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Microbial mat related structures (MRS) from Mesoproterozoic Chhattisgarh and Khariar basins, Central India and their bearing on shallow marine sedimentation

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A wide spectrum of macroscopic and microscopic features preserved on the bedding planes or frozen between the laminations of fine- to medium-grained sandstones are described from a number of stratigraphically and geographically separated localities within the Chhattisgarh (Bhalukona and Kansapathar Formations) and Khariar basins (Lower sandstone Formation), India and attributed to microbial mat related sedimentary structures. These include bedding plane features viz. wrinkle structures, palimpsest and patchy ripples, spindle-shaped and sub-circular microbial shrinkage cracks indicating original cohesiveness in sand-sized sediments, fragments of torn mat spread on bed surface suggesting mat erosion under high energy flow etc. and bed-perpendicular features e.g. wavy-crinkly laminae, iron oxide specks and stringers etc. The structures suggest different mat-induced biophysical interactions viz. growth, biostabilisation, binding, baffling and trapping or a combination of all. Mat growth also favoured preservation of self structure that usually has low preservation potential. The stratigraphic intervals from where the structures are described are assigned Mesoproterozoic time frame (~1.4 Ga) and modelled as products of near-shore environment i.e. wave-influenced shoreface - beach under widely different sea level stands viz. forced regression, low-stand and transgression. It is proposed that prolific mat growth may act as facilitator for preservation of thin forced regressive deposits in Proterozoic low-gradient epeiric basins.

Introduction

Interest in the search of early life forms in geological records emerged not only from the desire of knowing how, when and in what form life started on the Earth but also from the belief that the obtained understanding from the related studies will help in searching evidences of life, if any, in other planetary bodies e.g. Mars, where water existed sometime in its planetary existence (Kral et al., 2004; Pietrogrande et al., 2005; Sarkar et al., 2006). Siliciclastic lithologies, however, were largely overlooked for the signatures of earliest life forms (bacterial remains) as stromatolite-like constructions are usually not developed (Seilacher, 1999) and the organic material is easily destroyed (Park, 1977). The last decade witnessed a trend-shift as it is increasingly appreciated by the earth scientists that at least since 3 Ga. benthic microbiota colonized sandy substrates in full-spectrum of siliciclastic depositional settings ranging between continental (fluvial, eolian-desertic) and shallow marine (Schieber et al., 2007); the oldest record to date comes from the 3.2 Ga old siliciclastic tidal deposits of the Moodies Group, South Africa (Noffke et al., 2012). Termed as ‘Microbially Induced or Microbial-mat related sedimentary structures (MISS/ MRS)’, a distinctive group of penecontemporaneous features are reported from near-shore siliciclastic successions belonging to different geological time (Schieber, 1998, 1999, 2004; Gehling, 1999; Pfluger, 1999; Noffke, 2001, 2002, 2003a,b; Lan and Chen, 2012) and interpreted in terms of various physical processes operative either on microbial mats or on sediments entangled within the mat meshwork or glued together by adhesive mucilages (extracellular polymeric substances, EPS, Decho, 1990).

In India, a wide variety of microbial mat mediated features are described from the Paleoproterozoic (1.6 Ga) Chorhat Sandstone and Koldaha Shale Formations of the Vindhyan basin (Banerjee and Jeevan Kumar, 2005; Banerjee et al., 2006, 2010; Sarkar et al., 2006; Sur et al., 2006), central India and the Ediacaran (<700 Ma) Sonia sandstone, Marwar basin, Rajasthan (Sarkar et al., 2008). However, mat-related structures are yet to be reported from other contemporaneous areally-extensive Proterozoic basins of peninsular India viz.

Chhattisgarh, Cuddapah, Pranhita-Godavai (P-G) etc. Since many of the MRS reported from the Proterozoic siliciclastic rocks are not observed in modern microbial mat-dominated settings, the MRS from the Vindhyan and the Marwar basin successions are discussed and interpreted under genetic aspects and with the aim to understand the bio-physical processes in their formation; relationship with clastic depositional environments and distribution in stratigraphic columns formed at different sea level stands are yet to be characterised properly. This contribution aims at documentation of MRS assemblages with a wide range of morphological expressions from the near-shore clastic successions present within two Proterozoic basin packages from central India viz. Chhattisgarh and Khariar.

