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OBSERVATIONS OF TWO MOSAIC FRAGMENTS FROM THE UNDERWATER CITY OF BAIAE (NAPLES, ITALY): ARCHAEOLOGICAL, GEOLOGICAL AND BIOLOGICAL INVESTIGATIONS

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Abstract

Bioerosion of submerged Roman calcareous mosaic floors from the Underwater Archaeological Park of Baiae (Naples, Italy) was examined. Epilithic colonization and endolithic biodegradation of the tesserae were studied on two recovered mosaic fragments using different analyses. 32 taxa were identified. Polished thin sections were achieved to study mortars and lithotype. SEM observations permitted the identification of micro and macroborers by using the embedding-casting technique. The study showed that the damage of the limestone tesserae was higher on the peripheral parts of the fragments. The results characterized the bioerosion of the submerged floors and offered a useful contribution in defining future conservation strategies.

Keywords: *Baiae-Naples; Mosaics; Limestone tesserae; Bioerosion*

Introduction

The *in situ* protection and conservation of submerged archaeological sites is very problematic. International legislation, as the UNESCO Convention for the Protection of the Underwater Cultural Heritage (2001), the Valletta treaty (1992) and the ICOMOS Charter (1996), advise a strategy of preserving this heritage *in situ* where possible. Factors involved in the deterioration of underwater cultural heritage are physical, chemical and biological. In particular biological colonization leads to alterations of the original appearance of the artefacts and above all to the bioerosion of the substrate.

The present study involves mosaic floors of the site of Baiae that includes the remains of the ancient town (villas, tabernae, warehouses, port infrastructures, statues, etc.) lying underwater because of the phenomenon of negative bradyseism [1-4]. Since 2003, annual restoration works were conducted by ISCR in the frame of the Project *Restoring Underwater* in order to restore and preserve the archaeological structures included in the itinerary of the

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Underwater Park [5, 6]. Several studies were already carried out in this area in order to define the bioerosive role of macro-and microorganisms [7-12].

This paper is dedicated to the memory of Dr. Paolo CAPUTO (Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei), who recently passed away.

The aim of this work was to date, characterize the lithotype and mortar and define the biodegradation patterns of two mosaic fragments recovered in the Underwater Park of Baiae (Gulf of Pozzuoli, Naples, Italy). The results provide useful information concerning the *in situ* state of preservation of submerged mosaics and help to define the appropriate interventions to prevent biological colonization.

Materials and methods

Mosaic fragments

The study was carried out on two mosaic fragments (named 1 and 2), parts of the same floor, collected erratic on the seabed at a depth of about 5m below sea level. They were preserved at room temperature. The tesserae were counted and measured by calliper.

Mineralogical/petrographic analyses

Thin and polished cross sections were obtained from tesserae and mortars. They were observed under stereomicroscope (Wild M3Z) and optical microscope in reflected and polarized light (Leitz Laborlux 12 Pol) in order to define the textural features of samples. Sections were set up based on the standard [13]. The study was conducted following [14-16].

Study of biological colonization

The epilithic organisms colonizing the mosaic fragments were observed under stereomicroscope (Leica MZ 16) and optical light microscope (Leica DM RB).

To study the macro-endolithic colonization, rows of tesserae from fragments 1 and 2 both presenting highly degraded and best preserved elements, were chosen. The tesserae of fragment 1 (rows A, B and C) were cut longitudinally: three slices were obtained from each tesserae. The thickness of the slices ranged from 2 to 5 mm depending on the dimension of the tesserae. The tesserae of fragment 2 (row D) were cut transversally in five slices, with a thickness from 1.5 to 4 mm depending on the height of the tesserae. Tiles of each row were numbered starting from the outer one.

Each side of the slices was photographed and the images were standardized in size 6 x 6 cm (300 px /cm). The surfaces of the areas bioeroded by macroborers were measured through the program ImageJ. The percentage of the degraded part with respect to the total surface was defined.

The slices were impregnated with polyester resin (Styrene Styrol 2S, LEICA Microsystems SRL) to obtain casts of the bioeroders, following the procedure described by [9] and [17].

Tesserae, slices and casts were sputter-coated with gold and observed by scanning electron microscopy (SEM - Zeiss EVO 60, Oxford Instruments), under high vacuum conditions, using secondary electrons and backscattered electrons (BSE). To obtain positive casts of the macroborers, silicon rubber technique was used. Low-viscosity silicon rubber (Silical 120 - C.T.S. SRL) was mixed with hardener (Silical 125 - C.T.S. SRL) (95:5 ratio) and poured into the holes of the tesserae, previously treated with a release agent, in order to fill all the cavities. The casts were extracted after 48 h of polymerization.

