

Scleractinia Corals of the Jandaíra Formation (Turonian- Campanian), Rio Grande do Norte state, Brazil

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Abstract

This work deals with the systematic study of the corals collected in the Jandaíra Formation, Turonian-Campanian of the Rio Grande do Norte state, Brazil. The specimens were recognized as *Actinastrea decaturensis* (Vaughan, 1919), *A. guadalupae* (Roemer, 1849), *Stephanocoenia guadalupae* Wells, 1932, *Madracis johnwellsi* Frost and Langenheim, 1974, *Isastrea whitneyi* Wells, 1932, *Paracycloseris effrenatus* Filkorn and Pantoja-Alor, 2009 and *Orbicella travisensis* Wells, 1932, as well as *Isastrea* sp. and two doubtful species, *Turbinolia* (*Turbinolia*)? *insignifica* Vaughan, 1900 and *Placotrochus? texanus* (Vaughan, 1903). The majority of these species occurs in the Aptian-Albian of USA and Mexico, as well as the Lower Tertiary of Central America and north of South America. This fauna is the westernmost hermatypic assemblage of the Turonian scleractinian and has affinities with others shallow marine Cretaceous units within USA and Mexico.

Keywords: Brazil, corals, Jandaíra Formation, Scleractinia, Turonian.

Resumen

Varias especies de corales colectadas en estratos del Cretácico Superior (Turoniano-Campaniano), correspondientes a la Formación Jandaíra en el estado de Rio Grande do Norte, Brasil fueron identificadas y descritas en este trabajo. Esta fauna está representada por *Actinastrea decaturensis* (Vaughan, 1919), *A. guadalupae* (Roemer, 1849), *Stephanocoenia guadalupae* Wells, 1932, *Madracis johnwellsi* Frost y Langenheim, 1974, *Isastrea whitneyi* Wells, 1932, *Paracycloseris effrenatus* Filkorn y Pantoja-Alor, 2009 y *Orbicella travisensis* Wells, 1932, así como *Isastrea* sp. y dos especies dudosas: *Turbinolia* (*Turbinolia*)? *insignifica* Vaughan, 1900 y *Placotrochus? texanus* (Vaughan, 1903). La mayoría de las especies se registran en el Aptiano-Albiano de Estados Unidos y México, así como con el Terciario Inferior de América Central y norte de Sudamérica. Esta fauna es la asociación más occidental del conjunto hermatípico de escleractineos Turonianos y tiene afinidades con otras unidades marinas poco profundas del Cretácico de Estados Unidos y México.

Palabras clave: Brasil, corales, Formación Jandaíra, Scleractinia, Turoniano.

1. Introduction

The records of the corals of the Jandaíra Formation were collected in informal manuscripts without descriptions or illustrations, located in the Museu de Paleontologia at the old Escola Superior de Agricultura de Mossoró (ESAM). According to these notes, specimens are found in the cities of Ipanangaçu (5° 29' 56" S, 36° 51' 10" W), Upanema (5°

38' 32" S, 37° 15' 27" W) and Governador Dix Sept Rosado (5° 27' 34" S, 37° 31' 16" W) (Figure 1). The first and only systematic study was done by Fernandes and Wanderley (2000) whose three specimens were collected on an outcrop in Igarauçu (5° 34' 18" S, 36° 54' 36" W), individualizing two distinct taxa.

This paper deals the systematic studies on 10 specimens housed in the Professor Vingt-Un Rosado Maia collection

at Museu Câmara Cascudo - Universidade Federal do Rio Grande do Norte (MCC/UFRN), and other 3 specimens of the paleoinvertebrates collection at Museu Nacional/ Universidade Federal Rio de Janeiro (MN/UFRJ), from the cities of Ipanguaçu (5° 29' 56" S, 36° 51' 10" W), Pendências (5° 15' 28" S, 36° 43' 26" W) and Alto do Rodrigues (5° 17' 21" S, 36° 45' 29" W), chief fossiliferous localities of

the Jandaíra Formation (Figure 1). The majority of these corals were reef-building species, lived in symbiotic relationship with zooxanthellae algae, and limited their ecologic distribution to substrates in shallow, well-lit, warm marine waters.

This research expands the current knowledge about corals of the Brazilian Cretaceous, helping to define detailed

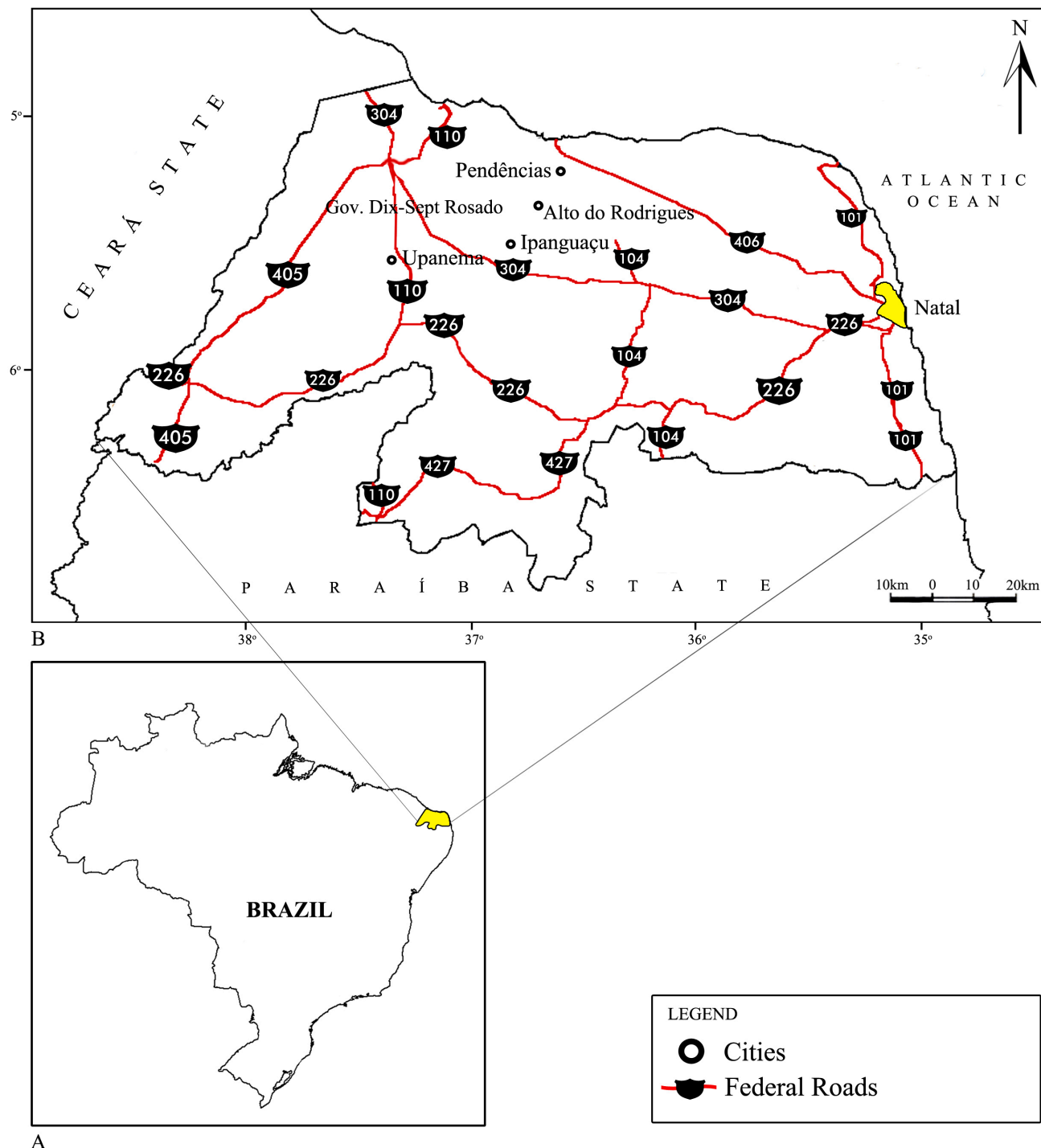


Figure 1: A. Map with special reference to the Rio Grande do Norte state, Brazil. B. Map showing the location of the study area in the Rio Grande do Norte state and the cities where the fossil corals were collected.

future biogeographic patterns in the Caribbean and South American regions of the Tethyan Sea.

