ORIGINAL RESEARCH ARTICLE

A new model for the formation of microbial polygons in a coastal sabkha setting

STEPHEN W. LOKIER*, LUIZA L. ANDRADE†, WESLEY M. COURT*, KIRSTEN E. DUTTON†, IAN M. HEAD†, CEES VAN DER LAND†, ANDREAS PAUL* and ANGELA SHERRY†

*Department of Geosciences, Petroleum Institute, Khalifa University of Science and Technology, Abu Dhabi, UAE (E-mail: slokier@pi.ac.ae)
†School of Civil Engineering and Geosciences, Newcastle University, Newcastle-upon-Tyne, UK

ABSTRACT

The stratigraphic record of microbially induced sedimentary structures spans most of the depositional record. Today, microbes continue to generate, bind and modify sediments in a vast range of depositional environments. One of the most cited of these settings is the coastal microbial mat system of the Persian/ Arabian Gulf. In this setting, an extensive zone of microbial mat polygons has previously been interpreted as resulting from desiccation-related contraction during episodic drying. This study employs 15 years of field-based monitoring of the interaction between environmental factors and the development and evolution of polygon morphologies to test the desiccation model in this setting. On the basis of these observations, a new model is proposed that accounts for the genesis and development of microbial polygons without the need for desiccation-induced shrinkage. Conversely, the formation, development and erosion of microbial polygons is a direct result of the production of large amounts of organic matter in a healthy, yet spatially limited, microbial community. The recognition of microbial polygons has previously been applied as a diagnostic tool for the reconstruction of ancient depositional environments. The present study calls these interpretations into doubt. It is inferred that preservation of the microbial polygons as a recognizable form would be rare. Biological degradation and compaction will reduce polygons to produce the 'wispy' laminae that are a common feature of ancient sabkha lithofacies.

INTRODUCTION

Microbially induced sedimentary structures have contributed to the stratigraphic record for more than 3·4 billion years (Walter *et al.*, 1980). Today, benthic microbial communities continue to control sedimentation in a wide range of freshwater, marine and hydrothermal environments where they produce an array of environmentally constrained sedimentary structures. Numerous studies have described these structures from a range of modern coastal settings including the sabkhas of the Persian/Arabian Gulf, hereafter referred to as the Gulf (Evans *et al.*, 1969; Court *et al.*, 2017), the coast and tidal flats of the Bahamas (Black, 1932; Hardie, 1977; Andres & Reid, 2006; Bowlin *et al.*, 2012), Caribbean (Bouton *et al.*, 2016; Trembath-Reichert *et al.*, 2016) and Mexico (Javor & Castenholz, 1984) and, perhaps most famously, the intertidal to subtidal settings of Shark Bay (Davies, 1970; Reid *et al.*, 2003; Jahnert & Collins, 2013; Suosaari *et al.*, 2016).

The microbial mat system of the Abu Dhabi sabkha forms a near-continuous 200 to 600 m wide shoreline-parallel belt in the upper portion of the intertidal zone (Fig. 1). The seaward limit of the microbial community is controlled by the grazing activity of herbivorous marine fauna while the shoreward margin is constrained by the lack of tidal inundation. The geographical zonation of distinctive microbial growth forms has been described in detail by numerous studies (Kendall & Skipwith, 1968; Kinsman & Park, 1976; Court *et al.*, 2017). One of the most striking and characteristic structures of the microbial mats of the Gulf is the presence of an extensive zone of microbial polygons that have been previously interpreted as resulting from desiccation during periods of emergence
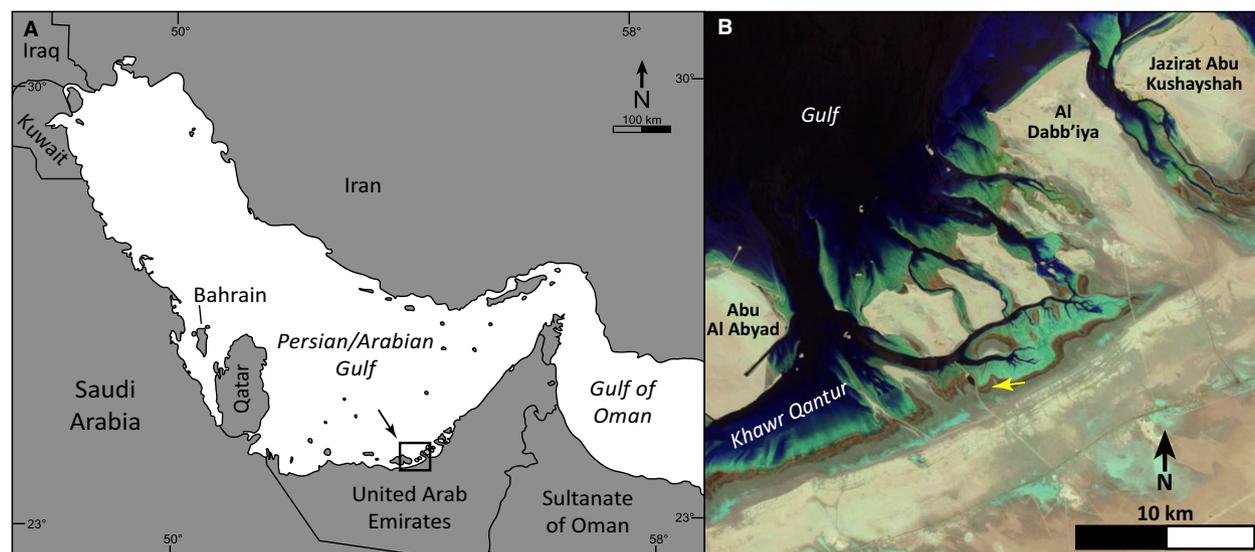
Fig. 1. (A) Map of the Gulf region (the arrowed box indicates the location of the satellite image in B). (B) Landsat Enhanced Thematic Mapper (ETM) image of the study area (acquired 3 July, 2002), see A for regional context. The location of the study area, in which the three transects were established, is indicated by the yellow arrow.

