CrossMark

# Bioerosion and encrustation rates in recent mollusk death assemblages on a supratidal siliciclastic setting, Playa Norte, Veracruz State, Mexico

Catalina Gómez-Espinosa[1] · F. Raúl Gío-Argáez[2] · Ester A. Farinati[3] · Salvador Aliotta[4] · Sergio Adrian Salgado-Souto[1]

## Abstract

This study presents both qualitative and quantitative data regarding marine mollusk (gastropods and bivalves) shell bioerosion and encrustation based on death assemblages obtained from a recent supratidal environment in Playa Norte, Veracruz State. The objectives of this study were to assess the nature of bioerosion and encrustation processes and to investigate the role of these taphonomic features contributing to the deterioration of natural shell accumulations within a tropical siliciclastic tidal environment. The assemblage comprises 31 species: 13 gastropods and 18 bivalves. The bioerosion and encrustation degrees were low to moderate for both types. The most abundant traces were predatory gastropod structures (*Oichnus paraboloides* and *O. simplex*), whereas sponge borings (*Entobia* isp.), polychaete dwellings (*Caulostrepsis taeniola*), and echinoid raspings (*Gnatichnus* isp.) were less frequent. The encrusting organisms include polychaete serpulids, bryozoans, and rare foraminifers (*Homotrema rubrum*). Because of the low bioerosion and encrustation degrees occurring in this area, accumulation is expected to predominate over biotic destruction. As deposition conditions (richly fossiliferous carbonate sandstone beds) were similar to those prevailing in the Tuxpan Formation during the Miocene (Langhian), it is suggested that this study provides an equivalent reference to interpret mollusk fossil assemblages located in this site.

**Keywords** Actualistic taphonomy · Bioerosion · Encrustation · Mollusks · Siliciclastic environment

## Introduction

Bioerosion is a term referring to the deterioration of hard substrates caused by biological processes. It entails complex biogeochemical interactions that modify carbonate skeletons and

✉ Catalina Gómez-Espinosa
c_gomez@ciencias.unam.mx

[1] Universidad Autónoma de Guerrero, Escuela Superior de Ciencias de la Tierra, Ex Hacienda San Juan Bautista S/N, 40323 Taxco el Viejo, Guerrero, Mexico

[2] Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Circuito exterior S/N, Ciudad Universitaria, 04510 Coyoacán, Mexico

[3] Departamento de Geología, Universidad Nacional del Sur, San Juan 670, Bahía Blanca, 8000 Buenos Aires, Argentina

[4] Instituto Argentino de Oceanografía, Camino a La Carrindanga km 7.5, Bahía Blanca, 8000 Buenos Aires, Argentina

rocky surfaces (Santos and Mayoral 2008), usually derived from a search for food or shelter. Bioerosion may adopt the shape of borings, etchings, nestlings, scrapings, raspings, or gnawings (Bromley 1981). It is an important process occurring in both modern and ancient marine environments, and it has a significant meaning for ecology and marine sedimentation, including the evolution of hard-substrate communities (Gibert et al. 2007). The results of these biological activities are important for paleoecological reconstructions because each era had its own characteristic communities and reflect an environmental or biogeographic difference (Vinn and Wilson 2010).

Several studies have been performed in order to detect bioerosion in shallow temperate to tropical carbonate environments. However, siliciclastic settings are frequently overlooked (Lescinsky et al. 2002), even when they represent around 40% percent of the global coastline beaches (Bird 2000) and are mostly distributed along Mexican coasts (Lara 2008). Bioerosional studies conducted on invertebrates have been focused mainly on corals (Walker et al. 1998); nevertheless, if mollusk bioerosion rate is similar to that observed in corals, those shells possessing only a few

⚛ Springer

millimeters of thickness would be destroyed in 1–2 years (Edinger 2001). The shells occurring in fossil records display a differential erosion rate when compared to that of coral and mollusks (Lescinsky et al. 2002).

Shell encrusters on living or dead organisms are the main component of both modern and fossil settings (Brett et al. 2012). Space is a limiting factor for encrusters; in soft bottoms, shells are the most important biogenic substrate available for encrusting (Nebelsick et al. 1997).

Encrusters are mainly studied because of their destructive effects, although they have received less attention from the taphonomic perspective as a tool intended to define and characterize environments (Brett et al. 2011). Marine encrusters are highly sensitive to environmental parameters, such as light intensity, sedimentation rates, and substrate type (Lescinsky et al. 2002).

Encrustation provides information about the encruster organisms themselves: biogenic substrates, and the general conditions prevailing within the community or those of the surrounding environment (Nebelsick et al. 1997). Hard-shelled or exoskeleton-bearing encruster organisms are taphonomically relevant because of their potential to be preserved in a fossil record. In intertidal and shallow sublittoral environments, bioeroder diversity is usually high, and it occurs additionally to encrustation (Santos and Mayoral 2008).

Actualistic taphonomy is the study of patterns and processes (death, decay, and burial) in contemporary settings intended to provide a reference to interpret the data preserved as a fossil record (Kowalewski and Labarbera 2004). Death assemblages are common in many modern depositional settings and some of them are shell-rich accumulations of marine mollusks that offer a wide diversity of research opportunities for the actualistic taphonomy field (Simoes 2010).

Taphonomic studies of modern ecosystems are used in the paleontology field in order to better understand fossil ecosystems (Behrensmeyer and Miller 2012), thus offering a reference to interpret fossilization processes as well as the nature of the fossil records. These are very useful for the conservational paleobiology field. Additionally, they are examples of how taphonomy may contribute to conservation and ecology studies (Behrensmeyer and Miller 2012). Moreover, it is a valuable tool that may be used to predict the potential future consequences derived from environmental changes (Anderson et al. 1998).

The identification of the agents that caused the deterioration of recent skeletal carbonate accumulations is important in order to identify a possible bias in the fossil record due to a high biodiversity during the Phanerozoic, especially in tropical environments (Best 2008). Mollusk shell accumulations are common within intertidal environments along the Gulf of Mexico, and they provide an opportunity for taphonomic research.

