Revista Brasileira de Paleontologia, 25(4):292–302, Outubro/Dezembro 2022
A Journal of the Brazilian Society of Paleontology
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doi:10.4072/rbp.2022.4.04

PALEOECOLOGICAL CHARACTERIZATION OF OSTRACODS IN BEACHROCKS FROM THE NORTHERN SECTOR OF THE RIO GRANDE DO SUL COASTAL PLAIN, BRAZIL

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ABSTRACT – A micropaleontological analysis on 15 beachrock samples from the Northern sector of Rio Grande do Sul Coastal Plain (RSCP), southern Brazil, revealed a relatively diverse and well-preserved ostracod assemblage composed of 16 species, including *Cyprideis multidentata* Hartmann, *Callistocythere nucleoperiscum* Whatley *et al*., *Cytheretta punctata* Sanguinetti, *Caudites ohmerti* Coimbra & Ornellas, and *Argenticytheretta levipunctata* Sanguinetti *et al*. Eleven ostracod species are left in open nomenclature or tentatively identified. Besides ostracods, some foraminifers, echinoderm spines, and fish remains (teeth) were also recovered; however, the scarcity of specimens or poor preservation precluded identification at species level. Based on the Ostracoda taxonomic composition it is proposed that the beachrocks characterize environmentally condensed assemblages. This preliminary study reveals the importance and potentiality of micropaleontology for understanding the processes involved in the formation of beachrocks.

Keywords: Pelotas Basin, Quaternary, coastal environments, micropaleontology, taphonomy.

RESUMO – O estudo micropaleontológico de 15 amostras de arenitos de praia provenientes do setor norte da Planície Costeira do Rio Grande do Sul (PCRS), sul do Brasil, revelou uma assembleia relativamente diversa e bem preservada de ostracodes, composta por 16 espécies, incluindo *Cyprideis multidentata* Hartmann, *Callistocythere nucleoperiscum* Whatley *et al*., *Cytheretta punctata* Sanguinetti, *Caudites ohmerti* Coimbra & Ornellas e *Argenticytheretta levipunctata* Sanguinetti *et al*. Onze espécies são registradas em nomenclatura aberta ou tentativamente identificadas. Além dos ostracodes, foraminíferos, espinhos de equinodermos e vestígios de peixes (dentes) foram também recuperados, contudo, a baixa abundância e/ou preservação impediram a identificação em nível de espécie. A composição taxonômica dos ostracodes indica que estas rochas registram assembleias ecologicamente condensadas. Este estudo preliminar revela a importância e potencialidades da micropaleontologia para a caracterização dos processos envolvidos na formação de arenitos de praia.

Palavras-chave: Bacia de Pelotas, Quaternário, ambientes costeiros, micropaleontologia, tafonomia.

INTRODUCTION

Beachrocks are sandstones typical of shallow marine environments (inner continental shelf) containing a variable amount of sediment matrix, mostly clastic sand and bioclasts, friable or cemented with carbonate (aragonite or calcite). These rocks are mainly formed in tropical/subtropical coasts under microtidal influence (Russel, 1962; Stoddart & Cann, 1965; Hanor, 1978; Turner, 2005; Vousdsoukas *et al*., 2007), and their fragments are commonly eroded and transported to the shore by waves. Quaternary beachrocks are characteristically well-cemented and contain a larger proportion of sandy matrix with bioclasts, whereas the poorly cemented shell debris with less matrix are designated coquinas (Bissell & Chilingar, 1967).

Darwin (1841) published the first description of a beachrock formation in the Brazilian coast, and Branner (1904) described several other formations (‘stone reefs’) in the northeastern Brazilian coast. Beachrocks formation is apparently restricted to foreshore settings, as result of precipitation of calcium carbonate dissolved in seawater, under influence of phreatic water and mean annual temperatures > 20ºC (Russell, 1962; Stoddart & Cann, 1965). Recent beachrock formations occur only in tropical areas of the coast from 4° to 16°S, but beachrocks of late Pleistocene-Holocene age are found along the southeastern and southern coasts, from the Rio de Janeiro to Rio Grande do Sul states (Mabesoone, 1964; Delaney, 1965; Suguio, 2001; Malta & Castro, 2018; Simioni *et al*., 2018). Considering their association with tropical settings, the beachrocks found in subtropical areas of the Brazilian coast are relevant from a paleoclimatic standpoint. Moreover, beachrocks are also relevant for their paleontological content, which varies significantly – even in macroscopic analysis – in terms of abundance, composition, and preservation of the bioclasts.