The following publications were used for the identification of epilithic [18-20], macro-endolithic [21-28], nestling and rasping *taxa* [23, 25].

Results and discussion

The mosaic fragments belonged to a large residential complex identified as the Villa dei Pisoni, because of the discovery of a *fistula aquaria*, still in its original position (the south corner of the courtyard) bearing the name of the proprietor, *Lucius Calpurnius Piso*. The powerful *Piso* family of the first Imperial era had its property confiscated in 65 AD, as the consequence of a failed conspiracy against Nero. The villa later became Imperial property and underwent significant development in the Hadrian era (117-138 AD), when the large central rectangular courtyard was added. It measured circa 60 × 100m and boasted richly decorated porticos on each side, some with curvilinear alcoves framed by half columns in brick. The SW wall of this structure, measuring around 60m, was restored by ISCR [29]. The studied fragments could be approximately dated to the imperial time since it has not been possible to locate their original position.

Description of fragments

Fragment 1, sub triangular, was formed by 20 tesserae (Fig. 1A). Fragment 2, irregular in shape, was made of 28 tiles (Fig. 1B). The tesserae had different dimensions: sides from 6 to 15mm, heights ranged between 18 and 30mm. Four morphological categories were observed for the upper surface: large sub square, small sub square, large sub rectangular and small sub rectangular. The small sub rectangular tiles were always paired. In both samples a mortar layer was present with a thickness ranging from 0.9 to 1.7cm (Fig. 1C).

Fig. 1. Mosaic samples: A- fragment 1; B- fragment 2;
C- lateral view of a side of the Fragment 1.

Characterization of materials and hypothesis of origin

Petrographic analyses of thin and cross sections showed that the tesserae are made of sub-crystalline limestone (Fig. 2A), beige in colour, probably coming from the Central Apennines (Campanian region). This lithotype is common within the geological units of Cretaceous [30, 31].

The mosaic fragments showed two layers of mortar: the upper one, white in colour, in which the tiles were inserted and the first part of the *nucleos* (Fig. 2B) (according to Vitruvius, De Architectura, VII, 1.2). In both samples the lower part of the *nucleos*, the *rudus* and the *statumen* were missing. The white layer had a thickness ranging from 2 to 3mm and was made of slaked lime. This mortar is present also between the tesserae and it was partially deteriorated by chemical-physical agents. The upper part of the *nucleos* had a thickness varying from 9 to 14mm and was made of slaked lime and grey pozzolan (volumetric ratio 1: 3/1: 4), coming from the surrounding area (Baiae and Puteoli), and composed of granules with dimensions ranging from 0.01 to 2.8mm.

In cross section some tiles showed oblique fractures crossing the whole height, with openings of up to 3mm filled by slaked lime (Fig. 2C). Concerning this kind of damage two hypotheses can be presented: 1- the tesserae were put in place in a fragmentary state during the construction of the floor; 2 - the slaked lime layer can be referred to an ancient consolidation and restoration work.

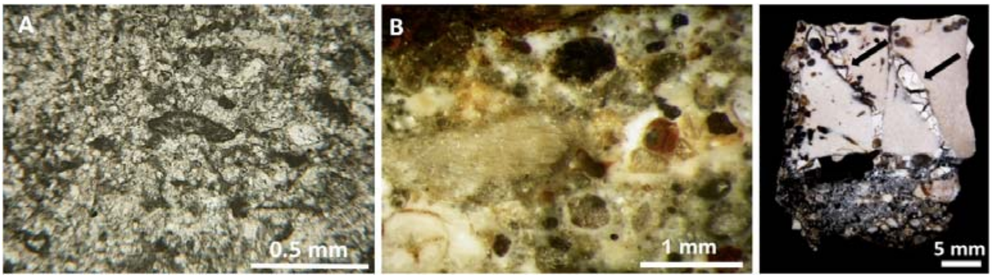

Fig. 2. A - optical photomicrograph of limestone with tests of foraminifera; B - stereomicroscope photograph of upper part of the *nucleos*; C- stereomicroscope photograph of a section of two adjacent tesserae with oblique fractures (black arrows).

Biological colonization

The fragments showed a remarkable biological colonization. 32 taxa of epilithic, endolithic, nestling and rasping micro- and macro-organisms were recorded on the surface and inside the tesserae (Tab. 1). Epilithic colonization caused only aesthetic modification of the original material, while endolithic and rasping species (*Chiton olivaceus*) produced mechanical and chemical damage on the stone. Nestling *taxa* (*Arca noae*) lived inside bioeroded cavities without interacting with the substrate in a destructive way.