Geological background

Recent studies (Bickford et al., 2011a, b, c; Das et al., 2009, Das et al., 2011; Patranabis-Deb et al., 2007) have convincingly established the Mesoproterozoic time frame for both Chhattisgarh and Khariar basin fills i.e. between ~1500 Ma and 1000 Ma. While Chhattisgarh basin fill (Chhattisgarh Supergroup; 2300 m thick; Chakraborty et al., 2010) is classified under three 'Group's viz. Singhora, Chandrapur and Raipur, in order of superposition (Das et al., 1992), the Khariar basin fill (Khariar Group, 1000 m thick; Das et al., 2001; Chakraborty et al., 2010) is represented by two arenaceous Members viz. Lower and Upper sandstone, intervened by an argillaceous Member i.e.

Middle Shale (Fig. 1). Within the Chhattisgarh succession the features are documented from two stratigraphic intervals viz. the Bhalukona Formation of Singhora Group and the Kansapathar Formation of Chandrapur Group, while features within the Khariar succession are described from the Lower Sandstone Formation (Datta, 1998). A sandy near-shore depositional environment ranging between lower shoreface to foreshore-beach, occasionally tidal have been invoked for all the three stratigraphic intervals dealt with under this study. Detailed facies and paleo-environmental appraisal for the discussed stratigraphic intervals of Chhattisgarh successions in sequence stratigraphic backdrop is available in Chakraborty and Paul (2008) and Chakraborty et al., (2012), and hence, are summarily discussed here. Whereas medium to fine-grained lowstand sandstones of the Bhalukona Formation (Facies Association (FA) III and IV; Chakraborty et al., 2012) are interpreted as products of lower to upper shoreface bar-interbar sequence stacked as meter-thick 'parasequence's in an aggradational to weakly retrogradational motif, the forced regressive middle to upper shoreface deposits of Kansapathar Formation (facies 'F' of Chakraborty and Paul, 2008; their Table 1) represent deposition under fair weather- and storm-wave influence and stacked as thickening- and coarsening-upward 'parasequence's indicating progradation. In the Khariar basin the features are documented from well-sorted sandstones representing a transgressive shoreface- beach sequence (Datta, 1998; Mishra, 2009) in the topmost part of the Lower Sandstone.

Figure 1. Location map of Chhattisgarh and Khariar basins, India with study area locations marked by bold black dots (a). Generalised stratigraphy, available paleoenvironmental models and age data indicating Mesoproterozoic time frame are given on the right. Asterisks mark the stratigraphic intervals from where the MRS are described (b).

Microbial mat-related structure (MRS)

In the studied stratigraphic intervals a variety of structures of potential microbial mat origin occur either on bedding planes or are found intrabed, which are described below:

Bhalukona Formation, Singhora Group, Chhattisgarh basin

Palimpsest ripples, cracks and ridges on the bedding plane exposures, and dark/ grey coloured laminae with wavy-crinkly and domal geometry in the bed-perpendicular sections are the commonly observed mat features within the fine- to medium-grained compact sandstones of Bhalukona Formation (Fig. 2a).

Palimpsest ripples

Replication of ripple forms in successive thin beds represents the palimpsest ripples. However, there is variation in the degree of replication; in some cases ripples on top of a very thin sandstone bed can be easily traced into the immediately underlying bed (Fig. 2b), while in others ripple geometry becomes unrecognisable, making the structure non-transparent (cf. Noffke, 2003).

Pfluger and Sarkar (1996) attributed palimpsest ripples to trapping of particles by filaments and extrapolymeric substance (EPS) of microbial mat grown uniformly over earlier formed ripple surface. In absence of mud and suspension fallout, replication of earlier morphology can only be explained by generation of enough cohesion by microbial mat growth within the sand that originally formed the rippled surface. Coherent mat matrices, consisting of cyanobacteria and their EPS, fix and glue together the surface sediment mimicking the earlier topography, a process termed as biostabilisation (Paterson and Daborn, 1991; Noffke and Krumbein, 1999). Definitely a moist condition and slow sedimentation rate help in the process. However, a higher growth of mat at the ripple troughs may also bring non-transparency in the structure causing ripple geometry unrecognisable (Sarkar et al., 2006).