2. Location and stratigraphy

The Potiguar Basin (Figure 2) is located in northeastern Brazil, between 4° 10' and 5° 50' latitude S and 35° 00' and 38° 20' longitude W, encompassing parts of the Rio Grande do Norte and Ceará states, covering an area of 21500 km² onshore and 26500 km² offshore. The sediments of this basin were deposited from the Early Cretaceous to present times, and are traditionally divided in the Rift (Early Cretaceous), Post-rift (Alagoas Age) and Drift (Albian to the Holocene) Supersequences (Santos Filho *et al.*, 2015).

The Jandaíra Formation belongs to the Drift Supersequence. It consists of calcarenites with bioclasts of mollusks, green algae, bryozoans and echinoids, bioclastic lime mudstones and calcilitites with bird's-eye structures. Its basal portion is intercalated with sandstones and shales deposited from tidal flats, lagoons, platform and open sea environments. The litostratigraphic unit represents the great

expansion of the carbonate domain, which encompassed the whole emerged area of the basin. Its upper contact is limited by a regional erosive unconformity that crops out in several places on the onshore section of the basin, which is the richest in fossils in the Potiguar Basin, including paleoinvertebrates, represented here by mollusks, echinoids, conchotracheans, bryozoans, corals and polychaetes (Cassab, 2003; Santos Filho *et al.*, 2015). The age of deposition of the Jandaíra Formation was considered to be Turonian, Coniacian, Santonian and Turonian-Maastrichtian. However, studies based on calcareous nannofossils and ostracods suggest a Turonian-Campanian age, also supported by mollusks (Cassab, 2003; Santos Filho *et al.*, 2015).

3. Material and methods

The collection analyzed comprises 13 specimens, all isolated corals, where colonial corals dominate. The cnidarians are filled or replaced with a fine, crystallized calcite and the surface structures and fine ornamentation of the septal borders are well preserved to a degree, while

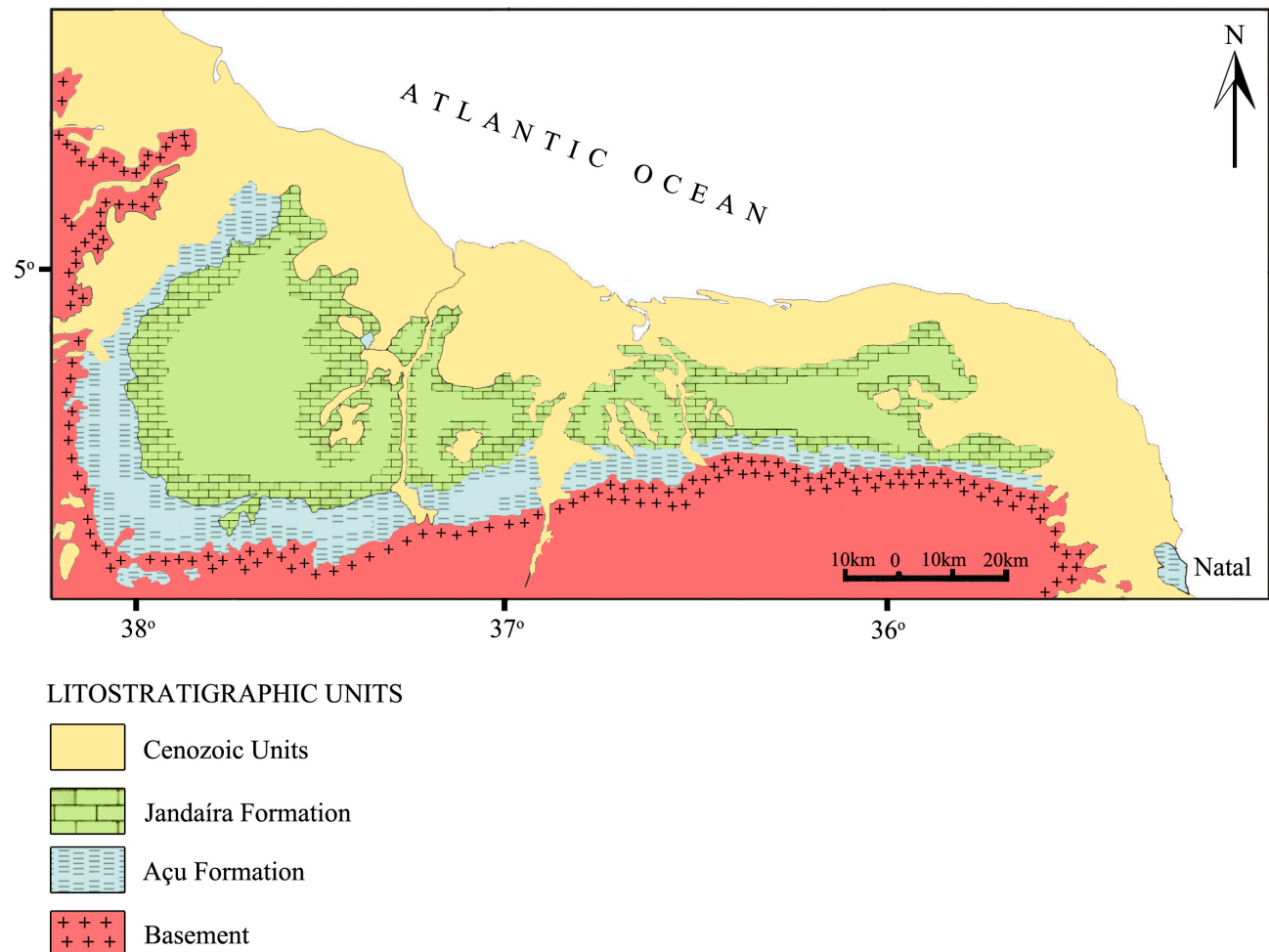


Figure 2. Geologic map of the Potiguar Basin (modified from Cassab, 2003).

the inner structures are partially destroyed due their more delicate nature. The examination of these corals was carried out using a binocular microscope, a precision caliper for obtaining measurements, and photographs taken by a Sony DSC-HX1 digital camera.

The corals at the Jandaíra Formation are very rare, and the specimens illustrated here are the best preserved. Detailed descriptions are provided depending on the degree of preservation of the material, especially in regards to the diagnostic morphological structures, such as the septa, pali and columella. These features were described with the help of a stereomicroscope, thus eliminating the need to make polished or thin sections.

4. Systematic descriptions

The systematic classification used in this paper as well as the essential terminology are mainly based on Wells (1956). The terms and nomenclature in the descriptions follow the proposals of Baron-Szabo *et al.* (2006), Baron-Szabo (2006, 2014), Filkorn *et al.* (2005), Filkorn and Pantoja-Alor (2009), Roniewicz and Stolarski (1999), Von der Osten (1957), and Wells (1932, 1933, 1934, 1941, 1945, 1946). In addition, complementary references such as Vaughan (1919), Geyer (1954), Budd *et al.* (1992), Löser (2013), and Fernandes and Wanderley (2000) were used.

The following abbreviations are used to indicate dimensions in the descriptions of the corals: h: height; l: length; w: width; cd: calicular diameter; s: septa; and cdp: calice depth. In the case of *Madracis johnwellsi*, measurements of the branch diameter (bd) and branch length (bl) are also included. The wt (wall thickness) is another dimension added to the descriptions of the cerioid and plocoid scleractinian taxa.

