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Status Report

Palaeobiological Constraints and the Precambrian Biosphere: Indian Evidence

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The Precambrian successions of India entomb many evidence of the evolution of the lithosphere, atmosphere and biosphere. The present paper enumerates the palaeobiological constraints in understanding the Precambrian biosphere. Records of the organismal evolution from India are discussed with their significance in global perspectives. The palaeobiological remains recorded from India are grouped and presented under nine categories: Stromatolites, megascopic carbonaceous remains, microfossils, Microbially Induced Sedimentary Structures (MISS), Pre-Ediacaran-Ediacaran fossils, bizzare forms, chemostratigraphy, molecular biology and astrobiology. Important contributions made during the last decade are discussed. The article also provides historical précis of the Precambrian palaeobiological studies in India; identifies the strength of the Indian researchers; articulates the unsolved problems and future research directions in the form of gaps and goals.

Key Words: Precambrian; Palaeobiology; Microfossils; Stromatolites; Astrobiology

Introduction

In India, over a century ago, Jones (1909) recorded circular discs from the Suket Shales of the Vindhyan Series (Supergroup). Until mid of the last century these carbonaceous remains were debated before being finally accepted as fossils of *Chuaria circularis*. The discovery of fossils carbonaceous discs is considered as heralding an era of the Precambrian palaeobiology in India. Over the years: Indian researchers have contributed to our understanding of the primitive life forms entombed in the Precambrian. Extensive exposures (Fig. 1) of the Precambrian sequences (both the Archaean and the Proterozoic) have provided avenues and several important evidence of early life. As a result of such palaeobiological studies the sequence otherwise considered younger in age, viz. Krol sequence of the Lesser Himalaya later proved to be the Precambrian-Cambrian sequence (Valdiya, 1980; Singh & Rai, 1983). On the global scale, the Precambrian palaeobiology have opened a new window to understand the early evolution of life which ultimately expressed in sudden explosion of diversified life forms at the Precambrian-Cambrian boundary. The two seminal papers in 1954 and 1965 (Tyler & Barghoorn, 1954; Barghoorn and Tyler, 1965) are considered to set the pace to discover the roots of life in the Precambrian. These investigations also provided the much needed support for the molecular phylogenetic studies that the three domains of living forms, viz. the Bacteria, the Archaea and the Eukarya (Woese, 1987, 2002; Woese *et al*., 1990) evolved, established and diverged from one another during the Archaean Eon. Indian studies also recorded several direct evidence, in the form of fossil remains, to support the evolutionary theory. These are discussed in following text. The results of these studies provided the direct evidence of the presence of prokaryotes, protists, advanced algal fossils, acritarchs and the indirect evidence incorporate stromatolites, trace fossils and geochemical fossils. Nature of these fossils are varied and preserved as compressions, impressions, permineralized and biomineralized remains. In the present paper, we summarize the contributions made by the Indian researchers in recent years and their impact on the global evolutionary understanding. We have also enumerated the gaps in our understanding and chart the goals for future studies.

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Fig. 1: Map of India showing distribution of different Proterozoic basins (modified after Raha and Sastry, 1982)

Historical Précis

Although the Precambrian rocks are replete with several biogenic structures yet the early signatures of life are difficult to interpret. Earliest report of stromatolite-like structures comes from India by McClelland (1834) who recorded them as ring-like features. Similar features were reported from the limestones of the Cuddapah Supergroup; these structures were described as *"Laminated and Segregated in Peculiar Way"* (King, 1872; p. 189-190, Fig. 29). In the Vindhyan basin, spheroidal bodies were recorded in the limestones by Auden (Auden, 1933, p l. 7, Fig. 2). Early geologists engaged in the mapping of different parts of the country were not sure about the biogenecity of such structures and therefore these structures were simply mentioned in their reports. Taxonomy of such forms, their importance in the context of evolution and biostratigraphy were not properly understood until sixties of the last century. Momentum gained in such studies after 1960s when extensive presence of stromatolites in almost all the Precambrian rocks of India were documented (Fig. 2a, b). Demonstrably, the studies on stromatolites have been divided into three phases: investigative phase (1900-1950 AD); stabilizing phase (1951-1975 AD); swinging phase of disinterest/interest in (1976-2000 AD) and the last