The objectives of this study were to assess the nature of bioerosion and encrustation as well as to describe and investigate the role of these taphonomic features contributing to the deterioration that natural accumulations of marine mollusk shells (bivalves and gastropods) undergo in a tropical siliciclastic tidal environment prevailing on Mexican beaches (Playa Norte, Veracruz State).

Past studies about the taphonomy in the Gulf of Mexico are related to the Shelf and Slope Experimental Taphonomy Initiative (SSETI) that was performed by Powell et al. (2011) over 13 years. Experiments of the SSETI project have been conducted not only on carbonates but also on siliciclastic environments on the Texas-Louisiana-Florida continental shelf and slope located 6–20 km from the coast (Powell et al. 2011); Regan's study (2017) additionally included the coast of Alabama. Among these studies, one emphasizes the difference in the quality of preservation among siliciclastic and carbonate settings (Best and Kidwell 2000). Nevertheless, until now, there has been not one taphonomic study performed on the Mexican coast of the Gulf of Mexico, and this study is the first attempt.

Most of the studies about the Mexican part of the Gulf of Mexico have examined factors such as provenance: provenance and geochemistry; petrography and geochemistry of the sand (Armstrong-Altrin 2009; Armstrong-Altrin et al. 2012; Armstrong et al. 2015; Okazaki et al. 2001; Kasper-Zubillaga and Dickinson 2001; Carranza-Edwards et al. 2001); mineralogy, geochemistry, and radiocarbon ages of deep sea sediments (Armstrong-Altrin and Machain-Castillo 2016; Ramos-Vazquez et al. 2017); geochemistry and geochronology of detrital zircons (Tapia-Fernandez et al. 2017); and heavy metal concentrations of the estuary sediments (Rosales-Hoz et al. 2015; Botello et al. 2015).

## Study area

The study area is located in the western part of the Gulf of Mexico, Veracruz State. The coast is classified as transgressive. The Gulf of Mexico geology is diverse, and the outcrops along the western part are composed of Quaternary alluvium and soils, Cenozoic volcanic rocks, Cenozoic and Mesozoic sedimentary rocks, and Paleozoic and Precambrian metamorphic rocks comprising schists and gneisses (Armstrong-Altrin et al. 2012). The climate is tropical to temperate with rainfall and temperature dependent on elevation (Tamayo 1991).

Barra de Cazones comprises five main beaches: Playa Sur, Playa Azul, Playa Boquitas, Playa Chaparrales, and Playa Norte (INAFED 2012). The subtidal accumulations of bivalve and gastropod shells (commonly termed "conchales") are well-known in Playa Norte and Playa Sur.

Playa Norte beach (20° 44′ 24″ N and 97° 11′ 50″ W) is the locality selected to conduct this study because it is a virgin beach with no permanent artificial structures and does not show the anthropic disturbances that tourism causes in the

other beaches of the same area. Playa Norte beach is located at the opposite side of the Cazones River base level (Fig. 1). This coast is positioned within a passive continental margin containing abundant sedimentary rocks and consists of primary volcanic and secondary coasts formed by marine deposition (Armstrong-Altrin 2009). Miocene calcareous sandstones of the Tuxpan Formation dominate the sedimentary rocks in this place. The sedimentary geology of this area has been described in detail by Butterlin (1958) and also by Cabrera and Lugo (1984).

## Material and methods

Five bulk sand samples of approximately 5 kg were collected during the dry season (April) along the supratidal area, encompassing an overall 2 km area northward. The number of samples correlates with the number of shelly clusters formed naturally (berms) on the Playa Norte beach. Shell remains were located approximately 1.5 m from the shoreline on a beach.

Each one of the five bulk samples was collected following the technique suggested by Anderson et al. (1998). Samples were washed with sea water and sieved at the sampling site by using 4-mm screens. The use of bioclasts above 4 mm is recommended for taphonomic studies of molluscan remains as smaller fractions display significantly lower damage than larger fractions.

Shells were stored in plastic bags and washed with tap water at the laboratory. Then, the samples were mixed to make one and taxonomic identification of mollusks was carried out. Beaked valves and shells displaying spires were selected to perform the taphonomic analysis in order to avoid double counting of a single individual.

All shells were first examined under the microscope at a ×10 magnification to identify the presence or absence of encrusting and/or bioerosion features. When detectable, visually based percentages of encruster surface area of coverage as well as bioeroder traces were estimated. When possible, the types of bioerosive traces and encrusting organisms were identified at both ichnogenus and ichnospecies levels and they were allocated to higher ichnotaxonomic levels.
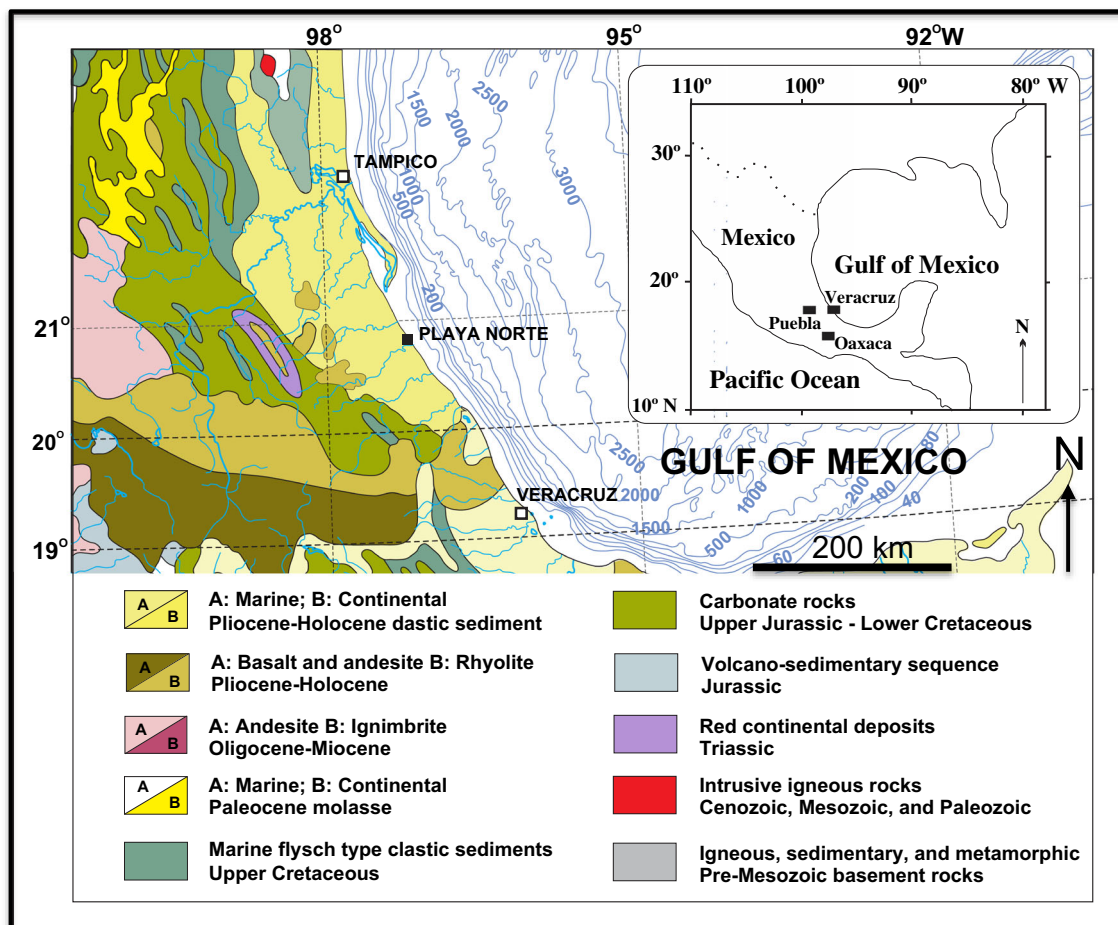