(Kendall & Skipwith, 1968; Evans *et al.*, 1969). The objective of this study is to test the validity of this model and offer an alternative proposed mode of formation and evolution for the microbial polygons. The preservation and recognition of these structures into the stratigraphic record, either as clotted thrombolites (Aitken, 1967) or laminated stromatolites (Walter, 1976; Dupraz *et al.*, 2009), provides an important diagnostic tool for the reconstruction of ancient depositional settings.

GEOGRAPHIC SETTING AND CLIMATE

The Abu Dhabi coastline of the Gulf comprises a low-angle ramp transitioning from a mixed evaporite-carbonate supratidal sabkha, through a broad intertidal zone, into a subtidal carbonate setting (Evans *et al.*, 1964). This topography is complicated by a complex of offshore shoals and islands that have accreted around Pleistocene limestone associated with the underlying Great Pearl Bank (Purser & Evans, 1973; Harris, 1994). Locally, these features have accreted to the shoreline to form a tombolo such as that seen at Al Dabb'iya (Fig. 1). The microbial mat belt is found within the upper reaches of the intertidal zone, both on the mainland and on offshore islands, where it marks the transition from the intertidal to the supratidal setting (Lokier & Steuber, 2008). Arid conditions prevail with mean annual evaporation of 2·75 m (Bottomley, 1996) far exceeding mean annual rainfall of 72 mm (Raafat, 2007). Air temperature in the study area regularly exceeds 50°C on summer days and may reach

7°C during winter nights (Lokier, 2012; Lokier & Fiorini, 2016). Surface temperature may exceed 60°C.

METHODOLOGY

Field-based observations of the microbial mat during all seasons of the year have been ongoing since 2002. The extremely low-angle nature of the sabkha surface results in any surface disturbance having significant consequences on microbial development, for example a single footprint has been observed to result in the onset of erosion or, conversely, the ponding of waters and consequent microbial mat thickening. For this reason, all observations were recorded on areas that had not been previously disturbed by anthropogenic activity. During the period of the study, any changes in surface morphology and their context in relation to environmental factors – including tides, storms and precipitation events were recorded. In order to statistically describe the polygons, three randomly oriented transects were established during April 2017 and the characteristics of a total of 60 polygons were measured in detail. Inspection trenches were dug at four localities to facilitate examination of the relationship between the surface microbial mats and the underlying substrate.

RESULTS

The longest axis of individual microbial polygons can reach up to 83 cm and shapes range from elongate (long to short axis ratio of 0·22) to circular (0·93) with an

average axis ratio of 0·60 (Fig. 2). All of the polygons have a distinctive open-bowl shape (Fig. 3A and B) with an uplifted margin that reaches between 0·5 and 5·2 cm (average 2·6 cm) above the polygon centre (Fig. 3C). The uplifted margins of the polygons typically are rounded and, in many cases, have an inner lip to the rim. Internally, the microbial mats typically are planar laminated with locally developed ptygmatic folding at the polygon centre and become increasingly convoluted towards the polygons margins (Fig. 3C and D). The centres of polygon mats have an average thickness of 3·9 cm. There is little, if any, lateral continuity of laminations between adjacent microbial polygons.

