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Microbial Mat Structures and role of microbes in Precambrian siliciclastic sedimentation: Evidence from Indian Proterozoic basins

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Microbes had been the sole occupant of the early biosphere and they strongly controlled the evolution of lithosphere, hydrosphere, biosphere and atmosphere. Many Microbes could form mat like structure on sea floor. During the Precambrian these microbial mats had a strong influence on sedimentation, and they facilitated the formation of a variety of mat-induced sedimentary structures (MRS/MISS) in siliciclastic and carbonate rocks. In last two decades many of these structures have been identified from the Indian Proterozoic rocks. Observation from modern environments indicates the formation of mat related structures in preferred segments of the shallow marine domain. We also investigate the cause and effect relationship between the mat-growth and the sequence building pattern during the Precambrian. The commonly present HSTs compared to those of corresponding TSTs possibly indicates that microbial mat-infested sea floor impedes erosion, while concomitant sediment supply facilitated formation and preservation of regressive packages during the Precambrian.

Introduction

Microbes were the dominant life form on earth in absence of grazing organisms during the Precambrian time. Microbial mats influenced the sedimentation in many ways through trapping, binding baffling and biostabilization. Moreover, Microbes play a major role in biomineralization. Extracellular polymeric substances (EPS), embedded within the biofilms of micro-organisms, often form a thixotropic layer enhancing cohesiveness of the sediments. It acts like a tough leathery material upon which micro-organisms leave

their proxy records (Schieber et al., 2007). Precambrian carbonates received considerable attention than their siliciclastics counterpart for microbial mat. Enormous morphological and taxonomical variations in stromatolites possibly resulted from by the early cementation in carbonate rocks. On the other hand, lack of early cementation resulted in poor preservation of microbial structures in Precambrian siliciclastic rocks. However, last two decades witnessed extensive documentation of microbial mat-induced sedimentary structures from Precambrian siliciclastics, both in sandy and shaley intervals world over, a substantial component of which are recorded from India (Sarkar et al., 2004, 2006, 2008, 2011, 2014, 2018; Samanta et al., 2015; Schieber et al., 2007; Noffke, 2008; Banerjee et al., 2010, 2014; Chakraborty et al., 2012 and many others). Davies et al. (2016) reported diverse kinds of microbial mat related sedimentary structures from different sedimentary environments in Phanerozoic. Microbial mat possibly diversified and expanded both siliciclastic shallow marine and continental settings soon after the Permo-Triassic biotic crisis (Chen et al., 2017). However, microbial mat signature is yet to be recorded in Phanerozoic siliciclastics of India. Potential microbial signatures, including pseudofossils and dubiofossils, discovered from Indian Proterozoic basins, created tremendous interests across the globe (Sarkar et al., 2005, 2006, 2007, 2014; Banerjee and Jeevankumar, 2005; Schieber et al., 2007; Banerjee et al., 2010, 2014; Samanta et al., 2015). Although limited studies contended for chronostratigraphic implications of MRS (Kumar and Ahmad, 2014), such claims remain largely unsubstantiated. The role of microbial mat on sedimentation dynamics remained the central theme in several studies (Sarkar et al., 2005, 2014; Banerjee and Jeevankumar, 2005; Chakraborty et al., 2012). The study of modern microbial mats provided additional clues for the interpretation of morphological variation in ancient intertidal-supratidal settings and resolving the origin of problematic features (Banerjee et al., 2010, 2014). The notion that the non-uniformitarian microbial mat influenced the Precambrian environment, taphonomy, depositional system and sequence building pattern is, nonetheless, yet to be consolidated. Generalization of the seldom perceived control of omnipresent mat ground on Precambrian sedimentation dynamics, bedforms migration, net sedimentation rate and sequence building is

necessary to understand Precambrian depositional system in proper perspective.

Noffke et al. (2001) introduced the acronym MISS (microbially induced sedimentary structures) to include microbial mat originated features on clastic sediments. As many of these features could form by the action of physical forces on biostabilized sediment surfaces, an alternative acronym, MRS (mat-related structures), remained equally acceptable, particularly to consider the wide spectrum of microbial mat-related features (Schieber, 2004; Schieber et al., 2007; Eriksson et al., 2010; Sarkar et al., 2016). Authors will follow the latter acronym to describe all varieties of microbial mat structures in this discussion. Microbial mats formed in wide ranging depositional domains covering both marine and continental. While the microbial mat structures from siliciclastics was reported from 3.48 Ga siliciclastics of the Dresser Formation, Pilbara in Australia (Noffke et al., 2013), the 1.8 Ga palaeodesert deposits of the Waterberg Group in South Africa recorded the oldest continental example (Eriksson et al., 2000). Increasing numbers of MRS have been described in recent years from some Precambrian basins of India (Fig.1) including Vindhyan basin (Sarkar et al., 2005, 2006, 2014; Banerjee and Jeevankumar, 2005; Banerjee et al., 2010, 2014), Chhattisgarh (Chakraborty et al., 2010; Sarkar et al. 2014), Cuddapah (Chakraborty and Shome, 2010; Pranhita (Deb et al., 2007) and Marwar (Sarkar et al., 2008; Samanta et al., 2011, 2015; Kumar and Ahmad, 2016; Pandey and Sharma, 2018). Authors investigate microbial mat-originated structures within siliciclastic sedimentary succession from several Proterozoic basins of India and highlight the influence of microbial mat on sequence building pattern and sedimentation dynamics of Precambrian sedimentary succession. Authors have also

discussed the significance of modern mat features for understanding the origin of mat-related structures.