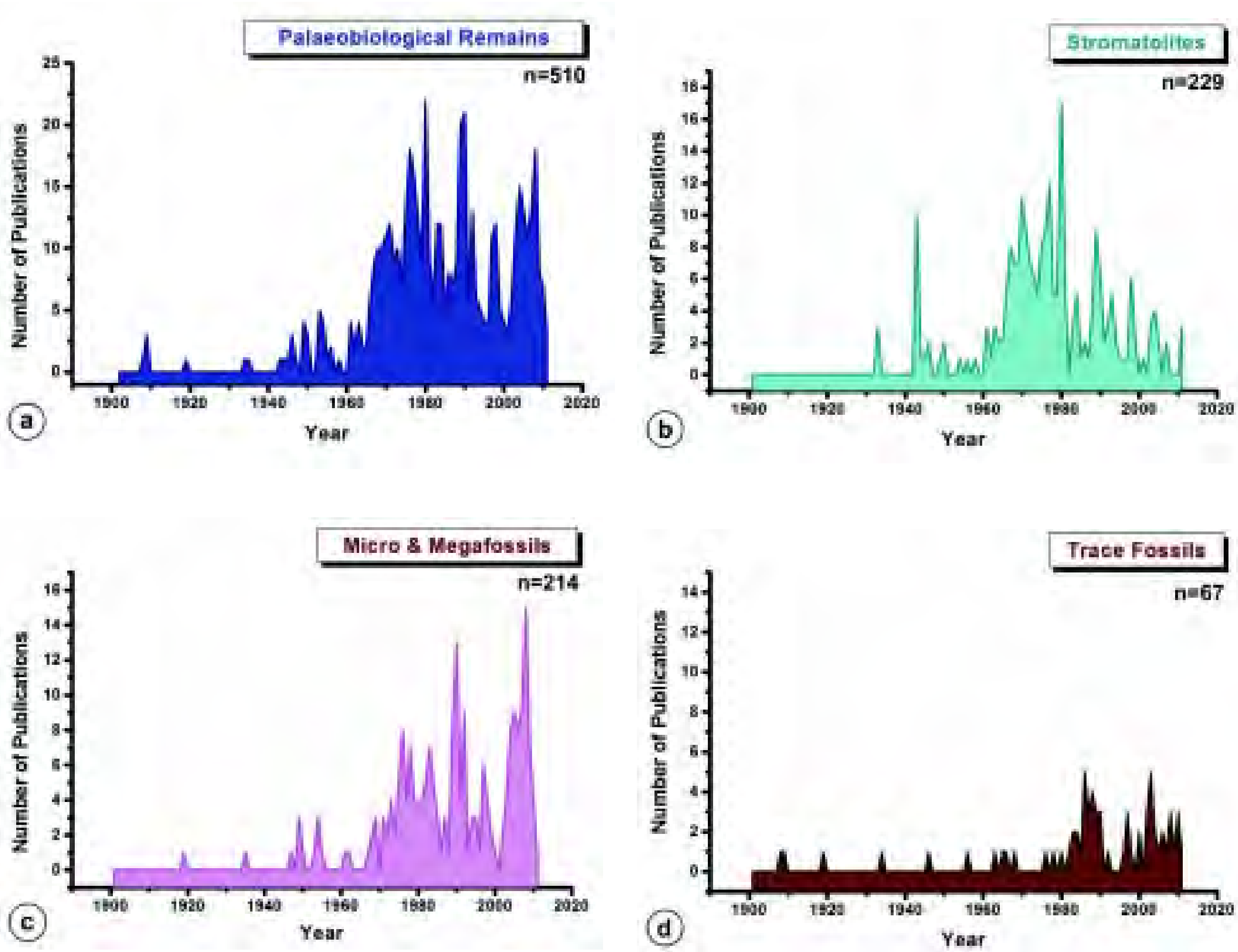

Fig. 2: Graphical representation of the number of publications on the palaeobiological remains from India. The graph is based on published records (Data source: Geo-Ref accessed on 30.03.2012 and personal collections of the authors) (a) Total publications on palaeobiology. The graph represents significant increase in publications on palaeobiology after 1960; (b) Publications on stromatolites increased considerably between 1960-1980 and thereafter reflects the decline in the interest of researchers; (c) interest in the study of micro and megafossils rose between 1960-2011; (d) publications on trace fossils increased between 1980-2011 and it is continuing even today

decade can be considered as a phase of renewed interest in stromatolites (Sharma, 2008a, Kumar, 1984; Venkatachala *et al*., 1996). Similarly, macrofossils, microfossils and acritarchs have also been recorded from several sedimentary basins in the country. Based on such fossil assemblages some attempts were made to interpret the biostratigraphy of some basins. Early palynological studies reported extensive Precambrian microfossils several of which later found to be contaminants. Contamination of extant material posed a serious challenge to the advancement of the Precambrian palynological studies. Many of these studies have, therefore, limited importance. The contamination problem in the study of microfossils and acritarchs, their utility and impact on the biostratigraphic interpretations and permineralized fossils in cherts have been discussed in many contemporary publications (Venkatachala *et al*., 1996; Kumar and Srivastava, 1989; Manoharachary *et al*., 1990; Sharma *et al*., 1992; Sharma *et al*., 2992; Sharma 2003).

