A review of biotic signatures within the Precambrian Vindhyan Supergroup: Implications on evolution of microbial and metazoan life on Earth

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This study presents a review of the wide spectrum of biotic signatures within the Precambrian Vindhyan Supergroup deposited during the ‘boring billion’ and assesses their biological affinity and age implications. The sedimentation took place in wide-ranging palaeo–environments from fluvial to offshore through shallow marine. While the lower part of the ~ 4500 m thick Vindhyan succession is older than 1650 Ma, the age at its top part is poorly constrained, ranging from 1000 to 650 Ma. Microbial records are abundant in the form of stromatolites in limestone and microbially induced sedimentary structures (MISS) on both siliciclastics and carbonates across the Vindhyan succession. The wide morphological variation of these two features corresponds to depositional processes, early cementation, as well as lithological variations. The stromatolite record, as well as calcified and chertified microbial fossils, attest to the Mesoproterozoic to Neoproterozoic age of the sediments. Although the carbonaceous body fossils do not have age implications, they indicate the proliferation of algal life during the Meso– to Neoproterozoic time. The Ediacaran–like fossils mostly relate either to ‘discoidal microbial colony’ or detached pieces of microbial mat. Wide-ranging putative metazoan fossil reports remain the focal point of attention for many years. Although most of these reports are found to be microbially originated, some of these features have the potential to highlight the evolution of multicellular life during the Precambrian.

Keywords: Stromatolite, Microbial mat, Discoidal microbial colony, Proterozoic, Vindhyan, Carbonaceous fossils

INTRODUCTION

A large part of the Precambrian biosphere was dominated entirely by the microbiota and devoid of any major biological evolution, hence it is considered to be ‘boring billion’ (1.8–0.8 Ga) (Brasier and Lindsay, 1998; Mukherjee et al., 2018). The sedimentary records of the early biotic signatures are poorly preserved, and therefore scientists search for indirect evidence of early life. The microbial record of Earth dates back to 3700 Ma (Nutmman et al., 2016). However, the macroscopic fossil records of the Precambrian remain controversial (Han and Runnegar, 1992; Knoll et al., 2006; Seilacher, 2007; Bengtson et al., 2009; El Albani et al., 2010; Bengtson et al., 2017; El Albani et al., 2019). Microbes dominated the Precambrian atmosphere and microbial mat cover developed profusely on the seafloor. The weakly metamorphosed Precambrian Vindhyan Supergroup of Indian peninsula often yields a wide spectrum of biotic records for understanding the evolution of life on earth (Sarkar et al., 1996; Seilacher et al., 1998; Sarkar et al., 2004; Bengtson et al., 2009; Banerjee et al., 2014; Bengtson et al., 2017). The Vindhyan succession has yielded wide-ranging microfossils, organo–sedimentary structures, carbonaceous fossils, Ediacaran fossils, and trace and body fossils of metazoans within the Vindhyan succession (Sarkar and Banerjee, 2019). The proliferation of moneran carpet on both siliciclastic and carbonate sediments depositing environment led to the formation of a diverse kind of biotic signatures (Sarkar and Banerjee, 2019), which needs a critical assessment. However, the role of environmental
processes on the morphology of microbial features is yet to be established. While some of these fossils provide meaningful age for Vindhyan sediments, many of them also produce contradictory results. Therefore, the biostratigraphic relevance for fossil records needs a thorough evaluation based on recent radiometric investigations. The reported fossils of the Vindhyan Supergroup are yet to be critically assessed for understanding the evolution of microbial and metazoan life in Earth’s history.

We have presented a brief review of varieties of biotic signatures of the Precambrian Vindhyan Supergroup. The objectives of the paper are: a) to present the wide spectrum of biotic signatures with the Vindhyan Supergroup, b) assess the environmental processes on microbial features, and c) to indicate the complexity in establishing metazoan affinity of the potential features. We have provided detailed elaborations of all varieties of microbial mat related structures and described all varieties of biogenic features within the Vindhyan Supergroup.

GEOLOGICAL BACKGROUND

The Vindhyan Basin (~ 104000 sq. km area and ~ 4.5 km thick) is the largest Proterozoic basin in India, the rocks of which are exposed in central and western India (Fig. 1). The gently metamorphosed and less deformed Vindhyan Supergroup overlying the Archean basement has two major subdivisions, the Lower Vindhyan/Semri Group and the Upper Vindhyan Group, separated by an unconformity (Fig. 2; Chanda and Bhattacharyya, 1982; Bose et al., 1997, 2001; Mondal et al., 2019). The sedimentation took place within a westward opening epicontinental basin in an intracratonic rift setting during the Lower Vindhyan, which evolved into a sag basin during the deposition of the Upper Vindhyan sediments (Bose et al., 1997, 2001, 2015). The sedimentation took place in varying environments including continental, shallow marine and offshore environments (Fig. 2; Bose et al., 2001).