**Fig. 1** Simplified geology map of the study area showing Playa Norte (map modified from carta Geologica, Direccion General de Geografia del territoria Nacional, scale 1:1,000,000) (modified after Armstrong-Altrin 2015)

Bioerosion and encrustation were studied for each bioclast and they were scored based on the following taphonomic scale: poor = grade 0 (absent), fair = grade 1 (> 50%) and good = grade 2 (< 50%) (Table 1). The taphonomic attribute frequencies were analyzed by using non-binomial 95% confidence intervals.

Because of the small number of bivalve specimens displaying encrustation and bioerosion, the inner/outer valve estimation was not analyzed separately. Gastropod and bivalve shells were individually considered for the taphonomic analysis. Bioerosion and encrustation frequencies for bivalve mollusks were calculated by dividing by two the number of disarticulated valves in order to correct for the frequency of bivalved organisms (Kowalewski 2002).

## Results

### Taxonomic composition

A total of 1930 shells were analyzed from all samples: 1791 corresponded to disarticulated valves from bivalves and 139 to gastropod shells (on-line resource). Resulting in 32 species identified, 19 from these are bivalves and 13 are gastropods.

Gastropod shells were assigned to *Astyris lunata*, *Costoanachis avara*, *Crepidula plana*, *Conus mus*, *Diodora cayenensis*, *Elachisina floridana*, *Epitonium albidum*, *Heliacus bisulcatus*, *Impages salleana*, *Olivella* sp., *Olivella minuta*, *Neritina virginea*, and *Stramonita haemastoma floridana*. Bivalves were represented by *Anadara transversa*, *Anadara* sp., *Anomia simplex*, *Argopecten gibbus*, *Brachidontes exustus*, *Caryocorbula dietziana*, *Caryocorbula contracta*, *Chione cancellata*, *Crassinella lunulata*, *Cyclinella tenuis*, *Diplodonta punctata*, *Donax variabilis*, *Isognomon bicolor*, *Ischadium recurvum*, *Lirophora obliterata*, *Lunarca ovalis*, *Mytilopsis leucophaeata*, *Timoclea grus*, and *Tucetona pectinata*.

**Table 1** Taphonomic attributes and scoring systems used to assess shell bioerosion and encrusting in the mollusk assemblages

| Taphonomic attribute | Damage state | Illustration |
| --- | --- | --- |
| Bioerosion | Grade 0 = absent | |
| | Grade 1 = < 50% of the shell area | Fig. 2a–d, h–i |
| | Grade 2 = > 50% of the shell area | Fig. 2e–g |
| Encrustation | Grade 0 = absent | |
| | Grade 1 = < 50% of the shell area | Fig. 3a, d–e, g–i |
| | Grade 2 = > 50% of the shell area | Fig. 3b–c, f |

## Taphonomic features

The bioerosion analysis showed the prevalence of shells unaffected by this processes (78% of the total), and a few of them showed intense bioerosion (Table 3, Fig. 2a).

The molluscan remains obtained from Playa Norte supratidal area contain a common and poor ichnofauna (Tables 2 and 3). The morphological analysis of different structures preserved from bioerosion has enabled the identification of four ichnotaxa that belong to three ethological classifications: domichnia (*Entobia* and *Caulostrepsis*), praedichnia (*Oichnus*), and pascichnia (*Gnatichnus*).

No evidence of occupation by fouling organisms (such as barnacles and vermetids) was observed. The dominant bioerosion structures were linked to the shell-boring performed by non-predatory organisms.

Ichnogenus *Entobia* Bronn 1837 represents a boring performed on carbonate substrates comprised from a single chamber to gallery networks connected to the surface by multiple openings (Fig. 2a). *Entobia*'s morphology (gallery diameter, chamber development, cameration) is modified along the ontogeny. Its descriptive morphology has been well studied by Bromley and D'Alessandro (1984) and also by Blissett and Pickerill (2007). The traces of this type are produced by clionid sponges (Fig. 2f–g).

Ichnogenus *Caulostrepsis* Clarke 1908 is a pouch-shaped or U-shaped boring that displays a vane connecting the limbs of the U-bent gallery (Fig. 2b) (Gibert et al. 2007). These types of traces are assigned to polychaete annelids from several families but particularly to Spionidae (Bromley and D'Alessandro 1984) (Fig. 2g–h), particularly to the *Polydora* Bosc, 1802 genus, although other polychaetes may also generate this type of traces.

Ichnogenus *Oichnus* Bromley 1981 is a circular- or subcircular-shaped hole commonly perpendicular or subperpendicular to the substrate's surface. This hole may pass through the substrate (Fig. 2a–d) (Blissett and Pickerill 2007). *O. simplex* (Fig. 2a–b) and *O. paraboloides* (Fig. 2c–d) are interpreted as gastropod predators: Muricidae and Naticidae, respectively (Bromley 1981).

