EARLY MARINE CEMENTATION IN SKELETAL SANDS AND THE CONTRAST TO DIAGENESIS IN NON-SKELETAL GRAINS

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KEY FINDINGS

- Cementation in skeletal sands occurs more slowly than in non-skeletal grains, likely due to differences in microbial associations. Non skeletal grains, such as peloids and ooids, commonly harbor microbial communities that promote early cementation. Other contributing factors include differences in porosity, organic content and heterogeneity of the grains.
- Similarly to non-skeletal grains, microbially mediated micritic contact cement are the earliest to form, followed by later stage isopachous and acicular cements.
- Due to the slower rate and reduced abundance of early cementation in skeletal sands, they are likely to preserve more primary porosity compared to non-skeletal sands.

PROJECT RATIONALE

One of the earliest products of marine cementation are grapestones and intraclasts in ooid shoals. In vitro experiments in the presence and absence of indigenous microbiota in ooids show that these early grapestone-producing cements is primarily assisted by exudates of microbial EPS, microbial filaments and metabolic activities within the sedimentary grains (Diaz et al. 2022). The newly formed microbial cements in intergranular areas are the result of both active (microbial metabolism) and passive mechanisms, supported by the degradation of the EPS matrix. This matrix acts as a template for the formation of ACC nanograins that develop along the edges of EPS and/or on microbial cell walls, which also act as matrices for crystal nucleation and growth (Diaz and Eberli, 2022). In skeletal sands, grapestones and intraclasts are very scarce, indicating that this early marine cementation is not as effective in skeletal sand as it is in ooid shoals. We hypothesize that this is the direct result of potential differences in both bacterial abundance and microbial community composition. To test this hypothesis, we repeated the in vitro experiment conducted with ooid sand with skeletal sand from the Florida Reef Tract. Given that ooids harbor an astonishing rich diversity of micro-organisms we expected cementation of skeletal grains to occur at a reduced rate.

THE IN VITRO EXPERIMENT

The skeletal sand for this experiment were collected offshore Marathon Key in the Florida Reef Tract. The experimental set-up was identical to the *in vitro* experiment of the ooid sands with the exception that we extended the experiment from 60 to 120 days (Figure 1; Diaz et al. 2022). The skeletal sands were

separated into two cohorts, one cohort was sterilized to ensure microbial free conditions in the skeletal sand. The other sample set consisted of skeletal grains

with their native flora. The packed grains were sealed with two porous disks, permitting the inflow/outflow of seawater through the sleeve. A continuous inflow of sterilized seawater (seawater not enriched with nutrients) was applied. The samples were subject to alternating cycles of daylight and dark conditions to allow 12 hours photosynthetic processes and 12 hours darkness to stimulate heterotrophic activity under low oxygen conditions (Figure 1). Four sample sets were to monitor the progress in one-month intervals. Microscopic examinations, assisted by stereomicroscopy, and scanning electron microscopy (SEM) provide the first results of this ongoing experiment.

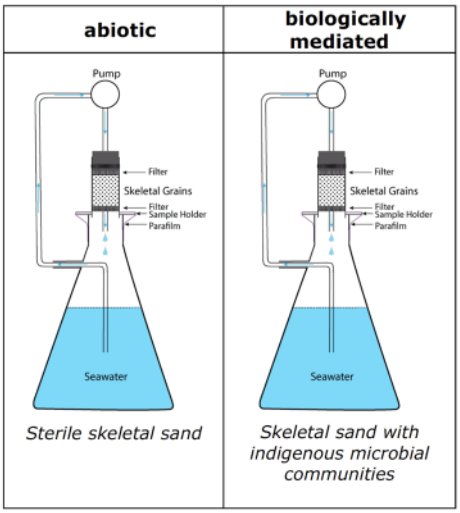

Figure1: Experimental setup

RESULTS

Under the stereoscope the skeletal sand from the Florida Reef Tract produced no visible grain aggregation in 30 and 60 days in neither the treated (sterile) not the skeletal grains with the indigenous microbial community (Fig. 2).