The age of the Vindhyan Supergroup has been a matter of debate over the last hundred years. Stromatolites within the Lower and Upper Vindhyan yield the age range from 1400–600 Ma (Prasad, 1980, 1984). Radiometric dating and palaeobiological evidence until the last century provided Meso- to Neoproterozoic age for the Vindhyan sediments (Rasmussen et al., 2002). The age of the Lower Vindhyan/Semri Group is well established (~ 1.8–1.5 Ga) by U–Pb, Pb–Pb geochronology by different groups of researchers (see Sarkar and Banerjee, 2019). On the contrary, the age of the Upper Vindhyan remains controversial. On the basis of palaeomagnetic and detrital zircon data, many investigators suggested

| Group          | Formations            | Age (Ma) | Palaeogeography                      |
|----------------|-----------------------|----------|--------------------------------------|
| Bander         | Upper Bander Sandstone| Fluvio-aeolian and marginally marine |
|                 | Sirka Shale           | Lagoon (lower part) and shelf (upper part) |
|                 | Lower Bander Sandstone| 600 (*Sr/^87Sr; Ray et al., 2002) | Coastal playa (Bose et al., 2001) |
|                 | Bander Limestone      | 908–72 (*Pb/^206Pb; Ray et al., 2002) | Shallow marine with occasional lagoon |
|                 | 720–650 (*Sr/^87Sr; Ray et al., 2003) | | |
|                 | 1075–900 (*Pb/^206Pb; Gopalakrishna et al., 2013) | | |
|                 | Garangwadi Shale      | Chenier |
| Rewa           | Rewa Sandstone        | Tidal to fluvio-aeolian |
|                 | Rewa Shale            | Shelf |
| Kaimur         | Upper Kaimur          | 1673 ± 13 (Ar-Ar; Laura et al., 2006 from Mahagawan Kimberlite) | Intertidal to shelf |
|                 | Lower Kaimur          | 1673 ± 13 (Ar-Ar; Laura et al., 2006 from Mahagawan Kimberlite) | Intertidal to shelf |
| Rohit           | Rohit Limestone       | 1599 ± 48 (*Pb/^206Pb; Surangi et al., 2004); 1631 ± 1 (*U-Pb Zircon; Ray et al., 2002) | Shelf |
| Rampur          | Rampur Shale          | 1602 ± 10 (SHRIMP; Rasmussen et al., 2002) | Shelf |
|                 | 1593 ± 12 (SHRIMP; Rasmussen et al., 2002) | | |
| Khentuja        | Chobatu Sandstone     | 1628 ± 10 (SHRIMP; Rasmussen et al., 2002) | Shallow marine |
|                 | Koldaha Shale         | 1631 ± 5 (*U-Pb zircon; Ray et al., 2002) | Shallow marine |
|                 | Porosellehte          | 1631 ± 5 (SHRIMP; Ray et al., 2002) | Subtidal to peritidal |
|                 | 1630 ± 7 ± 0.4 (*U-Pb zircon; Ray et al., 2002) | | |
|                 | 1640 ± 4.5 (*Pb/^206Pb; Bickford et al., 2017) | | |
|                 | Kairaishat             | 1631 ± 5 (*U-Pb zircon; Ray et al., 2002) | Subtidal to peritidal |
|                 | Arangi Shale          | Shelf |
|                 | Deoland               | Shallow shelf |

Figure 1. Geological map showing outcrops of the Vindhyan Supergroup in the Son valley and inset showing map of India.

Figure 2. Stratigraphy, age, and palaeogeography of the Vindhyan Supergroup.
that the closure of the basin before ~ 1.0 Ga (Fig. 2; Sarkar and Banerjee, 2019 and references cited therein).

BIOTIC RECORDS WITHIN THE VINDHYAN SUPERGROUP

Palaeobiological remains of the Vindhyan Supergroup may be categorized as stromatolites, macroscopic carbonaceous remains, microfossils, small shelly fossils, pseudos Ediacaran fossils, and microbially induced sedimentary structures (MISS). Microbial mats probably colonized on the sedimentary surfaces during the Precambrian both in carbonates and in siliciclastics (e.g., Schieber, 1999; Parizot et al., 2005; Sarkar et al., 2006; Schieber et al., 2007; Banerjee et al., 2010, 2014; Sarkar et al., 2014a). Stromatolite bears the interaction between benthic microbial communities and detrital/chemical sediments with records of three-dimensional convex upward geometry. In contrast to carbonate settings, the recognition of the microbiota within terrigenous sedimentary rocks has often some limitations. Therefore, their identification depends on indirect signatures/proxy structures resulted from trapping, binding, baffling, and biostabilisation of the non-cohesive clastic sediments. These proxy features are referred to as microbial mat induced sedimentary structures (Noeke, 2010). The range of biotic signatures in the Vindhyan Supergroup also covers carbonaceous body fossils including Chuaria and Tawuia, calcified and chertified microbial fossils, as well as traces of macroscopic fossils. A brief description of all kinds of biotic signatures is given below.