Order Scleractinia Bourne, 1900
Suborder Archaeocoeniina Alloiteau, 1952
Family Actinastreaeidae Alloiteau, 1952
Genus *Actinastrea* d'Orbigny, 1849

Type species. *Actinastrea goldfussi* d'Orbigny, 1850.

Diagnosis. Corallum colonial, massive, ramose or incrusting, cerioid to subcerioid or subplocoid. Corallites small, prismatic, directly united by septothecal walls, smooth or porous. Septa compact, radials, non-confluent and granulated laterally. Columella styliiform well developed. Paliform lobes and endothecal dissepiments sparse and thin. Synapticulae situated laterally. Based on Wells (1956) and Baron-Szabo (2014).

Distribution. Jurassic - Recent (Geyer, 1954; Wells, 1956; Baron-Szabo, 2014).

Actinastrea decaturensis (Vaughan, 1919)

Figure 3A

Description. Corallum colonial, massive, incrusting, cerioid to subplocoid, subeliptic in outline, transversally cut. Corallites numerous, small and subcircular, separated by slightly thick walls, smooth and narrowly merged. Calices polygonal and monocentric, hexagonal or pentagonal in outline, arched and moderately shallow. Septa straight, equal to subequal, laminar, equidistant, octamerally arranged in two incomplete to complete cycles, ranging from 14 to 16 units. Septal margins elevated until the surface of the calice, smooth to subcrenulated. The septa from the first cycle extends to the columella and its terminations are prominent in the separation walls between the corallites. The septa from the second cycle are about a quarter of the calicular diameter and, apparently, do not merge to the columella, which is well developed, cylindrical and styliiform. Holotheca, pali, synapticulae, trabecular structures, endothecal and exothecal dissepiments absent, as well as internal morphological details of the calices, septa and separation walls between the corallites.

Occurrence. Panama: Gatuncillo Formation, Middle Eocene; Antigua: Antigua Formation, Late Oligocene; Cuba: Mogote Peak, Late Oligocene; United States of America: Flint River, Early Miocene (Vaughan, 1919; Budd *et al.*, 1992). Brazil: Jandaíra Formation, Turonian-Campanian (present study).

Material. a fragment of a colony (MN 5566-I) found on the RN-118 road, 20 km from the crossroad with BR-304, Ipanguaçu city, Rio Grande do Norte state, Brazil. Deposited on the paleoinvertebrates collection at Museu Nacional/ UFRJ.

Dimensions. h: 11 mm; l: 32 mm; w: 12 mm; cd: 1.6 – 2.2 mm; s: 14 – 16; wt: 0.1 – 0.3 mm; cdp: 0.2 – 0.3 mm.

Discussion. The taxonomic relationship between *Actinastrea* d'Orbigny, 1849 and *Astrocoenia* Milne Edwards and Haime, 1848 has been discussed for the past 60 years. Initially, Milne Edwards and Haime (1848) individualized the genus *Astrocoenia*, and d'Orbigny (1849) proposed *Actinastrea* based on morphologically identical copies, characterized by its colonial cerioids with small calicular diameter. Alloiteau (1954) corroborated the existence of two genus, based on the differences of the calicular extremities, septal walls, endothecal dissepiments and columella. Ever since, the characterization of the species assigned to the *Astrocoenia* - *Actinastrea* clade was confused and insufficiently enlightening (Baron-Szabo, 2014).

Geyer (1954) considered *Astrocoenia* restricted to the Triassic, and attributed all of the Jurassic appearances of this clade to *Actinastrea*. Thus, all species of Central and South America considered as *Astrocoenia*, such as *A. barranquinensis* Wells, 1944, *A. dickersoni* Wells, 1941, *A. guadalupae* Roemer, 1848, *A. hexamera* Fritzsche, 1923, and *A. peruviana* Wells, 1941 must to be attributed in *Actinastrea*.

Although the internal structure of the calice, septa and separation walls between the corallites is usually destroyed by the recrystallization, the shape and diameter of the

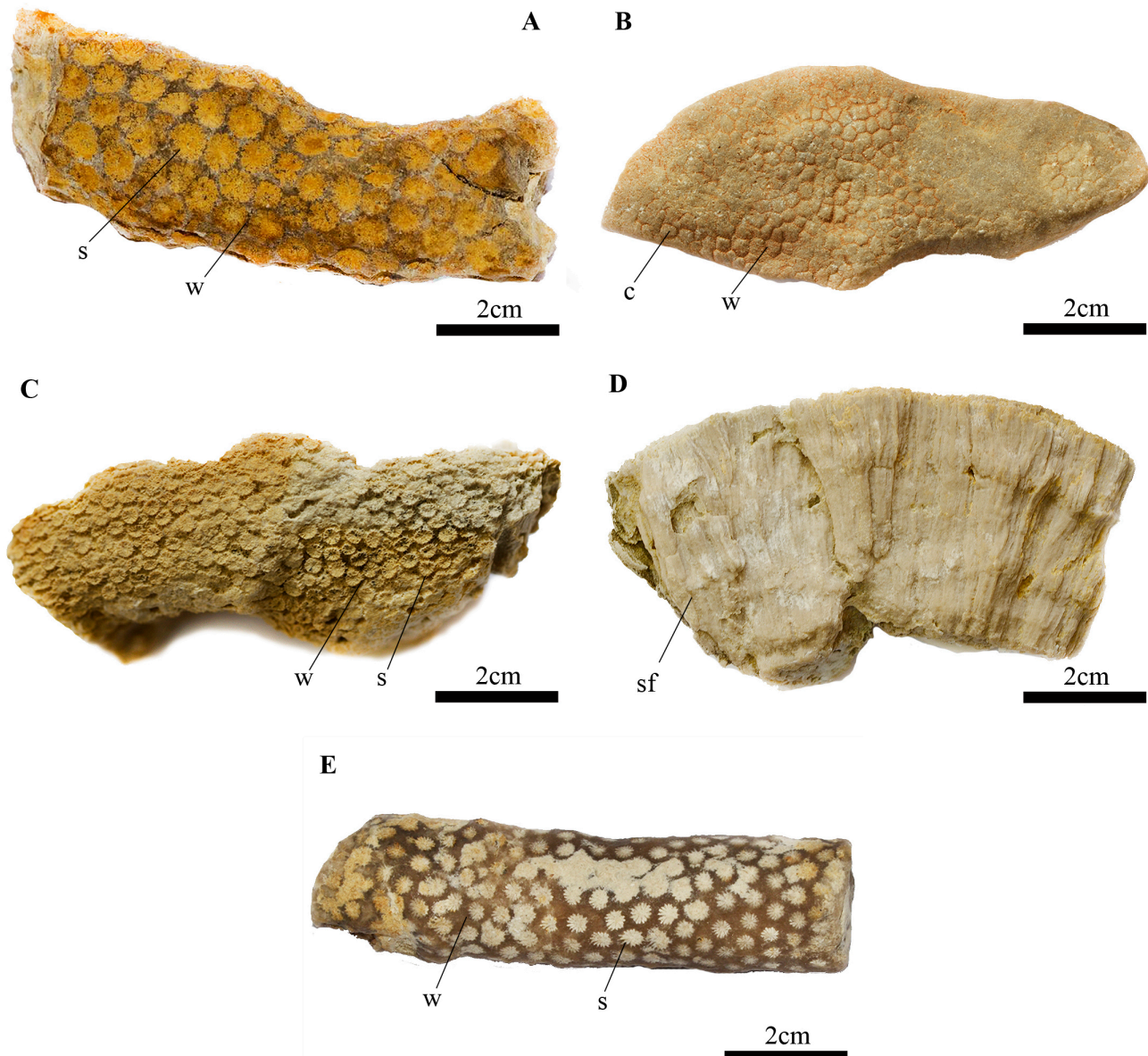


Figure 3. A. *Actinastrea decaturensis* (Vaughan, 1919) (MN 5566-1): corallum cerioid to subplocoid and subcircular corallites; B. *A. guadalupae* (Roemer, 1849) (MCC.C.2-363): corallum cerioid to subcerioid, prismatic corallites and shallow calices; C. *Stephanocoenia guadalupae* Wells, 1932 (MCC.C.2-108): corallum plocoid to subplocoid and small and circular corallites, closely separated; D. *Stephanocoenia guadalupae* Wells, 1932 (MCC.C.2-108): side view of holotheca showing the septal furrows; E. *Madracis johnwellsi* Frost and Langenheim, 1974 (MCC.C.2-350): corallum branch with numerous and spherical corallites, separated by thick walls (c: calice; s: septa; sf: septal furrows; w: walls).

corallites, the number, arrangement and septal disposition, and the thickness of the walls allow framing this specimen as *Actinastrea decaturensis* (Vaughan, 1919). Thus, this is the first occurrence of this species on the Cretaceous of South America, previously restricted to the Cenozoic of North and Central America.