Microbial mat related (MRS) on modern environments

Microbial mats grow abundantly on modern clastic sediments along the coastlines of the Gulf of Cambay (Fig.1d). Banerjee et al. (2014) recognized lateral variation in microbial mat features within a stretch of the coastal plain of the Gulf of Cambay. They noted increasing abundance of MRS accompanied by systematic variation in structures from the lower intertidal zone to the upper supratidal zone, resulting from decreasing wave/current actions, (Fig.2). The lower intertidal zone produced less diversified MRS including wrinkle structures, sieve-like surfaces and patchy ripples. While the reduced current action on the microbial mat layer as well as intermittent exposure led to the formation of diverse MRS including multi-directional ripples, patchy ripples, wrinkle structures, setulfs, sieve-like surfaces, gas domes, reticulated surfaces, rolled-up mat fragments, and cracked mat surfaces within the upper intertidal zone (Fig. 3). Banerjee et al. (2014) also established the increased occurrences of petee ridges, gas domes and cracked mat surfaces from the lower to upper supratidal zones besides the presence of abundant cracked mat surfaces, petee ridges, gas domes and wrinkle structures in both zones (Fig.2; see also Gerdes et al., 2007; Bose and Chafetz, 2009; Banerjee, 2012, 2013). Further, Banerjee et al. (2014) extrapolated the distribution of MRS in modern environment for the high-resolution palaeo-environmental interpretation of the ~1.6 Ga Chorhat Sandstone

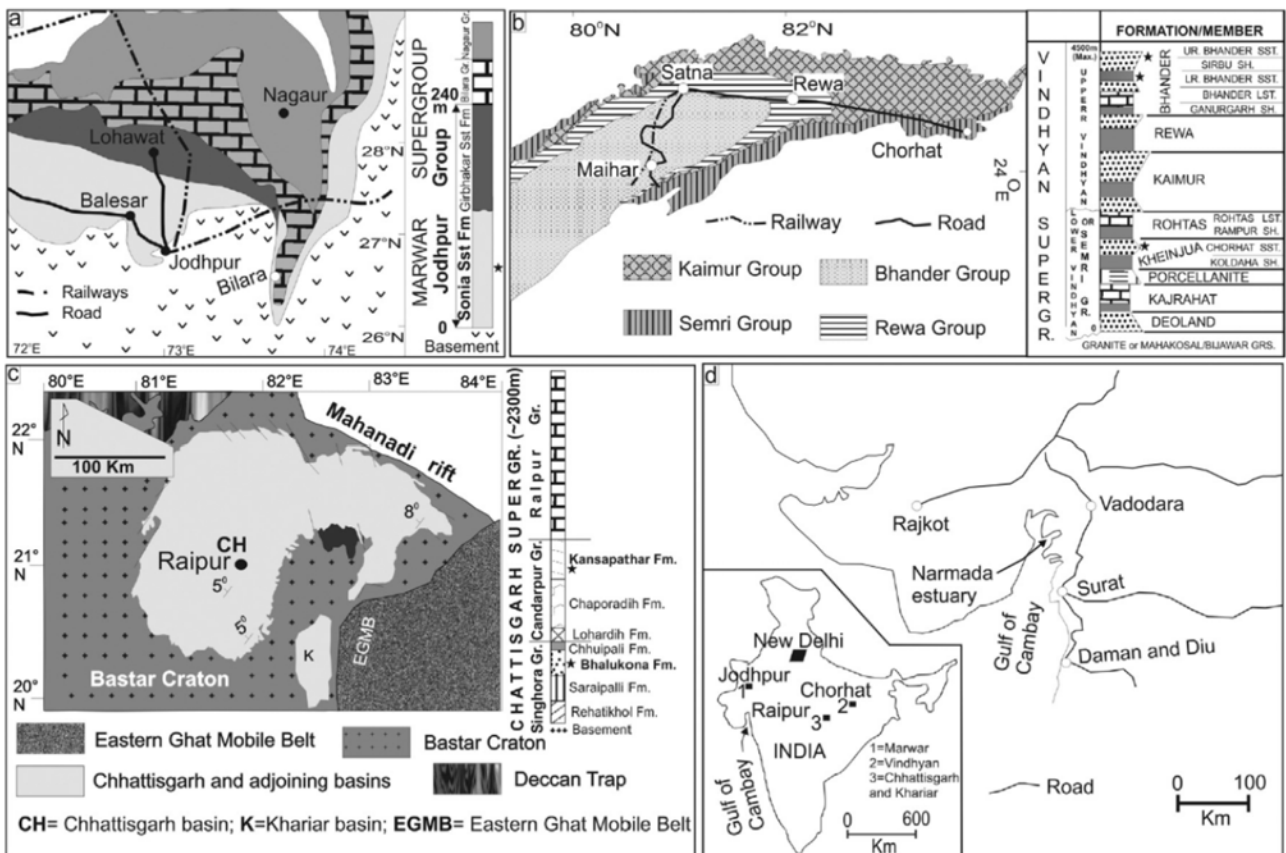


Figure 1. Studied Proterozoic basins, Marwar (a), Vindhyan (b), Chattishgarh (c) and the modern stretch along coastline, Gulf of Cambay (d).

of the Vindhyan Supergroup. Sarkar et al. (2011) investigated setulf in detail, one of the least studied small-scale sedimentary structures within the microbial mat covered coastal plains of eastern India. They found these features formed by the adhesion of wind-deflated sands

on microbial mat chips while the mat layer growing on the moist surfaces covered these minute structures within the littoral to supralittoral environments. They have identified same structures from the inferred similar coastal plain environment of the shallow marine facies