Stromatolites

Several workers reported stromatolites within different stratigraphic intervals of the Vindhyan Supergroup and inferred Lower to Upper Riphean age (1600-650 Ma) (Fig. 3). The upper part of the ~ 1.7 Ga-old Kajrahat Limestone preserves significant stromatolite varieties (Fig. 4a). The size of the stromatolite varies from large (average column height of 20 cm and diameter of 6 cm) to small (column height and diameter of 3.5 cm and 1.8 cm) (Banerjee et al., 2007). While columns of large stromatolites are mostly conical, those in small stromatolites are round-headed, inclined and branched. Microbial laminites are of laterally attached micro- and detached forms of stromatolites are abundantly present (Figs. 4b-4e). The latter variety branches upward, with prominent inter-columnar areas (Fig. 4f). Stromatolites may be micro-digitate, domal, arch-shaped, inclined and branched (Figs. 4b-4j). One form may change into other morphotypes vertically (Figs. 4d, 4k, and 4l). Digitate stromatolites are of laterally attached micro-scale variety, surrounded by comparatively larger laminae (Fig. 4b). Large arch-shaped stromatolites are laterally attached and are occasionally draped by wave ripples (Fig. 4h). Inclined, branched and small-headed varieties overlie the large arch-shaped stromatolites (Figs. 4e and 4f). Inclined columnar varieties show branching of the column with wide inter-columnar space. Small-headed stromatolites generally overlie the inclined columnar variety (Fig. 4j). They appear circular on the bedding plane. Occasionally desiccation cracks occur on the bedding surface of small stromatolites.

The different morphology of the stromatolites within the Bhandari Limestone indicates the variation in water depth within the depositional environment (Sarkar and Bose, 1992; Sarkar et al., 1996). Large stromatolites indicate a relatively deeper water environment compared to the small variety. The inclined stromatolites represent shallow water conditions within fair/storm weather wave base (Sarkar et al., 1996). The presence of occasional desiccation cracks on the bedding surface of the small-

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| Stratigraphic position | Reported stromatolites and reference | Age |
|------------------------|--------------------------------------|-----|
| Bhandari Limestone     | <i>Bacillaria baciliformis</i> (Kumar 1976a) | Middle to Upper Riphean |
| Roha Limestone         | <i>Collenia kusensis</i>, <i>Collenia baciliformis</i>, <i>Collenia kusensis</i> (Valdiya, 1969; Sharma, 1996) | 900-600 Ma |
| Koldahia Shale         | <i>Collenia cylindrica</i>, <i>Collenia columnaris</i>, <i>Collenia clappii</i> (Kumar, 1976b) | Middle Riphean |
| Kajrahat Limestone     | <i>Conophyton cylindrical</i>, <i>Collenia kusensis</i>, <i>Cryptospongiella occidentale</i>, <i>Colonnella Sp.</i>, <i>Collenia frequens</i>, <i>Conophyton inclinatum</i>, <i>Kussella kusensis</i>, <i>Kussella</i>, <i>Colonnella</i> (Prasad, 1980, 1984; Kumar and Gupta, 2002) | Lower Riphean |

Figure 3. Salient reports of stromatolites within the Vindhyan Supergroup.
headed stromatolites supports a very shallow water environment, with occasional exposure. The rare presence of wave ripples on the bedding surface of the large arch-shaped stromatolites indicates occasional wave influence. Branching of inclined columnar stromatolites supports wave/current actions (Sarkar et al., 1996). The preferred inclination in stromatolites indicates either action of strong current within the depositional environment or the phototactic movement of the microbial colony (Sarkar et al., 1996).

**Microbially induced sedimentary structures (MISS) in carbonates**

Although the MISS has been studied in detail from the siliciclastic rocks, carbonates of the Vindhyan Supergroup also display a similar group of two-dimensional bedding plane structures representing a proxy of the microbiota. The microbial mat usually forms three-dimensional stromatolites in carbonate depositional settings, while two-dimensional MISS occurs exclusively in siliciclastic settings. Although wide varieties of MISS are well-known from modern carbonate environments (Bose and Chafetz, 2011), wrinkle structures were only reported from the ancient rocks (Xiaoqing et al., 2008; Luo et al., 2013). Recently Sarkar et al. (2016, 2018) expanded the list of two-dimensional carbonate MISS from the lower parts of the Rohtas Limestone and Bhander Limestone of the Vindhyan Supergroup (Figs. 5 and 6). These workers considered carbonate MISS comparable to those found in siliciclastic rocks (Figs. 7–9).