The identifiable morphological features in *A. decaturensis* (Vaughan, 1919) differ from the previously described *A. guadalupae* (Roemer, 1849), because in *A. decaturensis* the corallites have subcircular shape, thicker separation walls and less numerous and octamerally arranged septa. Furthermore, Vaughan species present similarities with *A.*

incrustans (Duncan, 1873) and *A. jukesbrownei* (Wells, 1945), differentiated by the bigger diameter of the corallites and thicker separation walls.

Remarks. Fernandes and Wanderley (2000) marked this specimen as representative of the genus *Astrocoenia* Milne Edwards and Haime, 1848.

Actinastrea guadalupae (Roemer, 1849)

Figure 3B

Description. Corallum colonial, massive, incrusting, cerioid to subcerioid and subeliptical. Corallites numerous,

small and prismatic, separated by slightly thick walls, narrowly merged, smooth or ornamented by granules. Calices shallow, equivalent to the surface of the corallum, polygonal, monocentric, ranging among hexagonal, pentagonal, quadrangular and triangular in drawing. Septa equal or subequal, straight, laminar to thick, equidistant and hexamerally arranged in three cycles, incomplete to complete, ranging between 14 and 24 units. Septal margins smooth to subcrenulated. The first and second cycle septa are subequal, moderately thick and merge to the columella. The septa from the third cycle are less thick, less than one third of the calicular diameter and apparently do not merge to the columella. Columella little visible, small, cylindrical and styliiform. Holotheca, pali, synapticulae, trabecular structures, endothecal and exothecal dissepiments are absent, as well as the internal morphological details from the calice, septa and corallum.

Occurrence. United States: Edwards Limestone Formation, Middle Albian; Devils River Limestone, Late Albian; Mexico: Mal Paso Formation, Late Albian (Wells, 1933; Filkorn and Pantoja-Alor, 2009); Brazil: Jandaíra Formation, Turonian-Campanian (present study).

Material. a colony fragment (MCC.C.2-363) from the Mulungu locality, Pendências city, Rio Grande do Norte state, Brazil.

Dimensions. h: 24 mm; l: 103 mm; w: 43 mm; cd: 1.8 – 3.0 mm; s: 14 – 24; wt: 0.1 – 0.2 mm.

Discussion. *Actinastrea guadalupae* (Roemer, 1849) has morphological similarities with *Actinastrea barranquinensis* (Wells, 1944) in the shape and diameter of the corallites, as well as in the thickness of the wall that separates them. However, *A. barranquinensis* presents more septa, less thick and disposed in nonamers arrangement. Besides, the endothecal dissepiments are moderately developed in *A. barranquinensis*. On the other hand, the dissepiments in the *A. guadalupae* type were not individualized.

Affinities between *A. guadalupae* and *A. hexamera*, *A. dickersoni* and *A. peruviana* were also recognized. However the characters related to the septa (number and arrangement) and corallites (shape, disposition and diameter) are particularly distinct.

Remarks. We must highlight that the variation in the calice shapes regarding the calicular extremity and the corallites accretion pattern varies with the convexity of the substratum, and may interfere in the taxonomic characterization of the *Astrocoenia* - *Actinastrea* clade.

Suborder Astrocoeniina Vaughan and Wells, 1943

Family Astrocoeniidae Koby, 1890

Subfamily Astrocoeniinae Koby, 1890

Genus *Stephanocoenia* Milne Edwards and Haime, 1848

Type species. *Astrea intersepta* Lamarck, 1816

Diagnosis. Corallum colonial massive, plocoid to subcrioid. Corallites small to medium size, separated by

septothechal to parathechal walls. Septa disposed in three cycles with denticulate outlines and composed by a 12 paliform lobes system in the first two cycles. Columella styliiform. Endothecal and exothecal dissepiments, evenly spaced. Based on Wells (1956) and Budd (1987).

Distribution. Cretaceous - Recent (Wells, 1956; Budd, 1987).

Stephanocoenia guadalupae Wells, 1932

Figures 3C, 3D

Description. Corallum colonial massive, incrusting, plocoid to subplocoid and irregularly flat-convex. Corallites numerous, small and cylindrical, separated by thin, smooth or granule-ribs ornamented septothechal walls. Calices shallow, monocentric, circular projected above the surface of the corallum and elevated in its superior edges. Septa equal to subequal, straight, equidistant, laterally beaded and hexamerally arranged in three incomplete to complete cycles, ranging from 22 to 24 units. Septal margins arched upwards, denticulate and smooth. The septa from the first and second cycle are even, elongated, thick and merged internally in a ring-shaped system of 12 pali, surrounding the columella, with its thickness measuring less than two thirds based on the thickness of the first septa. The septa from the third cycle are short, laminated, less than half of the size of the first two types and does not merge to the paliform system. Columella well developed, thick and irregularly styliiform. Tabular exothecal dissepiments well developed and distributed through the side segments of the corallum. Delicate, continuous and closely spaced external septal furrows. Endothecal dissepiments absent.

Occurrence. United States: Cuchillo Formation, Early Cretaceous; Glen Rose Formation, Early Cretaceous; Venezuela: Barranquín Formation, Early Cretaceous (Wells, 1932, 1946; Von der Osten, 1957); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. a colony fragment (MCC.C.2-108) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. h: 41 mm; l: 73 mm; w: 25 mm; cd: 1.5 – 2.0 mm; s: 22 – 24; wt: 0.3 – 0.8 mm; cdp: 0.1 – 0.2 mm.

Discussion. *Stephanocoenia guadalupae* Wells, 1932 is similar to *S. intersepta* (Lamarck, 1816) in the general shape of the corallum, corallites, columella, septa number, arrangement of the paliform elements and calicular diameter. However, the calices in *S. intersepta* are shallower and there is no occurrence of the *S. guadalupae* diagnostic ornamentations. Another comparable species is *S. peruviana* Vaughan, 1922, but the number, shape and septa arrangement are dissimilar. There were also some recognized similarities with *S. formosa* Milne Edwards and Haime, 1849 and *S. storrsi* Wells, 1941, regarding the number and depth of the calice, the shape, number and arrangement of septa and corallites, as well as the paliform structures.

Family Pocilloporidae Gray, 1842
Genus *Madracis* Milne Edwards and Haime, 1849

Type species. *Madracis asperula* Milne Edwards and Haime, 1850.

Diagnosis. Corallum colonial plocoid, submassive to branchy. Septa few disposed in two octamer cycles, incomplete to complete. Septa from the first cycle merge to the collumela or with the paliform lobe system. Septa from the second cycle rudimental to absent. Columella styliform proeminent. Based on Wells (1956) and Neves and Johnsson (2009).

Distribution. Late Cretaceous - Recent (Wells, 1956; Baron-Szabo, 2006).

