

# Tafonomy of macroinvertebrates and Albian marine ingression as recorded by the Romualdo Formation (Cretaceous, Araripe Basin, Brazil)

Ludmila Alves Cadeira do Prado<sup>1\*</sup> ,  
Gelson Luís Fambrini<sup>1</sup>, Alcina Magnólia Franca Barreto<sup>1</sup>

**ABSTRACT:** *The Romualdo Formation, Araripe Basin, crops out in the municipality of Exu, Pernambuco State, exposing coquinas. Fauna survey, taphonomic analysis of the macrobenthos, and identification of sedimentary facies of the outcrop were carried out to contribute to paleoenvironmental understanding of the Romualdo Formation. The association of molluscs (*Cerithium* sp., *Tylostoma ranchariensis*, *Aguileria dissita*, *Brachidontes araripensis* and unidentified cassiopids) and echinoids of the species *Bothryopneustes araripensis* suggests sedimentation in the marine environment. The taphonomic similarities made possible the grouping of coquinas into two types. Coquinas type 1 exhibit characteristics of transport and reworking of bioclast generated by storms in proximal setting. Coquinas type 2 demonstrates echinoids in situ and articulated with spines connected to shells, suggesting a fast sedimentation by distal tempestite. Regarding sedimentary facies, the concentrations of invertebrates would have been formed in the transitional offshore zone of siliclastic platform. The results presented here evidence a broader distribution of echinoids and expand the geographic limits of the shallow marine environment in the Romualdo Formation.*

**KEYWORDS:** *echinoids; mollusks; tempestites; obrution deposits; South America.*

## INTRODUCTION

Taphonomic analysis based on concentrations formed by molluscs and echinoids has frequently been used to aid in the interpretation of paleoenvironment and fossilization processes (García and Aguirre 2004, Olóriz *et al.* 2008). This fact is due to the predominance of molluscs in most fossil associations (Staff and Powell 1988), and echinoids, given the structure of their multi-articulated skeleton, are considered good indicators of biostratigraphic processes (Nebelsick 1999b).

Toward the top of the Romualdo Formation, there are different limestone and calciferous sandstones strata, mostly forming coquinas, which occur widespread in the Araripe Basin and can reach one meter in thickness (Sales 2005, Assine *et al.*, 2014). These shell-rich rocks are formed by marine molluscs and echinoderms, clearly suggesting a marine

ingression in the basin (Beurlen 1966, 1971, Assine 1992, 2007, Sales 2005, Assine *et al.* 2014).

Coquinas in the Romualdo Formation were taphonomically identified as being a result of storm wave's action in shallow marine environment (Sales 2005). However, most of the studied coquinas were from the state of Ceará, and are exclusively formed by molluscs (Sales 2005, Prado *et al.* 2014, Batista *et al.* 2015). Echinoid-bearing coquinas had only been found in the west border of the basin, Araripina county, Pernambuco State, Brazil (Beurlen 1966, Prado *et al.* 2015, 2016) (Fig. 1). Taphonomic studies classified them as proximal tempestite and obrution deposits (*sensu* Brett 1995) formed in the marine environment (Sales 2005, Prado *et al.* 2015, 2016). On the other hand, sedimentological studies interpreted coquinas as residual lags originated above ravine surface and analyzed as a stratigraphic framework (Assine 2007).

<sup>1</sup>Department of Geology, Center of Technology and Geosciences, Universidade Federal de Pernambuco – Recife (PE), Brazil. E-mails: prado.lac@gmail.com, g\_fambrini@yahoo.com, alcinabarreto@gmail.com

\*Corresponding author.

Manuscript ID: 20180048. Received on: 04/24/2018. Approved on: 06/29/2018.

The new outcrop on the Cedro site, Exu county, Pernambuco State, has the most complete record of echinoids in the Araripe Basin so far, considering its abundance of fossil at various intervals in the sedimentary succession and distinct stages of disarticulation preserved. Taphonomic analyses, faunal survey and sedimentary facies analysis were performed to contribute to the interpretation of the Albian transgression in the Araripe sedimentary Basin.

### The Araripe Sedimentary Basin and the Romualdo Formation

The Araripe Basin is in northeastern Brazil, covering the boundary zones between the states of Pernambuco, Piauí, and Ceará (38°30' to 40°55'W — 7°07' to 7°49'S). It is an inverted intracontinental graben originated during the Mesozoic over a Paleozoic intracratonic synclises, and records pre-rift, rift and post-rift (I and II) strata formed mainly by fluvial and lacustrine strata (Assine 2007, Marques *et al.* 2014) (Figs. 1 and 2).

According to Maisey (1991), the Romualdo Formation (post-rift I strata) is known worldwide for being considered a deposit with a high concentration of well-preserved fossils (*Lagerstätten* sensu Seilacher 1970). The faunal composition in the Romualdo Formation (Albian) is typical of a transitional marine environment, by presenting organisms that tolerate different levels of salinity, such as fish, invertebrates (crustaceans, molluscs and echinoids), dinoflagellates and foraminifera (Mabessone & Tinoco 1973, Lima 1978, Arai & Coimbra 1990, Berthou *et al.* 1990, Bruno & Hessel 2006, Arai 2014).

According to Custódio *et al.* (2017), the Romualdo Formation comprises transgressive and highstand system

tracts. The coastal alluvial and tide-dominated facies represents the transgressive systems tract, the marine black shales corresponding to the maximum flooding zone, and the shell beds record brief transgressive events during stillstand phases.

It should be noted that the maximum flood surface has already been reported by Assine (2007) for the coquina level.

The Romualdo Formation crops out in the municipality of Exu (Pernambuco State, Brazil) showing strata of shales with limestone concretions followed by bioclastic-rich limestones which contain the macroinvertebrates.

## MATERIALS AND METHODS

Sedimentary and taphonomic data of the Romualdo Formation were acquired from a 5,5 m thick section outcropping at the Cedro site, Exu county (UTM N 0434996, E 9172325), located about 100 km from Araripina, Pernambuco State (Fig. 1). The levels of rocks that contained the macroinvertebrates had their base and top marked.

About 34 samples were collected and deposited in the Palaeontology Collection of the Geology Department (DGEO), Center of Technology and Geosciences (CTG), at Federal University of Pernambuco (UFPE), Pernambuco, Brazil. In the laboratory, a mean of 120 bioclasts ( $\geq 2$  mm) was analyzed in each skeletal accumulation, as proposed by Kidwell *et al.* (2001), to obtain reliable taphonomic results.

The analysis of the biostratigraphic and sedimentological features was performed according to Kidwell *et al.* (1986), Kidwell and Bosence (1991), Kidwell and Holland (1991), including the degree of bioclastic packaging, sorting in 4 size classes (mm): I (2.0–3.9), II (4.0–7.9), III

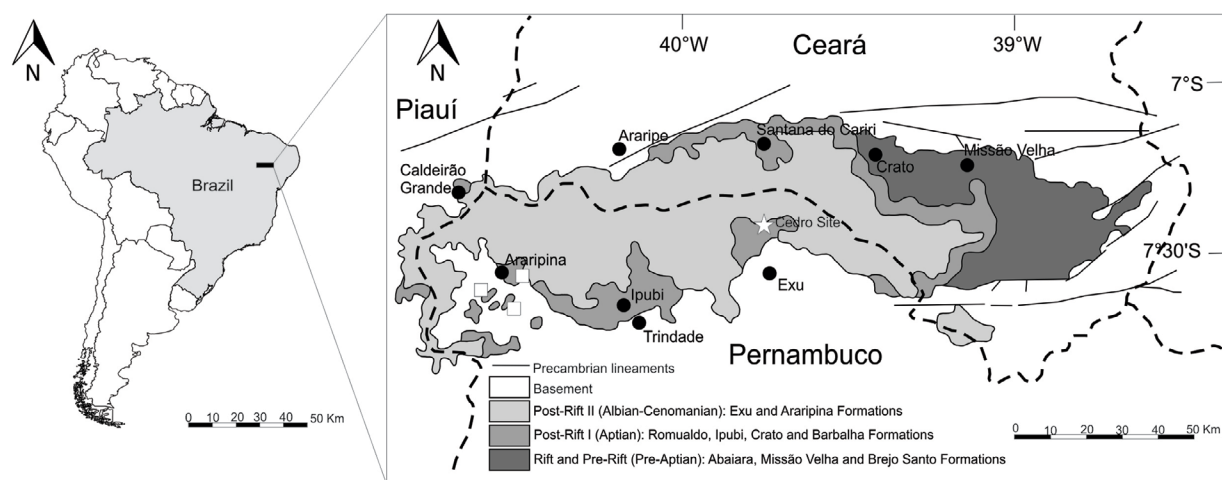


Figure 1. Location of echinoids-bearing coquinas in the Araripe Basin, northeast Brazil. The squares represent echinoid occurrences reported in previous studies, and the star shows the new occurrence on the Cedro site in Exu, Pernambuco State.

