Macrobioerosion and Microbioerosion in Marine Molluscan Shells from Holocene and Modern Beaches (39°−40°S, South of Buenos Aires Province, Argentina)

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Abstract: The marine sediments of the area of Verde Peninsula – Jabali Island (39°28′S/62°19′W–40°28′S/62°11′W) Holocene in age (3−2 ky), and modern beaches contain a significant amount of bioeroded mollusc shells. Fifteen sites were analyzed, in which 20.11% of the mollusc shells (2168 valves) presented bioerosion traces, in 54 species (30 bivalves and 24 gastropods). Fourteen ichnogenera were reported: *Entobia*, *Maeandropolydora, Iramena, Caulostrepsis, Pennatichnus*, *Pinaceocladichnus, Trypanites,* and *Gastrochaenolites* (Domichnia), *Gnathichnus* and *Radulichnus* (Pascichnia), *Finichnus* and *Centrichnus* (Fixichnia), *Oichnus* (Praedicnia) (macrobioerosion)*,* y *Semidendrina* (microbioerosion), the latter is first reported in mollusc shells in Argentina. Eleven ichnospecies were identified *Finichnus peristroma, Maeandropolydora sulcans, Gnathichnus pentax*, *Pinaceocladichnus onubensis, Caulostrepsis taeniola, Centrichnus eccentricus*, *Radulichnus inopinatus*, *Oichnus simplex*, *Oichnus paraboloides, Oichnus gradatus,* and *Gastrochaenolites torpedo* (lithic remains). The dominant ichnogenera in the Holocene deposits are *Iramena*, *Entobia* and *Oichnus*. The same ichnogenera are constant with different abundance in the modern beaches, and increasing representation of *Pinaceocladichnus* and *Pennatichnus*. The dominant ichnofacies in the Holocene deposits is *Trypanites*, revealing a benthonic marine community composed of cheilostome bryzoans, clionaid sponges, predator gastropods, regular echinoids, polychaete annelids, bivalves, thallophytas and fungi. Generally, the area was described as a sublittoral, low-energy, stable environment with high rate of oxygenation, and sandy bottoms, with rocky bottoms at Villalonga locality.

Key words: molluscan, bioerosion, Holocene, south of Buenos Aires Province

1 Introduction

Fossil traces are evidence of organisms not preserved in the fossil record which reflect the behavior of the organism on the substrate (consolidated or unconsolidated) revealing their morphology, life mode and trophic type.

Seilacher (1964, 1967) introduced the concept of ichnofacies in order to deduce ecological parameters such as energy and bathymetry, from fossil traces. He defined six original ichnofacies named by a characteristic ichnotaxon, four of which are soft-substrate marine ones: *Skolitos* (littoral environments),

Cruziana (sublittoral environments), *Zoophycos* (sublittoral-batial environments), and *Nereites* (batial-abysal environments), and the other two, *Glossifungites* for hard substrate of littoral environments, and *Scoyenia* for continental environments. Recently, other ichnofacies were added, such as *Gnatichnus* and *Entobia* joined together in a single one of *Trypanites* characterized by borings in hard substrates typical of continental environments.

Behavior of organisms and other biogenic structures are mainly controlled by bathymetry, as well as consistency of substrate, energy, type of food source, water turbidity, salinity, depositional rates, oxygenation and temperature, among others (MacEachern et al.,

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2007).

The biogenic structures analyzed in this paper are made on hard substrate of mollusc shells, known as bioerosion. It is a mechanism of taphonomic alteration caused by erosive action of a large number of organisms that may bore, penetrate, gnaw, graze or etch surfaces of hard substrate such as rocks, pebbles or skeletal material (Taylor and Wilson, 2003). These substrates offer to the colonizer organisms habitats of relative structural stability compared to the one offered by unconsolidated sediments.

Some fossil traces allow the recognition of different boring organisms. Among microboring organisms are the algae (Chlorophyta, Cyanophyta, Rodophyta), lichens, fungi and even bacteria; among macroboring, clionaid sponges (ichnogenus *Entobia*), polychaetes (ichnogenera *Maeandropolydora* and *Caulostrepsis*), cheilostome bryozoans (ichnogenera *Finichnus* and *Iramena*), echinoids (ichnogenera *Gnathichnus* and *Radulichnus*), bivalves (ichnogenus *Gastrochaenolites*), and carnivore gasteropods and/or octopuses (ichnogenus *Oichnus*). This taphonomic feature indicates enough primary productivity in the environment, since the abundance of suspension feeders is related to the presence of planktonic organisms (Lescinsky et al., 2002).

Bioerosion traces found on exoskeletons of Neogene marine mollusc are studied worldwide (e.g., Bromley, 1975, 1983, 1984, 1993; Mayoral, 1987, 1988ab, 1991; Taylor et al., 1999; Ruggiero and Annunziata, 2002; Verde, 2002; Taylor and Wilson, 2003; Santos et al., 2003; Kowalewski, 2004; Lorenzo and Verde, 2004; Casadio et al., 2007; El – Hedeny, 2007; Gibert et al., 2007; Doménech et al., 2008; Pereira et al., 2009; Martinell et al., 2010; Ruggiero and Raia, 2010; Ruiz et al., 2010; Lopes, 2011; Rojas et al., 2014; Klompmaker et al., 2015), and in Argentina (e.g., Aceñolaza and Aceñolaza, 2000, 2004; Farinati and Zavala, 2002; Farinati et al., 2002, 2006; Cárdenas and Gordillo, 2009; Gordillo and Archubi, 2012; Gordillo et al. 2014; Richiano et al., 2014).

Bioerosion is among the most relevant taphonomic features when interpreting specific environmental factors (e.g., depth, waves, salinity, turbidity, etc.), suggesting paleoenvironmental conditions, paleoecological significance, changes in the relative sea level (Santos and Mayoral, 2008) and biostratigraphy (Bromley, 2004), and the evolution of hard substrate communities (Taylor and Wilson, 2003).

The goal of this paper is to identify and describe bioerosion marks on marine bivalve and gastropod shells associated with Holocene deposits and sandbars of modern beaches, describing the environmental factors represented in the area Verde Peninsula–Jabalí Island, south of Buenos Aires Province.

2 Geological and Paleontological Framework

The littoral ridges and tidal plains of the south of the Buenos Aires Province have been studied from a geomorphological and paleontological standpoint (Weiler, 1984, 2000; Charó et al., 2013ab; Charó, 2014; Charó et al., 2015), but not as extensively from a taphonomical approach (Charó et al., 2012).

Bioerosion marks of the Quaternary have been studied mainly in Holocene ridges and modern beaches (Farinati and Aliotta, 1995; Farinati and Zavala, 1995; Pastorino and Ivanov, 1996; Arregui et al. 2009; Cárdenas and Gordillo, 2009; Gordillo and Archubi, 2012; Richiano et al., 2014).

Pastorino and Ivanov (1996) analyzed the bioerosion marks on mollusc valves from Holocene ridges of San Clemente del Tuyú (36°21′S/56º43′W, Buenos Aires Province). They studied mainly the ichnogenus *Oichnus* on valves of *Glycymeris longior*, *Pitar rostratus* and *Mactra isabelleana*. The boring was made selectively on the central area of *Glycymeris longior* and in the postumbonal area of *Mactra isabelleana*, and the producer was the carnivore gastropod *Notocochlis isabelleana* of the Family Naticidae, recorded in the Bonaerian coast.

Studies on the south of the Buenos Aires Province were focused on the characterization of bioerosion on micromollusc valves from Holocene marine deposits of Bahía Blanca (38° 35′ S/65° 13′ W), being the most outstanding ichnogenera, *Entobia*, *Oichnus*, *Leptichnus* and *Maeandropolydora* (Farinati et al., 2002, 2006). Over lithic remains the ichnogenera *Gastrochaenolites*, *Maeandropolydora*, *Trypanites*, *Gnathichnus* and *Radulichnus* were recognized (Farinati et al., 2002; Spagnuolo et al., 2013).

