloids represent sedimentary deposits related to the back of shallow sandy bars and environments at the interface with the lagoon. Grainstones whit ooliths, oncoids, intraclasts and bioclasts, with trough cross-bedding, represent a shallower shoreface environment over the shallow carbonate back on outer shelf. Cements and other post-depositional features suggest four different diagenetic environments: a) marine phreatic diagenetic environment with active water circulation; b) marine phreatic diagenetic environment with stagnant water; c) freshwater phreatic diagenetic environment; d) burial diagenetic environment. The sedimentary succession is formed by shallowing upward cycles overlain by a possible transgressive surface, which may indicate the passage of a lowstand to a transgressive system tract.

Keywords: Sergipe Basin; Riachuelo Formation; Albian; Microfacies.

Resumo

As rochas da Formação Riachuelo, Bacia de Sergipe, Brasil, representam um exemplo de sedimentação carbonática relacionada à fase *drift*, durante a abertura do oceano Atlântico Sul. As pedreiras Carapeba e Brejo exibem os melhores afloramentos *onshore* da seção carbonática *drift* em toda margem continental brasileira. Estudos de campo e análises microfaciológicas da seção sedimentar aflorante evidenciaram seis tipos de depósitos sedimentares relacionados à fisiografia de uma plataforma carbonática. Depósitos proximais mistos são representados por dolomitos ricos em terrígenos. Níveis alternados de arenitos e siltitos são aqui relacionados às fácies distais de leques subaquosos. *Mudstones* com miliolídeos e textularídeos representam ambiente lagunar em plataforma média, semirrestrita. *Packstones*, *grainstones* e eventualmente *wackestones* com oncólitos, intraclastos e peloides representam depósitos sedimentares relacionados à retaguarda de bancos arenosos rasos e ambientes na interface com a laguna. *Grainstones* com oólitos, oncólitos, intraclastos e bioclastos, com estratificação cruzada acanalada, representam ambiente de *shoreface* sobre o banco carbonático raso na plataforma externa. Os cimentos e outras feições pós-deposicionais observadas sugeriram diagênese progressiva em quatro ambientes diagenéticos: a) marinho freático com circulação de águas; b) marinho freático com água estagnada; c) meteórico freático; d) ambiente de soterramento. Os pacotes sedimentares formam ciclos de rasamento ascendente, sobrepostos no topo por uma provável superfície transgressiva, o que pode indicar a passagem de um trato de sistema de mar baixo para um trato de sistema transgressivo.

Palavras-chave: Bacia de Sergipe; Formação Riachuelo; Albiano; Microfacies.

INTRODUCTION

During the Albian period, with the Gondwanaland break-up and South Atlantic opening, large carbonate sedimentation platform began to form along the eastern coast of Brazil and in western coast of Africa (Cesero and Ponte, 1997). In the Sergipe Basin (NE Brazil), this carbonate sedimentation can be seen especially in the Riachuelo and Cotinguiba formations (Cainelli et al., 1987; Feijó, 1994).

The Riachuelo Formation shows evidence of deposition occurring in shallow platform environments, strongly controlled by the basement framework, represented by oncoidal-oolitic sandy banks associated to algal bio-constructions, clastic wedges comprising mixed deposits of carbonate and terrigenous sediments deposits of fan-deltas, as well as pelitic deposits of lagoonal origin (Cainelli et al., 1987; Feijó and Vieira, 1991; Koutsoukos et al., 1993).

In his pioneering work, using data from wells and outcrops, Bandeira Jr. (1978) describes and interprets some of the microfacies of the Cotinguiba and Riachuelo formations from the point of view of Plumley et al. (1962) energy levels. In this paper, ramp morphology is a depositional model, similar to what has been proposed by Ahr (1973), which was greatly influenced by successive variations of the sea level.

Geological studies of the same stratigraphic interval were also performed in the Sergipe Basin (Marçal, 1993; Koutsoukos et al., 1993; Mendes, 1994), focusing other areas, not included in the exclusive study based on microfacies analysis.

The purpose of this work was to describe and interpret some depositional, diagenetic and stratigraphic aspects in microfacies belonging to the Riachuelo Formation, Upper Albian section, Sergipe Basin.

The study is justified by the fact that Riachuelo Formation is one of the few formations in the Brazilian continental margin sedimentary basin where a carbonate section outcrops onshore, providing a model for analogy with the other similar formations.

On the other hand, the Albian carbonate section succeeds an evaporite interval related to important petroliferous plays in almost all marginal basins in Brazil.

The Sergipe Basin is located on the Brazilian eastern coast, between 09° and 11°30’ south latitude and 35°30’ and 37° west longitude, forming a narrow belt that is 140 km long, arranged in the N45°E direction. The study area is located between coordinates 10°45’ to 10°48’ south latitude and 37°08’ to 37°10’ west longitude (Figure 1).

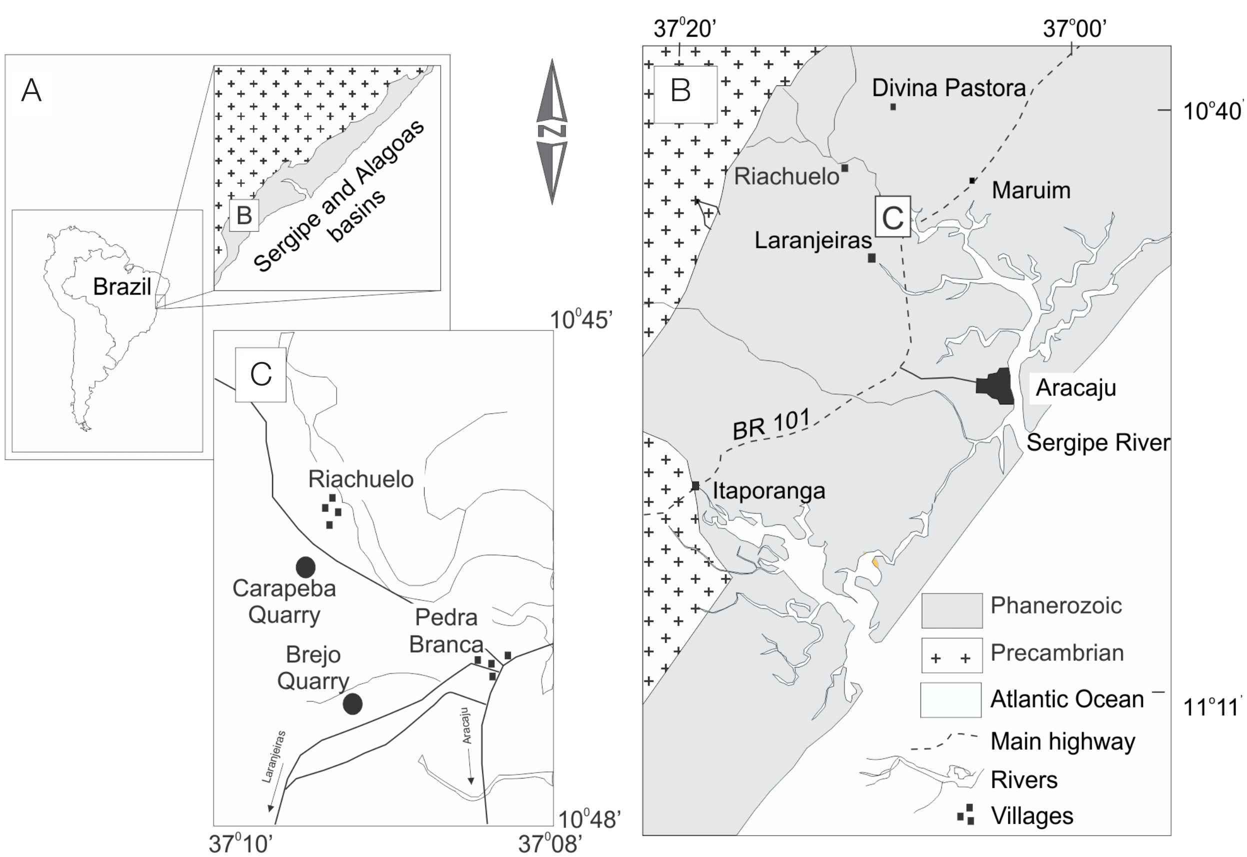


Figure 1. (A and B) Sergipe Basin location and simplified geological map; (C) location of studied outcrops.

MATERIALS AND METHODS

The study was based on detailed field observations as well as sedimentological and petrographic analysis. The field activities were limited to the Carapeba and Brejo quarries, Riachuelo Formation, where some of the best examples of Maruim Member can be seen. The studied areas have been selected from Beurlen (1968) biozones map, with reference to the Mortoniceras and Elobiceras zones (Ammonite), Upper Albian.

The description of outcrops and sampling was carried out using horizontal intervals of 5 m whenever possible, and vertical ones of 0,5 m each, or less, where the change of facies was apparent.

One hundred and twenty-two samples were then impregnated with blue coloring in a vacuum pump to enhance the pores. Subsequently, thin sections of the samples were made for petrographic analyzes, which was performed with a polarizing microscope of transmitted light.

The classification of carbonate rocks followed Dunham (1962) criteria, in which the name of the most abundant grain types is accompanied by the name of the lithotype. In this sense, mudstones are here defined as a mud rock composed by lime material. Terrigenous rocks were classified according to Folk (1974). The granulometric scale used to allochemical grains was based in Wentworth (1922). A crystal-size scale of Folk (1962) was used for authigenic constituents.

GENERAL ASPECTS ON THE BASIN EVOLUTION IN THE BRAZILIAN CONTINENTAL MARGIN

The genesis of the Brazilian marginal basins was directly linked to the fragmentation of Gondwanaland and the development of the South Atlantic rift from the Upper Jurassic-Early Cretaceous period (Cainelli and Mohriak, 1999).

Both in South America and Africa, this evolution involved distinct episodes of tectonism and sedimentation, which are pre-rift or continental phase, rift phase (continental and lake depositional systems), transitional or proto-oceanic phase, and oceanic or drift phase (Asmus and Porto, 1972; Asmus, 1975; Ponte and Asmus, 1978; Campos Neto et al., 2007).

