Excavating rates and boring pattern of *Cliona albimarginata* (Porifera: Clionaidae) in different substrata

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Abstract: Eroding sponges create a series of connected chambers and galleries into calcareous substrata where they live. While it is well known that only calcium carbonate is etched by sponge activity, no comparative data are available regarding the different forms of carbonate. In this work we investigate the erosion rates and erosion pattern of the tropical boring sponge *Cliona albimarginata* in different biogenic and non-biogenic calcareous rocks. In particular, we tested portions of the shell of the large bivalve *Hippopus* sp. and of the branches of the stony coral *Acropora* sp. together with different kinds of carbonate stones such as the Carrara marble, the Majolica of the Conero Promontory, the Finale medium-grained calcarenite, the Prun fine-to medium-grained limestone and the homogeneously fine-grained Vicenza limestone. The dissolution rates of the sponge on the different kinds of carbonate are highly variable and these differences are discussed in terms of crystal shape and aggregation, the rock fabric and the presence of other minerals.

Keywords: boring pattern, *Cliona albimarginata*, excavating rates, Indonesia, Porifera

Introduction

Excavating sponges are able to live in carbonatic substrata, perforated by mechanical and chemical activity of specialised etching cells (Rützler and Rieger 1973, Pomponi 1980). The contact of sponge canal system with water is ensured by portions of the sponge, called papillae, protruding from its substratum surface. This growing form known as \( \alpha \)-stage is, in some species, substituted by a complete removal of the substratum such that the sponge becomes a free-living organism (\( \gamma \)-stage). In other cases the epilithic portion continues to develop until the papillae are connected by a more or less thick crust of sponge (\( \beta \)-stage).

The activity of boring sponges has been documented especially in tropical waters, and several authors have shown their ecological role in coral reefs such as their influence on the balance of calcium carbonate stored in the reef (Hutchings 1986), the production of fine sediments (Fütterer 1974), their influence on reef morphology (Goreau and Hartman 1963), and their influence on coral asexual reproduction (Tunnicliffe 1981).

Sponges are able to excavate into both inorganic and biogenic calcareous materials. In some biogenic structures like mollusc shells, organic components, such as concholin, are digested by acid phosphatase released by the etching cell (Pomponi 1980) while the periostracum layer may prevent sponge erosion (Mao Che *et al.* 1996, Kaehler and McQuaid 1999). In the same way living tissue protects corals from sponge erosion as very few species are able to attack living tissue (Tunnicliffe 1979, 1981, MacKenna 1997, Schönberg and Wilkinson 2001, López-Victoria *et al.* 2003, López-Victoria and Zea 2005).

Very few comparative data are available regarding the differences in boring sponge activity in the substrate with different textures. Neumann (1966) suggested that mineralogy of the carbonates does not affect the process while the density of the substrate improves penetration (Highsmith 1982, Rose and Risk 1985, Schönberg 2002). Other physical and biological factors may also affect erosion, such as nutrient availability, temperature, symbiosis with zooxanthellae (Hill 1996), etc.

In this study we investigated the influence of the substrata with similar carbonatic composition but different microtexture and mineralogy composition on the erosion pattern and rate of the coral reef species *Cliona albimarginata* Calcinai *et al.* 2005. In particular we tested: i) metamorphic rocks with medium and regular grain and isorotation of calcitic grains; ii) sedimentary rocks with fine and homogeneous grain; iii) sedimentary rocks with fine and irregular grains; iv) sedimentary rocks with medium and irregular grain and a detrital component.

Materials and methods

Our experiment was carried out in the Bunaken Marine Park (North Sulawesi, Indonesia). Carbonatic blocks of
different mineral composition, texture and porosity were fixed, using wires and nails, on a single large specimen of *C. albimarginata* (about 15 m²) living 5 m deep on the edge of the coral reef (Fig. 1A, B). In this way, avoiding sponge grafts commonly used in this kind of experiment (Neumann 1966, Rützler 1975, Schönberg and Wilkinson 2001), we limited the stress to the sponge due to the handling procedure.

