

Bioerosion structures in high-salinity marine environments: Evidence from the Al–Khafji coastline, Saudi Arabia

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ABSTRACT

Salinity is one the major stress factors that controls the biotic activities in marine environments. In general, the mixture with fresh-water has been mention as a great stress factor, but the opposite, i.e. high-salinity conditions, is less developed in the ichnological literature. Along the Al-Khafji coastline, Saudi Arabia, hard substrates (constituted by gastropods, bivalves and coral skeletons) contain diverse and abundant bioerosion traces and associated encrusters. Field and laboratory observations allowed the recognition of eight ichnospecies belong to the ichnogenera *Gastrochaenolites*, *Entobia*, *Oichnus*, *Caulostrepsis* and *Trypanites*, which can be attributed to various activities produced by bivalves, sponges, gastropods and annelids. The borings demonstrate two notable ichnological boring assemblages, namely, *Entobia*-dominated and *Gastrochaenolites*-dominated assemblages. The highly diversified bioerosion and encrustation in the studied hard organic substrate indicate a long exposition period of organic substrate with slow to moderate rate of deposition in a restricted (high-salinity) marine environment. This bioerosion study shows that high-salinity, at least for the study area, is not an important controlling factor for ichnology.

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1. Introduction

Rocky coasts are special environments, with exceptional conditions for colonization by boring and encrusting organisms due to their reduced or null sedimentation rates (Santos and Mayoral, 2008). Animals, plants and microbes penetrate surfaces of hard substrates producing bioerosion structures (Bromley, 1992; Taylor and Wilson, 2003; Abdel-Fattah and Assal, 2016). Hard substrates in intertidal and shallow sublittoral environments play crucial roles in colonization of the seabed and sedimentation (Taylor and Wilson, 2003). Modern marine hard substrates include biogenic, abiogenic and anthropogenic structures (Svane and Petersen, 2001). Biogenic hard substrates comprise shells, wood and bones, while abiogenic materials comprise rocks of various origins (Gibert et al., 2012). Anthropogenic structures include wharves, boat hulls, concrete shore defenses and plastic debris drifting in the ocean (e.g., Winston et al., 1997). These hard

substrates may be colonized by a diverse array of endobionts, in addition to suspension feeding epibionts (Santos and Mayoral, 2008).

Bioerosion is widely considered as an important process affecting hard substrates (Farinati and Zavala, 2002). The effect of bioerosive processes on shelly substrates has received attention from several authors (Martinell and Domènech, 1981; Martinell, 1982; Bromley and D'Alessandro, 1984; Bromley and Martinell, 1991; El-Sorogy, 2015; El-Gendy et al., 2015; Richiano et al., 2015, 2017). Encrustations on Cenozoic shells are very common, but published studies have been limited, particularly in the Arabian region (e.g., Taylor and Wilson, 2003; Kidwell, 2013; El-Gendy et al., 2015). Taphonomically, important encrusters with hard parts include serpulid worms, bryozoans, corals barnacles and foraminifera (McKinney, 1996; Perry, 2000; El-Sorogy et al., 2003; El-Hedeny, 2007a,b). It is knowledge that salinity is an important stress factor for ichnology in brackish environments (e.g. MacEachern and Gingras, 2007; Schröder-Adams et al., 2014). Nevertheless, ichnological patterns in high-salinity environments is an unexplored topic.

Because of its shallowness and high evaporation rates in the hot

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summer season, the Arabian Gulf is one of the most saline seas (Dawoud and Al-Mulla, 2012). Fang et al. (2013) suggested that bioerosion rates increase under ocean warming. The main aims of this study are to: (1) for the first time, identify and describe the ichnotaxa present in the coastal environment of the Al-Khafji area; (2) document the ichnological assemblages, and their ichnospecies distribution and diversity; and (3), provide information on bioerosion structures recorded in high-salinity environments with implications for the fossil record.

2. Materials and methods

2.1. Study area

The Arabian Gulf is of great interest to marine scientist due to its seasonal variations on temperature and salinity. It is a shallow semi-enclosed marginal sea of 240,000 km² in area, with a pronounced shallowness, only 35 m depth on average (Bashitialshaaer et al., 2011). The salinity ranges between 38 and 42‰, reaching up to 70 in some embayments (John et al., 1990; Bashitialshaaer et al., 2011; Uddin, 2014).

The Al-Khafji coastline is located in the northeast of the Saudi Arabian Gulf (Fig. 1), and presents three types of sediments (Fig. 2). 1) Sandy-dominated shores (Fig. 2A), composed of sand and sandy mud with biogenic materials of bivalves, gastropods, foraminifers, ostracods, bryozoans and sea grass (Fig. 2B). 2) Artificial rocky-shores, which constructed to protect the coastline against high tides (Fig. 2C). 3) Natural rocky shores, composed of consolidated

sands, inhabited with barnacles, worm tubes and gastropods (Fig. 2D).