The pre-rift stage began during the Perm-Triassic and lasted until the Upper Jurassic. During this period, the area between the present margins of Brazil and Africa exhibited domal uplifts and flexural basins named peripheral depressions (Estrella, 1972), where Paleozoic sedimentation occurred.

The rift phase began in the Early Cretaceous with the rifting spreading from South to North, lasting until the Aptian (Feijó, 1994). At this stage, synthetic and antithetic faults established a series of half-grabens, filled by fluvial deltaic and lacustrine sediments, alternating with shallow water bioclastic banks (Lana, 1990; Cainelli and Mohriak, 1999).

The drifting of the South American and African continents during the Aptian created conditions for the formation of a narrow marine passage in the south (Chang et al., 1990). This new physiographic condition resulted in the establishment of a restricted and hypersaline gulf, with the formation of evaporites (Cainelli and Mohriak, 1999).

During the Upper Aptian, the effective separation of the continental crust between Brazil and Africa established effective marine conditions (Ponte and Asmus, 1978). It began with the deposition of a carbonate megasequence formed under hot and dry weather conditions, and lasted until the Albian (Dias Brito, 1982; Chang et al., 1990). In the Sergipe Basin, this sequence was subject to an active tectonic control that remained all the Albian (Koutsoukos et al., 1993; Destro, 1994), during which the Richuelo Formation sediments were deposited. In the structural highs of the basin, oolitic-oncoidal sand banks associated with algal biolitites began forming the Maruim Member. In the half-grabens, deep marine conditions generated the calcilutites of the Taquari Member. Near the edges of the basin, subaqueous fans composed by a mix of coarse clastics and carbonates formed the proximal turbiditics deposits of the Angico Member (Cainelli et al., 1987; Koutsoukos et al., 1991) (Figure 2).

At the end of Albian, the increasing crustal stretching and subsequent deepening of the basin promoted the establishment of full marine conditions with the deposition of sediments on passive margin (Koutsoukos and Dias Brito, 1987; Chang et al., 1990; Koutsoukos, 2000). This is represented by the Continguiba Formation in the Upper Cretaceous and the Piaçabuçu Group in the Cretaceous/Tertiary (Campos Neto et al., 2007).

RESULTS

Geological aspects of the studied area

The region presents a series of half-grabens, formed by normal faults with a regional dip towards SE and NW. The compartmentalized structure of the basin, with a series of half-grabens around structural highs, was essential to control the sedimentation of carbonate, both in shallow and deep waters (Koutsoukos et al., 1993).

The outcropping area of Maruim Member is irregular, interrupted by islands of sediments and rocks of the Barreiras Group (Souza and Santos, 1997), a Plio-Pleistocene sedimentary unit, or circumscribed by rocks of the Angico and Taquari members, which are not near the two quarries (Figure 3). The Angico Member is lithologically composed by layers of gravelly and sandy limestones, alternating with layers of conglomerates, sandstones, siltstones and shales containing mollusks eroded fragments. The Taquari Member is represented mainly by mudstones and rich-terrigenous dolostones containing a poorly diversified fauna, represented mainly by benthic foraminifera typical of lagoons, mostly miliolids, and colony of cyanobacteria forming thrombolytes.

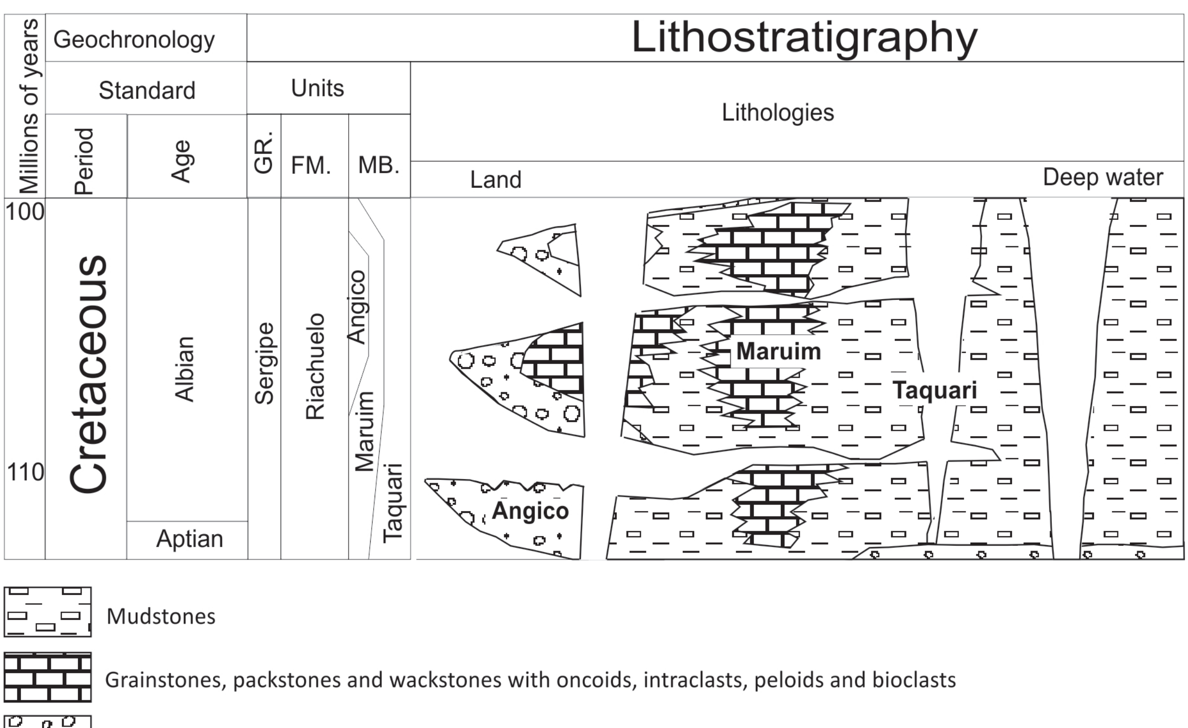
The absence of faults between the two quarries and their topographical positions suggests that the sedimentary pile in Brejo Quarry is stratigraphically positioned higher than the Carapeba Quarry (Figure 3).

The Carapeba Quarry is poorly preserved, being formed at its base by a small pit with a rise of 3.37 m of thick rock, followed by another with 1.70 m above. The main outcrop is formed by a vertical wall with approximately 15 m high and 50 m wide (Figure 4A). The Carapeba sedimentary section can be subdivided into cycles that start at the base, more commonly by bioclastic-peloidal mudstone, changing toward the top to intraclastic-peloidal grainstones and packstones, and finally to rich-terrigenous dolostones or peloidal-intraclastic-oolitic grainstone. Strata are massive or show coalescent lobe architecture. The top of each cycle exhibits ripple marks, trough cross-bedding and eventually Thalassinoides (Figures 4B to 4D).

The Brejo Quarry is a clean, well preserved outcrop, approximately 16 m high and 40 m wide (Figure 4E). The set of rocks forms cycles composed by oncoidal-intraclastic packstone to grainstone, or oncoidal packstone, evolving toward the top to oolitic-peloidal-intraclastic grainstone. Strata are massive, with tops that are mostly sharp and less commonly gradational. Their apical portions are marked by hardgrounds with oyster accumulations, vertical burrows and solution channels (Figures 4F and 4G). The top of the quarry is characterized by an interruption of the carbonate record, overlapped by a terrigenous package. It consists of five alternating cycles, formed by very fine yellowish sandstone and/or siltstones which pass abruptly to dark shales (Cycle 5 at the Figures 4E and 5B). The sandstones and siltstones became quite brittle, with hummocky cross-bedding.

Microfacies analysis

According to their compositional and textural characteristics, 11 different microfacies were recognized, which



GR.: Group; FM.: Formation; MB.: Member.
Source: adapted from Feijó (1994) and Manso and Souza-Lima (2003).

Figure 2. Stratigraphic chart of the Albian section in the Sergipe Basin.

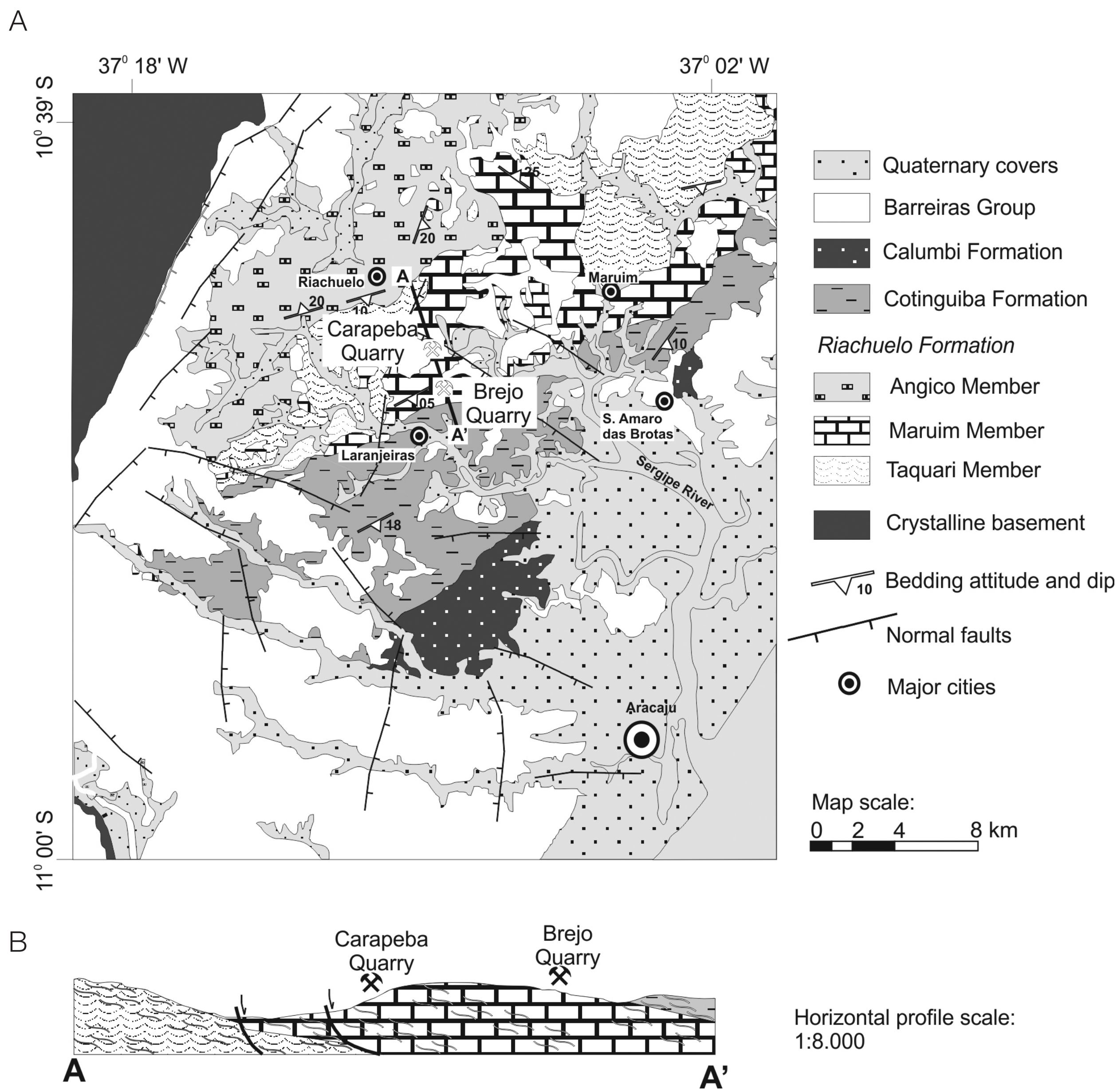
represents depositional environments or specific depositional conditions.

