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ARTICLE

Facies and depositional environments for the coquinas of the Morro do Chaves Formation, Sergipe-Alagoas Basin, defined by taphonomic and compositional criteria

Análise de fácies nas coquinas da Formação Morro do Chaves, Bacia de Sergipe-Alagoas, sob enfoque tafonômico e composicional

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ABSTRACT: Lacustrine carbonate rocks form important hydrocarbon accumulations along the Brazilian continental margin, some of which are contained in oil fields in which coquinas are one of the main reservoirs (viz. Campos Basin). The complexity and heterogeneity of these deposits make them a challenge in terms of reservoir description. For the necessary classification and paleoenvironmental interpretation of the coquinas, it is essential to evaluate many aspects including biological (such as carbonate productivity), sedimentological (energy regime in the depositional environment, transport of bioclasts, terrigenous supply), taphonomic (fragmentation of shells, abrasion) and diagenetic processes. The facies analysis applied in this study is considered a more appropriate classification approach to understand these coquinas, since it is more flexible and comprehensive than the existing classifications for carbonate rocks. The material investigated here consists of rock samples of the coquinas from the Atol Quarry of the Morro do Chaves Formation (Barremian/Aptian), Sergipe-Alagoas Basin. These rocks that crop out in the Atol quarry complex can be considered as a case study for similar coquinas reservoirs found in the Brazilian continental margin basins. Six sedimentary facies were described, using the main taphonomic (fragmentation of shells) and compositional (presence of micrite and siliciclastic matrix) features as a diagnostic criteria. Two carbonate facies, two mixed carbonate-siliciclastic facies and two siliciclastic facies (mudstones) were identified. From the facies succession, combined with a review of the literature on the subject, the following depositional paleoenvironments were defined: high-energy lake platform, lacustrine delta in a high-energy lake platform and lake-centre. In this paper, a new facies model for the studied coquinas succession is proposed.

KEYWORDS: Coquinas; Morro do Chaves Formation; Sergipe-Alagoas Basin; Facies.

RESUMO: *As rochas carbonáticas lacustres representam importantes reservatórios de hidrocarbonetos no Brasil, muitos dos quais relacionados a campos em coquinas. A complexidade e a heterogeneidade dessas rochas as tornam um desafio em termos de modelagem de reservatório. Para a correta classificação e interpretação paleoambiental das coquinas, é necessário avaliar critérios biológicos (como a produtividade carbonática), sedimentológicos (energia do ambiente, transporte dos bioclastos, aporte sedimentar), tafonômicos (grau de fragmentação de conchas, abrasão) e diagenéticos. O conceito de fácies apresenta-se como um adequado critério classificatório para as coquinas, uma vez que é mais flexível e abrangente que as classificações existentes para as rochas carbonáticas. O material para este estudo consiste nas coquinas da Formação Morro do Chaves, Bacia de Sergipe-Alagoas. Essas rochas, que afloram na Pedreira Atol (complexo da pedreira Atol), podem ser consideradas como um estudo de caso para os reservatórios similares na margem continental brasileira. Foram descritas seis fácies, definidas segundo as principais características tafonômica (fragmentação das conchas) e composicional (presença de micrita e grãos siliciclásticos), dentre as quais duas fácies carbonáticas, duas fácies mistas e duas fácies siliciclásticas (argilitos). A partir da sucessão de fácies, aliada à literatura sobre o tema, foram definidos os seguintes paleoambientes de deposição: plataforma carbonática lacustre de alta energia, delta lacustre em plataforma carbonática de alta energia e centro de lago. Com isso, foi proposto um modelo de fácies para a sucessão de coquinas estudada.*

PALAVRAS-CHAVE: *Coquinas; Formação Morro do Chaves; Bacia de Sergipe-Alagoas; Fácies.*

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INTRODUCTION

Lacustrine carbonate rocks are important hydrocarbon reservoirs in Brazil, present in oil fields such as in the Pampo, Badejo, Linguado and Trilha fields, in the Campos Basin. These reservoirs, known since the 1970s, were previously studied by Carvalho *et al.* (2000), Castro (2006), Muniz (2013), among others. With the recente discoveries in Pre-salt sections of Campos and Santos Basins in coquinas and microbialites, such reservoirs have received a growing interest in understanding their sedimentological and petrophysical aspects (Câmara 2013).

The material for this study consists of the coquinas of Morro do Chaves Formation, Sergipe-Alagoas Basin. These rocks, which crop out at the Atol quarry have been considered as analogues for similar reservoirs in Campos and Santos basins (Kinoshita 2007; Corbett *et.al.* 2013; Câmara 2013).

Pettijohn (1957) defined the coquinas as carbonate rocks that consist wholly or partly of mechanically transported and selected fragments of fossils. Schäfer (1972) restricted the term "coquina" to accumulations formed exclusively by shells or shell fragments deposited by the action of a transport agent. This definition is the most accepted in the literature; however, it is important to consider that most coquinas are not exclusively formed by shells and their fragments. For example, the coquinas of the Morro do Chaves Formation at the Atol Quarry can also contain high amounts of siliciclastic material, reaching values up to 50% of siliciclastic matrix.

Many biostratinomic and diagenetic processes affected these coquinas. The resulting complexity and heterogeneity of these deposits make them a challenge in terms of reservoir description. Tavares (2014) covered widely the diagenetic aspects, with the definition of diagenetic facies. Câmara (2013) detailed the main petrophysical characteristics of these rocks.

Schäfer (1972) considers that the laws of sedimentology govern the textural and sedimentological characteristics of the coquinas. However, Simões and Kowalewski (1998) point out that coquinas are commonly subjected to not only complex sedimentary processes but also to taphonomical and biological processes that operate for long periods of time. Thus, the analysis and classification of biological and sedimentological processes responsible for the fossil concentration complement the paleoecological interpretation (Kidwell *et al.* 1986). After death, these shells undergo many processes such as fracturing, abrasion, bioerosion, etc. For the accumulation of fossils, it should be considered that these skeletons resisted the biostratinomic processes and/or show a high productivity within their depositional environment, since the natural process would be the total destruction of the organisms. Kidwell *et al.* (1986) consider three basic types of fossil concentrations regarding the origin of concentration: biogenic, sedimentological and diagenetic. These types may also produce mixed deposits, as the one interpreted for the coquinas of Morro do Chaves Formation that exhibit characteristics of the three proposed accumulation processes (Tavares 2014).

For an appropriate classification of the coquinas, three points are then essential: taphonomy, composition and diagenesis. A classification scheme that is able to combine these elements is crucial and should be able not only to describe the coquinas but also to provide important interpretative aspects related to the reservoir quality.

It is within this context that the concept of facies can help in the classification. The concept of facies is more flexible, since the attributes can be selected according to the any proposed study (*qv*. Borghi 2000). An example of how the facies analysis can be useful in classifying the coquinas is shown in Fig. 1. It shows a coquina with little or no fragmented shells and about 20% micrite (Fig. 1A), and a coquina with fragmented shells, with estimated percentage of 25% of micrite (Fig. 1B). Considering the usual classification methods for carbonate rocks (such as Dunham 1962; Embry & Klovan1971; Folk 1962), these rocks would not present major differences in classification. However, the fragmentation of shells is the result of reworking during sedimentation within a higher energy setting and/or was exposed longer in taphocoenosis if compared to the sample with non-fragmented shells. Also very important is the fact that, in lacustrine environments, micrite usually precipitates directly from the water as cement.

Muniz and Bosence (2011) used the concept of taphofacies to assist in the interpretation of the coquinas from Coqueiros Formation deposits in Campos Basin, correlative to the ones studied here. Their classification scheme was based on the intensity of hydraulic reworking, transport and preservation of the shells in which ten taphofacies were defined. This classification was also used in this present work for the interpretation of the lithofacies of the Morro do Chaves Formation at the Atol Quarry. The model proposed by Muniz and Bosence (2011) applies to the coquinas investigated here, but it is important to highlight that the TF-7 and TF-8 facies defined by those authors consider fragments of basalt in its original setting in the Campos basin. In the Morro do Chaves Formation, the lithoclasts correspond to sedimentary, igneous and metamorphic rocks of the Sergipe-Alagoas Basin.