In spite of the abundance of beachrocks along the Rio Grande do Sul Coastal Plain (**RSCP**), paleontological studies on these rocks are completely absent in the literature. Macroscopically, the main bioclastic constituents of the beachrocks are mollusk shells, in some cases associated with vertebrate remains (Lopes & Ferigolo, 2015), but microfossils (foraminifers and ostracods) were also found in coquinas of carbonate-cemented sand and shells formed in lagoon settings (Lopes *et al*., 2021). The presence of microfossils increases the importance of beachrocks for the reconstruction of depositional environments and paleoecological studies. The main purpose of this work is, therefore, to contribute to the improvement of the knowledge on beachrocks found in the northern sector of the RSCP by means of a micropaleontological analysis focused mainly on the taxonomy and taphonomy of ostracods.

STUDY AREA

The Pelotas Basin is located in the southern portion of the Brazilian continental margin, and its filling began after the fragmentation of the Gondwana supercontinent (Dias *et al*., 1994; Bueno *et al*., 2007; Barboza *et al*., 2021). The subaerial portion of this basin consists of a > 700 km-long, 20 to 80 km-wide coastal plain. The innermost part of the plain, close to the rocky basement, consists of alluvial fans systems of Miocene–Pleistocene age (Closs, 1970), and four lagoon–barrier systems formed by glacioeustatic oscillations directly related to three Pleistocene and one Holocene interglacial marine isotope stages (**MIS**). The Lagoon–Barrier I System was presumably deposited during the MIS 11 (Villwock & Tomazelli, 1995), but numerical ages are not available so far, and the System II might have been formed during the MIS 9 (Villwock & Tomazelli, 1995), although numerical ages suggest a MIS 7 age (Lopes *et al*., 2014, 2020), which could indicate a MIS 9 age for the System I (Rosa *et al*., 2017). The System III was deposited during the MIS 5, and the system IV during the MIS 1 (Villwock *et al*., 1986; Villwock & Tomazelli, 1995; Dillenburg & Barboza, 2014).

The Holocene system IV corresponds to a ~750 km-long costal barrier with several lakes and lagoons developed landwards. It is assumed that around 17.5 ka BP the sea level was approximately 120–130 lower than today (Martins *et al*., 1985; Corrêa, 1996) and the coastline was located close to the shelf break. Since then, sea level rose about 1.2 cm/year (Corrêa, 1996) and reached a maximum level of +1 to +3 m relative to the present between 6 and 5 ka approximately, followed by a general falling trend up to the present (Angulo *et al*., 2006; Barboza *et al*., 2021). The coastal Holocene barrier presents different sectors with stable, progradational, and retrogradational patterns (Hesp *et al*., 2005; Travessas *et al*., 2005; Dillenburg *et al*., 2009, 2017; Barboza *et al*., 2011; Lima *et al*., 2013; Caron, 2014; Dillenburg & Barboza, 2014; Bitencourt *et al*., 2020).

MATERIAL AND METHODS

The shoreline along Rio Grande do Sul does not exhibit rocky outcrops, except for Mesozoic rocks in the northernmost sector, but linear structures are found submerged along the continental shelf up to depths of ~40 m (Delaney, 1965; Asp, 1999; Buchmann *et al*., 2001; Caron, 2014). These Quaternary structures, whose precise age is still indeterminate, are formed of sand and shells cemented by calcium carbonate, interpreted as paleo-shorelines, and are the source of beachrock fragments eroded and transported to the shore by waves. For this study, beachrock fragments of different sizes and composition were collected along a short beach sector (~2.5 km-long) in Imbé Municipality between the Tramandaí-Armazém inlet and the Tcherozin Creek (Figure 1), during the autumn and winter of 2021.

