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Organic-rich shale in the Palaeoproterozoic Kajrahat Formation, Vindhyan Supergroup, Son Valley: implications and genesis

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ABSTRACT

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The paper attempts to interpret the textural attributes of the shelf-originated, organic-rich shale unit of the Kajrahat Formation in the Proterozoic Vindhyan Supergroup. The black shales, alternating with thinly laminated dolomite beds exhibit many textural features, indirectly indicating microbial mat growth on muddy siliciclastics. The microbial mat features are subdivided broadly into three different categories related to growth, destruction and diagenesis of microbial mat. Wavy and crinkly laminated fabric is very characteristic of the shales, thin mud drapes imparting the wavy laminae conspicuous. Pyrite, formed because of anaerobic decay of microbial mat follows the carbonaceous laminae, rather than being disseminated. Cohesive behaviour of the shales is manifested by the folded and contorted nature of the carbonaceous laminae at places. Sticky nature of the microbial mats possibly generated the quartz-silt aggregates and abundant scattered quartz silts within the carbonaceous laminae. The black shale unit of the Kajrahat Formation, thus, appears to have microbial mat origin like many other contemporaneous black shales reported from Precambrian black shales. The occurrence of microbially originated, organic-rich shale suggests curtailment of siliciclastic supply.

Key-words—Microbial mat, Organic-rich shale, Wavy laminae, Palaeoproterozoic, Vindhyan Supergroup, Son Valley.

पुराप्रोटेरोज़ोइक कजरहाट शैलसमूह, विंध्य महासमूह, सोन घाटी : युगपत अंतर्वृद्धियां एवं उत्पतृतियाँ

एस. जीवन कुमार तथा शान्तनु बनर्जी

सारांश

शोध-पत्र प्रोटेरोज़ोइक विंध्य महासमूह में कजरहाट शैलसमूह के उपतट से उत्पन्न, कार्बनिक प्रचुर शेल यूनिट की गठन विशेषता की व्याख्या का प्रयास करता है। काले शेलों, अप्रत्यक्ष रुप से मटीले सिलिकीखंडज पर सूक्ष्मजैविक शैवाल वृद्धि दर्शाते हुए तनु रुप से स्तरिक डोलोमाइट संस्तर विभिन्न गठन आकृतियों सहित एकांतर प्रदर्शित करते हैं। सूक्ष्मजैविक शैवाल आकृतियां तीन विभिन्न श्रेणियों वृद्धि, अवक्षय तथा सूक्ष्मजैविक शैवाल के प्रसंघनन से संबंधित में स्पष्ट रुप से उपविभाजित हैं। तरंगित और घुंघराली स्तरिक संविन्यास शेलों के अधिक अभिलक्षणिक है, तनु मृदा ड्रेप तरंगित स्तरिका ध्यानाकर्षी प्रदान कर रही है। सूक्ष्मजैविक शैवालों के अवायवीय क्षय के कारण पाइराइट उत्पन्न हुआ जो कि कार्बनमय स्तरिका का अनुगमन करता है। इन जगहों पर कार्बनमय स्तरिका की वलित एवं कुंचित प्रकृति के द्वारा शेलों का संसंजक व्यवहार सुस्पष्ट है। सूक्ष्म जैविक शैवाल की चिपचिपी प्रकृति ने संभवतः स्फटिक-गाध पुंज को जनित किया तथा कार्बनमय स्तरिका में स्फटिक गाध प्रचुर मात्रा में फैल गई। कजरहाट शैलसमूह की काली शेल यूनिट, इस प्रकार, कैंब्रियनपूर्व काली शेलों से अन्य बहुत-सी समकालीन काली शेल प्राप्तियों की तरह सूक्ष्मजैविक शैवाल उद्गम सी प्रतीत होती है। सूक्ष्मजैविक रुप से उद्गम, कार्बनिक-प्रचुर शेल की प्राप्ति सिलिकीखंडज आपूर्ति की कटौती सुझाती है।

संकेत-शब्द—सूक्ष्मजैविक लता, कार्बनिक-प्रचुर शेल, तरंगित स्तरिका, पुराप्रोटेरोज़ोइक, विंध्य उच्चसमूह, सोन घाटी।

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INTRODUCTION

ALTHOUGH uncommon, organic-rich shales of appreciable thicknesses occur in some Proterozoic sedimentary basins around the world (Schieber, 1986; Korsch *et al.*, 1991; Crick, 1992; Warren *et al.*, 1998 and many others). The origin of these shales remains contentious. Microbial mat origin is inferred for some of the Proterozoic organic-rich shales (Schieber 1986, 1999, 2004; Fairchild & Herrington, 1989; Banerjee *et al.*, 2006; Sur *et al.*, 2006). Original microbial elements in shales are readily decomposed during burial, and are rarely preserved in the rock record because of absence of early cementation and appreciable compaction. Microbial mat growth, however, imparts certain characteristics to the shales, generating unique textural features (O'brien, 1990; Schieber, 1986, 1999, 2004). Microbial mat origin of shales is thus inferred largely by indirect evidences, based on detailed study of textural attributes of the rocks generated by microbe-sediment interaction. These features are very subtle in shales and are remain largely unnoticed.