2.2. Sampling

A total of 276 specimens of gastropods (43), bivalves (121) and corals (112) were collected from 26 localities at low tide from the intertidal zone of the Al-Khafji coastline, Arabian Gulf, Saudi Arabia (Fig. 1). During a field trip, four persons walk each one of the 26 stations, collecting sediment sample with gastropod and bivalve shells as well as coral skeletons (either have bioerosion signature or have not) from an intertidal area with a length of 75 m and 2–4 m wide. This methodology was repeated in all the stations. Specimens with evidence of bioerosion and encrustation were washed, cleaned, sorted, identified and illustrated. Dead skeletons were washed to remove sediments and deposited in the Department of Geology and Geophysics, College of Science, King Saud University (numbers from 1000 to 1276). The observed borings were then photographed, identified and the relative abundance and distribution were also documented. Some borings, especially those with small diameters were measured, examined and photographed under a binocular microscope.

3. Results

3.1. Bioerosion

A total of eight ichnospecies were identified on bioclast from the

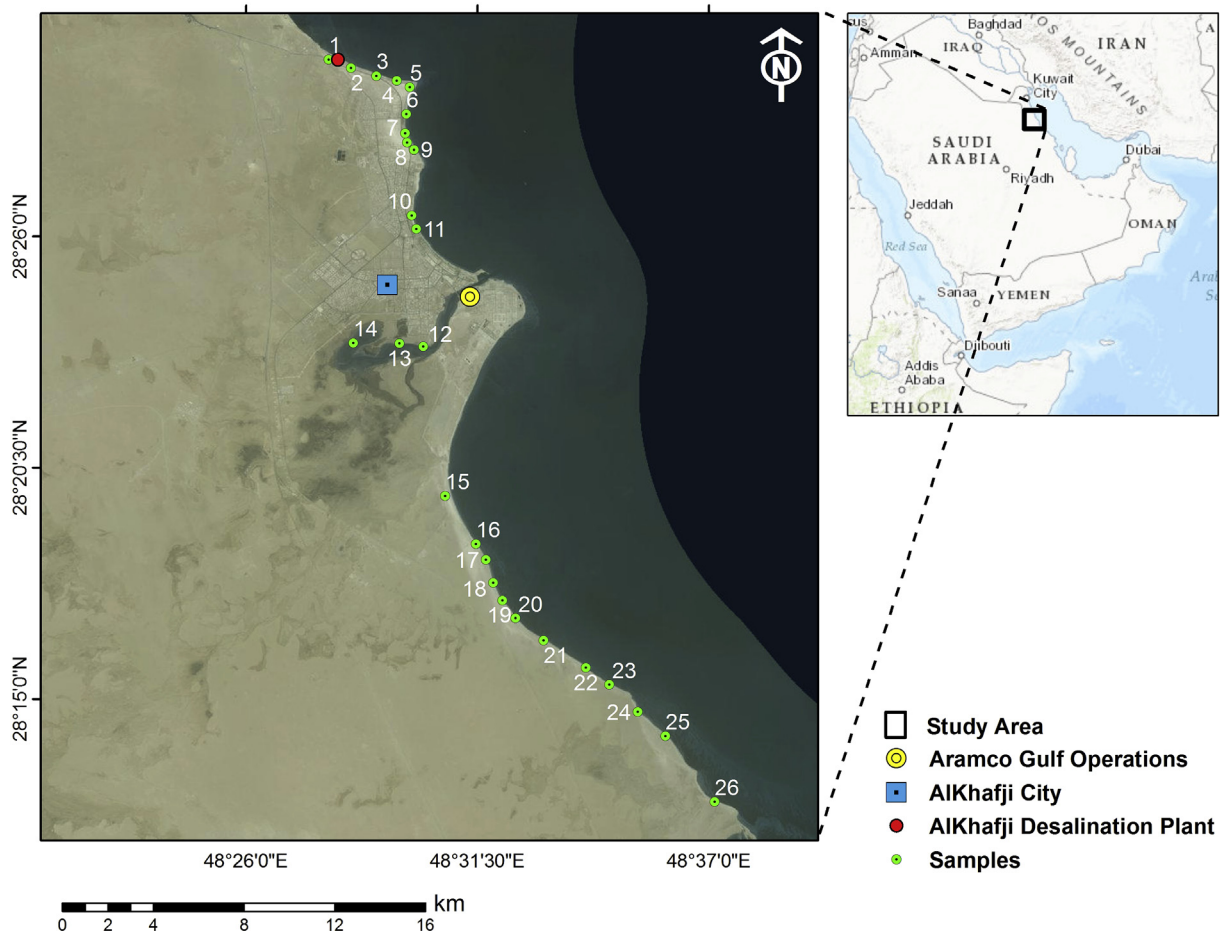


Fig. 1. Location map of the study area.