(8.0–15.9) and IV (16.0–31.9), orientation, fragmentation, corrosion, incrustation, articulation degree of shells, and sedimentary structures.

Regarding paleoecological features, life habits, composition (whenever possible, specimens were identified taxonomically to species or genus level) and relative abundance of the taxa were observed, considering as few abundant, abundant and very abundant those that represented < 20%, ≥ 20 and ≤ 80%, and > 80% of the fossil associations, respectively. Regarding the stratigraphic features, the thickness and stratigraphic contacts of the strata were analyzed. The genetic classification of the concentrations was performed according to Fürsich and Oschmann (1993).

## RESULTS

### Sedimentary facies

Six sedimentary facies were identified:

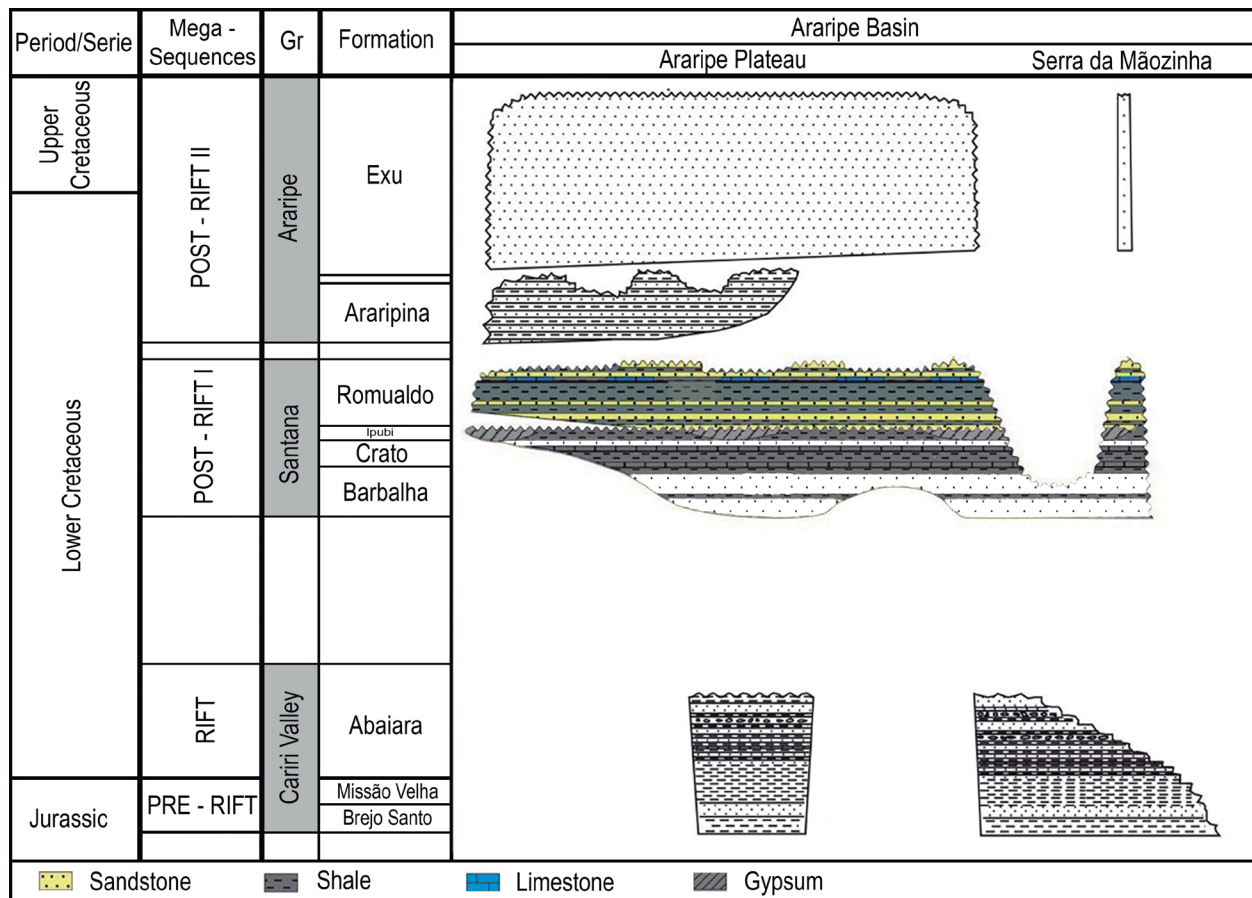
- (Cq) Coquinas;
- (Fl) Laminated shale;
- (Fml) Laminated mudstones;

- (Sm) Massive sandstones;
- (Sh) Laminated sandstones;
- (Sp) Tabular cross-stratification sandstones (Tab. 1).

At the Cedro site, the Romualdo Formation shows a succession of fossil-bearing shales (mainly fish remains and plant fossils in calcareous nodules — facies F1) interfingered by sandstone strata with planar and climbing ripple laminations (facies Sh and Sp), and thin layers of coquinas (Cq), labeled Layers of Cedro-LCE. Fifteen layers of calciferous sandstone (LCE1-LCE15) were observed. These layers are limited at the base by abrupt contacts, sometimes with incipient wavy truncated laminations (LCE1, LCE4, LCE5), intercalated with layers of laminated mudstones (Fml) or shales (Fl), apparently non-fossiliferous in LCE1-LCE5 and LCE6-LCE14 (Fig. 3).

### Survey of Macrobenthos

Macroinvertebrates form fossiliferous concentrations in all layers, except in LCE11, which has a single unidentified closed articulated bivalve. Since samples with less than 20 specimens are not reliable to determine taphonomic



Source: modified from Assine, 2007.

Figure 2. Stratigraphic chart of the Araripe Basin with emphasis on the Romualdo Formation, Post-rift I Megasequence.

signatures in single taxa assemblages (Kidwell *et al.* 2001), LCE11 has not been considered for analysis.

The shell-beds are polytypic and polyspecific, with variations in the relative abundance of taxa and in the size classes of the individuals between the layers. The fauna includes the gastropods *Tylostoma ranchariensis* (Pereira *et al.* 2015), *Cerithium* sp., unidentified cassiopids, bivalves *Aguileria dissita* (White 1887) and *Brachidontes araripensis* (Pereira *et al.* 2015) (Fig. 4), and irregular echinoids (i.e., *Bothryopneustes araripensis* Manso & Hessel 2007) (Fig. 5).

*Brachidontes araripensis* is abundant in all layers and only becomes less abundant in LCE4 and LCE5, in which echinoids are very abundant. Echinoids occur in all layers, except in LCE1 and LCE6, in which the species *Tylostoma ranchariensis* and *Brachidontes araripensis* are abundant. *Cerithium* sp. occurs where echinoids are predominant and are less abundant in LCE4 and LCE5, but abundant in LCE15. Cassiopids are less abundant, and *Aguileria dissita* ranges from less abundant to abundant along the layers (Fig. 3).

### Taphonomic data

The shell-beds show high levels of fragmentation and or disarticulation, except the gastropods present in LCE1, LCE2,

LCE7 and LCE8 (Fig. 3). The coquinas have low abrasion and no sign of bioerosion or corrosion. Bioclast orientation is concordant and polymodal regarding bedding plans, with concavities facing both upwards and downwards. Chaotic distribution, as displayed by vertical sections, is less frequent.

The coquinas quantitatively differ each to another concerning the taphonomic attributes (Fig. 3). However, similarities make possible to group them into two types (Tab. 2):

- Type 1, which has loose to dense packing, well-sorted, and nesting of bivalves (LCE2, LCE3, LCE6, LCE7, LCE8, LCE9, LCE10, LCE11, LCE12, LCE13, LCE14 and LCE15);
- Type 2, which present loose to disperse packing, poorly-sorted, and presence of articulated echinoids (LCE1, LCE4 and LCE5) (Figs. 3, 5 and 6).