In this study, six facies are described and a facies model of the coquinas of Morro do Chaves Formation is proposed according to two main features: taphonomy (fragmentation of shells) and composition (presence of micrite and siliciclastic grains). The facies succession and the paleoenvironmental interpretation follow the model proposed by Renault and Gierlowski-Kordesh (2010), since the data available at the moment were not enough to define a more accurate depositional model.

MATERIAL AND METHODS

Field work was conducted in the Atol quarry, located in the city of São Miguel dos Campos, Alagoas state, south of Maceió city (Fig. 2). A sedimentological profile (1:40 scale) of 53 m was built using ramp accesses. A description of the outcrop helped to identify major features, such as bedding geometry, cross bedding, plan-parallel lamination, sole marks, etc. The rocks were described according to Grabau's (1904) and Folk's (1974) schemes, considering the particle size of the carbonate grains (Grabau 1904) and the percentage of terrigenous clasts (Folk 1974). These classification schemes were chosen because they are purely descriptive and less suggestive in terms of interpretation.

Fourty-four samples of the coquinas from Morro do Chaves Formation were described and photographed in the Laboratory of Sedimentary Geology of UFRJ (Lagesed). They were prepared 36 petrographic thin sections, 25 at standard size (4.5 x 2.5 cm) and 11 at a larger size (7.0 x 4.5 cm). The larger thin sections were more appropriate to describe the coquinas since the samples are very heterogeneous and these larger thin sections allow more comprehensive analysis of these heterogeneities over a larger area. Petrographic analysis was performed with a Zeiss Imager A2 m microscope. The diagenetic sequence was defined using the concept of cement stratigraphy (Meyers 1974 and 1991) with the aid of cathodoluminescence (held in the equipment CITL Mk5-2/petrographic microscope Lay DM 2500P).

The facies analysis follows the definitiom from Borghi (2000), using the percentage of fragmented and/or non-fragmented shells and the percentage of micrite and terrigenous material as diagnostic attributes. The interpretation of the lithofacies used in the discussion of the depositional model for Morro do Chaves' coquinas refers to the literature on the theme (Figueiredo 1981; Azambuja *et al.* 1998; Carvalho *et al.* 2000; Kinoshita 2007; Renault and Gierlowski-Kordesh 2010; Jahnert *et al.* 2012; Teixeira 2012; Muniz 2013).

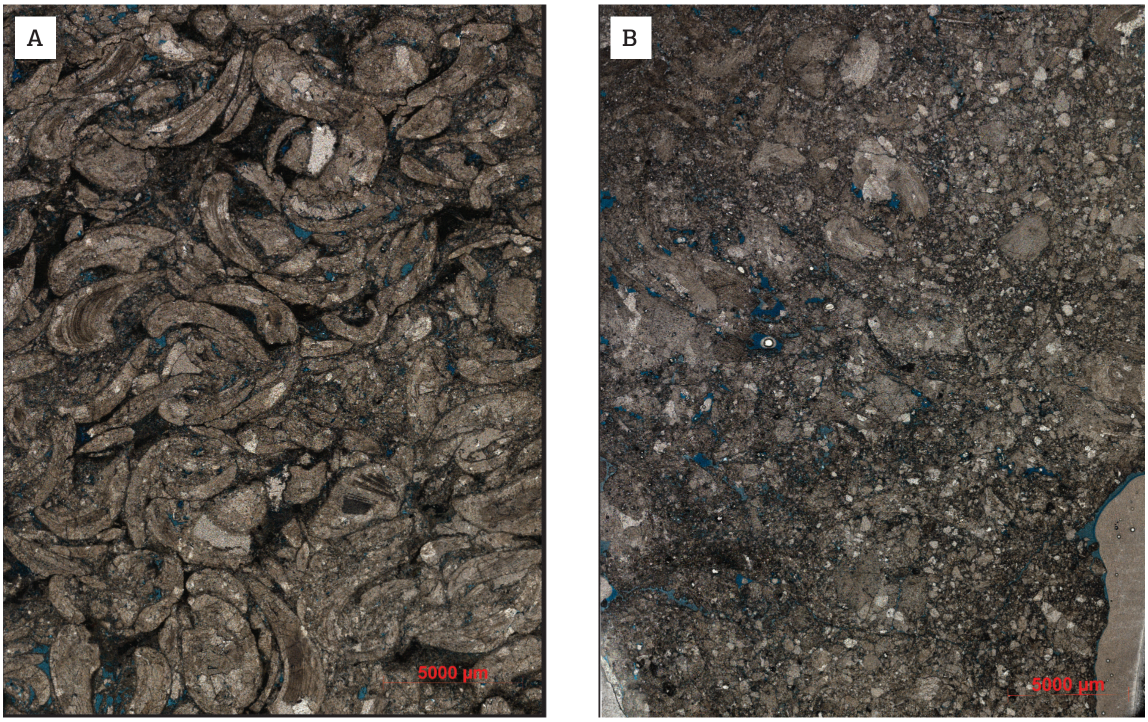

Figure 1. Two examples of coquinas with similar micrite content. (A) shows shells that are not broken while (B) shows large amount of fragmented shells. Usual classifications schemes for carbonate rocks do not differentiated these samples as they ignore taphonomy and shell fragmentation as a response of continous reworking whithin a moderate to high energy depositional environment.

GEOLOGICAL SETTING

The rocks of the Atol quarry consist mainly of coquinas, interbedded with mudstones, siltstones and sandstones, corresponding to the Morro do Chaves Formation. According to Azambuja *et al.* (1998), the coquinas of Morro do Chaves were deposited during Jiquiá (Barremian/Aptian) local stage in a lacustrine environment during a transgressive system tract of third order in the Sergipe-Alagoas basin, overlapping the fluvial deposits of the Penedo Formation. The upper contact is gradational to the Coqueiro Seco Formation, showing a progressive increase in terrigenous input into the basin with the establishment of fluvial-deltaic and alluvial systems. The Morro do Chaves Formation shows thicknesses of 50 to 350 m, with the thicker sections related to faulted blocks (Azambuja *et al.* 1998).

The coquinas of the Morro do Chaves Formation have calcite as a major mineralogical component (originally aragonite that underwent neomorphism) and are mainly composed of mollusc shells. The formation may also contain ostracods, gastropods and other bioclasts. The matrix contain micrite, clay, siliciclastic sand composed mainly by quartz, and some lithoclasts of igneous, sedimentary and metamorphic rocks (Fig.3). SEM (scanning electron microscope), BSE (back scatter electron) and EDX (energy dispersed x-ray analysis) analyses made by Mitchell (2014) confirmed the presence of pyrite, mica, zircon and clay. The clay minerals were identified as being mainly illite and, occasionally, kaolinite.

The fauna of the Morro do Chaves Formation consists mostly of shells from the molluscs *Anodontophora sp.*, *Gonodon sp.*, *Psammobia? Nuculacea sp.* and *Astarte sp*, (Borges 1937; Oliveira 1937 *apud* Souza Lima *et al.* 2002) and small gastropods. The mudstone are rich in fish fragments and ostracods (Souza Lima *et al.* 2002). Most of mollusc's bivalve shells through geological history are originally composed by aragonite, including two of the species identified in Morro do Chaves, *Nuculacea* and *Astarte sp*. (Taylor *et al.* 2011). In recent studies conducted by Thompson (2013), a diversity of marine bivalve genera was identified with subordinate marine gastropods, yielding evidence for marine incursions into the basin during the late Barremian.