Inspection of the untreated, microbial community bearing skeletal sands under the SEM at 0 days show rod shaped bacteria, EPS producing diatoms, and thin

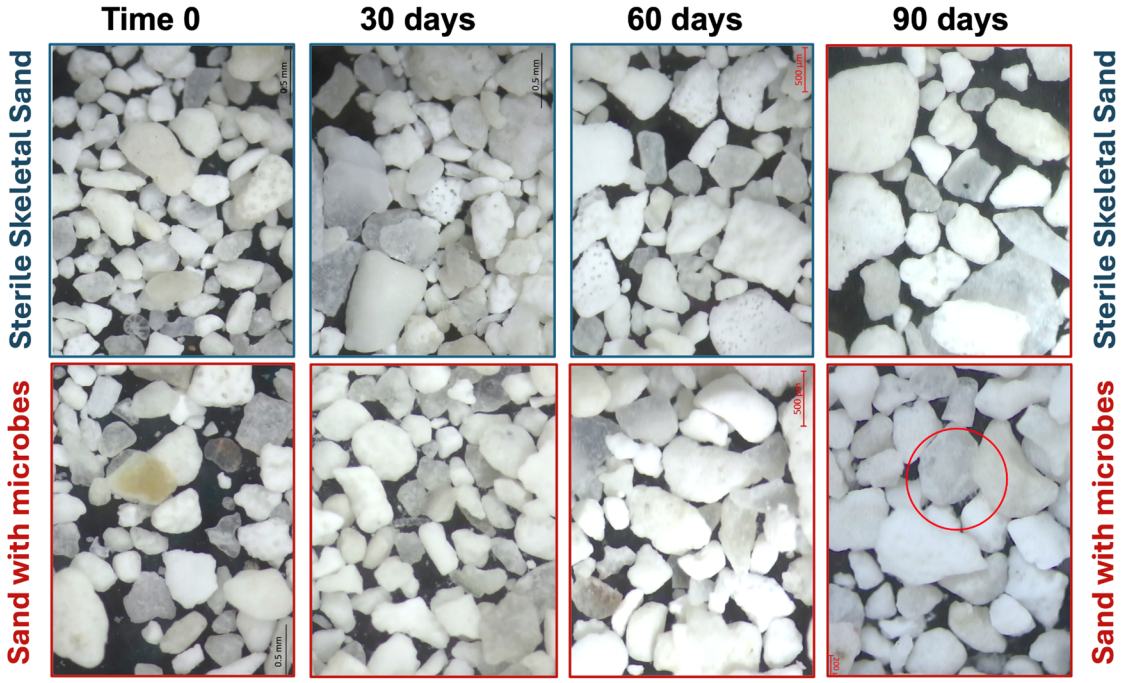

Figure 2: Stereoscope photographs of skeletal sand from the start of the experiment (time 0) and after 30, 60, and 90 days of incubation. The top row are the treated sterile samples (bleached and autoclaved. The bottom row depicts skeletal sand with their indigenous microbial community preserved. No cements are visible in both sample sets up to 60 days. After 90 days some grain fusion and thin cements are visible (red circle).

EPS filaments (fibrils) in pores of the skeletal fragment. In contrast, no organic material is present in the treated sterile sands. At 90 days, barely any cement is detected in the treated sterilized samples, whereas the untreated skeletal grains containing indigenous microbes show initial cement formation at grain contacts (Fig. 3). The contact cements range from a few to tens of microns in size and occur only in specific locations, rather than along the entire grain contact. This is in sharp contrast with the amount and size of micritic contact cements that forms in ooid sands after only 30 days (Fig. 3).