To simplify the correlation of microfacies types with their locations and levels in the lithostratigraphic columns of each quarry (Figure 5), the following abbreviations have been assigned to each group: muddy microfacies (MF), sandy microfacies (S) and terrigenous and mixed microfacies (TM).

Muddy microfacies

Peloidal-bioclastic mudstone (M1)

Its framework is composed by peloids and bioclast in very fine to fine sand granulometry, dispersed in bioturbed micritic matrix. Peloids occur as loosely defined grains, like ghosts of spherical micritic lumps. The bioclastic content



Source: adapted from Mendes (1994) and Souza and Santos (1997).

Figure 3. (A) Geological framework of the studied area; (B) geological profile. The geological profile is merely illustrative and the apparent dip of the fault planes does not represent the true apparent dips.

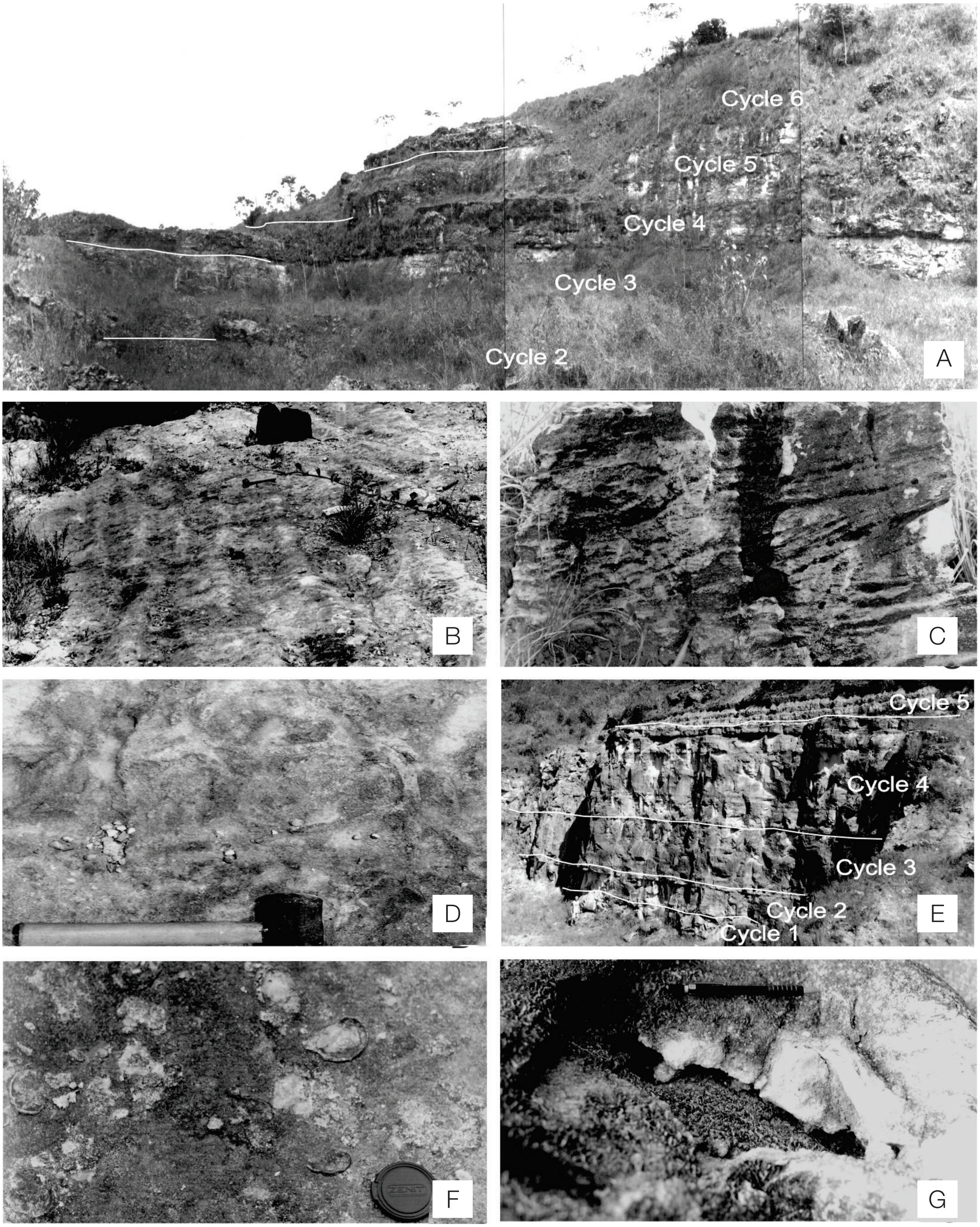


Figure 4. (A) Partial view of the Carapeba Quarry with depositional cycles; (B) ripple marks on the top of the first cycle, Carapeba Quarry; (C) trough cross-bedding in oolitic-peloidal-intraclastic grainstone at the top of Carapeba Quarry; (D) detail of Thalassinoides; (E) general view of the Brejo Quarry indicating some of its depositional cycles; (F) hardground with oysters marking the end of the fourth cycle of the Brejo Quarry; (G) solution channel at the top of the first cycle of the Brejo Quarry.

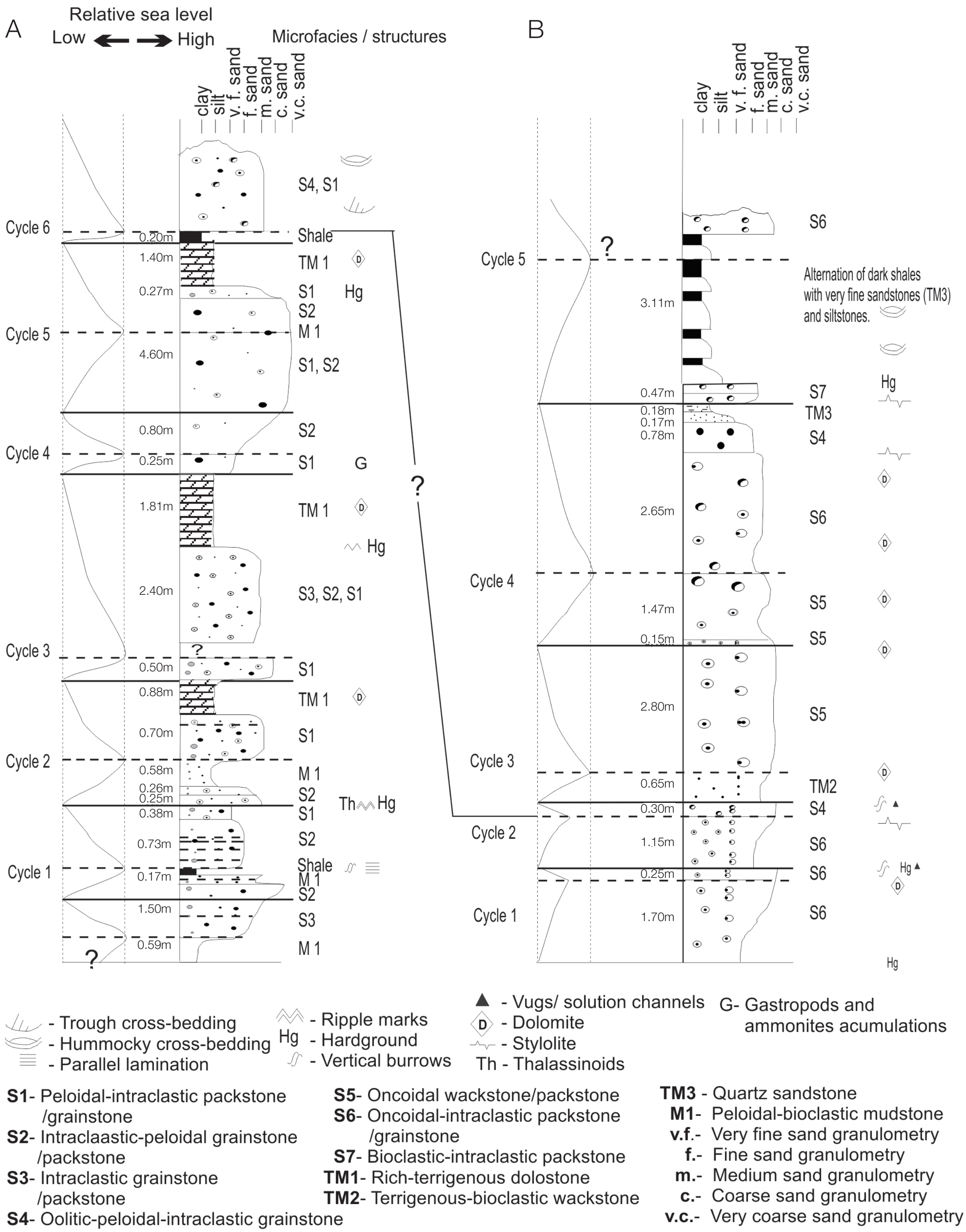


Figure 5. Lithostratigraphy and variation in sea level represented in Carapeba (A) and Brejo (B) quarries. The continuous horizontal lines represent the limits of each cycle. The horizontal dashed lines indicate maximum flooding surfaces. The interpretation of relative sea level rises was made based on the deeper and lower energy facies in each cycle. The low relative sea level is inferred from the high-energy shallow facies and from the features of subaerial exposure at the end of each cycle, like solution channels and vugs.