According to Teixeira (2012) and also observed in this study regarding the taphonomic aspects, shells with different sizes and degrees of fragmentation occur, and there are few interger shells and rare in life position or articulated, suggesting these shells have an allochthonous or parauthoctonous origin.

In the model proposed by Teixeira (2012) for the same Atol Quarry, the carbonate platform developed in shallow and structural highs in the flexural margin of the rift, in a lake where there was little contribution of terrigenous sediments and conditions of high energy. The shells were formed in different regions of the paleolake and were mainly transported by storm waves. During storm conditions, bivalves were removed from their habitat and launched towards the coast due to the surge of watermass toward the coast, thus providing the material for the accumulation of shells. The shell accumulations formed beaches in the sublittoral/littoral area of the paleolake, forming the coquina deposits.

According to the model of Azambuja *et al.* (1998), a faulted board of the rift created depocenters in which the coquinas reached thickness of up to 300 m. The anticline associated with rollover structures at the border fault formed structural highs that partially isolated the faulted blocks from other depositional environments of the basin and favoured the isolation of water bodies during lowstand

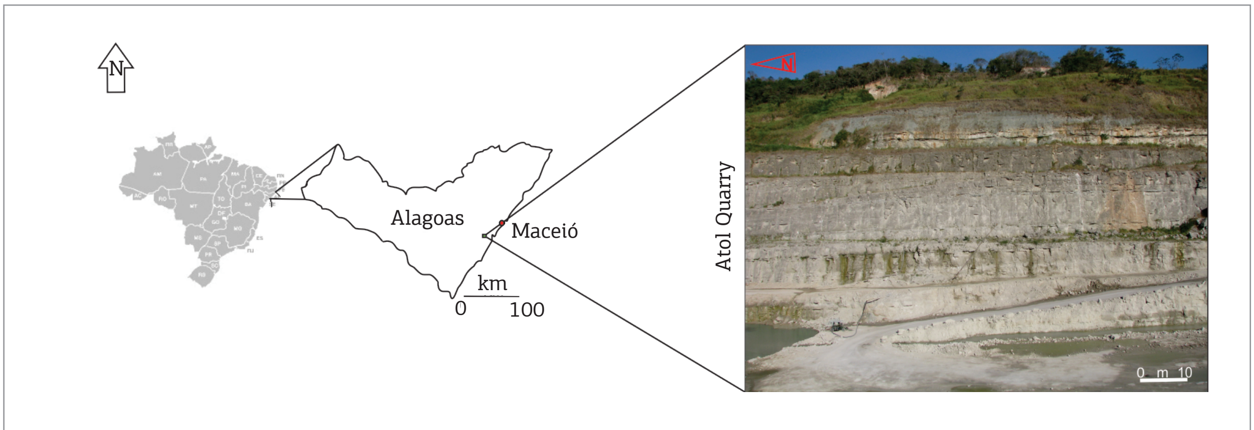

Figure 2. Localization map of the Atol Quarry in the Sergipe-Alagoas basin and panoramic view of the profile area at the studied outcrop.

levels. Abundant mudcrack horizons suggest frequent lake level fluctuations. During transgressions, large areas were flooded and a large lake formed. During dry periods, the lake would have a negative water balance and some parts of the lake became isolated from the main lake, favoring the deposition of shales rich in organic matter.

Still according to Azambuja *et al.* (1998), the shales were formed in relatively shallow lake waters, representing shallowing upwards cycles during the lowstand system tract of the lake, as indicated by the presence of desiccation cracks on top of some shales. High concentrations of ostracods and fish fragments within the shales would be due to the storm events that caused the mixture of oxic and anoxic waters, generating local mass extinction.

Teixeira (2012) argues whether the mudcracks observed in the Atol quarry are in fact desiccation cracks. According to this author, the shrinkage cracks in the Morro do Chaves Formation exhibit very unusual features in desiccation cracks. A single generation phase of the cracks is observed at the top of the shales, underlying the coquinas. These cracks are not continuously distributed over the bedding surface and they are associated to load casts. The infill seens to have been injected downward and upward, being deformed and sometimes broken. The inside laminations of the shales are deformed in contact of the "dykes" and the base of coquinas in contact with the shale is concave, indicating that the shale was hydrated in the time of cracks formation.

RESULTS

Six facies were defined according to the main attributes: taphonomic (fragmentation of shells) and compositional (presence of micrite and siliciclastic matrix) as shown in the summary table below (Tab. 1).

Facies characterization

Cf – Fragmented coquina with no micrite (Fig. 4)

Synonymy: R-cb (Muniz 2013), cAxb and cApp (Teixeira 2012).

Taphofacies (Muniz and Bosence 2011): TF-3b, TF-4 e TF-5.

Diagnosis: Coquina with more than 80% of fragmented shells, less than 10% of micrite and less than 10% of siliciclastics.

Description: Very coarse sand (average) to granule (max) size. Well to moderately sorted, with fragmented bioclasts between 80 and 100%. Sometimes, bioclasts are very fragmented, comprising fragments of silt size/clay. Non-fragmented shells may also occur, but always in a bioclastic sand matrix. There may be clay intraclasts and pyrite as an accessory and rare ostracods. In mesoscale (outcrop), it may have plane-parallel bedding/low angle cross stratification or massive aspect. The layers are metric in size and can occur amalgamated with thicknesses up to 6.7 m. The contact is usually erosive. It presents cream

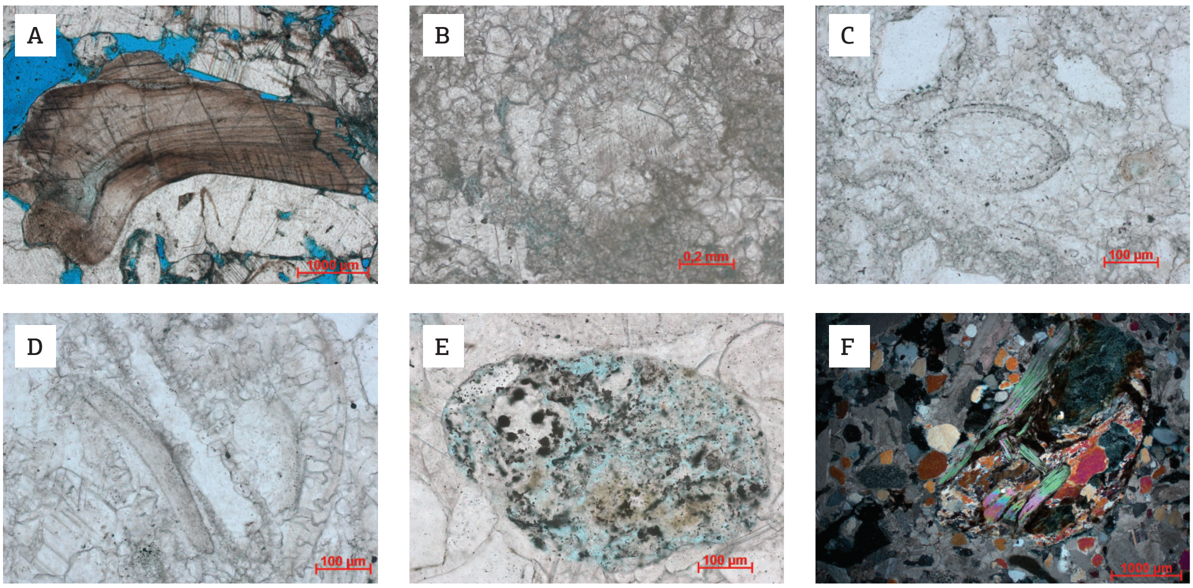

Figure 3. Thin-section photomicrographs of the main components of the coquinas from Morro do Chaves formation: (A) bivalve mollusc shells; (B) gastropods; (C) ostracods; (D) other bioclasts; (E) lithic fragments (igneous?) e (F) quartz e lithic fragments (metamorphic?).

colour, whitish gray. Apparent porosity is very variable, in a range of 5 to 10%. This facies corresponds to 45% of the described profile.