As both light and current enhance boring activity in sponges with zooxanthellae (Hill 1996) we chose a single specimen with the same light exposure and uniform current. The following materials were tested: 15 blocks of coral coming from branches of dead colonies of *Acropora* sp; 15 blocks obtained from the umbo portion of large shells of *Hippopus* sp.; 15 blocks of Carrara marble; 4 blocks of Finale fine-medium grained calcarenite; 5 blocks of Conero fine grained mudstone (Majolica); 4 blocks of homogeneously fine grained Vicenza limestone; 4 blocks of Prun fine-to medium-grained limestone. As control, for each kind of material 5 blocks were placed out of the sponge to evaluate the excavation due to microborers. Before the test, the blocks were dried and weighted. Each block surface was calculated using program Image-J v1.37.

After 200 days the blocks were removed from the sponge, cleaned in hydrogen peroxide (120 vol.), dried and weighed again. Encrusting organisms present on the blocks were manually removed. Sponge erosion rates (Kg/m²/y) were calculated as the difference in weight of the blocks, before and after the experiment, as microerosion due to microboring organisms was negligible.

To study the penetration of sponges together with rock microtexture some blocks were consolidated by epoxy resin, then processed to 30 µm thick section. The mineralogical and petrographic analysis of the biogenic or inorganic substrata was carried out by stereoscopic and transmitted light microscopy.

The mineral composition of substrata was analysed by X-ray diffraction (XRPD) using a Philips PW1140-X-CHANGE diffractometer (CuKα radiation; current 30 mA, voltage 40 kV, scan speed, 0.5° 2θ/min; scan interval, 3-70° 2θ) and interfaced with PC-APD software for data acquisition and processing.

**Results**

The boring rates of *Cliona albimarginata* into the different kinds of carbonates were highly variable (Fig. 2): 29.5 ± 2.2 Kg/m²/y for the Carrara marble; 24.2 ± 2.3 Kg/m²/y for the Finale calcarenite; 24.0 ± 2.6 Kg/m²/y for *Hippopus* sp. (umbo); 15.6 ± 4.7 Kg/m²/y for the *Acropora* (branch); 12.6 ± 2.9 Kg/m²/y for the Conero majolica; 11.01 ± 1.0 Kg/m²/y for the Vicenza limestone and 2.9 ± 1.2 Kg/m²/y for the Prun limestone. The dissolution rate in all the blocks placed outside the sponge, considered as control, was negligible.

Plotting the erosion rate vs specific gravity of the different materials it was possible to observe that for four materials (Vicenza limestone, *Acropora*, *Hippopus*, and Marble) the rate of erosion is directly related to the density of the different rocks while for the Finale calcarenite, the Majolica and the Prun limestone no obvious relationships could be observed (Fig. 3).

The maximum vertical penetration was also variable in different substrata, with the highest penetration in the biogenic substrata and in the marble, while the limestones were harder to penetrate and the Prun limestone was attacked only on the surface (Fig. 4).

The boring pattern produced by *C. albimarginata* was different in the tested substrata (Fig. 5). In the marble the sponge produced vertically elongated excavations, oval in section and tidily organised (Fig. 5A). In the compact *Hippopus* umbo, the sponge produced similar boring patterns in every direction (Fig. 5B). In the porous *Acropora* the sponge largely penetrated the pre-existing canals, producing a fine spongious pattern of erosion (Fig. 5C). In the Majolica the boring activity produced circular tunnels running in an

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**Fig. 1:** Images of the field experiment. A. General view of the experimental set with “Carrara” marble. Scale bar: 5 cm B. A detail of experimental set with *Acropora* sp. Scale bar: 2 cm.
indefinite directions (Fig. 5D). The Prun limestone was only slightly etched with superficial erosion marks (Fig. 5E). The Finale calcarenite was heavily affected by the sponge action that had detached the large biogenic elements (Fig. 5F).

Also at the level of rock microtexture, the activity of etching cells produced different results in the tested materials. *Hippopus* shell has crystals organized in layers that are deformed as kinks. The erosion pattern developed in the laminated layers of the shell produced rounded excavations 0.3 -1 mm that fused into each other to form lobated cavities (Fig. 6A, B).

*Acropora* is made of large rare aragonitic crystals (more than 0.2 mm in diameter). From this compact structure, sheaves with a centrifuge growth pattern of calcite fibres (about 0.002-4 mm long) had originated. The growth of coral was visible because of the parallel arrangement of fibrous radiating structure. The erosion pattern was affected by the isoorientation of the crystals. In fact the sponge produced...
elongated excavations (0.15-1.5 mm) that followed the orientation of the fibrous crystals (Fig. 6C, D).