Farther south, on the Argentine Patagonian littoral, Arregui et al. (2009) described bioerosion on mollusc valves from the area of Bustamente Bay (San Jorge Gulf, central Patagonia), between Estancia San Miguel (44º57′ S/66º11′ W) and Caleta Malaspina (45º09′ S/66º30′W). Three ichnogenera were described as a novelty, *Entobia*, *Maeandropolydora* and *Oichnus*, which allowed the recognition of the presence of naticid and muricacean gastropods, clionaid sponges and polychaetes respectively. In recent investigations, Richiano et al. (2014) completed the study of bioerosion marks in the same area with the description of a total of 13 ichnogenera. Three ethologic classes are

outstanding: *Domichnia*, *Fixichnia* and *Praedichnia*.

In the Beagle Channel (54°52′S/68º08′W, Tierra del Fuego), the studies were focused on the ichnogenus *Oichnus* from Holocene marine deposits (Gordillo, 1994, 2013), the predators responsible of such marks, and their paleoecologic role (Gordillo and Archubi, 2012).

However, no previous investigations were focused in the study of bioerosion pointing toward the paleoecologic and paleoenvironmental reconstruction of the south of the Buenos Aires Province, and their significance in the study of environmental factors during the marine Quaternary.

3 Study Area

A total of 15 sites were studied from the Verde Peninsula (39°21′S/62°5′W) to the Jabalí Island (40°28′S/62°11′W) (Trebino, 1987; Weiler, 2000) (Fig. 1a). Sites 1, 4, 6, 7, 9, 10, 12 and 13 belong to Holocene littoral ridges, and sites 2, 3, 5, 8, 11, 14 and 15 to modern beaches.

3.1 Holocene sites

Site 1 is Verde Peninsula (VP) (39º21′S/62º5′W), a Holocene littoral ridge 4 m height, composed by a level of fine sand dated in 2.17 ± 0.86 ka ^{14}C (Weiler, 1984).

Site 4 is Colorado River (CR) (39º34′S/62º12′W), a Holocene deposit 2 m thick with grayish brown homogeneous clayey silty sediment.

Sites 6, Villalonga Canal (VC) (40º01′S/62º19′W) and 9, Atlántica Quarry (CA) (40º11′S/ 62º21′W), are 3–3.5 m thick littoral ridges located on the north of Anegada Bay. They are composed by gravy levels with abundant gastropods and bivalves, and levels of sand with scarce marine malacofauna. There are also levels partially cemented by calcium carbonate.

Site 7, near Villalonga (V) (39º59′S/62º20′W), is a 6 m thick littoral ridge. This Holocene deposit is formed by stratified gravels and sands with shell remains.

Site 10, Los Pocitos (LP) (40º25′S/62º25′W), south of the Anegada Bay, is a 2 m thick exposure composed by sand and pebbles levels with valves in chaotic disposition, which represent microcliffs on the modern coast respect to the beach deposits.

Sites 12 (40º33′S/62º13′W) and 13 (40º34′S/62º14′W) at Jabalí Island (JI), north of San Blas Bay, are littoral ridges composed by low angle cross-stratified gray gravels and sands, 2–2.5 m thick, with fossil marine malacofauna (Fig. 1b).

3.2 Modern beaches

Site 2, Verde Peninsula Beach (39º23′S/62º0′W), is a sandy beach with a large amount of marine malacofauna. Most bivalve shells are complete, and gastropods such as *Zidona dufresnei*, are most frequently fragmented. It is outstanding the presence of *Brachidontes rodriguezii*, *Ostreola equestris*, *Mytilus edulis* and *Crepidula*.

Site 3, La Chiquita Beach (LCB) (39º35′S/62º5′W), is the largest beach of this region, located on the Verde Bay, in front of Wood Island. It is a wide sand beach characterized by a frontal dune 4 m height. On the berm near the coast line there are accumulations of complete shells with ligaments, most of them in articulation and preserving the color. *Amiantis purpurata* and
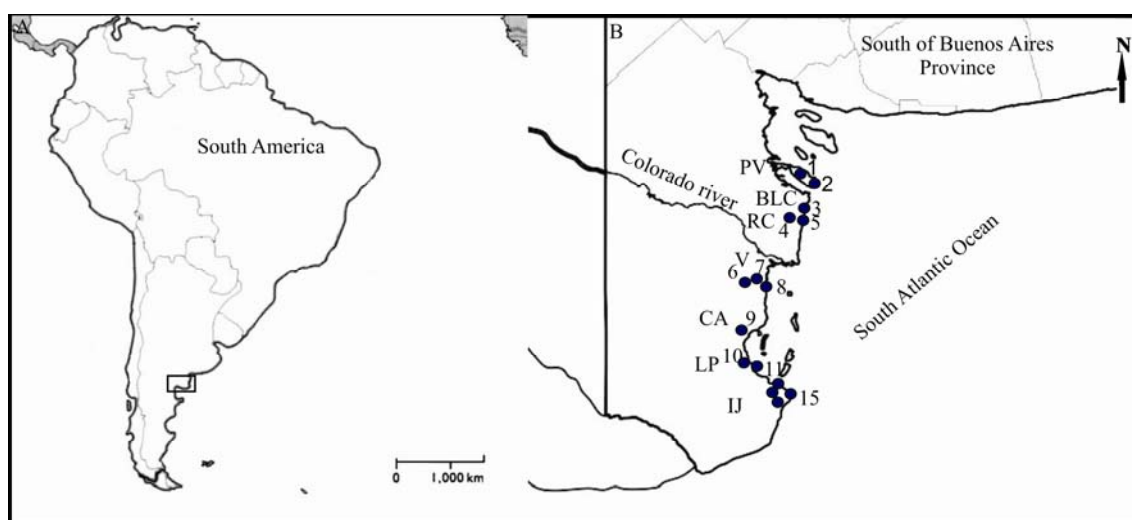

Fig. 1. (a), Study area of south of Buenos Aires Province, Argentina. 507′232 mm (72′72 DPI).
Fig. 1. (b), Schematic section of holocene deposists of south of Buenos Aires Province.
PV: Peninsula Verde; BLC: Balneario La Chiquita; V: Villalonga; BLP: Balneario Los Pocitos and IJ: Isla Jabalí. 115′121 mm (72′72 DPI)

Cyrtopleura lanceolata are among the most frequent bivalves.

Site 5, Modern beaches near the outlet of the Colorado River (39º34′S/62º12′W), are sandy and partly clayey silt with complete shells of *Amiantis purpurata* and *Ostrea puelchana* and *Zidona dufresnei* highly fractured.

Site 8, Villalonga (39º59′S/62º20′W), are silty-fine sand beaches; their molluscs have bad preservation of their color and are mostly fractured. Most frequent species are *Zidona dufresnei* and *Buccinanops globulosus*.

Site 11, Los Pocitos (40º26′S/62º25′W), are beaches of transitional environments with an intertidal sector that behaves as a sandy-silty marsh. Most common species are *Pitar rostratus*, *Crassostrea gigas* (introduced), *Corbula patagonica* and *Buccinanops globulosus*. The position of valves is concave upwards, and most of them show a slight degree of weathering.

Sites 14 (40º32′S/62º15′W), and 15 (40º35′S/62º10′W) at Jabalí Island (JI), are medium sand beaches with mostly fragmented valves. Frequent species are *Pitar rostratus*, *Brachidontes rodriguezii*, *Mytilus edulis* and *Bostrycapulus odites*.

4 Materials and Methods

Among the collected material (2168 valves) a total of 54 species of bivalves and gastropods, were recognized, 29 of them are bioeroded. Valves both of Holocene deposits and modern beaches are mostly well-preserved, little eroded, favoring the identification of the ichnogenera and ichnospecies.

The analysis of the Holocene deposits was made on samples 1dm^3 volume. Samples of modern beaches were collected on a 1m x 1m quadrant on transects perpendicular to the coast line. Once the valves were separated from the sediment with sieves, the proportion of valves with bioerosion was quantified.

The study of trace fossils was made following the different ethologic classes of Seilacher (1953) modified by Bromley (1981; 1994; 1996). Microscopic bioerosion marks were observed with naked eye, and images were digitalized through a scanner (HP Scanjet 300), following the technique used by Bromley and Ritcher (1999).