Fig. 2. Field pictures. **A.** Sandy-dominated shore, locality 6, Al-Khafji coastline. **B.** Accumulation of molluscs drifted by tidal currents on the sandy dominated shores, locality 7. **C.** Artificial rocky shores along the coast, locality 6. Green color illustrates the maximum high tide. **D.** Natural rocky shores composed of highly consolidated sands, locality 16. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

study area, which were grouped into five ichnogenera (Table 1). To characterize the documented biotic relationships, the present borings were divided by their producers, including structures produced by clionaid sponges (*Entobia*), naticid gastropods (*Oichnus*), endolithic bivalves (*Gastrochaenolites*) and polychaete annelids (*Caulostrepsis* and *Trypanites*).

3.1.1. Clionid sponge tracemakers

This group of traces includes the ichnogenus *Entobia* Bronn, 1837 (Fig. 3). This ichnogenus is strongly developed on external and somewhat internal surfaces of the bivalves *Glycymeris livida*,

Acrosterigma lacunose, *Plicatula australis*, *Barbatia foliate*, *Spondylus marisrubri* and the external surface of *Conus ardisiaceus*. It was also recorded in some scleractinian corals (*Porites* spp.). *Entobia* is represented by networks of chambers arranged parallel to the external surfaces of bivalves, gastropods and corals (Fig. 3 A–D), produced by siliceous clionid sponges related to the family *Clionidae*. In these samples, aperture diameter ranging between 0.5 and 2 mm, penetration depths do not exceed 2.5 mm, and they are nearly circular in shape. Traces are mostly distributed irregularly on the shell surfaces, but exhibit linear pattern on some gastropods (Fig. 3A). Ethologically, they are classified as domichnia. One

Table 1

Presence and absence of the different ichnotaxa identified in the 26 localities studied. G: Gastropods; B: Bivalves; C: Corals.

Ichnogenera	Host	Studied localities																									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
<i>Gastrochaenolites</i>	G																										
	B																										
	C																										
<i>Entobia</i>	G																										
	B																										
	C																										
<i>Oichnus</i>	G																										
	B																										
	C																										
<i>Caulostrepsis</i>	G																										
	B																										
	C																										
<i>Trypanites</i>	G																										
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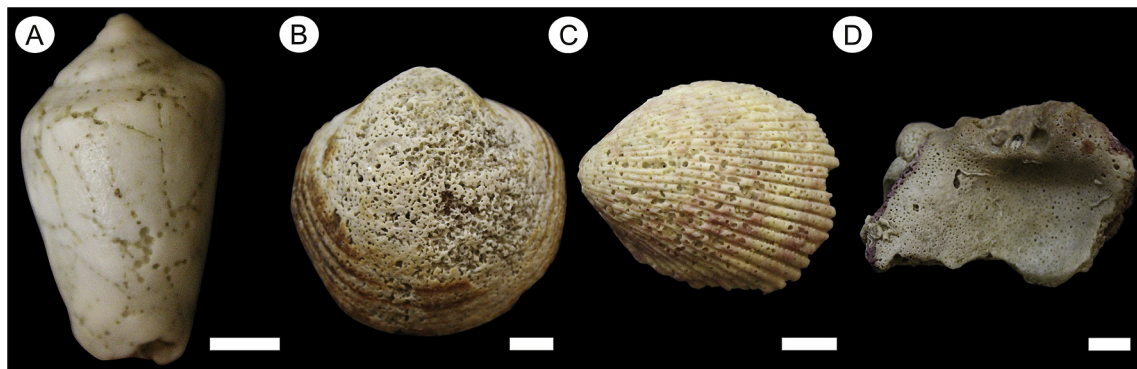


Fig. 3. Examples of traces made by Clioniid Sponges, *Entobia* ichnogenus. **A.** Linear traces on the external surface of *Conus ardisiaceus*. **B.** Dense traces on the external surface of *Glycymeris livida*. **C.** Traces on the radial ribs of *Acrosterigma lacunose*. **D.** Traces on the internal surface of *Spondylus marisrubri*.

ichnospecies, *Entobia ovula* was identified from the material presented in Bromley and D'Alessandro (1984).

3.1.2. Gastropod tracemakers

Traces produced by carnivore gastropods are grouped in the ichnogenus *Oichnus* (Wisshak et al., 2015). This ichnogenus is strongly developed on external surfaces of the bivalves *Pinctada cf. nigra*, *P. margaritifera*, *Barbatia parva*, *B. setigera*, *Spondylus marisrubri* and *Alectryonella plicatula* and the gastropods *Hexaplex kuesterianus*; *Diodora funiculata* and *Lunella coronata*. Small borings, circular to subcircular, with paraboloid shape 1.5–4.21 mm in diameter, are oriented perpendicular to the shell surface (Fig. 4 A–E). They were most likely produced by naticid gastropods as predatory structures (praedichnia). When the substrate is a thin shell, excavation passes directly through the substrate as a penetration and may end within the substrate as a shallow depression or sub-cylindrical pit (Fig. 4D). The incomplete hole indicates a failed drilling attempt by naticid gastropods (Chattopadhyay and Dutta, 2013).