Table 1. List of identified *taxa* on the tesserae

	taxa	epilithic	endolithic	nestling	rasping
Cyanobacteria	**Plectonema terebrans* Bornet & Flahault, 1889		+		
	**Hyella caespit*osa Bornet & Flahault, 1888		+		
Fungi	**Ostracoblabe implexa* Bornet and Flahault,1891		+		
Chlorophyta	**Ostreobium quekettii* Bornet and Flahault,		+		
	1889		+		
	**Acetabularia acetabulum* (Linnaeus) P.C.	+			
	Silva, 1952	+			
	Caulerpa racemosa (Forsskål) J. Agardh, 1873				
	Dasycladus vermicularis (Scopoli) Krasser in	+			
	Beck & Zahlbruckner, 1898				
	Cladophora prolifera (Roth) Kuetzing, 1843				
Phaeophyta	*Dictyota dichotoma* (Hudson) J.V.Lamouroux,	+			
	1809	+			
	Stypocaulon scoparium (L.) Kuetzing, 1843				
Rhodophyta	*Hydrolithon* sp. (Foslie) Foslie,1909	+			
	Pneophyllum sp. Kuetzing, 1843	+			
	Herposiphonia secunda (C.Agardh) Ambronn,	+			
	1880 *Peyssonnelia squamaria* (S.G. Gmelin)	+			
	Decaisne, 1842				
Mollusca	*Arca noae* Linnaeus, 1758			+	
	Chiton olivaceus Spengler, 1797				+
	Rocellaria dubia Pennant, 1777		+		
	Vermetus granulatus Gravenhorst, 1831	+			
Porifera	*Chondrilla nucula* Schmidt, 1862	+			
	Cliona celata Grant, 1826		+		
Anellida	*Pileolaria* sp. Claparède, 1868	+			

	Spirorbis sp. Daudin, 1800	+		
	Hydroides sp. Gunnerus, 1768	+		
	Spirobranchus triqueter Linnaeus, 1758	+		
	Janua pagenstecheri Quatrefages, 1866	+		
	Protula tubularia Montagu, 1803	+		
Arthropoda	*Perforatus perforatus* Bruguière, 1789	+		
	Amphibalanus amphitrite Darwin, 1854	+		
Bryozoa	*Schizobrachiella sanguinea,* Norman, 1868	+		
	Schizoporella errata Waters, 1878	+		
	Schizoporella unicornis Johnston in Wood, 1844	+		
Sipuncula	*Aspidosiphon muelleri* Diesing, 1851		+	

* These species were identified observing the casts of produced tunnels (ichnospecies), see § 4.3.2 Endolithics – Microborers.

Epilithics

The upper surfaces of the tiles and part of the vertical ones were largely colonized by micro and macroorganisms, many of them forming calcareous or organic encrustations (Tab. 1, Fig. 3A). Several encrusting species, mainly red coralline algae (Figs. 3 B-C), bryozoans (Fig. 3D), serpulids (Fig. 3E) and sponges (Fig. 3F), formed a heterogeneous layer with a thickness ranging from 0.1mm to 7mm. This layer sometimes covered the majority of the upper surfaces, hiding the original lithotype.