### Disarticulation stages of echinoids

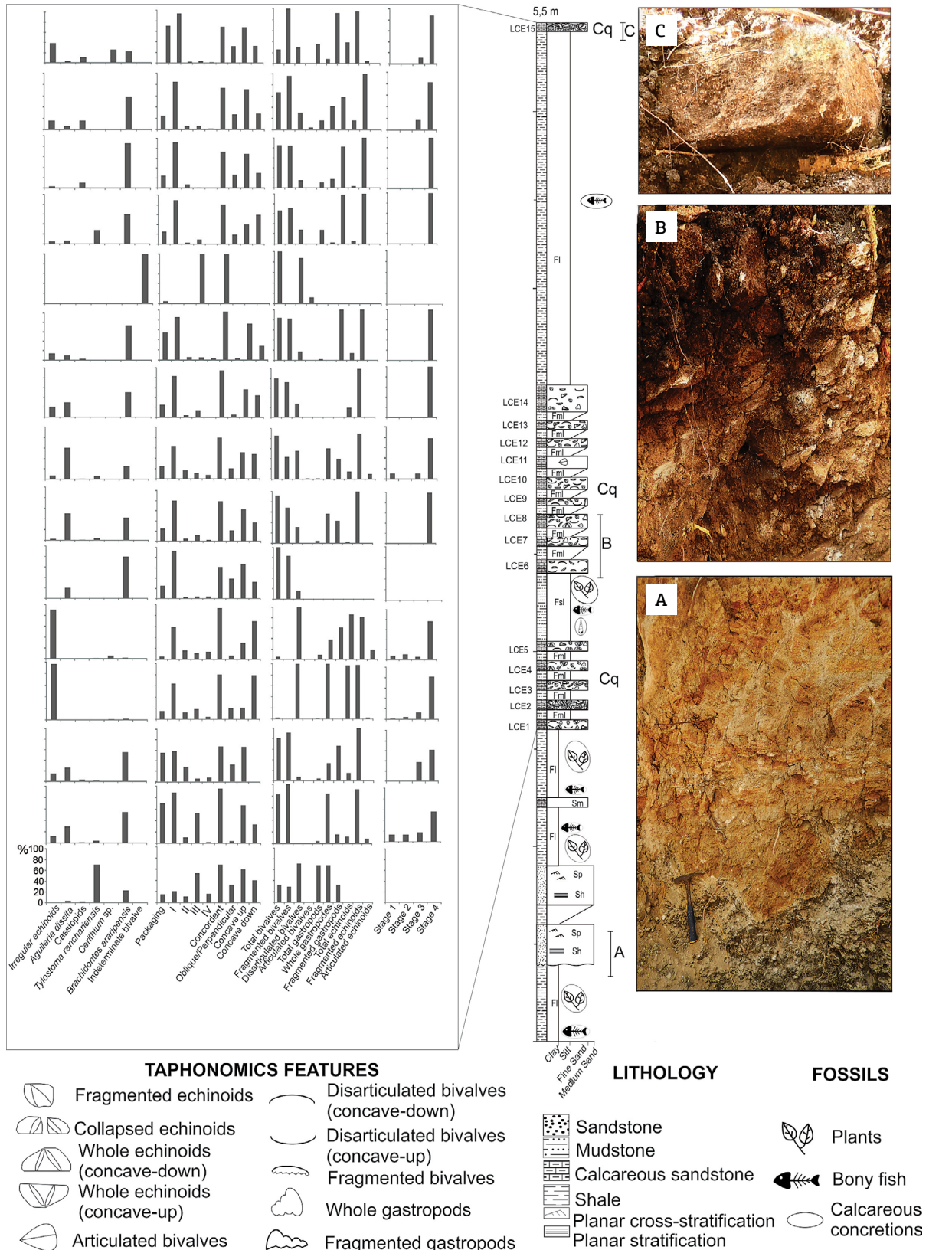
The echinoid shells have four disarticulation stages:

1. Fully articulated;
2. Collapsed and cracked radially;
3. Fragmented with many articulated plates; and
4. Fragmented into small parts (Fig. 5).

There is a predominance of fragmented individuals in the layers where echinoids occur (stages 3 and or 4). Stages 1 and 2 occur mainly in type 2 coquina (Fig. 3), sometimes

Table 1. Sedimentary facies of the Romualdo Formation in the study area.

Facies Code	Facies	Description	Interpretation
Cq	Coquinas	Yellow, fine calcareous sandstones with remains of shells, mostly fragmented, sometimes with incipient truncated wavy laminations.	Accumulation in high-energy events. Storm beds (tempestites) in a shallow environment.
Fl	Laminated Shale	Light gray to whitish gray shales, laminated, layered with lateral continuity and centimetric thickness, with horizontal lamination and expressive scattered fossil content. There is often the occurrence of centimetric to decimetric discoidal calcareous concretions in the fossils, rich in remains of plants and fish.	Decanting of clays in calm waters. The light coloring suggests oxidizing conditions at the depositional site. Fall-out deposits.
Fml	Laminated mudstones	Laminated mudstones laterally persistent in succession with up to 1 m thick. Features light gray to whitish color and light tints (cream, yellow) when altered. It is common the presence of carbonate nodules and discoidal calcareous concretions associated or not to the presence of fossil. Remains of fish (scales, teeth, and bones), coprolites, mollusks and rare plant fragments are common.	Deposition by decantation in calm waters, disoxic or anoxic conditions. Fall-out deposits.
Sm	Massive sandstones	Tabular centimetric layers, or lenticular, of very fine to fine calcareous sandstones, well sorted.	Bottom currents associated with storm waves.
Sh	Laminated Sandstones	Very fine sandstones, well sorted, light gray to whitish gray color, with horizontal lamination, arranged in centimetric to decimetric tabular layers.	Deposition by bottom currents in plane beds under conditions of upper flow regime.
Sp	Planar cross-stratification sandstones	Fine sandstones with small and low angle planar cross-stratification, arranged in decimetric tabular layers. Color is light gray to whitish.	Migrating forms of sub-aqueous beds of sinuous crest due to continued action of unidirectional currents.



Cq: coquina; Fl: laminated shale; Fml: laminated mudstone; Sm: massive sandstones; Sh: laminated sandstones; Sp: tabular cross-stratification sandstones; LCE1-LCE15: layers with macroinvertebrates.

**Figure 3.** Stratigraphic column of the Romualdo Formation in the study area. Abundance of taxa, biostratinomic and sedimentological features analyzed in the layers LCE1-LCE15 (n = 120). Size classes of bioclasts (mm): I (2.0-3.9), II (4.0-7.9), III (8.0-15.9) and IV (16.0-1.9). Disarticulation stages of echinoid shells: 1) fully articulated, 2) radially cracked, 3) large fragments, 4) small fragments. (A) Facies Fl, Sh and Sp. (B) Facies Fml and layers LCE6-LCE8. (C) Layer LCE15.

with spines attached to the shells, predominating those with the concavity facing upwards.

## DISCUSSION

Unlike the outcrops located in the eastern border of Araripe Basin analyzed by Custódio *et al.* (2017) to identify transgressive and highstand tracts of the Romualdo Formation, on Cedro site the concretions-bearing shale occurs not only below the coquinas, but between them. Facies of shales and mudstones in most of the studied outcrop indicate an environment with a predominance of sedimentation under low-energy condition. The presence of marine fish (e.g. *Lepidotes*, *Vinctifer*, *Cladocyclus* and *Rhinobatus*) in the limestone concretions in these facies suggests the existence of a seaway between Araripe Basin and the open marine environment, which allowed these organisms to migrate to the area (Silva Santos & Valença 1968, Martill 1988, 2007, Assine 2007, Assine *et al.* 2014).

The sandstone facies with planar cross-stratification (Sp facies), horizontal lamination (Sh facies) and structureless (Sm facies) are related to the action of unidirectional currents, deposition by bottom currents under upper flow regime and bottom currents associated with storm waves, respectively. This facies association is typically for wave-influenced coastal environments (Walker & Plint 1992, James & Dalrymple 2010). The association of mudstones and bioclastic sandstones with incipient wavy truncated laminations indicates sedimentation in the offshore transition zone of

siliclastic platforms (i.e., below the base level of fair weather waves and above the base level of storm waves; Reading & Collinson 1996, James & Dalrymple 2010, Mancosu *et al.* 2015, Horodyski *et al.* 2014) (Fig. 7).