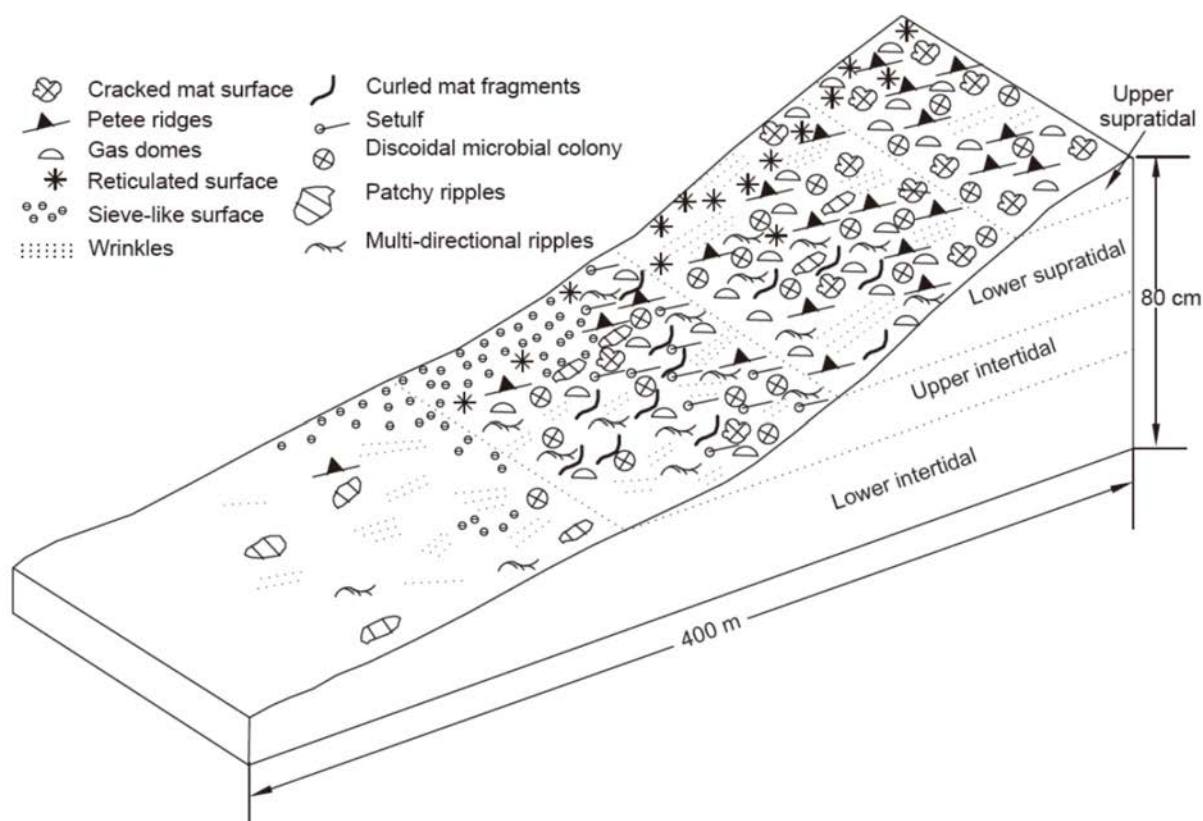


Figure 2. Distribution of microbial-mat related structures (MRS) within the coastal zones of Gulf of Cambay near Surat (note the variation in abundance of MRS within lower intertidal to supratidal zone)

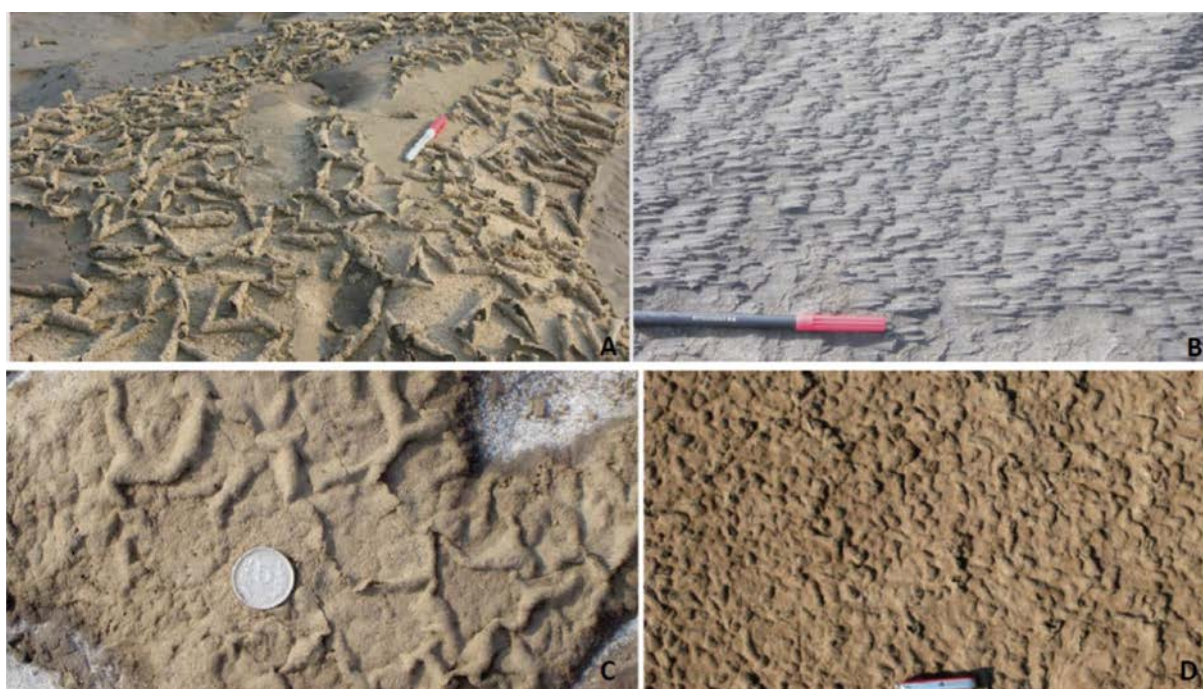


Figure 3. Modern MRS on coastal sediments of Gulf of Cambay, roll-up structure (A), setulf (B) petee ridges (C), domal structure (D) (pen length in A = 12.5 cm, pen length in B = 14 cm, coin diameter in C = 2.2 cm, swiss knife in D = 9.1 cm).

of the Proterozoic Upper Bhander Sandstone, Vindhyan Supergroup (Fig.1b) and in Sonia Sandstone of Marwar Supergroup (Fig.1a). In both the ancient formations setulfs occur on bedding surfaces of well-sorted sandstones, and are associated with planar laminae, profound wave ripples, parting lineation, occasional rill marks and local swarms of current crescents.