Most boreholes are observed on the central area below the umbo of the prey and a few boreholes lie marginally. A high proportion of drill holes in a central area may be associated with ease of handling by predators handling (Ziegelmeier, 1954) and/or the position of prey's adductor muscles (Chattopadhyay and Dutta,

2013). *O. simplex* Bromley, 1981 (Fig. 4A–C) and *O. paraboloides* Bromley, 1981 (Fig. 4D) were also identified in the studied material. *O. simplex* has a simple cylindrical or subcylindrical form with an axis more or less perpendicular to the substrate surface. On contrast, *O. paraboloides* is formed by holes “having a spherical paraboloid form, truncated in those cases where the boring penetrates right through the substrate” (Bromley, 1981).

3.1.3. Bivalve tracemakers

The traces produce by bivalves include the ichnogenus *Gastrochaenolites* Leymerie, 1842 (Fig. 5 A–C). This ichnogenus is strongly developed on the upper and lower surfaces of scleractinian skeletons (*Porites*, *Favia*, *Favites*, *Goniopora*, *Stylophora*, and *Acropora* spp.), and external and internal surfaces of the bivalves. The traces have a circular to oval aperture with subspherical to elongate main chambers, 10–35 mm in length and 5–12 mm in width. Some borings are produced approximately normal to the surface of skeletons, while others are parallel or located on the edge. The borings present a smooth internal surface or show a sculpture consisting of concentric lines or rugae. In rare cases, internal molds of the holes are preserved, revealing the structure's three-dimensional morphology. In some cases, the bivalve tracemakers are preserved into the bioerosion structure (Fig. 5b, red arrow).

Gastrochaenolites is classified as a domichnia trace. Borings of

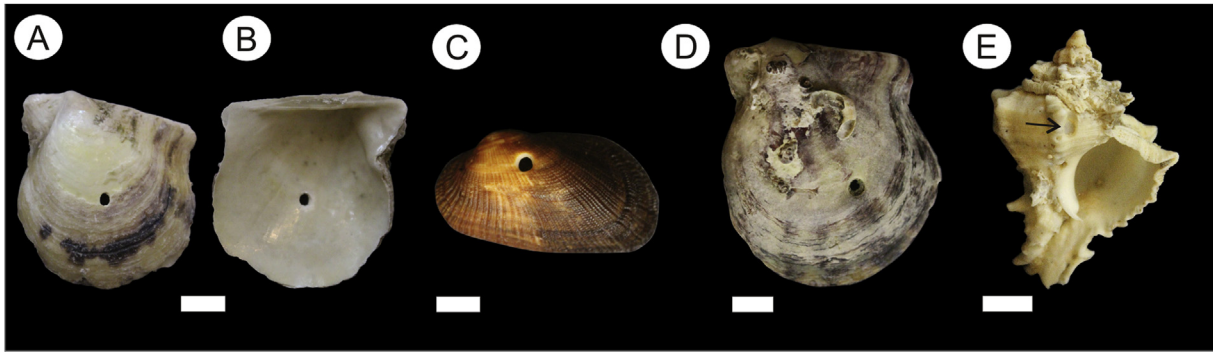


Fig. 4. Examples of traces made by carnivore Gastropods. **A-C:** *Oichnus simplex*; **D:** *Oichnus paraboloides*. **A, B.** Traces in the central part of *Pinctada margaritifera*. **C.** Trace in the umbonal area of *Barbatia parva*. **D.** Trace in the central part of *Pinctada* cf. *nigra*. **E.** Incomplete trace (black arrow) on the outer lip of *Hexaplex kuesterianus*.

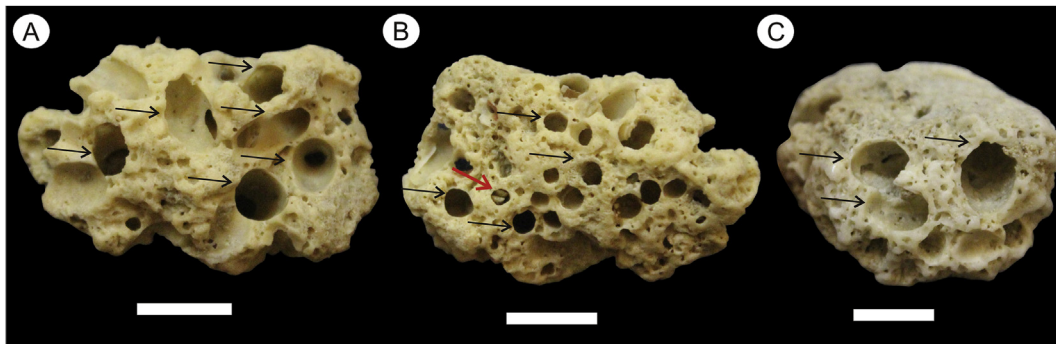


Fig. 5. Examples of traces made by mytilid Bivalves, *Gastrochaenolites* ichnogenus in different scleractinian skeletons. **A-C:** Dense preservation of *Gastrochaenolites* chambers (black arrows). Eventually, the trace-maker is preserved (red arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