Precambrian Palaeobiology

Stromatolites

Laminated spheroidal, conical, branched and columnar structures, known as stromatolites, are one of the definite evidence of life in Precambrian. Such structures are megascopic recognizable in the field. They have been extensively documented from the Archaean (Venkatachala *et al*., 1989) and Proterozoic sedimentary basins of India (GSI Misc. Publ., 1980). Two major publications are testimony of the engagement of research workers on the topic (GSI Misc. Publ., 1980; Valdiya, 1989). Some new attempts show realization of their importance in biostratigraphy (Raaben *et al*., 2001; Bose *et al*., 2001; Sharma & Shukla 2004a and b; Misra & Kumar, 2005; Kumar & Misra, 2007; Tewari & Seckbach, 2011; Pandey, 2011; Sharma & Pandey, 2012).

Megascopic Carbonaceous Remains

Carbonaceous macrofossils occurring on the bedding planes of the areno-argillaceous successions of the Precambrian are the other evidence of early life forms. Wide varieties of forms are described from the Vindhyan, Kurnool, Bhima, Chhattisgarh basins (Fig. 2c). The *Chuaria-Tawuia* assemblage invariably constitutes the most important element of megascopic carbonaceous remains. Recent discoveries have shown that the megascopic remains range from early Mesoproterozoic to Late Neoproterozoic successions (Kumar, 1995; Srivastava, 2002; Sharma, 2006c; Srivastava & Bali, 2006; Sharma *et al*., 2009; Sharma & Shukla, 2009 a and b). Some of the early Mesoproterozoic carbonaceous remains are prokaryotic (Sharma & Shukla, 2009b) whereas others represent either the eukaryote or some large filamentous forms, characteristic of pre-Ediacaran assemblage (Shukla, 2011; Sharma & Shukla, 2012a). Megascopic carbonaceous remains, not only, have provided an opportunity to study the morphological details, but also, provided an avenue to integrate the varied morphologies to inter-relate them and help reconstruct the connections to propose most feasible environmental and genetic models (Sharma *et al*., 2009; Kumar, 2001; Kumar & Srivastava, 2003).

Microfossils : Application of traditional palynological treatment of the Precambrian rocks revealed the presence of a diversified microbial world. Microfossils in the shale-facies were generally recorded in the early phase of the Precambrian palaeobiological studies followed by the documentation of microfossils in the chert-facies. There was an inherent problem in the study of shale-facies microfossils as these fossils were invariably recovered by maceration of rocks with acids. In this technique, rock samples are exposed to contamination by the extant materials giving rise to microfossil like structures. Therefore, microfossil studies involving maceration demand extra caution and care.

Chert-facies Microfossils

The discovery of microfossils in early diagenetic cherts (Tyler & Barghoorn, 1954; Barghoorn and Tyler, 1965) and subsequent detailed analysis of the Bitter Springs black chert (Schopf, 1968) showed the possibility of documentation of well preserved early life forms. Early diagenetic cherts belonged to a restricted biospheric realm as these cherts were generally formed in the peritidal to tidal carbonates. In spite of such restricted nature of the biological realm, these studies were favored due to excellent preservation of microfossils (Fig. 2c). In several pre-2008 publications chert-facies microfossils have been recorded from Vindhyan rocks. New addition to these studies comes from Srivastava (2009) (Fig. 3) (Sharma, 2006a). Similarly a large number of pre-2006 publications dealt with microfossils in Deoban Limestone, Infra-Krol, Krol, Tal Formations and Buxa Dolomite. New studies include rocks of the Marwar Supergroup (Mehrotra *et al*., 2008; Babu *et al*., 2009). These studies dealt with the taxonomy of the fossil assemblages while some also addressed taphonomy, depositional environment and the evolution. Several workers have reported acritarchs from the permineralized cherts of the Infra-Krol and Tal Formations of Krol Belt in the Lesser Himalaya and also from Deoban and Buxa Limestones in Eastern Himalaya. Rise in number of publications on microfossils and acritarchs will help in understanding this complex group of fossils (Fig. 2c).