The cm-scale, disc-shaped microbial colony (DMC) exhibiting a variety of internal structures is a unique feature of the coastal plains of the Gulf of Cambay. This feature exhibit rounded discs of a few mm reliefs, marked by sharp outline, with internal radial, concentric, reticulate or wrinkle features (Fig.4). Prominent grooves may divide the discs internally in places (see Banerjee et al., 2014). 'Discoidal microbial colony' is essentially a microbially-originated feature that



Figure 4. Discoidal microbial colony on modern coastal sediments: note a prominent groove with a few subordinate ones (top) and reticulate structures (bottom) (coin diameter= 2.2 cm)

resembles circular Ediacaran fossil, known as 'medusoid' in Precambrian rocks. Grazhdankin and Gerdes (2007) demonstrated unequivocal texture of microbial mats within the discoidal microbial colony in Neoproterozoics of Russia and ruled out its Ediacaran affinity.

Banerjee et al. (2010, 2014) and Sarkar et al. (2014, 2007) presented several examples of 'discoidal microbial colony' on siliciclastic rocks of the Vindhyan Supergroup and considered that both discoidal microbial colony and MRS lacks biostratigraphic significance and are not useful for the correlation of Precambrian stratigraphic successions. Similar features reported from the Bhander Formation in the Vindhyan Basin were considered earlier as Ediacaran fossils (see De, 2006). The recent chronostratigraphic information rules out the presence of any Ediacaran sedimentary rock within the Vindhyan Supergroup (cf. Rasmussen et al., 2002; Malone et al., 2008, Gilleaudeau et al., 2018).

Mat features in ancient siliciclastics

Schieber et al. (2007) presented a classification of MRS based largely on genetic processes involved, viz. mat growth, mat metabolism, physical mat destruction and mat decay and diagenesis. While the first two categories of structures are observed on the bedding surfaces, mat decay features are found on vertical sections across bedding. Sarkar et al. (2008) provided another classification of MRS that considers the role of mat, viz. mat layer, mat induced and mat protected types. Mat layer structures include those exhibiting *in situ* growth of microbial mat. The features include wide varieties of direct records of microbial mat originated discoidal bodies, often marked by small beads occurring within Chorhat Sandstone and Sirbu Shale of the Vindhyan Supergroup (Fig.5). These also include crumpled mat layers, mat curls, sand chips, kinneyia structures (Fig. 3, 6, Banerjee and Jeevankumar, 2005; Sarkar et al., 2004, 2006, 2014). Mat-induced feature reflects indirect indications of mat growth on substrate, including sand-cracks of different shapes including *Manchuriophycus*, petee ridges and domes (Fig.6, Sarkar et al., 2006, 2010; Banerjee et al., 2014). The mat protected features represent different varieties of patchy ripples, multidirectional ripples and palimpsest ripples.

Microbial mat features in shale

The documentation of the MRS remains challenging in fine-grained rocks because of the inherent cohesiveness of mud. However,

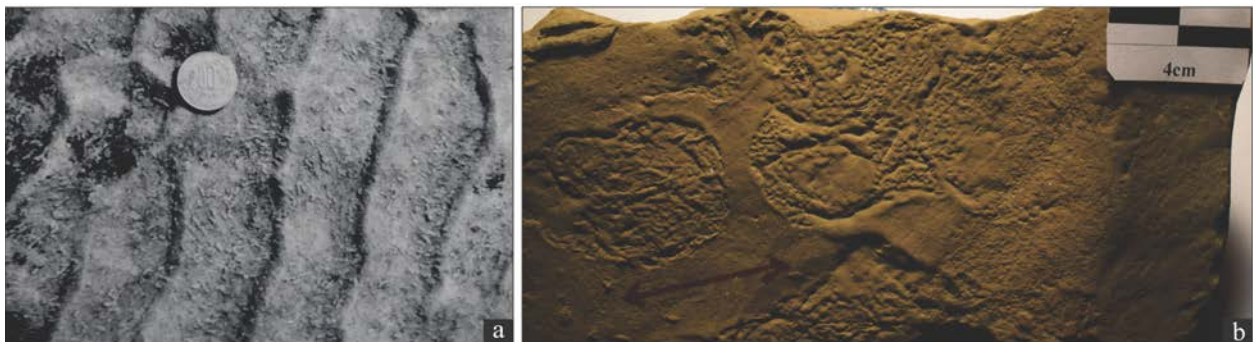


Figure 5. Microbial mat originated discoidal bodies, often marked by small beads occurring within Chorhat Sandstone (a) and mat impression at the undersurface of a bed in Sirbu Shale (b) (coin diameter in a=2.1 cm)