The observation of microscopic marks was made through a stereoscope microscope model SMZ 800 with a program NIS-Elements (INSUGEO-UNT, Yerba Buena, Tucumán) and scanning electron microscope (SEM-PHILIP-SEM 505; CINDECA, Centro de Investigación y desarrollo de Ciencias Aplicadas, La

Plata, Buenos Aires). Images were processed with Coreldraw 13 and Adobe Photoshop. The material was deposited in the collection PIL-Colección Sr. Nuñez by Dr. Charó Melisa.

Histograms were made with percentages of ichnotaxa represented in the sites. For a better description of structures, bivalves and gastropods were divided into sections. The surface of bivalves was divided into four sections: umbonal, central, muscle and ventral edge. Gastropods were divided into two sections: coil and last whorl, except for the genera *Crepidula* and *Bostrypapulus* which were studied as the sections of bivalves (Fig. 2).

5 Results

5.1 Bioerosion

Bioerosion marks were recorded in 20.11% of the analyzed valves. The largest percentages of bioerosion were found in the deposits of AQ (48%, Site 9) and JI (43.7%, Site 12), both Holocene in age, whereas those with lowest percentages of bioerosion were LP (2.85%; Site 10) Holocene, and JI (Site 15) in modern beaches. The largest number of ichnogenera (nine) was found in Site 6 (V, H), and the lowest number in Site 1 (VP, H) and Site 15 (JI, modern), both with two ichnogenera (Tables 1 and 2).

Bioerosion was found in 29 of the 54 species, 15 bivalves and 14 gastropods. Among the species with the largest amount of biogenic traces are the bivalves
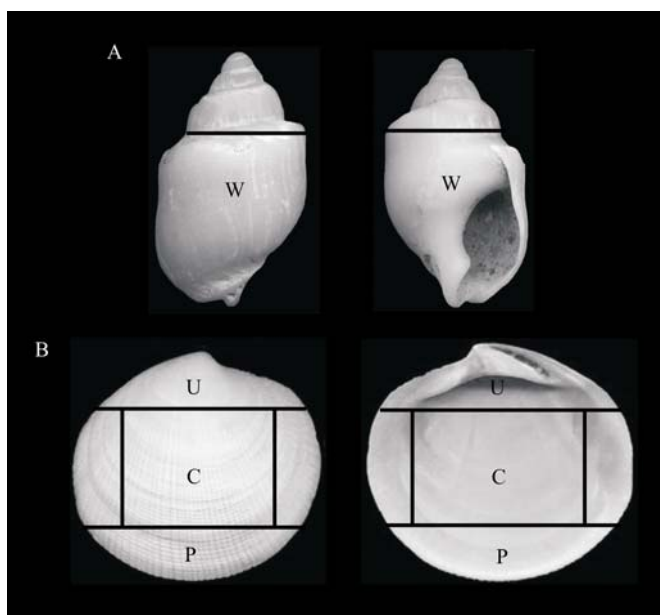

Fig. 2. (a–b) Gastropod and bivalve drawings displaying analyzed areas.
W: whorld, U: umbonal seccion; C: central seccion, M: muscular seccion and P: posterior seccion. 68×63 mm (72×72 DPI)

Table 1 Percentages of bioerosion and bioeroded species of all the sites in the south of Buenos Aires Province

Site	Nº total	S	% b	Sb	% Sb	Nº I
1	108	4	17,6	3	75	2
2	220	29	22,3	18	62.1	8
3	169	19	13,60	11	52.6	6
4	84	14	32,14	7	50	6
5	90	14	36,6	8	57.1	5
6	196	35	27,55	11	31.42	9
7	186	26	25,3	14	53.8	8
8	134	10	6,7	4	40	4
9	121	14	48	10	71.4	7
10	421	10	2,9	3	30	4
11	166	9	16,3	6	66.6	8
12	103	14	43,7	6	42.8	5
13	57	9	31,6	6	66.6	6
14	52	10	25	5	50	6
15	61	9	3,3	1	11.1	2
Total	2168					

S − species; b − bioerosion; Sb − bioeroded species; I − icnogenera.

Glycymeris longior, *Ostrea puelchana*, *Amiantis purpurata*, and *Pitar rostratus*, and the gastropods *Bostrycapulus odites* and *Crepidula argentina* (Table 3).

5.1.1 Domichnia

The ethologic class Domichnia includes permanent habitation structures produced by sessile or semi-sessile, suspension feeders, carnivores, and saprophagous organisms. Traces are generally simple or branched galleries, many of them U-shaped, cutting the stratification planes (Costa de Almeida, 2007). Organisms responsible for these traces seek protection in the substrate, and in this paper are represented by *Entobia, Maeandropolydora, Iramena, Caulostrepsis, Pennatichnus, Pinaceocladichnus, Semidendrina, Trypanites,* and *Gastrochaenolites*.

Entobia Bronn, 1838
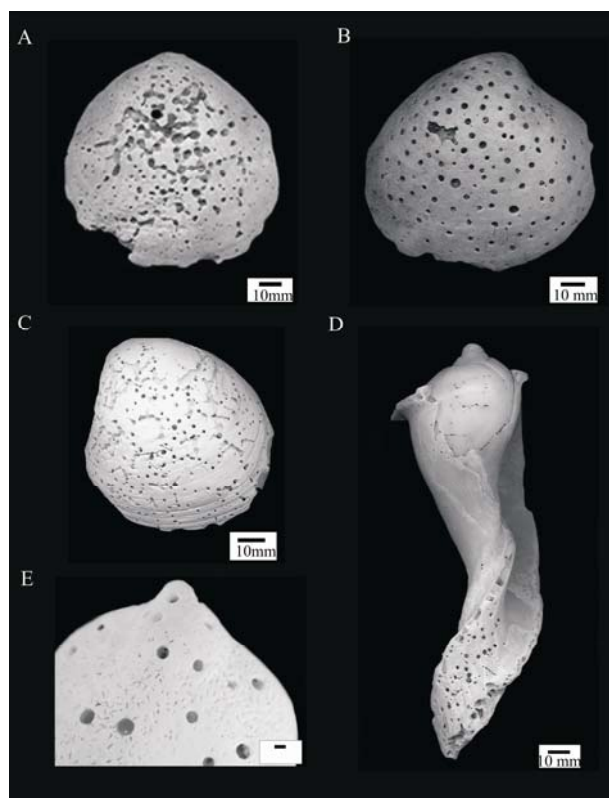
Diagnosis: Cylindrical galleries parallel to the

Fig. 3. Entobia isp. (a), Glycymeris longior of Site 6 (PIL: 13.873, V, Holocene); (b), Amiantis purpurata of Site 12 (PIL: 13.874, IJ, Holocene); (c), Pitar rostratus of Site 14 (PIL: 13.875, IJ, modern); (d), Adelomelon brasiliana of Site 6 (PIL: 15.151, CV, Holocene) and E) Crepidula argentina of Site 7 (PIL: 15.152, V, Holocene). 109´134 mm (72´72 DPI)

surface, composed by interconnected chambers, with network-shaped borings on the surface of the valve (Árpád, 2010). They are produced by siliceous sponges. The channels are exposed in some specimens as a result of weathering. They were observed in all sites except for Site 1.

