# Microbial mat-induced sedimentary structures in siliciclastic sediments: Examples from the 1.6 Ga Chorhat Sandstone, Vindhyan Supergroup, M.P., India

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This paper addresses macroscopic signatures of microbial mat-related structures within the 1.6 Ga-old Chorhat Sandstone of the Semri Group – the basal stratigraphic unit of the Vindhyan succession in Son valley. The Chorhat Sandstone broadly represents a prograding succession of three depositional facies ranging from shallow shelf to coastal margin with aeolian sandsheet. The mat-mediated structures were generated because of plastic or brittle deformation of sand, turned cohesive and even thixotropic because of microbial mat growth. Mat growth also favoured abundant preservation of structures that usually have low preservation potential.

Prolific growth of microbial mat in the subtidal to intertidal zone of the Chorhat sea was facilitated due to lack of grazing and burrowing activities of organisms in the Precambrian. It further indicates low rate of sedimentation between the storms, as also attested by frequent superposition of storm-beds, even near the storm wave base. It also reduces erosion and that, in turn, would imply low sediment concentration in flows leading to development of bedforms that are likely to be smaller in size and isolated from each other in a single train in contrast to those that form in mat-free sands.

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## 1. Introduction

Microbiota appeared on Earth before 3.8 Ga, and perhaps flourished during the Proterozoic time (Schopf 1999; Eriksson *et al* 2000). In Precambrian setting microbial mats understandably colonized most surfaces where predatory and/or competing organisms were absent (Walter and Heys 1985) as evidenced by the common occurrence of stromatolites and microbial laminites within Precambrian carbonate successions. However, microbial activity was comparatively reduced during the Phanerozoic and confined to stressful environments (Schieber 1998; Hagadorn and Bottjer 1999). In Precambrian siliciclastic successions, on the other hand, the evidence of microbial activity is subtle as mats lose their characteristic structures in the absence of early cement and hence only sparingly preserved (Pflüger and Sarkar 1996; Schieber 1998). Despite this rarity of evidence, in recent years, striking advances have been made, especially for mat-related features preserved in siliciclastic rocks (Schieber 1998, 1999, 2004; Gehling 1999; Hagadorn and Bottjer 1999; Pflüger 1999; Seilacher 1999; Eriksson *et al* 2000; Gerdes *et al* 2000; Noffke 2000; Noffke *et al* 2001, 2002, 2003a, b; Bouougri and Porada 2002; Prave 2002; Sarkar *et al* 2004, 2005; Banerjee and Jeevankumar 2005; Parizot *et al* 2005). A wide variety of Mat-Induced Sedimentary Structures (MISS, Noffke *et al* 2001; Schieber 2004) is reported from sand, modern and ancient. At times they are bizarre in nature and

**Keywords.** Microbial mat; Proterozoic; siliciclastics; mat-induced structures; 1.6 Ga-old Chorhat Sandstone.

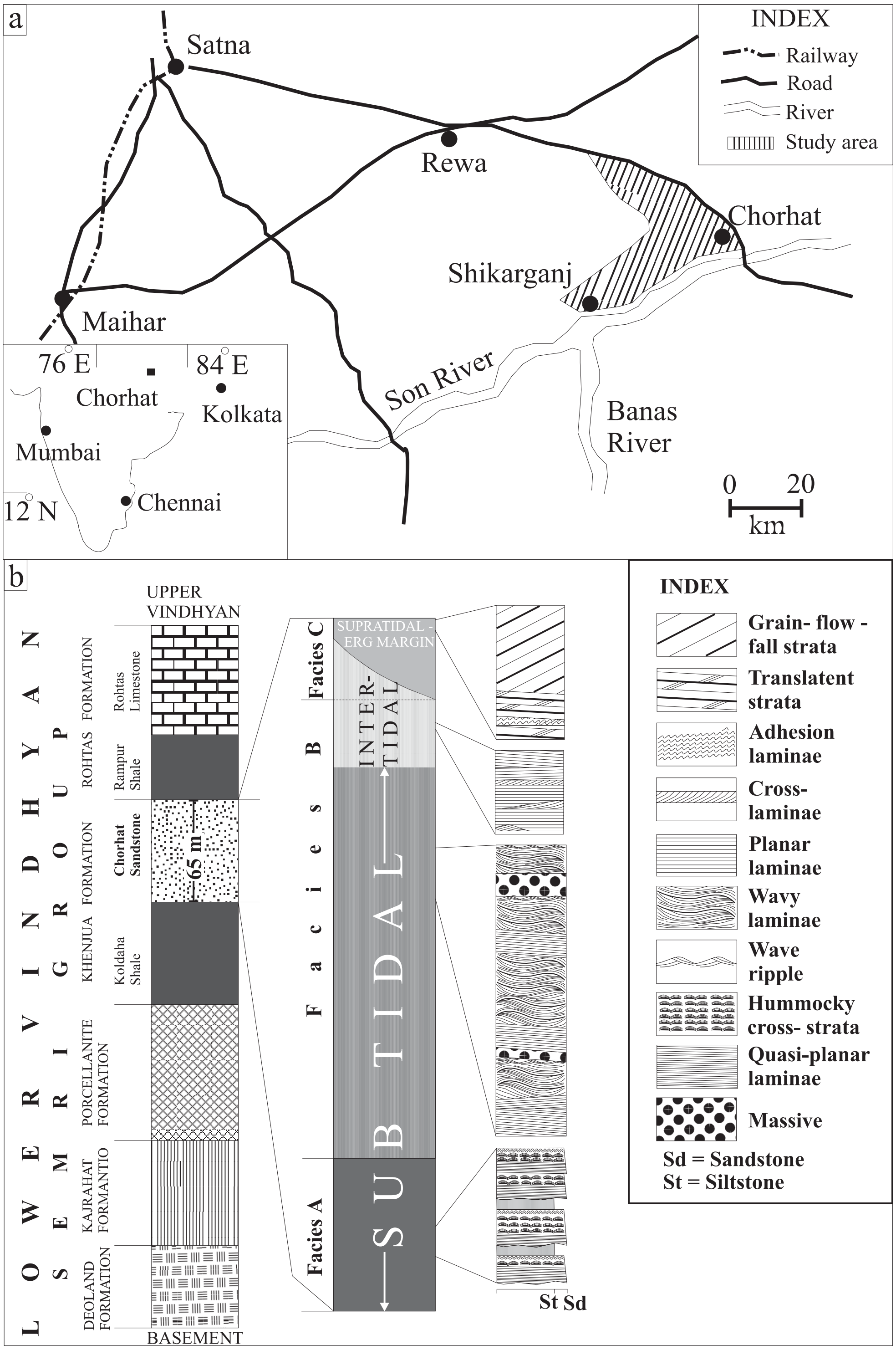

Figure 1. Location map with study area demarcated (map of India within inset). **(a)** Stratigraphic frame of the Chorhat Sandstone differentiated in facies superposed one over the other and their respective structural assemblages **(b)**.

may be misinterpreted as trace fossils (Seilacher 1999).