is formed by benthic foraminifera chambers (miliolid and textularid), globigerinids (Figure 6A), bivalves and rare fragments of solenoporoid red algae. The form of the bivalve shells are normally intact and may be internally dolomitized or neomorphosed to spatic microcrystalline calcite. The dolomitization process was not intense and ocurred localized. Crystals are zoned with intracrystalline porous (Figure 6A). On the other hand, they can also have dusty cores or be neomorphosed to microcrystalline calcite. Discrete channels porous formed by solution may be present, usually filled with spatic calcite (Figure 6B). The wider portions of the channels are filled by peloids, ooliths and micrite. The thin portions and the remaining porous spaces are filled by blocky cement of calcite.

Sandy microfacies

Peloidal-intraclastic packstone/grainstone (S1)

This microfacies consists of peloids and intraclasts with good grain sorting (Figure 6C), made up by fine sand to less commonly medium sand and associated with smaller quantities of bioclasts and ooliths, plus a small portion of terrigenous grains. Peloids are spherical or oval in shape and predominant in the fine sand fraction, comprising 40 to 60% of the grains. The intraclasts are micritic, present loosely defined shapes, and have been originated from peloidal-bioclastic mudstone microfacies (M1). They comprise 20 to 30% of the grains. Ooliths are superficial or composed by two or more lamellae around a peloidal core, comprising around 13% of the grains. The bioclasts are composed predominantly by fragments of bivalves, chambers of miliolid (Figure 6C) and textularid foraminifera. Spines of echinoids, fragments of gastropods, solenoporoid red algae, as well as tiny stems of dasycladacean green algae can also be seen in smaller quantities. Bivalve and gastropod are mostly coated by a micritic envelope, with the interior filled with spatic microcrystalline calcite. The rock framework can become intensely micritized, forming ghosts of grains with no internal structure (Figure 6D). When the matrix is absent, the intergranular spaces are filled with spastic microcrystalline calcite cement. The dolomitization occurred selectively in the matrix, associated with the presence of terrigenous grains.

Intraclastic-peloidal grainstone/packstone (S2)

Its framework is poorly to moderately sorted, with granulometry ranging from fine sand to granule. Minor amounts of bioclasts, ooliths, oncoids and terrigenous grains are visible (Figure 6E). The intraclasts vary from micritic types to fragments of peloidal packstone, in diverse shapes and sizes. Types containing ooliths and bioclasts are less common. The micritic types, in some cases, may be confused with fragments of micritized red algae. Its modal percentage is approximately 10 to 35%. Peloids comprise 20 to 55% of the grains and exhibit variation in size. Ooliths have peloidal cores and, less commonly, quartz and zircon. The coats are formed by calcite needles arranged perpendicularly to the surface. Its dimensions range from 0.2 to 0.3 mm and comprise about 7% of the grains. The bioclasts fragments are mainly composed by solenoporoid red algae (Figure 6F), as well as dasycladacean and codiacean green algae, and range between 5 to 15%. Bivalves, gastropods, spines and plates of echinoids and chambers of miliolid and textularid are also common. The bivalves are usually covered by a micritic envelope and may be filled with spastic microcrystalline calcite. The spines and plates of echinoids may be preserved, fully micritized or with a partially formed micritic envelope. Accumulations of gastropods are common in this unit. A mosaic of microcrystalline spatic calcite forms the cement. There is also sintaxial cement associated with plates and spines of echinoids. Features of dissolution and collapse are often observed, with channels filled by calcite cement, forming a blocky and spatic mosaic (Figure 6G). Dolomitization occurs as a process restricted to the matrix, as a rule where there is an increased amount of terrigenous grains.

Intraclastic grainstone/packstone (S3)

It shows a poorly to moderately sorted framework, sometimes with bimodality, where the main constituents are intraclasts with minor amounts of bioclasts, ooliths and peloids (Figure 6H). The intraclasts are formed by micritic grains or by fragments of peloidal-bioclastic packstone, with elongated or irregular shapes and borders with embayments, comprising 35 to 45% of the grains. Its dimensions range from 2 to 5 mm. Among bioclasts, there are fragments of solenoporoid red algae, molds of bivalves and gastropods coated by a micritic envelope and filled with spatic cement. Spines of echinoids are frequently found. Fragments of codiacean and dasicladacean green algae, as well as agglutinant chambers of foraminifera, are also common (Figure 7A). Bioclasts make up about 15% of grains. The main types of cements are microcrystalline mosaic, blocky spatic mosaic and sintaxial cement, associated with spines of echinoids. When composed mainly by grainstones, intraparticle and selective oomoldic porosity occurs (Figure 7B). Dolomitization is low and sparse.

Oolitic-peloidal-intraclastic grainstone (S4)

This microfacies is poorly sorted, with granulometry varying from fine to very coarse sand. It is composed predominantly by ooliths, peloids and intraclasts, with oncoids

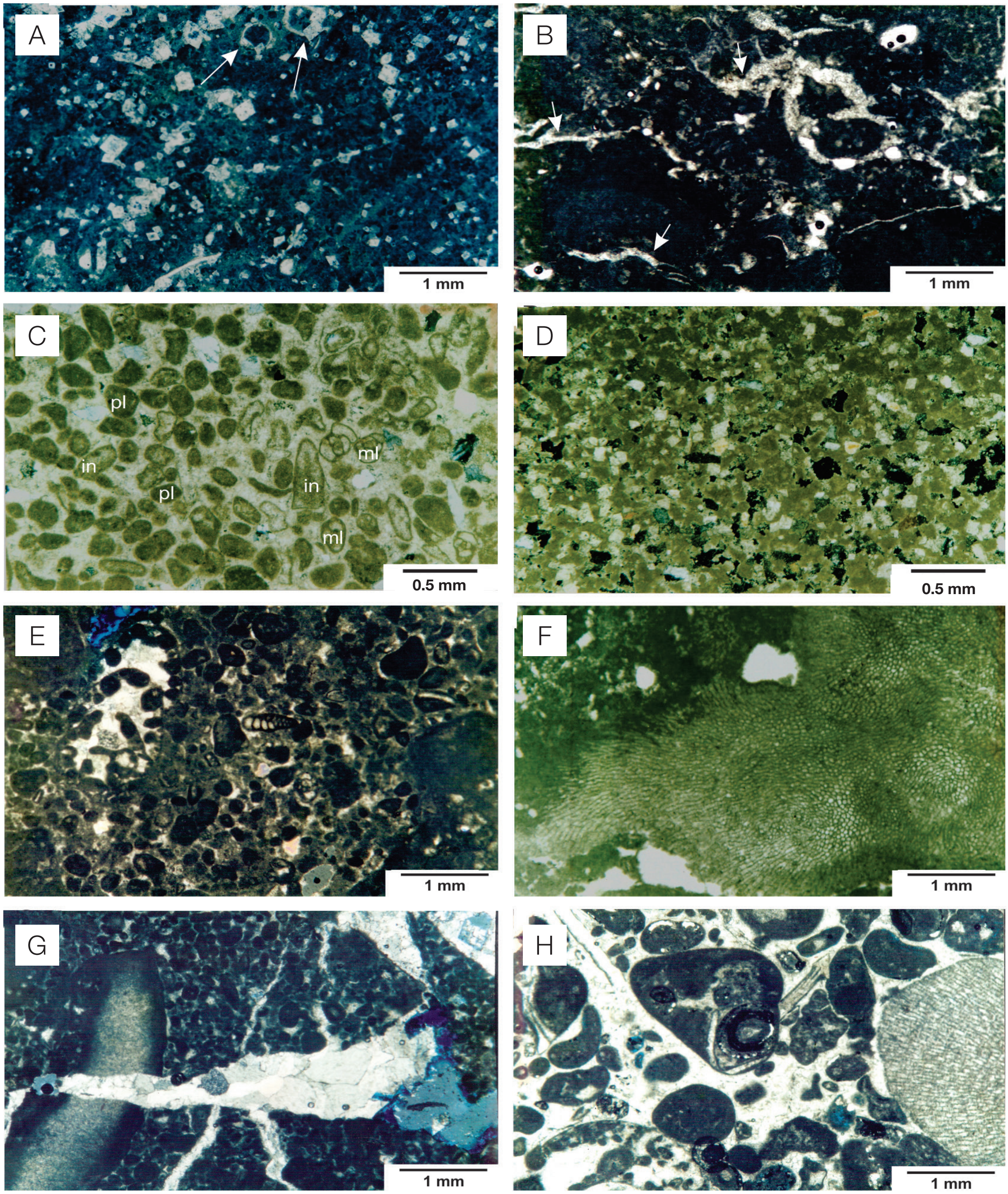


Figure 6. (A) General view of peloidal-bioclastic mudstone (M1) showing chambers of globigerinoid foraminifera (white arrows) as well as dolomite crystals with porous cores and immersed in the muddy matrix. Parallel polarizes; (B) solution channels filled by spatic calcite at the peloidal-bioclastic mudstone. White arrows are peloids. Parallel polarizes; (C) peloidal-intraclastic packstone/grainstone (S1) with its major constituents being peloids (pl), intraclasts (in) and miliolids (ml). Crossed polarizes; (D) ghosts of peloids reflecting an intense process of micritization at the peloidal-intraclastic packstone/grainstone (S1). Crossed polarizes; (E) general view of intraclastic-peloidal grainstone/packstone (S2). At the uppermost left part of the picture, a huge chamber of agglutinated foraminifer, filled by spatic cement, can be seen. Crossed polarizes; (F) fragment of solenoporoid red algae at the intraclastic-peloidal grainstone/packstone. Crossed polarizers; (G) solution channels filled by a mosaic of blocky spatic calcite at the intraclastic-peloidal grainstone/packstone. Crossed polarizes; (H) general view of intraclastic grainstone/packstone (S3). Observe the presence of a huge red algae fragment and an echinoid spine near an intraclastic at the center. Parallel polarizes.