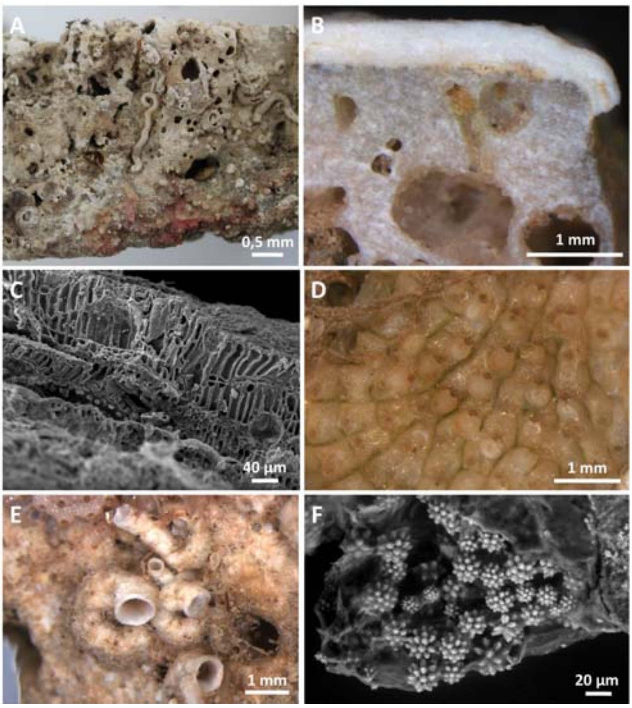

Fig. 3. Epilithic colonization:
A - biogenic encrustation with barnacles, serpulids and coralline algae;
B - stereomicroscope photograph of a longitudinal section of a tile showing a white layer of encrusting algae;
C - SEM micrograph of a thallus of Corallinaceae; D - stereomicroscope photograph of a bryozoan colony;
E - stereomicroscope photograph of calcareous tubes of serpulids (*Janua* sp.);
F - SEM micrograph of spicules of the epilithic sponge *Chondrilla nucula*.

Endolithics - Microborers

The presence of microborers was observed on sections of tiles as green layer spreading from the surface to a depth of 1 mm (Figs. 4A and B), both beneath the uncolonized surface and under the bryozoan colonies and Corallinaceae thalli. This layer was also located along the tunnels dug by endolithic sponges. These microenvironments are favourable for the development of sciaphilous or heterotrophic endolithic species which do not require high levels of light [32]. SEM observations of the green layer showed a diffuse bioerosion with tunnels and cavities (Fig. 4C). The casts of micro perforations obtained by embedding-casting technique and observed by SEM (Fig. 4D) were related to some ichnospecies (i.e. names of traces produced by endolithic species). *Scolecia filosa* Radtke1991, *Fascichnus dactylus* Radtke, 1991 and *Ichnoreticulina elegans* Radtke 1991 were the most common ichnospecies (Tab.1).

S. filosa, produced by the cyanobacterium *Plectonema terebrans* Bornet & Flahault, 1889, bored thin (width 3-5µm) and mainly unbranched galleries forming dense interwoven networks. It was recorded in coral skeletons and calcareous substrates [9, 33].

F. dactylus, produced by the cyanobacterium *Hyella caespitosa* Bornet & Flahault, 1888, showed thick (5-8µm in diameter) and straight galleries forming radiating bundles or expanded carpets. These tunnels had penetrated more than 400 µm into the tesserae. Usually this ichnospecies was reported in sediments, molluscan shells, reefs and limestone [32-36].

I. elegans, produced by the chlorophyte *Ostreobium quekettii* Bornet & Flahault, 1889, was characterized by filaments running parallel to the exposed surface of tesserae and forming a dense zigzag pattern meshwork. The diameters of the galleries were as much as 5µm. This ichnospecies was previously found in calcareous substrates, corals, shells and submerged artefacts [9, 33-34, 37-39].

Less frequently and only in the inner part of the limestone the ichnospecies *Orthogonum fusiferum* Radtke, 1991 was found. It is produced by the fungus *Ostracoblabe implexa* Bornet & Flahault, 1891, with straight and branched filamentous structures sometimes showing typical swellings; tunnel diameters ranging from 1 to 4µm. The ichnospecies was found in shells, carbonate substrates and archaeological remains [9, 39-43].

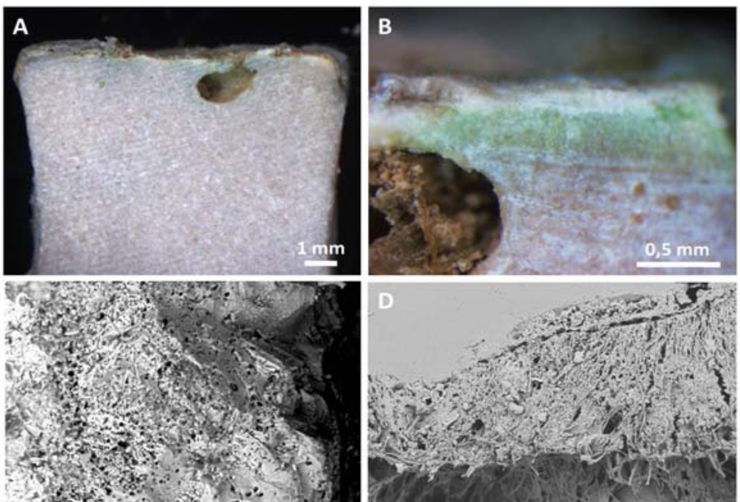

Fig. 4. A and B - stereomicrographs of a tessera with a green layer related to microboring activity; C - SEM micrograph of limestone with tunnels produced by microflorabiota; D - SEM micrograph of resin casts showing the trend of microboring perforations.