The substrate immediately below the microbial polygons locally varies from carbonate sands to laminated microbial material (Fig. 3C and D). Polygons are separated by gaps that average 10·1 cm in width (0 to 34 cm) and reach up to 10·5 cm (average 4·8 cm) below the peaks of the uplifted rims. Each polygon is surrounded by between 4 and 8 (average 6) immediate neighbours.

Although the Gulf is a microtidal sea, the low angle of the carbonate ramp results in significant lateral flooding during each tidal cycle. The polygonal microbial mats typically are inundated for a few hours during each flood tide although they may occasionally be exposed for up to 2 days during the lowest neap tides. As the tide recedes, water is retained both within the bowl-shaped polygons and in the gaps between them; subsequent evaporation increases the salinity from an initial value of between 52 to 75 g l^{-1}, thereby promoting the precipitation of halite. Although microbial polygon surfaces may appear 'dry',
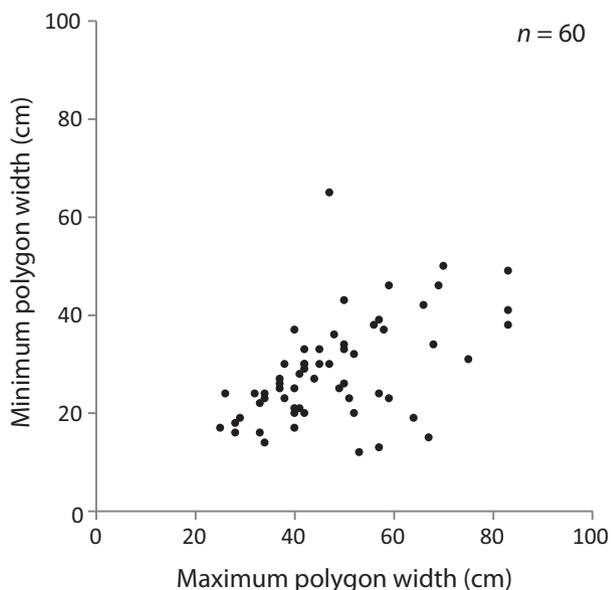
scratching will reveal dampness less than 1 mm below the surface. Over the extended period of observation, the substrate directly below the mat was always observed to be wet. A limited supply of moisture is also present in the form of early-morning dew. During summer months, air temperatures of over 50°C are not uncommon, temperatures at the surface of the dark microbial mats can exceed air temperature by over 15°C. During rare episodic high-energy events, such as storm surges, a thin veneer of sediment up to 2 mm thick may accumulate within and between polygons. Following storms, it is not uncommon to find that individual polygons have been removed from the surface of the polygonal mat zone exposing an area of laminar microbial growth.

Desiccation-induced shrinkage of the microbial mats was very rarely observed within the microbial polygon zone. On the rare occasions where lateral contraction was observed, this was in the form of discontinuous rips or tears that typically 'healed' on rehydration. Desiccation of the much thinner (1 to 3 mm) microbial mats landwards of the microbial polygon zone resulted in splitting, fragmentation and transportation of the desiccated material.

DISCUSSION

Existing models for the formation of microbial polygons in the Abu Dhabi sabkha have all invoked desiccation as the primary agent in the initiation and development of the polygon structure. Under this model, dehydration of the microbial mat results in shrinkage to form a network of polygonal cracks. Continued drying results in differential shrinkage between microbial layers, thereby causing the edges of each polygon to curl upward (Kendall & Skipwith, 1968; Friedman, 1995) and overturn. The overturned margins promote the trapping of saline water, resulting in faster upward growth at the edges (Kendall & Skipwith, 1968).

The observations herein motivate a new conceptual model which suggests that the formation of microbial polygons is a result of the production of a large amount of organic matter in a healthy, yet spatially limited, microbial community.

