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The influence of microbial mats on the formation of sand volcanoes and mounds in the Red Sea coastal plain, south Jeddah, Saudi Arabia

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ABSTRACT

Extensive areas covered by microbial mats have been found in the upper intertidal flats and supratidal pools in the Red Sea coastal plain of south Jeddah, Saudi Arabia. Numerous microbially controlled sediment-surface morphologies are evident, such as flat cohesive mats that commonly pass into mats with wrinkles, reticulates, and tufts, together with erosion pockets and mat chips. These microbial mats form cohesive surface layers that lead to biostabilization of the sediment surface. Fluidization of the underlying sediments is due to tidal influences and pressurized gas escape from decay and photosynthesis of microbial mats and causes deformation and rupture of the cohesive surface mat layer via vertical and sub-vertical pipes. Extrusion of fluidized sediments and water through these pipes leads to redeposition of sediment grains above the surface mat layer to form sand volcanoes and mounds. Most of the sand volcanoes present in the intertidal flats and supratidal pools show a symmetrical morphology, whereas in tidal channels asymmetrical forms are more common. Extrusion of underlying sediments through several adjacent vents leads to coalescence of sand volcanoes to form sand mounds. In this study sand volcanoes are also compared with other cone-like features from the Red Sea, such as gas domes and crab mounds. This comparison should help in differentiating similar cone-like features associated with microbial mats in the rock record.

1. Introduction

This paper investigates the potential relationship between microbial mats and extruded sediments (sand volcanoes and mounds formed by sand injection) in the upper intertidal flat and supratidal pools of coastal areas along the Red Sea, south of Jeddah, Saudi Arabia (Fig. 1). Microbial mats form the overlying, confining layer above the source bed, which contributes to the origin and geometry of the extruded sediments (referred to as extrudites; Hurst et al., 2006; Ross et al., 2013). Subrecent carbonate and siliciclastic sediments form the source layers that supply the extruded sediments. An upward directed force of hydraulic pressure from tides, plus the organic gases produced by decay and photosynthesis of microbial mats locally provides a potential for fluidization of the source sediments and wetting of the exposed microbial mats during dry periods. In this case the study is simplified by the presence of an underlying hardground, approximately 30 cm below the growth surface, which isolates the more recent depositional and diagenetic development from older structures.

Microbial mats are thick, carpet-like organic colonies consisting of biofilms together with prokaryotic and microscopic eukaryotic organisms which may cover many kilometers of tidal, lagoonal, lacustrine, continental shelf and other settings offering biologically available water and temperatures (Stolz, 2000; Krumbein et al., 2003; Porada et al., 2007; Bose and Chafetz, 2009; Franks and Stolz, 2009; Noffke, 2010; Cuadrado et al., 2012; Farías et al., 2014). These organic colonies enhance the stability of sediments as they secrete extracellular polymeric substances (EPS; Gerdes et al., 2000; Noffke, 2000; Sarkar et al., 2008; Bose and Chafetz, 2009; Petrisor et al., 2014) and also form a meshwork of interweaving filaments of cyanobacteria and other microbiota (Gerdes et al., 2000). These microbial influences produce characteristic morphologies on and within sand and sandstone beds such as blisters, wrinkles, tufts, pinnacles, domes, and roll-up that have been referred to as microbially-induced sedimentary structures (MISS; Noffke et al., 1996, 2001). Subsequently, MISS have been widely documented from many ancient and modern sedimentary rocks/sandy sediments deposited in a wide range of depositional environments (Gerdes et al., 2000; Golubic et al., 2000; Prave, 2002; Tice and Lowe, 2004; Sarkar

