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Foraminifera and ostracods from the semiarid Carrizal Bajo coastal wetland, southern Atacama Desert

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ABSTRACT. This study analyzes both the texture and foraminiferal and ostracod assemblages of recent (Quaternary) sediments from the Carrizal Bajo wetland, in the southern Atacama Desert of northern Chile. A transect carried out from the infralittoral zone to the landward margin of the active wetland allowed four coastal sectors to be differentiated based on the distribution and abundance of these faunal groups. The infralittoral, shallow marine areas (sector 1) are composed of bioclastic sandy sediments extremely rich in foraminifera and ostracods, which contrast with their marked scarcity or absence in the very fine sands and very coarse muds of the adjacent intertidal-supratidal zones and washover fans (sector 2). Scarce resedimented shells of ostracods and the gastropod *Heleobia copiapoensis* characterize the peaty sandy muds of the lagoon bottom (sector 3), a hostile environment for the groups studied due to intermittent anoxic conditions and frequent changes in salinity. The innermost (landward) margin of the wetland (sector 4) is characterized by sandy silts with a rich freshwater fauna in the vicinity of springs, as well as an unexpected occurrence of resedimented marine foraminifera ~650 m inland. These results can be applied in future research related to investigating: 1) the environmental degradation of the system, should the density and diversity of these faunal groups decrease or even disappear over time; 2) the reconstruction of paleoenvironments in recent Quaternary deposits, in case the taxa determined are present in the fossil record; or 3) the identification of recent Quaternary tsunamigenic layers along this coastline, characterized by the presence of infralittoral species within aeolian or wetland sedimentary sequences.

Keywords: Benthic foraminifera, Ostracod, Coastal wetland, Atacama Desert, Northern Chile.

RESUMEN. Foraminíferos y ostrácodos del humedal costero de Carrizal Bajo, desierto de Atacama. En este trabajo se presenta un análisis de la textura y meiofauna (foraminíferos y ostrácodos) en los sedimentos recientes (cuaternarios) del humedal costero de Carrizal Bajo (zona sur del desierto de Atacama, norte de Chile). Un transecto realizado desde la zona infralitoral hasta el margen interior del humedal activo ha permitido diferenciar cuatro sectores en función de la distribución y abundancia de estos grupos faunísticos. Las zonas marinas someras del ambiente infralitoral (sector 1) están compuestas por sedimentos arenosos bioclásticos extremadamente ricos en foraminíferos y ostrácodos, lo que contrasta con la marcada escasez, o incluso ausencia, de estos grupos en las arenas muy finas y limos muy gruesos de las zonas intermareal y supramareal adyacentes (sector 2). Escasas conchas resedimentadas de ostrácodos y del gasterópodo *Heleobia copiapoensis* caracterizan los fangos arenosos turbosos del fondo de la laguna (sector 3), un medio hostil para los grupos estudiados debido a un ambiente anóxico intermitente y frecuentes cambios de salinidad. El margen interior del humedal (sector 4) está formado por limos arenosos con una rica fauna dulceacuícola próxima a manantiales, así como por un sorpresivo registro de foraminíferos marinos resedimentados ~650 m tierra adentro. Los resultados obtenidos en este estudio pueden aplicarse en investigaciones futuras relacionadas con: 1) la degradación ambiental de estos sistemas, en caso de que la densidad y diversidad de estos grupos decrezca o incluso desaparezca; 2) la reconstrucción de paleoambientes en depósitos cuaternarios recientes costeros, si los taxones determinados están también presentes en el registro fósil; o 3) la identificación de niveles tsunamigénicos recientes a lo largo de este litoral costero, caracterizados por la presencia de especies infralitorales dentro de secuencias sedimentarias eólicas o en humedales costeros.

Palabras clave: Foraminífero bentónico, Ostrácodo, Humedal costero, Desierto de Atacama, Norte de Chile.

1. Introduction

Foraminifera and ostracods are among the most widely used biomonitors in the environmental assessment of coastal ecosystems, such as shallow marine areas, lagoons, wetlands, deltas, estuaries or fjords (Ruiz *et al.*, 2005; Naik *et al.*, 2023; Malek and Frontalini, 2024). Their temporal and spatial evolution provides useful information on eutrophication processes, paleogeographic changes, the impact of anthropogenic actions, and even the effects of high-energy events, such as storms or tsunamis (Ruiz *et al.*, 2005; Hart *et al.*, 2020; Francescangeli *et al.*, 2021).

Several studies on benthic foraminifera and ostracods from continental shelves have obtained similar distribution patterns using the total associations (live and dead specimens) and biocenosis (stained individuals) (Ruiz *et al.*, 1997; Donnici and Serandrei Barbero, 2002). In these marine areas, total counts (live + dead) are used to provide a tool for the interpretation of fossil foraminiferal and ostracod assemblages and their relationship with paleoenvironmental changes over time (Conradsen, 1993; Lo Giudice Cappelli *et al.*, 2019). Consequently, understanding complete assemblages in shallow marine areas, beaches, and wetlands in countries such as Chile, with a coastline exceeding 6,400 km, is essential for gaining new insights into the geological and paleoenvironmental evolution of the Chilean coastal margin during the recent Quaternary.