Madracis johnwellsi Frost and Langenheim, 1974
Figure 3E

Description. Corallum colonial thick, branching, cylindrical, dendroid and plocoid with oval extremity. Corallites massive, numerous, small and spherical, separated by thick granulated walls, smooth or beaded. Calices shallow equivalent to the surface of the corallum, monocentric, circular with slightly arched margins, corresponding to the septal elements. Septa equal to subequal, laminate to thick, equidistant and octamerally arranged in two incomplete to complete cycles, ranging from 14 to 16 units. Septal margins arched, subcrenulated and beaded by granules. The septa from the first cycle are equal, elongated, thick and internally merged in an eight pali ring-shaped system surrounding the columella, with its thickness equivalent to that of the first septa. The septa from the second cycle are rudimental, laminated, not merged to the paliform system. Columella well developed, thick, styliform, with a central tubercle inside. Holotheca, synaptical, trabecular structures, endothecal and exothecal dissepiments absent.

Occurrence. China: Gamba County Houshan, Campanian-Maastrichtian; Mexico: Cerralvo, Early Maastrichtian; Jamaica: Maldon Formation, Late Maastrichtian; Mexico: Ixtaclum Shale Formation, Late Eocene (Frost and Langenheim, 1974; Baron-Szabo, 2006). Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. A colony fragment (MCC.C.2-350) from Arapuá locality, Ipanguaçú city, Rio Grande do Norte state, Brazil.

Dimensions. bl: 42 mm; bd: 10 mm; cd: 1.1 – 1.5 mm; s: 14 – 16; wt: 0.6 – 1.5 mm; cdp: 0.1 – 0.2 mm.

Discussion. *Madracis johnwellsi* Frost and Langenheim, 1947 presents some morphological similarities with *M. vaughani* Wells, 1941 and *M. densa* Budd, 1992, particularly in the shape of the corallum, corallites, calices and columella. However, in Wells' species, the branches of the corallum are thinner, the corallites are bigger, the separation walls are thicker and the septa appear in larger

quantities, arranged in a decamer arrangement. Whereas Budd's species shows thinner separation walls between the corallites, deeper calices and septa disposed in a different arrangement, and displayed in different numbers.

Suborder Fungiina Verril, 1865
Family Montlivaltiidae Löser, 1994
Genus *Isastrea* Milne Edwards and Haime, 1851

Type species. *Astrea helianthoides* Goldfuss 1826

Diagnosis. Corallum colonial, massive and cerioid. Corallites monocentric or dicentric, polygonal over the calicular outline, separated by zig zag-shaped septothecal to parathecal walls. Costae rudimentary or absent. Septa delicate, compact, confluent, anastomosing in the axial zone, continuous, arched to recurved, rarely winding and uneven when it comes to length and width. Endothecal dissepiments numerous, small and vesicular. Synapticulae rarely present. Columella absent, but trabecular in depths of axial zone. Based on Wells (1956).

Distribution. Middle Jurassic - Cretaceous (Wells, 1956).

Isastrea whitneyi Wells, 1932
Figure 4A

Description. Corallum colonial, massive, incrusting, cerioid to subplocoid and irregularly convex. Corallites small and prismatic, separated by thick, continuous or zig-zag oriented synaptical walls. Calices subshallow, broad, monocentric, polygonal ranging from pentagonal to quadrangular in outline. Septa equal to subequal, straight, laminate, equidistant, continuous, compact and hexamerally arranged in four incomplete cycles, ranging from 28 to 44 units. Septal margins subcrenulated, slightly arched and beaded by granules. The septa from the first and second cycle are subequal, extended to the central area where it merges to the columella. Conversely, the septas from the third and fourth cycles are less thick than the first two types, apparently not merging to the columella. Columella poorly preserved subtrabecular to trabecular, continuous and elongated. Holotheca, pali, trabecular structures, endothecal and exothecal dissepiments absent, as well as the internal morphological details of the septa in the corallum.

Occurrence. United States: Cuchillo Formation, Early Cretaceous; Glen Rose Formation, Early Cretaceous; Venezuela: Barranquín Formation, Early Cretaceous (Wells, 1932, 1946; Von der Osten, 1957); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. a colony fragment (MCC.C.2-025) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. h: 26 mm; l: 36 mm; w: 30 mm; cd: 3 – 4.5 mm; s: 28 – 44; wt: 0.3 – 0.5 mm; cdp: 0.5 – 0.8 mm.

Discussion. The morphological features of *Isastrea whitneyi* Wells, 1932 are very similar to the ones recognized

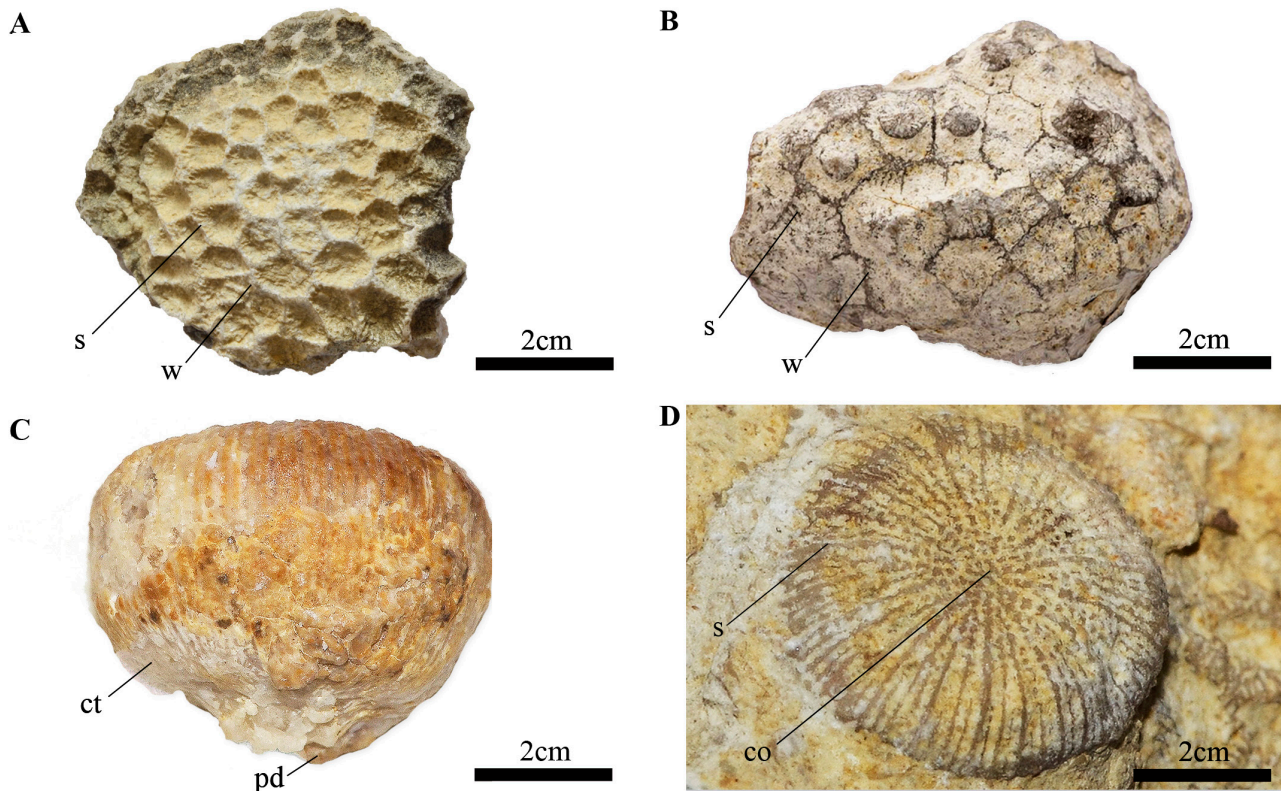


Figure 4. A. *Isastrea whitneyi* Wells, 1932 (MCC.C.2-025): upper surface view of prismatic corallites and polygonal calices; B. *Isastrea* sp. (MN 5565-I-A): corallum cerioid to subplocoid and big and prismatic corallites; C. *Paracycloseris effrenatus* Filkorn and Pantoja-Alor, 2009 (MCC.C.2-312): corallum tympanoid and cupuliform, with a small and delicate pedicel; D. *Paracycloseris effrenatus* Filkorn and Pantoja-Alor, 2009 (MCC.C.2-303): upper surface view of discoid calice and circular to subcircular calicular extremity (co: columella; ct: costae; s: septa; pd: pedicel; w: walls).

in some species of *Actinastrea* d'Orbigny, 1849, especially *A. kellumi* (Wells, 1946), *A. barranquinensis* (Wells, 1944) and *A. guadalupae* (Roemer, 1849) regarding the shapes of corallum, corallites and calices. However, *A. kellumi*, *A. barranquinensis* and *A. guadalupae* differentiate themselves by presenting smaller corallites in diameter, shallower calices, less numerous septa, styliform columella and abundant endothecal dissepiments.