Colonized area: In most bivalves they cover the

Table 2 Icnogenera found in all of the sites

Site	Area	Age	E	M	F	Pinne	I	Cau	O	G	Penna	Radu	Cen	Try	Semi	Gas	Nº shells bioeroded
1	PV	H	0	0	0	0	0	0	17	0	2	0	0	0	0	0	19
2	PV	M	5	1	1	10	6	0	11	0	15	0	0	0	2	0	49
3	BLC	M	10	0	1	5	5	0	1	0	1	0	0	0	0	0	23
4	RC	H	2	0	1	3	1	0	6	0	4	0	0	0	0	0	27
5	RC	M	2	1	0	3	1	0	9	0	0	0	0	0	0	0	33
6	CV	H	10	2	0	6	14	1	6	1	4	0	0	0	10	1	54
7	V	H	5	0	1	11	22	0	3	0	3	1	0	0	0	0	47
8	V	M	1	0	0	2	1	0	5	0	0	0	0	0	0	0	9
9	CA	H	20	3	0	6	14	0	2	1	5	0	0	0	6	0	58
10	BLP	H	2	0	0	0	2	0	8	0	0	0	0	0	0	0	12
11	BLP	M	6	1	0	2	11	1	4	0	1	0	0	1	0	0	27
12	IJ	H	25	4	0	2	13	0	1	0	0	0	0	0	0	0	45
13	IJ	H	8	2	0	1	5	0	1	0	0	0	1	0	0	0	18
14	IJ	M	4	2	0	1	2	0	3	0	0	1	0	0	0	0	13
15	IJ	M	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2
Total																	436

Age: H − Holocene and M − modern. Ichnogenera: E − *Entobia*; M − *Meandropolydora*; F − *Finichnus*; Pinne − *Pinaceocladichnus*; I − *Iramena*; Cau − *Caulostrepsis*; Sed − *Sedilichnus*; G − *Gnathichnus*; Penna − *Pennatichnus*; Radu − *Radulichnus*; Cen − *Centrichnus*; Try − *Trypanites*; Sem − *Semidedrina*; Gas − *Gastrochaenolites*.

entire external surface of the valve, and in gastropods, in the last whorl (Fig. 3).

Maeandropolydora **Voigt, 1965**

Diagnosis: Long and wide cylindrical galleries excavated parallel to the surface of the valve with dichotomic bifurcation (Santos et al., 2003). They are generated by polychaete annelids, mostly from the Family Spionidae.

The ichnospecies *Meandropolydora sulcans* (Bromley and D`Alessandro, 1983) was identified. It is represented by cylindrical borings, uniform in diameter, with irregular sinuous, plano-spiral and/or helicoidal shape.

Colonized area: In most bivalves it is located on the central and umbonal areas, and in gastropods in the section of the last whorl (Fig. 4a–e).

Caulostrepsis **Clarke, 1908**

Diagnosis: Borings of a single entrance, U-shaped, on the surface of the valve. The branches may be connected through a lamella, or merging the margins producing an oval or flat "pocket". The apertural
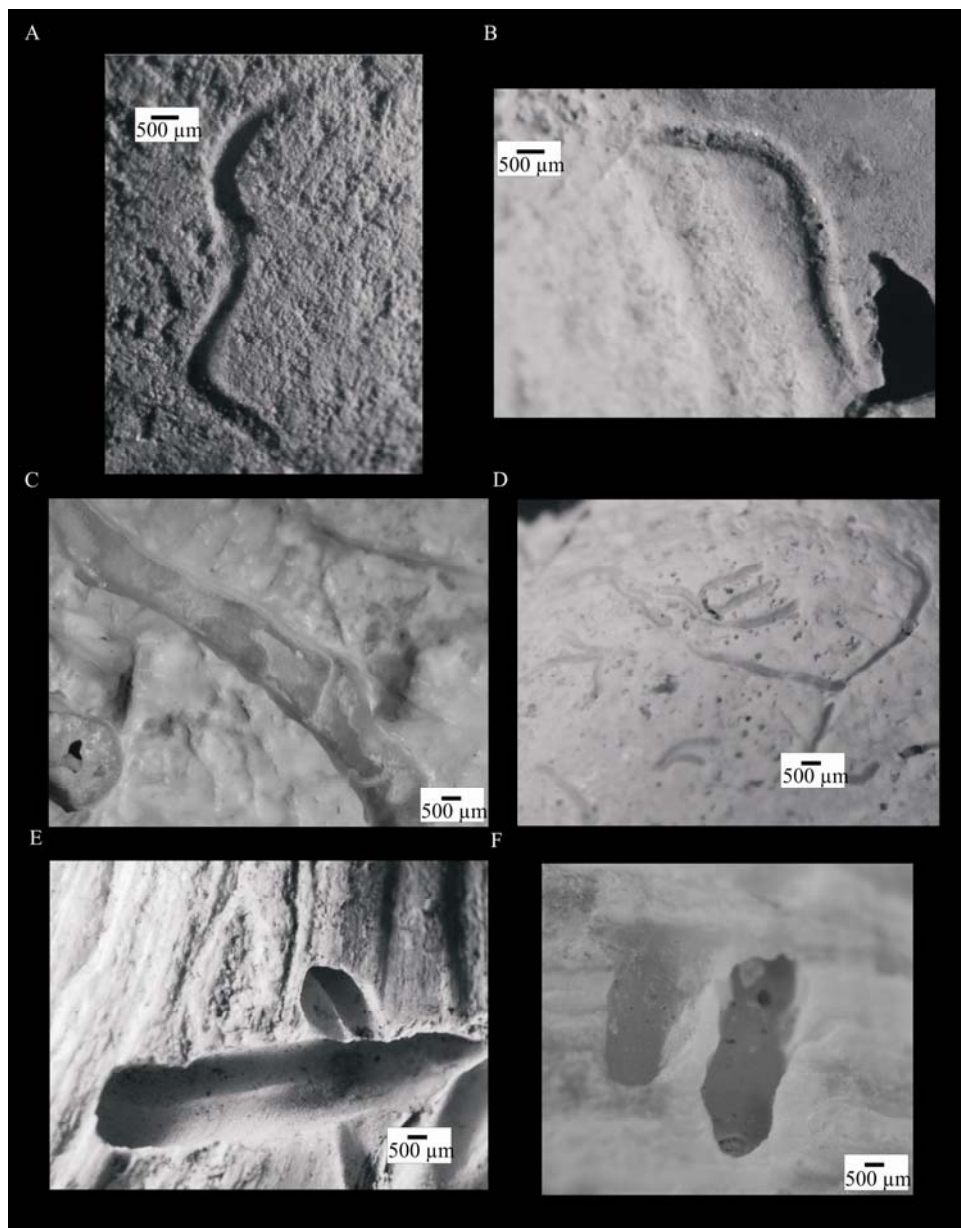

Fig. 4. *Maeandropolydora* isp. (a), Pitar rostratus of Site 12 (PIL: 15.153, IJ, Holocene); (b), Bostrycapulus odites of Site 14 (PIL: 15.154, IJ, modern); (c), Bostrycapulus odites of Site 14 (PIL:15.155, IJ, modern); (d), Bostrycapulus odites of Site 12 (PIL: 15.156, IJ, Holocene). The ichnospecie Caulostrepsis taeniola E) Adelomelon brasiliana of Site 6 (PIL: 15.157, V, Holocene). The ichnotaxa of Trypanites F) Ostrea puelchana of Site 11 (PIL: 15.158, LP, modern). 80´102 mm (72´72 DPI)

margin, is narrower than the distal width, but the cross-section may be approximately similar or subcircular (Verde, 2002; Lorenzo and Verde, 2004) (Fig. 4f). It is assigned to the boring activity of spionid polychaetes.

The ichnospecies *Caulostrepsis taeniola* Clarke, 1908 was identified. It is a subdivided U-shaped gallery, and the internal margins are connected by a sheath. It was recognized on the right margin of the internal valve of *Ostrea puelchana* (Site 11) and in the last whorl of *Adelomelon brasiliana* (Site 6).

Trypanites Mägdefrau 1932

Diagnosis: Simple borings, elongated or cylindrical, cross-section generally circular; they are produced by sipunculid annelids (Santos et al., 2010). Most often it occurs in inclined at low angle and may be parallel and perpendicular to the substrate (Fig. 4g).

This ichnogenus is recognized on the posterior margin of the valve of *Ostrea puelchana* in Site 11.

Pinaceocladichnus Mayoral 1988a

Diagnosis: Boring pattern constituted by a regular network of fine tunnels, slightly curved and laterally opposite, with spindle-shaped borings on the surface of the valve (Mayoral, 1988a). These tunnels may have features up to fifth order. They are produced by ctenostomate bryozoans and are observed mostly in all sections of the shells.