Organic-rich shales have been reported from the Proterozoic Vindhyan Supergroup in recent years and their origin is being investigated (Sur *et al.*, 2006; Banerjee *et al.*, 2006). This paper describes the textural features from the organic-rich shales occurring within the Kajrahat Formation near the basal part of the Vindhyan Supergroup in the Chopan area of Son Valley, Uttar Pradesh and suggests their microbial affinity.

GEOLOGICAL BACKGROUND

The outcrops of the Paleo-Neoproterozoic Vindhyan Supergroup are well exposed all along the Son Valley (Fig. 1). An unconformity and its correlative conformity divide the roughly 4500 m thick Vindhyan sedimentary succession into two, the lower Vindhyan or the Semri Group and the upper Vindhyan (Bose *et al.*, 2001). The organic-rich shale unit, discussed in this paper, occurs at the lower part of the Kajrahat Limestone Member overlying the grey shale-dominated Arangi Shale Member, near the basal part of the Semri Group (Fig. 2). Based on Sr isotope systematics, Ray (2006) considered that Kajrahat Limestone is approximately 1.72 Ga old. The Palaeoproterozoic age for the Kajrahat Limestone is consistent with the recent age data provided by the other workers (Rasmussen *et al.*, 2002; Ray *et al.*, 2002; Sarangi *et al.*, 2004). Despite its Proterozoic age the entire Vindhyan sedimentary succession is mildly deformed and mostly unmetamorphosed. The Vindhyan sediments are dominated by shallow marine sediments, with minor contributions from fluvial and eolian sediments (Bose *et al.*, 2001). Deposition of sediments possibly took place in an epeiric sea opening westward (Chanda & Bhattacharyya, 1982). The Vindhyan Basin originated as a rift-basin and it was transformed to a sag basin during the deposition of the upper Vindhyan (Bose *et al.*, 2001).

The roughly 12 m-thick black shale unit constitutes the lower division of the Kajrahat Limestone near Kajrahat Village (Fig. 2; Jeevankumar, 2006). Black shales beds of average thickness 12 cm thickness alternates with dolomites displaying either microbial laminae or plane laminae (Fig. 3). Black shales appear hard and compact and look massive in field. Total

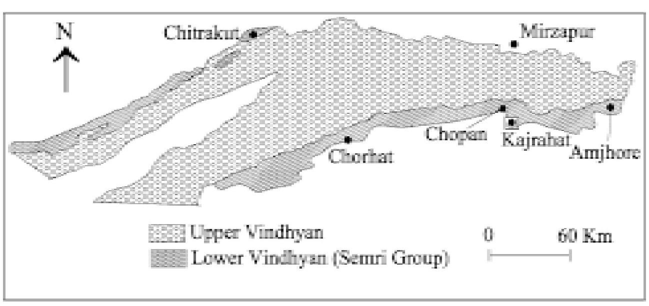

Fig. 1—Geological map showing outcrops of the Vindhyan Supergroup in the Son Valley (study area marked by rectangle).