Isastrea sp.
Figure 4B

Description. Corallum colonial massive, incrusting, cerioid to subplocoid and irregularly convex. Corallites big and prismatic, separated by thin, continuous and straight synapticulathecal walls. Calices shallow, broad, monocentric, polygonal ranging between pentagonal and hexagonal. Septa equal to subequal, straight, laminate, equidistant, continuous, compact and inferred from 20 to 24 units with no arrangement definition or cycle order. Columella, holotheca, pali, trabecular structures, endothecal and exothecal dissepiments absent, as well as diagnostic morphological details concerning the insides of the calices and septa.

Occurrence. Brazil- Jandaíra Formation, Turonian-Campanian (present study).

Material. two colony fragment (MN 5565-I-A and MN 5565-I-B) from the RN-118 road, 20 km from the crossroad with BR-304, Ipanguaçu city, Rio Grande do Norte state, Brazil, housed on the paleoinvertebrates collection at Museu Nacional/UFRJ.

Dimensions. (MN 5565-I-A) h: 14 mm; l: 31 mm; w: 23 mm; cd: 1.6 – 2 mm; s: 20 – 24; wt: 0.4 – 1.2 mm. (MN 5565-I-B) h: 17 mm; l: 30 mm; w: 24 mm; cd: 4.8 – 6.8 mm; wt: 0.2 – 0.3 mm; cdp: 0.5 – 0.8 mm.

Discussion. The cerioid shape of the corallum, polygonal corallites, septothecal walls and absent columella are enough to consider these specimens as *Isastrea*. The effects of the diagenetic processes destroyed or erased the morphological features of corallites, calice and septa, which impeded its identification at specific level.

Remarks. These specimens were identified only up to order level by Fernandes and Wanderley (2000).

Suborder Microsolenina Morycowa and Roniewicz, 1995
Family Felixaraeidae Beauvais, 1982
Genus *Paracycloseris* Wells, 1934

Type species. *Paracycloseris elizabethae* Wells, 1934

Diagnosis. Corallum solitary and depressed, cupolate, patellate, conical to convex and flat in shape. Epitheca thick, wrinkled and concentric, with indistinct walls. Calice circular, with oval to elongated fosseta, superficial on the juvenile and shallow on the adult specimens. Septa numerous, compressed, trabecular-fenestrated, united as in *Cycloseris*, with pores filled with lacerated teeth, and covered with granules. Columella thick, well developed, papillose. Irregular synpticalae on the corallum, around the border of the calice. Dissepiments absent. Diagnosis based on Wells (1934, 1956).

The morphological features of this taxon are very similar to the ones seen on *Podoseris* Duncan, 1869, especially regarding the size and shape of the corallum, the pattern and outline of the calice, and the number and disposition of the septa. However, this taxon is primarily distinguished by its septal trabecular microstructures around the central septa area, the ornamentation pattern of its epitheca, its styliform columella and the big number of endothecal dissepiments. (Löser, 2012).

Distribution. Early to Late Cretaceous (Wells, 1956; Filkorn and Pantoja-Alor, 2009).

Paracycloseris effrenatus Filkorn and Pantoja-Alor, 2009
Figures 4C, 4D

Description. Corallum small, solitary, free, tympanoid with a subconvex base on the juvenile specimen and flat cupuliform with a subconcave to convex base on the adult specimen. Calice monocentric, discoid, slightly depressed with circular to subcircular calicular extremity, fixed by a small and delicate pedicel with subdeltaic outline and rounded extremity. Epitheca ornamented by regularly spaced wrinkles, concentric transversal ripples and granules. Septa hexamerally arranged in five complete cycles and an incomplete one with about 104 units on the adult sample and five incomplete cycles with about 81 on the younger sample. Septa numerous, straight, equal to subequal, equidistant arched upwards, laminar, closely spaced and laterally granulated. The first two cycles are equal, thicker than the others, extended to the columella, its top edges are provided with well developed teeth. The septa from the third cycle are smaller than the ones from the first and second cycle, yet get attached to the columella with top edges with smaller teeth. The fourth cycle septa are fused to the fifth cycle septa, with its teeth being smaller than the first three cycles, but they do not merge to the columella. The few septal pairs on the sixth cycle are provided with smaller teeth compared to the bigger cycles and they do not merge to the columella. Fosseta elliptical and shallow. Columella well developed, subtrabecular, with its superior surface being papillose to spongy, vertically continuous and narrow. Synapticulae poorly preserved and present in medium-upper segments on the peripheral region next to the calice. Costae, endotheca, dissepiments and palliform lobes

not visible, as well as the morphological details concerning the wall of the corallum.

Occurrence. Mexico: Mal Paso Formation, Late Albian (Filkorn and Pantoja-Alor, 2009); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. A young specimen (MCC.C.2-303) and an adult specimen (MCC.C.2-312) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. (MCC.C.2-303) l: 9 mm; w: 8 mm; cd: 9 mm. (MCC.C.2-312) h: 13 mm; l: 16 mm; w: 15 mm; cd: 16 mm.

Discussion. Similarities between this species and *Paracycloseris elizabethae* Wells, 1934 were noticed regarding the general shape of the corallum, pattern and outline of the calice, shape and depth of the fosseta, ornamentation of the epitheca, presence of synapticulae on the peripheral portions of the corallum, and absence of dissepiments and columella shape. However, these species differ in the dimensions of the corallum, septa number and width of the columella. *P. elizabethae* displays a bigger calicular diameter and about 200 septa disposed in seven incomplete cycles. Moreover, the columella is well developed with its upper surface being papillose to spongy, trabecular and narrower in *P. effrenatus* and trabecular and thicker in *P. elizabethae*.

Family Merulinidae Verrill, 1866
Genus *Orbicella* Dana, 1846

Type species. *Madrepora annularis* Ellis and Solander, 1786

Diagnosis. Corallum colonial, equal to subequal corallites, with septothecal and parathecal separation walls. Calice circular, small in diameter (< 4 mm) and depth (< 3 mm). Septa laterally granulated arranged in three cycles, ranging between 24 and 36 units. Columella trabecular, discontinuous, either bigger or equal to a quarter of the calice diameter. Epitheca moderately to well developed. Paliform lobes absent. Diagnosis based on Wells (1932, 1956).

The diagnostic features of these taxa are similar to the features of *Polyphylloseris* Fromentel, 1857, especially the shapes of corallum, corallites and columella. However, Fromentel's genus is distinguished by the presence of bigger corallites, an elevated calice and abundant synapticulae and endothecal dissepiments. It is also possible to recognize affinities with *Montastraea* Blainville, 1830 regarding the shape of the corallum, corallites, calice and columella (Wells, 1941, 1956).

Distribution. Cretaceous - Recent (Wells, 1932).