Abundance of mat related structures in Proterozoic sandstone formations impart a distinct dimension to Proterozoic biosedimentology. These structures arise because sand responds to external stress differently when it is mat-infested; it turns cohesive, even thixotropic like mud (Schieber 1998; Eriksson *et al* 2000; Bouougri and Porada 2002). Extracellular Polymeric Substance (EPS) present in plenty within microbial mats provides the required glue for cohesiveness of sand (Flemming

Table 1. *Facies constituents of the Chorhat Sandstone and their interpretations.*

| Facies | Description | Interpretation |
|---|---|---|
| C | This is a medium-grained sandstone characterized mainly by adhesion laminae and translatent strata. Isolated cross-sets (< 32 cm thick) with inversely graded grainflow laminae alternating with finer grained grainfall laminae locally present. Maximum thickness 8 m and confined to the western sector only (max. outcrop length 40 m) | Aeolian sandsheet formed presumably in an erg-margin wet system, perhaps along a coastal fringe (supratidal- erg margin) |
| B | Fine-to-medium grained sandstone beds generally thicker than 10 cm, often amalgamated, massive or quasiplanar and wavy laminated, the latter intervened by wavy erosion surfaces. Wave ripples often preserved on bed top. The top ∼10 m of the facies unit immediately underlying the Rampur Shale, the sandstone bed surfaces often bear ripples migrating along troughs of larger ripples, divergent parting lineation, spectacularly preserved rill marks in abundance. Muddy siltstone, generally thinner than a centimeter locally occur within this part. Reddish mudclasts concentrate at the base of many sandstone beds. Wart marks and adhesion ripples occur locally. Maximum thickness of the facies unit is 45 m | Deposition presumably took place in shallower shelf, mostly within fair-weather wave base. Towards top depositional surface got exposed intermittently (subtidal to intertidal) |
| A | Characterized by fine-grained sandstone–siltstone interbedding. Sandstone beds are tabular in shape, often less than a centimeter thick; relatively thicker ones overall graded, have sharp erosional bases riddled with gutters and prods followed up by quasiplanar laminae, hummocky cross-stratification and finally wave ripples on bed-tops. Amalgamation between sandstone beds is not uncommon. Thins and eventually disappears westward within the studied stretch. Maximum facies unit thickness 15 m | Siltstone beds are autochthonous, while sandstone beds formed during high-energy events, probably storms. Common thinness of storm beds suggests deposition near the storm wave base (deeper subtidal) |

1991; Neu and Marshall 1991; Neu 1994; Noffke *et al* 2003a).

Most of the reported mat-induced structures in siliciclastics are confined mainly to Neoproterozoic formations. This paper, on the other hand, describes such features from the Chorhat Sandstone of the Lower Vindhyan in central India (figure 1a and b), which is of Paleoproterozoic–Mesoproterozoic age. The genetic implications of microbial mat-mediated structures are also explored.

## 2. Stratigraphic and depositional frame of the Chorhat Sandstone

The reddish brown 65 m-thick Chorhat Sandstone belonging to the Semri Group (figure 1b) is dated around 1.6 Ga on the basis of U/Pb and Pb/Pb ratios in SHRIMP analysis by two different groups of workers independently (Rasmussen *et al* 2002; Ray *et al* 2002). This dating is further reconfirmed by Pb–Pb data obtained from carbonaceous megafossils *Grypania* (1599 ± 48 ma) of the Rohtas Formation, the topmost unit of the Semri Group (figure 1b; Sarangi *et al* 2004). The Chorhat Sandstone overlies the dark coloured, offshore-originated Koldaha Shale (Sarkar *et al* 1996; Bose *et al* 1997, 2001; Banerjee 1997) and is, in turn, overlain by the Rampur Shale (Rao and Neelakantam 1978). The Chorhat Sandstone was deposited on a wave-dominated marine shelf (Seilacher*et al* 1998), bordered by a coastal flat with aeolian sand sheets (figure 1b; table 1). The lowermost facies (Facies A) is characterized by vertical stacking of 35–40 cm thick beds of light coloured, overall graded, tabular sandstone, alternating with siltstone less than 5 cm thick. The beds have sharp and erosional bases riddled with gutters and prod marks. The sandstone of this facies is characterized by hummocky cross stratification, quasiplanar strata and wave ripples. The middle one (Facies B) is characterized by well-sorted, fine-grained, wave-rippled sandstone with emergence features towards the top. The sandstones of this facies, like those of Facies A are well sorted and are completely devoid of mud (figure 2). The uppermost unit (Facies C) occurs locally and consists of well-sorted sandstone with various aeolian features (facies constituents summarized in table 1). The mat-related structures are mainly present within Facies A and B.

## 3. Microbial mat-related structures

A variety of structures of potential microbial mat origin occurs on bed surfaces or on bed interfaces of the Chorhat Sandstone as described below.