Cracks and Ridges

Mm-wide cracks, polygonal, semicircular, sinusoidal or spindle shaped in geometry, forming network are observed on the bedding planes of mud-free Bhalukona Sandstone (Fig. 2c, d). The cracks are invariably steep-sided and cut across one another in the network. Average depth of spindle-shaped cracks is measured as ~0.4 cm.

Earlier claims favouring trace fossil origin (animal trail) of circular and sinusoidal cracks on sandy surface are argued against in recent studies on the ground of steep flanks of these cracks and instead, an origin related to cracking of mat-infested sandy surface by desiccation or syneresis is invoked (Schieber, 2004). Indeed, cracking in sand cannot be explained unless development of cohesion is envisaged in presence of microbial mat. Irrespective of their desiccation (exposed surface) or syneresis (under water) origin, the near circular and sinuous cracks are identified as unequivocal expression of microbial mat cracking and well entrenched in literature under the name 'Manchuriophycus'. Spindle-shaped cracks are possibly related with syneresis, although several theories explaining formation of such cracks and ridges are available in literature viz. sub-aerial desiccation, post-depositional intrastratal dewatering of argillaceous beds and rapid

deposition of overlying bed, seismic shaking etc. The cross-cutting relationship between some of the crack fillings allowed us to support the syneresis hypothesis over other propositions (cf. Sarkar et al., 2006). Also, the interpreted under water paleo-depositional set up for the sediments, (Chakraborty et al., 2012) within which the cracks are noticed, supports the contention.

Wavy-Crinkly laminae

Some bedding plane surfaces show strong rust red colouration and presence of network constituted of elongated, irregular, highly curved mm-high ridges (Fig. 2e). At hand specimen scale in bed-perpendicular sections, sand laminae within these beds are highly irregular, wavy, curved and recurved, often swollen, and showing extreme fold-like crenulations indicating high flexibility (Fig. 2f). Under thin section the sandstones reveal an irregular laminated character; mm-thick dark layers with dispersed sand grains alternate with fine-grained sand layers composed of 95% quartz grains having sub-rounded shapes (Fig. 3a). In close-up, the dark layers are constituted of dark, opaque laminae, between 15 and 20µm thick, irregularly wrinkled, wavy in nature and interwoven like the network of a carpet. Solitary quartz grains are found floating within the dark, laminated matrix. Often, the long axes of the grains are found parallel to the laminae (Fig. 3b). Also, mica flakes are observed within the dark layers either in random orientation or arranged in a preferred orientation at an acute angle with the wavy-crinkly laminae (Figs. 3c, d). In cases, convex-up antigravity growth is noticed within the dark layers (Fig. 3e). Iron oxide grains either as specks or clustered in form of thin, laterally restricted stringers are noticed within the dark layers (Fig. 3f).

Laminated sandstones constituted of quartz-rich and wavy-crinkly, dark, opaque layers are reported from both modern shallow marine sands and ancient sandstones and attributed to microbial mat growth (Gerdes, 1991; Noffke et al., 2003). The laminated pattern arises from microbial mat growth forming the dark laminae in the interludes of sand deposition by currents. Schieber (1986) considered such wavy-crinkly lamination as the most striking indication of a cyanobacterial mat origin. Solitary quartz grains embedded in the organic mat fabrics with their long axes parallel to the microbial mat layer are a common textural feature in both ancient and modern microbial mats (Noffke et al., 2012). The mica flakes oriented randomly or arranged in preferred orientation within the wavy-crinkly laminae may imply trapping by microbial mat instead of vertical settling through the water column ('flypaper effect', Gerdes and Krumbein, 1987; Schieber, 2004). In rock records association of iron oxides with microbial mats are reported from different parts of the world e.g. Revett Formation, Belt Supergroup, USA (Schieber et al., 2007), Sonia Formation, Marwar Supergroup, India (Samanta et al., 2011).