The ichnospecies *Pinaceocladichnus onubensis* (Mayoral, 1988a) was identified, which is a pattern of straight to slightly arched main tunnels with verticillate and also random bifurcations. They have elongate cavities with apertures near the bifurcation of the tunnels (Verde, 2002). Some specimens bear this ichnospecies with a high degree of weathering, merging the apertures with the zooidal cavities (Fig. 5).

Iramena Boekschoten, 1970

Diagnosis: It is a boring system consisting in long primary tunnels little bifurcated, in irregular pattern with primary apertures, rounded to kidney-shaped, opening into a main cavity. Less conspicuous secondary tunnels open at approximately 90º (Mayoral, 1988a). They are produced by ctenostomate bryozoans.

This ichnogenus is represented in all sites except for 1 and 15. Borings are only superficial and colonize almost the entire external valve (Fig. 6a–c).

Pennatichnus Mayoral, 1988

Diagnosis: It is a system of long and thin tunnels which may have small axial apertures. Primary apertures are circular or drop-shaped, joined to the first order subordinate tunnels and a thin pedicle toward the main tunnel. The whole system of borings is feather like. It may also form a complex tunnel system with sharper angles of bifurcation (Pereira et al., 2009). They are produced by ctenostomate bryozoans (Fig. 6d and e). It was found in all sections. This ichnogenus was observed in the external surface.

Gastrochaenolites Kelly and Bromley, 1984

Diagnosis: It is a club-shaped boring on hard substrate, including biogenic and inorganic minerals, clasts, etc. The apertural region is narrower than the main chamber, and may be circular, oval or dumb-bell. It is perpendicular or parallel to the substrate surface (Gibert et al., 2004). The boring is made by a bivalve excavating mechanical and chemically the substrate. It is mostly produced by the Family *Mytiladae*.

One ichnospecies was recognized, *Gastrochaenolites torpedo* (Kelly and Bromley, 1984), which is an elongate, smooth and with the widest part near the base. It is produced probably by *Lithophaga patagonica*, and was found on lithic remains of Site 6.

5.1.2 Fixichnia

The ethologic class Fixichnia includes biogenic structures made by sessile organisms to provide fixation. Two types are recognized, those produced by the use of soft parts or those by the skeleton. In this paper two ichnogenera are included *Finichnus* and *Centrichnus*.

Finichnus (Taylor et al., 2013)

Diagnosis: Groups of elliptic or pear-shaped pits wider than deep, produced by ctenostomate bryozoans. Each pit represents one zooid of the bryozoan colony. All pits are excavated at the same depth and cut perpendicularly the substrate. It was localized at the umbonal section, and on the posterior margin of the internal valve.

The ichnospecies *Finichnus peristroma* Taylor et al., 1999 was recognized, which are subcircular to elliptic pits produced by multiserial chelistomate bryozoans. They are present in *Ostrea puelchana*, *Pitar rostratus*, *Crepidula argentina* and *Zidona dufresnei* (Fig. 7a and b).

Centrichnus Bromley and Martinell, 1991

Diagnosis: This is a biogenic trace drop or pear-shaped characterized by a ring pattern with concentric striae. It is originated by bivalves of the Family *Anomiidae* often secreting a calcified byssus that serves as a fixing organ (Bromley and Heinberg, 2006).
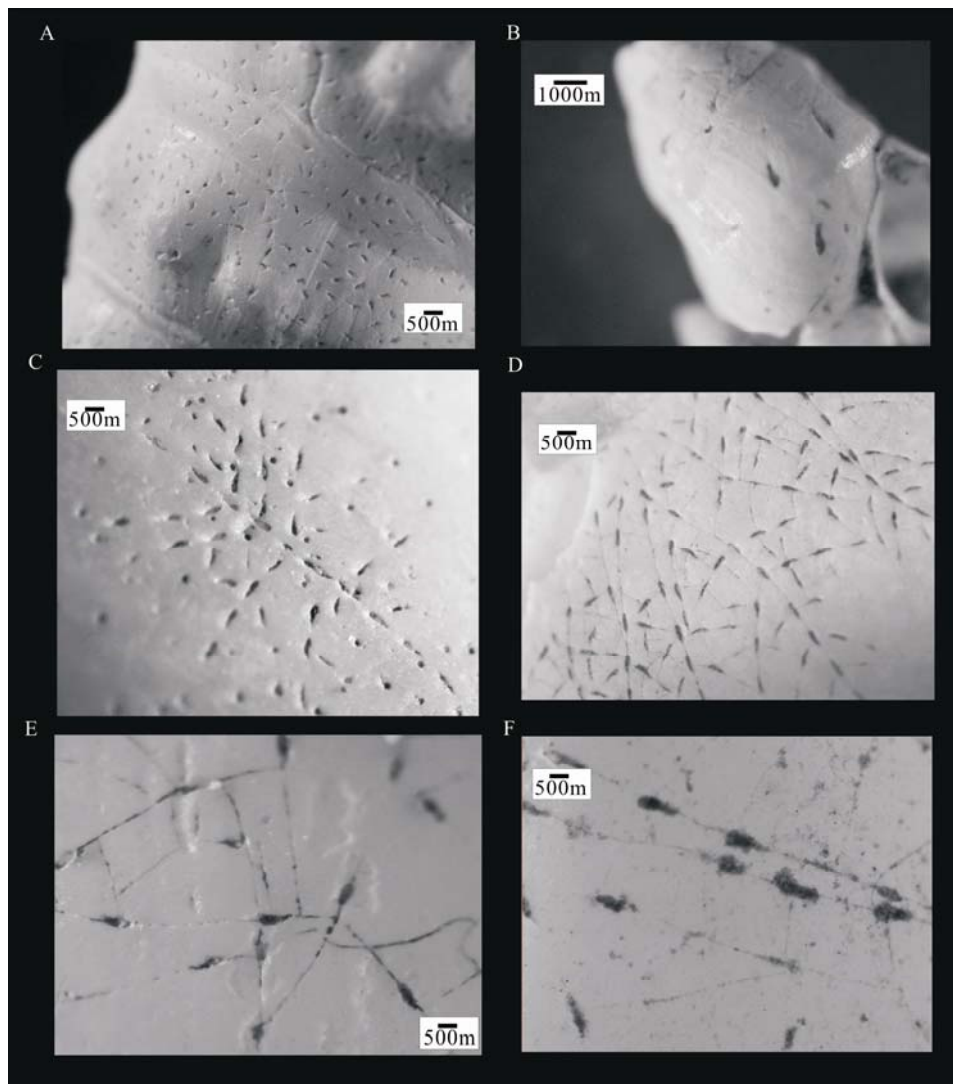
Fig. 5. Pinaceocladichnus onubensis (a), Buccinanops monilifer of Site 7 (PIL: 15.159, V, Holocene); (b), Heleobia australis of Site 11 (PIL: 15.160, LP, modern); (c), Zidona dufresnei of Site 2 (PIL: 15.161, PV, modern); (d), Amiantis purpurata of Site 9 (PIL: 15.162, V, Holocene); (e), Buccinanops cochlidium of Site 2 (PIL: 15.163, PV, actual); (f), altered Glycymeris longior of Site 8 (PIL: 15.164,V, modern). 120′136 mm (72′72 DPI)

The ichnospecies *Centrichnus eccentricus* Bromley & Martinell, 1991, is recognized, which is the imprint of the byssus (Neuman et al., 2015). In this case, the trace is incomplete, on the posterior margin of the valve of *Amiantis purpurata* from the Holocene of Jabalí Island (Site 13) (Fig. 7c and d).

5.1.3 Praedicnia

The ethological class Praedicnia is characterized by the evidence of different predator organisms. They are single holes and some times appear as incomplete borings.

Oichnus Bromley, 1981

Diagnosis: Circular, subcircular or oval borings perpendicular to the substrate that can or cannot perforate the surface. They are made by molluscs (gastropods, bivalves, cephalopods and scaphopods) (Wisshak et al., 2015).