The benthic fauna of the Chilean continental shelf and deeper environments has been the subject of numerous studies on foraminifera and ostracods, mainly focused in the central and southern part of the country (*e.g.*, Whatley *et al.*, 1997; Figueroa *et al.*, 2005; Hromic, 2011). However, research on these groups in shallow infralittoral zones and areas of high ecological value, such as lagoons and wetlands, is still very scarce (Zapata *et al.*, 1995; Fernández, 2010; Gómez-Martín *et al.*, 2025a, b). Knowledge of non-marine ostracods is also essential, as some environments present significant salinity variations (Cárdenas *et al.*, 2013). In the Atacama Desert of northern Chile, only Hartmann's studies on shallow marine ostracods (Hartmann, 1962, 1965) or works about the distribution of foraminifera in some bays (Páez *et al.*, 2001; Tavera *et al.*, 2022; Romero *et al.*, 2023) are available.

The present article analyzes the associations of benthic foraminifera and ostracods in a complete transect from the infralittoral zone (~10 m depth) of a bay to a semi-arid wetland bordering the coastal lagoon of Carrizal Bajo, one of the southernmost of the Atacama Desert. The main objectives of this study are: 1) to examine the faunal contents (mainly benthic foraminifera, ostracods and diatoms) in surficial sediments of this wetland and adjacent shallow marine areas; and 2) to investigate the use of these faunal groups as bioindicators of environmental conditions.

2. Study area

The Carrizal Bajo coastal wetland is located east of the eponymous town, a small fishing settlement at ~28° S at the southern end of the Atacama Desert (Fig. 1A). Local climate is cold semi-arid, with dry summers and oceanic influence

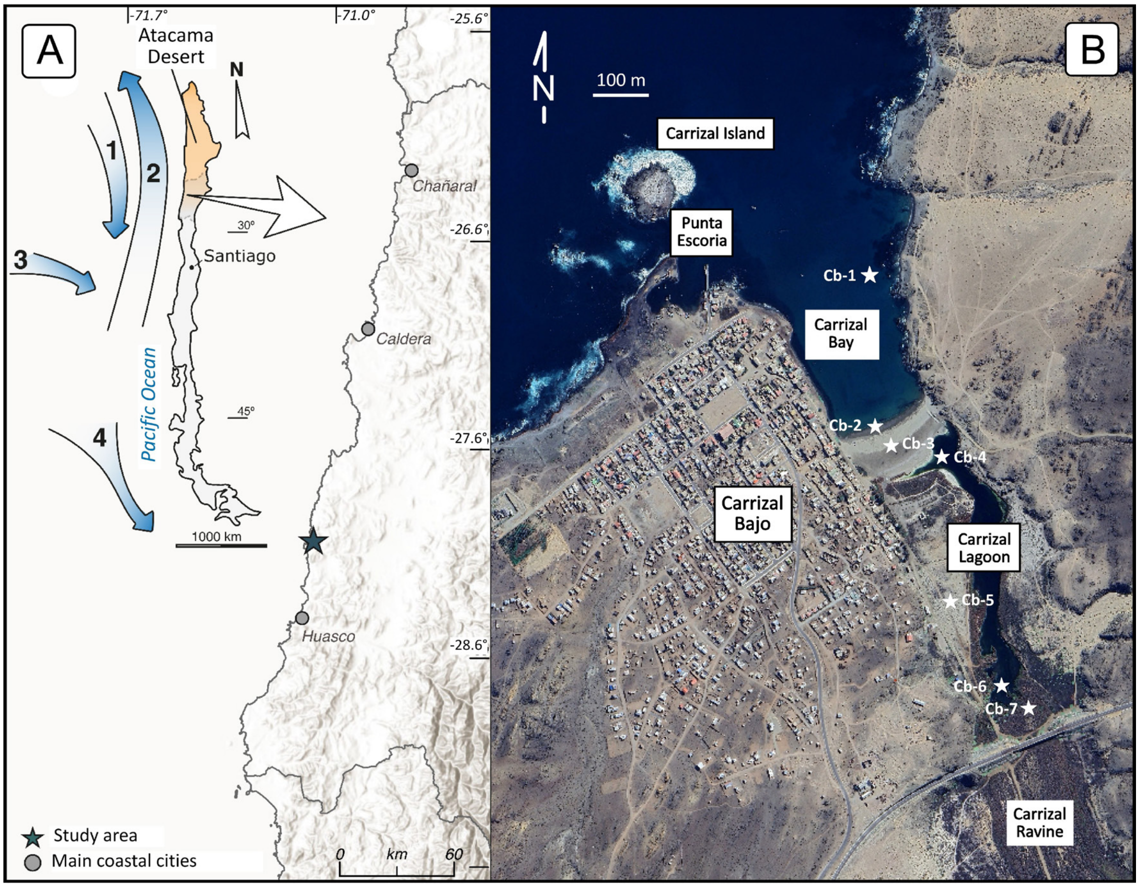

FIG. 1. **A.** Location of the Carrizal Bajo wetland in the southern Atacama Desert, with indication of ocean currents affecting the Chilean coasts. 1: warm countercurrent; 2: Humboldt current; 3: west drift current; and 4: Cape Horn current. **B.** Location of sediment surface samples collected in a transect between the infralittoral zone of the bay (Cb-1) and the coastal wetland at its southern edge (Cb-7).