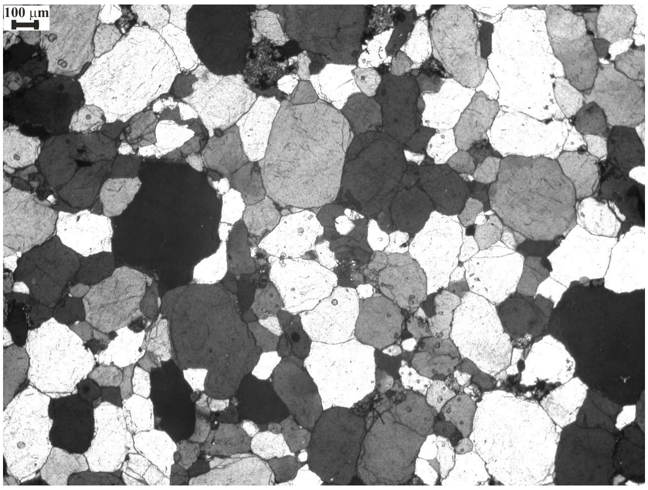

Figure 2. Well-sorted sandstone (Facies B). Note the absence of mud within the sandstone.

### 3.1 *Cracks and ridges*

#### 3.1.1 *Cracks*

Cracks, millimeter to centimeter in width, are common in occurrence on mud-free sandstone bed surfaces in the Chorhat Sandstone. Their geometry may vary from rectangular, polygonal, circular, sinusoidal to spindle-shaped (figure 3a, b, c). They may form a network or may run parallel to each other. In the networks they often cut across each other (figure 3a, b). They are invariably steep-sided and may occur selectively along crests or troughs of wave ripple (figures 3b, 4).

Steep flanks distinguish these from animal trails and identify them as cracks. Crack generation on sand itself indicates mat influence, contributing cohesion to the granular sediment, primarily noncohesive. Although the mat has now disappeared on degeneration and decomposition, the cracks bear a proxy record of the pristine mat. Desiccation might have been responsible for cracking of the mat-infested sediment surface (Schieber 2004), but the place where the cracks cut across each other, their subsurface syneresis origin is almost certain (figure 3a, b). Syneresis origin of the majority of cracks is further corroborated by their occurrence in sediments deposited well below the sea surface (Seilacher *et al* 1998; Facies A and lower part of Facies B unit, see table 1).

Confinement of cracks, generally sinusoidal in plan, often within ripple troughs is possibly because mat thickens within troughs and the sinusoidal geometry is owing to microscale variation in mat topography (Pflüger 1999; Scheiber 2004; Parizot *et al* 2005). On certain instances these trough-confined cracks are short and straight, and oriented at an acute angle to the trough axis. Plummer and Gostin (1981) suggested shrinkage of syneresis-related swelling of clay veneers at sediment–water interface and/or floundering under sediment overburden. Schieber (2004) and Parizot *et al* (2005) attribute similar cracks to

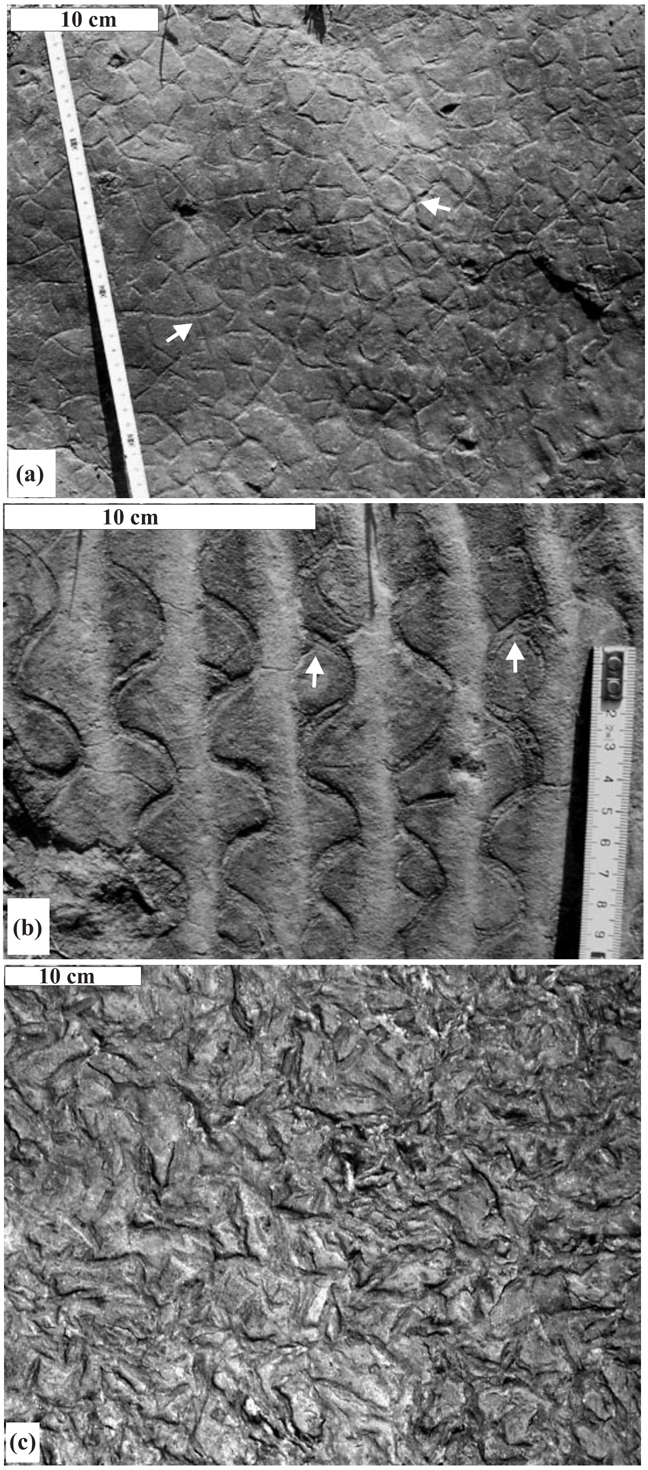

Figure 3. Cracks within sandstone: Rectangular **(a)**, sinusoidal **(b)** and spindle-shaped **(c)**. Arrows point cross-cut between cracks.

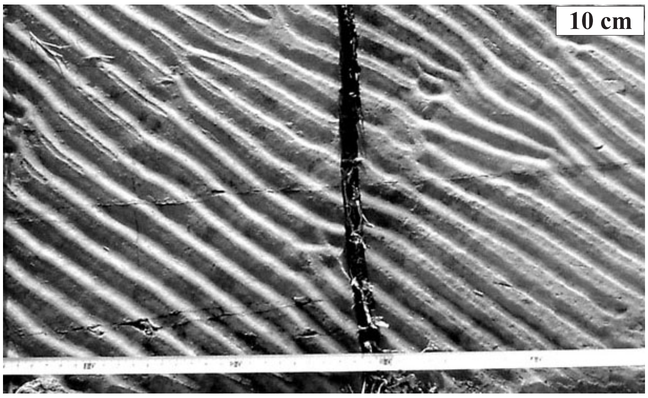

Figure 4. Cracks along crests of wave ripples, often spindle-shaped within Chorhat Sandstone.