The green alga *Acetabularia acetabulum* (Linnaeus) P.C. Silva, 1952 (Dasycladales) was sporadically observed on the tesserae. It is known that its rhizoidal apparatus is able to bore hard and organogenic substrates (Fig. 5A) [33, 44, 45]. The traces of the rhizoids, known as the ichnospecies *Fascichnus grandis* Radtke, 1991, were observed by SEM as cylindrical structures often dichotomically branched in the terminal part (Fig. 5B). Polished sections showed a penetration depth of 0.5mm inside the stone. The bioerosive role of this species on submerged archaeological artefacts in the Underwater Archaeological Park of Baiae (Fig. 5C), was recently described [12].

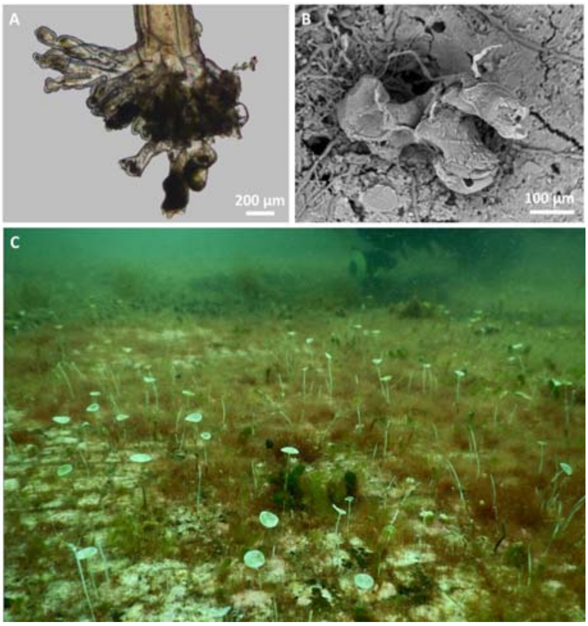

Fig. 5. *Acetabularia acetabulum*: A - stereomicroscope photograph of endolithic rhizoids; B - SEM micrograph of the resin casts of the rhizoid perforations; C - underwater photo of living specimens on a roman mosaic floor (Underwater Park of Baiae).

Endolithics - Macroborers

Macrobioerosion was mainly produced by sponges and bivalves together with Sipunculans. The erosion activity due to boring sponges produced an extensive and severe damage on the tesserae. These animals excavated circular papillar perforations (0.5-2mm in diameter), often arranged in rows, on the surface of the tesserae (Fig. 6A). Optical and SEM observations of the skeletal arrangement showed the presence of straight fusiform spicules with a pointed end and a globular or ovoid tyle, tylostyles (Figs. 6B and 6C), and the morphology of the bioerosion micro-patterns (Fig. 6D). These features led to the identification of the sponge *Cliona celata* Grant 1826 (Hadromerida, Clionaidae), known to be an excavating species (Fig. 6E) [26, 46-49]. SEM analyses of the casts obtained with the resin embedding-casting technique and stereomicroscope observations of silicone casts allowed us to define the morphology of the chambers and galleries produced by *C. celata.* The cavities had sub-globular shape with an average size from 0.17 to 4.22mm, often coalescent and interconnected by narrow galleries, forming three-dimensional structures (Fig. 6F). The resin casts of the traces were attributed to the ichnogenus *Entobia* Bronn, 1837 (Fig. 6G) [50]. Previous studies reported the presence of this species as colonizer of several submerged mosaics and calcareous artefacts (Fig. 6H) [9, 51-52].