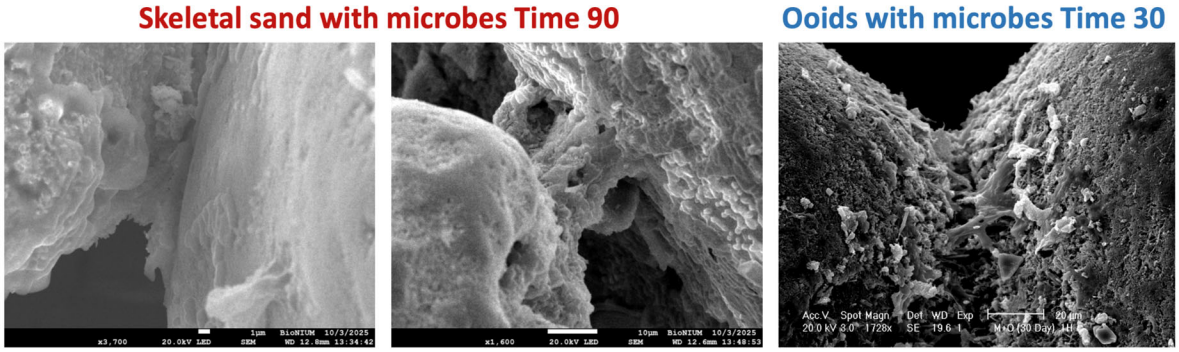

Figure 3: SEM images of micritic bridging cements after 90 days of incubation with skeletal sands (left two images) and after 30 days in the ooid experiment. Note the sparse and small content of cements in the skeletal sand after 90 days, in contrast to the more abundant cements observed in the ooids after only 30 days.

DISCUSSION AND IMPLICATIONS

In a landmark study, Grammer et al. (1999) quantified rates of syndepositional marine cementation by deploying different types of carbonate sand in deeper platform environments in the Bahamas. In the paper only the cement rates of the ooid sands are reported and these fast rates are generally used for modeling of diagenetic processes. The cementation of the skeletal sands in his experiment was less pervasive but occurred in patches in the sample and was not reported. It was, however, the first indication that cementation is not solely determined by the saturation state of the water and other factors such as the configuration of the substrate/grain or the microbial load might play an important role.

To test if the indigenous microbial community within the ooids is responsible for the cementation, we conducted experiments with two cohorts of samples from an active ooid shoal (Diaz and Eberli, 2022). In one sample set, which was sterilized to remove the organic matter and microbial community, no early cements formed during the 60-day experiment. In the other sample set with the indigenous microbial community contact cements formed. The newly formed microbial cements were the result of both active (microbial metabolism) and passive mechanisms, involving an amorphous ACC phase that forms along the edges of decaying EPS and/or microbial cell walls acting as matrices for crystal nucleation and growth (Diaz and Eberli, 2022). This new experiment with the same experimental setup tested if the surface microbial load on skeletal carbonate grains is sufficient to produce the same amount of early cement. As predicted, the rate and extent of cement formation are significantly lower in skeletal carbonate sands compared to the ooids (Fig. 2). This suggest that

microbial communities within the ooids are likely responsible for the rapid cementation and fusing of ooid grains, ultimately leading to the formation of grapestones. Besides potential differences in microbial communities, the higher porosity, heterogeneity and irregular morphology of skeletal grains – in contrast to the smooth, rounder surface of ooids – may further contribute to the slower and more uneven development of early precipitates in skeletal grains.

The differences of cementation of non-skeletal microbe-bearing grains (ooids) versus skeletal grains with little to no microbial load are also visible in the lithified seafloor of shallow water areas. Thin sections from the lithified pavement with

Figure 4: Comparison of amount of cementation in an oolitic hardground and the skeletal pavement in Hamelin Pool. A) Abundant microbial micritic cements and subsequent acicular cements form the hardground at the southern end of the Tongue of the Ocean. B) In contrast, the pavement in Hamelin pool is made of coquina that are cemented by sparse micritic microbial cements and very little crystalline cements (not present in this sample).

skeletal grains (coquinas) in the Hamelin Pool show very little cement while oolitic hardgrounds from the southern end of Tongue of the Ocean in the Bahamas display extensive micritic and acicular cements (Fig. 4). In both cases, however, the earliest cements are micritic cements followed by acicular aragonite cements (Diaz and Eberli, 2022).

The variable rate and amount of early marine cements potentially have implications for reservoir quality. The reduced amount of early cement in skeletal carbonate shoals could preserve more primary porosity and allow for a higher permeability. Even when marine and burial diagenesis continues, the originally preserved porosity renders a rock with high permeability as is documented in Miocene skeletal grainstone succession on the Marion Platform (Ehrenberg et al., 2004).

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