*Brachidontes araripensis* occurs in all coquinas, indicating these organisms were highly adapted to local environmental conditions, perhaps because this species could tolerate variations in salinity as well as the living species of this genus (Terranova *et al.* 2007). However, the other identified taxa occur in marine waters (Wenz 1938, Stephenson 1952, Morter 1984, Hessel & Junior 1989, Cleevely & Morris 1988, Sälgeback & Savazzi 2006), indicating that, although there were variations in salinity, it would still be sufficient for the establishment of benthic marine communities with echinoids (*Bothryopneustes araripensis*), which are found in most of the coquinas.

Although coquinas are similar regarding their taxonomic composition, they differ in the abundance of groups. Thus, overtime, the environment would have maintained the abiotic conditions necessary for the establishment of a fauna with possible salinity variations that would favor the predominance of certain groups, as it has been already observed in previous studies (Pereira *et al.* 2015, Prado *et al.* 2016).

The species identified in the Cedro outcrop have an epifaunal and or semi-infaunal mode of life, i.e., they have a lower preservation potential in comparison with infaunal individuals. That is because they remain longer on the sediment-water interface and are more easily exposed to the turbulence of the environment in low

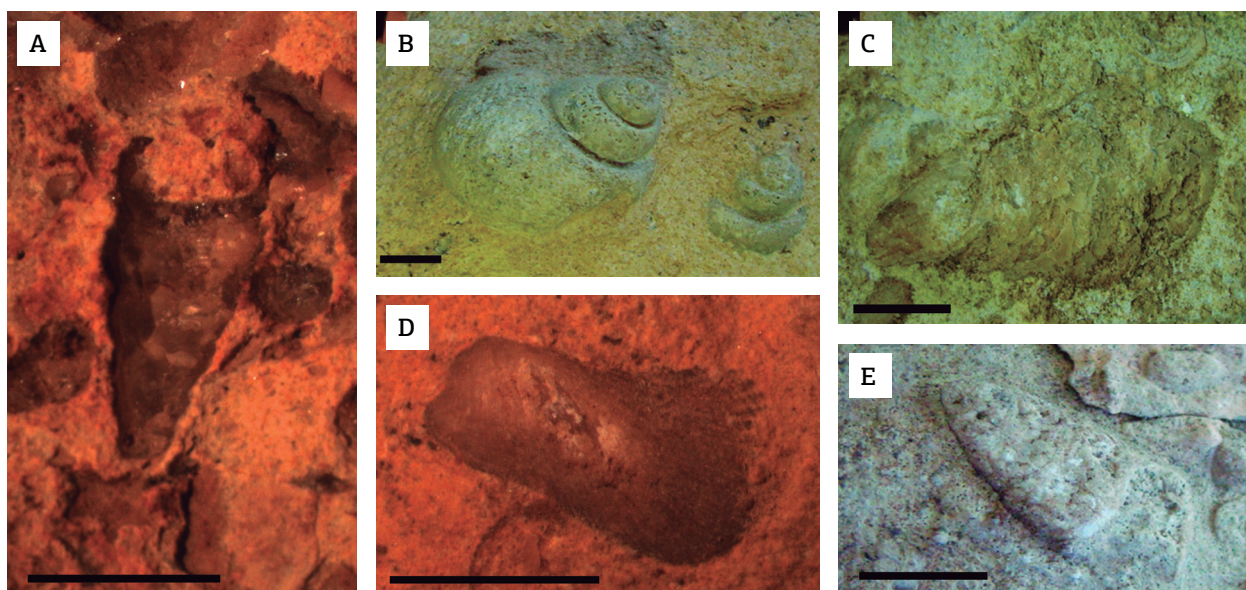


Figure 4. Macroinvertebrates identified in the prospected outcrop: (A) *Cerithium* sp. (DCEO-CTG-UFPE-8712), (B) *Tylostoma ranchariensis* (DCEO-CTG-UFPE-8681), (C) *Aguilera dissita* (DCEO-CTG-UFPE-8684), (D) *Brachidontes araripensis* (DCEO-CTG-UFPE-8681), (E) Cassiopids gastropod (DCEO-CTG-UFPE-8712). Scale: 1 cm.

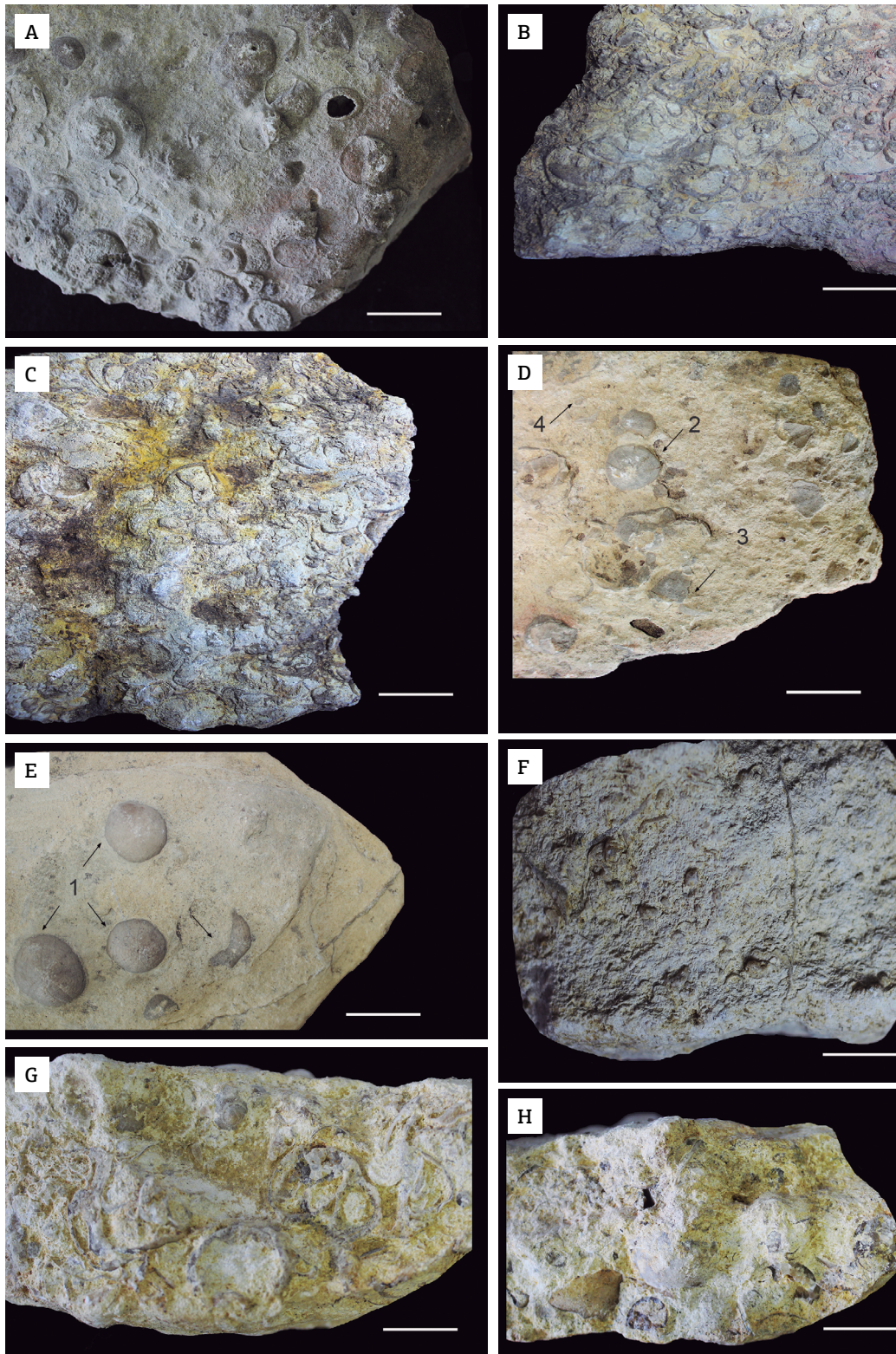


Figure 5. Coquinas types 1 and 2: (A) LCE1 (DGEO-CTG-UFPE-8680), (B) LCE2 (DGEO-CTG-UFPE-8682), (C) LCE3 (DGEO-CTG-UFPE-8683), (D) LCE4 (DGEO-CTG-UFPE-8692), (E) LCE5 (DGEO-CTG-UFPE-8694), (F) LCE6 (DGEO-CTG-UFPE-8701), (G) LCE7 (DGEO-CTG-UFPE-8702), (H) LCE8 (DGEO-CTG-UFPE-8703) . Notice in the coquinas type 2 the loose (D) to disperse (A and E) packed fossil association, shells of echinoides of the *Bothryopneustes araripensis* species facing upward and downward (E), and desarticulation stages of irregular echinoid: 1) Fully articulated shell (E), 2) radially cracked shell, 3) fragmented shell with many articulated plates, 4) shell fragmented into small parts (D). Observe in the coquinas type 1 the loose (F, G and H) to dense (B and C) packed fossil association, good sorted and chaotic distribution. Scale: 1 cm.

sedimentation rate conditions, usually predominant in the day-to-day (Kidwell 1986, Best & Kidwell 2000), justifying the high index of fragmentation in the coquinas on the Cedro site.