(Sarricolea *et al.*, 2017). Precipitation is low, with a mean annual value typically below 30 mm, while temperatures range between 9.9 and 23.9 °C. This wetland is considered a point of high biodiversity within the Atacama Desert, hosting 49 species of flora, 76 birds, 10 reptiles, 2 amphibians, and 12 mammals (Acevedo *et al.*, 2012; Urenda, 2015). It was declared as a Nature Sanctuary in 2019 by the Chilean Ministry of Environment.

The Carrizal coastal lagoon extends from the coast to the southeast, following the homonymous ravine along a length of approximately 600 m and connecting with the wetland, which has a total area of ~9 hectares including the water body (Fig. 1B) (Navarro *et al.*, 2021). The lagoon is separated from the sea by a narrow sandy barrier ~150 m wide, which is only breached during severe winter storms and tsunamis, generally accompanied by the formation of overtopping fans on the landward side (Navarro *et al.*, 2021). According to historical records, in the last 100 years, this barrier was destroyed during the 1922, 2011, and 2022 near- and far-field tsunamis (El Noticiero de Huasco, 2011; Abad *et al.*, 2023). In this coastal area, the dominant surface ocean circulation is from south to north (Fig. 1A). This circulation pattern is part of the Humboldt Current Surge System, considered one of the most biologically productive upwelling systems on the planet (Thiel *et al.*, 2007). The mean tidal range is approximately 1 m, and the wave regime is low-energy, although the mean significant wave height estimated for this coastal segment is ~2 m (Campos, 2016).

The Carrizal lagoon is occasionally inhabited by the fish *Mugil cephalus*, an abundant species in the Chilean coasts, whereas groundwater springs from an alluvial aquifer at the southern boundary of the lagoon allow plant species such as *Typha angustifolia* to thrive. It has been estimated that groundwater discharges to the coastal lagoon at an average rate of ~35 l/s (DGA, 2009). These waters have typically low conductivity (33-35 µS/cm) (DGA, 2021).

This temporary closed system is, however, subject to changes in water quality, especially during the dry season, which promotes eutrophic conditions: high concentrations of nutrients, organic pollutants, chlorophyll, turbidity, and a decrease in dissolved oxygen (DGA, 2021). Some episodes of anoxia have also been recorded, with dissolved oxygen levels as low as 3%. A recent study analyzed organic pollutants in coastal sediments and determined that the Carrizal lagoon was degraded, with total concentrations of 358.98 µg/g in the wetland and 217.88 µg/g on the beach (Tovar-Salvador *et al*., 2023). The major contributors were the nonylphenol ethoxylates, commonly used as an adjuvant for fertilizers, fungicides, and insecticides, along with UV filters and fragrances (galaxolide), and organophosphate compounds (organophosphate flame retardants). According to Tovar-Salvador *et al.* (2023), these high concentrations might be caused by uncontrolled untreated sewage discharges into the lagoon, which intensify during the summer months due to tourism.

3. Methodology

Seven sampling sites were selected along the Carrizal Bajo wetland area, from the shallow littoral zone to the active inner margin (Fig. 1B). Sample spacing was based on the expected representation across the different environments and served as a first approximation to characterize the wetland microfauna. Samples were collected along an ~800 m long transect from the infralittoral zone (Cb-1; 12 m depth) to the southern edge of the wetland (Cb-7; 2.5 m a.s.l.), including the intertidal zone of the beach (Cb-2; 1 m depth), the sandy barrier (Cb-3; 1 m a.s.l.), the lagoon's inner beach and old washover fan (Cb-4; 0 m a.s.l.), an active eolian sheet (Cb-5; 2 m a.s.l.), and the bottom of the lagoon (Cb-6; ~0 m a.s.l.).

All samples were taken from the upper 10 cm of the surface. This boundary was chosen as several infaunal species of benthic foraminifera may be present at this depth (Goldstein *et al*., 1995; Fentimen *et al*., 2018). Cb-1 sample was collected by professional divers under the Marine Sediment Quality Atacama project (FONDECYT-11180015) of the Chilean National Agency for Research and Development (ANID), while the remaining ones were obtained with a plastic spatula and preserved in plastic bags.

The physicochemical parameters of the lagoon waters in Cb-4 and Cb-6 (pH, electrical conductivity, and dissolved oxygen concentration) were determined by using a Hanna HI98195 multi-parameter probe during the summer of 2022. On the other hand, according to DGA (2021) and Bonnail *et al*. (2023), the physicochemical properties of the seawater in the bay (Cb-1) and in the intertidal zone of the beach (Cb-2) are within normal marine ranges.

Textural analyses were carried out by using a Malvern Mastersizer at the University of Huelva, Spain, with the main constituent minerals noted, and grain-size statistics determined in Gradistat v8.0 (Blott and Pye, 2001). In parallel, seven subsamples (25 g) were wet sieved through 250 µm and 125 µm sieves and analyzed for faunal content with a Leica SAPO stereoscopic binocular microscope to identify foraminiferal and ostracod specimens. This quantity of sediment sample is sufficient in (paleo)environmental analyses based on these microorganisms (*e.g*., Martínez *et al*., 2018; García *et al*., 2024). The most representative taxa were photographed with a Leica Flexcam C3 camera coupled to microscope.