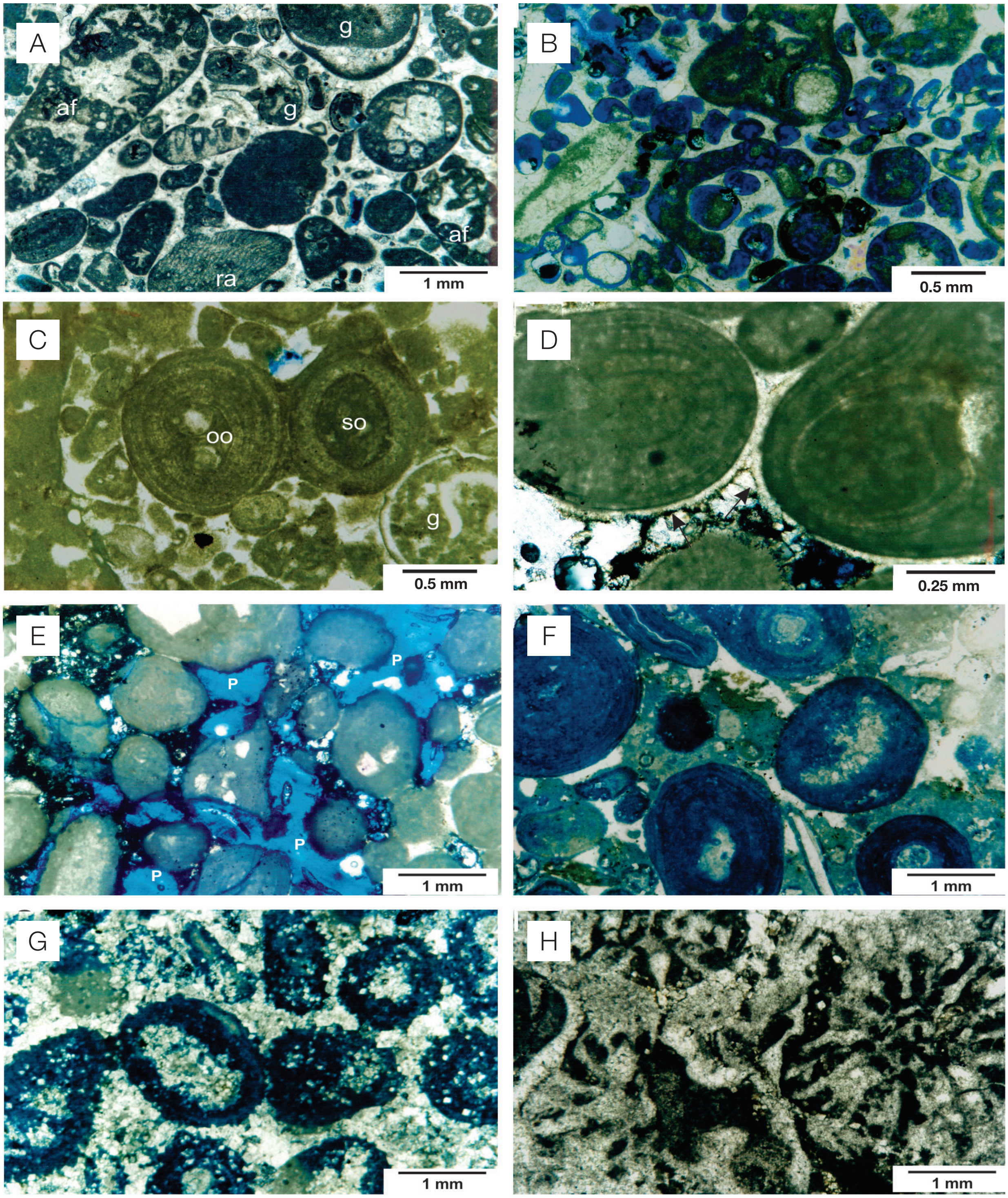


Figure 7. (A) Intraclastic grainstone/packstone (S3) exhibiting fragments of gastropod (g), red algae (ra) and a chamber of bentonic agglutinated foraminifer (af).The cement is formed by a mosaic of spatic calcite. Crossed polarizes; (B) selective and moldic porosity in some portions of the intraclastic grainstone/packstone. Parallel polarizes; (C) detail of oolitic-peloidal-intraclastic grainstone (S4) with prominent aggregate of oolith (oo), superficial oolith (so) and gastropod fragment (g). Parallel polarizes; (D) ooliths coated by a thin isopachous rim (arrows) of microcrystalline calcite. Parallel polarizes; (E) intergranular porosity (P) enhanced by dissolution in the Oolitic-peloidal-intraclastic grainstone. At the Brejo Quarry this feature is related to the top of each cycle. Crossed polarizes; (F) view of Oncoidal wackestone/packstone (S5). The oncoids exhibit cores with peloids and bioclasts. The micritic matrix is segregated and share intergranular spaces with microspar calcite. Crossed polarizes; (G) oncoidal wackestone/packstone with matrix and cores of oncolites completely dolomitized. Crossed polarizes; (H) detail of hexacoral polips at the Oncoidal wackestone/packstone. Parallel polarizes.

and bioclasts in smaller quantities (Figure 7C). The ooliths are formed by visible concentric layers with radial calcite needles, surrounding peloidal or terrigenous cores (Figure 7D). They constitute about 18% of the grains. Peloids exhibit various shapes, and their sizes are smaller than 0.15 mm, comprising about 25% of the grains. The intraclasts are composed by peloidal packstone or by a mosaic of microspatic calcite, with terrigenous grains in the interior. Sometimes, it can be surrounded by a thin micritic envelope. Its dimensions can reach up to 8 mm and it composes 15% of the grains. Oncoids exhibit micritic nucleous, having small terrigenous grains trapped in their lamellae. In average, it composes 7% of the grains. The bioclasts are represented by fragments of solenoporoid red algae, gastropods, spines of echinoids, miliolide and textularide chambers, agglutinating foraminifera, as well as codiacean and dasicladacean green algae. The amount of bioclasts does not exceed 5% of the grains. The intergranular space is filled by spatic and blocky calcite or by a microspatic mosaic. On some levels, a finely granulated and isopachous rim of microcrystalline calcite occurs involving the grains (Figure 7D). Solution channels appear cutting cement and grains, establishing communication between voids formed by the dissolving of bivalve shells. The channels and voids are filled with spatic and blocky cement. Sometimes, it is observed vuggy porosity associated with intergranular porosity, both enhanced by dissolving (Figure 7E).

Oncoidal wackestone/packstone (S5)

Normally, it shows facies strictly formed by wackestones or by packstones, although a mix of both is usual. It is a lithotype with oncoid as is its main allochemical grain, usually associated with intraclasts and lower amounts of bioclasts, as well as rare occurrences of peloids and terrigenous grains (Figure 7F). The framework has moderate to good sorting and the granulometry varies from medium to very coarse sand. The oncoids comprise at least 43% of the grains and may have various kinds of nucleus such as other oncoids, peloids, quartz, echinoids fragments, bivalve shells and gastropod fragments. They can be partially or completely dolomitized (Figure 7G). The main bioclasts amount nearly 1.5% of the grains and are composed by fragments of bivalves, echinoids spines, gastropod shells and, less commonly, fragments of condiaceans green algae and coral (Figure 7H). The shell structures of bivalves may display neomorphism, or, like other bioclasts, a thin micritic envelope. The intraclasts account for around 5% of the grains and display different types, varying from micritic fragments to oncoidal wackestone. Among the main terrigenous grains, ordinary and polycrystalline quartz, microcline, plagioclase and pertite can be found. The matrix is abundant, about 45%, and can be either preserved or fully dolomitized (Figure 7G). In some places, it is segregated, forming clumps or sharing the intergranular spaces with spatic or microspatic cement. On the grains surface, it is possible to observe the presence of a thin and granular isopachous fringe around the grains, especially where there is no matrix. The selective dissolution and formation of channels are responsible for the porosity in this microfacies. The selective dissolution occurs principally in the intercrystalline porous spaces between crystals of dolomite.

Oncoidal-intraclastic packstone/grainstone (S6)

In these rocks, the main framework grains are oncoids and intraclasts, with minor quantities of peloids and bioclasts. The framework is badly sorted, with granulometry varying from very fine to coarse sand (Figure 8A). The oncoids usually have a core with peloids, bioclasts (Figure 8B) and terrigenous grains, although they may also be composed by other oncoids. Sometimes, the cores are dolomitized or with neomorphism to microspar. Its dimensions range from 0.5 to 2 mm, and it accounts for 20 to 50% of the grains. The intraclasts are micritic and elongated with oncoids, peloids, fragments of bivalves, gastropods, echinoids, foraminifera chambers and dolomite crystals dispersed on the inside. Some resemble aggregates, formed by peloids immersed in a micritic matrix. The intraclasts represent 18 to 30% of the grains. The main types of bioclastic grains are composed of gastropod shells, fragments of bivalves, plates and spines of echinoids, as well as codiaceans and dasicladaceans green algae. Less commonly, solenoporoid red algae can be found. The bivalves and gastropods may be preserved or neomorphized to microspar, when showing a thin micritic envelope. The green and red algae may contain a micritic envelope or a thin algalic lamination on the edges of the bioclast. The amount of bioclasts ranges between 5 and 15% of the modal percentage. The dolomitization process is selective and limited to the matrix. The intergranular spaces, free of the matrix, as well as solution channels, vugs and digging tunnels (Figure 8A), are filled by spatic and blocky cement. Some sintaxial cement appears associated with fragments of echinoids. The most common porosities are the intercrystal, which is formed in dolomitized areas, as well as moldic and vuggy ones. Stylolites can also be seen in thin section (Figure 8C).