The samples were classified according to macroscopic features, and a preliminary analysis under stereomicroscope was carried out to detect the presence of microfossils. A total of 15 samples with the highest number of foraminifers and ostracods were more appropriate for micropaleontological study, including two samples (9 and 10) consisting of crusts of cemented sand formed inside oyster shells. The beachrock samples were washed in tap water to remove loose materials (sand, bioclasts, and other debris), mechanically fragmented, and soaked in Becker glasses with hydrogen peroxide (H_2O_2) p.a., for up to four hours, depending on the reaction of each sample. The Becker then was heated, and the reaction activated for approximately 20 minutes. Following that, the samples were let cooling at room temperature, and the final residue washed through a sediment sieve of 0.063 mm mesh and oven dried. All microfossils found were picked under stereomicroscope and stored in micropaleontological slides for study. Specimens of each morphotype were selected for scanning electron microscopy (**SEM**) at the Instituto Tecnológico de Paleoceanografia e Mudanças Climáticas – OCEANEON of the Universidade do Vale do Rio dos Sinos (**Unisinos**), for identification at the lowest taxonomic category possible. All ostracod specimens figured in this work are held at the ostracod collection of the Museu de Paleontologia Irajá

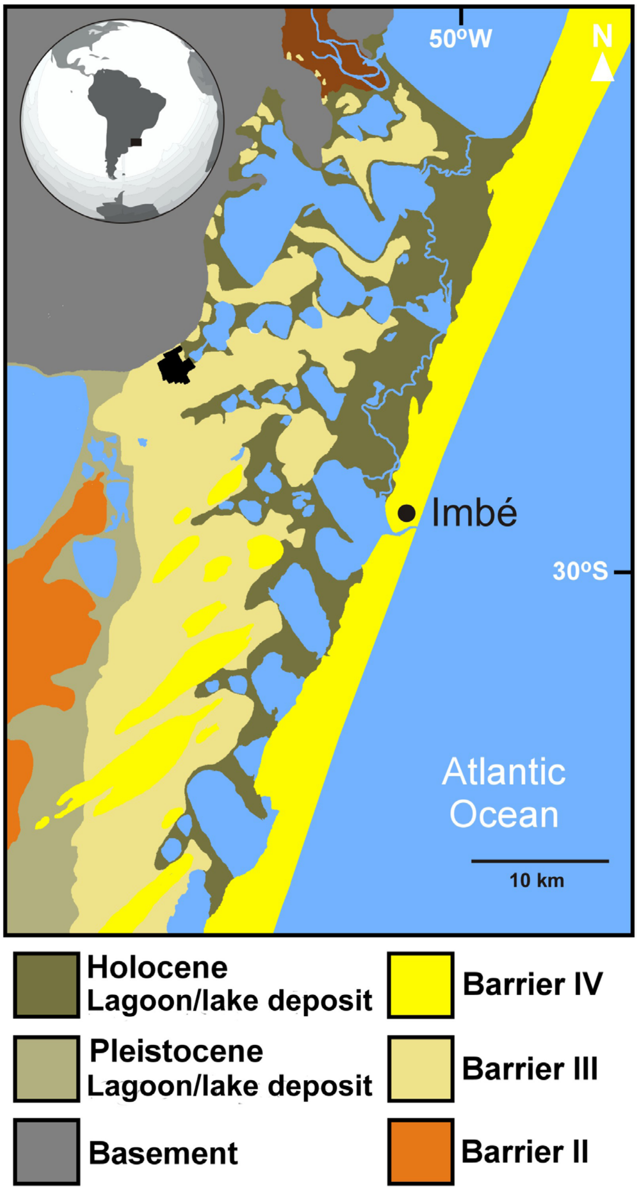

Figure 1. Geological characterization of the RSCP and location of the study area in Imbé Municipality, Rio Grande do Sul State.