Foraminifera were classified after Boltovskoy *et al.* (1980), Loeblich and Tappan (1988), Páez *et al.* (2001), Hromic (2009), and the World Register of Marine Species (WoRMS). The classification of ostracods was carried out by comparison with Hartmann's illustrations (Hartmann, 1962) and the WoRMS database. Following Martínez *et al*. (2018) and García *et al*. (2024), the abundance of the different taxa was categorized as rare (R: 1-3 specimens/25 g), common (C: 4-9 specimens/25 g), abundant (A: 10-100 specimens/25 g), and very abundant (VA: >100 specimens/25 g). The main taphonomic processes (*e.g*., preservation, fragmentation, abrasion) were also noted. The detailed taphonomic analyses were performed on foraminiferal and ostracod specimens, recording their preservation state as follows: excellent for specimens lacking sedimentary reworking, well-preserved for those showing minor shell damage or abrasion, and poor for specimens with clear evidence of transport.

Finally, the abundance of other faunal groups (*e.g.*, siliceous sponges, echinoderms, bryozoans, mollusks, diatoms) was also identified for fractions >125 µm. The same quantitative categorization described for foraminifera and ostracods was followed, with the objective of completing the environmental information provided by these two groups.

4. Results

4.1. Textural analysis of sediments and physico-chemical parameters of waters

The bottom of the infralittoral zone (Cb-1) is composed of coarse and very coarse sands with very abundant bioclastic fragments and turritellid gastropod specimens. Average grain size decreases in the intertidal zone (Cb-2), the inner beach (Cb-3), and the aeolian sand sheet (Cb-5), mostly composed of mud (>50%) and very fine sands (>15%) (Fig. 2). Fragments of bivalves and echinoderms are frequent in Cb-2 and Cb-3 but disappear in Cb-5- Similarly, bryozoans are abundant only in Cb-1, rare in Cb-2 and Cb-4, and absent from the remaining samples (Table 1). The remaining three samples were taken in the lagoon (Cb-4, Cb-6) and wetland (Cb-7), and their common characteristic is the frequent to very abundant presence of the gastropod *Heleobia copiapoensis* (Biese, 1944) (Table 1). Grain size decreases from the muddy sands of the former washover fan (Cb-4) to the peaty sandy muds of the lagoon bottom (Cb-6) and the muds of the wetland boundary (Cb-7) (Fig. 2).

The pH and electrical conductivity values in the lagoon waters near the beach (Cb-4) indicated normal levels for coastal marine environments (pH 8.28; electrical conductivity 33,700 µS/cm), with slightly more basic and less saline conditions near the wetland (Cb-6) (pH 7.68; electrical conductivity 32,600 µS/cm). The dissolved oxygen concentration measurements obtained were relatively low near the shoreline (5.4 mg/l), decreasing towards the landward edge of the lagoon (0.9 mg/l).

4.2. Foraminifera

A total of 1,547 foraminifera belonging to eighteen species, fifteen of them benthic and three planktonic, were extracted (Fig. 2; Table 1). These microorganisms are diversified and abundant in the infralittoral zone (14 species; >60 specimens/gram), while they are very scarce or even absent in the remaining samples (Fig. 2; Table 1). The most abundant species are *Cibicides aknerianus* (d'Orbigny, 1846) and *Melonis affinis* (Reuss, 1851), followed by *Buccella peruviana* (d'Orbigny, 1839). These species are abundant to very abundant in Cb-1, some occur sporadically from Cb-2 to Cb-5, and others are even found in Cb-7, ~650 m inland. In this latter sample, a total of 260 frustules belonging to non-marine diatoms of the genera *Campylodiscus, Cocconeis* and *Thalassiosira* were identified (Table 1).

Taphonomic analysis also helped differentiate the outer bay from the lagoon environments. The shells extracted from the infralittoral zone (Cb-1) and the wetland boundary (Cb-7) generally showed an excellent to well-preserved state (63%), while those in between (Cb-2 to Cb-6) showed clear evidence of fragmentation and abrasion (>90%).

4.3. Ostracods

Nine species were determined in the taxonomic study of 1,389 specimens (Fig. 2; Table 1). Most of these species (8) are abundant and very abundant in the infralittoral zone, among which stand out (>4 valves/gram) *Paracytheridea granti* LeRoy, 1943, *Paracytheridea longicaudata chilensis* Hartmann, 1962, *Patagonacythere tricostata* Hartmann, 1962, *Hemicytherura reticulata* Hartmann, 1962, and *Semixestoleberis debueni* Hartmann, 1962. Although all specimens appeared with disarticulated valves, their taphonomic characteristics are highly variable, with well-preserved specimens dominating (57%), followed by those in excellent (18%) and poor (25%) conditions.

The rest of the ostracofauna is concentrated mainly on the southern edge of the Carrizal Bajo wetland (Cb-7), with more than 24 individuals per gram of *Heterocypris salina* (Brady, 1868) and some valves of *S. debueni* and *Cyprideis beaconensis* (Le Roy, 1943). The latter species is common in the bottom of the lagoon (Cb-6), while these microcrustaceans are typically absent in the rest of the samples. Similarly, almost all ostracod specimens are either excellent or well-preserved in these samples (>84%), particularly *H. salina*, which commonly occurs with both valves articulated.