Shale-facies Microfossils : The most common Proterozoic and Early Cambrian acritarchs are represented by simple sphaeromorphs and morphologically complex acanthomorphs, herkomorphs, netromorphs, prismatomorphs and pteromorphs. Some of these microfossils have close association with fossils of extant chlorophyceae and many large sphaeromorphs have close affinity with prasinophytes. Mesosphaeromorphs (60 to 200 µm) are well known in the Cambrian sequence, while megasphaeromorphs (~200 µm) most dominant in the Terminal Proterozoic, are of rare occurrence in the Phanerozoic (Tappan, 1980). Acanthomorphic acritarchs play an important role in the Cambrian biostratigraphy, as they are unknown in the Archaean (Schopf & Walter, 1983) and infrequent in the Palaeo-Meso- Proterozoic (Hofmann & Schopf, 1983). Well documented acanthomorphic acritarchs are confined to Neoproterozoic (900-550 Ma) and in younger strata (Schopf, 1992). There is a general decrease in size range of acritarchs from the Proterozoic to the Cambrian.

Microfossils recovered from shale-facies constitute comparatively large assemblage in the Precambrian. A number of publications described acritarchs from Precambrian south Indian basins, most of which were of questionable status. Similarly, the Vindhyan sequences also revealed a diversified acritarch assemblages Recent studies of the drill hole material of the Ganga basin. Vindhyan and Marwar Supergroups revealed the presence of several taxonomically important acritarch genera which were used in the biostratigraphy (Prasad & Asher, 2001; Prasad *et al*., 2005; Prasad *et al*., 2010). Acritarchs have also been