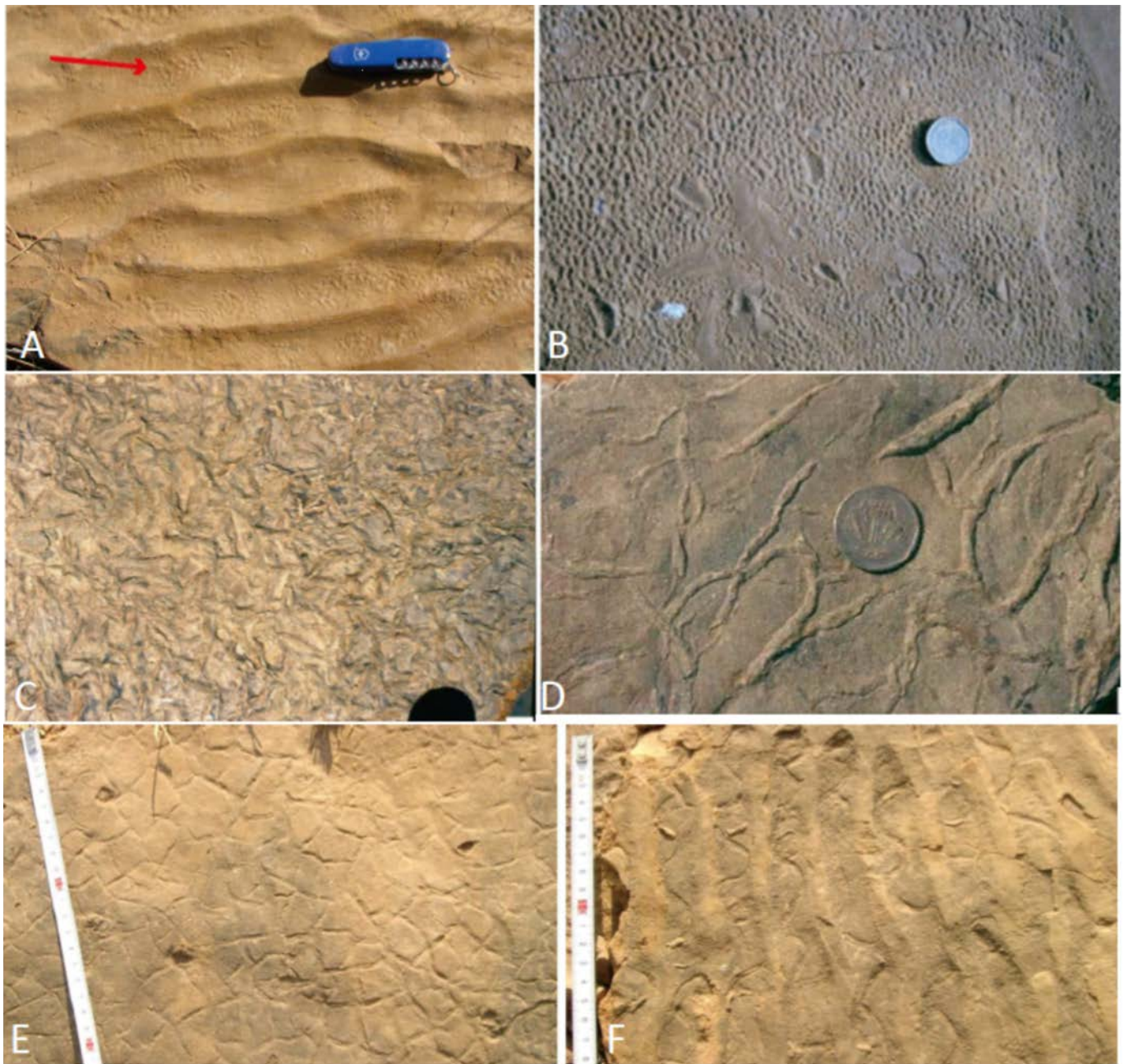


Figure 6. Microbial mat structures on bedding surfaces of the Chorhat Sandstone including wrinkle structures (A), kinneyia ripples (B), petee ridges (C and D), sand-cracks (E and F) (coin diameter in B and D = 2.3 cm, length of swiss knife in A = 9.1 cm, len cap diameter in C = 3.6 cm)

petrographic investigation presents many features equivocal of microbial mat growth including wavy-crinkly laminae, extra-cohesive behavior of carbonaceous laminae exhibiting rolled and folded margins, 'teeth and socket' structure, pseudo cross-lamination, wavy pyritic laminae. Occurrence of these features within the organic-rich shales in Rampur and Bijaigarh Formations of the Vindhyan Supergroup indicates microbial mat colonization of the sediment depositional surfaces (Fig.7 Banerjee et al., 2006; Sur et al., 2006; Schieber et al., 2007; Deb et al., 2007). Although wavy and crinkly laminated microfabric suggests microbial mat growth on seafloor, the same lamina style may also be non-mat origin. A differential compaction of organic-rich layer against resistant particles like quartz silts, micro-nodules or fecal pellets may result the waviness in shale microfabric. Distal storm or turbidite beds may often overlie on

growing mats causing interruption of microbial mat growth. Alternate deposition of mat layer and storm/turbidite beds may form 'striped shale' in the Somanpalli Formation (Schieber et al., 2007b). As microbial mat cover expands laterally on muddy substrate, clay drapes can result pseudo-cross-lamination at the edge of the expanding mat patches (Schieber et al., 2007b). This feature reflects the rapid re-establishment of mats on top of the recently deposited clay drapes, followed by their lateral expansion (Schieber, 1986). The mat layer may often display abundant micas (flypaper effect, Fig.8a), that essentially reflects the trapping actions of microbial filaments (Schieber et al., 2007). The microbial originated black shales often reveal roll-up structures, over folded mat layers as well as torn pieces of irregular mat fragments displaying frayed edges (Banerjee et al., 2006; Sur et al., 2006; Schieber et al., 2007; Fig. 8b). These features