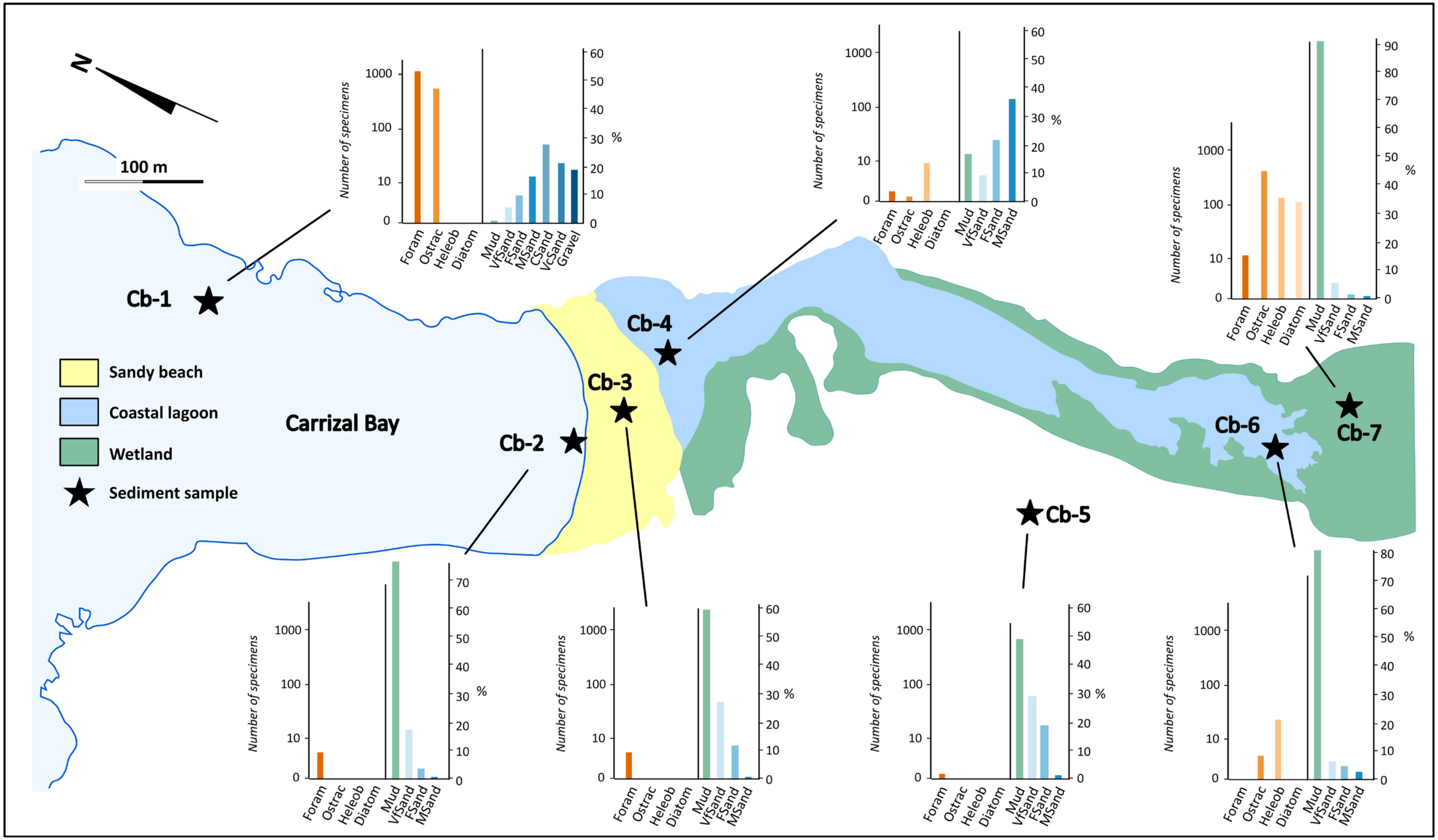

FIG. 2. Granulometric distribution and abundance of different groups (foraminifera, ostracods, gastropods, diatoms) in the Carrizal bay and the Carrizal Bajo wetland. Foram: foraminifera; ostrac: ostracods; Heleob: *Heleobia copiapoensis*; diatom: diatoms. VfSand: very fine sand; FSand: fine sand; MSand: medium sand; CSand: coarse sand; VcSand: very coarse sand. The number of species was obtained in 25 g of sediments.

TABLE 1. DISTRIBUTION AND ABUNDANCE OF FORAMINIFERA, OSTRACODS AND OTHER BIOLOGICAL GROUPS IN THE CARRIZAL BAJO WETLAND.