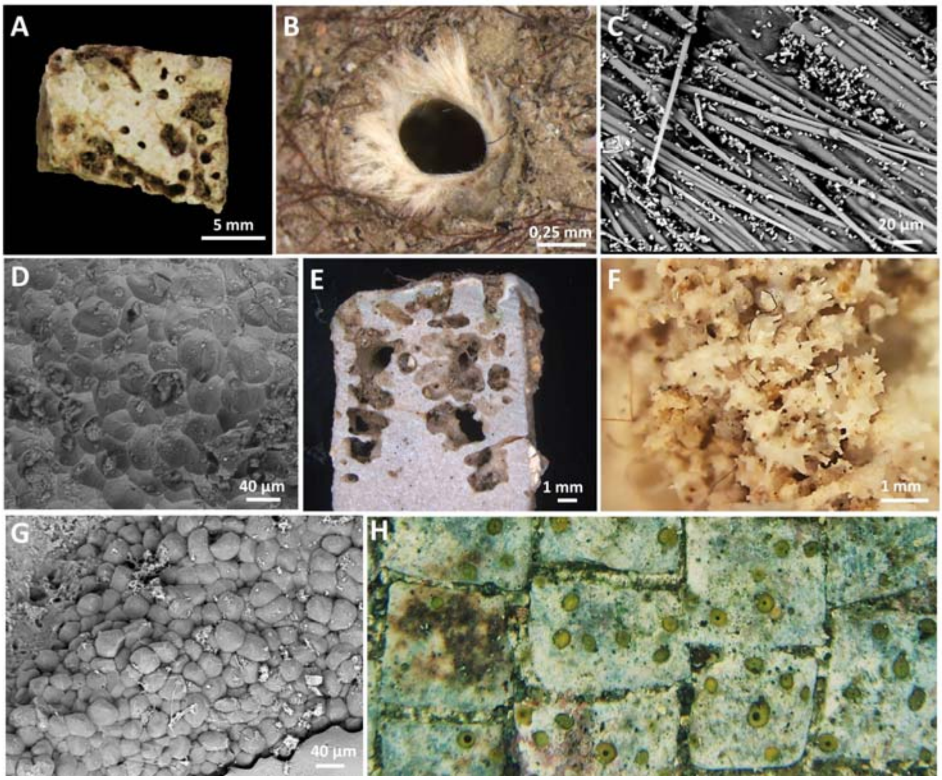

Fig. 6. Boring sponges:
A - stereromicroscope photograph of a tessera with papillar perforations.
B - external hole surrounded by spicules; C- SEM micrograph of tylostiles of *Cliona celata*;
D - SEM micrograph of the micro-patterns;
E - stereomicroscope photograph of a section of a tessera showing internal chambers;
F - silicone cast of interconnected chambers; G- SEM micrograph of resin casts of the excavating pattern;
H - underwater photo of a mosaic with living specimens of *Cliona celata* (Underwater Park of Baiae).

The group of endolithic bivalves was represented by the species *Rocellaria dubia* Pennant 1777 (Euheterodonta, Gastrochaenidae), whose presence was inferred by typical 8-shaped holes on the surface of tesserae (Fig. 7A). The shells were found inside the limestone vertically or sub-horizontally (Fig. 7B) and affected one or two adjacent tiles (Fig. 7C). The specimens ranged from 11 to 13mm in length. This species prefers horizontal or slightly inclined surfaces. The siphonal holes are surrounded by a more or less elongated aragonitic deposit (Fig. 7D). It is able to change the orientation of the perforation to avoid contact with other endolithic organisms and to bore softer areas [11, 27, 53-54]. Experimental studies carried out in the site of Baiae on submerged limestone panels showed the rapid spread (12 months) of this species [36, 55].

The third group of macroborers belongs to the phylum Sipuncula, vermiform animals that excavated tunnels up to 3 mm in diameter inside tesserae and mortar (Fig. 7E). The specimens found in the burrows were referred to the species *Aspidosiphon muelleri* Diesing 1851 (Aspidosiphonida, Aspidosiphonidae) (Fig. 7F). The bioerosive action of the genus *Aspidosiphon* was already reported in previous studies on natural substrata and archaeological artefacts [10, 56, 57].