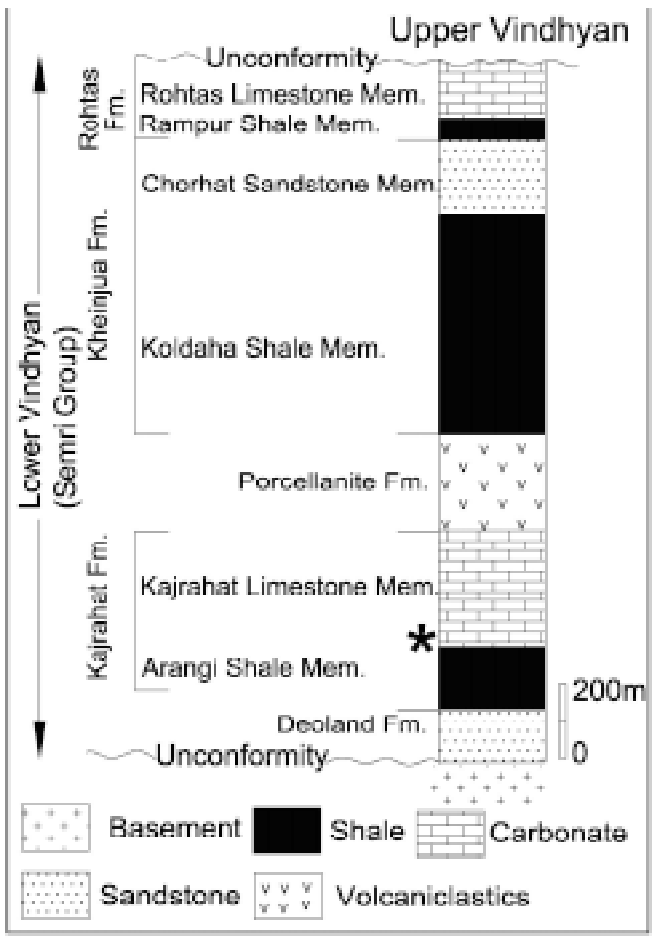

Fig. 2—Detailed stratigraphy of the Vindhyan Supergroup (after Bose *et al.*, 2001) and broad lithological variation across the succession. Asterisk mark the stratigraphy of the black shale unit studied.

organic content (TOC) of the black shales frequently exceeds 2% and is up to 3.1% (Banerjee *et al.*, 2006). Based on overall depositional scenario and detailed facies analysis Jeevankumar (2006) considered outer shelf origin of the black shale dominated lower division of the Kajrahat Limestone. Complete absence of emergence features within this division rules out its lagoonal origin. The Kajrahat Limestone is overall shallowing upward and is emergent at the topmost part (Jeevankumar, 2006).

METHODOLOGY

Fresh samples were collected from the field noting their exact stratigraphic position. Thin sections of the shales were prepared in the laboratory. The rock chips were hardened using Beuhler vacuum impregnated unit before further cutting and polishing. Remaining portions of the samples are kept in the sedimentological repository of the Department of Earth Sciences, IIT Bombay. Thin sections of the shales were examined and photographed using a Nikon Eclipse E 600 polarizing microscope with an attached Nikon coolpix 8700 camera.

POSSIBLE MICROBIAL FEATURES

The possible microbial mat features in the shales are subdivided into three different categories- mat-growth, mat-destruction and mat-diagenetic features following Schieber's (2004) scheme of classification of microbial structures in siliciclastics.

Mat growth features

Mat-growth features are essentially formed because of active growth of microbial mat cover. These include wavy-crinkly laminae, scattered quartz silts and pseudo-cross laminae.

Wavy-crinkly Laminae

The black shales in the Kajrahat Limestone exhibit conspicuous wavy and crinkly laminae (Schieber, 1999, 2004). The wavy-crinkly laminae are very prominent when carbonaceous laminae alternate with thin layers clayey laminae/seams (Fig. 4a). Detrital quartz silt grains are common within the carbonaceous laminae and rare within intimately associated clayey laminae. The bases of the clayey laminae are sharp whereas their tops are gradational. The clayey laminae often incorporate torn pieces of carbonaceous materials. Thicknesses of the carbonaceous laminae vary from 0.5 to 3 mm and that of the clayey laminae vary from 0.3 to 0.8 mm. Wavy laminae within the shale can be recognized even though the clayey laminae/streaks are thin and discontinuous (Fig. 4b). A total absence of the clayey laminae/streaks imparts a massive appearance to the black shales (Fig. 4c).

The wavy-crinkly, carbonaceous laminae of the black shales in the Kajrahat Limestone are distinct from the carbonaceous laminae of the Phanerozoic black shales. The latter exhibits smooth and parallel laminae and are originated through passive accumulation of organic materials and clayey sediments from the water column (Schieber, 1986). The observed wavy-crinkly and carbonaceous laminae closely resemble microbial mat laminae of modern and ancient microbial