Growth and shedding

The initiation, development and subsequent erosion of microbial polygons can be explained purely on the basis of the production of organic material by a healthy microbial community under optimum (regularly flooded), but vertically restricted, growth conditions. The microbial community within the mats requires an adequate supply of water that is, typically, replenished during each tidal cycle. During periods when neap tides fail to flood the

Fig. 2. A plot of the maximum polygon width (*x*-axis) against the minimum polygon width (*y*-axis).
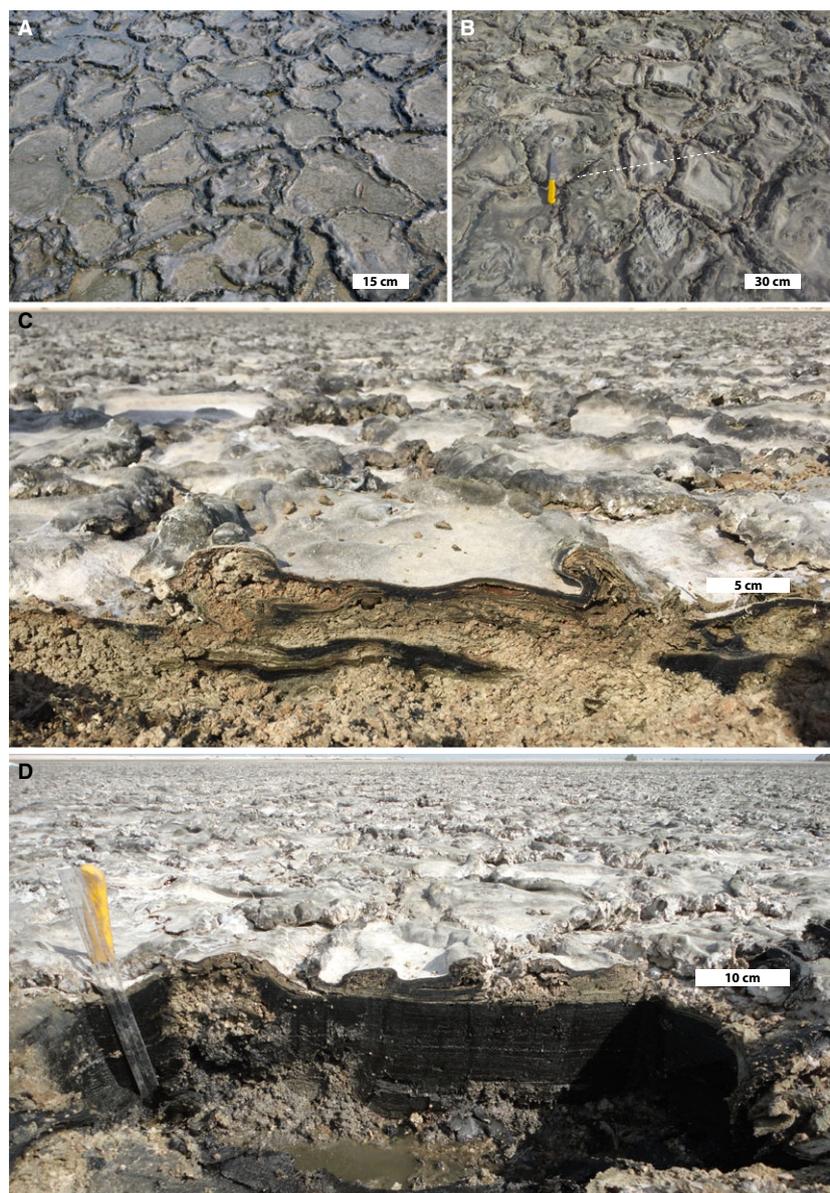
Fig. 3. Field photographs from the polygonal microbial mats. (A) Recently flooded polygons retaining water both within the polygons and in the inter-polygon gaps. (B) During low neap tides, the water within and between polygons may completely evaporate thus precipitating halite (the lighter colour within and between some polygons). The dashed line indicates the location of the cross-section in D. (C) A cross-section through polygons developed on a carbonate sand substrate, note the presence of two 'wispy' polygons within the sands. (D) A cross-section through microbial polygons developed over a substrate of planar-laminated microbial mats. Refer to Fig. 4 for a close up of the central polygon within this image.

mats, the supply of water is limited to sub-surface recharge via capillary processes. This places a vertical constraint on the upward growth of the microbial mat. The lateral growth of the microbial community is not so absolutely constrained.