Bioclastic-intraclastic packstone (S7)

The rock framework is poorly sorted, varying from silt to very coarse sand, occasionally with terrigenous grains. The bioclastic grains are formed mainly from plates and spines of echinoids, gastropod shells, fragments of mollusks, codiacean, and dasicladacean green algae. The

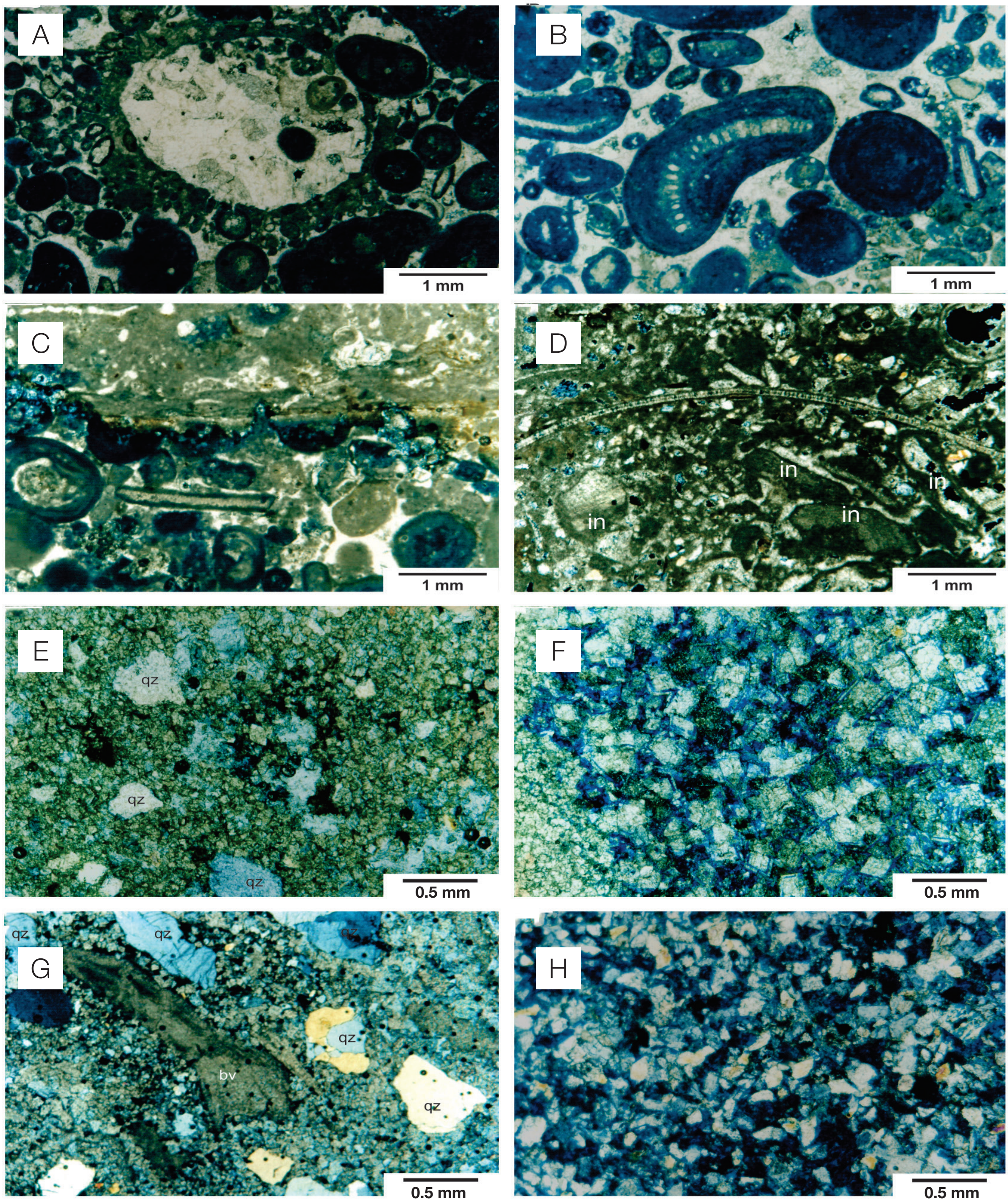


Figure 8. (A) General view of oncoidal-intraclastic packstone/grainstone (S6) with an digging tunnel completely filled by spatic and blocky calcite. Crossed polarizes; (B) detail of oncoidal-intraclastic packstone/grainstone exhibiting a segregated matrix at the right lowermost portion of the photo, as well as a spatic calcite cement. The core of the oncolite at the center is constituted by a fragment of dasicladacean green algae. Crossed polarizes; (C) stylolites and micritic envelope at the oncoidal-intraclastic packstone/grainstone. Crossed polarizes; (D) general view of bioclastic-intraclastic packstone/grainstone (S7) showing the fusiform shape of micritic intraclasts (in). At the center, it is possible to observe a fragment of inoceramid bivalve with preserved internal structure. Crossed polarizes; (E) the variable content of terrigenous grains such as quartz (qz) in the rich-terrigenous dolostone (TM1) can imprint variations of colors and textures in the rock. Crossed polarizers; (F) intracrystal and intercrystal porosity at the rich-terrigenous dolostone. Crossed polarizes; (G) general view of terrigenous-bioclastic wackestone (TM2) with bivalve fragments (bv) and quartz (qz) grains. The micritic matrix is partially dolomitized. Crossed polarizes; (H) general view of Quartz Sandstone (TM2). Crossed polarizes.

gastropod and bivalve fragments have a micritic envelope and can be neomorphized inside. The intraclasts are rounded and elongated, composed by bioclasts and rare terrigenous grains embedded in the micritic matrix. Sometimes, it is possible to observe types with a fusiform geometry, resembling clay clasts ripped from the substrate and worked by the action of the currents (Figure 8D). The terrigenous grains are composed by quartz and plagioclase. Spatic and blocky calcite cement can be seen filling interparticle porous or solution channels.

Terrigenous and mixed microfacies

Rich-terrigenous dolostone (TM1)

It is almost entirely dolomitized with euhedral to subhedral dolomite crystals, associated with carbonized plant remains and terrigenous grains, composed entirely of common polycrystalline quartz, plagioclase, microcline, and, less commonly, muscovite (Figure 8E). The rock has intercrystal and intracrystal porosities. The intracrystalline porosity develops from cleavage or twinned planes of calcitized dolomite crystals by selective dissolution. The intercrystalline porosity originates from the chaotic arrangement of the crystals and the selective dissolution of the remaining calcite, favoring the formation of voids (Figure 8F).

Terrigenous-bioclastic wackestone (TM2)

It presents a poorly sorted framework and granulometry, varying from very fine sand to coarse sand. It is composed of terrigenous grains and bioclasts, although intraclasts can be present (Figure 8G). The set of terrigenous grains comprises polycrystalline quartz, microcline, pertite, plagioclase, quartz and schist fragments. Quartz grains comprise at least 20% of all grains, while other terrigenous grains account for 12%. Bioclasts are composed by echinoids, bivalves and gastropods fragments and account for 7% of grains. Normally, these original structures are modified to a microspar mosaic. The intraclasts are composed by micritic grains, partially modified to microspar or by a mosaic of blocky spar calcite surrounded by a rim of micrite. Sometimes, solution channels appear filled by blocky spar cement. The micritic matrix is strongly dolomitized. It can reach up to 60% of modal percentage.

Quartz sandstone (TM3)

It is a well sorted rock with particle sizes varying from very fine to fine sand, with grains ranging from sub-rounded to rounded with low to high sphericity. All are dispersed in a clayed matrix. Around 96% of the framework (Figure 8H) are consisted of grains of quartz. Microcline, plagioclase and muscovite appear in much lower amounts, nearly 4%. The cement is formed by microcrystalline silica. This microfacies can be seen in the apical portion of the Brejo Quarry, and is included in the cycles associated with upper shales.

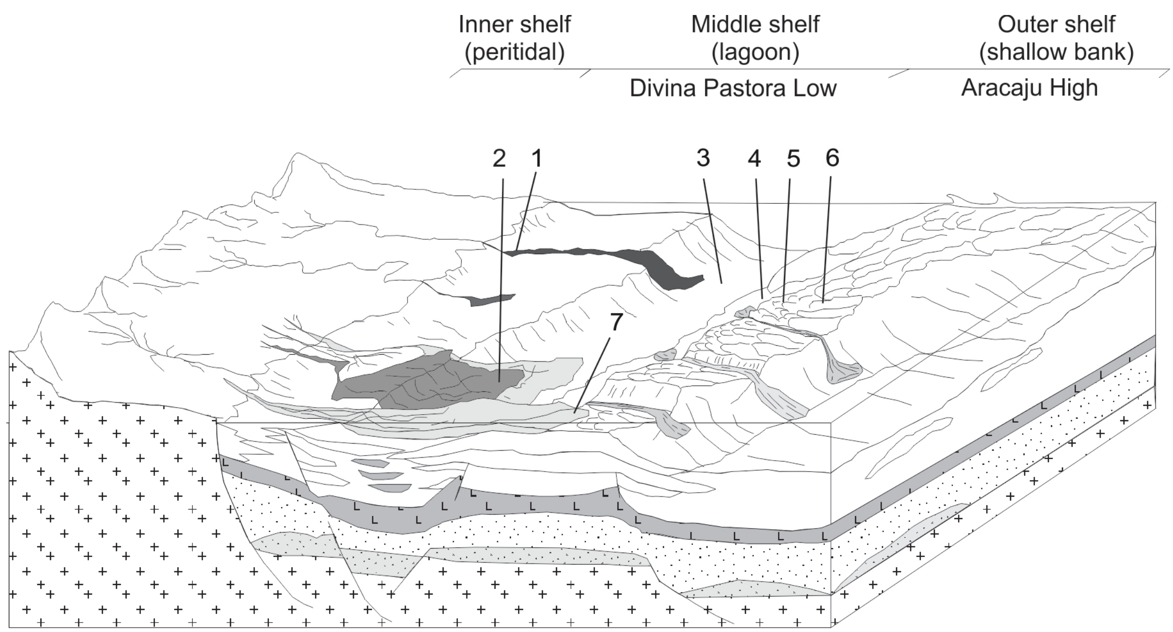
DISCUSSION

Paleoenvironments and depositional model

During the Albian, the region went through a period of transition to a typical passive continental margin, with the extensional tectonics ceasing at the Upper Albian, (Koutsoukos et al., 1993; Destro, 1994). Locally, this influenced the structuring of the Aracaju High and of the topographically lower, adjacent relief, known as Divina Pastora Low (Koutsoukos et al., 1993). This physiograph allowed the formation of a carbonate shelf where, according to Wilson and Jordan (1983), it is possible to define three main depositional domains: a) inner shelf or peritidal environment; b) middle shelf or lagoonal environment; c) outer shelf or shallow carbonate bank (Figure 9). The outer shelf was responsible for sedimentation of the sand shoals, while the middle shelf was responsible for the formation of pelitic facies, represented mainly by mudstones. Rocks and features related to the inner shelf are not well recognized in the Riachuelo Formation.

