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Beachrock formation via microbial dissolution and re-precipitation of carbonate minerals

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ABSTRACT

Cementation of beach sand in the intertidal zone produces beachrock, such as that found on Heron Island (Heron Reef, Great Barrier Reef, Australia). Although common to coastlines in many low-latitude beach environments, the cause of cementation is not fully understood. In this investigation, electron and X-ray fluorescence microscopy were used to characterize previously undocumented features of beachrock. Two generations of beachrock were examined as a means of understanding the progression of cementation. Meniscus-shaped attachments at point contacts appear to be the first cements to form in biofilms near the beachrock surface. This is followed by isopachous fringe cements within the now 'enclosed' beachrock, composed of aragonite needles that are enriched in strontium and contain extracellular polymeric substances (EPS). Cement precipitation is driven by locally high concentrations of cations in solution, undoubtedly generated via microbial dissolution of the detrital carbonate grains. Binding to negatively charged bacterial EPS retains these cations within beachrock microenvironments. The metabolism of cyanobacteria and associated heterotrophs induce the supersaturating conditions needed for cement precipitation. Deeper within beachrock (mm to cm-below the surface), abundant microbialites are found on the edges of grains and contain trapped and bound detrital material. These structures are laminated, enriched in strontium in some layers, and contain microfossils. The results of this investigation clearly demonstrate a biological influence in the precipitation of aragonite cement involving internal recycling of cations through microbial dissolution and precipitation of carbonate minerals.

1. Introduction

Beachrock is the product of lithification of beach sediment by carbonate cement in the intertidal zone of low-latitude coastlines (Hanor, 1978; Neumeier, 1999; Vousdoukas et al., 2007). Beachrock outcrops typically exhibit the bedding, seaward dip (~5–15°), and sedimentary structures of the parent beach sediment (Davies and Kinsey, 1973; Krumbein, 1979; Vousdoukas et al., 2007). Beach sediment becomes consolidated to form beachrock through the precipitation of aragonite or high-Mg calcite cements, which can exhibit isopachous, meniscus, and pendent fabrics (Scoffin and Stoddart, 1983). Several studies have demonstrated that beachrock cementation can occur on the timescale of a few years (Frankel, 1968; Easton, 1974; Chivas et al., 1986; Vousdoukas et al., 2007). Relict beachrock has been used as an indicator of Quaternary shorelines and sea levels (Ramsay and Cooper, 2002; Tatumi et al., 2003; Vousdoukas et al., 2007; Mauz et al., 2015). The formation of beachrock greatly alters beach morphodynamics and shallow marine hydrodynamics by altering the patterns and rates of sediment deposition and erosion, as well as the focus of wave energy (Vousdoukas et al., 2007). In some cases, beachrock prevents erosion of shorelines by shielding unconsolidated beach sediments from wave action and reducing wave energy (Kindler and Bain, 1993; Chowdhury et al., 1997; Dickinson, 1999; Calvet et al., 2003). Beachrock alters longshore sediment supply by locking sediment into place, resulting in excess erosion of sediment on the seaward side of beachrock and in some cases leading to the formation of a gutter immediately in front of the beachrock (Cooper, 1991; Larson and Kraus, 2000; Sumer et al., 2005).

In spite of being the focus of many previous studies, the process(es) responsible for beachrock cementation remain(s) enigmatic. Proposed physicochemical methods of beachrock formation include direct cement precipitation from meteoric water (Russell and McIntire, 1965) or marine water (Alexandersson, 1969; Alexandersson, 1972; Magaritz et al., 1979; Gischler and Lomando, 1997), mixing of marine and meteoric waters (Moore, 1973; El-Sayed, 1988), evaporation (Ginsburg, 1953), and degassing of CO_2 (Meyers, 1987; Dickinson, 1999). Microorganisms, known to play an important role in carbonate

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mineral precipitation in a variety of environmental settings, may also play a role in the formation of beachrock (Krumbein, 1979; Novitsky, 1981; Webb and Jell, 1997; Neumeier, 1999; Webb et al., 1999). Ureolytic bacteria have previously been used to induce small-scale beachrock formation, however, the conditions utilized in these experiments did not account for key components of the natural beachrock formation environment, such as the presence of phototrophs, natural nutrient concentrations, tidal activity, and diurnal light cycling (Danjo and Kawasaki, 2013; Khan et al., 2016). The structure and mineralogy of beachrock enables it to host a range of lithophytic microorganisms, including euendoliths, cryptoendoliths, chasmoendoliths, epiliths, and hypoliths (Golubic et al., 1981; Webb et al., 1999; Cockell et al., 2005). These habitats provide microenvironments wherein microorganisms can interact with their lithic host.

Reasonable ideas have been reported previously in support of each of the proposed beachrock formation mechanisms, but no one mechanism is able to explain the formation of every beachrock outcrop. In many cases beachrock generation is attributed to a combination of factors. Early studies concluded that microbial activity does not play a major role in cementation of the beachrock on Heron Island, Great Barrier Reef (GBR) (Davies and Kinsey, 1973). The beachrock on Heron Island is primarily cemented by isopachous, acicular aragonite; however, more recent investigations have found additional micritic cement in association with microbialites (Webb et al., 1999). Microbialites are organo-sedimentary structures in which sediments are trapped, bound, and/or precipitated within microbial biofilms (Burne and Moore, 1987), and are found within the beachrock on Heron Island (Webb and Jell, 1997; Webb et al., 1999). The apparent nucleation of this micritic cement on a framework of organic material suggests microbially induced precipitation was a factor in its formation (Webb et al., 1999). An important question in regards to abiotic explanations is: why is beachrock not more evenly distributed if the physicochemical conditions common to all carbonate beaches are all that is required for its formation? In this investigation, high-resolution electron microscopy and synchrotron-based X-ray fluorescence microscopy (XFM) were used to characterize the structure and chemistry of cements in beachrock samples from Heron Island. The Maia detection system deployed at the Australian Synchrotron XFM beamline enables fast, high definition elemental mapping of complex natural materials (Ryan et al., 2010; Paterson et al., 2011; Ryan et al., 2014). The purpose of this study is to characterize the structure and chemistry of beachrock cement, and address the possibility that endolithic microorganisms play a critical role in the cementation of these coastline deposits.