Kansapathar Formation, Chandrapur Group, Chhattisgarh basin

Wrinkle structures (kinneyia ripples), ripple patches exposed due to microbial mat erosion, millimetre-wide cracks on ripple crests, false impression of sharp ripple crests and casts of rafted, overfolded mat fragments strewn over rippled bed surface, are the commonly observed mat-related features on mud-free sandstone bed surfaces in the Kansapathar Formation (Fig. 4a).

Figure 2. (a) Thick amalgamated medium-grained quartz arenites of Bhalukona Formation. Note mud-free, well sorted character given in the inset. (b-d) features noted on bedding planes: (b) Palimpsest ripples; note inheritance of same ripple morphology in successive younger beds (arrowed); cracks: semi-circular, sinuous (c) and spindle-shaped (d). Rust brown coloured bedding plane with network of curvilinear ridges (e) and its polished bedding perpendicular slab (f); Note wavy, irregular, swaley (arrowed) lamination character.

Figure 3. Microphotographs showing (a) alternation between sandy quartz layer and dark, wavy laminae bearing filamentous microstructures (b) entanglement of detrital quartz grains within wavy, crinkly laminae (arrowed). Mica grains with random orientation (c) and with preferred orientation (d) within the dark laminae, (e) Stabilisation of quartz grain surface by microbial mat growth (arrowed). Note convex-up growth of dark laminae, (f) Specks (arrowed) and microlaminations of iron oxides within the dark laminae.

Wrinkle structures and patchy ripples

Network of mm-scale shallow load depressions separated by minute ridges mark the wrinkle structures with crinkled appearance (Fig. 4b), which are seen in two different motifs viz. (i) occupying the ripple troughs and (ii) spread as a veil covering both ripple crests and troughs. Occasionally, the parallelism of ridges in the wrinkle

structures resembles kinneyia ripples (Sarkar et al., 2006, 2008). Wrinkle structures with unidirectional asymmetry are also not uncommon. On some bedding plane surfaces, bearing wrinkle marks, have ripples in discrete patches; the limbs of the ripples being abnormally steep and their surfaces exceptionally smooth (Fig. 4c). In cases, exceptionally well-preserved ripples show smooth, sloping lateral upward transition to a surface that records multidirectional

Figure 4. Well-sorted mud-free sandstones of kansapathar Formation (a). Wrinkle marks on bedding surface (b), ripples in patches (arrowed) with adjoining bedding surface marked with wrinkles. Note smooth, steep limbs of ripples (c), cracks along the crest lines of ripples (d; arrowed), semi-circular patches (arrowed) on the bedding surface bearing impression of rafted mat (e).

bedforms and wrinkle structures. The ripples along their crest lines bear cracks, which are linear and millimetre-deep (Fig. 4d).

One major goal of MRS study is to assign biogenicity in the structures. Loading and dewatering of microbial mat layers are the most favoured explanation for the presence of wrinkle marks on mud-free sandstone bedding surfaces (Noffke et al., 2003a, b; Sarkar et al., 2006). Wrinkle structures with unidirectional asymmetry in profile that is common in the mud-free Kansapathar Sandstone might have developed under shear of gentle wave or current on a microbially

mediated cohesive sand surface. The discrete ripple patches in otherwise wrinkled bed surface are developed with partial erosion of mat stabilised sand surface that allowed formation of ripples by wave action. The abnormal limb steepness and smoothness of surfaces of the ripples is suggestive of microbial mat growth following the ripple formation as well. The cracks along ripple crests may represent desiccation of exposed mat-bound ripple crests leading to incipient tears in the mat cover (Schieber, 2004; Sarkar et al., 2008). That the rippled surface got exposed and undergone desiccation gets

independent support from the presence of caliche' paleosol immediately above the rippled surface (cf. Chakraborty and Paul, 2008).

Rafted mat

Irregular, semi-circular patches (diameters in cms-scale) are observed on the bedding planes of Kansapathar sandstone; internally the patches are constituted of irregular, curved centimetre-long ridges and depression of 1 to 2 cm in width and several tenths of a millimetre in height. Often, ridges tend to overthrust on their adjacent depressions. Such patches are scattered both on limbs and crests of ripples (Fig. 4e).