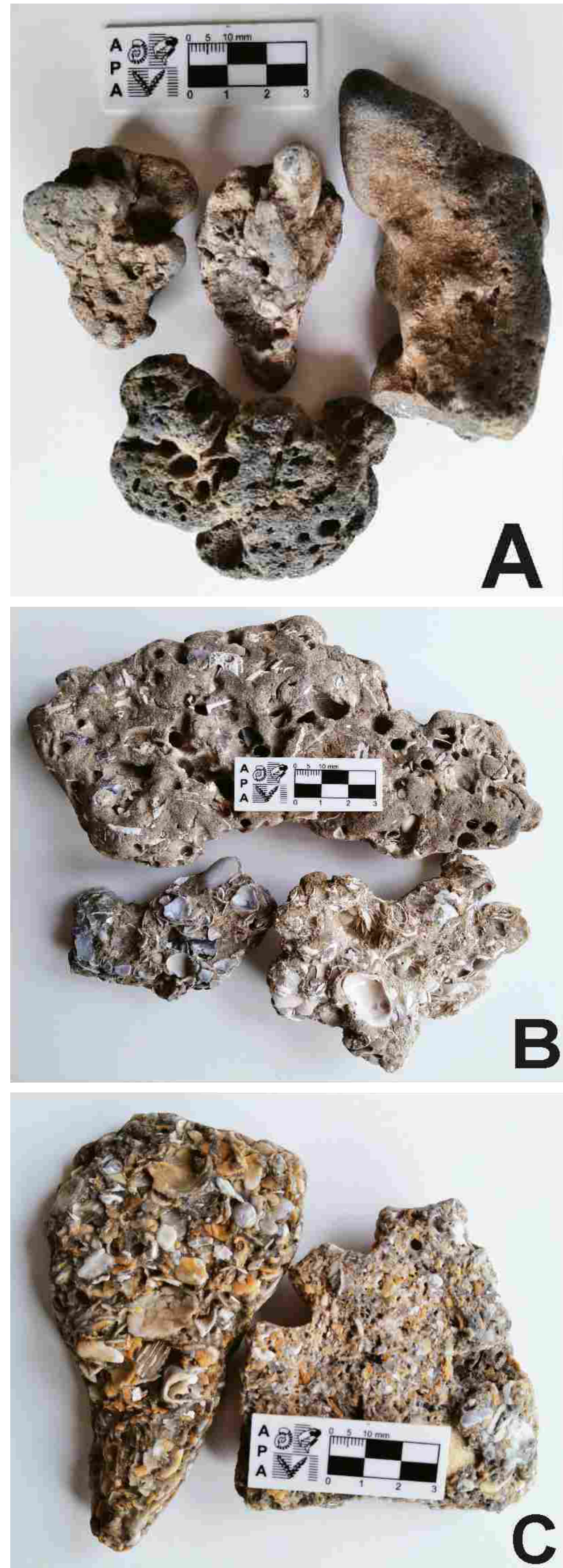

Figure 2. Beachrock types. **A**, Type 1: no macroscopic bioclasts; **B**, Type 2: bioclasts abundant; **C**, Type 3: highly cemented.

Damiani Pinto of the Universidade Federal do Rio Grande do Sul (**MP-O**) under the curatorial numbers 3153 to 3168.

RESULTS

Macroscopically, the samples differ mainly in color and amount of bioclasts, which consist predominantly of mollusks with occasional occurrence of cirripeds. In a microscopic scale, the biogenic constituents also include foraminifers, ostracods, rare fish remains (teeth), and echinoderm spines. Beachrocks classification involves microscopic analysis for identification of the cement and petrologic characterization of these sandstones (Ferreira Jr. *et al*., 2011). However, as this work focused on the analysis of the ostracod assemblages, the samples were classified simply according to their macroscopic characteristics, which resulted in three groups (Figure 2):

Type 1. Composed mostly of siliciclastic sand (quartz) without macroscopic bioclasts (Figure 2A).

Type 2. Siliciclastic matrix with abundant bioclasts (predominantly mollusks), with occasional occurrence of fish teeth and other biogenic remains. The size and concentration of bioclasts is variable. In some cases, the bioclasts are totally dissolved, resulting in high porosity (Figure 2B).

Type 3. Composed mostly of tightly cemented bioclasts with few matrix. The dissolution of this type of beachrock using hydrogen peroxide is very difficult and the recuperation of microfossils was not possible (Figure 2C).

Only beachrocks of the types A and B were examined in this study and microfossils were present in all the samples, yet with variable degree of abundance and preservation (Table 1). The micropaleontological analysis showed the presence of ostracods (**O**), foraminifers (**F**), micromollusks (**M**), fish teeth (**T**) and echinoderm spines (**E**). Microfossils not identified at species or genus level are referred as "**NI**". However, only ostracods were abundant and well-preserved enough to allow taxonomic identification. The 16 ostracod species recorded in 14 of the examined samples were classified into 15 genera and 12 families (Figure 3; Appendix 1). Five ostracod species were identified (*Cyprideis multidentata* Hartmann, 1955; *Cytheretta punctata* Sanguinetti, 1979; *Argenticytheretta levipunctata* Sanguinetti *et al*., 1991; *Callistocythere nucleoperiscum* Whatley *et al*., 1997; *Caudites ohmerti* Coimbra & Ornellas, 1987) and one was tentatively identified (*Costa riograndensis*? Sanguinetti *et al*., 1992). In terms of abundance *C. multidentata* corresponds to 49.6% of the specimens recovered, followed by *A. levipunctata* (16.8%) and *Cytherella* sp. (10.9%).