Ichnogenus *Gnatichnus* Bromley, 1975 are star-shaped traces of regular echinoids that represent rasping activity (pascichnia) (Fig. 2i) (Spagnuolo et al. 2013).

In order of abundance, the evidence of bioerosion included: *Oichnus* in 162 valves and 17 gastropod shells (9.7%), *Caulostrepsis* in 93 valves and 15 gastropod shells (5.6%), *Entobia* in 52 valves and 4 gastropod shells (2.9%), and *Gnatichnus* in two valves (0.10%) (Fig. 2i).

Some specimens have trace associations, such as *Caulostrepsis-Oichnus* in 54 valves and 9 gastropod shells (3.26%), *Entobia-Oichnus* in 17 valves (0.88%), *Entobia-Caulostrepsis* in 8 valves and 2 gastropods (0.52%), and *Entobia- Caulostrepsis-Oichnus* in 3 valves (0.16%) (Fig. 2e).

**Fig. 2** Bioerosive traces identified on bivalves and gastropods **a**, **d** *Oichnus simplex* in **a** *Donax variabilis* outer side of a valve, near the umbonal area, grade 1 bioerosion; **b** *Epitonium albidum* gastropod showing grade 1 bioerosion; **c–d** *Oichnus paraboloides* in **c** *Impages salleana* gastropod shell, grade 1 bioerosion; **d** *Lunarca ovalis* outer side of a valve, grade 1 bioerosion; **e** Ichnogenera association *Entobia-Caulostrepsis-Oichnus* on the bivalve *Lunarca ovalis*, outer side of a valve showing an almost fully bioeroded surface, grade 2 bioerosion; **f** *Entobia* isp, on *Lunarca ovalis* valves inner side showing a fully bioeroded surface, grade 2 bioerosion, **g–h** *Caulostrepsis taeniola* in **g** *Anadara transversa* bivalve, outer side of valve, grade 2 bioerosion; **h** body whorl of gastropod *Olivela* isp, grade 1 bioerosion. **i** *Gnatichnus* isp in *Donax variabilis* inner side of a valve grade 1 bioerosion
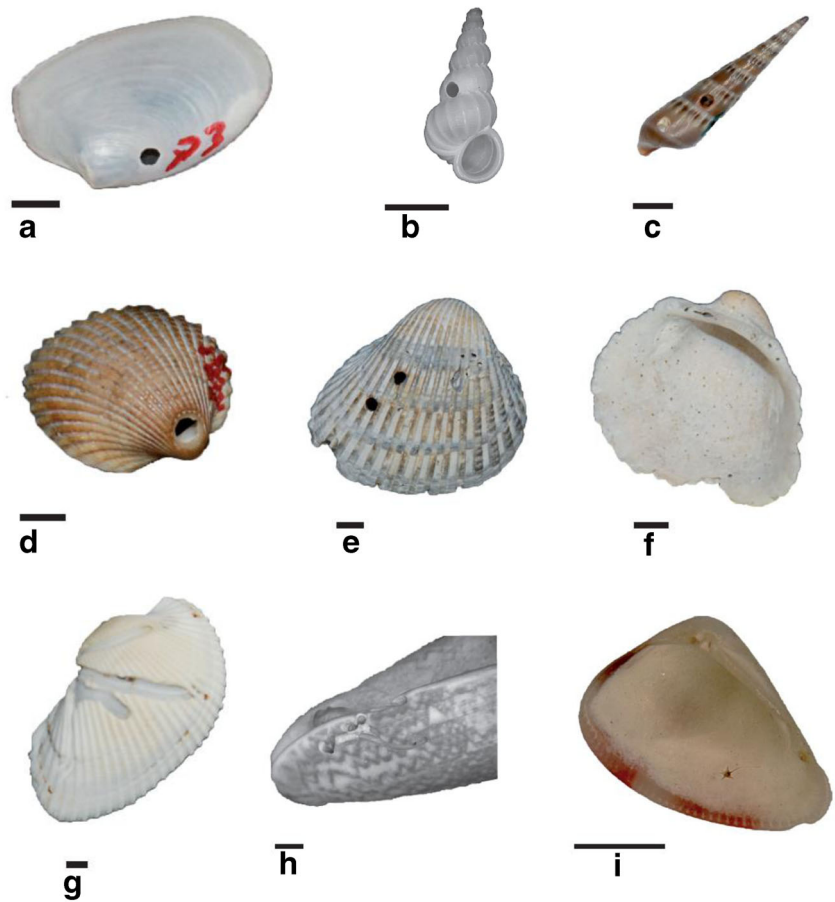


A lower encrustation incidence (5%) was identified on bivalve and gastropod shells, whereas almost every shell was pristine (86.32%) (Tables 2 and 3). Serpulid polychaetes are dominant among all encrusters (Fig. 3e–i). Encrusting bryozoans are also present, and they show very high sites coverage on individual shells, although they are less numerous (Fig. 3a–c). Encrusting foraminifera *Homotrema rubrum* was also present but with low frequency (Fig. 3d).

No significant differences were observed regarding the encrusting and bioerosion frequencies when gastropods and bivalves were compared. Encrustation was identified as "poor" in both gastropods and bivalves, whereas bioerosion was "poor-fair" in gastropods and "poor" in bivalves, although the results are not significantly different ($p < 0.05$).

## Discussion

Because of the nature of the encrusters and bioeroders, we consider that bioerosion and the encrustation have occurred in subaquatic conditions, and then the shells were transported to the supratidal beach where they were deposited and accumulated. Particularly, clionid sponge colonization occurs in shallow, exposed sites (Bromley 1970); they are common but are less active in deeper euphotic settings (Brett et al. 2011). Data obtained from Playa Norte mollusk shells will be discussed in the following sections.