this type are constructed by endolithic bivalves such as *Lithophaga*, one of the most abundant and the best known mytilid borers, largely confined to calcareous substrates (e.g. Kelly and Bromley, 1984; Bromley and D'Alessandro, 1987). The preserved morphologies of the present borer match with *Gastrochaenolites lapidicus* (Kelly and Bromley, 1984). Such borings are attributable to the recent coralliophilid gastropods and some sipunculan worms (Bromley, 2004). Also, borings of *G. lapidicus* are attributable to the borer pholadid *Barnea candida* found in the middle of the intertidal zone around the coast of the British Isles (Donovan, 2013).

3.1.4. Polychaete annelid tracemakers

The ichnogenera *Caulostrepsis* Clarke, 1908 (Fig. 6) and *Trypanites* Mägdefrau, 1932 (Fig. 7) were the two types of structures produced by annelids in the studied samples. *Caulostrepsis* is common and abundant in some bivalves (*Barbatia*, *Arca*), gastropods (*Conus*) and coral specimens (*Porites*). The borings consist of smooth a U-shape galleries and a central axial depression. Boring galleries range from straight to curved, 2–8 mm in length and 0.25–1.5 mm in width. *Caulostrepsis* is produced by spionid polychaetes annelids (Bromley, 2004), and has been recognized in Neogene bivalves (Mayoral, 1991; Farinati and Zavala, 2002; Santos

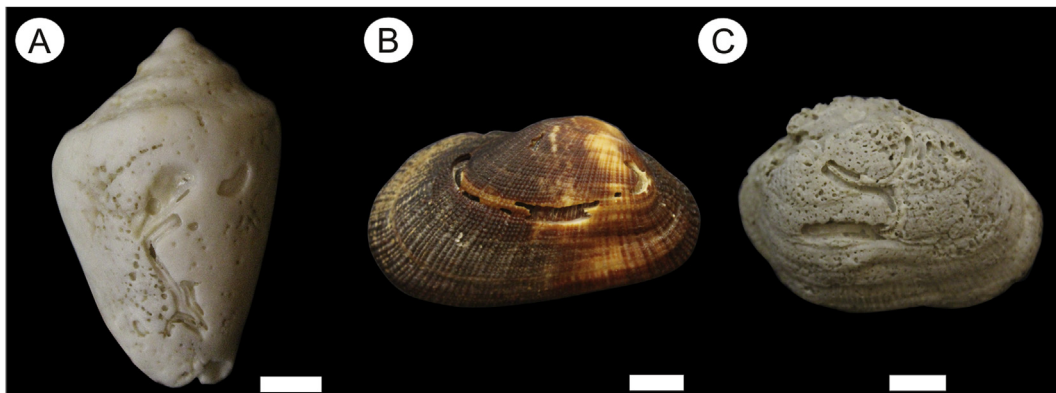


Fig. 6. Examples of traces made by worms, *Caulostrepsis* ichnogenus. **A.** Traces on the external surface of *Conus* sp. **B.** Traces on the external surface of *Barbatia* sp. **C.** Traces on the external surface of *Arca* sp. In A and C examples the *Caulostrepsis* (u-shaped tunnel trace) is associated with *Entobia*.

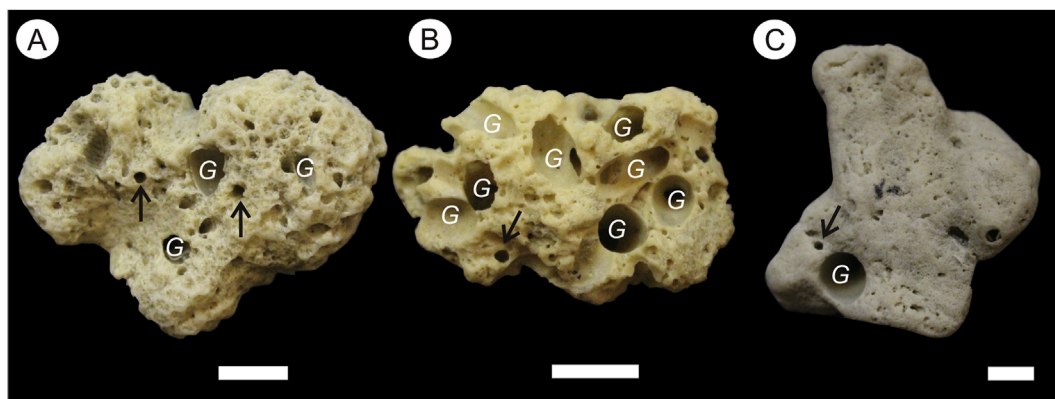


Fig. 7. Examples of traces made by worms. A–C: *Trypanites ichnogenus* (black arrows) in different scleractinian skeletons associated with *Gastrochaenolites* (G).