Cfi – Impure fragmented coquina with no micrite (Fig. 5)

Synonymy: Rc-b, Rt-b? (Muniz 2013) and cAxb, cApp, cRxt (Teixeira 2012).

Taphofacies (Muniz and Bosence 2011): TF-3b, TF-4 e TF-5.

Diagnosis: Coquina with more than 40% of fragmented shells, less than 10% of micrite and more than 10% of siliciclastics.

Description: Very coarse sand (average) to pebble (maximum). Moderately to poorly sorted. It is composed of highly fragmented bioclasts and coarse sand matrix (10 to 55%). The sand is poorly sorted, composed by mono- and poly-crystalline quartz, lithic fragments, sub-rounded to subangular. Sometimes, clay intraclasts occur composing pseudomatrix. Some of the intraclasts present disarticulated

Table 1. Facies summary for the Atol Quarry.

Designation	Diagnosis	Interpretation
Fragmented coquina with no micrite (Cf)	Coquina with more than 80% of fragmented shells, less than 10% of micrite and less than 10% of siliciclastics.	Coquina reworked by traction flows, in an intermediate subaquous lacustrine domain.
Impure fragmented coquina with no micrite (Cfi)	Coquina with more than 40% of fragmented shells, less than 10% of micrite and more than 10% of siliciclastics.	Coquina reworked by traction flows, in an intermediate subaquous lacustrine domain, with siliciclastic input.
Non- fragmented coquina with micrite (Cm)	Coquina with more than 20% of non-fragmented shells, more than 10% of micrite and less than 10% of siliciclastics.	Coquina in a deep subaquous lacustrine domain.
Impure non-fragmented coquina with micrite (Cmi)	Coquina with more than 20% of non-fragmented shells, more than 10% of micrite and more than 10% of siliciclastics.	Coquina in a deep subaquous lacustrine domain, with siliciclastic input.
Green shale (Fv)	Laminated green mudstone.	Mud and ostracode settling in a deep subaquous lacustrine domain under suboxic conditions
Black shale (Fp)	Laminated black mudstone/siltstone.	Mud and ostracode settling in a deep subaquous lacustrine domain under anoxic conditions

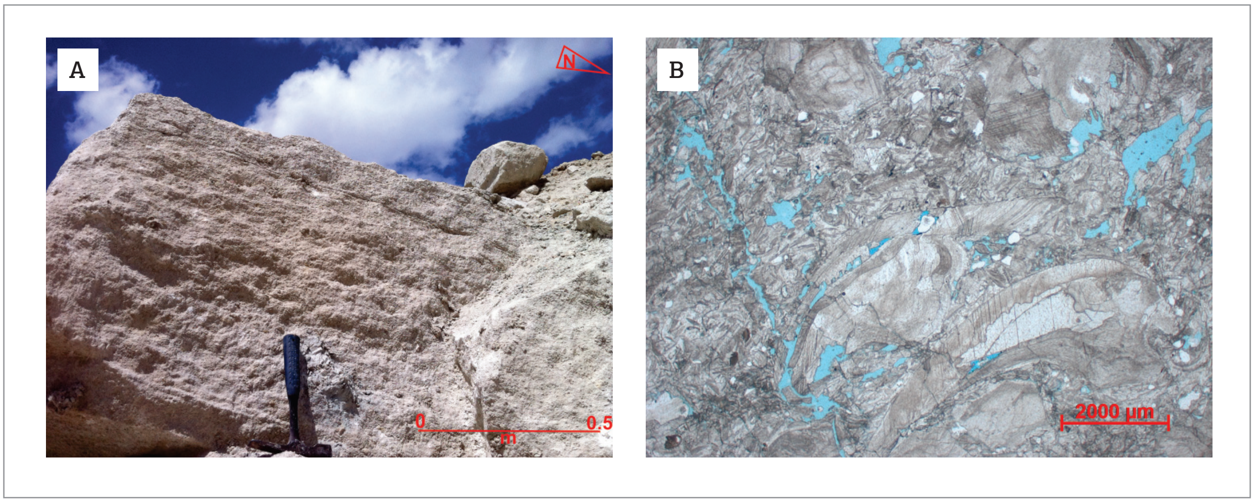

Figure 4. Photograph and photomicrograph with the main features of Facies Cf. (A) outcrop image showing the plan-parallel lamination (2.5 m of profile) and (B) photomicrography (sample at 4.5 m of profile, 1,25X, PL) that shows the highly fragmented shells with less tham 10% of micrite.

ostracod valves. Mesoscale, plane-parallel stratification/ low angle cross-stratification and undifferentiated cross stratification were also seen. Decimetric to metric layers are amalgamated, up to 3 m thick. Usually, the basal contact is planar. It presents brownish cream colour. Porosity varies widely, from 5 to 25%. Dead oil indications were observed in some samples.

This facies corresponds to 10% of the described profile.

Cm – Non-fragmented coquina with micrite (Fig. 6)

Synonymy: R-mb (Muniz 2013).

Taphofacies (Muniz and Bosence 2011): TF-2b, TF-3a.

Diagnosis: Coquina with more than 20% of non-fragmented shells, more than 10% of micrite and less than 10% of siliciclastics.

Description: Granule (average) to pebble (maximum) size. Moderately sorted. Dense packing, with consistent orientation parallel to bedding (shells oriented by physical compaction). It comprises non-fragmented bioclasts in major proportion (typically 80 to 100%) and micrite 10 to 30%, and occurs rarely as articulated shells. Usually, occurs as decimetric layers, which can amalgamate with thicknesses up to 2 m. It presents whitish cream color, whitish gray and greenish gray. Apparent porosity of 5 to 10%. This facies corresponds to 20% of the described profile.

Cmi – Impure non-fragmented coquina with micrite (Fig. 7)

Synonymy: Rt-b (Muniz2013), CRal ? (Teixeira 2012).

Taphofacies (Muniz and Bosence 2011): TF-2b, TF-3a.

Diagnosis: Coquina with more than 20% of non-fragmented shells, more than 10% of micrite and more than 10% of siliciclastic material.

Description: Granule (medium) to pebble (maximum). Poorly sorted. Dense packing. It is generally composed of 80 to 100% of non-fragmented bivalve shells. In the matrix (corresponding to 10 – 40%), are also observed rare gastropods and ostracods. Terrigenous composition presents the average size of fine sand, 10 to 35%, particularly quartz; moderate to well sorted, rounded to subangular. Rare rounded lithic fragments were also observed. Sometimes, they are observed thin layers of medium to coarse sand and fine sand. In some samples, the matrix is composed by marl that occurs rarely bioturbated. It presents yellowish cream to greenish gray color. Apparent porosity of 5% maximum. The facies Cmi corresponds to 20% of the described profile.

Fv – Green shale (Fig. 8)

Synonymy: Fv (Teixeira 2012).

Diagnosis: laminated green mudstone.

Description: Colour green mudstone, fissile, with some levels of ostracods and fish fragments.

Fp – Black shale (Fig. 8)

Synonym: Fp (Teixeira 2012).

Diagnosis: laminated black mudstone.

Description: Silty mudstone, black, físsil, with some levels of ostracods, fish fragments and pyrite. The Fv and Fp facies occur associated, corresponding to 5% of the described profile.

Diagenesis

The diagenesis of the coquinas from the Morro do Chaves Formation was widely discussed in Tavares (2014).