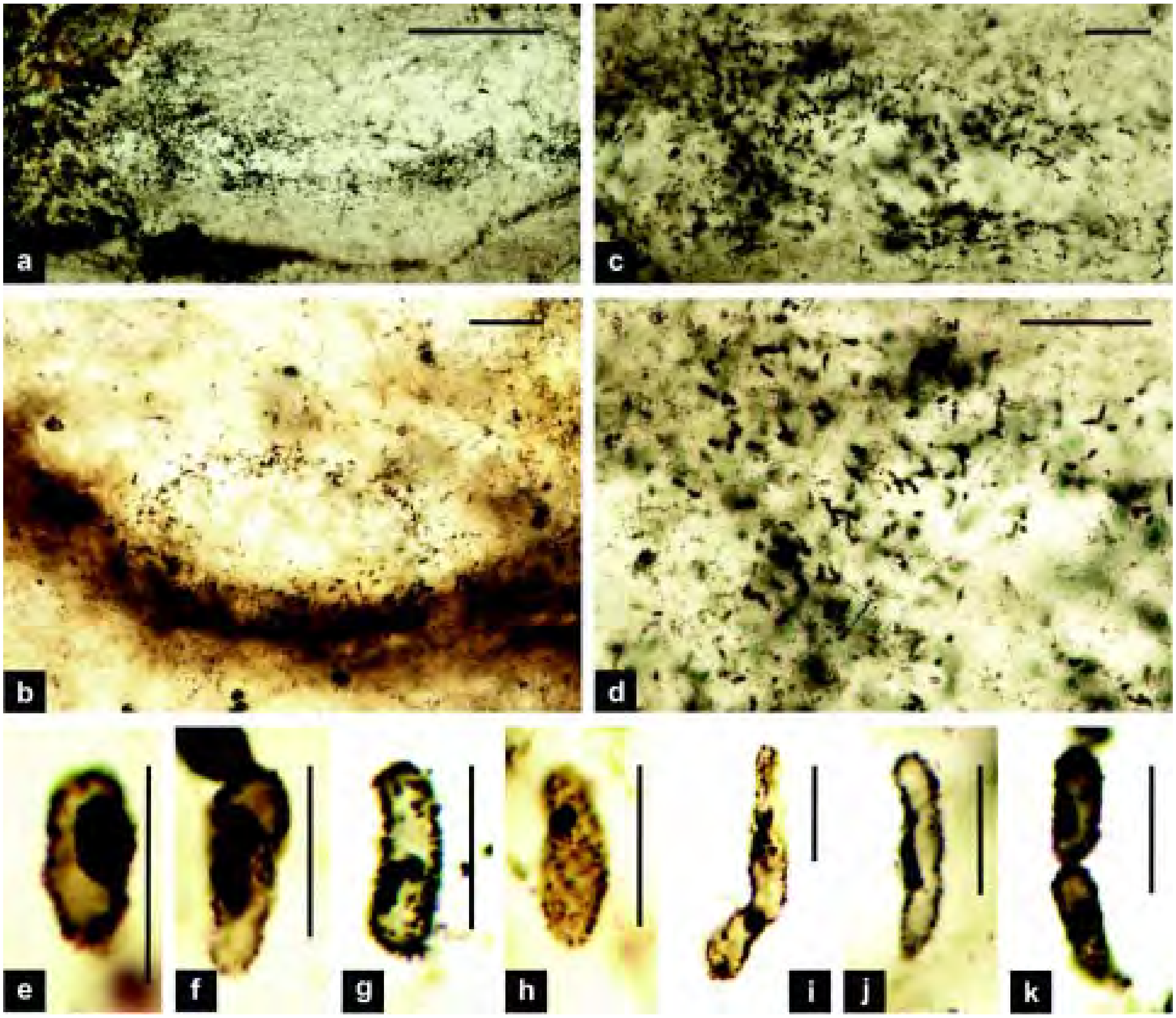

Fig. 3: An assemblage of akinetes of Nostocalean cyanobacteria recorded from the stromatolitic cherts of the Salkhan Limesone, Semri Group. (a) A low magnification view of the cluster of different species of akinetes *Archaeoellipsoides*; (b) Another cluster of *Archaeoellipsoides* at low magnification; (c and d) Gradual high magnification view of (a); (e-h, k) *Archaeoellipsoides minor*; (i, j) *Archaeoellipsoides major.* Scale bar = 500 µm for (a); 100 µm for (b-d); 10 µm for (e-k)

reported from the Gangolihat Formation (Tiwari & Pant, 2009).

The microfossils preserved in the chert nodules of Infra-Krol rocks have been attributed to non-septate and septate cyanobacterial filaments, coiled filaments, coccoids, large sphaeromorphs, small and large acanthomorphic acritarchs and VSMs. The cyanobacterial filaments and coccoids are identified as *Siphonophycus typicum*, *Siphonophycus robustum*, *S. kestron*, *S. inornatum*, *S. punctatum*, *Polytrichoides bipartitus*, *P. lineatus*, *Obruchevella parva*, *O. magna*, *Oscillatoriopsis media*, *Oscillatoriopsis* sp., *Eomicrocoleus crassus*, *Polybessurus crassus*, *Salome hubeiensis*, *Myxococcoides* sp., *Sphaerophycus parvum*, *S. medium*, *Huroniospora psilata*, *Palaeoanacystis vulgaris*, *Tetraphycus* sp., *Wengania globosa*, *Bavlinella faveolata* and *Melanocyrillium horodyskii*.

Large sphaeromorphic and acanthomorphic acritarchs are very prominent in the assemblage. These acritarchs are identified as *Leiosphaeridia crassa*, L. sp., *Ericiasphaera spjeldnaesii*, *Echinospheridium maximum*, *Asterocapsoides sinensis*, *Asterocapsoides* sp. and *Cymatiosphaeroides yinii* (Fig. 4). Venkatachala *et al.* (1990) considered them to be of Vendian age. Based on large acanthomorphic acritarchs (*Ericiasphaera spjeldnaesii*, *Echinosphaeridium* and *Asterocapsoides*), large filamentous cyanobacteria (*Salome hubeiensis*) and multicellular thallophyte (*Wengania globosa*) an Early Vendian age for the Infra-krol Formation was suggested (Tiwari & Knoll, 1994). Gigantism was the characteristic feature of the assemblage. Prasad *et al.* (1990) recorded acritarchs assemblage of the Vendian and Early Cambrian age from the Tal Formation in Garhwal syncline placing Blaini-Infra-krol and Krol A, B, C, and D in Vendian and the Krol E & Lower Tal in Early Cambrian. The microfossil assemblage includes *Granomarginata*, *Lophosphaeridium*, *Micrhystridium*, *Baltisphaeridium*, *Cymatogalia*, *Saharadia* and *Leiovalia*.