Semi-circular patches having irregular ridges and depressions resemble microbial mats that became wrinkled due to shrinkage during sub-aerial exposure or to thin subaqueous mats that became detached as a result of flow turbulence. This feature was first described by Horodyski (1982), and attributed to dried-out fragments of episodically exposed thin microbial mats those curl up and then transported by wind or flowing water. Schieber (1999) and Simonson and Carney (1999) inferred that the overfolded structures or thin, wavy rock beds reflect the cohesive properties of bacterially bound deposits. Strata composed of eroded mat fragments are also interpreted as storm event layers (Bouougri and Porada, 2002). Taking into consideration i) absence of any feature indicating sub-aerial exposure and desiccation, and ii) storm origin of the strata within which these structures are observed (Paul, 2005), we are inclined to assign the detached mat origin triggered by tearing of mat under the storm action. The deformation of soft, cohesive mat fragment possibly caused the upward movement of the soft sediment

generating the ridges those often overthrust on their adjacent depressions.

Distribution of MRS within progradational package(s)

The preferential distribution of MRS within the Kansapathar stratigraphic column is illustrated in Fig. 5. Stacked progradational packages (cf. Catuneanu, 2006) record repeated transitions from lower to middle/upper shoreface characterise the studied section. Within individual package, while the wrinkle structures covering both crests and troughs of ripples dominate the basal lower shoreface part, the wrinkles are found to be restricted within the ripple troughs in the middle shoreface. Interestingly, the rafted, overfolded patches are seen only in the upper shoreface part that bears the evidences of storm action.

In a sequence stratigraphic backdrop, Chakraborty and Paul (2008) modelled the Kansapathar shoreface packages as part of forced regressive wedge. While the wrinkle marks covering both crests and troughs of ripples are restricted within the sandstones representing the deepest bathymetry i.e the lower shoreface part, their counterparts within the middle/upper shoreface are essentially confined within the ripple troughs, which are likely to be more moist part in the shallower bathymetry. Occasional high energy event like storm torn the cohesive mat layer and spread the mat fragments on the rippled bed surface.

Lower Sandstone, Khariar basin

Stacked meter-thick beds of fine- to medium-grained, well-sorted sandstones constituted of plane lamination and trough cross-

Figure 5. Progradational stratal stacking with measured litholog from Kansapathar shoreface succession. Asterisks alongside the right hand litholog indicate the levels from which the MRS are documented. Note wrinkle marks within lower shoreface covering both trough and crest of ripples, whereas those within the middle shoreface are confined within ripple troughs. The torn mat fragments are noticed in the upper shoreface that bear evidences of storm action.

stratification, occasionally intervened by thin-bedded rippled strata, represent the shoreface-beach succession present at the lower part of Khariar succession. An upward progradation from lower/ middle shoreface to upper shoreface/beach setting can be noticed upward within the stratigraphic column with systematic increase in bed thickness and decrease in the abundance of thin-bedded rippled strata. The structures described herein (setulf, ridges) are documented from the upper part of the lithopackage, inferred as the product of supratidal upper shoreface-beach set-up.

Setulf

Swarms of positive relief structures, distinctly steep at one end and flaring at other, strongly unidirectional in orientation are observed on the bedding planes of sandstones which are internally plane laminated or cross-stratified (Fig. 6a, b). Dimension of these structures is quite uniform; average length, width and height recorded are 7 cm, 3 cm and 1.5 cm, respectively.

Friedman and Sanders (1974) reported similar small-scale unidirectional positive relief structures from modern beach and termed them as 'setulf' i.e inverted flutes. Sarkar et al.,

(2011) from their studies within both modern sediments and ancient rock record suggested an origin for these structures in which trapping of wind-deflated sands on the lee sides of small, moist obstructions in littoral- supra littoral depositional set up is identified as the possible reason behind generation of positive relief. These workers, however, expressed their apprehension on preservation of these delicate, positive relief structures in the geological record unless they get the chance of

being fossilised under microbial mat cover. Suggesting a bias of these structures within the sedimentary archives of Proterozoic-Paleozoic time, these authors cited examples from two Neoproterozoic (~ 600 Ma) Indian examples, viz. the Upper Bhander sandstone, Vindhyan basin and the Sonia sandstone, Marwar basin. The present example dates back the antiquity of these structures within ca. 1400 Ma old Khariar sandstones.