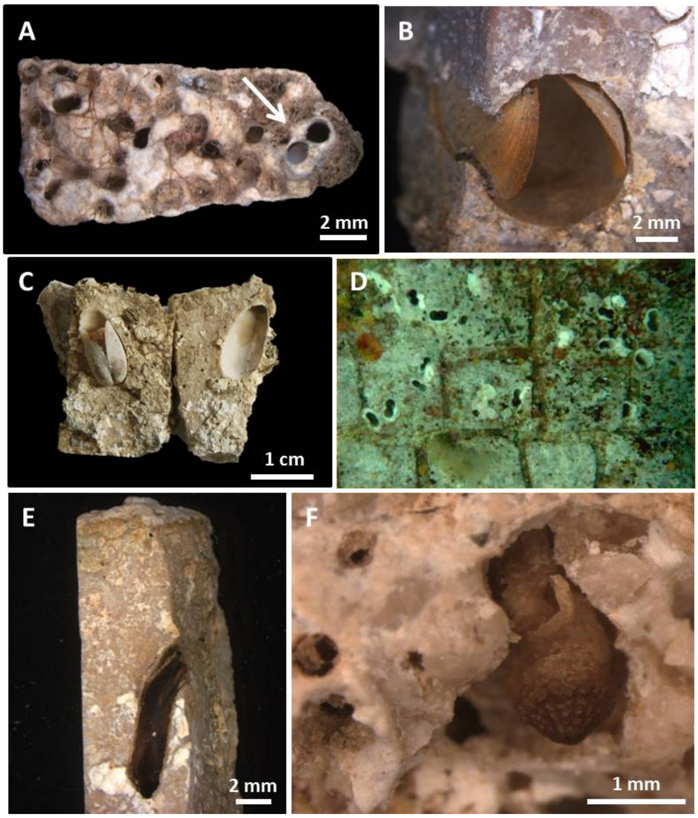

Fig. 7. Bivalves and Sipunculans:
A - stereromicroscope photograph of a tessera with 8-shaped apertures of the bivalve *Rocellaria dubia* (white arrow);
B - stereomicroscope photo of *R. dubia* inside the borehole;
C - stereomicroscope photograph of *R. dubia* grown in two adjacent tesserae;
D - underwater photo of a mosaic with living *R. dubia* (Underwater Park of Baiae);
E - stereromicroscope photograph of a tessera with a burrow produced by the sipunculan *Aspidosiphon muelleri*;
F - steromicroscope photograph of a specimen of *A. muelleri* inside its burrow.

Bioerosion levels

Visual observations showed that the tiles located along one of the edges of fragment 1 were more degraded than those located on the other part of the fragment (Fig. 1A). The tesserae showed numerous circular perforations of sponges, which affected most of the exposed surfaces. The same degradation was observed on the vertical sides of the tesserae along the perimeter of the fragment.

Levels of bioerosion caused by macro-endolithics were defined analysing cut slices of tesserae. Percentages of bioeroded surfaces are reported in Fig. 8. The observations of the longitudinal sections confirmed and quantified the damage inside the tesserae. The rows A, B and C showed a similar trend in the percentage of bioeroded surface. The tiles A1, B1 and C1, located on the peripheral part of the fragment, showed the highest percentages, with a peak of 68% in B1. The tesserae A2, B2 and C2 were less degraded. The other tiles (n. 3, 4 and 5) showed a more variable trend. On row C, the decrease was progressive with the lowest value of 0.88% on tile C5. On the other two rows the trend was more irregular with a sharp decrease on tiles n. 3 (A3 = 0. 21%; B3 = 4.10%), as seen in figure 8.

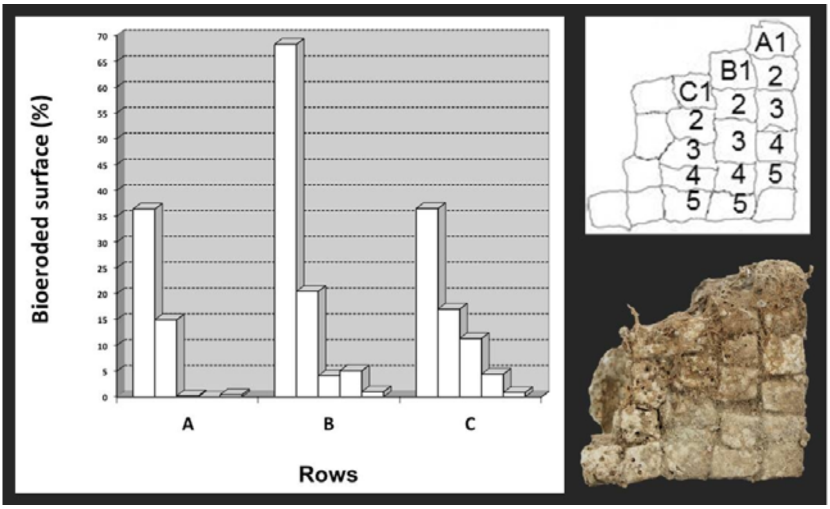

Fig. 8. Fragment 1. Bioeroded surface (%) of the three rows (A,B,C) of tesserae calculated in the longitudinal sections.

The transversal sections of 6 tiles of fragment 2 (row D) showed that the level of sponge bioerosion did not decrease from the surface towards the lower part (Fig. 9). In some cases (D1), cavities spread more or less homogeneously in the slices. A different pattern was observed on tesserae D3 and D5 where cavities were present only in the lower slices (D3 slices III and IV, D5 slice V) because the endolithic attack had taken place from the lateral sides.