The three-dimensional stromatolites reflect the early cementation and repetitive process of baffling, trapping and mineralization in limestone. However, the absence
of early cementation results in two-dimensional geometry in MISS. Most MISS in carbonates involves microscale deformation indicating delayed cementation of the carbonate sediments. The activity of sulfate reducing bacteria (SRB) facilitates the CaCO3 precipitation within a thin microbial mat (Sarkar et al., 2016). The delayed cementation of the sediments corresponds to the acidic composition of EPS secreted by the microbes (Sarkar et al., 2018 and references cited therein). The near-equatorial palaeolatitudinal position of India (Scotese, 2001; Personen et al., 2003; Evans and Mitchell, 2011; Zhang et al., 2012) during the Mesoproterozoic time might have restricted the growth of SRB, and the rate of sulfur reduction, resulting the delayed cementation and preservation of MISS in carbonates (Sarkar et al., 2016, 2018; Choudhuri, 2019).

Microbially induced sedimentary structures (MISS) within siliciclastics

The Vindhyan Supergroup is globally well known for excellent preservation of MISS from siliciclastics within Kheinjua and Bhandar Formations (Sarkar et al., 2004, 2005; Banerjee and Jeevankumar, 2005; Sarkar et al., 2006; Banerjee et al., 2006; Sarkar and Banerjee, 2007; Schieber et al., 2007; Banerjee et al., 2010, 2014; Sarkar et al., 2014b, 2016). The sandstone beds at top of HSTs (Highstand Systems Tracts) bear excellent MISS varieties on the bed-surfaces in different stratigraphic intervals. However, the prolific mat growth in shales corresponds to maximum flooding zones (Figs. 7–9). The morphological variations of these features (Figs. 7 and 8) correspond to growth, destruction and diagenesis of microbial mats.

Carbonaceous shale (total organic carbon content

Figure 5. Field photographs showing: (a) Wrinkle structures and synaeresis cracks on the bedding plane of the Bhandar Limestone. (b) Pustules (arrowed) on the bedding plane of the Rohtas Limestone. (c) Domes (arrowed) and their casts preserved on the bedding plane of the Rohtas Limestone. (d) Astropolithons with central craters (arrowed) preserved in the Rohtas Limestone. (e) Loads at the sole of the bed (right side) and their casts on top of the underlying bed (left side) preserved in the Bhandar Limestone. (f) Palimpsest ripples preserved in the Bhandar Limestone, with thin calc-arenite layer mimicking the underlying ripple morphology. (g) Swarms of setulfs (arrowed) on the bedding plane of the Bhandar Limestone. (h) Irritatingly sharp-crested ripples in the Bhandar Limestone. (g) Cracks preserved on the bedding plane of the Rohtas Limestone. Knife length, 8.5 cm; Hammer length, 38 cm; Pen length, 14.5 cm.
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exceeding 1.5%) associated with the stratigraphically condensed zones exhibit wavy, crinkly, carbonaceous laminae, pyritic laminae, pseudo cross-strata, rolled-up, and folded carbonaceous laminae within Rampur Shale, Sirbu Shale, and in Kajrahat Formation, suggesting microbial mat growth in mid- to outer-shelf depositional conditions (Figs. 7d and 7e; Banerjee et al., 2006; Sur et al., 2006). Banerjee and Jeevankumar (2005) and Sarkar et al. (2004, 2005, 2006) recorded several microbial structures within Vindhyan shales. Recent ultramicroscopic studies within Rampur Shale have revealed different morphotypes of the microbial population (Mondal et al., 2019).