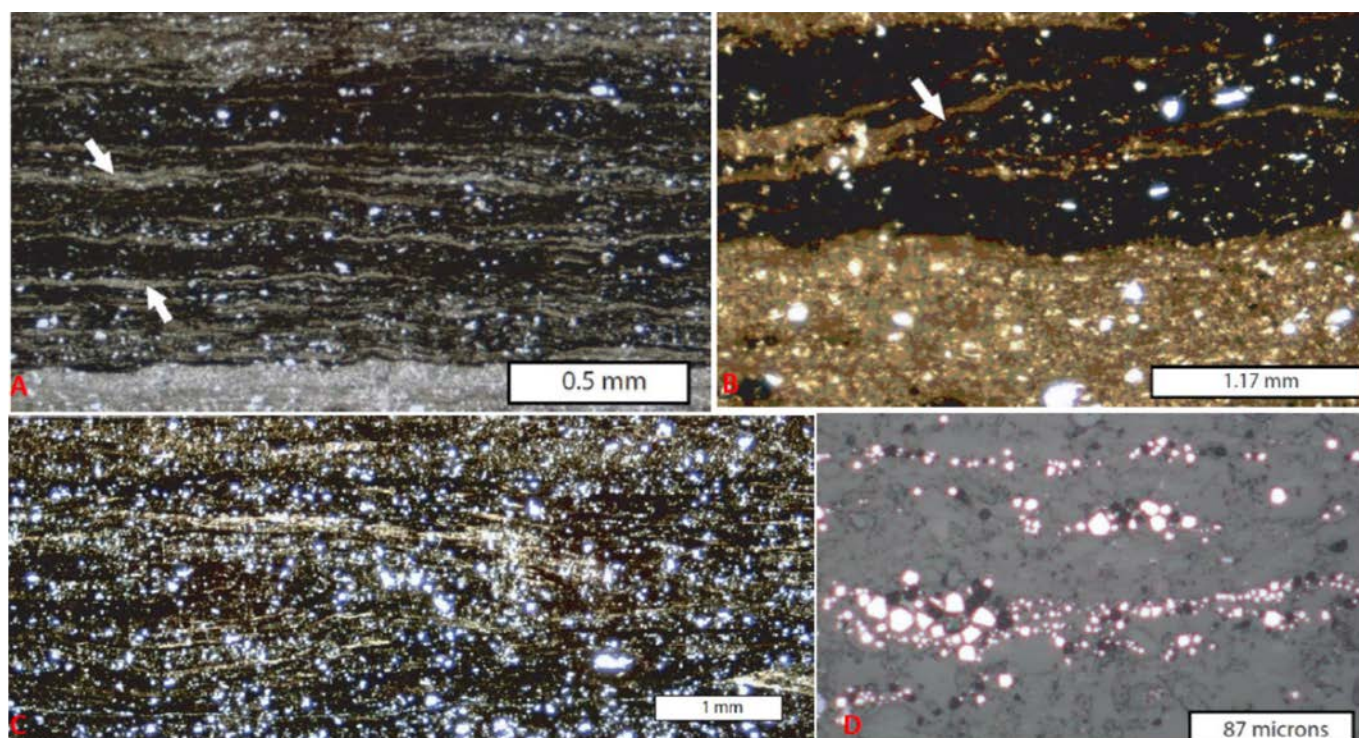


Figure 7. Microbial mat features in Precambrian black coloured Rampur shales including wavy crinkly laminae (A) folded carbonaceous laminae (B), contorted mat layer (C) and wavy pyritic laminae (D).

result by the physical destruction and subsequent transportation of extra-cohesive microbial mat bound mud layer. The wavy, pyritic laminae probably represent the mineralized microbial mat laminae (Fig.7, Schieber 1989). The decay of organic matter beneath a growing mat may form local anaerobic condition that may induce formation of pyrite in marine environment. The availability of iron determines whether the tiny pyrite grains remain sprinkled within the carbonaceous laminae or strongly pyritic laminae forms that mimic the wavy-crinkly anastomosing mat texture (Sur et al., 2006). Pyrite tends to be more disseminated in case of Phanerozoic black shale (Schieber, 2007).

Microbial mat-originated Precambrian black shale may contain high amount of organic content, TOC value (total organic carbon) exceeding 2 to 5 wt%, although thermally over mature (Banerjee et al., 2006). Banerjee et al. (2006), related the organic-rich shale in the Vindhyan Supergroup to maximum flooding surfaces, as low rate of sedimentation facilitated the prolific mat growth enhancing organic matter content in sediments. Microbial mats remained primary product in case of Precambrian black shale while organic content of the Phanerozoic black shales is related to planktonic productivity (Banerjee et al., 2006; Schieber et al., 2007). Compared to the deep basinal origin of the Phanerozoic black shale, the microbial mat-originated Phanerozoic variety typically formed in shallow subtidal depositional conditions (see Sur et al., 2006; Banerjee et al., 2006; Schieber, 2007); mats stabilized sediments, recycled organic matters, and remained the primary producers during the Precambrian (Schieber et al., 2007).

Chemical analysis, including carbon and sulfur isotopic and biomarker studies of the microbial mat layer provide information regarding the types of microbes. Deb et al. (2007) presented biomarker data from black shale and stromatolitic carbonates of the Raipur Group of the Chattisgarh Supergroup and indicated bacterial origin of the

hopane-dominated biomarker assemblage. Sarkar et al. (2010) considered stratified water column for the Vindhyan Sea with anoxic sulfidic conditions on the basis of heavy $\delta^{34}\text{S}$ values ($25.5 \pm 8.7\text{‰}$) in sedimentary pyrites associated with black shale in the Bijargarh Shale Member. While Singh et al. (2018) considered euxinic condition for the black shale of Arangi, Rampur and Bijargarh Formations on the basis of trace element concentration.

Occurrence of MRS in different basins

The following sections present a brief description of the MRS features reported from Proterozoic sedimentary basins of India in their depositional context.