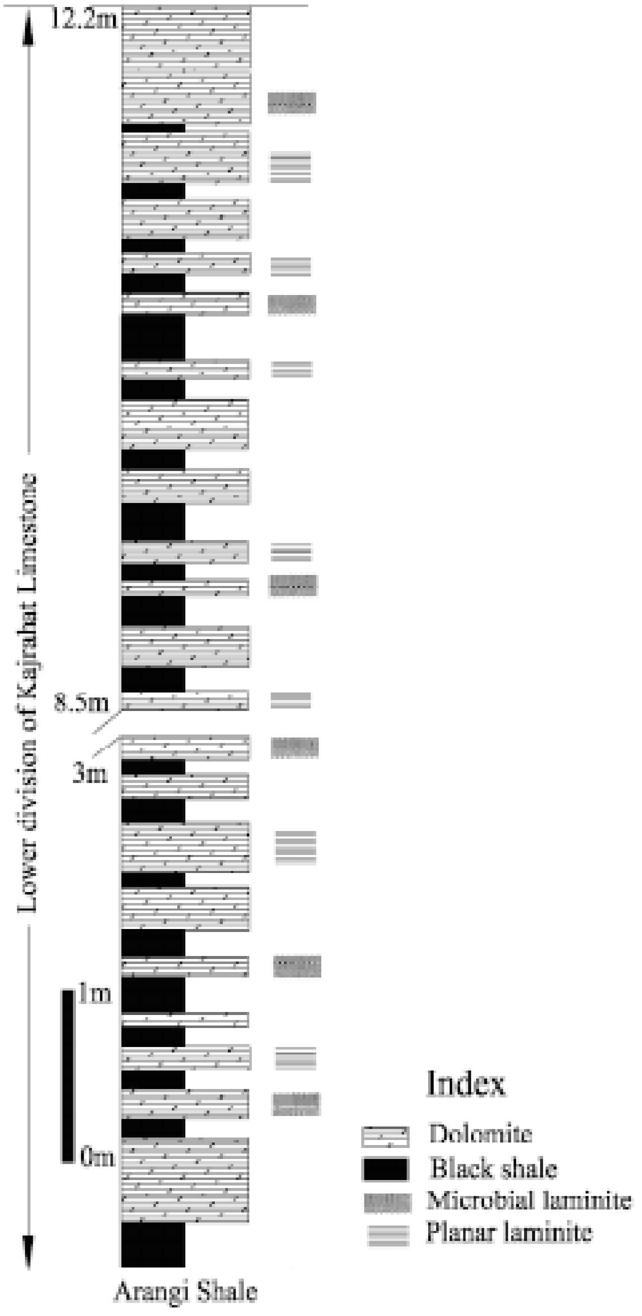

Fig. 3—Litholog showing part of the lower division of the Kajrahat Limestone in the Chopan area and sedimentary structures in the dolomite.

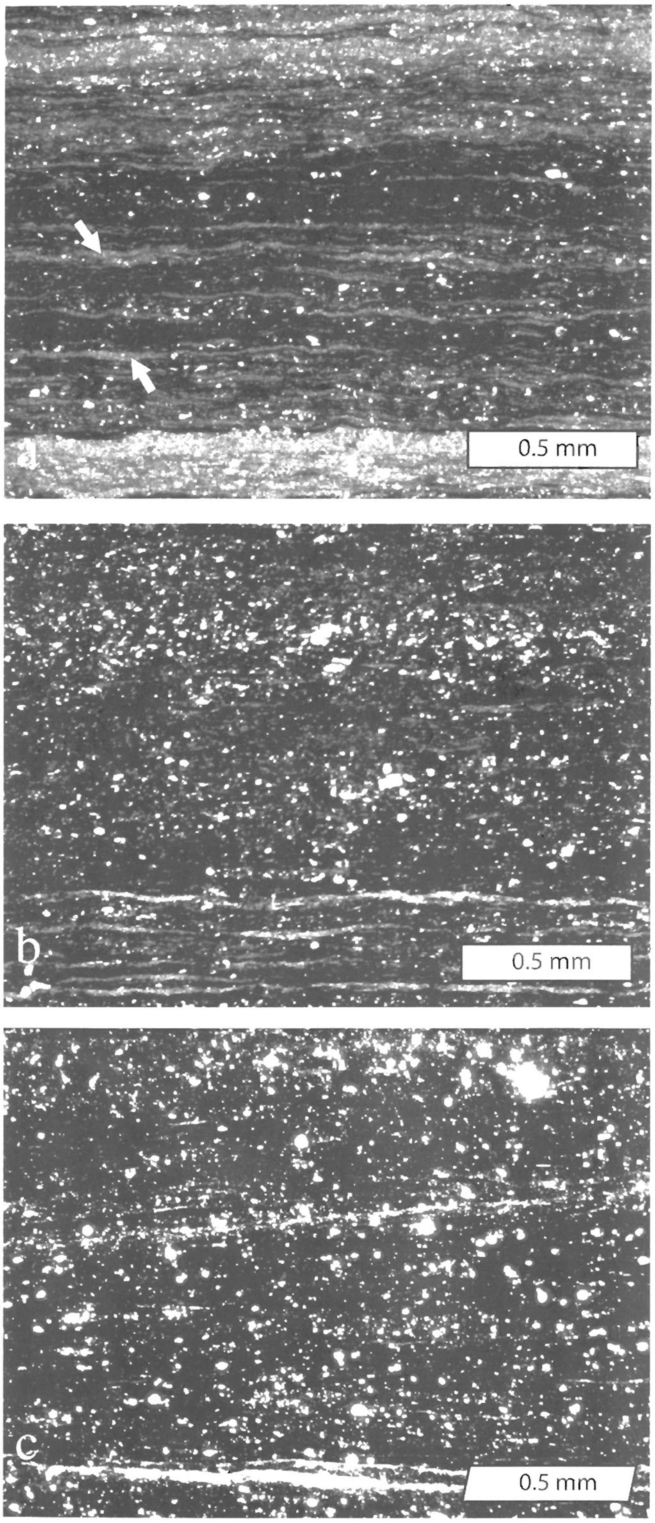

Fig. 4—Photomicrograph in transmitted light showing wavy crinkly laminae, arrows indicating clayey laminae (a). Photomicrograph in transmitted light showing discontinuous wavy laminae at bottom and middle part (b). Photomicrograph of black shale in transmitted light showing massive fabric (c). Note abundant quartz silts of different sizes in all the photographs.