### Bioerosion

*Entobia* was the most common and pervasive bioerosional trace. Regarding bioeroding sponges, it has been suggested

**Table 2** Absolute and relative frequency of taphonomic attributes (bioerosion and encrustation) in bivalves and gastropods

| | Bivalves | | | Gastropods | | |
|---|---|---|---|---|---|---|
| | $n_i$ | $f_i$ | 95% CI | $n_i$ | $f_i$ | 95% CI |
| Bioerosion | | | | | | |
| Grade 0 | 699 | 0.78 | ± 1.18 | 92 | 0.66 | ± 1.17 |
| Grade 1 | 173 | 0.19 | | 43 | 0.31 | |
| Grade 2 | 23.5 | 0.02 | | 4 | 0.03 | |
| Encrustation | | | | | | |
| Grade 0 | 777 | 0.87 | ± 1.10 | 112 | 0.81 | ± 1.10 |
| Grade 1 | 106.5 | 0.12 | | 20 | 0.14 | |
| Grade 2 | 12 | 0.01 | | 7 | 0.05 | |

**Table 3** Encrusting organism and bioerosional traces identified on bivalve and gastropod shells grouped by major taxon

| Taxonomic group | Taxon name | Illustration |
|---|---|---|
| Bioerosional traces | | |
| Porifera: Clionidae | *Entobia* isp | Fig. 2e–f |
| Annelida: Polychaeta | *Caulostrepis taeniola* | Fig. 2g–h |
| Mollusca: Gastropoda | *Oichnus simplex* | Fig. 2a–b |
| | *O. paraboloides* | Fig. 2c–d |
| Echinodermata: Echinoidea | *Gnatichnus* isp | Fig. 2i |
| Encrusting organisms | | |
| Protista: Sarcodina: Foraminiferida | *Homotrema rubrum* | Fig. 3d |
| Annelida: Polychaeta | Serpulids | Fig. 3e–i |
| Bryozoa: Ctenostome and cheilostome | Bryozoan | Fig. 3a–c |
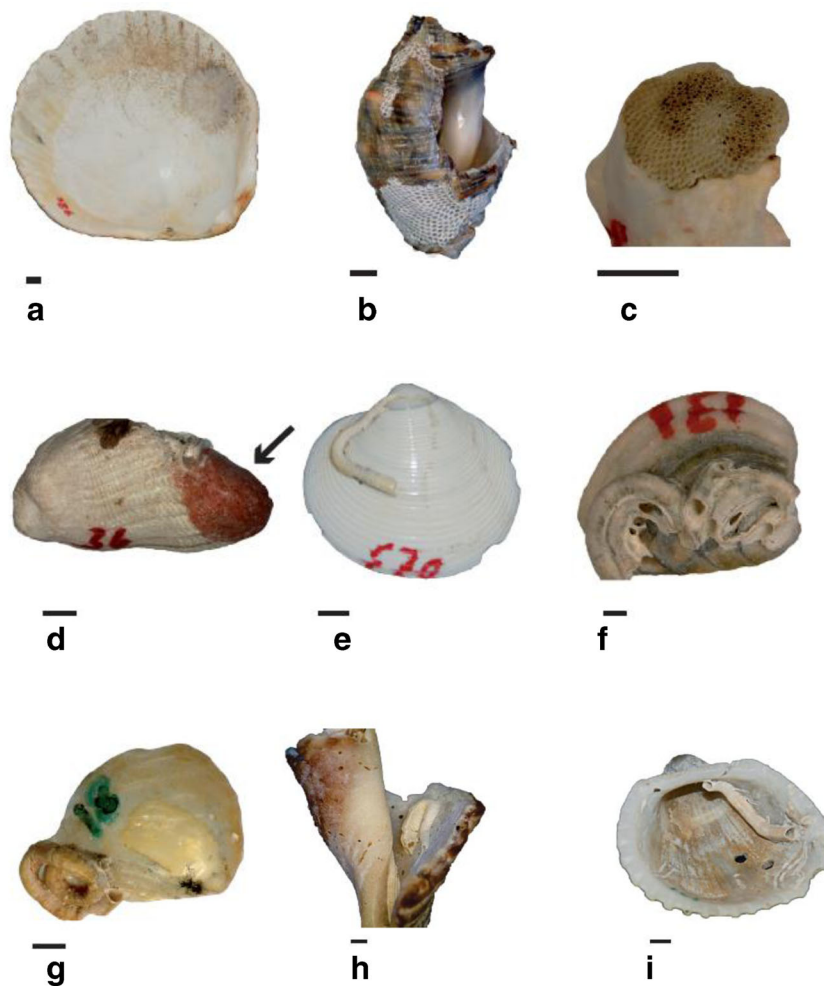


**Fig. 3** Encrusting organisms **a**–**d** Bryozoan encrusting bivalves and gastropods, **a** Non-identified bivalve, inner side of a valve showing an almost circular bryozoan colony, taphonomic grade 1; **b** detail showing the bryozoan colony; c) *Stramonita haemastoma floridana* gastropod showing an external surface encrusted by bryozoans, taphonomic grade 2; **d** Non-identified fragment of a bivalve, showing an almost circular colony on the outer side, taphonomic grade 2; **e** *Homotrema rubrum* foraminifer on the outer side of a valve of *Caryocorbula dietziana*, taphonomic grade 1; **f**–**k** Serpulid polychaete encrusting bivalves and gastropods, **f** *Diplodonta punctata* outer side of a valve with an almost complete covered surface, taphonomic grade 2; **g** *Lirophora obliterata* outer side of valves showing serpulid tube-worms, taphonomic grade 1; **h** outer side of *Crepidula plana* gastropod showing serpulid tube-worms, taphonomic grade 1; **j** Non-identified gastropod, fragment of the body whorl showing a U-shape serpulid tube-worm in the inner, taphonomic grade 1; **k** *Lunarca ovalis* inner side of a valve showing a serpulid tube-worm. Scale bar 2.5 mm

that they are more frequently linked to either eutrophication or nutrient levels but not to environmental parameters (Holmes et al. 2009). The recycling of shells as hard substrata is reflected by the association of traces, such as the four bioerosion types registered in Playa Norte: *Caulostrepsis-Oichnus*, *Entobia-Oichnus*, *Entobia-Caulostrepsis*, and *Entobia-Caulostrepsis-Oichnus*.