In the Carrara marble (Fig. 6E, F) the average crystal size is 0.2 mm and the grains are regularly arranged in a mosaic texture. The sponge produced excavations that were regularly spaced following the regular orientation of the crystals. Under a transmitted polarised light, the boundary of the cavity was clearly thinned, and the sites of more pervasive etching exhibited micro-lobes along the external portion of the calcite grain. In fact, excavations can merge but the regular pattern of corrosion is maintained.

The Prun mudstone displays an inhomogeneous texture characterized by fine-grained calcite with patches of coarser sparry calcite and scarce detrital fraction made by chlorite. The rock showed submillimetric fractures filled by clay minerals and hydroxides and clusters of forams occurring as biointraclasts. The erosion pattern was evident only where the sponge met an embedded shell that the sponge reached through a fracture filled by coarse grained spatic calcite (Fig. 6G, H).

The Vicenza limestone is a biodetritic rock with the grain size varying irregularly between 0.004 and 0.1 mm. It contains forams, bivalve shells and sea urchin fragments, together with iron oxides and hydroxides. The primary porosity was distributed irregularly. The erosion pattern of the sponge was very irregular (Fig. 6I, J).

The Finale calcarenite is composed of fine-medium-grained detrital limestone, rich in detrital fossiliferous content and terrigenous minerals (quartz, lithic fragments) in sparry cement. As a consequence the texture within recrystallized areas showed irregular granulometry. Calcite grains present in the cement were between 0.01 and 0.2 mm of diameter. The sponge avoided the cement. The erosion pattern showed merging lobate excavations that led to irregular and wide galleries (Fig. 6K, L).

The Conero majolica mudstone is fine-grained (< 0.01 mm) and pervasively recrystallized. It includes nannofossils and scarce impurities of detrital quartz. The calcite crystals are fine but coarser than those found in the Prun mudstone. The erosion pattern produced lobate cavities with stochastic directions (Fig. 6M, N).

Discussion

Even if Cliona albimarginata exclusively perforates corals in the field, it is able to bore a wide variety of both mineral and biogenic substrates. The sponge had excavated all the substrata used with different intensity.

The microtexture of rock substrata affects the microscopic pattern of erosion. Observation by optical techniques (transmitted light microscopy) reveals that the erosion pattern of sponge erosion may be affected by the mineral setting (i.e. rock fabric) of the substrate. In fact, the sponge produces excavations that follow the preferred orientation of fibrous calcite crystals (Acropora), or the parallel lamination within the Hippopus sp. shell. Conversely, the anisotropic granoblastic and mosaic texture of Carrara marble turns out to be etched with preference along the flow schistosity. Within a fine-grained, virtually isotropic material such as limestones (Conero Majolica or in Vicenza limestone), the general behaviour of the sponge is to etch the rock with irregular, randomly oriented, erosion patterns.

The boring pattern is also affected at macroscopic scale by the characteristic of the substrata such as crystal preferred orientation (e.g. marble), pre-existing cavities (e.g. Acropora) or the presence of silicatic fragments (e.g. Prun limestone). For example in the compositionally homogeneous, massive, flow oriented, medium grained marble, the sponge produces vertically elongated excavations, oval in section and regularly organised. This suggests that dissolution is driven by crystal organisation. In the Acropora skeleton the sponge widely uses
the pre-existing canals producing a fine spongious pattern around the principal tunnels (Fig. 5C). The regular pattern is lost in the Finale stone because the sponge detaches the large biogenic elements. In this way the substratum appears to be widely destroyed. In the Prun stone, chambers or tunnels are not detectable because the rock is only slightly etched with superficial erosion due to the presence of silicatic fragments in the stone that are not excavated by the sponge.

Some authors (Hoeksema 1983, Bromley and D’Alessandro 1984) report that the macroscopic pattern of excavation, produced by a sponge species, may be different because of its substrate dimension or its age. Other authors (Rützler 1974, Schönberg 2000) have demonstrated that this character might be useful to differentiate among various species. Our data demonstrate how the previous cited characteristics of the substrata may affect the macroscopic erosion pattern produced by the boring sponge. In this way the use of the erosion pattern as a taxonomic tool requires some caution.