Vindhyan Basin

Although the Vindhyan Supergroup received considerable attention for putative trace fossils (Sarkar et al., 1996; Seilacher et al., 1998), oldest red algae (Begtson et al., 2017) and well preserved stromatolites in carbonate rocks (Sarkar et al., 1996; Chakraborty et al., 2005; Banerjee et al., 2007; Sharma et al., 1996), it is also well known globally for superb preservation of delicate MRS (Sarkar et al., 2004, 2005, 2006; 2016a,b; Banerjee and Jeevankumar, 2005; Banerjee et al., 2006, 2010, 2014; Sarkar and Banerjee, 2007; Schieber et al., 2007b; Eriksson et al., 2010). The two-tiered Vindhyan Supergroup consists of alternate HSTs and TSTs, separated by condensed zones (Bose et al., 2001). The deposition of sediments took place in wide ranging environments including outer to inner shelf, littoral, fluvial with local eolian patches (Bose et al., 2001). Organic-rich shales (TOC content exceeding 1.5%) characterize the condensed zones (Banerjee et al., 2006; Sur et al., 2006). Wavy crinkly

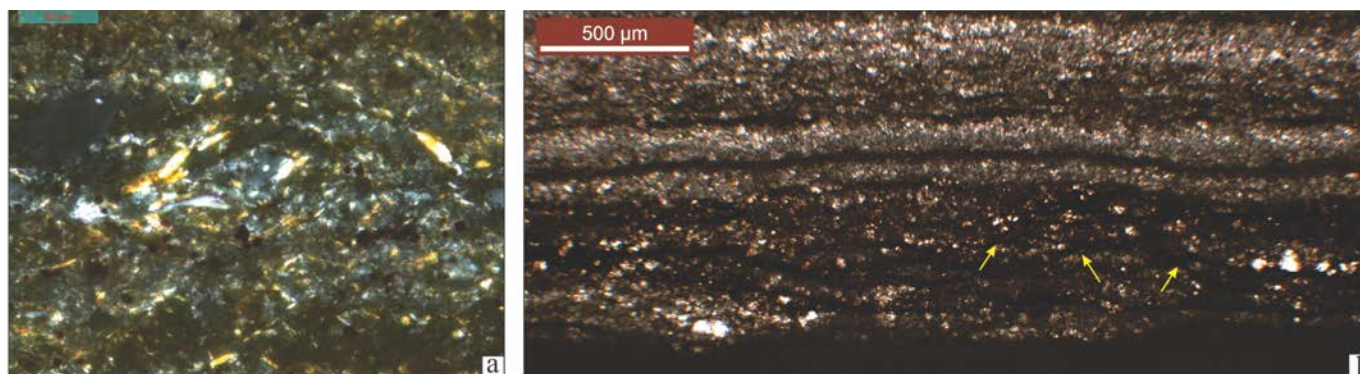


Figure 8. Microbial mat layer show flypaper effect (a) and displaying frayed edges(b)

carbonaceous laminae, pyritic laminae, pseudo cross-strata and rolled-up and folded carbonaceous laminae in Rampur Shale, Sirbu Shale and in Kajrahat Formation suggest microbial mat growth in mid- to outer-shelf depositional conditions (Banerjee et al., 2006). Banerjee and Jeevankumar (2005) recorded systematic changes in wrinkle structures within the middle to inner shelf originated Koldaha Shale in response to variation in energy conditions of the depositional environment. While the low-relief wrinkles form in deeper setting, the high relief and more complex varieties form by the strong shear on microbial mat covered sandy surfaces (Banerjee and Jeevankumar, 2005). The shelf-originated Sirbu Shale exhibits broadly similar features, but include wide variations of patchy mat fragments and disc-shaped impressions at the soles of the storm-originated sandstone beds (Sarkar et al., 2016). However, the best preservation of MRS occurs on shallow subtidal to supratidal segments of the HSTs, which are superbly exposed in the Chorhat Sandstone and the Upper Bhandar Sandstone (Sarkar et al., 2006; 2014a). The features include sand-cracks of different shapes and sizes, gas domes, petee ridges, wrinkle structures, kinneyia, palimpsest ripple, patchy ripples, rolled-up mat fragments and microbial sand chips. Microbial mat features are well preserved at the interfaces of vertically stacked storm sandstone beds, with no visible signs of erosion (Banerjee, 1997; Sarkar et al., 2006; Bose et al., 2007). Microbial mats must have protected sandstone beds from erosive actions of storms (Sarkar et al., 2006). Sarkar et al. (2016a) compared similar sets of MRS on bedding surfaces between siliciclastics and carbonates in the Chorhat Sandstone and the Bhandar Limestone respectively. They attributed the preservation of the MRS within limestone possibly because of delayed cementation.

Marwar Basin

Abundant microbial mat related structures within the shore face to supra-littoral-originated Neoproterozoic Sonia Sandstone indicates unusually high cohesiveness of sandy sediments. A large variety of microbial MRS at different stratigraphic level within the lower HST comprising the Sonia Sandstone indicates intermittent sedimentation and severely curtailed sediment reworking (Sarkar et al., 2008; Samanta et al., 2011). The littoral–supra-littoral environments characterize wide varieties of wrinkles, patchy ripples and mat colonies whereas high littoral to supra-littoral zones exhibit crumpled structures. The supra-littoral zone shows abundant desiccation cracks and petee ridges. Ripples may occur as casts on the under surfaces of the overlying storm beds in vertically amalgamated sandstone beds. The near-planar, non-erosive beds resemble distal storm deposits.

Samanta et al. (2011) presented many varieties of features on the vertical section across microbial mat layers to reflect decay and diagenesis beneath mat layers. Kumar and Ahmad (2014) reported several examples of microbial growth related structures, including morphologies like *Arumberia banksi*, *Rameshia rampurensis* and *Jodhpuria circularis*, which they argued to represent Neoproterozoic varieties, as originally considered by Glaessner and Walter (1975). However, Davies et al. (2016) demonstrated many examples of *Arumberia* within Phanerozoic deposits and ruled out biostratigraphic relevance of these features, and even debated for their abiotic origin.