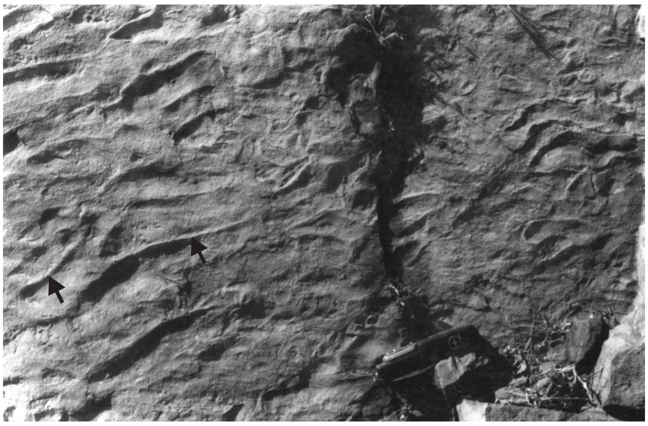

Figure 5. False impression of sharp ripple crests (arrows) within Chorhat Sandstone, though close observation reveals that crests of the ripples are, indeed, rounded (knife length 7.5 cm).

desiccation of mats. This structure is widely known as 'Manchuriophycus' and whether generated on exposed surface or under water, they are now widely accepted as mat features (Gehling 1999; Parizot *et al* 2005), occasional invocation of trace fossil origin notwithstanding (e.g., Kulkarni and Borkar 1996).

Spindle-shaped cracks along ripple crests (figure 4) owe their origin to shrinkage of very thin surficial sediment on top of the rippled sand. Since these cracks are never reported from modern mats, it is difficult to say whether they formed at sediment–air interface, sediment–water interface or in shallow subsurface (Parizot *et al* 2005); the tensile shear needed for their formation might have been induced by desiccation or by sediment overburden, stress accentuating on the highs (Sarkar *et al* 2004). Beveled edges of the surface layer created by the cracks may give a false impression of unusual sharpness of the ripple crests formed under combined operation of wave and current (figure 5). Gehling (1999) reported similar sharp crests of combined flow-ripples from a Neoproterozoic succession.

### 3.1.2 *Ridges*

Ridges with heights $\sim 0.5$ cm and similar geometric variation as the cracks, but generally wider than them (often $> 1$ cm), are also common on sandstone bed surfaces (figure 6a, b, c). Unlike cracks they generally have a rounded bottom in profile. While forming a network these ridges may also cut across each other.

Small-scale antiform structures, generally in polygonal form, developed through buckling, doming and rupturing of microbial mats called pette structure are reported from modern settings (Reineck *et al* 1990; Gerdes *et al* 1993) as well as from the rock record (Gehling 1999) and have been attributed to winds, currents and gas development as well as intermittent drying (Schieber 1999, 2004). Perhaps a more likely explanation of these linear ridges would be deformation of a syneresis crack because of flowage of the cohesive mat layer converging from two sides of the crack under confined pressure enclosing the crack-fill derived from the younger bed. Presence of median furrows in many such ridges depicting meeting of two flanks of the cracks together at their tips further corroborates this inference (figure 6b, c). The crack-fills stand out on bed surfaces as the sandstones surrounding them are degraded on exhumation. These ridges have the potential for misguided identification as burrows.

### 3.2 *Wrinkle structures*

Wrinkle structures are common throughout the Chorhat Sandstone (figure 7a, b). The minute ridges generally have a crinkled appearance, may be parallel to each other (*Kinneyia ripples*) or may form a network. In networks they may cross-cut (figure 7b, arrows) each other or may share the same crests at their meeting points (figures 7a, b; Banerjee and Jeevankumar 2005).

Wrinkle structures on sandstone bed surfaces defy any explanation unless mat growth is invoked particularly where mud is absent. Loading and dewatering processes during burial of microbial layers may be a likely explanation (Noffke *et al* 2003a) because of the water content (around 90%) of mats (Neu 1994). Margins between very shallow load depressions may, indeed, appear as wrinkles. However, in modern intertidal settings wrinkle marks on mats are common in occurrence at the sediment–water interface. Gas build-up because of