Foraminifers are represented by a few morphotypes, including some miliolids, but preservation did not allow identification at species level, because the tests were either strongly dissolved or incrusted with carbonate cement. Fish teeth, although well preserved, were recorded only in the samples 5 and 13 and could not be ascribed to any taxon at species or genus level. The echinoderm spines found in the samples 1 and 13 belong to echinoids (sand dollars) possibly of the species *Encope emarginata* Leske, 1778 or *Mellita quinquiesperforata* Leske, 1778, previously recorded in Quaternary deposits of the RSCP (Lopes, 2011) (Table 1).

Table 1. Occurrence and abundance of ostracods and other microfossils in the samples studied. **O**, ostracods; **F**, foraminifers; **M**, micromollusks; **T**, fish teeth; **E**, echinoderm spines; **NI**, unidentified microfossils.

Sample	Volume (cm^3)	*Apatihowella* sp.	*Argenticytheretta levipunctata*	*Argilloecia* sp. 1	*Argilloecia* sp. 2	*Callistocythere nucleoperiscum*	*Caudites* sp.	*Copytus* sp.	*Costa riograndensis?*	*Cyprideis multidentata*	*Cytherella* sp.	*Cytheretta punctata*	*Cytheropteron* sp.	*Hulingsina* sp.	*Parakrithe* sp.	*Pellucistoma* sp.	*Xestoleberis* sp.	Other microfossils (NI)
1	49									4v	1v	1c, 2v						FE
2	29		1c	1v		1c												
3	13	1c	3c		1c				1c	6c	3c, 2v				1c		1c	F
4	20									1c								F
5	29									1c								FMT
6	30									2c		3v						FM
7	34		6c, 3v	1v		8c		1c		18c, 22v	5c							F
8	25																	MO
9	3		2c, 2v				1v			1c, 3v	1c, 1v		1v	1c		2v		F
10	5																	OF
11	22																	F
12	13		1c, 1v															
13	34									1c								FET
14	37																	FO
15	36																	OM