| Strata | Type | Description | Interpretation |
|--------|------|-------------|----------------|
| Rohtas Limestone and Bander Limestone | Wrinkle structure | Wrinkle marks appear as minute ridges which may be laterally continuous or discontinuous (Fig. 5a); generally asymmetric in profile; in certain patches, the ridges are flat topped resembling Kimmeia structures. | Wrinkle structures are correlated with growth of microbial mats; unidirectional asymmetry in indicates presence of shear of gentle wave or current action on mat infested surfaces (Sarkar et al., 2016). |
| Rohtas Limestone | Pastules | Positive surface structures; resembles to small warts (approximately 5 mm in diameter and ~2.5 mm in height; spacing between them is on average ~1 cm (Fig. 5b)). | Products of interrupted mat growth and localized cell division of coccoids (Sarkar et al., 2018). |
| Rohtas Limestone | Domes | Positive relief structures, larger than pastules (diameter 6.5 cm and height 3 cm); locally present in linear series having ~8 mm space in between each other (Fig. 5c). | Surface expressions of decay-related fluid trapped under microbial mat (Sarkar et al., 2018). |
| Rohtas Limestone | Astropolitons | Similar to dome structures; radial cracks with a central crater are present on their crests on the bed surface (Fig. 5d). | Resulted from release of the pore pressure; radial cracks around the crater indicate cohesiveness of the sediment generated by the microbial mat (Sarkar et al., 2018). |
| Rohtas Limestone and Bander Limestone | Loads and their casts | Loads appear as small mounds in clusters at the sole of the beds and their casts appear as steep-sided circular pits on the bed-top of the underlying beds (Fig. 5e). In cross-section, it is revealed graded silt layers sunk into the underlying carbonate-rich mud layer. | Possibly the thickest mat layer was present just beneath the surface. Presence of one layer (Sarkar et al., 2016); carbonate mud layer was loaded by a graded silt-rich layer indicates the carbonate sediment surfaces were still not fully cemented and the sudden introduction of quartz silt by some episodic events. |
| Bander Limestone | Palimpsest ripple | Thin granular calcareous sheet (average 10 mm in thickness) is spread across pre-existing wave ripple forms (Fig. 5f); the granular sheet reflects inherited features from the underlying beds which are still visible underneath with no reworking in between them. | The preservation of two sets of ripples without any erosion in between suggests the presence of a microbial mat cover on the upper surface of the underlying bed, which protects the earlier ripples from reworking. Low rate of sedimentation and complete cessation of erosion are also responsible for the generation of palimpsest ripples (Sarkar et al., 2016). |
| Bander Limestone | Seulf | Positive in relief and very delicate structure; look like inverted flutes and occur in swarms (Fig. 5g); when the overlying bedding planes are poised open, their casts are preserved at the sole of the overlying beds. | Preserved due to protection by a microbial mat cover on the surface as has been observed in the modern environment (Sarkar et al., 2016). |
| Bander Limestone | Sharp crested ripples | Unusually sharp crested ripples, many of the ripples bear spindle-shaped cracks on their crests (Fig. 5h). | Possibly preserved because of the protective influence of microbial mats; the beveled edge of the bed surface layer thus gives a false impression of unusual sharpness of the ripple crests (Sarkar et al., 2016). |
| Rohtas Limestone and Bander Limestone | Cracks | Millimeter-to-centimeter-scale cracks of variable geometry (e.g. rectangular, polygonal, spiral, and sinuous to spindle-shaped) are preserved on bed surfaces (Fig. 5a, i); on rippled surfaces they occur preferentially within the ripple troughs. | Cracks bear a proxy record of the microbial mat; indicate mat influence, contributing cohesion to the granular sediments; destruction in commonly inferred for cracking of mat-infested sediment surfaces, while cracks cross-cutting each other are likely to be of syneresis origin; preferential occurrence within ripple troughs is possibly due to thicker mat growth (Sarkar et al., 2016, 2018). |

**Figure 6.** MISS recorded within carbonates of the Vindhyan Supergroup.

**Carbonaceous macrofossils and microfossils**

Figure 10 provides a summary of various kinds of carbonaceous fossils and calcified/certified microfossils within the Vindhyan Supergroup. While these reported fossils provide a broad Mesoproterozoic age for the Semri/Lower Vindhyan Group, the same indicates a Neoproterozoic age for the Upper Vindhyan (Venkatachala et al., 1996; Sarkar and Banerjee, 2019). However, the age implication of these fossils remains controversial (cf. Brasier et al., 2002).
Ediacaran–like fossils

Several reports indicate the presence of probable Ediacaran–like fossils within the Vindhyan Basin including Ediacaria flindersi, Cyclomedusa davidii, Medusinites, Medusinites asteroides, Dickinsonia, and Beltanelliformis brunsae (for details see Sarkar and Banerjee, 2019). De (2003) reported possible Ediacaran fossils within the Bhander Formation to consider the Proterozoic age for the Vindhyan. However, researchers questioned the Ediacaran affinity of the features because of their resemblance with MISS (Banerjee et al., 2010, 2014; Sarkar and Banerjee, 2019).