Microbially Induced Sedimentary Structures (MISS)

Adhesive property of the mucilage of microbes was postulated long ago with the report of laminated structures from limestones (Kalkowsky, 1908). The role of microbes in formation of the stromatolites is well established. But, occurrence of certain peculiar structures on the shales and sandstone surfaces are not explainable by sedimentological process. It was Schieber (1986) who invoked the microbial processes in the formation of such structure and identified the microbial mat deposits in and on the sandstone and mudstone. The role of microbes in accretion and diagenesis of siliciclastic rocks was documented in detail (Hagadorn *et al.*, 1999; Riding & Awramik, 2000). A recent atlas of microbial mat features (Schieber *et al.*, 2007) is a testimony of the interest of the geological community in the study of Mat Induced Sedimentary Structures (MISS) in the siliciclastic rocks. Microbial mats flourished in most Precambrian environments with optimum moisture content and sedimentation rate and greatly influenced sediment depositional systems and architecture of the stratigraphic record (Schieber *et al.*, 2007). Although microbial mats exist till today, these are largely confined to stressful environments because of grazing and burrowing activities of metazoans. Microbially originated carbonates are well documented from the Precambrian, while microbial influence in siliciclastics is largely overlooked. Microbes impart unusual cohesiveness to sands, and physical processes acting on cohesive and leathery microbial mats produce a wide range of sedimentary structures. The shallow marine clastic rocks of the of the 1.7-0.6 Ga old Precambrian Vindhyan Supergroup in central India are well studied to understand microbial mat influence in the Precambrian clastic sedimentation (Banerjee & Jeevankumar, 2005; Banerjee *et al.*, 2006b, 2010; Sarkar and Banerjee 2007; Sarkar *et al.*, 2005, 2006; Bose *et al.*, 2007; Deb *et al.*, 2007; Schieber *et al.*, 2007). These shallow marine sandstones exhibit wide varieties of delicate sedimentary structures in well sorted sandstones suggesting unusually high cohesiveness. These features include desiccation-cracks in well sorted sandstones, sand chips, patchy occurrences of ripples on bed surfaces with sharp outlines, curled and rolled-up sand fragments, wrinkle structures of various shapes and sizes on bedding surfaces, unusual steepening of the ripple crests, flute cast-like features on top surfaces of the sandstone bed (setulf) and tiny circular pits as well as domes and ridges on sandstone bed surfaces. Extensive exposures of siliciclastic rocks of the Indian Precambrian basins need exploration to document the variety of MISS and understand the role of microbial community in their formation. Interaction of microbial communities with clastic sedimentation has been recorded in the Palaeoproterozoic Cuddapah Supergroup (Chakrabarti & Shome, 2010). Three types of microbial mats have been recorded from the Shikaoda Sanstone of the Bhander Group, viz. *Arumberia banksi*, *Arumberia vindhyanensis*, *Rameshia rampurensis* (Fig. 5) (Kumar & Pandey, 2008a). It was suggested to have formed in shallow marine tidal settings and Ediacaran age is proposed. A wide variety of microbial mat mediated structures have also been reported from the Sonia Sandstone of the Marwar Supergroup (Sarkar *et al.*, 2008; Samanta *et al.*, 2011). *Arumberia banksi* and *Rameshia rampurensis* have also been recorded from the Sonia Sandstone exposed in the Khatu area of Rajasthan (Kumar & Pandey, 2009). Vast expense of the Neoproterozoic siliciclastic successions awaits investigation for the documentation of MISS. Banerjee and Jeevan Kumar (2005) and Sarkar *et al.* (2005) discussed about uniqueness of Precambrian sequence stratigraphic framework and explained vertical stacking of highstand systems tracts without intervention of significant transgressive deposits. Banerjee and Jeevan Kumar (2005) reported variation of wrinkle structures within a highstand systems tract in response to continued progradation. Further, Banerjee *et al.* (2006b) demonstrated that occurrence of organic-rich (TOC > 2%) shales are closely related to the maximum flooding surfaces. The wavy-crinkly laminated pyritic carbonaceous shales are found to be microbial mat-originated (Sur *et al.*, 2006; Schieber *et al.*, 2007). Deb *et al.* (2007) reported similar carbonaceous shales from the Mesoproterozoic Somanapalli Group, Pranhita-Godavari basin and demonstrated their microbial mat origin. Unlike their Phanerozoic counterparts the black shales in Precambrian rocks are exclusive microbially-originated forming in shallow, subtidal depositional setting (Schieber *et al.*, 2007).