Also the erosion rates are affected by the characteristic of the substrata. *C. albimarginata* is a highly destructive species. It may erode 300 - 400 kg per year of corals supplying a corresponding amount of fine sediments to the bottom. These values are similar to those of a few other excavating sponges (Schönberg 2002). Neumann (1966) studied the

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**Fig. 5:** Macroscopic boring pattern of *Cliona albimarginata* in the tested substrata. **A.** Vertical, tidy organised excavations in the compact marble. **B.** A boring pattern, similar in both directions is produced in *Hippopus* sp. umbo. **C.** A fine spongious pattern produced by *C. albimarginata* that uses in *Acropora* the pre-existing canals of the coral. **D.** Tunnels, circular in section and running in indefinite direction in the Majolica. **E.** Superficial erosion marks are produced by *C. albimarginata* in the Prun stone. **F.** *C. albimarginata* detaches the large biogenic elements in the Finale stone, that is strongly eroded. Scale bars: 1 cm.
Fig. 6: Polarized light microphotographs. 

A. Longitudinal section of perforated Hippopus sp. The texture is microcrystalline; the fine-grained crystals are optically discontinuous and define a layered fabric of the shell, having kinked or sheaf textured appearance inside the laminae. The erosion proceed from the outer (large cavities) to inner layers (finer cavities) of the shell, following the shape of calcite grains. 

B. Longitudinal section of perforated Hippopus sp. The stratified structure is evidenced by the contrasting orientation of crystals. Inside the cavities a detrital fraction is preserved, most likely deriving from the mechanical action of the sponge. 

C. Acropora sp. exhibits an inner fabric characterized by fibrous calcite (about 0.1 mm long) elongated towards the top of the organism. The erosion pattern is sinuous and cavities are oblate and generally parallel to the fibre length. In the cavities, a fine grained detrital fraction, most likely deriving from the mechanical erosion, is preserved. 

D. Open cavity in Acropora sp.: the overall shape is elongated with sinuosity with lobate boundaries. 

E. “Carrara” marble has homogeneous granoblastic mosaic texture. The cavities are rounded with apparently lobate boundaries like “bites”. 

F. Close up of the rock-hole area in “Carrara” marble: the calcite grain is thinned and corroded with lobate geometry. A detrital fraction is preserved in the cavity. 

G. The Prun fine-grained limestone is a mudstone (bioclasts < 10%). 

H. The erosion on the Prun limestone was restricted to coarse grained bioclasts (bivalve shell fragment), made of sparry (i.e. coarser than matrix) calcite. 

I. The Vicenza limestone is characterized by abundant bio- and intraclasts cemented by sparry calcite. The excavations are regularly dispersed, rounded to sub-rounded and flattened when two rounded holes merge. 

J. Detail of an excavation in the Vicenza limestone: the boundaries are finely lobated, with selective etching at the expense of sparry calcite. 

K. Microtexture of the Finale calcarenite. The rock is mostly formed of sparry cement including the terrigenous fraction. The excavation is developed in a patch of sparry calcite. 

L. Detail of an excavation etched in an organic fragment, made of sparry calcite. 

M. The “Conero” Majolica is made of nannofossils in a very fine-grained micrite matrix (mudstone). 

N. Erosion pattern in the “Conero” Majolica. Subrounded excavations tend to merge. Top, centre: a relic mudstone septum is almost isolated within a cavity. Scale bars A-D, G-N: 1 mm; E-F: 0.5 mm.
boring activity of Cliona lamp a on substrata with a different mineralogy (calcite or aragonite) concluding that the density of the substrata is important to determine the value of the erosion rates. This is due to the fact that the sponge in a porous material first occupies the available spaces before excavating resulting in reduced erosion rates. Schönberg (2002) came to a similar conclusion for C. orientalis. Our data suggest a more complex scenario where density is only one of the factors affecting erosion rate. Here we have shown that there is a group of substrata where the erosion rate is directly related to substratum density. Nevertheless, other characteristics of the substratum are involved in this phenomenon. High values of erosion rates are obtained for the Finale calcarenite in spite of its low density due to the removal of entire large clasts of the biogenic fraction during the erosion activity. On the contrary, the presence of silicatic fragments in the substrate, that are not excavated by the sponge reduces the erosion rate in the Prun stone. Also the size of the crystals affects the erosion rate. In fact the low erosion rate showed by the Majolica in spite of its high density (Fig. 3) is quite likely related to the randomly oriented very small grains.

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