mat deposits (Horodyski *et al.*, 1977; Krumbein & Cohen, 1977; Schieber, 1986: O'Brien, 1990). The sharp based clayey laminae, with occasional torn pieces of carbonaceous materials alternating with the carbonaceous laminae suggest frequent interruption of microbial growth by sedimentation pulses from storms. This is also to be mentioned that wavy lamination is not a reliable indicator of microbial mat growth always (Schieber, 1999). One should be very careful as the type of laminae can also be an artifact produced because of differential compaction around resistant particles like quartz and clay lenses. Nevertheless, the black shales in Kajrahat Limestone contain wavy lamination in places where there are negligible quartz and clay lenses suggesting primary waviness of the carbonaceous laminae.

Scattered quartz silts

Silt size quartz grains varying in sizes from 0.05 to 0.25 mm frequently occur within the carbonaceous laminae of the black shales (4 a-c). These quartz silts are scattered in variable frequency within the carbonaceous laminae and are most conspicuous in relatively thicker carbonaceous laminae (Fig. 4c). Interestingly, such quartz silts are absent within the adjacent clayey laminae. The proportion of quartz silt grains to carbonaceous matters may vary from 10% to 35%. The quartz silt grains are mostly angular, larger grains being better rounded.

The occurrence of silt size quartz grains within the carbonaceous laminae is unusual as silt grains are not in hydrodynamic equilibrium with the clay or organic matters. The wide grain size range of quartz silts is also an important point to be considered. If the organic matter and the quartz silts are considered detrital and transported by currents or waves, then they are expected to sort out according due to their specific gravity during deposition. Carbonaceous material and quartz silts are expected to concentrate in discrete laminae in such cases. The silt content of the carbonaceous laminae possibly suggest particle trapping on mucilaginous microbial mat surfaces (fly paper effect, Schieber, 1998). Microbial mats have gelatinous sticky surfaces made of exo-polymeric substances (EPS) that trap particulate matter varying from silt to coarse sand moving over the mat surface (Bauld, 1981). The scattered quartz grains of various size fractions within the carbonaceous laminae are possibly related to the cohesive and binding nature of the microbial filaments. Absence of quartz silts within the closely associated clay seams further supports this contention.

Pseudo cross-lamination

Both clayey laminae and carbonaceous laminae are occasionally arranged resembling small scale cross-laminae (Fig. 5). Carbonaceous laminae tend to terminate against the clayey laminae immediately underlying them and show low angle discordance at the boundary (Fig. 5). The individual

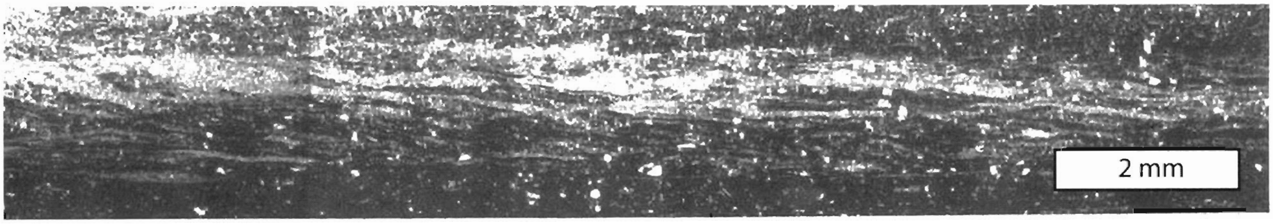

Fig. 5—Photomicrograph in transmitted light showing pseudo cross-lamination.

carbonaceous lamina pinches out between the clayey inter laminae. A detailed observation of Fig. 5 shows that the carbonaceous laminae are abundant and appears massive towards the bottom part. Towards the top, the carbonaceous laminae bear a sharp truncation and pinch out between the clayey laminae. The pinch out of carbonaceous laminae shifts sideways in a systematic way and imparts a cross laminated appearance. The feature has been described as pseudo-cross lamination by Schieber (1986).

Pseudo-cross lamination is formed when the microbial mat cover develops on slightly inclined surface and microbial growth is frequently interrupted by deposition of clayey sediments. The lower part in Fig. 5 exhibiting abundant carbonaceous laminae possibly indicates uninterrupted microbial growth. The clayey laminae, which are more frequent in the upper part, might have been deposited by sheet floods caused by strong, sporadic terrigenous influx like storms. Rapid deposition of clayey sediments covers the microbial mat cover instantaneously. Motile filamentous microorganisms escape upward and re-colonize on clayey sediment surface. The new mat then expands laterally until it is covered again by another clayey drape. Because of repetition of these processes carbonaceous laminae alternates with the clayey laminae on inclined surfaces forming pseudo-cross lamination.