Although bioerosion and encrusting are activities contributing to the deterioration of shell remains, they are considered mutually exclusive as encrustation may inhibit bioerosion (Walker et al. 1998). Nevertheless, in this case, encrustation inhibition may be attributed to bioerosion as the former was classified as poor. Additionally, it is possible that low encrusting and bioerosion levels occurred because shells are frequently found on high intertidal zones, thus the subaereal exposure protects them from biological damage (Kowalewski et al. 1995). The obtained values were lower than those expected from tropical areas, despite the fact that bioerosion is the main cause of dissolution in marine carbonate environments (Best 2008). This study corroborates that bioerosion is relatively limited in siliciclastic environments, as previously suggested by Kidwell et al. (2005) and Best (2008).

Dead shell accumulations from siliciclastic environments display occasional encrustation and microboring, such as bioerosion, when compared to assemblages from carbonate settings. In these, higher encrustation levels are observed as well as macroscopic bioerosion (Best 2008). Based on the low bioerosion degree (Table 2), bioaccumulation is the dominant pattern regarding the mollusk setting in this study. However, this does not ensure the preservation of these remains as part of the fossil record, and other taphonomic and sedimentologic features must be considered (mainly mechanical fragmentation and chemical dissolution).

The low bioerosion observed on some traces may be caused by the hydrodynamic settings, just as waves and particles transport, and by the sedimentation rates in those cases where bioerosion occurred.

## Encrusting

The low encrusting density for mollusks may be the consequence of a relatively short exposure period of the remains before burial occurs (Brett et al. 2011), low nutrient levels (Lescinsky et al. 2002), constant shell motion that inhibits the encruster setting, or either by quickly wearing off encrusters and a decreased biological activity in siliciclastic environments as consequence of their high turbidity (Parsons-Hubbard 2005). In carbonate sites, low values range from near zero were reported in stressed environments and highest values at shallow upper euphotic zone (Brett et al. 2011).

We suggest that low skeletal coverage values shown in Playa Norte are mainly a consequence of the remains' exposure period (a short-time result in less encrusting), followed by frequent exhumations. They may be also a consequence of a constant shell motion. Both explanations are dependent on the sedimentation rate.

The relatively low encrusting activity on the shell remains cannot be attributed to the low nutrient levels prevailing in the seawater, because of the proximity with the Cazones River base level. Nutrients and suspended particulates are abundant and the river brings lots of organic matter to this site. Neither can be explained based on a large number of soft-body organisms living in the community (Vinn and Wilson 2010), such as algae films, because only one shell showed grazing bioerosional evidence. A low encrusting rate caused by a quick encruster wear-off is also discarded based on the markings identified under the microscope, as they possibly represent serpulid and bryozoan colonies—although there were no skeletons present, the marks of them remain on the shells—thus they were considered as encrustings.

Generally, encrusters are not selective for inner or outer shell surface, although more bryozoans were observed in inner shells, whereas more serpulids occurred on the outer side. It has been suggested that bryozoans prefer cryptic surfaces due to predation pressure created by grazers on the upper surface (Vinn and Wilson 2010).

Our results do not show spatial competition between encrusters, i.e., none of them showed outgrowth evidences regarding the other. Low bioerosion rates are considered a particular feature of quiet, mud-influenced intertidal environments (Stearley and Ekdale 1989). However, in this case, an environment possessing suitable aeration conditions and clear water prevailed.

## Utility in paleoenvironmental interpretation: Tuxpan Formation

Because death assemblages represent the first step during fossil assemblage formation, we suggest that our results represent an important tool for biological and paleontological studies aimed to understand ecological and taphonomic processes occurring in any coastal setting, especially in Paleocene-Neogene deposits along the Gulf of Mexico coast areas.

During the Oligocene, the Mexican coast of the Gulf of Mexico was predominantly terrigenous. The Appalachian uplift that occurred during the Miocene produced a considerable amount of sediments that were subsequently transported to the south (Davis 2011) to be finally deposited in continental, marine, and transitional environments (Wicander and Monroe 2000). By association, this approach could be applied particularly to the rich fossiliferous sandstones beds from the Tuxpan Formation (Miocene), in which depositional environment as well as the content of biogenic remains are similar in the grain-size, environmental deposit, and faunistic association.

The Tuxpan Formation (Dumble 1911) consists of clay and sandy clay, blue sandy shale, and calcareous sandstone (Hernández et al. 2004). Strata are parallel and almost horizontal with little alternation of foraminifera, ostracods, mollusks, crustacean remains, echinoderms, and annelid burrows (*Skolithos* isp.) (Vega et al. 1999). Based on its fossil content, Barker and Blow assigned this unit to the Lower Miocene (Burdigalian-Langhian). Shallow water transgression was the underlying cause of the deposition of these sediments. However, the subsequent regression caused its current position on the Gulf of Mexico (PEMEX 2013). Based on its lithology and fauna composition, it may be inferred that this deposition occurs between 10 and 30 m depth in euryhaline, tropical waters with a salinity range between 32 and 36‰ psu (Carreño 1986; Perrilliat 1994; Vega et al. 1999).

The ichnofabric pattern of Tuxpan Formation suggests a shallow marine environment. *Skolithos* are traces left by organisms in subtidal areas, usually in the sand, and they are considered a typical ichnogenus of marine sandstones (Bhattacharya and Bhattacharya 2007).

López-Ramos identified the formation along the Gulf of Mexico's coast comprising more than 125 km from Gutierrez Zamora to Cerro Azul, from south to north, having a 15-km average width (ranging from 1 to 20 km in some points) (Hernández et al. 2004).

The outcrops are being constantly subjected to eolian and hydric erosion, therefore they contribute to the sand accumulation that has become one of the main causes for mollusks to be rapidly buried. As a result, preservation is helpful to retain the original shell colors.

So far, there are no studies focused on the taphonomy of fossil remains, specifically on the Tuxpan Formation. The similarity between the recent assemblage and the outcrops from this formation identified in the same area are evident as they display a specific fauna type and sand-sized sediments. Moreover, the paleoecological interpretation during the Langhian is comparable to the current conditions prevailing in Playa Norte. Future studies will also include the study of fragmentation, dissolution, abrasion, physical processes, as well as the intrinsic factors of the mollusk in order to assess their importance in defining shell assemblage deterioration or preservation in this type of depositional settings to generate a taphonomic pattern.