Preservation of the organism is also directly influenced by its skeletal type (Speyer & Brett 1988). Fragmentation and disarticulation is high in all taxonomic groups, especially in the echinoids (stages 3 and 4), because the structure of their multi-element skeleton (*sensu* Speyer & Brett 1988) is more susceptible to disarticulation, occurring from within a few hours up to a few days (Schäfer 1972). The exceptions are the gastropods, which due to their univalve skeleton and absence of ligament tissue are physically more resistant hence more frequently preserved (Speyer & Brett 1988).

The disarticulation and fragmentation seems to be more related to the high energy of the environment than to biological or chemical processes since it is observed in all taxonomic groups and because there are no signs of corrosion and bioerosion. The absence of corrosion and bioerosion also suggests that the individuals remained for a short time exposed to the water-sediment interface, being rapidly buried after dying (Davies *et al.* 1989).

The degree of packing ranges from dispersed to dense, suggesting there would be variations in the hydraulic selection of the matrix or in the availability of bioclasts (Kidwell *et al.* 1986, Holz & Simões 2002, Schmidt-Neto *et al.* 2014).

### Genetic classification of the concentrations

According to Aigner and Reineck (1982) and Aigner (1985), sedimentary records in siliciclastic platforms are controlled mainly by tempestite events. However, even though they are formed by the same type of event, the fossiliferous concentrations have peculiar taphonomic features along the shallow to deep-water gradient (Fürsich & Oschmann 1993).

Coquinas type 1 has characteristics of bioclastic transport and reworking through storm waves, such as the presence of well-selected bioclasts and nested valves (Allen 1990, Kidwell

& Bosence 1991). Because they present a typical transport biofabric with few signs of abrasion, these coquinas would have been formed by para-autochthonous and allochthonous individuals through short-term currents such as those generated by storm in proximal settings (Fig. 7) (Simões *et al.* 2000, Fürsich & Oschmann 1993). The absence of any sedimentary structure that could indicate the action of storm events is justified possibly due to the high availability of bioclasts that would have obliterated the sedimentary record. For bioclastic concentrations in storm-influenced shelf environments, Kidwell & Bosence (1991) estimate a time-averaging ranging from a few decades to a few thousands of years.

In coquinas Type 2, the transport seems to have been less significant as suggested, for example, by the poor selection of bioclasts and preservation of several whole specimens. The presence of articulated concave-upwards echinoid shells (stages 1 and 2) with the concavity facing upward, sometimes with spines, indicates that a rapid sedimentation process buried the echinoid still alive in situ (obrution deposits), representing the best evidence of autochthony. The few signs of abrasion indicate that coquinas were formed in areas of low hydrodynamic energy, and the stability of the bottom of this area was only altered by episodic events, i.e. storms (Schmidt-Neto *et al.* 2014).

Obrution deposits are generated from sudden sedimentological events, of which identification is facilitated by the presence of well-preserved epifaunal benthic organisms (Brett 1995). This type of fossil association is most often identified at the final transgressive stage or at the beginning of the highstand deposits (Brett & Seilacher 1991), and corresponds to what Kidwell and Bosence (1991) denominate *census assemblages*, which is the type of fossil accumulation most similar to the original communities, with no time-averaging or time-averaging ranging from days to hundreds of years (Kidwell & Bosence 1991, Kidwell 1997). Obrution deposits are most commonly found in calm sedimentary environments such as in areas more distant from

Table 2. Main taphonomic features of coquinas type 1 and 2 and their interpretations.

Coquinas	Taphonomic signatures	Interpretation
Type 1	High levels of fragmentation and or disarticulation, low abrasion and bioerosion and corrosion absent. Good sorted and loose to dense packed fossil assemblage. Bioclast orientation on bedding plans is concordant and polymodal, with the concavities facing both upwards and downwards. In cross section, chaotic distribution is less frequent. Presence of nesting of bivalves.	Transport and reworking of bioclastic through storm waves in proximal setting of transitional offshore zone.
Type 2	High levels of fragmentation and or disarticulation, low abrasion and abrasion and bioerosion and corrosion absent. Poor sorted and loose to disperse packed fossil assemblage. Bioclast orientation on bedding plans is concordant and polymodal, with the concavities facing both upwards and downwards. In cross section, chaotic distribution is less frequent. Presence of articulated echinoids with spines attached to the shells.	Rapid sedimentation of echinoids in situ by storms in more distal setting of transitional offshore zone.