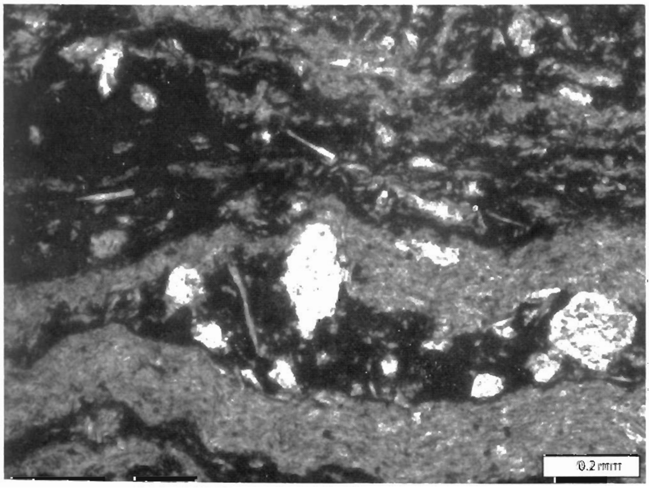

Fig. 6—Photomicrograph in transmitted light showing folded over carbonaceous laminae (black) alternating with clayey laminae.

Mat destruction features

Physical destruction of mat cover by waves and currents generates the mat-destruction features. The various features which are possibly generated because of destruction of microbial mat cover are discussed as follows.

Folded-over carbonaceous laminae

Petrographic observation often shows deformed and folded-over 0.25-0.5 mm thick carbonaceous laminae (Fig. 6). The carbonaceous laminae behaved as a coherent layer during the folding. The clayey laminae occurring in between the carbonaceous laminae are either squeezed out during the folding or folded along with carbonaceous laminae. The overlying and underlying laminae are continuous and are not affected by the deformation.

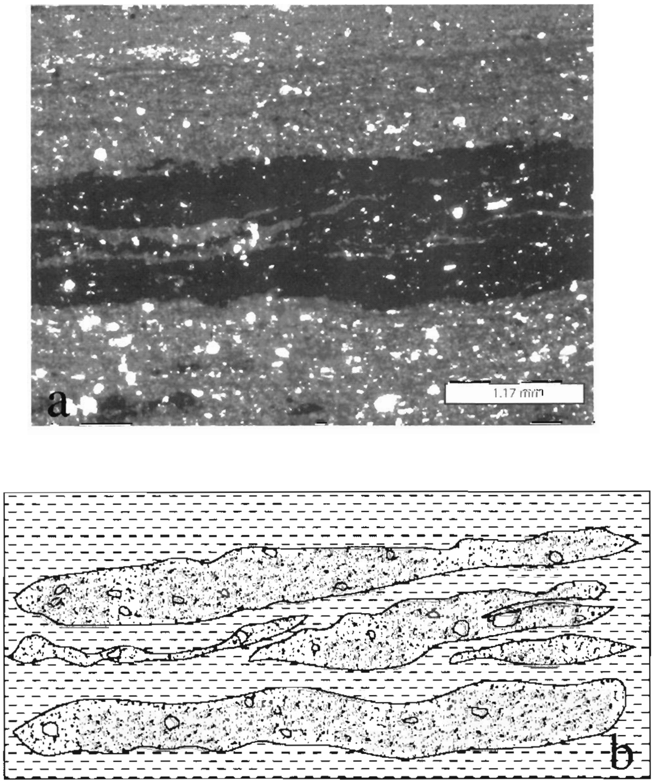

Fig. 7—Photomicrograph in transmitted light showing roll-up structures at the centre (a) and sketch showing vertical section of the same structures (b).

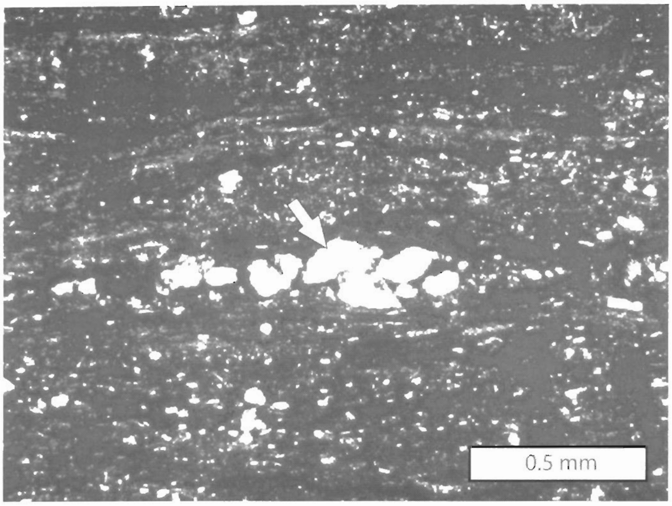

Fig. 8—Photomicrograph in transmitted light showing quartz silt aggregate (arrow) within the carbonaceous laminae.