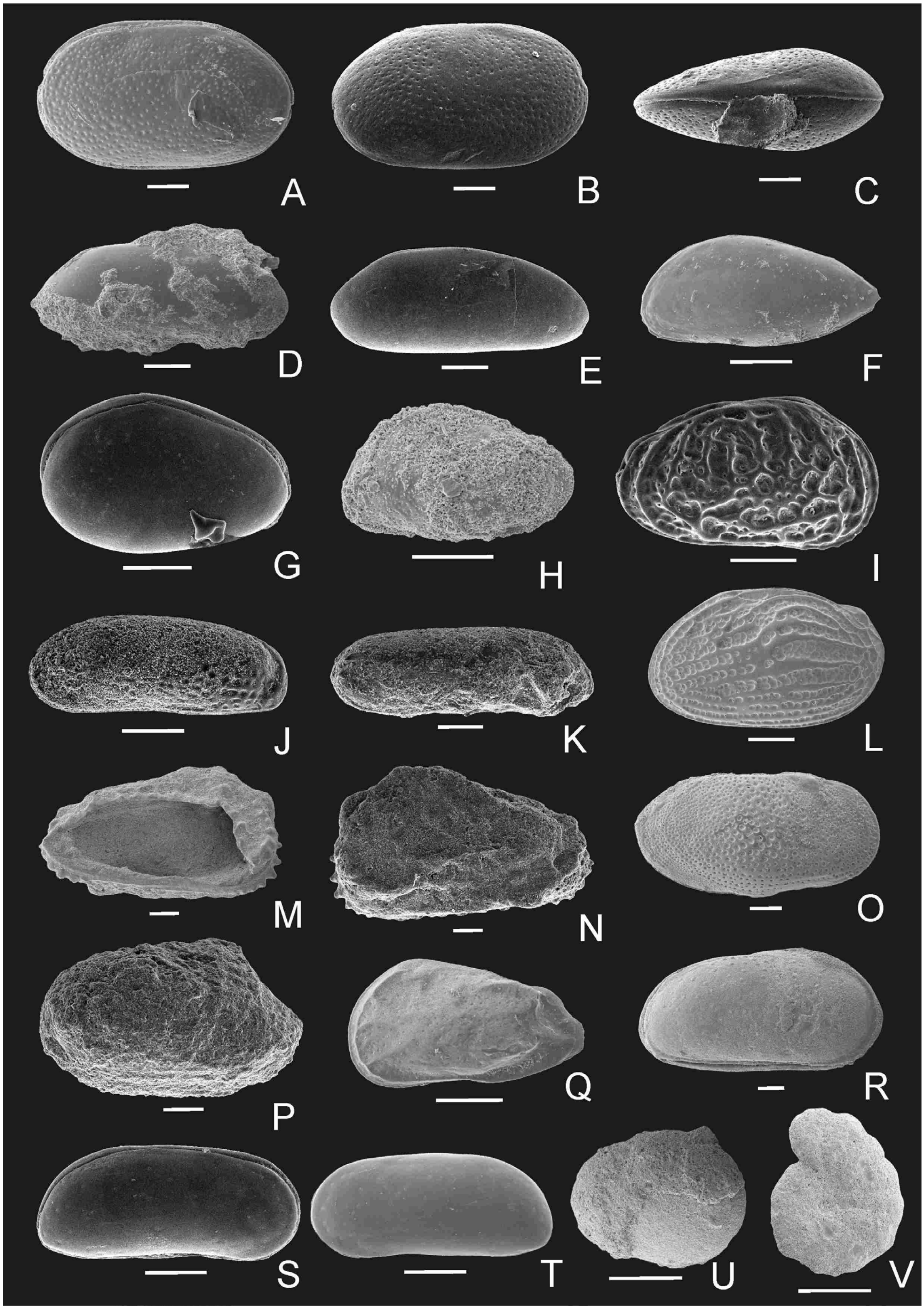

Figure 3. A–C, *Cytherella* sp. **A**, carapace left lateral view (MP-O-3153); **B**, same specimen right lateral view; **C**, carapace dorsal view (MP-O-3154); **D**, *Argilloecia* sp. 1, carapace right lateral view (MP-O-3155); **E**, *Argilloecia* sp. 2, carapace right lateral view (MP-O-3156); **F**, *Pellucistoma* sp., left valve (MP-O-3157); **G**, *Xestoleberis* sp., carapace right lateral view (MP-O-3158); **H,** *Cytheropteron* sp., left valve (MP-O-3159); **I**, *Callistocythere nucleoperiscum* Whatley *et al*., 1997, carapace right lateral view (MP-O-3169); **J**, *Hulingsina* sp., carapace left lateral view (MP-O-3160); **K**, *Copytus* sp., carapace right lateral view (MP-O-3161); **L**, *Cytheretta punctata* Sanguinetti, 1979, left valve (MP-O-3162); **M–N**, *Costa riograndensis*? Sanguinetti *et al*., 1992, **M**, broken carapace inner view (MP-O-3163); **N**, same specimen left lateral view; **O**, *Argenticytheretta laevipunctata* Sanguinetti *et al*., 1991, right valve (MP-O-3164); **P**, *Apatihowella* sp., broken carapace right lateral view (MP-O-3165); **Q**, *Caudites ohmerti* Coimbra & Ornellas, 1987, juvenile left valve (MP-O-3166); **R**, *Cyprideis multidentata* Hartmann, 1955, carapace right lateral view (MP-O-3167); **S–T**, *Parakrithe* sp., **S**, carapace right lateral view (MP-O-3168); **T**, same specimen left lateral view; **U-V**, Foraminifera. **U**, Foraminifera gen. *et* sp. indet.; **V**, *Elphidium* sp. Scale bars = 0.1 mm.

DISCUSSION

Marginal marine environments represent the transition between the sea and coastal areas, and their dynamics are influenced by climate variability, short-term sea level oscillations (tides and storms) and marine transgressions in longer (geological) timescales. Foraminifers and ostracods are important paleoenvironmental indicators of these systems due to their sensitivity to water salinity (*e.g.*, Cabral *et al*., 2006; Laut *et al*., 2011; Cronin *et al*., 2012; Sousa *et al*., 2020; Horne *et al*., 2021; Martins *et al*., 2021).