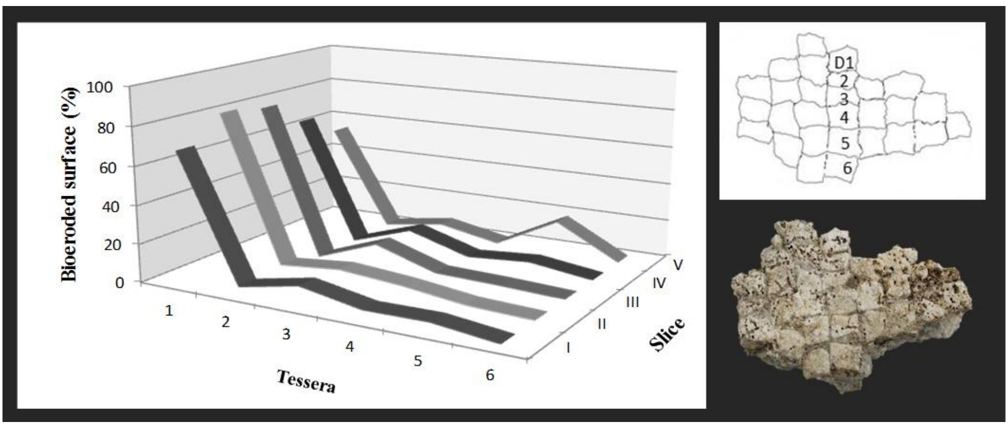

Fig. 9. Fragment 2: Bioeroded surface (%) of the row D calculated in the cross sections.

These results show that the outward appearance does not always represent the real conservative condition of the tesserae. In some cases tiles with well preserved upper surface can be affected by endolithic attacks in the lower parts, while others with degraded surfaces may not always be compromised in the inner part.

The study defines the degradation levels affecting the submerged mosaic floors documenting this aspect in detail and quantifying the extent of degradation. The studied fragments reflect the different conservative situations of the submerged archaeological site. It has been demonstrated that the peripheral parts of the underwater floors are subjected to greater damage: in this case tesserae have both horizontal and vertical sides exposed, increasing the biological colonization. Figure 10 illustrates a part of a mosaic still in the Underwater Park of Baiae with a degradation pattern very similar to the analyzed fragment (Fragment 1). A comparable condition can be found in lacunae, placed in the internal part of floors, where the tesserae are affected by an analogous colonization.

Fig. 10. Underwater photo of a mosaic floor (Underwater Archaeological Park of Baiae): peripheral part with evident bioerosion.

In particular the mosaics made of limestone tiles can be dangerously exposed to the action of several endolithic micro-organisms and organisms. Micro-crystalline structure of this lithotype facilitates endolithic colonization with respect of other calcareous materials with different crystal arrangement (e.g. white marble). The colonization begins with the adhesion and subsequent implantation of microorganisms and juvenile stages of reproduction of organisms. Clionaid sponges are the most aggressive group of bioeroders, widely spread on submerged artefacts. Their action leads to a more or less pronounced loss of material and can cause its total destruction. Even bivalves and sipunculans play an important role in the biodegradation processes eroding large burrows in both tesserae and mortar.

Epilithic colonization mainly composed of encrusting microflora and fauna does not have a protective effect against the endolithic attack because this calcareous layer is affected by bioerosion phenomena.

This study highlights the need to periodically monitor the state of preservation of artefacts, especially of mosaic floors made of small and cubical tesserae that can be faster bioeroded.

To contrast the biological colonization three preservation methods can be used. Submerged artefacts can be covered with geotextiles that create an unfavorable environment for the growth of most of biodeteriogens [58, 59]. In particular Terram geotextiles had been successfully used in Baiae to cover some floors [60, 61]. Reburial is a useful method to protect findings against bioerosion, hydrodynamism, abrasion and anthropic damages, by covering them with a layer of sand, taken from the adjacent seabed [62]. Finally, the restoration of the edges of floors with hydraulic mortars decreases biological attacks by limiting the exposition of the lateral parts. Furthermore it prevents the detachment of fragments like those studied in this work.

Conclusions

This study highlighted the susceptibility to biological degradation of submerged archaeological artefacts, such as mosaic floors. A high level of bioerosion attributable to endolithic microorganisms and organisms was observed. Investigations carried out in this research allowed us to observe cavities and burrows inside the lapideous substrate.

Furthermore a distinction between epilithic and endolithic colonization was reported and the presence of nestling and rasping species was documented.

The results showed that the limestone of the tesserae is a material particularly suitable to endolithic degradation on the basis of its mineralogical features. This susceptibility leads to the need to periodically monitor the state of preservation of the material, in order to prevent irrecoverable damage and to plan conservative interventions.

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