	SPECIES/SAMPLES	Cb-1	Cb-2	Cb-3	Cb-4	Cb-5	Cb-6	Cb-7
BENTHIC FORAMINIFERA	*Ammonia beccarii* (Linnaeus, 1758)	C				R		R
	Anomalinoides incrassatus (Fichtel & Moll, 1798)	C						
	Buccella peruviana (d'Orbigny, 1839)	A	R	R		R		
	Cibicides aknerianus (d'Orbigny, 1846)	A			R			C
	Cibicides moyanoi Marchant, Giglio & Ramírez, 2005	A	R	R				R
	Cibicides lobatulus (Walker & Jacob, 1798)	C						
	Cibicidoides wuellerstorfi (Schwager, 1866)		R	R	R			
	Discorbis vilardeboanus (d'Orbigny, 1839)	A						
	Heterolepa ornata (Cushman, 1921)	A						
	Melonis affinis (Reuss, 1851)	VA						
	Quinqueloculina seminulum (Linnaeus, 1758)	A						
	Spirillina sp.	R						R
	Rosalina globularis d'Orbigny, 1826	A						
	Triloculina planciana d'Orbigny, 1839	A						
	Valvulineria inflata (d'Orbigny, 1839)	A						
PLANKTONIC FORAMINIFERA	*Globigerina bulloides* d'Orbigny, 1826	R						
	Globigerina sp.	R						
	Neogloboquadrina pachyderma (Ehrenberg, 1861)	R						
INDIVIDUALS/25 g; FRACTION > 125 µm		**1515**	**6**	**5**	**2**	**2**		**17**
OSTRACODS	*Cyprideis beaconensis* (Le Roy, 1943)	A					C	C
	Hemicythere foveata Hartmann, 1962	A						
	Hemicytherura reticulata Hartmann, 1962	VA						
	Heterocypris salina (Brady, 1868)							VA
	Loxoconcha fluctushumboldti Hartmann, 1962	A						
	Paracytheridea granti LeRoy, 1943	VA						
	Paracytheridea longicaudata chilensis Hartmann, 1962	VA			R			
	Patagonacythere tricostata Hartmann, 1962	VA						
	Semixestoleberis debueni Hartmann, 1962	VA						C
	INDIVIDUALS/25 g; FRACTION > 125 µm	**748**			**1**		**6**	**634**
DIATOMS	*Campylodiscus* sp.							VA
	Coscinodiscus sp.	R						
	Cocconeis scutellum Ehrenberg, 1838							A
	Thalassiosira sp.							A
	FRUSTULES/25 g; FRACTION > 125 µm	**1**						**260**
OTHERS	Mollusk fragments (mainly gastropods)	VA	A	A	C	R	C	R
	Heleobia copiaponensis (Biese, 1944)				C		A	VA
	Echinoderm spines and ossicles	A		C	C			
	Siliceous sponge spicules	A						
	Bryozoans	A	R		R			
	Fish teeth	R						
	Characean gyrogonites						R	
	Plant debris			R	C	A	A	VA
	Peat		A	A	A	A	A	A

R: rare (1-3 specimens/25 g), **C**: common (4-9 specimens/25 g), **A**: abundant (10-100 specimens/25 g), and **VA**: very abundant (>100 specimens/25 g). See figures 1 and 2 for locations. Gray-shaded cells indicate samples in which that group was absent.

5. Discussion

5.1. Environmental sectors of the Carrizal Bajo wetland

Textural analysis, the abundance and distribution of foraminiferal and ostracod species, as well as the presence of other faunal groups, define four sectors in the Carrizal Bajo wetland and the adjacent marine zone (Fig. 3). Sector 1 (infralittoral; sample Cb-1) is characterized by assemblages of both benthic foraminifera (*e.g.*, *Melonis*, *Buccella*, *Cibicides, Cibicidoides*, *Quinqueloculina*) and ostracods (*e.g.*, *Cyprideis, Hemicytherura*, *Paracytheridea, Patagonacythere, Semixestoleberis*), typical of the Chilean shallow shelf at depths between 0 and 100 m (Hartmann, 1962, 1965; Zapata and Gutiérrez, 1995; Zapata *et al.*, 1995; Páez *et al.*, 2001; Figueroa, 2005; Hromic, 2009; Finger, 2013). Some species of foraminifera (*Buccella peruviana*, *Quinqueloculina seminulum, Ammonia beccarii, Cibicides* spp.) and ostracods (*Cyprideis beaconensis*) have also been found in bays, estuaries and lagoons of the Atlantic coast of Argentina (Laprida, 1998; Laprida and Bertels-Psotka, 2003), and *C. beaconensis* has been cited in brackish to hypersaline coastal lagoons and estuaries in California (Le Roy, 1943; Kern, 1971; Scott *et al.*, 2011). Overall, this foraminiferal-ostracod assemblage is characteristic of well-oxygenated shallow marine waters, with moderate hydrodynamics and depths less than 50 m, often close to estuaries, bays, lagoons and river mouths.

Sector 2 (samples Cb-2 to Cb-5) includes different intertidal and supratidal environments whose common characteristic is the scarcity of both foraminifera and ostracods. This intermediate area is distinguished by the rare presence of marine foraminifera (*A. beccarii*, *B. peruviana*, *Cibicides moyanoi*, *Cibicidoides wuellerstorfi*) and ostracods (*Paracytheridea longicaudata chilensis*) with clear evidence of transport. The taphonomic status and the abundant presence of these marine taxa in the shallow marine zone of the bay (Cb-1) seem to reflect a process of reworking and inland transport of these specimens from the infralittoral zone to the outer sandy beaches and the lagoon, often accompanied by echinoderm remains and mollusk fragments (Table 1). Two of the species described in the Cb-2 to Cb-5 samples (*A. beccarii* and *B. peruviana*) were proposed by Laprida *et al.* (2011) as dominant taxa in beach and dune environments of some Argentinean coasts, as a result of taphonomic processes that favor their selective preservation with respect to other species with less robust shells. A similar circumstance may have occurred with the thick-walled ostracod *P. longicaudata chilensis* (Cb-4).