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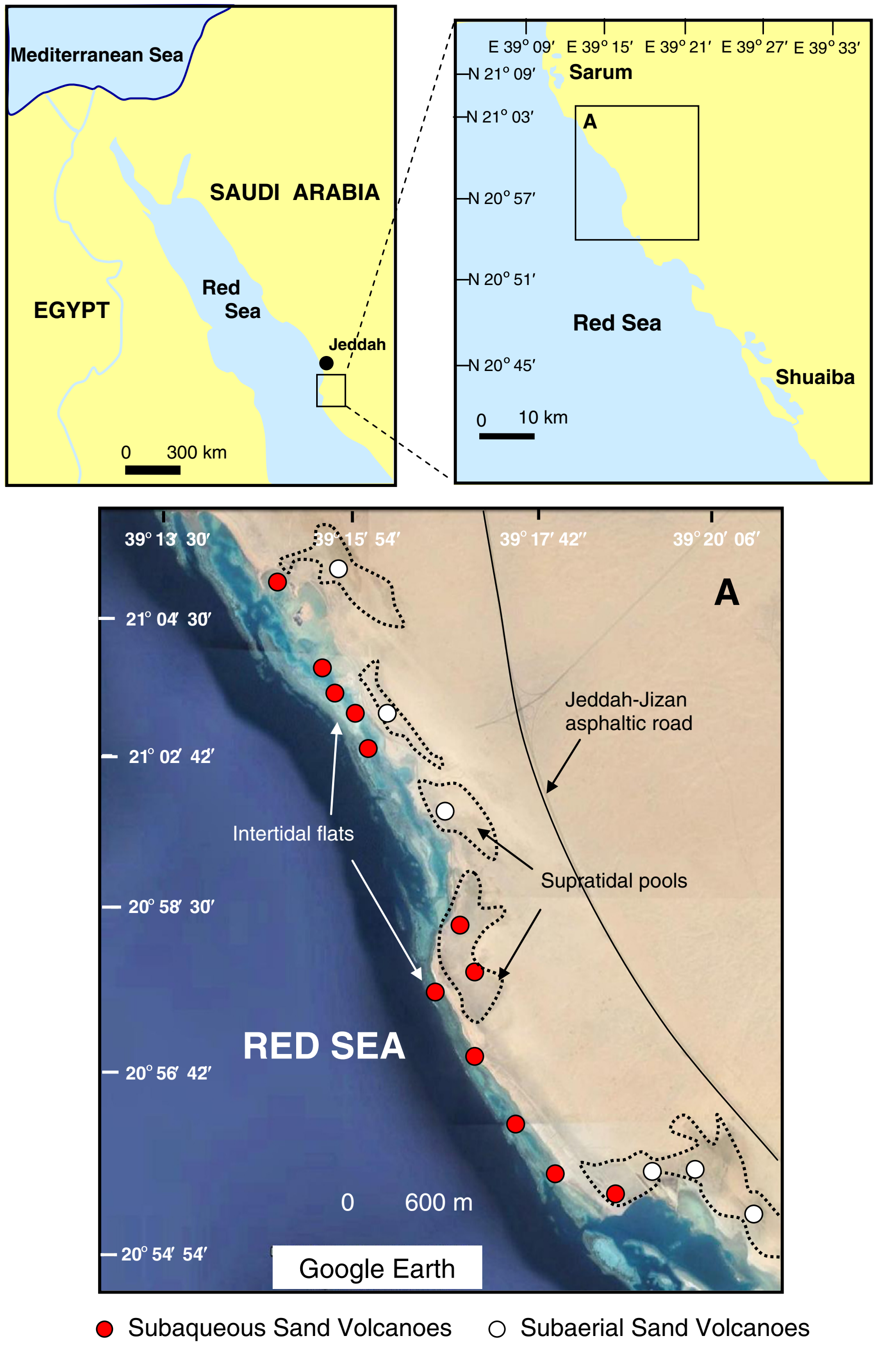

Fig. 1. Location map of sand volcanoes in the intertidal flat and supratidal pools, south of Jeddah, Saudi Arabia. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2006, 2008; Noffke, 2010; Lan and Chen, 2012, 2013; Cuadrado et al., 2013; Lan et al., 2013; Noffke and Awramik, 2013; Noffke et al., 2013; Aref et al., 2014).

The biological contribution to MISS morphogenesis is frequently entangled with both physical and chemical influences (Grotzinger and Knoll, 1999) leading to substantial controversy as to the origins of specific structures (Shepard and Sumner, 2010). Many MISS share similar morphologies with structures created by non-microbial processes such as biotic (stromatolite domes) and abiotic (wrinkle structures, sand volcanoes or adhesion warts) (McLoughlin et al., 2008; Wilmeth et al., 2014), making them non-diagnostic of microbial behaviors. Fortunately, there are many microbially-related morphologies that suggest more direct links between biological behavior and morphological forms such as stromatolite reefs, and conical and branched pseudocolumnar stromatolites formed within Archean dolostones of Australia (e.g., Sumner, 1997; Hofmann et al., 1999; Allwood et al., 2006; Shepard and Sumner, 2010).

Sand injection is the forced emplacement of sand through fractures into an adjacent lithology (Duranti and Hurst, 2004) and if breaching the overburden to intersect with the sediment–water surface (here, the microbial mats), sand extrusion results (Hurst et al., 2006; Ross et al., 2013). The products of these processes, such as intrusive sand dikes and sills and extrusive, discrete sand volcanoes and mounds, and areally extensive sand sheets have been identified around the world for almost two centuries (e.g. Murchison, 1827; Diller, 1889; Cross, 1893). They have been most commonly associated with pore fluid escape processes (Lowe, 1975; Nichols et al., 1994; Boehm and Moore, 2002; Jolly and Lonergan, 2002; Mörz et al., 2007; Frey et al.,