Ostracod marginal marine assemblages in Paleozoic (*e.g.*, Tibert & Scott, 1999; Williams *et al*., 2006; Bergue *et al*., 2020), Mesozoic (*e.g.*, Boomer *et al*., 2001; Bergue *et al*., 2011; Piovesan *et al*., 2015) and Cenozoic (*e.g.*, Coimbra *et al*., 2006, 2007; Linhares *et al*., 2017; Linhares & Ramos, 2022) deposits exhibit in general low diversity and high abundance. The ecological complexity of these environments results mainly from the seasonal influence on salinity and temperature, which might also induce polymorphism or intraspecific morphologic variation in carapace size and sculpture (Carbonel, 1988; Frenzel & Boomer, 2005; Horne *et al*., 2021). Therefore, analyses in cores with high-resolution sampling supply not only valuable ecological data, but also insights for understanding the radiations of ostracods toward limnic environments along the Phanerozoic (Horne, 2003; Bennet, 2008; Iglikowska, 2014; McGairy *et al*., 2021). These data can be strengthened with use of geochemical analyses of metal-calcium ratio and stable isotopes (Horne *et al*., 2012).

The study of reworked fragments of beachrocks, however, presents restraints compared to core sampling due to the complete absence of stratigraphic control, which precludes accurate ecological interpretation. Notwithstanding, ecological knowledge on the ostracod recorded allows to assume that the assemblages here examined are composed by taxa from both marine and mixohaline settings. Most of these species have been recorded as fossils or living from marginal marine to inner shelf settings in southern Brazil, Uruguay, and northern Argentina. The main components of the assemblages (*i.e.*, *Cyprideis multidentata*) is a typical inhabitant of estuaries and lagoons (*e.g.*, Bertels *et al*., 1982; Coimbra *et al*., 2006, 2007; Kihn *et al*., 2016, 2017; Campos *et al*., 2021). On the other hand, *Parakrithe* sp., *Caudites* sp., *Costa riograndensis*?, *Argilloecia* spp. and *Copytus* sp. are typically marine (Sanguinetti *et al*., 1991, 1992; Aiello *et al*., 1993; Whatley *et al*., 1997; Coimbra *et al*., 2020).

Based on the taxonomic composition, therefore, it is concluded that the beachrocks probably record environmentally condensed ostracod assemblages (Fürsich, 1978; Kidwell, 1997). Considering the geological history of the RSCP this mixture could have been the result of sea-level rise on the barrier-lagoon systems of the RSCP driven by glacial-interglacial cycles. That process causes the exposure and erosion of lagoon deposits on the shoreface due to landward migration of barriers on top of those deposits, as recorded in sectors of the Holocene Barrier IV, including the northern RSCP (Tomazelli & Villwock, 1991; Dillenburg, 1996; Campos *et al*., 2021; Lopes *et al*., 2022). The change from lagoon to fully marine environments is indicated by mixed Holocene assemblages of estuarine and marine invertebrates in Mirim and Patos Lagoons (Santos-Fischer *et al*., 2018; Lopes *et al*., 2021, 2022). The available data, however, do not permit to infer the degree of temporal mixing, the proportion of reworked specimens, or their respective absolute ages.

Regarding taphonomy, the ostracod specimens are predominantly adults and late instars, with low incidence of fragmentation and moderate dissolution. Several articulated carapaces are observed in *Cyprideis multidentata*, *Argenticytheretta levipuncatata*, *Callistocythere nucleoperiscum* and *Cytherella* sp. High incidence of articulated carapaces in the fossil record is ascribed to fast burial and low transport/reworking after deposition, although its multiple causes bring difficulties to the interpretation (Zuschin *et al*., 2003). In ostracods, for instance, high incidence of carapaces in fossil assemblages is influenced by morphological characteristics such as overlap, hinge composition and the ventral knob (Whatley, 1988). These features are observed at least in some of those taxa and, therefore, in part explain the pattern of preservation observed. Ventral knob occurs in *Callistocythere* (van Morkhoven, 1963), whilst *Argenticytheretta* has a robust hinge with strong overlap in both cardinal angles (Sanguinetti, 1979). Paradoxically, *Cyprideis* does not have neither strong overlap nor well-developed teeth and sockets, whilst a hinge is even absent in *Cytherella*. In spite of this, carapaces of both species are common in the studied material.