Macroscopic/metazoan fossils

A few authors reported traces of advanced organisms within the Vindhyan succession (see Venkatachala et al., 1996 for details). Later workers considered these reports as considered them as dubiofossils (Chakrabarti, 2001; Sarkar and Banerjee, 2019). The metazoan fossil reports of Misra and Awasthi (1962), Mathur (1983), and Singh and Sinha (2001) possibly represents shrinkage-related cracks (Kumar, 2001). Azmi (1998) reported controversial small shelly fossils of Cambrian age affinity from the phosphoritic stromatolitic dolomite in the basal part of the Vindhyan Supergroup from Chitrakut area. Bengtson et al. (2009, 2017) reinterpreted the fossils as filamentous and coccoid cyanobacteria and filamentous eukaryotic algae and confirmed their Mesoproterozoic age. Bengtson et al. (2017) considered these multicellular fossil organisms as the earliest known crown group of eukaryotes. Recently Sallstedt et al. (2018) provided the evidence of oxygenic phototrophy developed by the filamentous microorganisms from the same stratigraphic interval.

Trace fossils

Discovery of traces of motile organisms/worm burrows living under thin microbial mat cover from the Chorhat Sandstone (Sarkar et al., 1996; Seilacher et al., 1998) raised many debates within the scientific community. The reports of Chorhat worm burrows were criticized by several workers (Conway Morris, 2000; Fedonkin, 2003; Peterson and Butterfield, 2005; Jensen et al.,...
Figure 8. Field photographs showing MISS within the Chorhat Sandstone, Vindhyan Supergroup: (a) Spindle-shaped cracks preserved within the ripple troughs. (b) Wrinkle structures preserved on the bedding plane. (c) Sand bulges in multiple numbers on the bedding plane. (d) Patchy ripples. (e) Bulbous loads at the bottom of the sandstone (right) and their casts preserved on top of the underlying ripple (left) laminated sandstone. (f) Elliptical sand clasts (arrowed). (g) Elongated silt curls (arrowed). (h) Thin layer of microbial mat mimics the underlying ripple laminated sandstone generating palimpsest ripple. Knife length, 8.5 cm.
Seilacher (2007), however, withdrew the original interpretation of Chorhat triploblastic worm burrows mainly because of the radiometric dates which constrain the age of deposition older than 1.6 Ga.

### DISCUSSION AND CONCLUSIONS

The Precambrian Vindhyan Supergroup hosts diverse types of biotic signatures including microbial mat-induced sedimentary structures (MISS), micro and macro-

| Stratigraphy | Type | Descriptions | Interpretation |
|--------------|------|--------------|----------------|
| Upper Bhaner Sandstone | Setup | Swarms of unidirectional miniscule positive relief structures on well sorted sandstone beds (Fig. 7a). | Sand grains deflated against an obstruction; windblown origin was interpreted; preserved due to presence of protective mat layers on the depositional surface. |
| | Sand chips | Chips with rounded edge made up of sandstone, may be spherical, ellipsoidal, triangular. | Storm-induced flows eroded the mat infested sand layers and generated chips out of sand; Deformed sand chips indicate flexible nature of sandstone intraclasts. |
| | Wrinkle marks | Appear as minute ridges, wrinkled layer having unidirectional symmetry. On the bed surface on mud free sandstone, may be parallel to each other; sometimes may form a network. | Crinkled appearance indicates mat growth, on mud free sandstone bed surface; developed due to flow shear, micro scale loading, dewatering or dessication processes during burial and decay of mat layers; unidirectional symmetry in profile points to shear stress played on mat infested cohesive sand surface. |
| Siruba Shale | Disc-shaped microbial colonies | Roughly circular, wrinkled masses of positive hyporelief features preserved at the bottom of fine-grained storm induced sandstone beds; dimension of the discrete circular masses is variable (Fig. 7 b). | The wrinkled circular masses have appearance similar to Ediacaran fossil Nimba though, the Ediacaran origin of the feature was ruled out on the basis of radiometric age; it may be a representative of impressions of torn pieces of microbial mats or a disc-shape microbial colony. |
| | Arumberia | Mm to cm scale radial grooves alternating with mm-scale ridges preserved preferably on the crests of the ripple and form peculiar circular to semi-circular pattern in places (Fig. 4 c). | Mm-scale ridges possibly form by the action of currents on soft and cohesive microbial mat cover. Initially Arumberia was considered as a cup-shaped animal trace of coenocritate. The growth of microbial mat may form similar pattern. |
| | Cracks | Mm to cm scale, steep-sided, of variable geometry, occasionally occur on bed surface of well sorted sandstone, mostly also along ripple crests or trough (Fig. 8 a). | Steep margins of the structures indicate crack; behaviour of non-cohesive well sorted granular sand as a cohesive mud indicate mat growth on sand surface. Cracks within ripple troughs indicates thicker mat growth. |
| | Wrinkle structures | Similar to previous description in Upper Bhaner Sandstone (Fig. 8 b). | Similar interpretation like Upper Bhaner Sandstone. |
| | Ruptured domes | Appear as positive relief dome like structures with a central depression. | Mat layers formed on the sand-surface got upheaved because of gas expulsion generated on decaying of mat layer underneath. |
| | Sand bulges | Also appear as dome like structures lacks the central crater unlike ruptured domes (Fig. 8 c). | Possibly created due to entrapment of Gas under the mat and later those upturned space filled by gas was replaced by underlying sand layers. |
| Chorhot Sandstone | Patchy ripples | The first variety recognised as patchily preserved ripples with jagged and stepped margins; in between the ripple patches the bed surfaces are planed off; also a first-generation ripple is overprinted by later ripples due to patchy reworking (Fig. 8 d). | Jagged and stepped margins of the ripples indicate preservation of ripples under the residual mat layer after it was torn by strong current/wave. Occasionally destroyed portion of mat layer reworked he first generation ripples patchily. |
| | Load casts | Closely spaced steep sided depressions circular in section, occur both on ripple troughs and between the amalgamated mud free sandstone (Fig. 8 e). | Resulted from loading due to rapid deposition of massive sandstone beds over another gelatinous mat layer; preferential presence of loadings within ripple troughs indicate thick mat growth within ripple troughs. |
| | Sand chips | Similar to previous description in Upper Bhaner Sandstone (Fig. 8 f). | Similar interpretation like Upper Bhaner Sandstone. |
| | Silt curls | Present on bed surface, mud free coarse siltstone gets curled up similar to mud curls of modern environment, often oriented parallel to each other (Fig. 8 g). | Silt curls were generated because of desiccation on acquisition of high degree of cohesiveness in presence of microbial mat; mutual parallel orientation indicates they were reworked by later generation currents. |
| | Palimpsest ripples | Very thin overlying bed replicates the ripple form of the underlying layer (Fig. 8 h). | Generated due to very low rate of sedimentation and complete cessation of erosion together, replication of earlier ripple forms took place through trapping of particles by filaments and EPS of uniformly grown microbial mat over earlier ripples. |