Banerjee *et al.* (2010) studied both modern and ancient examples of the microbial mat features to explain the enigmatic features in Precambrian sedimentary

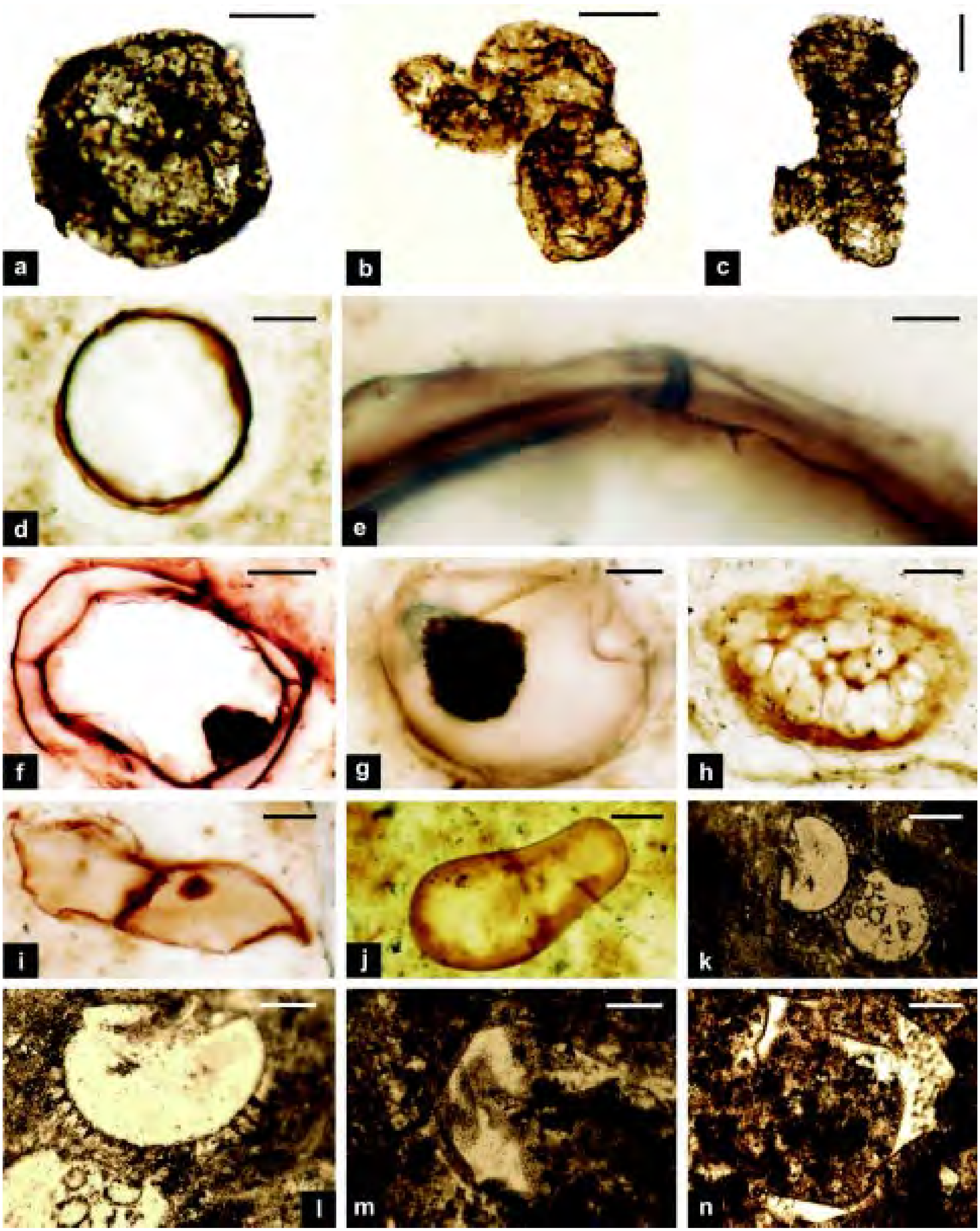

Fig. 4: Organic walled microfossils recorded from the Owk Shale, Kurnool Group. (a-b) *Leiosphaeridia crassa*; (c) Spirally coiled helix of *Obruchevella parva;* (d-j) Few complex morphologies in petrographic thin sections and macerated slides of chert from the Vindhyan Supergroup, India; (k-n), Acritarchs reported from Lesser Himalaya (k-l) *Asterocapsoides sinensis*; (m-n) *Ecinosphaeridium maximum*. Scale bar = 20 µm for (a-c, e, g, i); 50 µm for (d); 100 µm for (f, h, j, l-n) and 200 µm for k