Ridges

Many of the mud-free sandstone bed surfaces of the Lower sandstone unit of the Khariar Basin bear spindle-shaped, curled, folded and meandering ridges, which are broadly parallel to one another (Fig. 6c). Ridge widths vary between 0.02 and 1 cm and their maximum continuity is traces up to 9.5 cm. Ridges, curled, folded and meandering in nature, are analogous with 'petee' structures described from modern settings (Gerdes et al., 1993) and ancient rock records (Gehling, 1999), and interpreted as the product of drying and subsequent buckling, curling and rupturing of mat layer under wave and/or current action. Citing occurrence of median furrow along some ridges, Sarkar et al. (2006, 2008) suggested an alternate model in which flowage of cohesive mat layer converging from two sides of a crack under confining pressure from overlying younger bed is considered as the more preferred reason behind formation of the ridges. In absence of such median furrow, we are more inclined to relate the ridges within the Khariar sandstones with the first proposition. Supratidal depositional setting for the sandstones corroborates this contention.

Discussion

Alike Vindhyan and Marwar basins, a wide range of microbial mat related structures within the Chhattisgarh and Khariar basin successions bear clear indication for microbial mat proliferation in siliciclastic depositional environments of Indian sedimentary basins during the Mesoproterozoic time, as recorded in other parts of the world (Schieber et al., 2007). Table 1 summarises the observed MRS, their topology and characteristic expressions in the rock record. Unlike many of the MRS bearing sections around the Globe those represent tidal-supratidal paleogeography, the present structures are described essentially from wave-influenced foreshore/shoreface sections. Incidentally, Sarkar et al (2008) also described a spectacular range of MRS from the wave-agitated shoreface succession of the Sonia Sandstone, Marwar basin that shows transition up to supralittoral eolian setting. Indeed, microbial growth and associated sedimentation are likely to be most favoured in environments with low sedimentation rate, low to moderate energy and alternate domination of physical and biological processes. A (fair weather) wave-dominated shoreline with intermittent incursion of storm events may be a suitable environmental set up in this regard instead of perpetual tidal action that would impede mat growth (Bouougri and Porada, 2002). Possibly the dissipation of wave energy at the low-gradient Proterozoic epeiric sea margins (Friedman et al., 1992) combined with a low rate of sedimentation (lower freeboard; Eriksson et al., 1999) allowed microbial mat growth in the wave-dominated coastlines. A persistent, uniform shelf circulation and maintenance of delicate balance between sediment supply and subsidence in the epeiric basins (Eriksson et al., 1998) would have helped in the process. Above these, absence of grazers and bioturbators allowed mat proliferation and thereby

Figure 6. Plane-laminated and cross-stratified well-sorted quartz arenites in Lower Sandstone, Khariar basin (a), Swarms of setul on bedding surface (b), rolled-up mats on the bedding plane forming sub-parallel ridges (c).

Table 1. Mat features in the studied formations with their imagery expressions and mode of occurrence (upper/lower surface of bed or intrabed)

Formation/ Group	Observation made in	Nature of Structure	Topology	Imagery Expression
Bhalukona Formation, Singhara Group	outcrop	1. Palimpsest ripple	Bedding plane (Upper surface)	
		2. Cracks and ridges	Bedding plane (Upper/Lower surface (cast))	
		3. Manchuriophycus	Bedding plane (Upper surface)	
		4. Wavy crinkly laminae		
	Hand specimen polished section	a. Highly irregular, wavy, curved, and recurved laminae	Intra-bed	
	Under microscope	b. Dark grey laminae with wavy-crinkly and domal antigravity structure	Intra-bed	
		c. Detrital grains entangled in mat	Intra-bed	
		d. Specks and stringers of iron oxide	Intra-bed	
		e. Mica grains in a preferred arrangement (fly paper effect)	Intra-bed	
Kansapathar Formation, Chandrapur Group	Outcrop	5. Wrinkle structure Kenneyia ripple	Bedding plane (Upper surface)	
		6. Patchy ripple	Bedding plane (Upper surface)	
		7. Cracks in ripple crests	Bedding plane (Upper surface)	
		8. Fragments of torn mat	Bedding plane (Upper surface)	
Lower Sandstone Formation, Khariar Group	Outcrop	9. Setulf	Bedding plane (Upper surface)	
		10. Peetee structure	Bedding plane (Upper surface)	