It is also noteworthy that one of the two samples obtained from inside oyster shells (sample 9) revealed higher incidence of juveniles and adults of small species (*e.g.*, *Cytheropteron* sp., *Pellucistoma* sp. and *Hulingsina* sp.) compared to the other samples. Although the available data does not permit to ascertain whether the oyster and their microfossils have the same age, it demonstrates that trapping inside large mollusk shells might constitute a taphonomic window influencing positively ostracod preservation.

FINAL REMARKS

The results obtained in this pioneering yet preliminary study on ostracod assemblages in beachrocks from the northern sector of the RSCP demonstrate that micropaleontological research can provide valuable data for the understanding of the coastal dynamics. The heterogeneity in composition and diagenesis observed in the samples, however, revealed that improvements in the rock disaggregation methodology are necessary to increase fossil recuperation. The presence of both marginal marine and neritic ostracods are evidence of temporal and spatial mixing, possibly related to the events of sea-level oscillations that shaped the RSCP during the late Quaternary. The occurrence of several micro and macrofossils, whose study could not be detailed in this preliminary work (*e.g.*, foraminifers and fish teeth), indicates the possibility of development of an innovative research field that will contribute particularly to the understanding of the depositional environment and sedimentary processes involved in the formation of the RSCP.

ACKNOWLEDGMENTS

The authors express their gratitude to the National Council for Scientific and Technological Development (CNPq), process 402860/2021-7, for financial support. The authors are also deeply grateful to M.F.I. Ramos and J.C. Coimbra whose criticism and review improved the earlier version of this paper.

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Received in 04 August, 2022; accepted in 12 September, 2022.

Appendix 1. The suprageneric taxonomy herein used follows mainly Liebau (2005).

Subclass OSTRACODA Latreille, 1806
Order PLATYCOPIDA Sars, 1866
Superfamily CYTHERELLOIDEA Sars, 1866
Family CYTHERELLIDAE Sars, 1866
Cytherella Jones, 1849
Cytherella sp.
Order Podocopida Sars, 1866
Sudorder Cypridocopina Jones, 1901
Superfamily Pontocypridoidea Müller, 1894
Family Pontocyprididae Müller, 1894
Argilloecia Sars, 1866
Argilloecia sp. 1
Argilloecia sp. 2
Suborder Cytherocopina Gründel, 1967
Superfamily Paradoxostomatoidea Brady & Norman, 1889
Family PARADOXOSTOMATIDAE Brady & Norman, 1889
Pellucistoma Coryell & Fields, 1937
Pellucistoma sp.
Superfamily Xestoleberidoidea Sars, 1928
Family Xestoleberididae Sars, 1928
Xestoleberis Sars, 1866
Xestoleberis sp.
Superfamily Cytheroidea Baird, 1850
Family Leptocytheridae Hanai, 1957
Callistocythere Ruggieri, 1953
Callistocythere nucleoperiscum Whatley *et al*., 1997
Family Cytheruridae Müller, 1894
Cytheropteron Sars, 1866
Cytheropteron sp.
Family Cushmanideidae Puri, 1974
Hulingsina Puri, 1958
Hulingsina sp.
Family COPYTIDAEe Coimbra, Bergue & Ramos, 2020
Copytus Skogsberg, 1939
Copytus sp.
Superfamily Trachyleberidoidea Sylvester-Bradley, 1958
Family Trachyleberididae Sylvester-Bradley, 1958
Apatihowella Jellinek & Swanson, 2003
Apatihowella? sp.
Cytheretta Müller, 1894
Cytheretta punctata Sanguinetti, 1979
Argenticytheretta Rossi de García, 1959 *emend*. Sanguinetti, Ornellas & Coimbra, 1991
Argenticytheretta levipuctata Sanguinetti *et al*., 1991
Costa Neviani, 1928
Costa riograndensis? Sanguinetti *et al*., 1992
Family Hemicytheridae Puri, 1953
Caudites Coryell & Fields, 1937
Caudites ohmerti Coimbra & Ornellas, 1987
Superfamily Cytherideoidea Sars, 1925
Family Krithidae Mandelstam, 1958
Parakrithe van den Bold, 1958
Parakrithe sp.
Family Cytherideidae Sars, 1925
Cyprideis Jones, 1857
Cyprideis multidentata Hartmann, 1955