In this physiographic context, the interpretation of the microfacies allows us to suggest six different deposits: 1) proximal mixed subaqueous deposits; 2) distal subaqueous fan deposits; 3) middle shelf lagoonal deposits, on the Divina Pastora Low; 4) deposits related to the interface area between the lagoon and the sandy bars; 5) deposits related to sandy bars, behind the shallower shoreface environment; 6) deposits related to the shallower shoreface environment, on the Aracaju High (Figure 9).

The rich-terrigenous dolostone (TM1) contains elements with strong continental influence, especially terrigenous grains and carbonized wood fragments. It is known that a large part of the dolostones has its origin in peritidal environments, where freshwater from the land mixes with the saline water from the sea (Shinn et al., 1965; Lucia, 2007). However, rich-terrigenous dolostones have neither fossils nor sedimentary structures related to intertidal or supratidal environments that could prove these influences on the dolomitization process. According to previous works (Cainelli et al., 1987; Koutsoukos et al., 1991), terrigenous facies interbedded with calcareous ones in the Riachuelo Formation represent fan-delta deposits of the Angico Member. Otherwise, it is impossible to determine the nature of the calcareous material that originated the dolomite crystals only from microfacies analysis.



1- Proximal mixed subaquous deposits (TM Microfacies)
2- Distal subaqueous fan deposits (cycles with shale and TM microfacies)
3- Middle shelf lagoonal deposits (M Microfacies)
4- Lagoonal / sandy bars deposits (S1, S2 and S3 microfacies)
5- Sandy bars backward of shallower shoreface deposits (S5 and S6 microfacies)
6- Shallower shoreface deposits (S4 Microfacies)
7- Deposits related to reworked material from de floor (S7 Microfacies)

Evaporites (transitional phase)
Terrigenous of rift phase
Clastics of pre-rift phase
Basement

Source: adapted from Koutsoukos et al. (1991) and Mendes (1994).

Figure 9. Sketch showing the carbonate shelf in the Sergipe Basin during the Upper Albian.

A plausible interpretation of these rocks is that they were possibly made up of a combination of micrite from the lagoon and terrigenous grains transported by subaqueous fluxes from the basin border. It is supposed that, from this kind of deposit, whole micritic sediments were subsequently dolomitized.

Subaqueous fan deposits are interpreted here based mainly on interbedded siltstones and sandstones (TM3) with dark shales. These deposits overlay the carbonate sand banks and reflect the water depth, which, at the time, was probably shallow enough for the fans containing terrigenous sediments to transgress the borders of the basin and the lagoon, depositing over the banks. According to the faciological characteristics of these deposits, they can represent the terminal portions of subaqueous fans, in the manner of turbidites (Walker, 1992). Sediments were moved and constantly reworked by storms, forming hummocky cross-bedding.

The existence of calm and semi-restricted lagoonal waters in a middle shelf was deducted from pelitic facies, mainly by the peloidal-bioclastic mudstone (M1). This microfacies represents the rocks related to the Taquari Member and exhibits a biota with poor taxa diversity. Environments that are relatively poor in taxa diversity are related to restricted water bodies (Wilson and Jordan, 1983). The presence of globigerinids in the marine environment where the mudstone was formed suggests deep and more open conditions, although miliolids are typical lagoonal foraminifera (Brasier, 1980). Thus, it is likely that the inner shelf has maintained limited connection with the sea, creating an environment with varying conditions of salinity and depth.

Shallow carbonate banks of Maruim Member were interpreted by a zonation of facies that marks the transition from the lagoon to shallower areas over the Aracaju High. Packstones and grainstones with coated grains, bioclasts and peloids allows the characterization of two distinct environments on the banks. The first is located at the interface between shallow banks and the lagoon, and is characterized by environments with progressively lower energy toward the deeper region. The second is related to regions with higher energy, where sand bars were developed in locations similar to the shoreface zone. The distal portion of the banks at their interface with the lagoon is exemplified by the peloidal-intraclastic packstone to grainstone (S1). At the stratigraphic section, the peloidal-intraclastic packstone to grainstone facies overlaps the peloidal-bioclastic mudstone facies (M1), indicating progradation of shallow sandy banks over the lagoonal sediments. Its biota, consisting predominantly of miliolids and textularids, also reflects this interface.

The peloidal-intraclastic packstone/grainstones (S1) is overlapped by intraclastic-peloidal grainstone to packstone (S2) and by intraclastic grainstone to packstone (S3). These facies possibly represent sands derived from the disintegration of partially lithified sediments in shallow areas, transported to the transitional environment between the sandbanks and the lagoon by waves and tides (Jones, 1992). As a result of its location, this environment received contributions of intraclasts and ooliths from areas of higher energy. The typical bioclasts of the backward zone of the shallow banks are best represented by the large solenoporoid fragments of red algae, codiacean and dasicladacean green algae, as well as algalic concretions. As described by Ginsburg et al. (1972), codiacean and dasicladacean green algae normally inhabit the lagoonal region, although red algae usually colonize the shallower zones like sand banks and reefs. Depositional lobes behind of the shallow banks, rich in algae fragments, were described in Bermudas, extending itself for almost 4 km toward the lagoon (Garrett and Scoffin, 1977).

The oncoidal wackestone to packstone (S5) and oncoidal-intraclastic packstone to grainstone (S6) are related to the deposition in a progressively calmer environment, behind the shallow banks. Although some oncoids develop in low energy waters formed in calm environments (Scholle and Ulmer-Scholle, 2003), some energy is necessary to move the core and to generate the grain, as in intertidal channels (Dahanayake, 1978). There must be enough energy to keep the cores in movement, promoting the formation of oncoids (Logan et al., 1964), but not too much energy as to promote the genesis of ooliths. Intraclasts are also indicators of relatively high energy (Scholle and Ulmer-Scholle, 2003) because they are formed in events such as spring tides, currents and storms (Enos, 1983). The presence of terrigenous grains in this location demonstrates a continental influence.

The region of highest energy of the system is characterized by a clean lithotype, free of the micritic matrix, represented by oolitic-peloidal-intraclastic grainstone (S4). The deposition and reworking of the constituent grains of carbonate microfacies occurs mainly in crests of bars that would have been located in portions corresponding to the shoreface zone, characterized by the formation of trough cross-bedding. This region was strongly influenced by storms, which was inferred from the presence of hummocky cross-bedding.

After the deposition of the terrigenous fans, a fauna of encrusting algae, corals, mollusks and echinoderms began colonizing the area concurrently with the normal sedimentation of carbonate. New turbiditic sedimentation pulses began, incorporating produced carbonate material. Fragments of carbonate substrate were stripped, reworked, rounded and arranged in the direction of the flow. The effect of this process was a mass containing bioclasts, intraclasts and terrigenous grains immersed in a micritic matrix, characterized by bioclastic-intraclastic packstone (S7) (Figure 9).

The marginal position of the Carapeba and Brejo quarries in relation to the Aracaju High was probably the crucial factor in the predominance of oncoidal grains and peloids over ooliths, reflecting a loss of energy from the system. The highest energy facies only migrated over these sites in periods when the relative sea level was very low.

Diagenetic aspects and their related environments

The sequence of diagenetic events shows a succession of three likely nearsurface diagenetic environments, as suggested by Longman (1980) (marine phreatic diagenetic environment with active circulation of water; marine phreatic diagenetic environment with stagnant water; freshwater phreatic environment), as well as of a burial diagenesis regime (Scholle and Ulmer-Scholle, 2003).

At the marine phreatic environment with active water circulation, the principal phenomenon observed is the precipitation of a thin isopachous and microcrystalline calcitic fringe around the grains, especially in the oolitic-peloidal-intraclastic grainstone (S4).

Solution channels and vugs existing mainly at the top of a few cycles are probably related to dissolution by meteoric water. Most microfacies containing these features also have cement in the form of an isopachous rim of microcrystalline calcite. Thus, a plausible interpretation for this association is superficial and shallow marine cementation, followed by shorts periods of subaerial exposure and dissolution by meteoric waters. The porous structures formed by them are isolated and have walls covered by crystals of dolomite with a drusy structure.

The environment of stagnant marine water was inferred by the micritization of grains and by the formation of a micritic envelope around most bioclasts. Some grains, described as peloids or micritic intraclasts, can instead be ooliths and micritized algae fragments.

The diagenesis in a freshwater phreatic zone was inferred from the selective leaching of grains forming moldic porosity. The selective dissolution acted mainly on fragments of some species of bivalves, probably from aragonitic material. Precipitation of microspatic as well as spatic and blocky cements is another related feature. Finally, in this domain, the neomorphism of aragonitic grain or Mg-calcite to common calcite is a common process. The microspatic calcite contained within many bioclasts probably resulted from neomorphism. Moldic porosity is associated mainly to intraclastic grainstone to packstone. As per the vuggy porosity, it has low expression in volume and area, with almost no intercommunication between them.

