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Feedbacks between flow, sediment motion and microbial growth on sand bars initiate and shape elongated stromatolite mounds

G. Mariotti *, J.T. Perron, T. Bosak

Department of Earth, Atmospheric and Planetary Sciences, MIT, Cambridge, MA, United States

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ABSTRACT

Elongated stromatolites are often used as indicators of current direction and shoreline orientation, especially in paleoenvironmental reconstructions. However, mechanisms that create shore-parallel, m-scale elongated stromatolite mounds in carbonate sand are not well understood. We propose that this geometry is initiated by microbial growth on the parts of sand bars that experience low wave-induced bed shear stresses. We test this idea by growing microbial mats on carbonate sand bars in a laboratory wave tank. Cyanobacterial mats grow on the bar runnels, where sediment motion is negligible, but are absent from the bar ridges, where the waves generate migrating ripples. When microbially-promoted lithification reinforces and preserves this initial pattern, elongated stromatolites should initiate in the runnels of sand bars, with long wavelengths (5–100 m) and small width-to-wavelength ratios (∼0.3). These dimensions are consistent with modern shore-parallel stromatolites in Hamelin Pool, Western Australia, and with patterns of microbial colonization in other sandy sediments. This model of elongated stromatolite mounds can inform paleoenvironmental reconstructions by clarifying and quantifying feedbacks among waves, sediment transport and microbial growth.

1. Introduction

Stromatolites are laminated sedimentary structures that exhibit a variety of macroscopic shapes, including domes, cones, clubs, cylinders, sheets and elongated mounds. Most columnar and elongated stromatolite morphologies larger than a centimeter have accreted in the presence of waves, currents and moving sediments (Altermann, 2008; Bosak et al., 2013a; Sakurai et al., 2005). However, it is not clear whether and how the sizes, shapes and spacings of these stromatolites reflect interactions between waves, currents, sediment motion and the growth of microbial mats, nor is it clear how microbes and stromatolites grow in areas where sediments are often mobilized (Bosak et al., 2013a; Tice et al., 2011; Gebelein, 1969).

Stromatolites with an elongated form present an especially intriguing case of interactions between microbial growth and the physical environment. If the factors that generate this elongated form are understood, elongated stromatolites could be used to infer the orientations of paleoshorelines, the directions of current-dominated and wave-dominated flows, and the feedbacks between microbial growth, hydrodynamic conditions and sedimentary landscapes in carbonate systems through time (Bosak et al., 2013b). For example, ancient marine stromatolites from upper intertidal areas are often elongated perpendicular to the shore, and are thought to be shaped by currents that drain the tidal platform (Logan, 1961; Hoffman, 1967, 1974; Gebelein, 1969; Playford, 1980; Truswell and Eriksson, 1973; Eriksson and Truswell, 1974). The formation of ancient shore-parallel elongated stromatolites has similarly been attributed to shore-parallel currents (Young and Jefferson, 1975; Young and Long, 1976; Jefferson and Young, 1989), even though modern stromatolite-forming environments offer little evidence of these currents.

Stromatolites forming in modern environments are particularly useful for understanding the environmental conditions and factors that shape stromatolites. Hamelin Pool, a ∼20 km wide hypersaline embayment in Western Australia (Jahnert and Collins, 2013), harbors stromatolites that form by trapping and binding sand and by microbial precipitation of carbonate minerals (Reid et al., 2000). Large cylindrical stromatolites have grown on steeper platforms (slope of 40 m/km) at headlands (Fig. 1C), whereas shore-parallel elongated stromatolite mounds (Fig. 1A, B, D) are found on gently sloping platforms (2 m/km) in bights (Fig. 1C) (Jahnert and Collins, 2013). These mounds have a wavelength (the distance between two adjacent rows) of about 10 m and a width-to-wavelength ratio of about 0.3. Closer to shore, the shore-parallel mounds transition in few tens of meters to elongated forms that are shore-perpendicular (Fig. 1B) and have a narrower wavelength of ∼2 m and a larger width-to-wavelength ratio of ∼0.65 (Fig. S1, Supplementary Information). These differences in the geometry and

* Corresponding author.

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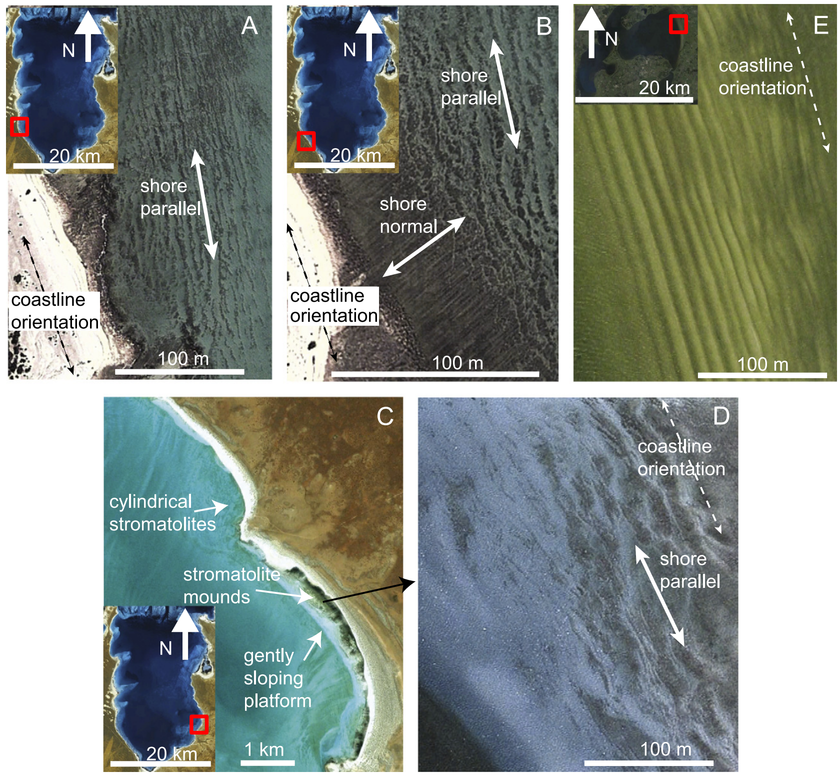