and Mayoral, 2008) and bouchardiid brachiopods (Rodrigues et al., 2008). The morphological characteristics of the samples recovered are close to that of *Caulostrepsis taeniola* Clarke 1908. Ethologically, it has been classified as domichnia.

Trypanites borings are common on coral specimens (*Porites* and *Goniastrea*), and they are constituted by narrow, cylindrical, and unbranched borings, with lengths up to 50 times the widths (Fig. 7 A–C). These are formed in shoreline rocks or in lithified limestone hardgrounds on the seabed. The stratigraphic range of *Trypanites* extends from the Lower Cambrian to Recent (James et al., 1977). It uses an acid to dissolve the carbonate hardgrounds and calcium carbonate shells (Taylor and Wilson, 2003). The morphological characteristics are close to that of *Trypanites solitaries*. Ethologically, it has been classified as domichnia.

3.2. Associated encrustation

In the study area, different types of encrusters were recorded in three hard substrates, in descending order of abundance, bivalve-hosted, coral-hosted and gastropod-hosted communities. The bivalve-hosted community is mainly composed of shells of living epifaunal bivalves. Oysters and scallops, among others, are particularly prone to biofouling causing problems for commercial shell fisheries, especially through the shell weakening effects of boring sponges and spionid polychaetes (e.g., Korrington, 1954; Taylor and Wilson, 2003). Four types of encrusters were recorded on the studied bivalve shells, balanoid barnacles (Fig. 8A), calcareous tube-forming worms (Fig. 8B), bivalves and bryozoans. The barnacle *Balanus perforatus* is the most common encrusters and samples have nearly similar morphological sizes and same directions. They are well developed as aggregates on the external and internal surfaces of the bivalves, *Acrosterigma lacunose*, *Pinctada margaritifera* and *Marcia flammea*. The calcareous serpulids appear as dense clusters and small aggregates on the internal surfaces and partially on the external ones of many molluscs (e.g. *Pinctada margaritifera*, *Anadara antiquata*, *Glycymeris pectunculus*, *Barbatia setigera*, *Brachidontes variabilis*, *Alectryonella plicatula*, and *Plicatula australis*). Some bivalves, as *Alectryonella*, *Chama* and *Spondylus* spp. are encrusted by other bivalves to form banks. In addition, the bryozoans, *Parasmittina*, *Holloporella*, and *Biflustra* spp. are encrusted parts of the smooth surfaces of bivalves, gastropods and corals. The bryozoan zoaria range from a few millimeters to a few centimeters in diameters, and rarely covering the complete shell surface.

The coral-hosted community is composed of *Porites*, *Goniastrea* and *Favites* spp., which are encrusted with aggregates of barnacles; the bivalves *Chama asperella*, *Ch. reflexa*, and *Spondylus hystrix*; and

bryozoans *Parasmittina* sp. and *Biflustra* sp (Fig. 8 C–E). As in all modern shallow marine environments, the balanoid barnacles *Balanus perforatus* is the most common encrusters in the study area.

The gastropod-hosted community includes cerithid gastropod shells, which are rarely colonized by zoobionts of balanoid barnacles (Fig. 8F). Balanoids attach to the external surfaces of gastropods, *Conus boschorum*, *C. milesi*, *Siphonaria belcheri*, and *Lunella coronata*. In addition, the calcareous tube-forming worms sometimes appear as dense clusters, on the inner apertures of *Conus boschorum*.

4. Discussion

The identified borings represent typical rocky shore communities of bivalves, sponges, worms and gastropods. Nevertheless, recent studies have hypothesized that the palaeo-community in rocky shores is much higher in diversity and abundance than previously described (Furlong et al., 2016). On the other hand, if we consider the architectural designs of the traces (named Ichnodisparity, Buatois and Mángano, 2013; Buatois et al., 2017), the number of these are the same, five ichnogenera with five architectural designs (*Trypanites*/simple vertical borings, *Oichnus*/circular holes, *Caulostrepsis*/pouch borings, *Gastrochaenolites*/flask-shaped borings, *Entobia*/multiple-apertured multi-chambered borings; Buatois et al., 2017). This aspect is very important at the moment to interpret environmental factors with the trace fossils recovered. In our case of study, either considering ichnodiversity or ichnodiparity the result is the same.