The peaty bottom of the lagoon (Sector 3; sample Cb-6) is characterized by the absence of foraminifera, the common presence of the ostracod *C. beaconensis*, as well as an abundant population of the gastropod *H. copiapoensis*. This sector presents very unfavorable conditions for the development of benthic foraminifera, due to the high concentration of organic matter (Table 1) and low oxygen content by decomposition of plant debris (*e.g.*, Alve, 1990; Gupta and Machain-Castillo, 1993), as well as frequent fluctuations in salinity. These conditions, close to anoxia, would be caused by the low hydrodynamics of the waters, the permanent disconnection of the lagoon with marine waters and the episodes of eutrophication that it experiences intermittently, which would have led to the disappearance of the lagoon foraminifera.

The specimens of *C. beaconensis* and *H. copiapoensis* found in sample Cb-6, better adapted to the frequent fluctuations in salinity and oxygenation of the waters, most likely came from the edges of the lagoon, a location with more intense hydrodynamics and better oxygenation (Cazzaniga, 2011; Scott *et al.*, 2011). In this regard, the presence of organic pollutants in the lagoon (DGA, 2021; Tovar-Salvador *et al.*, 2023), likely associated with agricultural activities upstream of the wetland, may have acted as a contributing factor to hypoxia and anoxia in the bottom of the lagoon by promoting the rapid and massive growth of algae and macrophytes in the water body due to nutrient enrichment. At the time of sampling, the pH and electrical conductivity of lagoon waters adjacent to the beach (Cb-4) were within typical ranges for coastal marine environments. In contrast, waters near the wetland (Cb-6) exhibited slightly more basic and less saline conditions, likely influenced by groundwater discharge in this area. Dissolved oxygen concentrations were relatively low near the shoreline and decreased markedly toward the landward margin of the lagoon. This last parameter, together with the elevated concentrations of organic pollutants in the lagoon, points to adverse conditions for benthic microfauna, as evidenced by the faunal diversity discussed above.