It was identified in all sites, on bivalves they are mostly on the umbonal, central and muscle areas, and in gastropods, on the last whorl. This ichnogenus is represented by three ichnospecies, *Oichnus paraboloide*, *Oichnus simplex*, and *Oichnus gradatus*.

Oichnus paraboloide Bromley, 1981 is a paraboloid aperture perpendicular to the substrate (Zonneveld and Gingras, 2015). In this case, it was produced by naticid gastropods and coincides with the presence in the area of *Notochoclis isabelleana*. This ichnospecies is represented in the bivalves *Glycymeris longior, Brachidontes rodriguezii, Pitar rostratus, Carditamera*
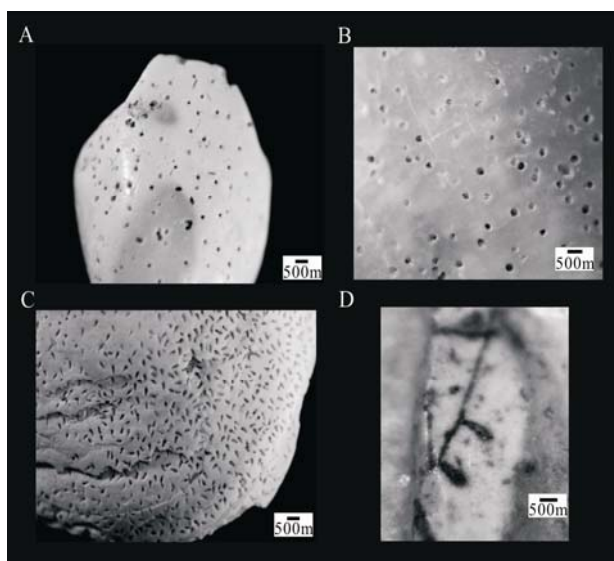
Fig. 6. Iramena isp. (a), Crepidula sp. of Site 4 (PIL: 15.165, RC, modern); (b) Crepidula argentina of Site 15 (PIL: 15. 166, IJ, modern), The ichnotaxa of Pennatichnus (c) Overlapped traces trace in Crepidula argentina of Site 7 (PIL: 15.167,V, Holocene); and (d), Altered Ostreola equetris of Site 2 (PIL: 15.168, PV, modern). 85´69 mm (72´72 DPI)

Fig. 7. Finichnus peristroma (a), Crepidula argentina of Site 15 (PIL: 15.169, IJ, modern); (b), Bostrycapulus odites of Site 9 (PIL: 15.170, Villalonga, Holocene). Centrichnus eccentricus; (c–d), in Amiantis purpurata of Site 13 (PIL: 15.171, IJ, Holocene). 115´100 mm (72´ 72 DPI)

plata, and *Corbula patagonica* and the gastropod *Heleobia australis* (Fig. 8a–b, d, f–g).

Oichnus simplex Bromley, 1981 is characterized by a cylindrical or subylindrical aperture, perpendicular to the surface of the substrate. It is produced by muricacean gastropods, related to the predator *Trophon patagonicus*. This ichnospecies is represented in the bivalves *Glycymeris longior*, *Crassostrea rizophorae*, *Corbula patagonica*, *Mactra guidoi* and the gastropod *Heleobia australis* (Fig. 8c).

Another ichnospecies, *Oichnus gradatus* Nielsen and Nielsen, 2001, which are borings with abrupt changes in diameter, the inner narrower than the outer, and both concentric, is less represented (Wisshak et al., 2015) (Fig. 8e).

This ichnogenus is best represented in the gastropod *Heleobia australis*, with both ichnospecies *O. simplex* and *O. paraboloide* in the last whorl. *O. simplex* is present on the umbonal and central sections of *Bostrycapulus odites*. *O. paraboloides* is recorded in the muscular section, mainly in the umbonal section of *Brachidontes rodriguezii* and *Crassostrea gigas,* and in the central section of *Corbula patagonica*, and *Pitar rostratus*.

5.1.4 Pascichnia

The ethologic class Pascichnia is a group of feeding traces (grazers), produced by microphage organisms (fine detritus particles), on or near the interface water/sediment. It is c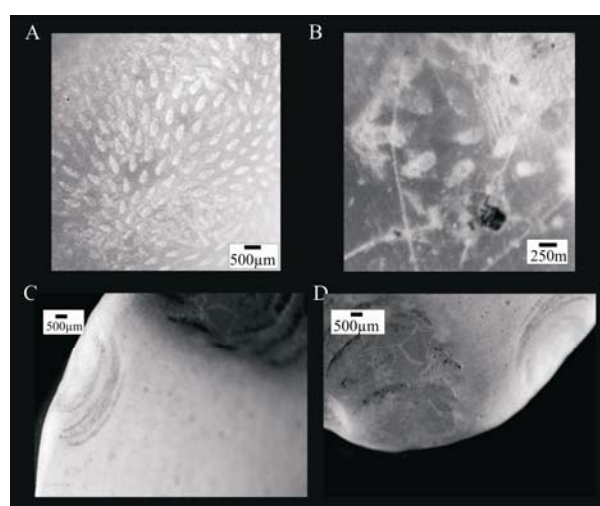haracterized by regular patterns, plane, sometimes discontinuous and sinuous (meandriform, spiral). It is represented by *Radulichnus* and *Gnathichnus*.

Radulichnus Voigt, 1977

Diagnosis: Grazing traces, rather meandriform, shallow grooves arranged in parallel groups that intersect, or rotating around one point on the surface (Jaght, 2003). They are produced by the grazing activity due to the activity of the radulae of herbivore gastropods or polyplacophorans. The ichnospecies *Radulichnus inopinatus* Voigt, 1977, was recorded on *Amiantis purpurata* of modern beaches of Jabalí Island (Fig. 9a–b).

Gnathichnus Bromley, 1975

Diagnosis: Grazing traces that are formed by sets of parallel pentaradiate grooves, that may completely cover or not the surface of the valve infected by algae. Their size is variable and can be frequently seen through a stereomicroscope or naked eye. They are produced by regular echinoids.

The represented ichnospecies is *Gnathichnus pentax* which is characterized by five star-shaped grooves (Reolid et al., 2015). Each groove is straight, ≥ 100 μm long. It is represented on *Buccinanonps cochlidium*. When superposed star-shaped patterns are observed on the last whorl, the pattern cannot be identified (Fig. 9c). Besides, it was found on the inner valve of *Amiantis purpurata* and *Glycymeris longior* near the muscular section and the ventral margin.
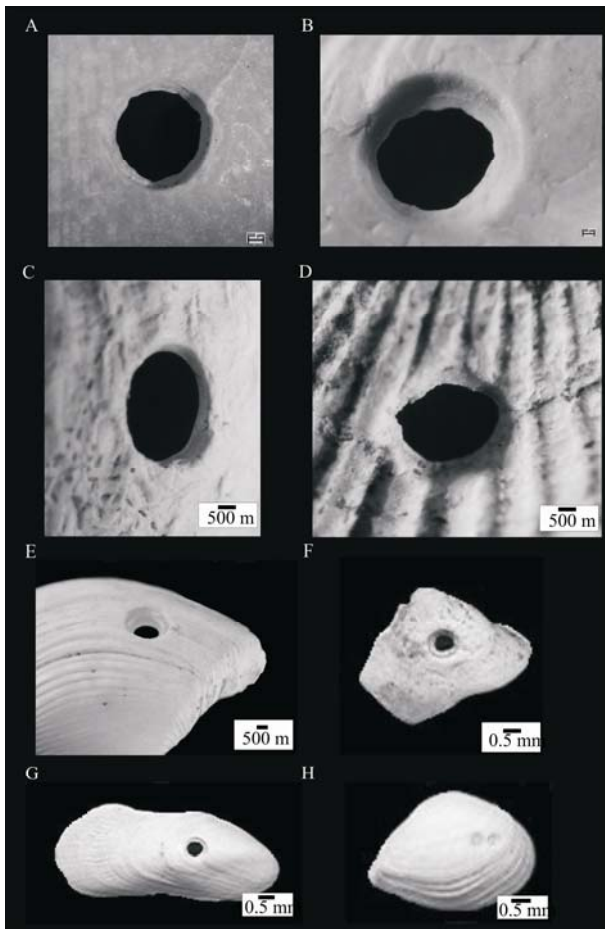
Fig. 8. Oichnus isp. (a), Glycymeris longior of Site 7 (PIL:15.172 , V, Holocene); (b), Brachidontes rodrieguezii of Site 6 (PIL: 15.173, V, Holocene); (c), Bostrycapulus odites of Site 7 (PIL: 15.174, V., Holocene); (d), Carditamera plata of Site 1 (PIL: 15.175, PV, Holocene); (e), Oichnus gradatus in Corbula patagonica of Site 6 (PIL:15.176, V., Holoceno); (f), Pitar rostratus of Site 10 (PIL: 15.177, LP, Holocene); (g), Brachidontes rodriguezii of Site 6 (PIL: 15.178, V, Holocene). Incomplete borings in Oichnus; (h), Corbula patagonica of Site 6 (PIL: 15.179, V, Holoceno). 102´151 mm (72´72 DPI)