Orbicella travisensis Wells, 1932
Figure 5A

Description. Corallum colonial massive, incrusting, subplocoid to plocoid, subelliptical outline, convex. Corallites numerous, small and cylindrical, separated

by septothecal thick walls, beaded by granules and ribs corresponding to the septa. Calices shallow, monocentric, circular and elevated in its superior edges. Septa equal to subequal, straight to recurved, laminated, equidistant, laterally granulated and hexamerally arranged in three incomplete to complete cycles, ranging between 20 and 24 units. Septal margins denticulate, smooth and arched to upper segments to the calice. The septa from the first and second cycles are subequal, thick and extended to the center where they merge to the columella. The septa from the third cycle are less thick, rarely extended to more than a third of the length of the first ones. Columella trabecular, well developed, continuous and elongated. Exothecal dissepiments sparse, present on the separation walls between the corallites. Holotheca, pali, synapticulae, trabecular structures and endothecal dissepiments absent.

Occurrence. United States: Travis Peak Formation, Early Cretaceous (Wells, 1932); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. Two colony fragments (MCC.C.2-105 e MCC.C.2-111) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. (MCC.C.2-105) h: 15 mm; l: 72 mm; w: 30 mm; cd: 1.7 – 2.1 mm; s: 20 – 24; wt: 0.5 – 1.1 mm. (MCC.C.2-111) h: 21 mm; l: 65 mm; w: 20 mm; cd: 1.6 – 2 mm; s: 20 – 24; wt: 0.4 – 1.2 mm.

Discussion. *Orbicella travisensis* Wells, 1932 has some similarities with *O. whitneyi* (Wells, 1932) and *O. roemeriana* Wells, 1933 related to the general shape of corallum and corallites, calice depth, and number, shape and disposition of calices. However, the corallites in *O. whitneyi* are smaller, the separation walls between them are less thick, columella is spongy and exothecal dissepiments are more abundant. On *O. roemeriana* the corallites are bigger, the separation walls between them are thicker and the columella is spongy to styliform.

Suborder Caryophylliina Vaughan and Wells, 1943

Family Turbinoliidae

Subfamily Turbinollinae Milne Edwards and Haime, 1848

Genus *Turbinolia* Lamarck, 1816

Type species. *Turbinolia sulcata* Lamarck, 1816 emend. Milne Edwards and Haime, 1850.

Diagnosis. Corallum solitary trochoid, ceratoid, conical and circular on the calicular outline. Walls smooth or externally perforated, separated by deep furrows. Septa disposed from two to four cycles, duplicated in number around the calicular border. Columella styliform or laterally compressed, formed by the fusion of primary septa. Pali absent. Diagnosis based on Wells (1956, p. F425).

Distribution: Eocene - Oligocene (Wells, 1956; Cairns, 1989).

Subgenus *Turbinolia* (*Turbinolia*) Lamarck, 1816

Type species. same as the genus.

Diagnosis. Walls and septa smooth and not ornamented. Diagnosis based on Wells (1956).

Distribution. same as genus (Wells, 1956).

Turbinolia (*Turbinolia*) *insignifica*? Vaughan, 1900

Figure 5B

Description. Corallum solitary, small, free, conical to turbinated and laterally compressed. Calice subcircular, monocentric, shallow, with slightly convex edges, smooth and continuous in extremity and oval to subelliptical outline. Pedicel small, cylindrical and well developed with rounded and oblate base. Costae smooth and well defined on the calicular margin, regularly spaced and bounded by dense ribs corresponding to the first septal cycle, separated by shallow and planed furrows. Septa arranged in a heptamerally complete cycle with seven units, well developed, straight, equal to subequal, dense, smooth, equidistant and regularly spaced. Septa joined by the base to the pedicel, radially arched above the calice surface, shaped by pronounced denticulations that merge themselves to form the columella. Pit subcircular and shallow. Columella styliform and papillose. Synapticulae, trabecular structures, paliform lobes, endothecal and exothecal dissepiments absent.

Occurrence. United States: Red Bluff Formation, Oligocene (Vaughan, 1900); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. a juvenile specimen (MCC.C.2-359) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. h: 14 mm; l: 11 mm; w: 10 mm; cd: 9 mm.

Discussion. *Turbinolia* (*Turbinolia*) *insignifica* Vaughan, 1900 is recorded on the Oligocene of North America. However, its morphological affinities with the specimen here described may represent the first occurrence of this taxon, so as *Turbinolia* Lamarck, 1816 in the Cretaceous. The reported specimen presents similarities with *T. (T.) insignifica* in the shape and size of corallum, calice, pedicel and columella, as well as in costae and septa arrangement. But the internal diagnostic morphological features of the calice, and the morphology and septal organization of the epitheca, are little visible due to the preservation process, preventing the undoubted positioning as *T. (T.) insignifica*.

There were also some recognized affinities with *T. sulcata* Lamarck, 1816 and *T. pharetra* Lea, 1833, both Cenozoic species. In Lamarck's species, besides the general shape of calice, pedicel and columella, and the costae arrangement being similar, the corallum is more flattened and septa are present in bigger number and divergent arrangements. In relation to *T. pharetra*, the general shape of the calice and columella are similar, where in Lea's specie, the corallum is more elongated, the septa are more numerous and ornamented and the pedicel is more tapered.

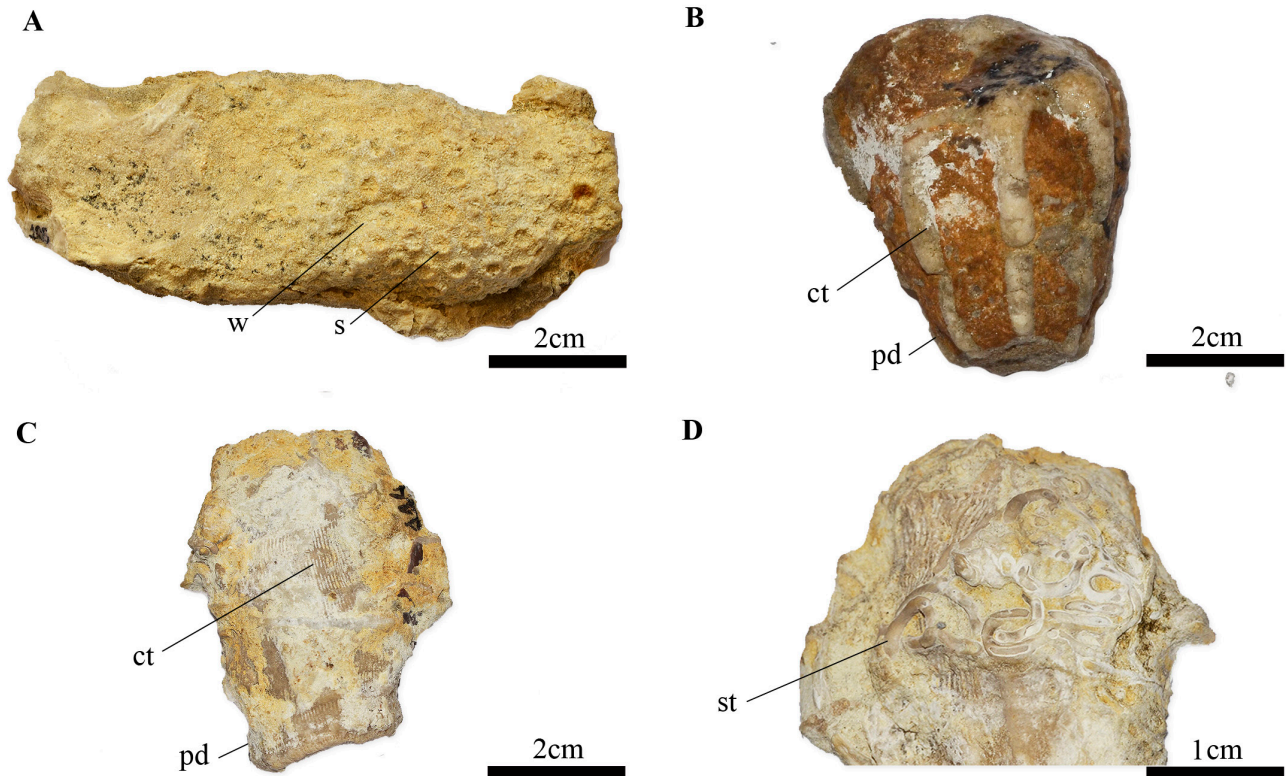


Figure 5: A. *Orbicella travisensis* Wells, 1932 (MCC.C.2-105): corallum subplocoid to plocoid with small and cylindrical coralites, separated by thick walls; B. *Turbinolia (Turbinolia)? insignifica* Vaughan, 1900 (MCC.C.2-359): lateral view of corallum conical and turbinated and a cylindrical and well developed pedicel; C. *Placotrochus? texanus* (Vaughan, 1903) (MCC.C.2-114): lateral view of corallum tympanoid to turbinated, moderately recurved and a well developed pedicel; D. *Placotrochus? texanus* (Vaughan, 1903) (MCC.C.2-114): lateral view of the corallum and thick stereome deposits. (ct: costae; pd: pedicel; s: septa; st: stereome; w: walls).