Fig. 1. Elongated features parallel to modern, gently-sloping coastlines. (A, B, D) Large elongated stromatolites are approximately parallel to the coastline in Hamelin Pool, Western Australia. These stromatolite mounds are about 2 m wide and have a wavelength (the distance between two consecutive rows) of about 10 m. Images from Google Earth (recorded 6/17/2012, DigitalGlobe). Note in (B) the presence of shore-normal elongated stromatolites with a wavelength of few meters in the upper intertidal area. (C) Cylindrical stromatolites are found at headlands characterized by a steep platform (40 m/km); stromatolite mounds are found at bights characterized by a gentle sloping platform (2 m/km) (Jahnert and Collins, 2013). Image from Google Earth (recorded 12/20/2006, DigitalGlobe). (E) Sand bars in Lovns Bredning Bay, Denmark, a bay similar in size to Hamelin Pool. Image from Google Earth (recorded 7/30/2005, Scankort).

orientation of stromatolites imply either that the currents change abruptly from shore-parallel to shore-normal, or that factors other than currents shape the widely spaced stromatolites on the gently sloping platform. Because the shore-parallel stromatolites in Hamelin Pool are approximately parallel to the prevailing wind direction, their formation has been attributed to an unknown wind-induced process (Playford and Cockbain, 1976), possibly a Langmuir circulation (Playford, 1980), which consists of helicoidal cells aligned with the wind direction at the water surface. However, Langmuir cells drift crosswind within tens of minutes (Gargett and Wells, 2007), i.e., much faster than the minimum time of a few weeks required to establish visible microbial mats that protect sandy sediments from erosion (Fang et al., 2013). Thus, factors responsible for the formation of elongated of stromatolites with a wavelength of approximately 10 m in Hamelin Pool, or even larger elongated stromatolite mounds in the geologic record (Truswell and Eriksson, 1973; Eriksson and Truswell, 1974; Hoffman, 1974; Young and Long, 1976; Beukes, 1987) remain unclear.

Here, we consider the similarity between shapes and sizes of modern sand bars and shore-parallel elongated stromatolites and hypothesize that interactions among microbes, waves and the motion of carbonate sediments on sand bars control the geometry of widely spaced, elongated, shore-parallel stromatolites. Intertidal sand bars, or sand waves as defined by Masselink et al. (2006), consist of elongated ridges and runnels that are generally parallel to the coastline, and are found in low wave energy settings characterized by gentle bed slopes (∼10 m/km) and moderate fetches (5–50 km) (Evans, 1950; Dolan and Dean, 1985; Elgar et al., 2003; Masselink et al., 2006). Sand bars are regularly spaced, have a wavelength of 5–100 m and an amplitude of ∼0.5 m, and can be found in configurations with tens of rows (Fig. 1E). Sand bars form through a positive feedback between hydrodynamics and morphodynamics. When a partially standing water wave is present over a flat bed, the Lagrangian drift near the bottom of the boundary layer converges toward the nodes and diverges from the antinodes of the surface wave, while the opposite occurs near the top of the boundary layer (Mei, 1985). As a consequence, sand grains transported as bed-load accumulate below the nodes, generating sand bars with a wavelength that is one half of the surface wave (O'Hare and Davies, 1990; Yu and Mei, 2000). If smaller particles are present and are transported in suspension, they accumulate below the wave antinodes (Landry et al., 2007). A feedback exists because standing or partially standing waves are generated by wave reflection over the sand bars (Davies, 1982; Mei, 1985; Heathershaw, 1982). For a fully standing wave, sand bars have ridges centered below the wave nodes, where the horizontal velocities are maximized, and runnels centered below the wave antinodes, where the horizontal velocities are minimized. For a partially standing wave, bar ridges and runnels are slightly shifted seaward with respect to the wave nodes and antinodes (Hancock et al., 2008).

We hypothesize that the lower shear stress, reduced sediment motion and accumulation of fine sediments in the runnels of carbonate sand bars can allow microbial growth and lithification in these areas. At the same time, sediment motion in sand bar ridges prevents microbial colonization. This spatial pattern of microbial growth initiates shore-parallel elongated stromatolites that form by microbial trapping and binding of sediments and lithification. We test this hypothesis by growing microbial mats on active sand bars in a laboratory setting. We perform experiments with a fully standing wave, and then apply a simplified hydrodynamic model to extend the results to the case of a partially standing wave. Finally