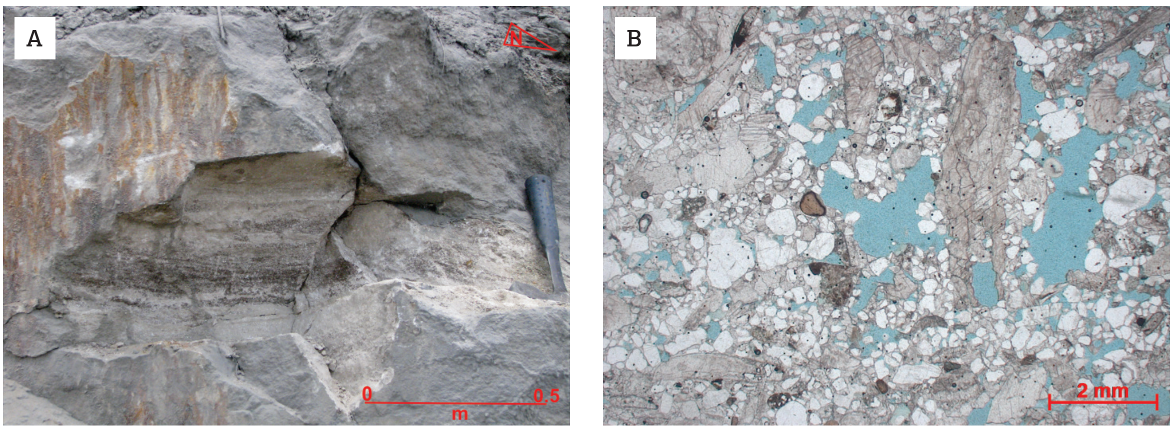

Figure 5. Photo and photomicrography of Facies Cfi. (A) outcrop image showing the plan-parallel lamination (37.5m of profile) and (B) photomicrography (sample at 28.5m of profile, 1,25X, PL) that shows highly fragmented shells, more than 10% of siliciclastic sand and lack of micrite, typical features of facies Cfi.

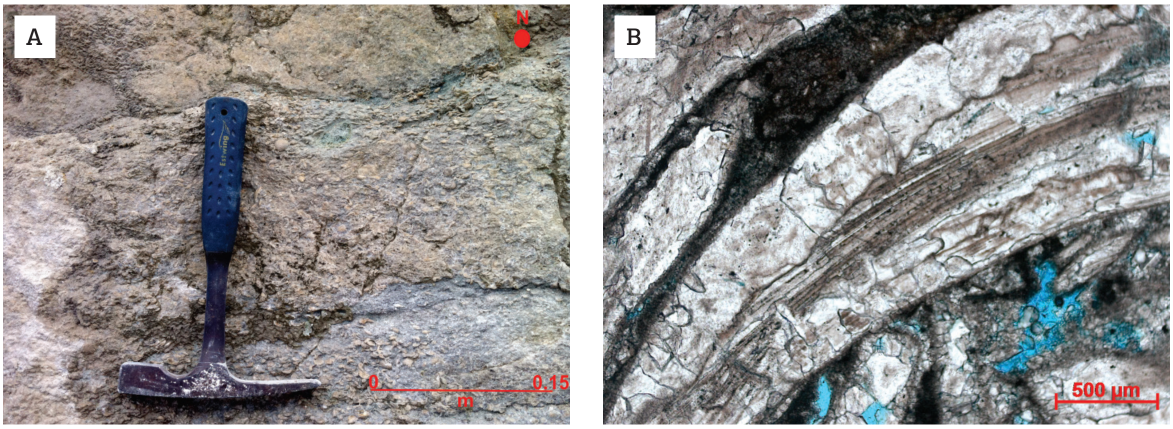

Figure 6. Photo and photomicrography showing the main features of Facies Cm. (A) outcrop image (6.0m of profile) and (B) photomicrography (sample at 1.7m of profile,5X, PL) that shows the whole shells and more than 10% of micrite.

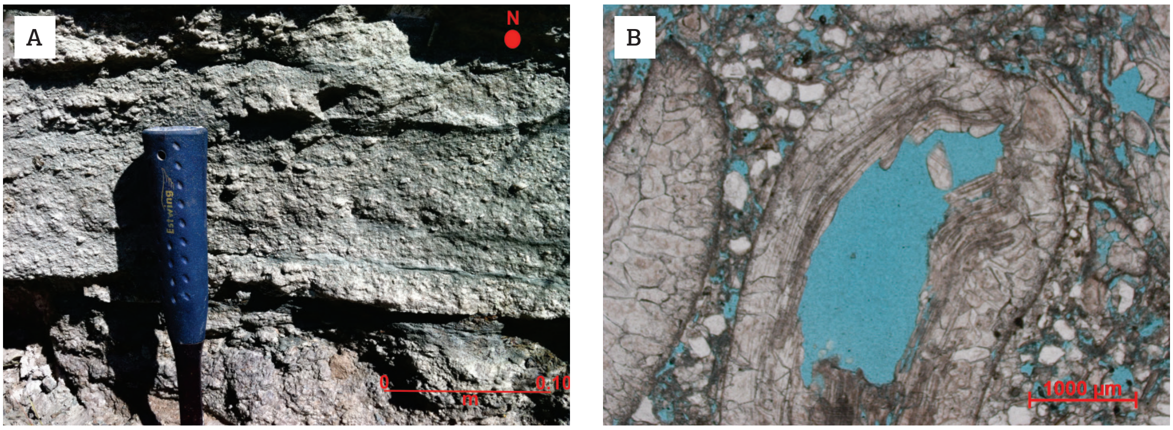

Figure 7. Photo and photomicrography with the main features of Facies Cmi. (A) outcrop image (19.0m of profile). It is possible to observe the argilaceous matrix. (B) photomicrography (sample at 42.5m of profile,5X, PL) that shows the whole shells, with siliciclastic sand and micrite, typical of facies Cmi.

Some of the diagenetic products are independent from the sedimentary facies; so, diagenesis was treated separately from the facies analysis performed in this paper. The coquinas of the Morro do Chaves Formation have a complex diagenetic history, with eight stages of cementation having been identified, with various stages of dissolution, micritization, neomorphism (shells and micrite), physical and chemical compaction (Fig. 9). Dolomite was not seen in the analized samples of the Atol quarry. The general diagenetic sequence is presented in Tab. 2.

Facies discussion

Facies Cf and Cfi represent deposits of allochtonous bivalve mollusc shells in an intermediate subaqueous lacustrine environment, above the fair weather wave base. They are

Figure 8. Facies Fv and Fp in outcrop photo (3.0m of profile). These facies occur associated.