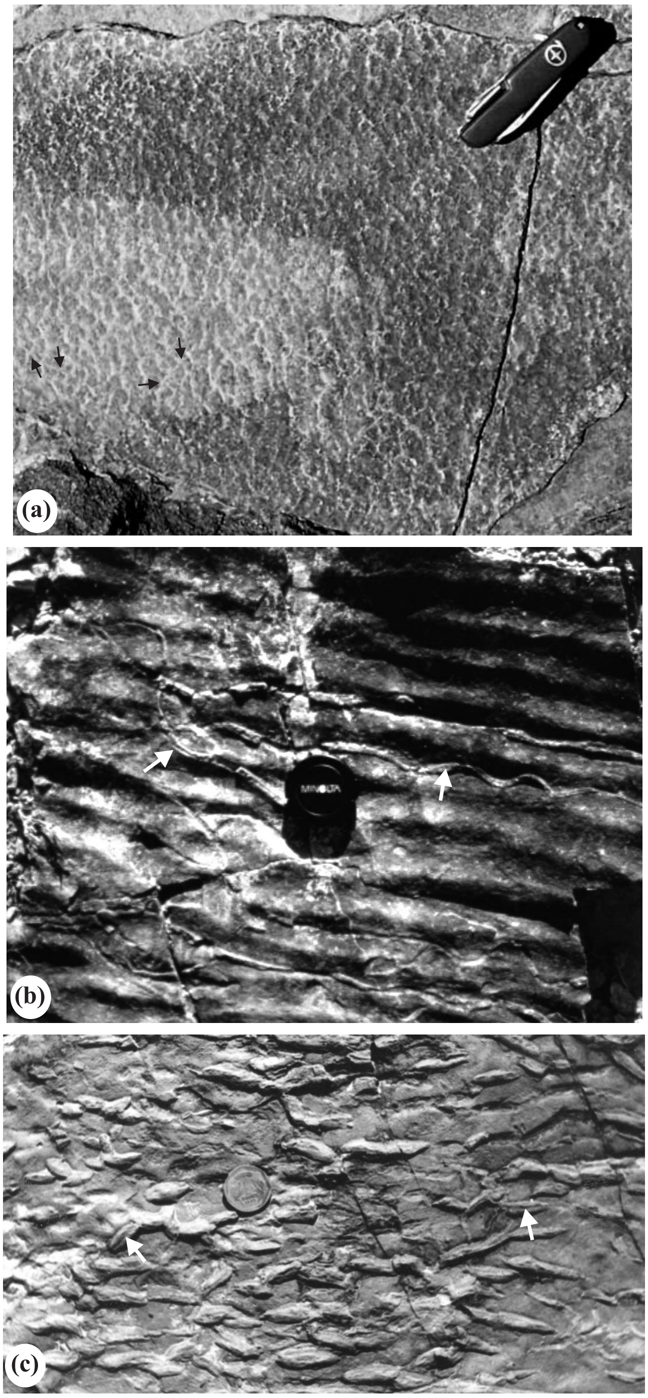

Figure 6. Polygonal ridges locally cross-cutting each other (arrows) (knife length 7.5 cm) **(a)**, meandering ridges preferably along ripple troughs (lense cap diam. 5 cm) **(b)** and spindle-shaped ridges (coin diam. 2.6 cm) **(c)** on sandstone bed surfaces. Note median furrows on the ridges in (b) and (c) (arrows).

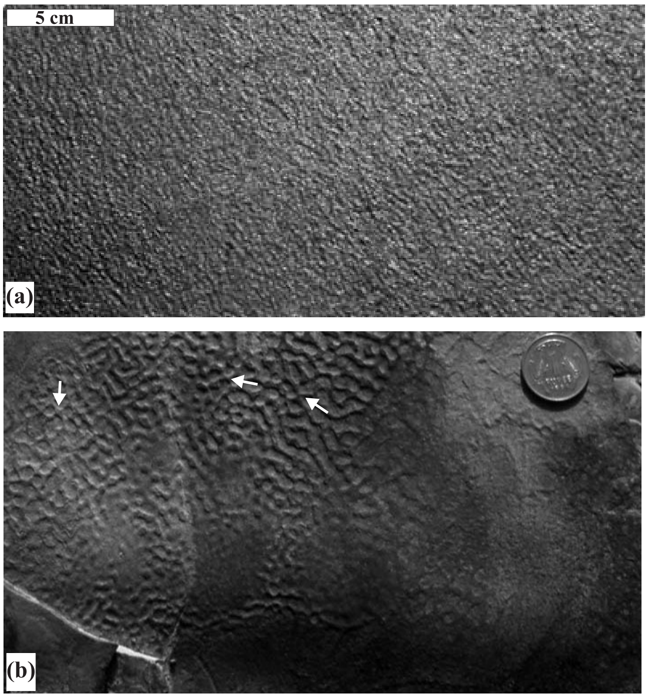

Figure 7. Wrinkle marks **(a)** and kinneyia ripples (coin diam. 2.6 cm) **(b)** on sandstone bed surface.

decay at mat bottom can generate wrinkle structures commonly with steep slopes of their troughs (Gerdes *et al* 2000) and Pflüger (1999) generated similar structures under gas pressure in experimental setting. Gentle wave or current shear may also form the wrinkle structure on mat (Hagadorn and Bottjer 1997; Bouougri and Porada 2002; Banerjee and Jeevankumar 2005). Wrinkle structures with unidirectional asymmetry in profile that is common in the Chorhat Sandstone might have developed under shear of gentle wave or current on a microbially mediated cohesive sand surface. The two sets of cross-cutting wrinkles within Chorhat Sandstone were presumably formed by variably directed flow shears (Banerjee and Jeevankumar 2005).

### 3.3 *Ruptured domes and sand bulges*

#### 3.3.1 *Ruptured domes*

Domal structures with a crater-like depression and of different diameters (up to 5 cm) are locally common on sandstone bed surfaces (figure 8a). Some of them have radiating cracks around them (figure 8b) and are named as 'Astropolithon' described by Pflüger (1999).

Expulsion of fluid, particularly gas generated by decay at mat bottom, is a likely explanation for these structures; radial cracks around them corroborate mat-induced cohesiveness of the sand.

#### 3.3.2 *Sand bulges*

Unruptured domes about half a centimeter high and about a centimeter in diameter are locally common within Chorhat Sandstone (figure 9). They

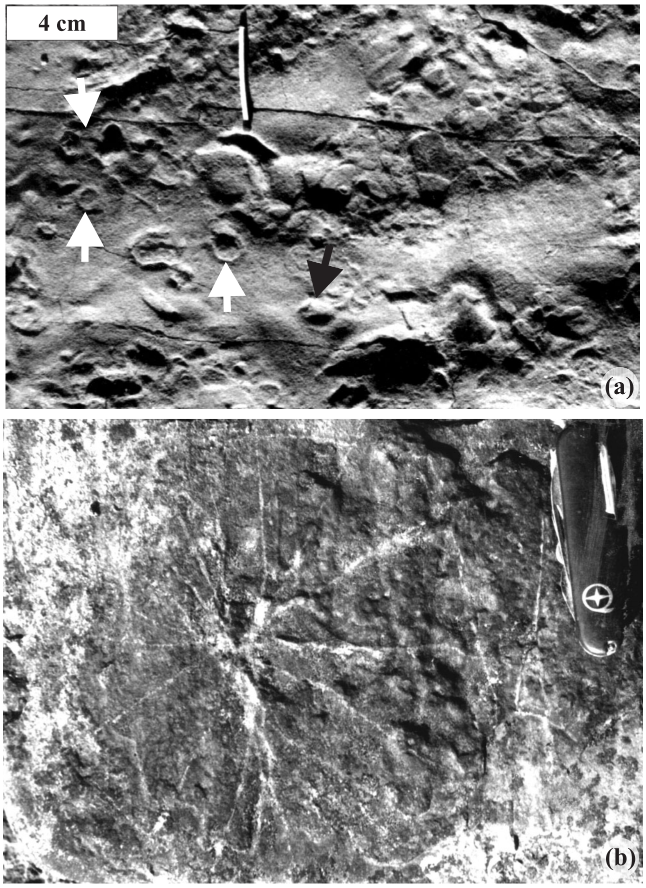

Figure 8. Domes with craters (white arrows), a dome without crater is marked by black arrow **(a)**; sand volcano with radial cracks (knife length 7.5 cm) **(b)**.