As the microbial mats grow laterally, 'competition' for space results in deformation to produce localized topographic highs that will eventually rupture and fail with one newly developed margin being overthrust above its neighbour (Fig. 4). The uplifted margin is somewhat isolated from the supply of moisture and may therefore suffer episodic drying during which the contracting uppermost layers will contort the lip of the rim inwards and downwards. Continued microbial growth overgrows the uplifted margin to produce a rounded profile. The uplifted margin creates an open-bowl structure in which
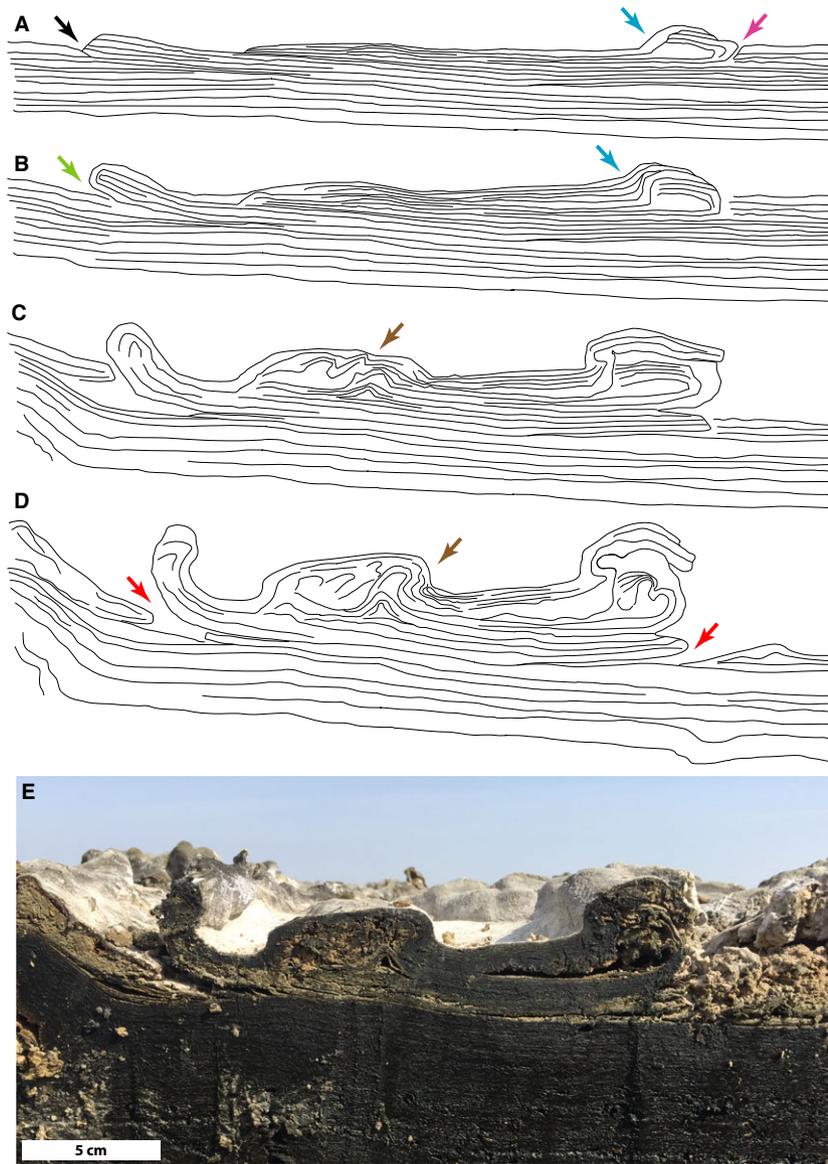
Fig. 4. A series of schematic diagrams showing the development of the microbial polygon shown in cross-section in E (see Fig. 3D for the context of this feature). (A) Optimum growth conditions result in displacive lateral growth of the microbial mats resulting in overthrusting (black arrow) and localized overturning (pink arrow) of the polygon margin. Continued microbial growth overgrows the margin to produce a rounded profile (blue arrow). (B) Continued laterally displacive growth increases overthrusting (green arrow) whilst vertical growth consolidates the margin (blue arrow). (C) As horizontal displacement continues, a new area of uplift is produced (brown arrow). (D) Polygon interior uplift continues (brown arrow). Increasing displacement at the polygon margins results in detachment of the polygon from the underlying substrate (red arrows) – the polygon is now susceptible to erosion. (E) Field photograph of a cross-section of a single microbial polygon.

sea water is retained during low tides thereby enhancing microbial mat growth. As the interior of the polygon thickens, the upper surface will become increasingly prone to desiccation, resulting in successive generations of margin uplift and overturning. This process effectively lifts the margin of the polygon away from the underlying substrate (Fig. 4). Ponding of water within the gaps between adjacent polygons promotes the development of a new microbial layer that will extend beneath the uplifted margins of the microbial polygon. With increased detachment from the substrate, the relatively high-relief polygon is increasingly susceptible to erosion and transport during high-energy events such as storms. Shedding of the polygon exposes the underlying microbial community that was developing immediately below the polygon.