influence the clastic sediment dynamics near the coastlines of the Proterozoic basins. Possibly a hydrodynamic flow condition that is sufficient to sweep mud but not strong enough to erode cohesive microbial mat infested surface was prevalent in the Chhattisgarh and Khariar wave-influenced shorelines. Although it is presumed that outer shelf storms would have been more regular in the Proterozoic time, the prolific presence of mat structures within the near shore sandstones of both the basins suggest significant quiescence and very low sedimentation between the high energy events.

In the studied sections the microbial imprints are noticed both on bedding plane and bed-perpendicular sections. Considering the processes involved in generation, Noffke (2009) classified MRS under five category viz. (i) growth, (ii) biostabilisation, (iii) binding, (iv) baffling and trapping, and (v) structures induced by the combination of all/some of the processes. The present MRS assemblages fall under all the categories. The wavy-crinkled laminae, ridges, cracks and setulfs represent the mat growth and biostabilisation, grains within the mat layer bear signature of trapping and binding and wrinkle marks, patchy ripples, impression of rafted mat fragments suggest combined actions of all the processes including the tearing of mat layer under high energy event/s.

Occurrence of MRS in the stratigraphic sections can mostly be correlated with regression-transgression cycle with dominant development within the transgressive portions of the rock sequence. Although as a general caveat this may be valid, the present study documents presence of MRS within the forced regressive and lowstand deposits of the Kansapathar Formation and the Bhalukona Formation as well. On low-gradient epeiric shelf under low continental freeboard, chances of preservation for forced regressive products are likely to be less because of their thin character and possibility of getting reworked by subsequent transgression and ravinement. Restricted erosion due to microbial mat cover of the sediment surface possibly allowed the forced regressive sediment on the Kansapathar sea floor escape the erosion from the flooding that established the lowstand system immediately above. In the Bhalukona Formation, it needs to be judged whether the aggradational stacking of lowstand is a reflection of increasing sediment supply keeping balance with generated accommodation due to rising sea level or because of high net sedimentation resulted from restricted erosion of mat infested sandy surfaces (cf. Sarkar et al., 2005).

Conclusions

Presence of a wide spectrum of MRS within the near shore sandstones of Mesoproterozoic Chhattisgarh basin and Khariar basin suggest unequivocal influence of microbial mat on shallow marine clastic sedimentation of Indian Proterozoic basins. The structures mostly generated either by deformation and loading of mucilaginous, sticky mat surface or their cracking in course of desiccation or syneresis. The waves and currents that prohibit the deposition of mud at the sites of microbial colonization, however, are not strong enough to erode the microbial mats once they are established. Retention of low-preservation structures viz. setulf show that stabilisation of sandy surfaces by mat successfully protected the depositional surfaces against erosion through high-energy flows. Tearing of mat and spreading of its fragments on bedding surface corroborates well with extreme high energy event e.g. storm. To escape complete destruction, mat fragments have to be deposited nearby, and covered by sediment to become preserved. Abundant mat growth on shallow marine

sandstones of the Chhattisgarh and the Khariar basins implies slow rate of sedimentation, in general, except phases when storms struck the shorelines.

Documentation of the MRS within the products of forced regression, lowstand and transgression suggests that the microbial mat growth and proliferation was pervasive in clastic nearshore sediments of Proterozoic basins irrespective of the sea level stand in which they belong. Variation in the character of the MRS within the progradational shoreface packages of Kansapathar Formation clearly shows importance of taphonomy i.e. subsequent sedimentary events that lead to the complete formation of a microbial mat, in the growth and preservation of these structures. It is presumed that on low-gradient Proterozoic epeiric shelves under low freeboard, infestation of microbial mat cover may increase chances of preservation for thin forced regressive products manifold from subsequent transgression and ravinement. Due to biostabilizing microbial activities, it is possible that more of them have escaped erosion than would have been the case without the presence of microbes.

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