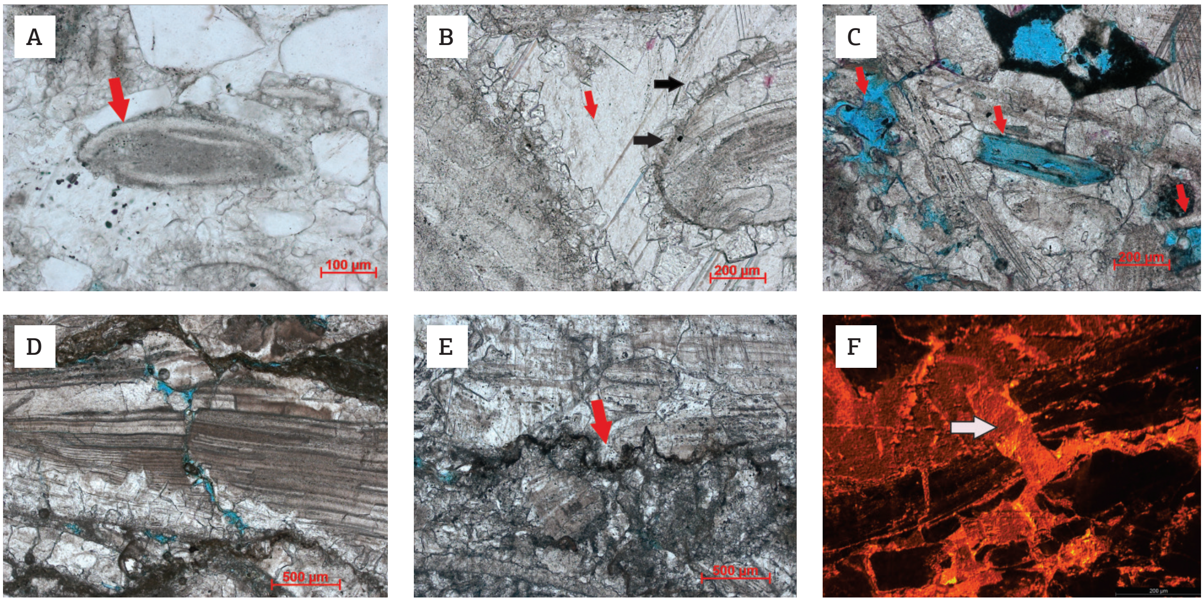

Figure 9. Photomicrographs showing the general diagenetic features of the Morro do Chaves Formation. (A) Micritized ostracod (red arrow). Micritization occurs early in the diagenetic history. (B) Three cementation phases can be observed: two phases of calcite fringe cement (black arrows), one phase of poikilotopic calcite cement filling the pore (red arrow). In Morro do Chaves Formation eight cementation phases were recognized. (C) Bioclasts dissolution (red arrow). Coquinas are afected by various dissolution events. (D) Neomorphised shell. The shell is also broken by physical compaction. (E) Microstilolite formed by chemical compaction (red arrow). (F) Catodoluminescence image showing the poikilotopic calcite cement covering the fractured grain (white arrow). Catodoluminescence was used to distinguish cement phases and to define the diagenetic sequence.

Table 2. Diagenetic sequence of Morro do Chaves Formation at Atol Quarry (Tavares, 2014).

Diagenetic processes	Eogenesis/ Surface		Mesogenesis/Burial			Telogenesis/ Surface
			Shallow	Intermed.	Deep	
Precipitation of micrite cement						
Precipitation of isopachous calcite fringe cement						
Micritization						
Dissolution						
Neomorphism (Shell and micrite)						
Precipitation of a second phase of isopachous calcite fringe cement						
Precipitation of poikilotopic calcite cement						
Precipitation of blocky calcite phreatic cement						
Precipitation of prismatic/bladded calcite fringe cement						
Physical compaction						
Chemical compaction						
Precipitation of late poikilotopic calcite cement						
Precipitation of intramoldic hialine calcite cement					?	

interpreted as coquina bar deposits in a subaqueous environment, as signs of subaerial exposure were not observed. The high fragmentation of shells and little micritic content indicates constant reworking, in a high to moderate energy environment, being exposed to this environment a sufficient time to be fragmented and reworked (taphocoenosis). At the mesoscale, these facies present sometimes plane-parallel bedding and low angle cross-stratification, indicating possible oscillatory flow regime (waves) of low to moderate energy (fair weather) to high energy (storm). It is possible to interpret a gradual increase in lake level, which in these facies represents the increase in the proportion of non-fragmented shells and the presence of ostracods, especially in layers preceding the shales. The siliciclastic content of facies Cfi indicates a constant supply of siliciclastic material during rainy seasons (higher humidity), with the establishment of a fluvial system, which reworks the bioclastic deposits. Between 0 to 25 m of the profile, this facies corresponds to an isolated interval (1.4 m), indicating an episodic precipitation. From 28 m to the top of the profile, facies Cfi occurs associated to facies Cmi, indicating the establishment of a fluvial-lacustrine system in a more humid climatic condition. Facies Cfi also presents undifferentiated cross-stratification related to unidirectional flows, interpreted as episodic higher energy river intake. In Teixeira's work (2012), facies Cf and Cfi represents the cAxb and cApp facies, interpreted by the author as beach deposits and shallow platform. Teixeira (2012) observed some levels with subaerial exposure evidences, so he interpreted as the swash zone. The facies identified by Teixeira (2012), in well cores, are located further south of the outcrop, suggesting a possible coastline further south, in shallower environment than the facies Cf and Cfi. In Muniz's (2013) work, the facies Cf corresponds to R-cb facies, interpreted in the context of lacustrine carbonate platform in a shallow water of moderate to high energy.

Facies Cm and Cmi represents deposits of parautochtonous bivalve mollusc shells deposited in a deep subaqueous lacustrine environment, between the fair weather wave base and the storm weather wave base. The shells occur non-fragmented and rarely articulated, in a typical lacustrine micritic matrix, which shows little transport and reworking, in a subaqueous regime of calm waters. In Muniz's work (2013), facies Cm corresponds to the facies Rm-b that is related to a facies association of lacustrine carbonate platform in deep subaqueous environment, above the storm weather wave base.

Facies Cmi presents siliclastic sand and mud, corresponding to episodic fluvial influxes, in the most distal portion of the lake (deep subaqueous). This interpretation is supported by the particle size, predominantly fine to medium sand and mud. From 0 to 25 m of the profile, facies Cmi occurs rarely, with thicknesses up to 40 cm formed during episodic floods. From 25 m to the top, facies Cmi often occurs, forming a series of layers up to 5.3 m thick. Facies Cmi corresponds to facies Rt-b from Muniz (2013), which is related to a lacustrine carbonate platform in the flexural margin of the rift. Muniz (2013) associates the layers to tempestites deposits. However, the facies described by this author is decimetric and it is intercalated with the carbonate facies of shallow platform. Facies Cmi is metric and constant, and occurs associated to Cfi facies, from 25 m to the top of the profile, indicating a constant climate change. Some samples present marl as matrix and it is also possible to observe bioturbation. Tucker and Wright (1990) discuss the possibility of bioturbation in the deeper portions of a lake during long period of oxic conditions. Prolonged periods of rain, with siliciclastic input, can promote circulation of the lake, providing oxygenation of the deeper portions. These bioturbated levels occur just below the storm wave base level, but right next to it. Teixeira (2012) recognizes similar facies, with marl matrix (cRal) and shear planes. The author interprets it as a subaqueous facies deposited under the debris flow process triggered by river floods or earthquakes.

Facies Fv was formed by settling mud in a low-energy environment, near to the center of the lake in suboxic conditions. It is associated to facies Fp that represents periods of anoxic conditions. Some of the shales have shrinkage cracks on the top. It is also possible to note bioturbation in some shales.

Facies successions and cyclicity

The facies Cf and Cm occur together and are related to high-frequency cycles interpreted as variation in the lake level, in metric scale (from 2 to 10 m), shallowing upwards. The gradual increase in the lake level in Cf facies is represented by the increase in the proportion of non-fragmented shells and by the presence of ostracods, especially in layers preceding the shales. Thus, shales are interpreted here as subaqueous and related to highstand lake level and not as lowstand lake level, as suggested by Azambuja *et al.* (1998). Shales correspond to the base of the cycles and the observed cracks should therefore not be dissication, as discussed by Teixeira (2012).

Cfi and Cmi facies occur together and also represent high frequency cycles, shallowing upwards, of 5 to 10 m width in average. It is also observed a thickening upwards, in a cycle of a greater magnitude (50 m), observed in the outcrop scale, on the establishment of greater accommodation space or increase in sediment supply. Since there is no biostratigraphic data and there are many complicating aspects to propose a hierarchy of cycles for tectonically active rift basins, this paper used a direct analogy to the hierarchy of cycles proposed by Muniz (2013) for Coqueiros Formation in the Campos basin. From the base to 25 m of the profile, cycles of 2 m are observed (Fig. 10A), which would be related to coastal lake dynamics associated to the carbonate productivity, analogous to the hierarchy 4 cycles of Muniz (2013). From 25 m to the top, where the siliciclastic influence increases (Fig.10B), these smaller cycles only occur from 25 to 28 m. Greater magnitude cycles (5 to 10 m) throughout the profile, related to the lake level variations due to local climatic factors, are observed. These cycles correspond to the hierarchy 3 cycles of Muniz (2013). It is observed also in the scale of outcrop (Fig. 10C) a thickening upwards, with the creation of greater accommodation space or increase in sand supply. From 25 m (to the top), there is a change in the composition of rocks, with higher amount of siliciclastic material, usually with moderate textural maturity, which can be interpreted as the establishment of a fluvial-lacustrine system, in a more humid climate or may be related to a tectonic pulse. It is not possible to establish the thickness of this cycle, since it may exceed the outcrop, but it is minimally in the outcrop scale, about 70 m. It can correspond to a hierarchy 2 cycle of Muniz (2013), related to global climate change or the hierarchy 1 cycle, related to tectonic events. With the drilling of more wells and the acquisition of more data, these cycles may be better established and interpreted.