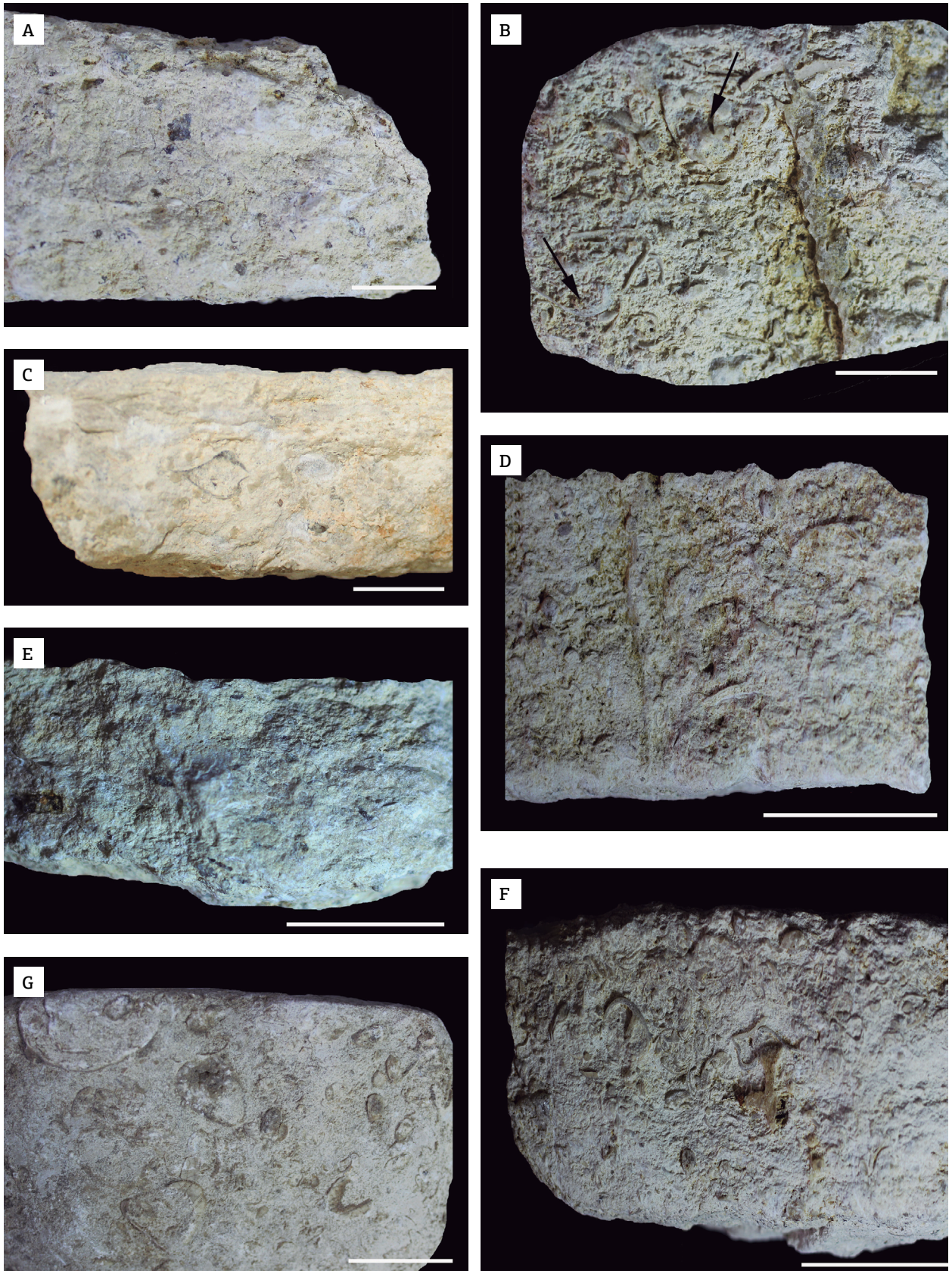
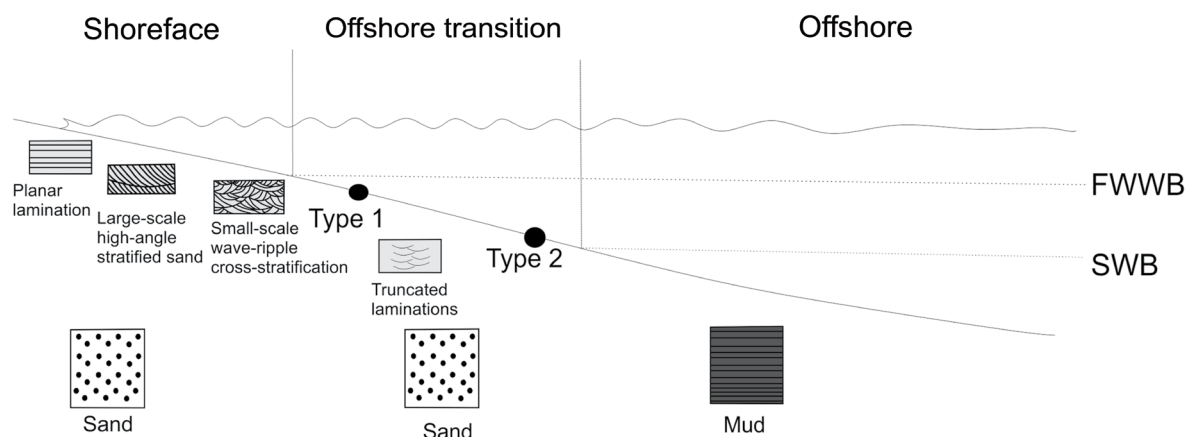


Figure 6. Coquinas type 1: (A) LCE9 (DGEO-CTG-UFPE-8704), (B) LCE10 (DGEO-CTG-UFPE-8705), (C) LCE11 (DGEO-CTG-UFPE-8706), (D) LCE12 (DGEO-CTG-UFPE-8707), (E) LCE13 (DGEO-CTG-UFPE-8708), (F) LCE14 (DGEO-CTG-UFPE-8709), (G) LCE15 (DGEO-CTG-UFPE-8710). Notice the chaotic distribution, nesting of bivalves (B), and loose (A, C, D and E) to dense (B, F and G) packed fossil association. Scale: 1 cm.



Source: modified from Dumas and Arnott, 2006.

**Figure 7.** Shoreface-offshore marine profile. Note the distribution of coquinas type 1 and 2 in the transitional offshore zone.

the platform (Fig. 7), due to the decrease of turbidity currents that settle the suspended sediment (Brett *et al.* 1986, 1997, Donovan 1991, Walker & Plint 1992). In fact, the echinoid *Bothryopneustes araripensis* identified in the Type 2 coquinas has also been interpreted as typical of low energy marine environments (Manso & Hessel 2012).

Sedimentation in the bioclastic sandstone seems to have occurred in an offshore-transition zone due to the sandy granulometry and the presence of sedimentary structures related to storm events, such as truncated laminations, usually preserved in these areas (Reading & Collinson 1996). Moreover, a better preservation of regular echinoids is also expected in the transition zone, where there would be less physical and biological reworking (Kidwell & Baumiller 1990).

In coquinas Type 2, articulated echinoid shells are also found, not in a life position (concavity facing downwards). According to Brett *et al.* (1997), echinoids can be transported still articulated in few hours after their death. Fragments in these coquinas indicate the influence of mixed taphonomic processes, related to energy events that would have carried remains of fossil from other areas and incorporated them into the bottom sediment for longer periods (Speyer & Brett 1991, Reid *et al.* 2015). Therefore, part of the fauna preserved in these coquinas would have represented para-autochthonous and allochthonous individuals.

Nebelsick (1999a) observed that the radial fissure in sand dollars (an irregular echinoid of the order Clypeasteroida) resulted from the sediment load on the fossil shells. Post-depositional changes of this type may also be related to the preservation of radially collapsed and cracked echinoids in the coquinas Type 2, as already suggested by Sales (2005).

## CONCLUSION

The facies and fossils in the Romualdo Formation on the Cedro site indicate an environment with marine influence and predominantly calm sedimentation, represented by shales/mudstones with fossils of fish and vegetables, sometimes interrupted by tempestite sedimentation forming coquinas. The sedimentation of macrobenthos seems to have occurred in a transitional offshore marine environment, sometimes influenced by proximal storms, with coquinas exhibiting a transport biofabric and sometimes by more distal storms, representing the best evidence of in situ preservation of echinoids in the area.

The new occurrence of autochthonous echinoids in the municipality of Exu, Pernambuco, confirms the marine entry into Araripe and expands its paleogeographic boundaries to the west.

## ACKNOWLEDGEMENTS

The authors thank Capes and CNPq for the fellowships; the geologist Alexandre Magno Feitosa Sales (*in memoriam*) for his friendship and valuable scientific contributions. We also thank Dra. Paula Sucerquia for her suggestions and the Exu city council, Pernambuco State, and Genilma Cordeiro and Cícero Marcelino for the pleasant company in the field work. We are grateful as well to Michael Holz and the anonymous reviewer for their accurate comments that improved the present paper.