## Conclusions

There are no significant differences between gastropod and bivalves regarding bioerosion and encrustation; both displayed in a low grade. Poor bioerosion and encrustation scores may be originated by hydrodynamic conditions, including constant shell motion and frequent exhumation processes. Clionid sponges, spionid polychaetes, and gastropods are the main bioeroders. The dominant bioerosion structures were correlated to a boring activity performed by non-predatory organisms. Encrustation is mainly caused by serpulids and rarely by bryozoans and foraminifera. The analysis conducted on bivalve and gastropod natural assemblage obtained from Playa Norte, Gulf of Mexico, indicates that biological activity in siliciclastic environments (bioerosion and encrusting) is not important for the obliteration of biotic remains. Considering the reduced evidence of biological activity, it was the case that mollusk shells accumulation prevailed over biotic destruction. The present study suggests that systematic study of encrusting and bioerosion have potential to elucidate ancient coastal environments in conjunction with the study of other indicators, and may permit more precise paleoreconstructions.

## References

Anderson LC, McBride RA, Taylor MJ, Birnes MR (1998) Late Holocene record of community replacement preserved in time-averaged molluscan assemblages, Louisiana chenier plain. PALAIOS 13:488–499

Armstrong-Altrin JS (2009) Provenance of sands from Cazones, Acapulco, and Bahía Kino beaches, Mexico. Rev Mex Cienc Geol 26:764–782

Armstrong-Altrin JS, Machain-Castillo ML (2016) Mineralogy, geochemistry, and radiocarbon ages of deep sea sediments from the Gulf of Mexico, Mexico. J S Am Earth Sci 71:182–200

Armstrong-Altrin JS, Lee Y, Kasper-Zubillaga JJ, Carranza-Edwards A, Garcia D, Eby GN, Balaram V, Cruz-Ortiz NL (2012) Geochemistry of beach sands along the western Gulf of Mexico, Mexico: implication for provenance. Chemie der Erde 72:345–362

Armstrong-Altrin JS, Nagarajan R, Balaram V, Natalhy-Pineda O (2015) Petrography and geochemistry of sands from the Chachalacas and Veracruz beach areas, western Gulf of Mexico, Mexico: constraints on provenance and tectonic setting. J S Am Earth Sci 64:199–216

Behrensmeyer AK, Miller JH (2012) Building links between ecology and paleontology using taphonomic studies. In: Louys J (ed) Paleontology in ecology and conservation. Springer, New York, pp 69–91

Best MMR (2008) Contrast in preservation of bivalve death assemblages in siliciclastic and carbonate tropical shelf settings. PALAIOS 23: 796–809

Best MMR, Kidwell SM (2000) Bivalve taphonomy in tropical mixed siliciclasticcarbonate settings. I. Environmental variation in shell condition. Paleobiology 26:80–102

Bhattacharya B, Bhattacharya HN (2007) Implications of trace fossil assemblages from late Paleozoic Glaciomarine Talchir Formation, Raniganj Basin, India. GR 12:509–524

Bird E (2000) Coastal geomorphology: an introduction. Wiley, England, p 322

Blissett DJ, Pickerill RK (2007) Systematic ichnology of microborings from the Cenozoic White Limestone Group, Jamaica, West Indies crescent-shaped boring. Scrip Geol 134:77–108

Botello AV, Soto LA, Ponce-Vélez G, Villanueva SF (2015) Baseline for PAHs and metals in NW Gulf of Mexico related to the Deepwater Horizon oil spill. Estuar Coast Shelf Sci 156:124e133

Brett CE, Parsons-Hubbard KM, Walker SE, Fergusond C, Powell EN, Staff G, Ashton-Alcoxe KA, Raymondg A (2011) Gradients and patterns of sclerobionts on experimentally deployed bivalve shells: synopsis of bathymetric and temporal trends on a decadal time scale. Palaeo 3(312):278–304

Brett CE, Smrecak T, Parsons-Hubbard K, Walker S (2012) Marine sclerobiofacies: encrusting and endolithic communities on shells through time and space. In: Talent, JA (ed.). Earth and life. Springer, New York, pp 129–157

Bromley RG (1970) Borings as trace fossils and Entobia cretacea Portlock, as an example. In: Crimes TP, Harper, JC (ed.). Trace Fossils. Seel House Press, Liverpool, pp 49-90

Bromley RG (1975) Comparative analysis of fossil and recent echinoid bioerosion. Palaeontology 18:725–739

Bromley RG (1981) Concepts in ichnotaxonomy illustrated by small round holes in shells. Acta Geol Hisp 16:55–64

Bromley RG, D'Alessandro A (1984) The ichnogenus Entobia from the Miocene, Pliocene and Pleistocene of southern Italy. Riv Ital Paleontol Stratig 90:227–296

Butterlin J (1958) A propósito de la edad de las formaciones Escolín, Coatzintla y Tuxpan de la cuenca sedimentaria Tampico-Misantla. Bol Asoc Mex Geól Petrol 10:595–601

Cabrera R, Lugo JE (1984) Estratigrafía-sedimentología de las cuencas terciarias del Golfo de México. Bol Asoc Mex Geol Petrol 36:3–55

Carranza-Edwards A, Centeno-García E, Rosales-Hoz L, Cruz RLS (2001) Provenance of beach gray sands from western México. J S Am Earth Sci 14:291–305

Carreño A (1986) Los ostrácodos de edad Oligo-Miocenica de la Subprovincia Tampico-Misantla, área centrooriental de México. Parte II. Mioceno: Formaciones Mesón y Tuxpan. Rev Inst Geol 6:178–192

Clarke JM (1908) The beginnings of dependent life. New York State Mus Bull 121:149–169

Davis RA Jr (2011) Sea-level changes in the Gulf of Mexico. In: Davis RA Jr (ed) Sea-level changes in the early history of the Gulf of Mexico, Eberbest Printing co., China, pp 17–38

Edinger EN (2001) Bioerosion. In: DEG B, Crowther PR (eds) Paleobiology II. Blackwell, Oxford, pp 273–277

Gibert JM, Domènech R, Martinell J (2007) Bioerosion in shell beds from the Pliocene Roussillon Basin, France: implications for the (macro) bioerosion ichnofacies model. Acta Palaeontol Pol 52:783–798