Chhattisgarh Basin

A wide spectrum of MRS occurs within two stratigraphic intervals, the Bhalukona Formation of Singhara Group and the Kansapathar Formation of Chandarpur Group within the Chhattisgarh Supergroup and Khariar Group (Chakraborty et al., 2012; Sarkar et al., 2014). The medium to fine-grained sandy lower to upper shoreface bar–interbar package of the Bhalukona Formation represents a lowstand systems tract deposits consisting of m-thick ‘parasequence’s. The forced regressive middle to upper shore face deposits of the Kansapathar Formation represents deposition under fair-weather and storm-wave influence. The well-sorted sandstones with retrogradational stacking in the Lower Sandstone Formation of the Khariar Group represent a transgressive shoreface beach deposits formed in shallow marine environment. Palimpsest ripples, torn mat fragments, wrinkle structures, setulfs, cracks and petee ridges occur on the sandstone bedding surfaces, whereas vertical sections exhibit highly irregular, wavy and crenulated sand laminae within the Bhalukona Sandstones. A preferential concentration of MRS occurs in the lower to middle/upper shoreface sandstones constituting the progradational packages within the Kansapathar Sandstone. Wrinkle structures in lower shore face cover both crests and troughs of ripples, while those in upper shore face occur exclusively within the troughs of ripples (Chakraborty et al., 2012).

Other Precambrian basins

MRS including wrinkle structures, kinneyia ripples, palimpsest ripples, elephant skin structures occur within the basal Gulcheru Formation (~1.8 Ga) of the Proterozoic Cuddapah Supergroup within the intertidal environment (Chakrabarti and Shome, 2012). Deb et al. (2007) reported striped shale and wavy laminae within black mudstones and shales of the Mesoproterozoic Somanpalli Group in

the Pranhita-Godavari Basin. Van Loon and Mazumder (2013) mentioned about wavy to undulatory bedding surfaces within the shales comprising the Palaeoproterozoic Chaibasa Formation in Singhbhum craton, which they inferred as equivalents of stromatolites. Mukhopadhyay and Thorie (2016) reported MRS within the mixed siliciclastic carbonate succession of the Proterozoic Kuniyar Formation, Simla Group, including wrinkle structures, kinneyia ripples, domal structures, sand chips, palimpsest and patchy ripples (Mukhopadhyay and Thorie, 2016).

Discussion and conclusions

Study of modern microbial mat reveals maximum diversification of MRS in littoral to supra-littoral environments. The MRS in modern environment provides useful insights for the palaeo-environmental implications of similar features in ancient siliciclastics. However, modern MRS is essentially investigated in peritidal settings while MRS formed in wide ranging depositional conditions in the past. Microbial mat growth has been documented in varied depositional conditions from shallow intertidal-supratidal to offshore in several Precambrian basins in India. While petee ridges, wrinkle marks, gas domes sand-cracks, multi-directed ripple marks, setulf, and sieve-like surfaces, occur at the shallowest part of the marine basins, roll-up structures, wrinkle structures, kinneyia and patchy ripples occur within a broad range of palaeogeographic settings from the supratidal to subtidal conditions. Whereas, features like setulf and petee ridges are definite indicators of littoral environment. Preservation of delicate textural details like wavy-crinkly, carbonaceous laminae, wavy pyritic laminae and torn pieces of mat fragments indicates microbial mat growth in both shallow and deep subtidal environments. Various morphologies of 'discoidal microbial colonies' provide alternate and more plausible explanations of microbial origin of similar features in Precambrian rocks.

Unique characteristics of microbial mat structures provide valuable insights to examine microbial life in other terrestrial planet like Mars. Noffke (2015) recently compared MRS formed in earth with those occur in Mars on the basis of images obtained by Curiosity Rover mission. Sandstone beds of the <3.7 Ga Gillespie Lake Member on Mars displays cm- to m-scale structures similar to terrestrial MRS including erosional remnants and pockets, mat chips, roll-ups, desiccation cracks and gas domes (Noffke, 2015). MRS has been investigated in relation to sequence building pattern in a few studies. Exceptional preservation of MRS in Vindhyan, Marwar, Chhatisgarh and Khariar basins allows to investigate the role of microbial mat on sequence building pattern during the Precambrian (Sarkar et al., 2005, 2016a; Banerjee and Jeevankumar, 2005; Chakraborty et al., 2012). These authors also present sequence stratigraphic context of MRS in four Precambrian successions, namely the Marwar Supergroup, Vindhyan Supergroup, Chhattisgarh Supergroup and the Khariar Group. These siliciclastic successions exhibit contrasting trends of sequence building in comparison to those in Phanerozoic sedimentary basins. These Precambrian sequences generally lack of well-developed transgressive systems tracts (TSTs), instead consists dominantly of stacked prograding and aggrading 'normal regressive' systems tracts. While the Phanerozoic sequences exhibit fully developed TSTs in between regressive systems tracts (LSTs and HSTs; Vail et al., 1977; van Wagoner et al., 1988, 1990) and thus the formation and the preservation of transgressive systems tracts may represent a key difference between the Precambrian and the Phanerozoic sequence

architecture. Sarkar et al. (2005, 2016) addressed the issue of absence of transgressive shales or thinning of transgressive deposits in Precambrian sequences. A combination of low gradients of sea floor that promote rapid transgressions and a low rate of sedimentation explains the absence of transgressive deposits in the studied Precambrian sequences. In several cases, the record of transgression is marked by a few cm-thick transgressive lags, forming stacked highstand systems tract deposits (Sarkar et al., 2005, 2016; Banerjee et al., 2005; see also Catuneanu and Eriksson, 2007). Prolific growth of microbial mats below the fair weather wave-base prevented erosion of microbially bound sediments (Sarkar et al., 2005). Stacked packages of normal regressive systems tract, therefore, should characterize the sequence stratigraphic architecture of the Precambrian successions instead of transgressive-regressive systems tract as usually observed in the Phanerozoic successions. Mat-infested sea-floor might have restricted erosion and concomitant sediment supply and facilitated formation and preservation of forced regressive sedimentary unit in the sequence architecture of the Precambrian formations (Chakraborty et al., 2012; Sarkar et al., 2005). Future research is likely to consolidate ideas proposed in this paper.

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