The ichnofacies concept is not usually applied to mobile substrates (e.g. shells, wood), but in this case, we can associate our results with the *Trypanites* ichnofacies (a synonym of the *Entobia* association; see Buatois and Mángano, 2011 for a detail discussion). The studied borings can be grouped into two diagnostic assemblages of traces, one dominated by *Entobia* and the other by *Gastrochaenolites*. These ichnoassemblages could represent two different positions in a reef environment (Fig. 9), following the model of Abdel-Fattah and Assal (2016) for Miocene examples.

4.1. *Entobia* ichnoassemblage

This assemblage is characterized by the ichnospecies *Entobia ovula*, associated with *Gastrochaenolites lapidicus* and *Trypanites solitaries*. The *Entobia* assemblage is composed of dense networks and boxworks of clionaid sponges (Bromley and D'Alessandro, 1984, 1989). This assemblage reflects lagoonal patch reefs to back reefs, as well as fore-reef and offshore sites (Hernández-Ballesteros et al., 2013). The *Entobia*-dominated assemblage has been recorded

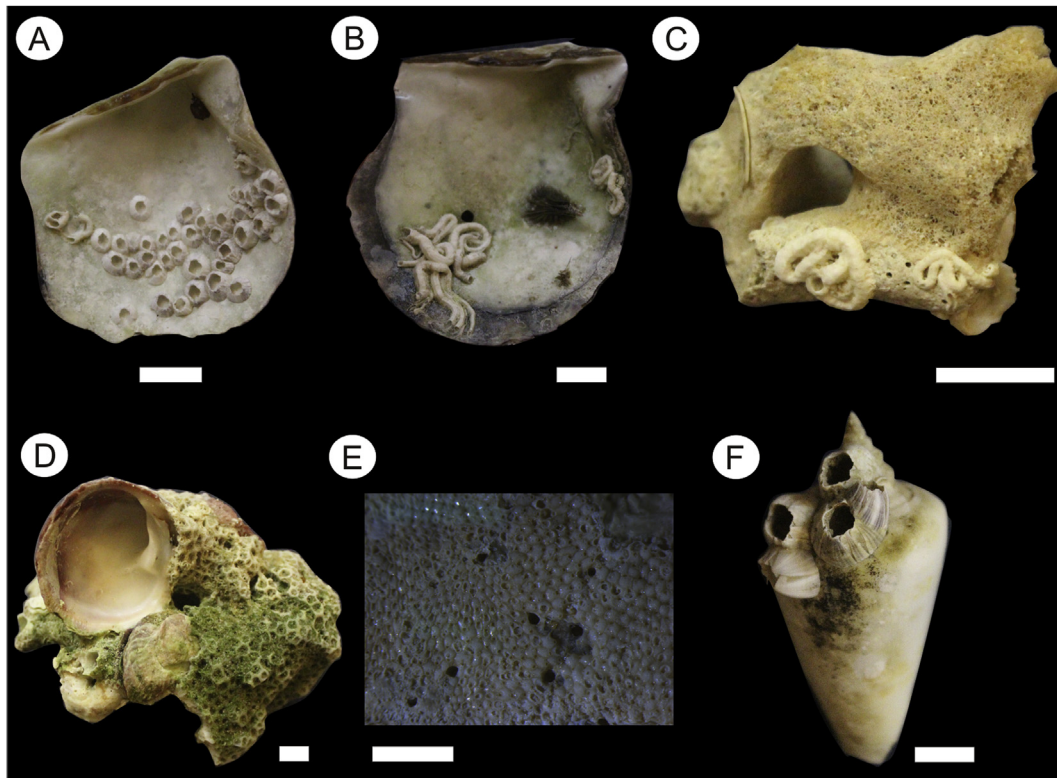


Fig. 8. Encrustation examples. **A–B.** Encrustations on bivalve shells. **A:** balanoids; **B:** polychaetes; **C–E.** Encrustation on corals. **C:** polychaetes; **D, E:** bryozoans; **F.** Encrustation on gastropods: balanoids.

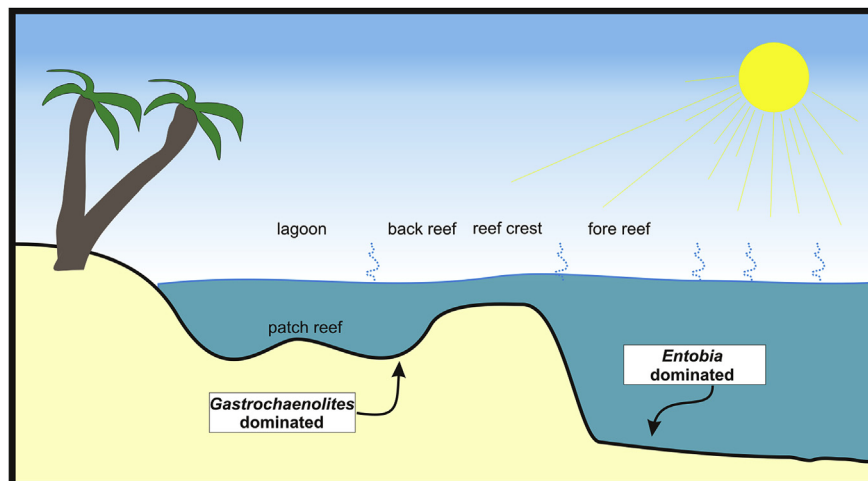


Fig. 9. Hypothetical distribution of the two ichnoassemblages recognized in the study area in the schematic model of the reef zone proposed by Abdel-Fattah and Assal (2016).