Hernández U, Velez D, Ruíz H, Martínez J, Ghosh JK, Jacobo J (2004) Oligicene-Miocene sedimentation along the Western Gulf Coast: Insights from Outcrops and Subsurface Data, Onshore-Offshore Northern Veracruz, Mexico. Field Guide for AAPG International Conference and Exhibition. AAPG: 40

Holmes G, Ortiz JC, Schönberg CHL (2009) Bioerosion rates of the sponge Cliona orientalis Thiele, 1900: spatial variation over short distances. Facies 55:203–211

INAFED (2012) Cazones de Herrera http://www.inafed.gob.mx/work/enciclopedia/EMM30veracruz/municipios/30033a.html. Accessed 28 Jan 2016

Kasper-Zubillaga JJ, Dickinson WW (2001) Discriminating depositional environments of sands from modern source terranes using modal analysis. Sediment Geol 143:149–167

Kidwell SM, Best MR, Kauffman DS (2005) Taphonomic trade-offs in tropical marine death assemblages: differential time averaging, shell loss, and probable bias in siliciclastic vs. carbonate facies. Geology 33:729–732

Kowalewski M (2002) The fossil record of predation: an overview of analytical methods. In: Kowalewski M, Kelley PH (eds) The fossil record of predation. Paleontological society special papers 8, pp 3–42

Kowalewski M, Labarbera M (2004) Actualistic taphonomy: death, decay, and disintegration in contemporary settings. PALAIOS 19:423–427

Kowalewski M, Flessa KW, Hallman DP (1995) Ternary taphograms: triangular diagrams applied to taphonomic analysis. PALAIOS 10: 478–483

Lara JR (2008) Los ecosistemas costeros, insulares y epicontinentales. Conocimiento actual de la biodiversidad. CONABIO, México, pp 109–134

Lescinsky HL, Edinger E, Risk MJ (2002) Mollusc shell encrustation and bioerosion rates in a modern epeiric sea: taphonomy experiments in the Java Sea, Indonesia. PALAIOS 17:171–191

Nebelsick JH, Schmid B, Stachowitsch M (1997) The encrustation of fossil and recent sea-urchin tests: ecological and taphonomic significance. Lethaia 30:271–284

Okazaki H, Stanley JD, Wright EE (2001) Tecolutla and Nautla Deltas, Veracruz, Mexico: texture to evaluate sediment entrapment on deltaic plains and bypassing onto Gulf of Mexico margin. J Coast Res 17:755–761

Parsons-Hubbard KM (2005) Molluscan taphofacies in recent carbonate reef/lagoon systems and their application to sub-fossil samples from reef cores. PALAIOS 20:175–191

PEMEX (2013) Provincia Petrolera Tampico-Misantla https://www.academia.edu/12567219/tampico_misantla Accesed 12 Feb 2018

Perrilliat C (1994) Bivalvos de la Formación Tuxpan, (Mioceno medio) Estado de Veracruz, México. Rev Mex Cienc Geol 2:232–242

Powell EN, Brett CE, Parsons-Hubbard KM, Callender WR, Staff GM, Walker SE, Raymond A, Ashton-Alcox KA (2011) The relationship of bionts and taphonomic processes in molluscan taphofacies formation on the continental shelf and slope: eight-year trends: Gulf of Mexico and Bahamas. Facies 57:15–37

Ramos-Vazquez MA, Armstrong-Altrin JS, Rosales-Hoz L, Machain-Castillo ML, Carranza-Edwards A (2017) Geochemistry of deep-sea sediments in two cores retrieved at the mouth of the Coatzacoalcos River delta, western Gulf of Mexico, Mexico. Arab J Geosci 10:148

Regan A (2017) Comparative taphonomy of molluscan death assemblages from the Gulf of Mexico. KECK Geology Consortium 30 Ann Symposium Vol: 1–7

Rosales-Hoz L, Carranza-Edwards A, Martínez-Serrano R, Alatorre MA, Armstrong-Altrin JS (2015) Textural and geochemical characteristics of marine sediments in the SW Gulf of Mexico: implications for source and seasonal change. Environ Monit Assess 187:1e19

Santos A, Mayoral E (2008) Bioerosion versus colonisation on Bivalvia: a case study from the Upper Miocene of Cacela (southeast Portugal). Geobios 41:43–59

Simoes MG (2010) Actualistic taphonomy: putting the Holocene shells to work. X Congreso Argentino de Paleontología y Bioestratigrafía y VII Congreso Latinoamericano de Paleontología http://sedici.unlp.edu.ar/handle/10915/16751 Accesed 28 Jan 2018

Spagnuolo JO, Farinati EA, Aliotta S (2013) Rodados bioerosionados en depósitos marinos holocenos del estuario de Bahía Blanca, Argentina: consideraciones paleoambientales y procedencia. Lat Am J Aquat Res 41:412–422

Stearley RF, Ekdale AA (1989) Modern marine bioerosion by macroinvertebrates, northern Gulf of California. PALAIOS 4:453–467

Tamayo JL (1991) Geografía Moderna de Mexico. Mexico, Trillas, p 400

Tapia-Fernandez HJ, Armstrong-Altrin JS, Selvaraj K (2017) Geochemistry and U-Pb geochronology of detrital zircons in the Brujas beach sands, Campeche, Southwestern Gulf of Mexico, Mexico. J S Am Earth Sci 76:246–361

Vega FJ, Feldmann R, Villalobos JL, Gío-Argaez R (1999) A new deca-pod fauna from the Miocene Tuxpan Formation, Eastern Mexico. J Pal 73:407–413

Vinn O, Wilson M (2010) Microconchid-dominated hardground asso-ciation from the late Pridoli (Silurian) of Saaremaa, Estonia. PE 13(2):9A

Walker SE, Parsons-Hubbard K, Powell EN, Brett CE (1998) Bioerosion or bioaccumulation? Shelf-slope trends for epi- and endobionts on experimentally deployed gastropod shells. Hist Biol 131:61–72

Wicander R, Monroe JS (2000) Historical geology: evolution of earth and life through time. Brooks/Cole, California, pp 1–464