Under burial conditions, the neomorphism of some portions of the micritic matrix to a microspar mosaic has occurred. Other features are the sintaxial cement around fragments of echinoids, as well as dissolution by compression, forming stylolite.

The dolomitized rich-terrigenous dolostone present the best porous characteristics. The chaotic arrangement of dolomite crystals, followed by the dissolution of any traces of calcite present between them, favored the formation of pores with a good connectivity. Similarly, the effects of the dedolomitization dissolved the lamellae of calcite, forming intracrystal porosity. This porosity is present only in areas where the crystals are bigger in size and the crystals fabric is more open.

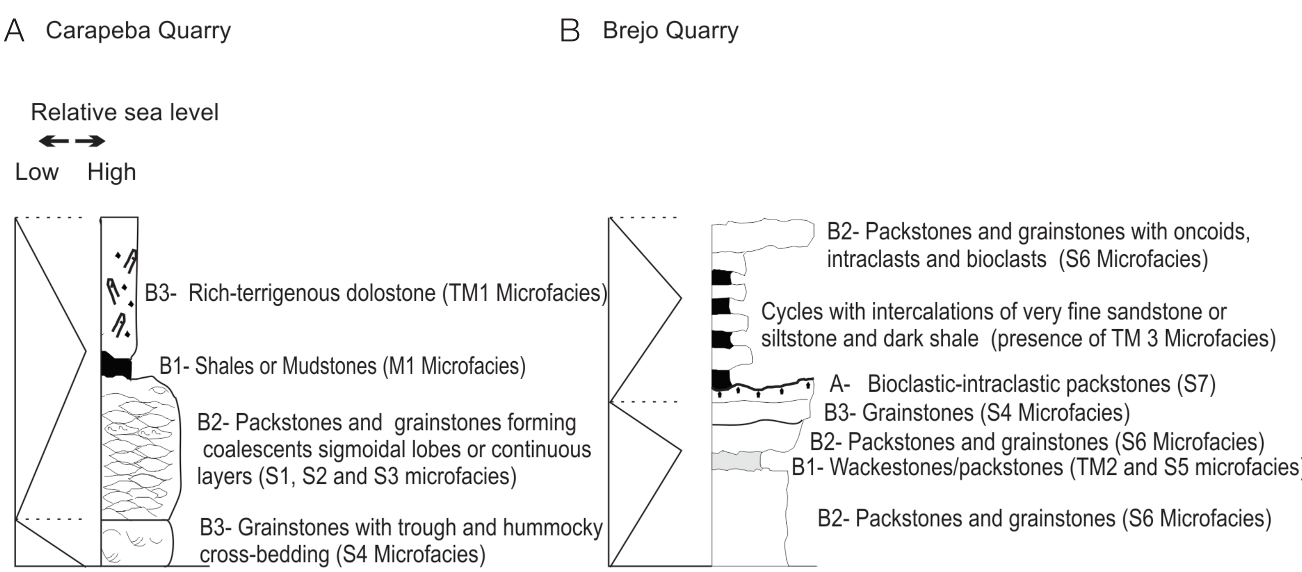
The dolomitization observed in many of the microfacies appears to be related to more than one type of processes. The complexity of the study and the need for additional analytical techniques did not allow substantial conclusions to be achieved, being therefore outside the scope of this work.

Cyclicity of facies and stratigraphic inferences

The stratigraphic pile in both quarries have sets of cycles which were interpreted based on the concepts of shallowing upward cycles (James, 1984; Pratt et al., 1992) and punctuated gradational cycles (Goodwin and Anderson, 1985), which describe vertical successions of facies composed by cycles that are progressively shallower toward the top. To simplify the understanding of the lithostratigraphic pile in both quarries, two hypothetical models were made based on shallowing upward cycles (Figure 10). Therefore, levels which tops represent a transgressive surface reworked by the action of waves are here represented by "A" (Figure 10). By presenting features formed in a predominantly subtidal zone with different energy levels, the other lithofacies were subdivided into three subdomains: a basal subtidal or "B1", the intermediate subtidal or "B2", and the uppermost part of subtidal zone or "B3".

Mudstones (M1) have apparently lagoonal origin and represent subtidal deeper facies (B1). The others represent subtidal intermediate facies (B2), characterized by wackestones and packstones, mainly related to depositional lobes formed by coalescing behind the shallow banks. The upper subtidal (B3) intervals are characterized mainly by grainstones and packstones/grainstones, with little or no matrix, trough cross-bedding and hummocky cross-bedding. Most of them have developed hardgrounds, with ripple marks and vertical burrows below. Rich-terrigenous dolostones (TM1) also represent B3 intervals, reflecting the influx of terrigenous material into the basin, bringing freshwater and promoting the dolomitization process of this microfacies.

At the Carapeba Quarry (Figure 10A), the beginning of the flood event is therefore set in each cycle by packstones and grainstones with peloids and intraclasts



Source: based on the models of James (1984) and Pratt et al. (1992).

Figure 10. Hypothetical models for shallowing upward cycles in the Carapeba (A) and Brejo (B) quarries.

(S1 and (or) S2), while the maximum flooding surfaces are guided at the top by mudstones (M1), peloidal-intraclastic packstone/grainstone (S1) or by overlying levels of shales (Figures 5A and 10A).

Unlike the Carapeba Quarry, in the Brejo Quarry (Figure 10B), the cycles begin with oncoidal-intraclastic packstone to grainstone (S6), evolving toward the top to oolitic-peloidal-intraclastic grainstone (S4), representative of the regions with higher energy (B3) (Figure 10B). The maximum flooding surfaces were inferred from the tops of the packages of terrigenous-bioclastic wackestones (TM2) or oncoidal packstone (S5), which represent the maximum depth to which the environment has been submitted. The presence of solution channels and vugs on the top of each cycle can be an indicator of subaerial exposure on the end of each of them.

The repetition of the cycles observed in both quarries suggests high frequency cyclicity, formed by allogenic factors in the range of Milankovitch Orbital cycles.

In both quarries, but mainly in the Brejo Quarry, the tops of the cycles appear to have been stalled by the development of hardgrounds, vertical burrows, ripple marks and, eventually, solution channels and vugs. These elements showed that the production of carbonate stopped, and was followed by the preservation of these surfaces and by subaerial exposure, possibly marking the end of a depositional event. For some time there would have been a static period in carbonate sedimentation representing the climax and the end of production, due to lack of space for accommodation in the basin. The creation of more accommodation space begins with the deposition of a new cycle.

The set of cycles possibly represent a progressively shallower sequence toward the top, starting at the Carapeba Quarry, which shows facies more directly related to the lagoon and the areas behind the shallow bank, and continuing towards the Brejo Quarry, where the microfacies are closer to the shallow shelf environment.

At the top of the Brejo Quarry, the positioning of intraclastic-bioclastic packstone (S7) bellow the package of terrigenous sedimentation may be of stratigraphic significance, not only because its lithological contrast, but mainly because of the microfacies characteristics. This lithotype is unique in all section, showing intraclasts and bioclasts imbricated and eroded. These elements could reflect a probably transgressive surface. The transgressive surface generally reworks debris found at the surface, forming a thin gravel deposit over the lowstand system tract, according to Posamentier and Vail (1988) concept. Thus, the transgressive surface could mark the beginning of a drowning event in a transgressive system tract, as expected in the Albian/Cenomanian passage on the Brazilian continental margin (Koutsoukos and Dias Brito, 1987; Chang et al., 1990). These changes in the microfacies can also be found in the subaqueous fan deposits. There is an overlapping of distal fan facies with turbiditic characteristics (cycles consisting of pairs of fine sandstone and shale at the Brejo Quarry) over nearby facies, with a mixture of terrigenous and carbonate. This overlap may reflect a retreat of the coastline and associated environments at the time.

CONCLUSIONS

Field studies of two main outcropped areas of Riachuelo Formation, Albian of Sergipe Basin, Brasil, coupled with the microfacies analysis of its lithostratigraphic pile, allowed the following conclusions:

1) There are, at least, 11 microfacies forming the stratigraphic section of both Carapeba and Brejo quarries. These microfacies comprise sets of rocks that can be separated, according to their textural and framework constituents, into muddy, sandy, terrigenous and mixed microfacies groups that represent specific sedimentary deposits and environments.
2) Both the microfacies and the structural characteristics of the Sergipe Basin during the Albian allowed the recognition of environments with specific sedimentary deposits within a carbonate shelf model. Semi-restricted lagoonal environments and deposits are related to the muddy microfacies containing both benthic and planktonic foraminifera. Shallow carbonate banks with shoreface deposits are associated mainly to oolitic-intraclastic-peloidal grainstone containing trough cross-bedding. Intermediate deposits and environments located between shallow banks and lagoons are indicated by the presence of wackestones, packstones and grainstones containing peloids, intraclasts, oncoids and bioclasts, such as green and red algae, benthic foraminifers, gastropods and bivalves. Distal facies of fan-delta deposits are associated to cycles containing sandstones and siltstone or shale.
3) Cyclicity of facies in the quarries can be related to shallowing upward cycles. It is likely that the set of cycles represent a progressively shallower sequence toward the top, starting at the Carapeba Quarry and continuing toward the Brejo Quarry. On the top of the Brejo Quarry, a bioclastic-intraclastic packstone with imbricate grains suggests a transgressive surface, marking the beginning of a drowning event in a transgressive system tract, as expected in the Albian/Cenomanian passage on the Brazilian continental margin.
4) At least three near surface diagenetic environments can be traced by microfacies analysis. Marine phreatic environment with active water circulation precipitated a thin isopachous and microcrystalline calcitic fringe around the grains. The environment of stagnant marine

water was inferred by the micritization of grains and by the formation of a micritic envelope around most bioclasts. The diagenesis of a freshwater phreatic zone was inferred from the selective leaching of grains forming moldic porosity, precipitation of microspatic, spatic and blocky cements. Diagenesis under burial conditions was inferred mainly by neomorphism of some portions of the micritic matrix to a microspar mosaic, due to the presence of sintaxial cement around fragments of echinoids and the dissolution by compression, forming stylolites. Vugs and solution channels at the top of some cycles are related to dissolution by meteoric water in short periods of subaerial exposure.

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