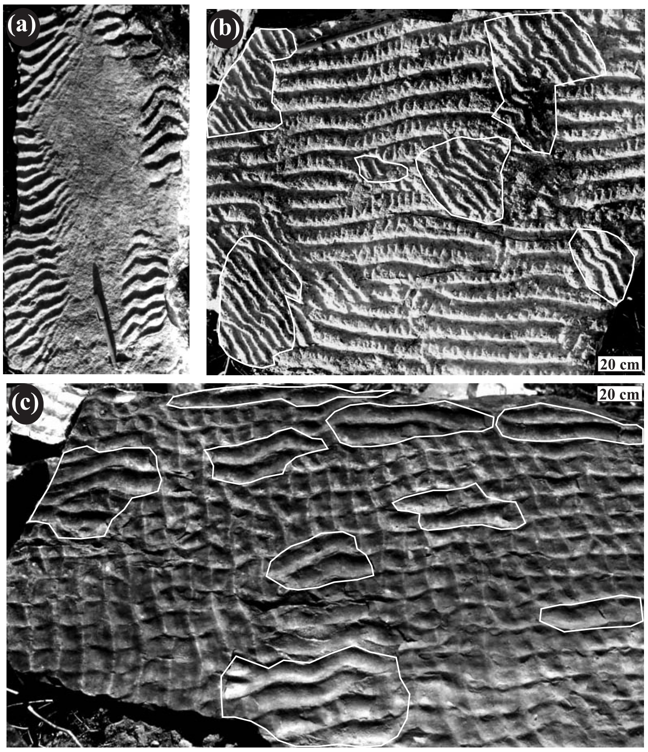

Figure 10. Patchy ripples: partially washed out (note jagged and stepped margin on the right while the margin on left shows reworking) (pen length 14 cm) **(a)**; in the midst of three generations of ripples the youngest one occurs in isolated patches (outlined) **(b)**; among two generations of ripple trains, that of the first generation has escaped reworking in isolated patches (outlined) **(c)**.

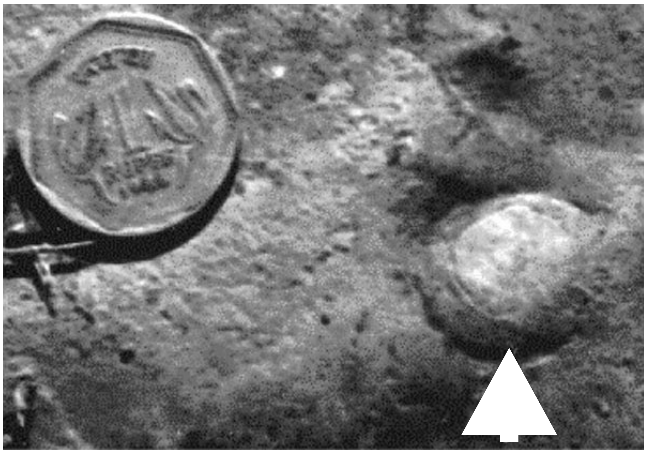

Figure 9. Sand bulge with rim around (arrow) on Chorhat Sandstone bed surfaces.

may coexist with the ruptured domes on the same bed surface.

Apparently gas was trapped under microbial mat left intact and sand filling the space created under the mat. Coexistence of the bulges with ruptured domes further corroborates this contention. Although similar structures commonly form under mat covers in modern intertidal settings, their Vendian counterparts are often identified as Medusa (e.g., Fedonkin 1990, his plates 1 and 2). Such identification would be far-fetched for the structures from 1.6 Ga-old Chorhat Sandstone.

### 3.4 *Patchy ripples, erosional and depositional*

Patchy occurrence of discrete sets of ripples is a common feature throughout the Chorhat Sandstone (figure 10a, b and c). In some cases the preservation of a single train of ripples is patchy, margins of the patches are jagged and stepped and the bed surfaces between the patches are planed off (figure 10a). On other instances, a first generation ripple is reworked by a second-generation ripple, but in patches (figure 10b and c).

In the first case the important question is how the ripple patches were retained after the onslaught of a strong flow-shear that generally planed off the bed surface. A protective mat cover on the patches has to be invoked. Possibly the mat cover had been widespread, but was torn away from most parts by a strong current or wave. Ripples were preserved under the residual mat that still stuck to the rippled surface. Jagged and stepped margins of the patches strongly corroborate this contention. In the second case, the first generation ripple was reworked subsequently, but in patches; a mat cover must have been present where it escaped reworking.

### 3.5 *Load casts*

Many sandstone bed surfaces in the lower part of Facies B bear closely spaced steep-sided depressions (depth $< 1$ cm), almost circular in cross-section and diameter ranging from 0.5 to 3.5 cm, more or less uniform on a single bed surface (figure 11a, b). On rippled bed surfaces the depressions have preferred occurrence within the ripple troughs (figure 11c). Several interfaces between amalgamated sandstone beds when prized open show the depressions on top of the bed lying below and their casts at the sole of the bed lying above. No mud exists at the interfaces, not even within the depressions.

The depressions and their mound-like casts at the sole of the bed immediately overlying them are clearly results of loading. Although loading between two sandstone beds essentially similar in composition is a bit unusual, the bed lying below must have responded thixotropically to the loading; the bed lying above and always massive in nature must have been deposited rapidly, possibly from storm-induced flow. The planar flat nature of the top surface of the bed lying above indicates that the relief variation generated by the depressions was eliminated during sedimentation of this bed. Evidently the deformation involved is synsedimentary in origin as load casts are.