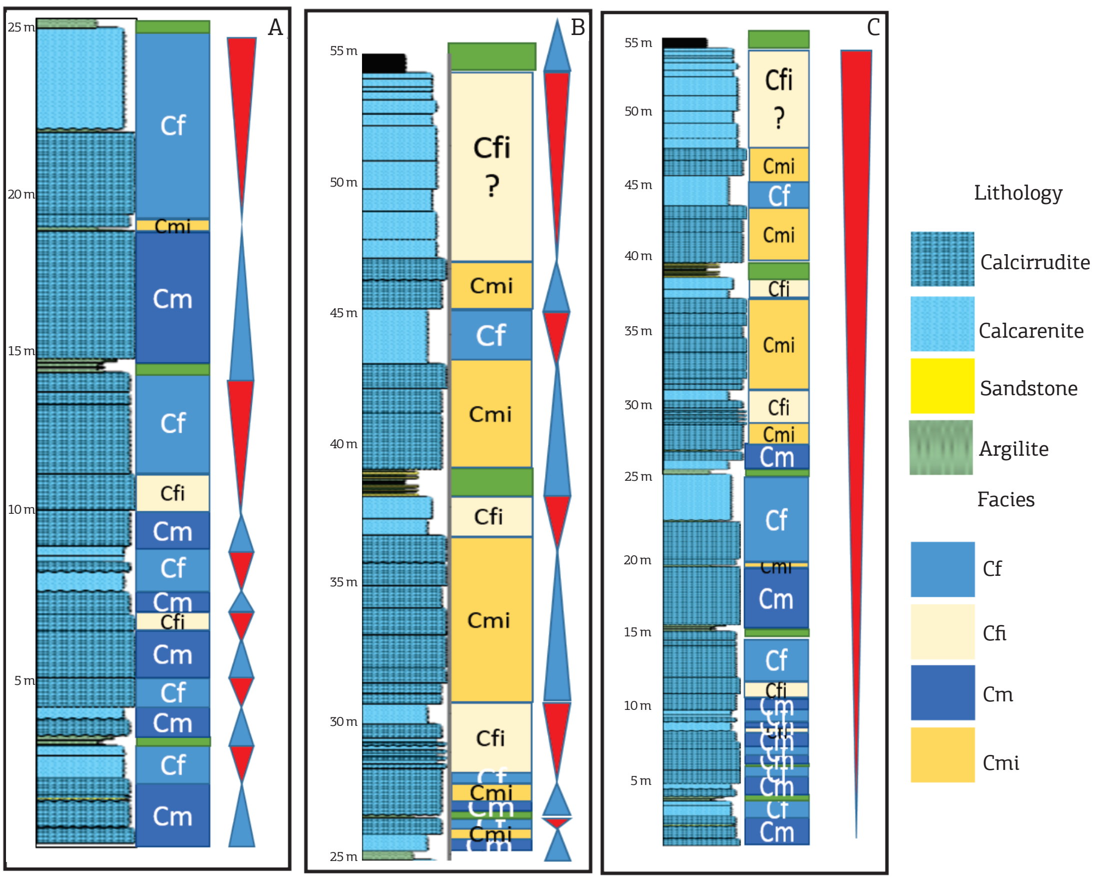

Figura 10. (A) Cycles recognized according to Muniz`s (2013) cycles hierarchy scheme in the interval 0 to 25 m. Cycles of hierarchy 4 in the base of profile are related to coast dynamics and carbonate produtivity. It is also possible to recognize cycles of hierarchy 3, related to local lake level flutuations. (B) Cycles recognized according to Muniz`s (2013) cycles hierarchy scheme in the interval 25 to 55 m. The cycles of hierarchy 4 remains until 28m. The siliciclastic input increase and cyles of hierarchy 3 are predominant. These cycles are related to local lake level flutuations. (C) Outcrop profile. It is observed a thickening upwards. It is not possible to define the magnitude of this cycle. It could be 1- related to tectonic event or 2- related to global climate changes according to Muniz (2013) scheme.

Facies model

In the interpretation of Muniz (2013) for Coqueiros Formation, similar facies to the facies described here correspond to a facies association of a lacustrine carbonate platform, related to the flexural margin of the rift, which coincides with the model proposed by Teixeira (2012) to Morro do Chaves Formation. Using as background the facies model of Muniz (2013), the distribution of shell deposits of Kidwell *et al.* (1986), and the analysis done in this paper, Fig. 11 illustrates how the facies are distributed along the carbonate platform in two stages: base to 25 m and 25 m to the top of the profile. In the model proposed by Muniz (2013), it was interpreted a protected inner platform, behind a shoal zone. In this work, for the Morro do Chaves Formation. Therefore it was not characterized a protected area, such as a lagoon, landward of the lacustrine margin. Resulting in the interpretation of a platform without a significant break, ramp type, or with a distal break.

Paleoenviromental interpretation

The environments and facies of the coastal region of a lake vary especially with the platform slope and the energy level on the coast. Lakes with moderately steep margins along their shorelines can develop carbonate benches, while the gentle slope margins form ramps (Renault and Gierlowski-Kordesh 2010). The energy of the coastal environment also distinguishes a diverse association of facies. Siliciclastic sediments, interpreted here as being of fluvial origin, reach coastal and deeper facies. In the facies Cfi (shallower) the particle size of siliciclastic material is fine to coarse sand, and in the facies Cmi (deeper) it is fine to medium sand. It was not found any typical facies of an inner platform. Based solely on the facies association, in this paper, the lake shore is interpreted as a ramp with a gentle slope and or a distally-steepened slope. However, Figueiredo (1981) based on seismic interpretation, noted some sublacustrine canyons along the edges of the stable Morro do Chaves platform and recognized at least one large sublacustrine lobe. The author interprets that these canyons were formed by instabilities in the slope (and therefore a platform with significant break), reworked by lake currents. It is noteworthy that the facies association below (Tab. 3) is suggested according to the model proposed by Renault and Gierlowski-Kordesh (2010), since the data available at the present time are not sufficient to define a more accurate three-dimensional depositional model and to set the correct distinction between ramp and a moderately to high steep margin. Therefore, we will use the generic term "platform." This term was also used, by way of comparison, in the model proposed by Muniz (2013) for the coquinas from Coqueiros Formation in the Campos basin.