Semidendrina Glaub, 1994

Diagnosis: Tree-shaped pattern, little extended originated from a subcircular aperture, and semicircular, overall fan-like shape. They are considered as microborings made by talophytes (Santos and Mayoral, 2008). This pattern is similar to the ichnogenus *Dendrina* but the rosette is quite smaller, no more than 1 mm, as well as the conducts or filaments. It is recognized as morphotype B_4 of Mayoral (1988b) (Fig. 9d). It was found in only three species, *Glycymeris longior*, *Ostreola equestris* and *Crepidula argentina*, on the inner valve.

Biogenic traces:
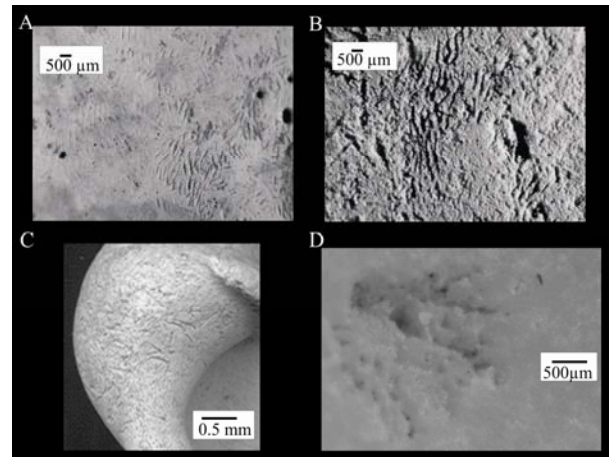

Fig. 9. Radulichnus isp. (a) Internal surface and (b) external surface of Amiantis purpurata of Site 14 (PIL 15.180, IJ, modern). (c), Gnathichnus pentax in a section of the last whorl in Buccinanops cochlidium of Site 6 (PIL: 15.181, V, Holocene). (d), Semidendrina isp. in internal surface of Glycymeris longior of Site 6 (PIL: 15.182, V, Holocene). 119´95 mm (72´72 DPI)

Microborings made by talophytes were found in low frequency, all of them on the inner valves of bivalves and gastropods.

On the inner valves of two species of epifaunal gastropods, *Crepidula* and *Bostrycapulus*, there were microborings in a star-shaped or tree-shaped pattern. This trace is related to the ichnospecies *P. onubensis*, similar to the pattern of morphotype B, probably B_5 of Mayoral (1988b) (Fig. 10a, b).

Another biogenic structure is characterized by circular microborings between 50−80 μm in diameter, not perforating the whole valve, but colonizing most of it. Mayoral (1988b) described a similar morphotype (morphotype A) and attributed it to the activity of Chlorophyceae algae similar to *Codiolum*. It was observed in *Pitar rostratus* in the modern beach of Colorado River (Site 3) (Fig. 10c).

Another microboring pattern consists of a series of more or less radial furrows and a rounded central cavity not quite defined, dichotomically bifurcated and Y-shaped. It is recognized as morphotype B in Mayoral (1988b). It was found on the inner valve of *Bostrycapulus odites* in the Holocene of Villalonga Canal (Site 6; Fig. 10d).

In observations with MEB one specimen of *Urosalpinx cala* (Site 6) could be observed together with the microborings of the spyra section. They are biogenic cavities characterized by subhorizontal to oval forms with smooth or crenulate margins that do not penetrate the whole valve. Blisset and Pickerill (2007) recognized these marks in one gastropod specimen from the Middle Eocene Somerset Formation of
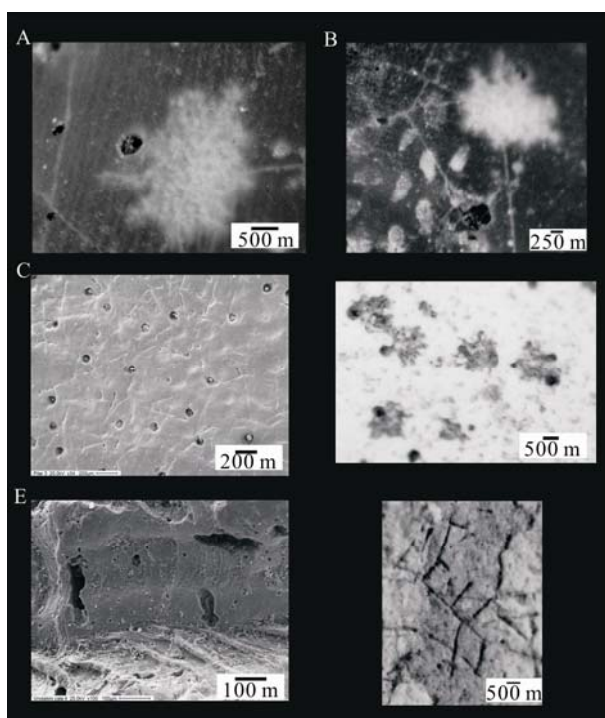
Fig. 10. Biogenic traces of dendritic/tree-shaped pattern (a) in (b). odites in the Site 7 by stereoscope microscope (PIL: 15.183, V, Holocene) and (b) Bostrycapulus odites of Site 7 (PIL: 15.184, V, Holocene; (c), surface borings with a diameter ≤ 100 μm in Pitar rostratus of Site 3 (PIL: 15.185, RC, modern); (d), Amiantis purpurata of Site 9 (PIL: 15.186, Villalonga, Holocene); (e), Biogenic cavities on the seccion of a whorl of Urosalpinx cala from Site 6 (PIL: 15.187, V, Holocene); and (f), Amiantis pupurata of Site 12 (PIL: 15.188, IJ, Holocene) displaying lines of orthogonal model. 81′89 mm (72′72 DPI)

Jamaica (Fig. 10e).

Another biogenic trace is a series of cylindrical conducts very uniform in diameter with a bifurcated pattern in almost orthogonal angles that can bifurcate again in the same way or more frequently as Y-shape. In this case they are much shorter than the first ones. It is considered by Mayoral (1988b) as morphotype C, and is a "fungal" boring pattern. It was found in the inner valve of *Amiantis purpurata* from the Holocene of Jabalí Island (Site 12) (Fig. 10f).

6 Discussion

A total of 14 ichnogenera in 280 bioeroded valves were found in mollusk valves of Holocene sites of the south of Buenos Aires Province; whereas in modern beaches, 10 ichnogenera were found in a total of 156 bioeroded valves. The most frequent ichnogenera in Holocene deposits of this area are *Iramena* (28.5%), *Entobia* (28.45%) and *Oichnus* (15.45%). In modern beaches the same ichnogenera are represented with

different abundances *Entobia* (20.5%), *Oichnus* (20.5%), *Iramena* (17.9%), except for the ichnogenus *Pinaceocladichnus* which was recorded 17.2% more than in the Holocene (Figs. 11 and 12).

The most bioeroded species are O. *puelchana* with nine ichnogenera, and then *A. purpurata, G. longior* and *P. rostratus*; among gastropods, *B. odites* and *C. argentina* with seven ichnogenera (Table 3).