Figure 9. Brief descriptions and interpretations of MISS within siliciclastics of the Vindhyan Supergroup.
fossils, carbonaceous fossils, Ediacaran–like fossils, and traces of megascopic fossils (see Sarkar and Banerjee, 2019 and references cited therein for details). Stromatolites or microbialites are three-dimensional organo-sedimentary structures formed as a result of interaction between the benthic microbial mat and the sediments through trapping, binding, baffling of the sediments, and biostabilisation. Stromatolites acquire three-dimensional structures through repetitive mineralization and fossilization (Noffke, 2000; Noffke et al., 2003; Noffke, 2010; Noffke and Awramik, 2013). Apart from the stromatolites, Vindhyan siliciclastic rocks preserve an array of bedding plane microbial mat related structures with two-dimensional geometry, known as MISS (see Fig. 9). The prolific growth of microbial mat on sediment surfaces stabilized the sediments, resulting in a reduced rate of erosion compared to that in Phanerozoic time. The reduced rate of sedimentation results in the preservation of regressive system tracts more in numbers than that of transgressive system tracts (TST) during the Proterozoic time (Sarkar et al., 2005; Catuneanu, 2006; Sarkar et al., 2014a). Therefore, MISS in Proterozoic rock records have an immense influence on the preservation of the system tracts (Sarkar et al., 2005; Banerjee and Jeevankumar, 2005; Eriksson et al., 2010; Banerjee et al., 2014). Depending on their preferential relationship to the palaeoenvironments, MISS were classified into three broad categories - (a) occurring in shallow marine littoral–supratidal settings, (b) shallow subtidal to deep marine settings, and (c) those not having any preferential occurrence to an environmental setting (Eriksson et al., 2010). Although siliciclastic formations yielded MISS in the past, recent studies indicated the formation of similar features within ancient carbonate sediments in case of late clementation (Fig. 6; Sarkar et al., 2016, 2018; Choudhuri, 2019). Most of the siliciclastic MISS within the Vindhyan Supergroup develop within shallow marine littoral–supratidal environments whereas carbonate MISS represents restricted to quiet lagoonal environments. On the other hand, variations in stromatolite morphology both from the Kajrahat Limestone and Bhandar Limestone correlates with the change in the water depth of the depositional basin. Therefore, both stromatolites and MISS are useful tools for high-resolution palaeoenvironmental interpretations in Proterozoic shallow marine successions (Banerjee et al., 2014).