2. Materials and methods

2.1. Heron Island beachrock

Heron Island is a sand cay on Heron Reef, which is a lagoonal platform reef in the Capricorn Group in the southern GBR (Fig. 1) (Jell and Webb, 2012). The island is ~750 m by ~240 m in size, while the reef is 10 km long with a maximum width of 4.5 km (Webb et al., 1999). Beachrock occurs on the northern and southern beaches of Heron Island and outcrops are as much as 20 m in width, with seaward dip angles of 4–16° (Fig. 2A). Multiple stages of beachrock formation have occurred on Heron Island, as is well demonstrated along the south-eastern shoreline, with pebble to boulder sized blocks of older beachrock occurring cemented within younger generations of beachrock on the edge of the outcrop furthest from the ocean (Fig. 2B). Microorganisms inhabit the beachrock in the form of epilithic mats on the surface (Fig. 2C), as euendolithic communities boring into sediment grains, and as cryptoendolithic communities in the interstices within the beachrock (Fig. 2D). Pike et al. (2015) found that although the microbial community composition varied by location in the beachrock, it is typically dominated by non-heterocystous cyanobacteria. For the present study, samples were collected to include both the older re-cemented blocks and an associated younger beachrock that held the older blocks in place at the time of sampling (Fig. 2B).

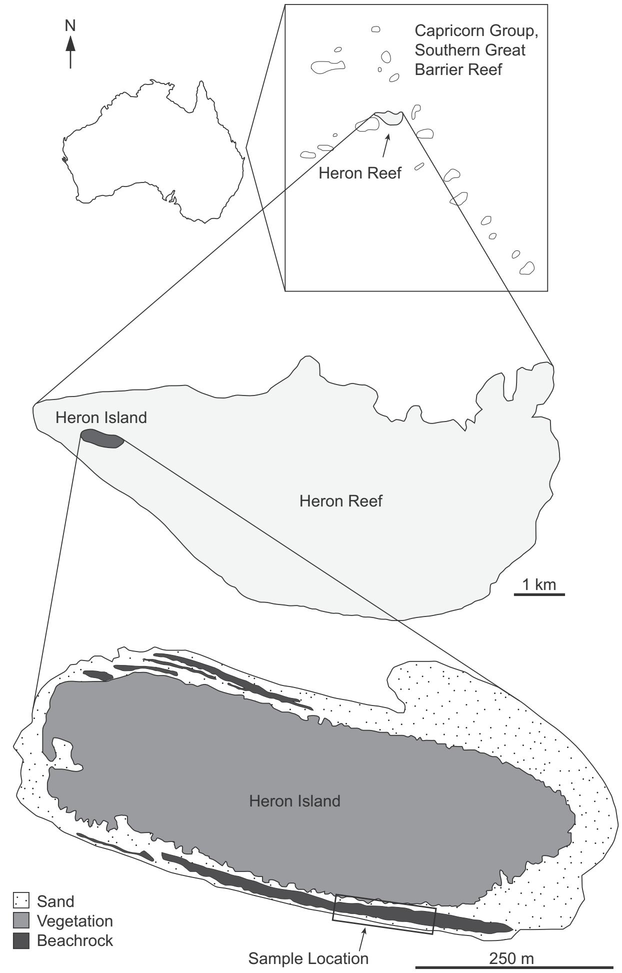

Fig. 1. A composite map highlighting the location of Heron Island, a sandy cay on Heron Reef, in the Capricorn Group of the southern Great Barrier Reef off the east coast of Australia (Google Earth, 2014). Representative samples of beachrock were collected from the south shore of Heron Island (see box on lower image) to examine less consolidated (younger) versus more consolidate (older) beachrock cements.

2.2. Electron and optical microscopy

Polished thin-sections and small pieces of beachrock were characterized using scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDS) using a Zeiss Leo 1540 XB microscope equipped with an Oxford Instruments INCA x-sight energy dispersive spectrometer for elemental analysis, as well as a JEOL JSM-7100F Field Emission SEM (FE-SEM). Whole pieces of beachrock (~5 mm in diameter) were fixed using 3% glutaraldehyde and dehydrated through an ethanol dehydration series (25%, 50%, 75%, 100%, 100%, 100%) before being critical point dried. The whole samples were mounted on stainless steel pin stubs using adhesive carbon tabs. Thin sections were coated with 10 nm osmium using a Filgen OPC80T osmium plasma coater prior to examination using back-scattered electron (BSE-SEM) mode at 10 kV and a working distance of 12 mm. Whole mount samples were coated with 5 nm of osmium, and analyzed using secondary electron SEM at 1 kV and at a working distance of 4 mm. Polished thin-sections of beachrock were observed using plane and cross-polarized optical microscopy using a Leica DM6000M microscope equipped with a Leica DFC310 FX camera as a means of characterizing grain contacts in the two generations of Heron Island beachrock.