The record of *Iramena*, as one of the dominant ichnogenera of the entire area except for Site 1 (VP, H), and together with the increase of *Pinaceocladichnus, Pennatichnus*, in modern beaches, reveal the existence of ctenostomate bryozoans. These latter are not competing for space and are generally replaced by sponges in stable substrates which tend to avoid ephemeral substrates or intermediate in stability. Their increasing record in modern beaches suggests water currents and larger availability of phyto and zooplankton in the environment. The second ichnogenus in frequency is *Entobia* which suggests environments of low energy, since most silica sponges prefer habitats with low wave action. It would also reveal long periods of exposition, presence of phytoplankton, no sediment in suspension, and optimal oxygenation of the environment allowing the presence of a diverse fauna of boring and incrusting organisms (sponges). The third ichnogenus in dominance is *Oichnus* both in the Holocene and modern beaches, which suggests the presence of muricaceans (*T. patagonicus*) and naticids (*N. isabelleana*) in the assemblages, but not suggesting any particular environment, which is an indicator of behavior issues.

In Holocene sites, three ichnogenera were recognized (*Gastrochaenolites, Centrichnus* and *Gnathichnus*), absent in modern beaches sites, and with little representation in the area. The presence of *Gastrochaenolites* in Site 6 (VC, H), suggests a shallow coastal marine environment with certain stability so that it can be colonized, and low sedimentation rate. The
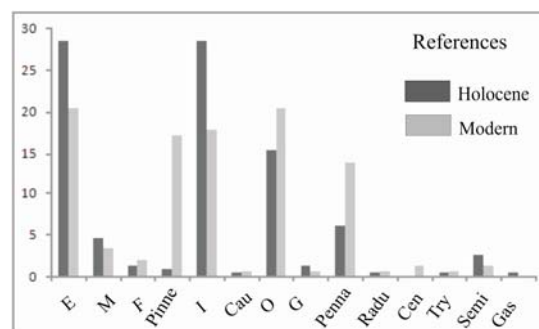

Fig. 11. Proportion of ichnogenera in sites from the Holocene and modern beaches form southern Buenos Aires shores (Eastern Argentina). 171′83 mm (72′72 DPI)

Table 3 Inchnogenera found in species of bivalves and gastropods of the south of Buenos Aires Province, Argentina

Species	Domichnia								Pascichnia		Fixichnia		Praedichnia	Microbioerosion
Bivalves	E	M	I	Cau	Penna	Pinne	Try	Gas	G	Radu	F	Cen	O	Semi
G. longior	x	x	x		x	x			x				x	x
B. rodriguezii													x	
C. patagonica	x		x										x	
P. rostratus	x	x	x		x	x				x	x		x	
Ostrea sp.	x													
O. puelchana	x	x	x	x	x	x	x	x			x			
O. equestris	x	x			x	x							x	
A. purpurata	x		x		x	x			x	x		x		x
C. gigas	x													
C. rhizophorae													x	
M. edulis			x											
C. lanceolata													x	
M. guidoi			x			x							x	
M. patagonica						x								
C. plata													x	
Gastropods														
L. henseli														
T. patagonica	x		x			x							x	
B. odites	x	x	x		x	x					x		x	
Z. dufresnei	x		x		x	x					x			
H. australis						x							x	
C. argentina		x	x		x	x					x		x	x
O. tehuelcha													x	
B. globulosus	x		x		x	x								
N. isabellei			x											
T. patagonicus	x	x	x			x							x	
A. brasiliana		x			x	x						x	x	
O. urceus	x													
B. cochlidum			x			x			x					
B. monilifer						x								

ichnogenus *Centrichnus* is only present in Site 13 (JI, modern), indicating a low energy environment.

The ichnogenera least represented in the area are *Gnathichnus*, only in sites 6 (VC, H) and 9 (AQ, H), and *Radulichnus*, in sites 7 (V, H) and 14 (JI, modern). Both indicate the existence of regular echinoids, and a short colonization period, spatially restricted and unstable substrate, and shallow water. They are particularly common in hard substrates related to the photic zone (internal platform).

Microborings are first recognized in the area and are attributed to algal and/or fungal organisms. They were recognized in sites 2 (VP, modern) and 6 (VC, H). Borings were probably made by algal organisms, which suggest a lower photic zone, 20–50 m deep. The record of fungal organisms in Site 12 (JI, modern) probably represents a lower photic to aphotic zone. All the borings were made on the inner valve of the organism suggesting postmortem colonization.

The dominant ichnofacies in most sites is *Trypanites* which is characterized by assemblages of borings in typically hard substrates of littoral to sublittoral environment. It is represented by cylindrical forms, U-shaped, tear-shaped to irregular in shape. They have an anastomosed boring pattern (sponges and bryozoans), and are made by suspensivores or passive carnivores. Gnawing and grazing organisms such as chitons and echinoids are also present. Most trace fossil included in this ichnofacies are represented in *Domichnia* (*Trypanites*, *Gastrochaenolites*, *Entobia*, *Meandropolydora* and *Caulostrepsis*). Diversity is moderately low, although borings and/or grazing marks are abundant.

North of the study area, Holocene marine deposits were studied in the Bahía Blanca estuary. Farinati et al. (2006) identified three ichnogenera in micromolluscs, *Lepticnicus*, *Oichnus* and *Meandropolydora*, as well as two ichnogenera in *H. australis* (*Lepticnicus*, *Oichnus*) and three ichnospecies (*O. simplex*, *O. paraboloides* and *L. dromeus*). Whereas in this paper, near the outlet of the Colorado River (Site 3), the highest percentage of bioerosion was identified in *H. australis* with three ichnospecies *O. simplex*, *O. paraboloides* and less represented *Pinaceocladichnus onubensis*. This latter ichnospecies was first recognized in the area, in *Heleobia australis*.

In the Quaternary along the Argentine coast, Richiano et al. (2014) recognized 13 ichnogenera; among the most dominant are *Entobia*, *Oichnus*, *Maeandropolydora* and *Leptichnus*. In most mollusc valves, depending on the ethologic type, *Dominchnia* is frequent, and in bivalves, the dominant is *Praedichnia*.

The most relevant ichnogenera of the study area are *Iramena*, *Entobia* and *Oichnus* not distinguishing between gastropods and bivalves. The ichnogenus *Iramena* is present in 17 species (7B nd 10G), and *Entobia* and *Oichnus* are present in 15 species (8B and 7G). The borings were most frequent in the gastropod *H. australis* and the bivalve *P. rostratus*, being predation not present only in bivalves species.

7 Conclusions

Fossil traces are common elements in modern sediments of marine shorelines, with different ichnoassociations representing a varied spectrum of environment and facies. In eastern Argentina, along the southern shores of Buenos Aires Province (from Peninsula Verde to Jabalí Island), the dominant ichnofacies of most sites is *Trypanites*, that is characterized by boring associations on typical hard substrates. From the ethological point of view, the dominant ichnofacies are Domichnia and Praedichnia, with Pascichnia and Fixichnia less represented. The association displays a total of 14 ichnogenera and 11 ichnospecies identified so far, with a number of undifferentiated forms within a same environmental framework.

During in Holocene, the representative ichnotaxa in most sites of southern Buenos Aires shores are *Iramena*, *Entobia* and *Oichnus*, which reveal the presence of bioeroded organisms as ctenostomate bryozoans, clionid sponges and carnivorous gastropods. The abundance of ctenostomate bryozoans (*Iramena*) and clionid sponges (*Entobia*) describes a sublitoral environment with sandy bottom rich in nutrients and high oxygenation water. In Villalonga Quarry the predominance of regular echinoids (*Gnathichnus*) and boring bivalves (*Gastrochaenolites*) in Holocene deposits describes an environment of high exposition periods and rocky bottoms. In all modern beaches sites *Pinaceocladichnus* and *Pennatichnus* increase, both ichnospecies are assigned to ctenostomate bryozoans, associated to a slightly different environment, characterized by strong stability, an even marine salinity, oxygenated waters with subtidal low sediment suspension on sandy bottoms.

Acknowledgements

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