## REFERENCES

- Aigner T. 1985. *Storm depositional systems-dynamic stratigraphy in modern and ancient shallow-marine sequences*. New York, Lecture notes in Earth Sciences, 174 p.
- Aigner T., Reineck H.E. 1982. Proximity trends in modern storm sands from the Helgoland Bight (North Sea) and their implication for basin analysis. *Senckenbergiana Maritima*, **14**:183-215.
- Allen J.R.L. 1990. Transport - hydrodynamics: shells. In: Briggs D.E.G., Peter C. (Eds.). *Palaeobiology: a synthesis*. Oxford, Blackwell Science, p. 227-229.
- Arai M. 2014. Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective. *Brazilian Journal of Geology*, **44**:339-350. <http://dx.doi.org/10.5327/Z2317-4889201400020012>
- Arai M., Coimbra J.C. 1990. Análise paleoecológica do registro das primeiras ingressões marinhas na Formação Santana (Cretáceo Inferior da Chapada do Araripe). In: Simpósio sobre a Bacia do Araripe e Bacias Interiores do Nordeste, 1., Crato. *Atas...* v. 1, p. 225-239.
- Assine M.L. 1992. Análise estratigráfica da Bacia do Araripe, Nordeste do Brasil. *Revista Brasileira de Geociências*, **22**:289-300.
- Assine M.L. 2007. Bacia do Araripe. *Boletim de Geociências da Petrobras*, **15**:371-389.
- Assine M.L., Perinotto J.A.J., Custódio M.A., Neumann V.H., Varejão F.G., Mescolotti P.C. 2014. Sequências deposicionais do Andar Alagoas da Bacia do Araripe, Nordeste do Brasil. *Boletim de Geociências da Petrobras*, **22**:3-28.
- Batista M.E.P., Sales A.M.F., Pinheiro A.P., Barros O.A. 2015. Tafonomia de moluscos do sítio Barreiros, município de Moreilândia, PE, Bacia do Araripe. *Estudos Geológicos*, **25**:53-60.
- Berthou P.Y., Viana M.S.S., Campos D.A. 1990. Coupe de la Formation Santana dans le secteur de Pedra Branca (Santana do Cariri; Bassin d'Araripe, NE du Brésil): contribution a l'étude de la sedimentologie et des paleoenvironnements. In: Simpósio sobre a Bacia do Araripe e Bacias Interiores do Nordeste, 1., Crato. *Atas...* v. 1, p. 173-191.
- Best M.R., Kidwell S.M. 2000. Bivalve taphonomy in tropical mixed siliciclastic-carbonate settings. II. Effect of bivalve life habits and Shell types. *Paleobiology*, **26**:103-115. [https://doi.org/10.1666/0094-8373\(2000\)026%3C0103:BTITMS%3E2.0.CO;2](https://doi.org/10.1666/0094-8373(2000)026%3C0103:BTITMS%3E2.0.CO;2)
- Beurlen K. 1966. Novos equinóides no Cretáceo do Nordeste do Brasil. *Anais da Academia Brasileira de Ciências*, **38**:455-464.
- Beurlen K. 1971. As condições ecológicas e faciológicas da Formação Santana na Chapada do Araripe (Nordeste do Brasil). *Anais da Academia Brasileira de Ciências*, **43**:411-415.
- Brett C.E. 1995. Sequence stratigraphy, biostratigraphy and taphonomy in shallow marine environments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **10**:597-616. <https://doi.org/10.2307/3515097>
- Brett C.E., Moffat H.A., Taylor W.L. 1997. Echinoderm taphonomy, taphofacies, and lagerstätten. *Paleontological Society Papers*, **3**:147-190. <https://doi.org/10.1017/S1089332600000243>
- Brett C.E., Seilacher A. 1991. Fossil lagerstätten: a taphonomic consequence of event sedimentation. In: Einsele G., Ricken W., Seilacher A. (Eds.). *Cycles and events in stratigraphy*. Berlin, Springer-Verlag, p. 283-297.
- Brett C.E., Speyer S.E., Baird G.C. 1986. Storm-generated sedimentary units: Tempestite proximity and event stratification in the Middle Devonian Hamilton Group of New York. In: Brett C.E. (Ed.). *Dynamic stratigraphy and depositional environments of the Hamilton Group (Middle Devonian) in New York State*. *Museum Bulletin*, New York, p. 129-156.
- Bruno A.P., Hessel M.P. 2006. Registros paleontológicos do Cretáceo marinho na Bacia do Araripe. *Estudos Geológicos*, **16**:30-49.
- Cleavelly R.J., Morris N.J. 1988. Taxonomy and ecology of Cretaceous Cassiopidae (Mesogastropoda). *Bulletin of the British Museum (Natural History)*, **44**:233-291.
- Custódio M.A., Quaglio F., Warren L.V., Simões M.G., Fürsich F.T., J. Perinotto, J.A., Assine, M.A. 2017. The transgressive-regressive cycle of the Romualdo Formation (Araripe Basin): Sedimentary archive of the Early Cretaceous marine ingressão in the interior of Northeast Brazil. *Sedimentary Geology*, **359**:1-15. <http://dx.doi.org/10.1016/j.sedgeo.2017.07.010>
- Davies D.J., Powell E.N., Stanton R.J. 1989. Relative rates of shell dissolution and net sediment accumulation-a commentary: can shell beds form by the gradual accumulation of biogenic debris on the sea floor? *Lethaia*, **22**:207-212. <https://doi.org/10.1111/j.1502-3931.1989.tb01683.x>
- Donovan S.K. 1991. The taphonomy of echinoderms: calcareous multi-element skeletons in the marine environment. In: Donovan S.K. (Ed.). *The process of fossilization*. London, Belhaven Press, p. 241-269.
- Dumas S., Arnott R.W.C. 2006. Origin of hummocky and swaley cross-stratification - The controlling influence of unidirectional current strength and aggradation rate. *Geology*, **34**:1073-1076. <https://doi.org/10.1130/G22930A.1>
- Fürsich F.T., Oschmann W. 1993. Shell beds as tools in basin analysis: the Jurassic Kachchh, western India. *Journal of Geological Society*, **150**:169-185. <https://doi.org/10.1144/gsjgs.150.1.0169>
- García J.Y., Aguirre J. 2004. Quantitative taphonomic analysis and taphofacies in lower pliocene temperate carbonate-siliciclastic mixed platform deposits (Almería- Níjar basin, SE Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **207**:83-103. <https://doi.org/10.1016/j.palaeo.2004.02.002>
- Hessel M.H.R., Junior N.P.F. 1989. Algumas espécies de Aguilera (Bivalvia) do Albiano Inferior de Sergipe. In: Congresso Brasileiro de Paleontologia, 11., Curitiba. *Anais...* p. 301-315.
- Holz M., Simões M.G. 2002. *Elementos Fundamentais de Tafonomia*. Porto Alegre, Universidade/UFRGS, 231 p.
- Horodyski R.S., Holz M., Grahm Y., Bosetti E.P. 2014. Remarks on sequence stratigraphy and taphonomy of the Malvinokaffric shelly fauna during the Kacák Event in the Apucarana Sub-basin (Paraná Basin), Brazil. *International Journal of Earth Sciences (Geologische Rundschau)*, **103**:367-380. <https://doi.org/10.1007/s00531-013-0954-9>
- James N.P., Dalrymple R.W. 2010. *Facies Models 4*. Canada, Geological Association of Canada, 574 p.
- Kidwell S.M. 1986. Taphonomic Feedback in Miocene Assemblages: Testing the Role of Dead Hardparts in Benthic Communities. *Palaios*, **1**:239-255. <https://doi.org/10.2307/3514688>
- Kidwell S.M. 1997. Time-averaging in the marine fossil record: overview of strategies and uncertainties. *Geobios*, **30**:977-995. [https://doi.org/10.1016/S0016-6995\(97\)80219-7](https://doi.org/10.1016/S0016-6995(97)80219-7)
- Kidwell S.M., Baumiller T. 1990. Experimental disintegration of regular echinoids: roles of temperature, oxygen and decay thresholds. *Paleobiology*, **16**:247-271. <https://doi.org/10.1017/S0094837300009982>
- Kidwell S.M., Bosence D.W. 1991. Taphonomy and time- averaging of marine shelly faunas In: Allison P.A., Briggs D.E.G. (Eds.). *Taphonomy: releasing the data locked in the fossil record*. New York, Plenum Press, p. 115-209.