Perhaps only gelatinous microbial mats could turn granular sand thixotropic at top of the bed lying beneath the interface. Preferred occurrence of the depressions along ripple troughs can then be readily explained by the known preference of mat to grow within the troughs.

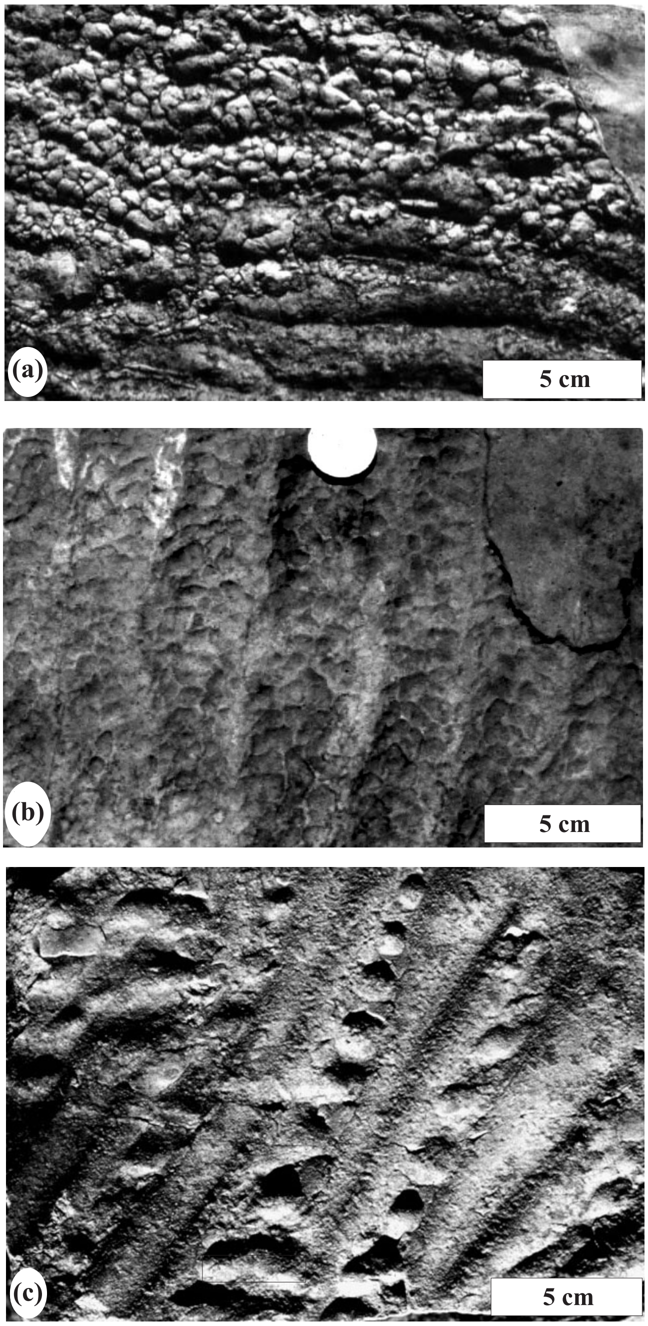

Figure 11. Loads at the sole of a bed **(a)**, load casts on top of a bed with a thin storm bed overlying it at right top **(b)** and load casts along ripple troughs on top of another bed **(c)**. In all the cases the beds are of sandstone.

### 3.6 *Sand chips*

Some bed surfaces in Facies A are mantled by a lag of sand chips (figure 12). The chips are spherical, ellipsoidal, triangular, crescent-shaped or without any definite geometry. Crescent-shaped ones are presumably deformed. The chips are, however, generally rounded at their edges and measure in length up to 5 cm. Locally they may have discernible preferred orientation. The sand chips are well-sorted under microscope.

Sand chip-bearing intraformational conglomerates have been reported from all ages (Menzies 1990; Runkel 1994; Pflüger and Greese 1996). Early carbonate cement/mineral cement formation between grains before reworking can explain clast generation from granular sand. In the Chorhat Sandstone there is no carbonate or evaporite mineral cement that can be attributed to early diagenesis. The only cement present is of iron oxide and silica that succeeded pressure welding of grains. Deformation indicates flexible response of

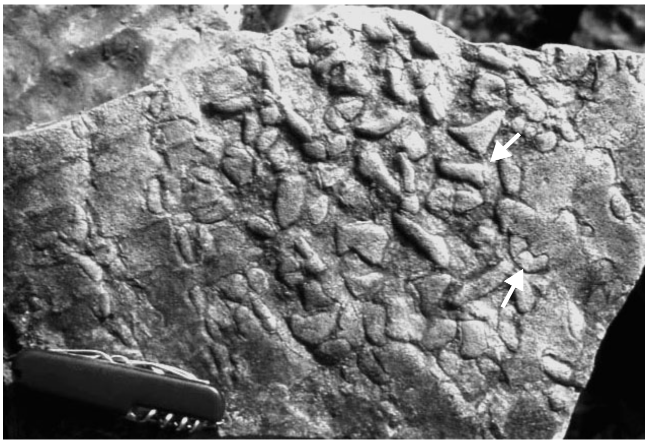

Figure 12. Sand chips on top of a sandstone bed. Some of the chips are deformed (arrows) (knife length 7.5 cm).

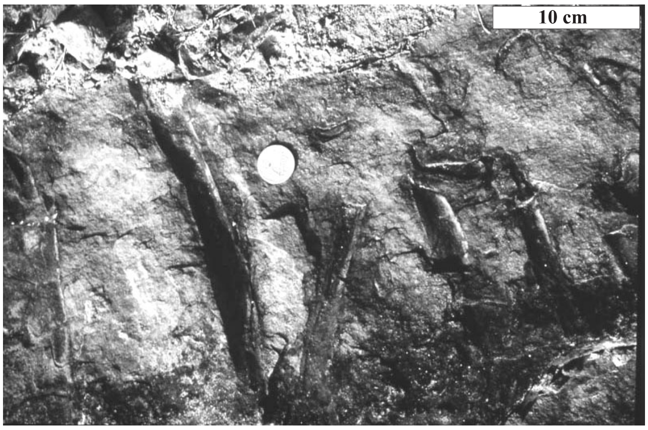

Figure 13. Silt curls oriented roughly parallel to each other embedded within a sandstone bed.

the intraclasts and implies presence of an elastic binding agent, such as, flexible organic tissues of microbial mat (Pflüger and Greese 1996). Occasional storm-induced flows were presumably responsible for the erosion of the mat infested sand layers under the Chorhat Sea.