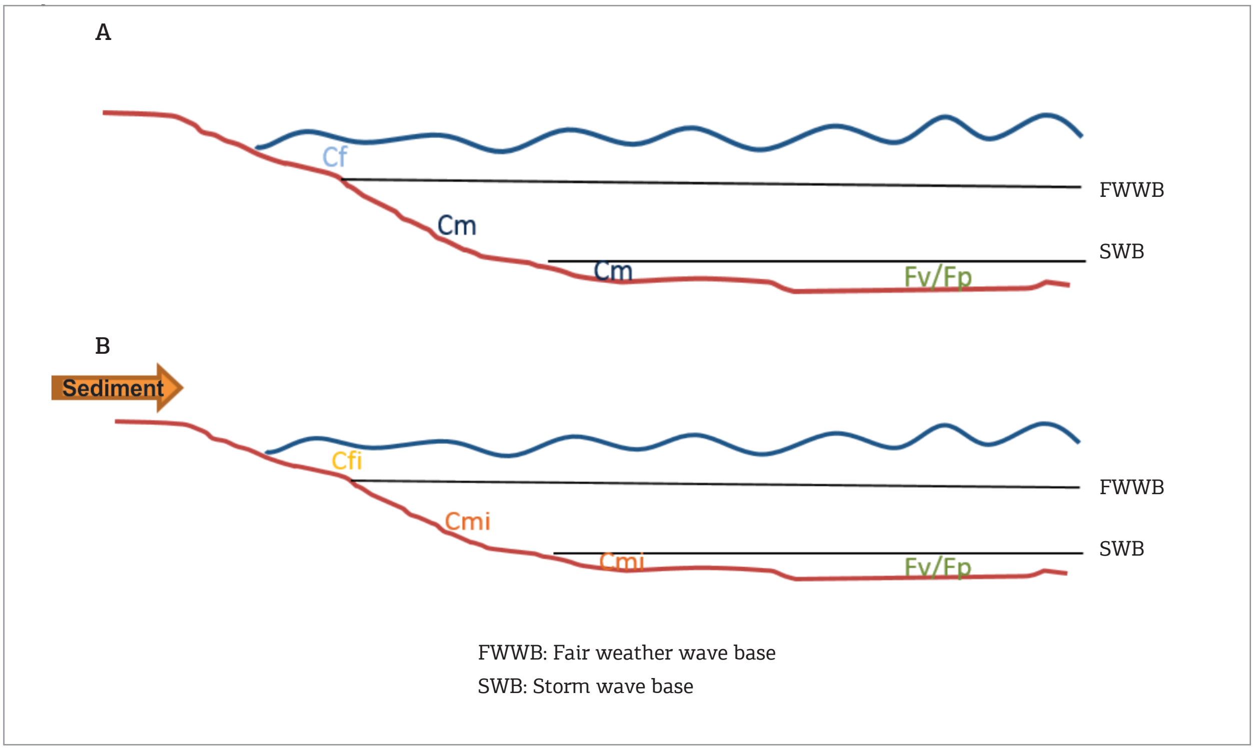

Figure 11. Facies model proposed for the analized sucession of Morro do Chaves Formation. (A) Facies distribution from 0m to 25 m of the profile. It corresponds to the carbonate platform. (B) Facies distribution after 25 m, with the increase of siliciclastic input, interpreted in this papes as lake delta in a carbonate platform. Facies Cm and Cmi occur generally above storm wave base, but sometimes, they can also occur below SWB, with bioturbation when the lake presents more oxic conditions.

Table 3. Facies sucession and paleoenviroment interpretation in the Atol Quarry.

Facies	Interpretation (Based on facies model from Renault and Gierlowski-Kordesh 2010)
Cf e Cm	High energy carbonate platform
Cfi e Cmi	Lake delta in a high energy carbonate platform
Fv e Fp	Lake centre

High energy carbonate lake platform

The facies Cf deposits are located above fair weather wave base level, in the coastal area of the lake, being under the action of waves and currents induced by winds and storms, forming cross stratification, especially low angle and plane-parallel stratification. The grains are composed of bivalve shells and rare ostracods, usually fragmented by constant reworking. The facies Cm is located between the fair weather wave base and storm wave base, on the lake sub-littoral zone, representing for the most part, a low energy environment with massive deposits (at the studied scale), micritic, with non-fragmented shells (mostly) and some fragmented shells. Changes in the lake level can also produce palustrian facies, which were not observed in this work. The facies Cf and Cm are subaqueous. This facies association occurs mainly from 0 to 25 m of the profile, representing a high-energy carbonate platform in a lacustrine environment.

Lake delta in high energy carbonate platform

Facies Cfi and Cmi are also positioned relative to the fair weather and storm wave base levels, like facies Cf and Cm. However, the siliciclastic content exceeds 10% of the rock volume. From 0 to 25 m, these facies occur episodically, in centimetric to decimetric layers, and may be associated with occasional floods. From 25 m to the top of the profile, the facies are continuous. Two hypotheses are possible: occurrence of tectonic pulses and/or establishment of a fluvial deltaic system in a condition of greater regional humidity. Only regional stratigraphic studies, the analysis of the geometry of the deposits and provenance studies can correctly define this paleoenvironment and deposition conditions. In this work, based on petrography and on the regional context, we consider the lacustrine delta model established in a regional climate change scenario. Siliciclastic sediments have moderate maturity textural and compositionaly. Even though the source of these sediments are rift and pre-rift deposits that correspond to a fluvial-lacustrine system that generally exhibit moderate textural maturity, angular fragments were not observed, the lithic fragments were less than 5% and the greater lithic fragments (pebble) were very rounded. There was no evidence of breccia either.

Lake centre

This environment is characterized by mudstones, corresponding to the facies Fv and Fp. The lake central area is directly influenced by coastal processes, fans and deltas, and it is characterized by sediments carried in suspension deposited below the storm wave base level. These sediments come from various sources, some are allochtonous and others are essentially autochtonous. Mudstones could be silt and clay in size, siliciclastic or carbonate, and could be derived from the river inflow and coastal erosion, which are transported to the center of the lake by currents (Renault and Gierlowski-Kordesh 2010). The presence of fish fragments and ostracods in Fv and Fp facies suggest a condition of brackish waters, with some freshwater inflow. Alternating moments occur between suboxic (Fv) and anoxic (Fp) conditions. Calcilutites also occurs, which in this environment could have many sources. It can be detritic, or, more commonly, derived from the bioinduced precipitation of calcite or aragonite directly from the lake water. However, the calcilutite are not always preserved. The preservation depends on the lake anoxia level (determined by the stratification of lake), the bottom lake temperature and the amount of organic matter available for degradation and, consequently, production of CO_2 (Renault and Gierlowski-Kordesh 2010). These muddy sediments are generally laminated and cyclic, which record a seasonal sedimentation, such as floods or anoxic conditions due to lake level variations.

CONCLUSIONS

To understand the dynamics of the formation of the coquinas deposits, it is essential to use sedimentological, taphonomic and biological criteria. Six lithofacies were recognized in the Morro do Chaves Formation in the study area, using as a diagnosis the fragmentation of shells (taphonomic criteria) and the presence of micrite and siliciclastic sand (compositional criteria). A facies succession was established, and it was suggested a paleoenvironmental interpretation, recognizing three environments: high energy carbonate lake platform, lake delta in a high energy carbonate platform and lake centre. It was also suggested a facies model for the coquinas from Morro do Chaves Formation. With the available data, it is not possible to distinguish the type of carbonate platform. Based solely on facies analysis, it is suggested that the studied area is a carbonate ramp with gentle to moderate slope. It was decided to use the generic term "platform" until more detailed regional studies can correctly define the type of platform.

There is a gradual transition from Morro do Chaves to Coqueiro Seco Formation with a progressive increase in terrigenous input in the basin, with the establishment of a fluvial-deltaic system, as described by Azambuja *et al.* (1998) and Figueiredo (1981). The shales that occur amongst the coquinas deposit cannot be yet clearly understood, and suplementary studies are required. The gradual increase in the lake's level in facies Cf is represented by the increase in the proportion of non-fragmented shells and the presence of ostracods, especially before the shales. Thus, the shales in this study were interpreted as subaquous and related to highstand lake level and not to lowstand lake level, as suggested by Azambuja *et al.* (1998). The shales correspond to the base of the cycles and the observed shrinkage cracks could not be desiccation cracks related to exposure, as questioned previously by Teixeira (2012).

The use of taphonomic and compositional criteria proved to be a suitable tool to evaluate the coquinas deposits and define facies models and paleoenvironmental interpretations.

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