- Kidwell S.M., Fürsich, F.T., Aigner, T. 1986. Conceptual framework for the analysis and classification of fossil concentrations. *Palaios*, **1**:228-238. <https://doi.org/10.2307/3514687>
- Kidwell S.M., Holland S.M. 1991. Field description of coarse bioclastic fabrics. *Palaios*, **6**:426-434. <https://doi.org/10.2307/3514967>
- Kidwell S.M., Rothfus T.A., Best M.M.R. 2001. Sensitivity of taphonomic signatures to sample size, sieve size, damage scoring system, and target taxa. *Palaios*, **16**:26-52. <https://doi.org/10.2307/3515551>
- Lima M.R. 1978. *Palinologia da Formação Santana (Cretáceo do Nordeste)*. PhD Thesis, Universidade de São Paulo, São Paulo, 337 p.
- Mabesoone J.M., Tinoco I.M. 1973. Paleogeology of the Aptian Santana Formation (Northeastern Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **14**:97-118. [https://doi.org/10.1016/0031-0182\(73\)90006-0](https://doi.org/10.1016/0031-0182(73)90006-0)
- Maisey J.G. 1991. *Santana fossil an illustrated atlas*. Neptune City, New Jersey, T.F.H. Publications, 459 p.
- Mancosu A., Nebelsick J.H., Kroh A., Pillola G.L. 2015. The origin of echinoid shell beds in siliciclastic shelf environments: three examples from the Miocene of Sardinia, Italy. *Lethaia*, **48**:83-99. <https://doi.org/10.1111/let.12090>
- Manso C.L.C., Hessel M.H. 2007. Revisão sistemática de *Pygidiolampas araripensis* (Beurlen, 1966), (Echinodermata: Cassiduloidea) da Bacia do Araripe, Nordeste do Brasil. *Geociências*, **26**:271-277.
- Manso C.L.C., Hessel M.H. 2012. Novos equinóides (Echinodermata: Echinoidea) do Albiano da Bacia do Araripe, Nordeste do Brasil. *Revista Brasileira de Geociências*, **42**:187-197.
- Marques F.O., Nogueira F.C.C., Bezerra F.H.R., Castro D.L. 2014. The Araripe Basin in NE Brazil: An intracontinental graben inverted to a high-standing horst. *Tectonophysics*, **630**:251-264. <http://dx.doi.org/10.1016/j.tecto.2014.05.029>
- Martill D.M. 1988. Preservation of fish in the Cretaceous Santana Formation of Brazil. *Palaeontology*, **31**:1-18.
- Martill D.M. 2007. The age of the Cretaceous Santana Formation fossil konservat lagerstätte of North-east Brazil: a historical review and an appraisal of the biostratigraphic utility of its palaeobiota. *Cretaceous Research*, **28**:895-920. <https://doi.org/10.1016/j.cretres.2007.01.002>
- Morter A.A. 1984. Purbeck-Wealden beds mollusca and their relationship to ostracod biostratigraphy, stratigraphical correlation and palaeogeology in the Weald and adjacent areas. *Proceedings of the Geologists' Association*, **95**:217-234. [https://doi.org/10.1016/S0016-7878\(84\)80009-7](https://doi.org/10.1016/S0016-7878(84)80009-7)
- Nebelsick J.H. 1999a. Taphonomic comparison between recent and fossil sand dollars. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **149**:349-358. [http://dx.doi.org/10.1016/S0031-0182\(98\)00211-9](http://dx.doi.org/10.1016/S0031-0182(98)00211-9)
- Nebelsick J.H. 1999b. Taphonomy of clypeaster fragments: preservation and taphofacies. *Lethaia*, **32**:241-252. <https://doi.org/10.1111/j.1502-3931.1999.tb00542.x>
- Olóriz F., Reolid M., Rodríguez-Tovar F.J. 2008. Taphonomy of fossil macro-invertebrate assemblages as a tool for ecostratigraphic interpretation in Upper Jurassic shelf deposits (Prebetic Zone, Southern Spain). *Geobios*, **41**:31-42. <http://dx.doi.org/10.1016/j.geobios.2006.03.003>
- Pereira P.A., Cassab R.C.T., Barreto A.M.F., Almeida J.A.C. 2015. Moluscos da Formação Romualdo, Aptiano-Albiano, Bacia do Araripe, Nordeste do Brasil. *Boletim do Museu Paraense Emílio Goeldi. Ciências Naturais*, **10**:231-246.
- Prado L.A.C., Pereira P.A., Sales A.M.F., Barreto A.M.F. 2014. Análise tafonômica e taxonômica da concentração de invertebrados fósseis do topo da Formação Romualdo, Cretáceo Inferior da Bacia do Araripe em Araripe, Ceará (CE). *Estudos Geológicos*, **24**:53-64. <http://dx.doi.org/10.18190/1980-8208/estudosgeologicos.v24n1p53-64>
- Prado L.A.C., Pereira P.A., Sales A.M.F., Barreto A.M.F. 2015. Taphonomic and paleoenvironmental considerations for the concentrations of macroinvertebrate fossils in the Romualdo Member, Santana Formation, Late Aptian-Early Albian, Araripe Basin, Araripina, NE, Brazil. *Journal of South American Earth Sciences*, **62**:218-228. <http://dx.doi.org/10.1016/j.jsames.2015.06.005>
- Prado L.A.C., Pereira P.A., Sales A.M.F., Barreto A.M.F. 2016. Tafonomia dos invertebrados do Sítio Canastra, Formação Romualdo, Cretáceo Inferior, Bacia do Araripe, Araripina, Pernambuco, Brasil. *Anuário do Instituto de Geociências*, **39**:77-87. [http://dx.doi.org/10.11137/2016\\_2\\_77\\_87](http://dx.doi.org/10.11137/2016_2_77_87)
- Reading H.G., Collinson J.D. 1996. Clastic Coasts In: Reading H.G. (Ed.). *Sedimentary Environments: Process, Facies and Stratigraphy*. Cornwall, Blackwells, p. 154-231.
- Reid M., Bordy E.M., Taylor W. 2015. Taphonomy and sedimentology of an echinoderm obrution bed in the Lower Devonian Voorstehoeek Formation (Bokkeveld Group, Cape Supergroup) of the South Africa. *Journal of Africa Earth Sciences*, **110**:135-149. <http://dx.doi.org/10.1016/j.jafrearsci.2015.04.009>
- Sales A.M.F. 2005. *Análise tafonômica das ocorrências fossilíferas de macroinvertebrados do Membro Romualdo (Albiano) da Formação Santana, Bacia do Araripe, NE do Brasil: significado estratigráfico e paleoambiental*. PhD Thesis, Universidade de São Paulo, São Paulo, 160 p.
- Sälgeback J., Savazzi E. 2006. Constructional morphology of cerithiform gastropods. *Paleontological Research*, **10**:233-259. <https://doi.org/10.2517/prpsj.10.233>
- Schäfer W. 1972. *Ecology and paleoecology of marine environments*. Chicago, University of Chicago Press, 568 p.
- Schmidt-Neto H., Guimarães Netto R., Tognoli F.M.W. 2014. Análise tafonômica das concentrações fossilíferas da Formação Rio Bonito na região de Taió, Sul do Brasil. *Revista Brasileira de Paleontologia*, **17**:208-225. <http://dx.doi.org/10.4072/rbp.2014.2.08>
- Seilacher A. 1970. Begriff und bedeutung der Fossil-Lagerstätten: Neues Jahrbuch für Geologie und Paläontologie. *Monatshefte*, **1**:34-39.
- Silva Santos R., Valença J.G. 1968. A Formação Santana e sua paleoictiofauna. *Anais da Academia Brasileira de Ciências*, **40**:339-360.
- Simões M.G., Kowalewski M., Torello F.F., Ghilardi R.P., Mello H.C. 2000. Early onset of modern-style shell beds in the Permian Sequences of the Paraná Basin: implications for the Phanerozoic trend in bioclastic accumulations. *Revista Brasileira de Geociências*, **30**:499-503.
- Speyer S.E., Brett C.E. 1988. Taphofacies models for epeiric sea environments: middle Paleozoic examples. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **63**:225-262. [https://doi.org/10.1016/0031-0182\(88\)90098-3](https://doi.org/10.1016/0031-0182(88)90098-3)
- Speyer S.E., Brett C.E. 1991. Taphofacies controls: background and episodic processes in fossil assemblage preservation. In: Allison P.A., Briggs D.E.G. (Eds.). *Taphonomy: releasing the data locked in the fossil record*. New York, Plenum Press, p. 501-545.
- Staff G.M., Powell E.N. 1988. The paleoecological significance of diversity: the effect of time averaging and differential preservation on macroinvertebrate species richness in death assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **63**:73-89. [https://doi.org/10.1016/0031-0182\(88\)90091-0](https://doi.org/10.1016/0031-0182(88)90091-0)

Stephenson L.W. 1952. *Larger invertebrate fossils of the Woodbine Formation (Cenomanian) of Texas*. Washington, D.C., United States Government Printing Office (USGS Numbered Series, 242), 226 p.

Terranova M., Lo Brutto S., Arculeo M., Mitton J., 2007. A mitochondrial phylogeography of *Brachidontes variabilis* (Bivalvia: Mytilidae) reveals three cryptic species. *Journal of Zoological Systematics and Evolutionary Research*, **45**:289-298. <https://doi.org/10.1111/j.1439-0469.2007.00421.x>

Walker R.G., Plint A.G. 1992. Response to sea level change, wave and storm dominated shallow marine systems. In: Walker R.G., James N.P. (Eds.). *Facies Models*. St. John's, Geological Association of Canada, p. 219-238.

Wenz W. 1938. Gastropoda teil I: allgemeiner teil und prosobranchia. In: Schindewolf O.H. (Ed.). *Handbuch der Paläozoologie*. Berlin, Band, 948 p.

White C.A. 1987. On new generic forms of Cretaceous Mollusca and their relation to other forms. *Proceedings of the Academy of Natural Sciences of Philadelphia*, **39**:32-37.