Comparison between models

The new 'growth and shedding' model addresses a number of inadequacies with the previously posited 'desiccation models' for microbial polygon formation (Kendall & Skipwith, 1968; Evans et al., 1969; Noffke et al., 2001). The desiccation model for the Abu Dhabi sabkha requires sufficient 'drying' of the microbial mat to allow relatively deep vertical cracks to develop and for the mat to uplift and roll back. An alternative model, developed from observations of thin microbial mats on the Mediterranean coast of Tunisia (Noffke et al., 2001), also relies on periods of desiccation to initiate cyclic episodes of polygon development. Such conditions are highly unlikely under the regularly flooded optimum growth conditions (Kendall & Skipwith, 1968) in which the polygonal mats are developing. Deep desiccation fissures have been observed within microbial mats elsewhere within solar salt pans but these have developed under significantly drier condition than those observed at the Gulf coast (Bernier et al., 1991; Cornee et al., 1992).

During over 15 years of field observations, desiccation-driven shrinkage of the microbial mats in the polygonal mat zone was only rarely witnessed and bore no resemblance to observed microbial polygon morphologies. Desiccation, observed at the landward limit of the Abu Dhabi microbial mats, results in the splitting and fragmentation of mats making them susceptible to aeolian and storm-surge erosion, a similar relationship has been reported elsewhere (Logan et al., 1964; Davies, 1970; Bouton et al., 2016) but does not produce polygons. Kinsman & Park (1976) illustrated desiccation structures from the microbial mats of Abu Dhabi. However, these features are morphologically distinct from the microbial polygons as they have only limited uplifted rims, with no evidence of overturn or buckling, additionally, laminae are laterally continuous between bodies and gaps are narrow, vertical and infilled.

All of the desiccation models rely on shrinkage as the driving mechanisms for microbial polygon formation. Field observations of uplifted and overthrust margins and ptygmatic folding of microbial laminae clearly demonstrate that the microbial polygons are, in fact, products of lateral and, to some extent, vertical growth and expansion rather than shrinkage. The shedding of polygons from the surface of the microbial mat is entirely unaccounted for in any of the desiccation models.

Potential for preservation into the depositional record

As has been documented elsewhere, most microbial structures are lost during early burial, with planar lamination, polygons and stacked saucers being the most likely features to persist into the depositional record (Kendall & Skipwith, 1968; Evans et al., 1969; Kinsman & Park, 1976; Park, 1977; Court et al., 2017). The eventual fate of most microbial polygons is to be shed and transported either into the supratidal environment, where they will ultimately suffer desiccation and aeolian erosion, or into the marine setting where they will be consumed.

The potential for preservation is enhanced where the microbial polygons have formed over binding planar microbial mats, in such circumstances isolated polygons may be overgrown by the laminar mats thereby facilitating burial and preservation. Within the depositional record, such structures would be recognized as isolated discontinuities that may be misinterpreted as microbial rip-up clasts, an interpretation that it would be difficult to disprove. Under rare circumstances, near-complete polygonal microbial mat systems may be preserved into the stratigraphic record. Superbly preserved fossil examples of microbial mat polygons have been documented from the Archean of South Africa (Noffke et al., 2008). Cross-sections of these mats clearly document the displacive nature of polygon growth resulting in overthrusting of polygon margins (Noffke et al., 2008, fig. 12).

Microbial polygons formed over an unlithified substrate are similarly likely to be lost to the burial regime. Where isolated microbial polygons are buried (Fig. 3C), then biological degradation and compaction are likely to reduce them to indistinct, laterally discontinuous, thin 'wispy' seams of organic residue. Wispy seams are a common feature of the interpreted intertidal facies of the Jurassic Arab Formation of the Middle East.

CONCLUSIONS

The proposed growth and shedding model explains the genesis and development of microbial polygons without the need to invoke desiccation-induced shrinkage. The production of microbial polygons is a result of the production of significant quantities of organic matter in a healthy, but spatially limited, microbial community. It is likely that these microbial polygons are only rarely preserved into the depositional record in an easily recognizable form. The model for preservation may account for some of the discontinuous wispy organic seams that are ubiquitous within the intertidal units of ancient sabkha-system lithofacies.

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