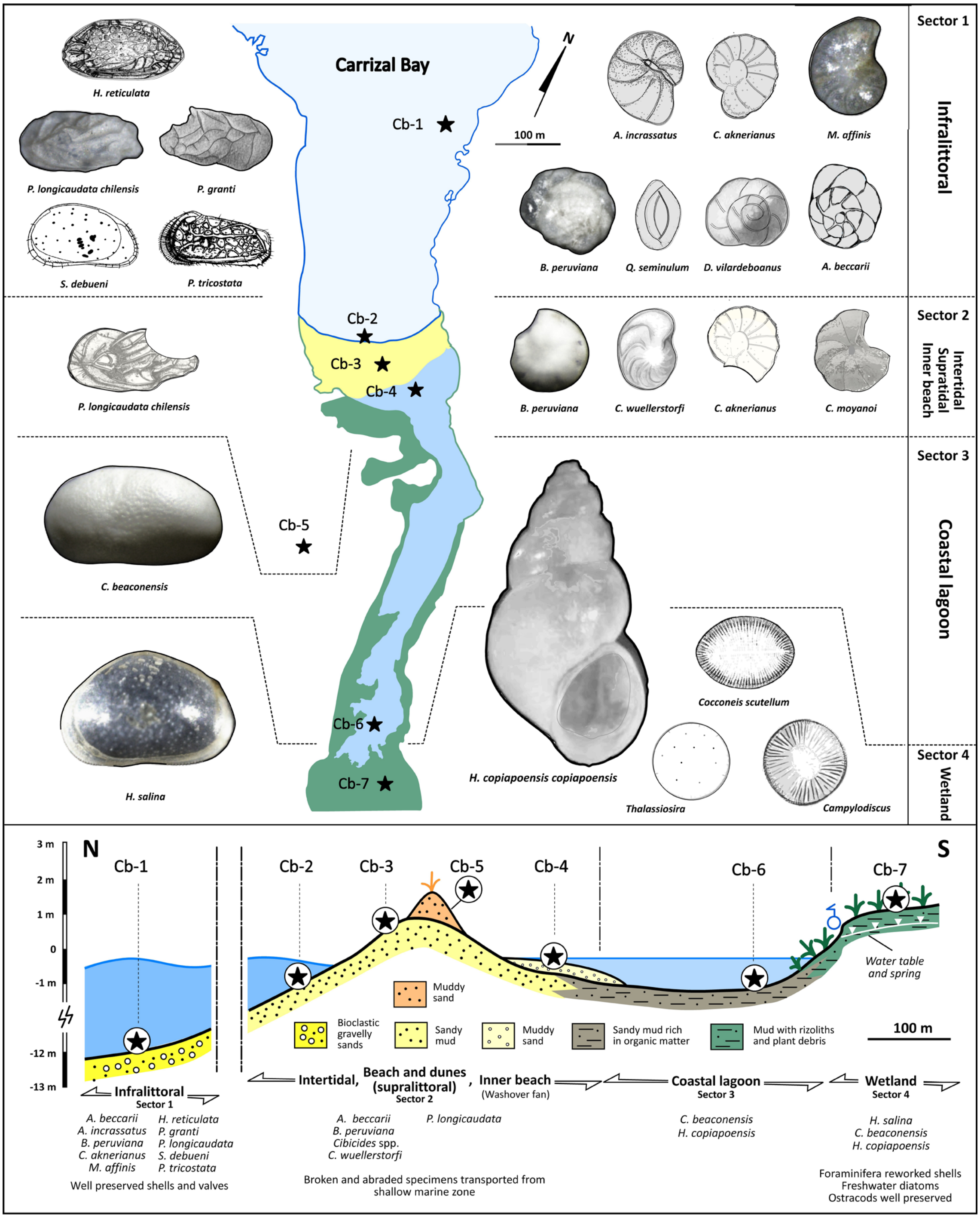

FIG. 3. Main species in the different environmental sectors of the bay and wetland-lagoon system of Carrizal Bajo. Photographs of the most representative species are included. Below, a schematic profile highlighting the main sedimentary and faunal associations is shown.

The landward edge of the wetland (Sector 4; sample Cb-7) shows an interesting joint occurrence of abundant and well-preserved complete carapaces of the non-marine ostracod *H. salina* and the euryhaline ostracod *C. beaconensis*, together with some reworked marine species of foraminifera and ostracods (Table 1). *H. salina* is an ostracod with a cosmopolitan distribution and broad ecological requirements, but it is frequent in freshwater to slightly saline lakes and inland wetlands, as well as in coastal areas (Ganning, 1967; Cárdenas *et al.*, 2013). In Chile, this taxon has been described ~250 km south of Carrizal Bajo, in the coastal wetland of Pachingo (Tongoy Bay), along with some intertidal benthic foraminifera and other freshwater and marine ostracod species, suggesting either coastal environments intermittently subjected to increased marine influence or increases in the discharge of inland waters to the system (May *et al.*, 2013).

The most reasonable explanation for the co-occurrence of marine, brackish and freshwater species in the landward zone of the wetland lies in the recent high-energy marine flooding experienced by the Carrizal lagoon during the far-field tsunamis of 2011 and 2022. In these events, the lagoon overflowed and emptied, with the possible supply of small amounts of sediments from the infralittoral/supralittoral area to this zone of the wetland. According to recent studies, the mixture of different associations of marine, brackish and freshwater microfauna has been proposed as a highly reliable indicator for the identification of tsunami deposits in coastal environments (Ruiz *et al.*, 2008; Mamo *et al.*, 2009; Nelson *et al.*, 2015; Quintela *et al.*, 2016; Gaffney *et al.*, 2020). The nature of the high-energy process is also reflected in the presence of poorly preserved marine foraminiferal and ostracod shells (Dawson and Stewart, 2007; Abad *et al.*, 2022), mixed with the better-preserved valves of *C. beaconensis* and *H. salina*.

5.2. Recommendations into recent paleo-environmental reconstructions

The results of this research are directly applicable to the following topics:

1. Transgressions and regressions. In the Central Chile region (Algarrobo coast), the presence of a sandy layer with *A. beccarii* and *C. beaconensis* interbedded between fluvial deposits allowed reconstructing a mid-Holocene transgressive event that formed an estuary (Encinas *et al.*, 2006). Dramatic environmental modifications, such as coastal uplift and subsidence linked to megathrust earthquakes, can also be recorded by abrupt changes in the shallow marine to coastal microfauna association (*e.g.*, Melnick *et al.*, 2012; Dura *et al.*, 2016; Easton *et al.*, 2022).
2. Environmental health of wetlands. The rotting of plant remains at the bottom of wetlands can cause episodes of anoxia, which can be evidenced by the absence or scarcity of microfauna. Low foraminiferal density and diversity have been found in areas with oxygen depletion (Ruiz *et al.*, 2012).
3. High-energy events. The tsunami associated with the 2010 south-central Chile earthquake caused the deposition of a sandy layer with a mixture of microfauna (diatoms, ostracods, broken foraminifera) from different environments (Horton *et al.*, 2011), as in Cb-7. Consequently, this article encourages the search for new evidence of these high-energy events in Carrizal Bajo and similar wetlands along the southern Atacama Desert (Abad *et al.*, 2020; Salazar *et al.*, 2022).

6. Conclusions

1. The analysis of a transect of seven samples taken from the bay to the landward limit of the Carrizal Bajo wetland allowed the determination of 18 species of foraminifera and 9 species of ostracods from the study of almost 3,000 specimens.
2. The spatial distribution of these microorganisms, in conjunction with the data provided by textural analyses, and the diatom species identified, allowed the recognition of four coastal sectors: infralittoral; intertidal and supratidal; lagoon bottom; and the innermost (landward) edge of the wetland.
3. The state of preservation of the specimens and the mixture of species from different environments suggest a significant transport of sediments from the infralittoral zone up to even 650 m inland, due to the effect of high-energy events, possibly tsunamis.
4. The results of this study have immediate applicability in the reconstruction of recent paleoenvironmental scenarios in the coastal deposits of the southern Atacama Desert.

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