previously in Oligocene reefs (Grand Cayman), Miocene reefs (Mallorca and Egypt), Pleistocene Falmouth Formation (Jamaica) and Holocene Caribbean reefs (Pleydell and Jones, 1988; Perry, 1996, 1998; Abdel-Fattah and Assal, 2016, 2000).

4.2. *Gastrochaenolites* ichnoassemblage

This assemblage is composed of borings of *Gastrochaenolites* and *Oichnus* of relatively large sizes. This assemblage also includes commonly distributed ‘worm’ borings (*Caulostrepsis* and *Trypanites*). The *Gastrochaenolites*-dominated assemblage reflects

shallow-marine conditions, in a water depth less than a few meters. This is supported by the abundance of polychaetes and sipunculans, the crowded individuals of *Gastrochaenolites* and presence of the bivalve *Lithophaga lithophaga*, which in the Mediterranean Sea is restricted depth of 0–10 m (Kleemann, 1973; Bromley, 1978, 1994). The *Gastrochaenolites*-dominated assemblage has been recorded previously in the Pleistocene in Bahamas and Jamaica; the Oligocene to Miocene in Grand Cayman, the upper Miocene reefs in Egypt (Wilson et al., 1998; Perry, 1996, 2000; Pleydell and Jones, 1988; Abdel-Fattah and Assal, 2016).

4.3. Encrusters

In general, in descending order of preference, the encrustation is recorded on bivalves, then corals and finally gastropods. Nutrient levels and protection from predation have been hypothesized to play an important role in determining the degree of fouling of living molluscs and degree of encrustation or may function in defense of the host against predators (Voight and Walker, 1995). Surfaces of seashells act as the hard substrate needed for larval settlement and ontogeny development.

Barnacles and bivalves present as aggregates on the external and internal surfaces of the bivalve shells. Taylor and Wilson (2003) mentioned many processes for producing aggregation, including limited substrate availability; variations in the surface topography of the substratum and active selection by larvae at sites close to adults of the same species. The existence of barnacles, worms, and bryozoans, as encrusters, and boring initiated on an interior surface of the shells, are strong indications that the shell substrate was dead at the time of colonization (McKinney, 1995).

4.4. Implication for the fossil record of bioerosion structures

In reef deposits, the relative contribution of sponges to macro-bioerosion increases with exposure time (Carreiro–Silva and McClanahan, 2012). The abundance of *Entobia* and *Gastrochaenolites* in the studied ichnoassemblages is interpreted as very shallow marine environments with only a few meters in depth and a low or null sedimentation rate (Bromley and Asgaard, 1993; Bromley, 1994; Gibert et al., 1998). The locally dense concentrations of *Gastrochaenolites*, and its vertical position support this environmental assignment.

Given that all of these bioerosion structures are developed in high-salinity marine waters, it is important to highlight that this well-known stress controlling factor for ichnology is insufficient in restricting the bioerosion diversity. Moreover, all recovered traces show normal sizes, instead of smaller sizes, which would be expected for a high-stress environment. This case study presents an important example of an unconventional ichnological approach to environmental factors. Even when the high-salinity environment is confirmed without problems, the bioerosion structures appear to have developed under normal conditions. Consequently, we can confirm, at least for our study area, that bioerosion should not be assumed as an indicator of salinity stress.

5. Conclusions

1. The Al–Khafji coastline along the Arabian Gulf is differentiated into sandy–dominated shores, Artificial and natural Rocky shores with accumulation of bivalves, gastropods, corals and other bioclats.
2. Eight ichnospecies belonging to five ichnogenera (*Entobia*, *Gastrochaenolites*, *Oichmus*, *Caulostrepsis* and *Trypanites*) are identified from the Al–Khafji coastline.
3. The spatial and sequential distribution of the borings demonstrates two notable ichnological boring assemblages. *Gastrochaenolites*–dominated assemblage marks shallow–marine conditions at back–reef to patch–reef zones of a lagoonal environment. The *Entobia*–dominated assemblage indicates relatively deeper marine conditions, mostly in forereef zones of the studied coastal environment.
4. At least for the study area, bioerosion structures are not important tools to identify salinity stress factor.

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