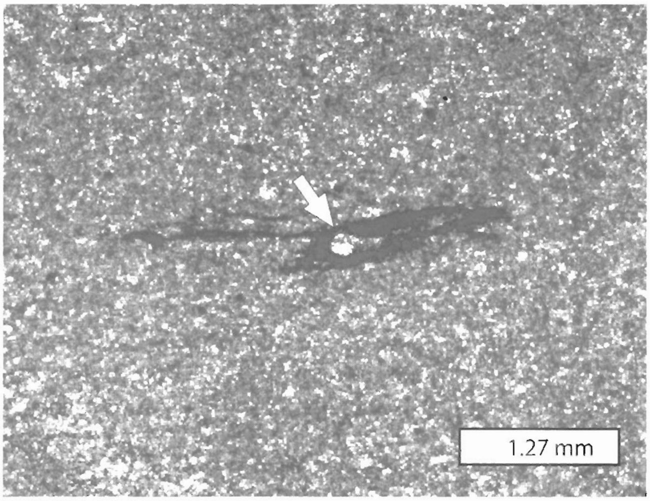

Fig 9—Photomicrograph in transmitted light showing thin mat shred, with a quartz silt attached (arrow).

Folding of the carbonaceous laminae is possible only when the mat layers are cohesive and tough. The undeformed clayey layers occurring above and below the overfolded carbonaceous laminae indicate that deformation happened very soon, presumably before deposition of overlying laminae. The cohesive and tough carbonaceous laminae are torn and overfolded possibly by strong flow shear related to violent storms. The flexible response distinguishes the microbial mat layers from cohesion caused by synsedimentary cementation (Schieber, 1999; Simonson & Carney, 1999; Eriksson *et al.*, 2000).

Roll-up structures

The carbonaceous laminae are locally deformed into small cigar-shaped or roll-up fragments occurring within the dolomite band. In cross-section the roll ups are elliptical in shape, up to 1 mm in size and aligned parallel to the bedding plane. Their length varies between 5 to 8 mm. Within the small folds carbonaceous laminae are closely intercalated with relatively thinner dolomitic bands (Figs. 7a, b). The dolomitic laminae occurring above and below it are undeformed and bear a sharp contact with the carbonaceous laminae.

Like the folded-over carbonaceous laminae, the roll-up structures also indicate the cohesive behaviour of benthic microbial mat (Schieber, 1986; Simonson & Carney, 1999). The undeformed underlying and overlying silt laminae further corroborates the syn-depositional origin for the roll up structures. When the microbial mat cover is subjected to storm currents they may be rolled to form roll up structures.

Quartz silt aggregates

The black shales often contain curious clusters of quartz silt grains within the carbonaceous laminae (Fig. 8). The aggregates appear elliptical in sections perpendicular to bedding. Length of the long axis of the ellipse varies from 0.5 to 1 cm. Closer observation reveals thin carbonaceous films surrounding individual quartz grains. Size of individual quartz silt grains vary from 0.05 to 0.1 mm. The carbonaceous laminae occurring above the clusters seem to wrap it evenly.

The clay aggregates are not in hydrodynamic equilibrium with the surrounding finer material. The clusters possibly represent dried out microbial mat chips formed at the shallower part of the basin and then transported by storm currents into the deeper sea (Olsen *et al.*, 1978; Schieber, 1999).

Thin shreds of mat fragments

Thin shreds of carbonaceous fragments (3 mm thickness) can be seen encased within the dolomites (Fig. 9). The mat fragments vary in length from 0.5 to 1.5 mm. Edges of these mat fragments have characteristically frayed appearance. Often these carbonaceous fragments contain quartz silts attached to the shreds.

The thin shreds of mat fragments possibly represent pieces of mat fragments produced because of storms actions on microbially covered bed surfaces. The very thin, detached mat fragments must be cohesive enough to be carried by the storm currents. The attached quartz silts corroborate that thin shreds are far more cohesive than ordinary muds. Cohesive behaviour of the mat fragment identifies them as of microbial mat.

Mat diagenetic features

Decay and diagenesis of microbial mat cover generates the mat-diagenetic features. The most common product during diagenesis of mat is pyrite laminae.