Family Flabellidae Bourne, 1905

Genus *Placotrochus* Milne Edwards and Haime, 1848

Type species. *Placotrochus laevis* Milne Edwards and Haime, 1848

Diagnosis. Corallum solitary cuneiform, turbinated and laterally compressed. Epitheca well developed and tecal extremity ornamented by thorns. Septa numerous, disposed in four to seven cycles. Columella rudimentary and irregularly lamellar. Pali absent. Diagnosis based on Wells (1956).

Distribution. Late Cretaceous - Recent (Wells, 1933; 1956).

Placotrochus texanus? (Vaughan, 1903)

Figures 5C, 5D

Description. Corallum solitary, cuneiform, moderately recurved, tympanoid to turbinated, laterally compressed, elliptical when transversally cut and subconvex base. Calice monocentric, elliptical on the upper edge and fixed by a well developed pedicel endowed with subcircular outline and irregularly rounded extremity. Costae equivalent to the septal walls, ornamented by granules and thorns. Epitheca

well developed, discontinuous due to thick stereome deposits in medium-superior segments of the corallum. Septa hexamerally arranged in six incomplete cycles with about 110 units, numerous, straight, equal to subequal, laminated and laterally granulated. Fosseta subcircular. Columella rudimentary, elongated and irregularly lamellar. Synapticulae, paliform lobes and dissepiments not visible, as well as the morphological details of the septa in the calice and corallum.

Occurrence. United States: Buda Formation, Late Cretaceous (Wells, 1933); Brazil: Jandaíra Formation, Turonian - Campanian (present study).

Material. an adult specimen (MCC.C.2-114) from São José locality, Alto do Rodrigues city, Rio Grande do Norte state, Brazil.

Dimensions. h: 33 mm; l: 25 mm; w: 14 mm; cd: 17 mm.

Discussion. The North American species *Placotrochus texanus* (Vaughan, 1903) was the first one belonging to *Placotrochus* Milne Edwards and Haime, 1848 to be recognized in the Cretaceous. The sample here described presents similarities with this species in the general shape of corallum and calice, costae arrangement, septal number and disposition, shape of the columella, presence of tereome,

and absence of dissepiments. Moreover, the dimensions of the North American species are smaller and proportional to the specimen here studied. However, the internal diagnostic morphological features of the calice and septa are poorly visible, preventing the undoubted framing as *P. texanus*.

There were also recognized similarities with *P. fuscus* Vaughan, 1907 and *P. laevis* Milne Edwards and Haime, 1848, both Cenozoic species. In Vaughan's species, the shape of corallum and columella, epithecal development and septal ornamentations are similar, but the shape of calice and pedicel, costae disposition and number of septa are really distinct. *P. laevis* shares a similar shape of calice and columella, epithecal development and septal number and arrangement. However, the calice from the individual that belongs to the Jandaíra formation is compressed laterally to a bigger extent, the septa are present in bigger number and the pedicel is more pronounced.

5. Age and palaeobiogeographic distribution

The high diversity in the coral associations studied in this work suggests proximity to center-of-diversity and high ocean surface temperature. This scenario reveals that the species are transported on surface currents into high-diversity regions from surrounding, isolated peripheral areas and subsequently dispersed from these high-diversity centers. The Cretaceous corals of southwestern Mexico are very important due to southern continental Mexico being centrally positioned in the tropical western Tethyan region during the Early and Middle Cretaceous (Filkorn and Pantoja-Alor, 2009).

The faunal similarity among the early Aptian coral species of Mexico and the coral fauna of the European region with adjacent areas of southeastern Mexico, northern South America, northwestern Mexico-southwestern USA and northern Mexico-Texas, indicates that the species were dispersed to North America and Mexico from localities in the European region, first by a westward flowing surface current, then by a southern route through the western Tethys Sea, typifying a very low endemism (Filkorn and Pantoja-Alor, 2009). The temporal-spatial distribution of the species in the late Albian-early Cenomanian indicates a much higher endemism, as well as the development of a south to southwest flowing surface current from Texas to southern Mexico and the Caribbean region (Filkorn and Pantoja-Alor, 2009), probably spreading continuously to northeastern Brazil during the Turonian-Campanian. This distribution attests to the existence of a southward flowing surface current streaming from the northeastern Mexico-Texas region to southwestern Mexico during the middle to late Albian. The occurrence of the genus *Paracycloseris* Wells, 1934, for example, in the Albian of Egypt, the late Albian-early Cenomanian of Mexico, and Upper Cretaceous of Jamaica, Cuba, Mexico and Brazil may help to establish

a dispersal pathway along the more southern route. Also, the corals of the Jandaíra Formation show affinities to Lower Tertiary faunas of Central America (Panama, Jamaica, Cuba, Antigua) and Venezuela in South America. Future studies will allow to define other possible intermediate biogeographic connecting points existing in the Caribbean and South America regions (Filkorn and Pantoja-Alor, 2009), as suggested by the occurrence of the *Stephanocoenia guadalupae*, *Isastrea whitneyi*, *Actinastrea guadalupae*, *Paracycloseris effrenatus* and *Orbicella travisensis* species, typical of the Lower Cretaceous. The recognition of *Actinastrea decaturensis* and *Turbinolia (T.) insignifica* is seen to be related to the scleractinian high diversity that occurs in the Cretaceous (Budd, 2000) and which lasted until the Neogene.

The record of the Agaricidae Gray, 1847, Caryophyllidae Gray, 1847 and Flabellidae Bourne, 1905 families and the Fungiidae Dana, 1846 and Faviidae Gregory, 1900 superfamilies in the Jandaíra Formation (Turonian of northeastern Brazil) and the Pirabas Formation (Lower Miocene of northern Brazil) confirms that a dispersal pathway along to southern route was very important to scleractinian establishment and biogeographical spreading in the South Atlantic during the Tertiary and Quaternary.

6. Conclusions

This work presents the first detailed taxonomic study of the Turonian - Campanian coral fauna from the Jandaíra Formation of Rio Grande do Norte state, Brazil. This fauna is composed of 10 species, including 7 colonial, reef-building species and 3 solitary species. This is the first time that 9 of these 10 species have been reported from Brazil. The majority of these species are restricted to the United States and Mexico. Moreover the coralino-fauna shows close affinities to Lower Tertiary faunas of Central America (Panama, Jamaica, Cuba, and Antigua) as well as Venezuela in South America.

This similarity supports the correlation of the Jandaíra Formation with other shallow marine Cretaceous units within the United States and Mexico. The studied association represents the westernmost hermatypic assemblage of the scleractinian coral occurrence of the Turonian, characterized by massive and branching growth types and plocoid, cerioid and dendroid polyp integration types. Tympanoid, cuneiform and conical solitary taxa were also found.

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