Many of the MISS structures, e.g., Manchuriophyceae, have previously been thought of as metazoan burrows (Kulkarni and Borkar, 1996 and many others). The re-examination of these features, however, confirmed the microbial mat origin of the sinuous cracks on the sandstone surfaces (Sarkar et al., 2005, 2008; Banerjee et al., 2010, 2014). Many of the wrinkle structures, petee ridges, and gas domes with central depressions were mistakenly interpreted as organism remnants, horizontal burrows, and jellyfish impressions, respectively by different workers (see Banerjee et al., 2010 and Sarkar and Banerjee, 2019 for a detailed discussion). Upon comparison with their modern equivalents, many of these features were explained as MISS (Banerjee et al., 2010, 2014). Apart from organo-sedimentary structures, the Vindhyan Supergroup yielded several carbonaceous macro and microfossils, and Ediacaran–like fossils (Fig. 10; Sarkar and Banerjee, 2019 and references cited therein). However, many of the Ediacaran–like fossils were later re-interpreted as discoidal microbial mat growth/colony (Banerjee et al., 2010).

Seilacher et al. (1998) documented traces of triploblastic worm burrows under mat cover on the sandy bed surfaces of the Chorhat Sandstone. This sensational report inspired many scientists for the search of an advanced mode of life from ancient rocks before the Cambrian explosion. Subsequently, the age of the Chorhat

| Stratigraphy     | Carbonaceous macrofossils                          | Microfossils                                                   |
|------------------|---------------------------------------------------|----------------------------------------------------------------|
| Sirsiu Shale      | Chuaria circularis, Tawania dalensis              | Archaeorhitis sp., Sphaerophycus paradoxum, Mysococoides psilata, Protosphaerium desum |
| Bhandar Limestone| Chuaria circularis, Tawania dalensis              | Bicatenaoides spharcula, Sphaerophycus paradoxum                |
| Rewa Shale       | Chuaria circularis, Tawania dalensis, Chuaria circularis, Tawania dalensis | Mysococoides psilata, Nanococcus vulgaris                        |
| Rohtas Limestone | Krishnaia aconitata, Krishnaia multistrata, Chuaria circularis, Geysania sp., Chuaria circularis, Chuaria gigantia, Chuaria melanoendritis, Geysania spiralis, Geypania sp., Phyllonia bistaria | Mycoscoidea globosa, Palaeomyctys subtenens, Mitharea psilata, Leiptsphaeridia densum |
| Rampur Shale/Suket Shale | Chuaria minima, Tyristozaena sp. | ..... | Eomyctys septa | Sphaerophycus paradoxum, Botophyllum belcheriensis, Oscillatoriopitites brevisconvera, Mycoscoidea minor, Terebellipherus congruens, Kiddinella aff. |
| Chorhat Sandstone | ---                                                | Palaeomyctys subtenens, Eomyctys filiformis                   |

Figure 10. Salient reports of carbonaceous macrofossils and microfossils in the Vindhyan Supergroup (see Sarkar and Banerjee, 2019 for original citations of fossils reports).
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Sandstone was constrained to ca 1.6 Ga (Rasmussen et al., 2002). This prompted Seilacher (2007) to discard his idea of triploblastic worm burrows. However, it is difficult to explain the origin of these structures having constant width, pervasive shapes (both branching and meandering patterns) with a diverse orientation by physical/chemical processes. Moreover, recent reports of multicellular organelles and bundles of tubular filaments within the Semri Group (cf. Bengtson et al., 2009, 2017) have again created an option for the scientific community to rethink about the metazoan divergence before the Cambrian explosion. Recent findings of multicellular organisms, cf. Franceville biota of ~ 1.8 Ga (Bengtson et al., 2010, 2014), Sterling biota of ~ 1.3 Ga (Zhu et al., 2017), Montana biota of 1.5-1.3 Ga (Zhu et al., 2016), and motile organisms from 2.1 Ga old rocks (El Albani et al., 2019), inspire a re-assessment of the Vindhyan metazoan records for the evolution of advanced life forms during Precambrian. Therefore, a detailed investigation with most advanced techniques is necessary to correctly assess the affinity of some of the problematic features within the Vindhyan succession. We conclude the following points based on our investigation of biogenic structures within the Vindhyan Supergroup.

a) The radiometric dating brackets the Vindhyan Supergroup within 1.7 to 1.0 Ga while stromatolites, carbonaceous fossils, and microfossils provide Mesoproterozoic to Neoproterozoic ages for the same.

b) Microbial mat proliferates on the Vindhyan Sea, leaving a wide range of proxy features in both siliciclastics and carbonates.

c) Many of the fossil reports of metazoan life have been re-interpreted as microbial mat originated sedimentary structures.

d) In view of recent reports of the existence of metazoan life in rocks of Palaeoproterozoic age from other parts of the world, the Vindhyan fossils need a thorough re-examination in the future for their exact affinity without having any bias.

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