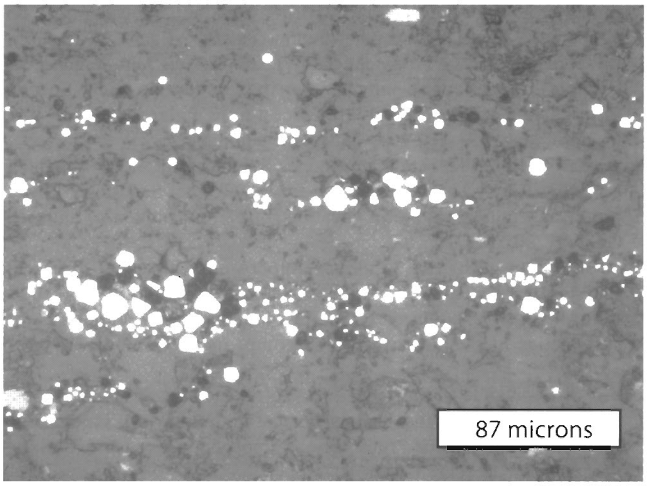

Fig. 10—Photomicrograph in reflected light showing wavy pyritic laminae.

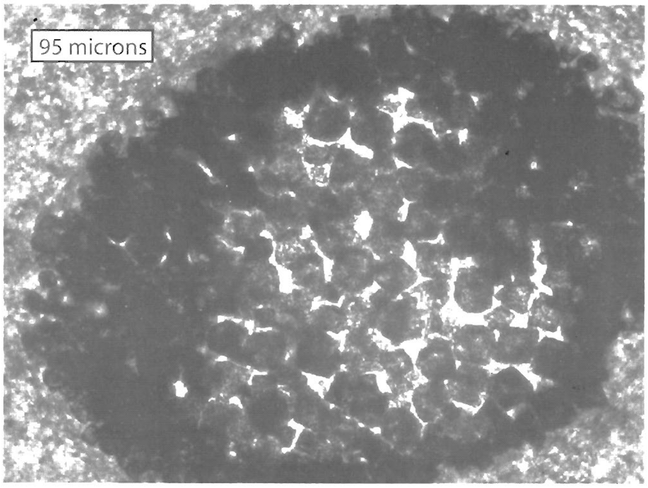

Fig. 11—Photomicrograph in transmitted light showing pyrite framboid.

Pyritic laminae

The wavy-crinkly, carbonaceous laminae very often exhibit clusters of pyrites confined within the laminae (Fig. 10). Although concentration of pyrites within the black shale are less (<1% of the rock volume), the wavy laminated nature distribution is significant. Such pyritic laminae are wavy laminated. Within the pyritic laminae pyrites occur as euhedral to subhedral crystals of 5 to 10 microns in size. Pyrites also occurs as framboidal aggregates within the laminae (Fig. 11).

In Phanerozoic black shales pyrite tends to be disseminated and do not form laminae. The black shales of the Semri Group exhibit wavy pyritic laminae which are bedding parallel suggesting possible mineralized microbial mat laminae (Schieber, 1998, 1999, 2004). The decay of the microbial mat in the marine setting produced hydrogen sulphide which in presence of reactive irons formed pyrites (Berner, 1984). The general absence of this lamina type from Phanerozoic black shales reflect rarer occurrence of benthic microbial mats in Phanerozoic black shale forming environments. Availability of iron, duration of anoxic condition and thickness of the decayed mat determines the quantity of pyrites.

DISCUSSION AND CONCLUSIONS

Microbial mats flourished in Precambrian seas in absence of grazing organisms and influenced Proterozoic sediment depositional systems in a major way. Although microbially mediated structures are well documented from Proterozoic carbonates, their siliciclastic counterparts are yet to be known properly. Microbial mat origin in siliciclastic rocks are inferred based on indirect evidences, in finer grained rocks the features are very subtle. The organic-rich shale unit of the Kajrahat Formation exhibits many subtle textural features which indirectly suggest their microbial mat origin. Wavy, crinkly carbonaceous laminae are in direct contrast with the planar laminated fabric of most of the Phanerozoic black shales. Wavy laminae are suggestive of microbial mat growth on muddy siliciclastics. Current actions, possibly by occasional storms created physical destruction of microbial mat layers generating some features like the folded over carbonaceous laminae, roll-up structures and occasional torn pieces of the mat layers. All the features suggest that the black shale deposition possibly took place in outer-shelf depositional setting, which is disturbed by violent storms. The Phanerozoic black shales, form due to passive accumulation of organic matter are deep basinal origin, whereas the microbially originated black shales of the Kajrahat Formation represent predominantly shelf depositional setting. Microbial mats impart unusual cohesiveness to the muddy sediments, which is revealed by the features like folded over carbonaceous laminae and roll-up structures. Decay of microbial mats produces local anaerobic conditions which is conducive for the formation of pyrites following the carbonaceous laminae. Growth of microbial mat requires sediment starvation in the basin. The black shale unit therefore represents a maximum flooding surface (Posamentier *et al.*, 1988) in the overall depositional scenario (Bose *et al.*, 2001; Jeevankumar, 2006) and is a key sequence stratigraphic element within the Vindhyan Supergroup.

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