### 3.7 *Silt curls*

Curls of mud-free coarse siltstone up to 18 cm in length are present, albeit rarely, on bed surfaces at the upper part of Facies B (figure 13). Their diameter varies from 2 to 4 cm. The silt curls on a single bed surface are oriented parallel to each other (figure 13).

The silt curls in the Chorhat Sandstone are essentially similar in form with mud curls that are generated on desiccation. Mutually parallel orientation of the clasts speaks for their reworking by strong flows. It is, however, intriguing how such curls form in granular, non-cohesive silt and how these curls could sustain reworking by a strong flow. Even if we surmise derivation in a viscous flow for explaining sustenance of these delicate curls, the curling sediment must have acquired a very high degree of cohesiveness presumably because of microbial mat growth. Similar sandy or silty mat curls generated through desiccation are common in occurrence in modern tidal flats (Reineck *et al* 1990; Witkowski 1990) and their ancient equivalents are reported from a few other shallow marine successions (Noffke *et al* 1997; Demicco and Hardie 1994). Eriksson *et al* (2000) reported similar parallely oriented sand roll-up structure also from 1.8 Ga aeolian interdune deposit of Waterburg Group, South Africa.

Figure 14. Palimpsest ripples (finger pointing) on top of the thin younger bed partially preserved on right; the rippleform is inherited from the underlying bed exposed on left (transparent). Towards top of the photo the rippleform is no more recognizable on account of leveling (non-transparent).

### 3.8 *Palimpsest ripples*

These are rippleforms replicated from the bed underlying (figure 14). For such replication, the overlying bed has to be very thin. This structure is commonly found in Facies A with occasional amalgamation of storm beds, but by no means exclusive to it.

Palimpsest ripples (Pflüger and Sarkar 1996) wrongly depict the hydrodynamic condition of deposition of the bed on which they are found; in fact, they carry the memory of hydrodynamic conditions that prevailed during deposition of the underlying bed. Such replication is attributed to trapping of particles by filaments and EPS of microbial mat grown uniformly over ripples formed earlier (Pflüger and Sarkar 1996). A combination of very low rate of sedimentation and complete cessation of erosion is an essential prerequisite for generation of palimpsest ripple (Noffke 2000). Degree of replication may, however, vary. When ripples on underlying bed is replicated well, the structure is called 'transparent' and when thicker mat growth within ripple troughs renders the ripple geometry unrecognizable, the structure is called 'non-transparent' (figure 14; Noffke *et al* 2003a). Thicker growth of mat within depressions tending to remove relief variation on the depositional substratum thus leads to 'leveling' (Noffke *et al* 2001).

## 4. Implications of microbially originated sedimentary structures

Abundant occurrence of microbial mat-related structures on almost every storm-deposited sandstone bed surface indicates that very little sedimentation took place during the intervals between episodic storms (Seilacher *et al* 1998), as documented from deposits of epeiric seas (Shaw 1964). Very frequent amalgamation of successive storm beds not only in Facies B, but also in Facies A, deposited near the storm wave base, attests to this contention.

Almost ubiquitous preservation of these structures clearly points to severe impediment to erosion. Sand-laden flows derived most of their loads from outside the depositional system since contribution from the depositional substratum had been very limited. A profound tendency for the flows to be relatively depleted in sediment concentration or, in other words, a negative sediment budget can be surmised. It is implied that bedforms would tend to be small with reference to the flow potential and detached from each other in a single train (Kocurek 1996). Detached bedforms are, indeed, common in occurrence within the Chorhat Sandstone and Sarkar *et al* (in press) have cited an excellent record from the late Proterozoic Sonia Sandstone, Rajasthan.

The mat-related structures, except possibly some of the cracks and the silt-curls, in the Chorhat Sandstone were generated in subtidal setting. In contradiction to this observation, no significant occurrence of microbial mat is expected in modern subtidals because grazers and bioturbators are present in plenty to destroy them. Since both kinds of destroyers were generally absent, subtidal mat structures are present in profusion in the Chorhat Sandstone formed during the Paleoproterozoic–Mesoproterozoic transition. Abundance of mat-related structures in subtidal facies can, therefore, be a good criterion to distinguish formations of Precambrian age from those in the Phanerozoic.

Since microbiota constitute the earliest form of life, knowledge about microbial mat-related structures in sandstones, as described above, has a great potential in Planetary Geology, looking for relict of life where water existed once upon a time, such as in Mars (Kral *et al* 2004; Pietrogrande *et al* 2005).

## 5. Conclusions

Microbial mat-related structures present aplenty in numbers and varieties in the $\sim 1.6$ Ga-old Chorhat Sandstone in Central India reveal that the mud-free granular sands and silts at bed surfaces frequently acquired unusual cohesiveness. The structures were generated mostly by deformation of sticky, leathery or gelatinous mats in response to forces applied from below and above or developed within them by shrinkage. Mats also ensured retention of structures of low preservation potential even after the onslaught of high-energy flows.

In the prograding Chorhat Sandstone succession that developed mainly in a storm-dominated shelf and ultimately emerging above the sea surface, the majority of mat-related structures formed in the subtidal zone. Modern and Phanerozoic counterpart of that is virtually devoid of microbial mat in general presence of animal grazing and bioturbation. Indigenous mat structures of subtidal origin, therefore, make a distinctive criterion for Precambrian successions.

Abundant mat growth on almost all sand bed surfaces in the Chorhat Sandstone implies slow rate of sedimentation in the intervals between storms, and frequent storm-bed amalgamation, even in the distal offshore and near the storm wave base, testifies it. This profusion of mat must have acted as a great impediment to erosion. As a corollary, sand-laden flows derived their loads mostly from outside the depositional system and there must have been a tendency of the sediment budget of the flows to turn negative.

Familiarity with mat-related structures in sandstone, as described here from the Chorhat Sandstone, can go a long way in discovering evidence of life in other planets where water is likely to have existed at an early stage of evolution.

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