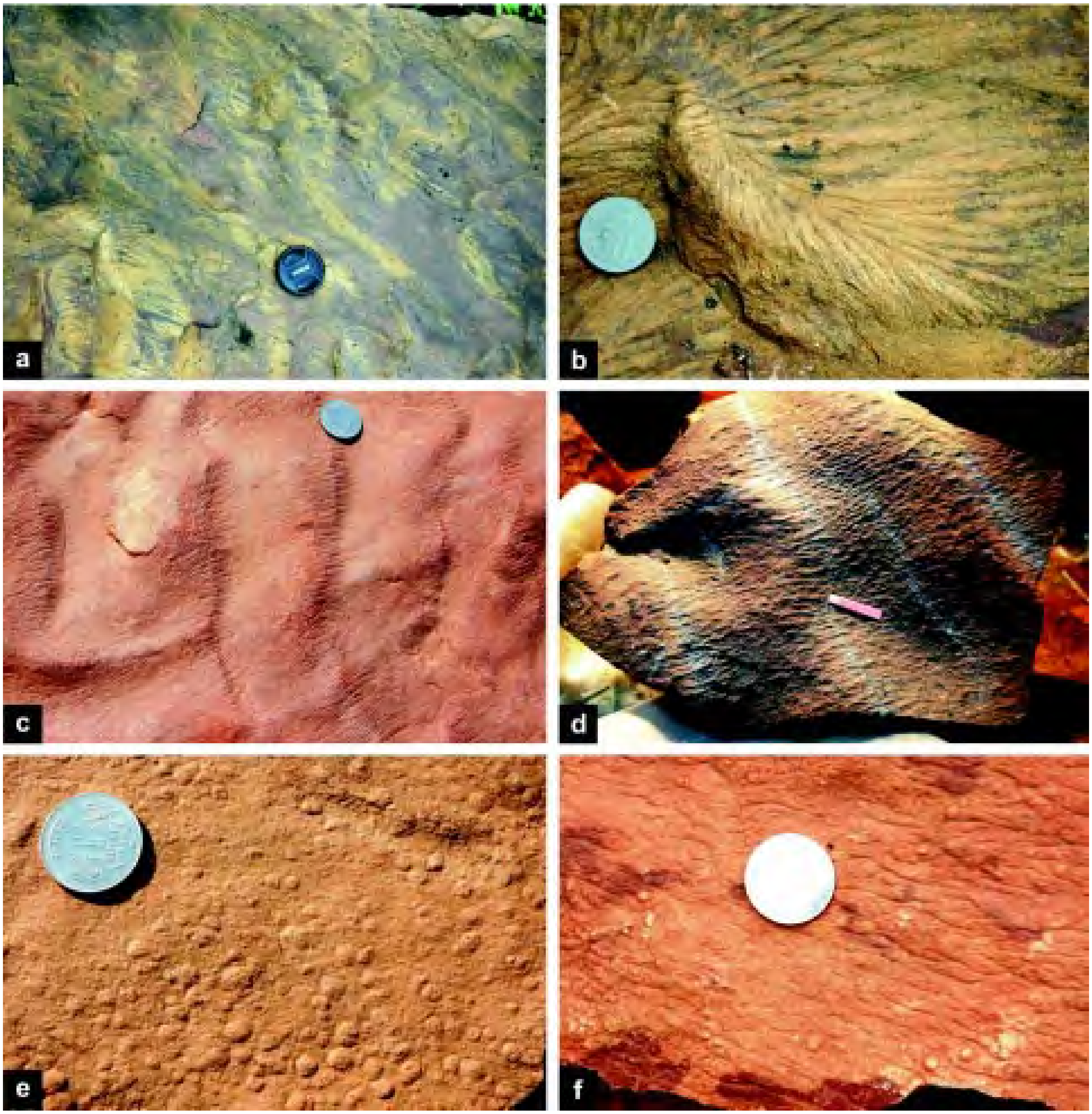

Fig. 5: A set of Microbially Induced Sedimentary Structures (MISS) from the Vindhyan and Marwar Supergroups. (a) *Arumberia banksi* on the flute casted surface of the Maihar Sandstone, Bhander Group, Vindhyan Supergroup (Diameter of lens cap = 5.5 cm); (b) Close-up view of *Arumberia banksi*, Maihar Sandstone, Bhander Group, Vindhyan Supergroup (Diameter of coin = 2.2 cm); (c) *Arumberia banksi* on the rippled surface, Sonia Sandstone, Marwar Supergroup (Diameter of coin = 2.5 cm); (d) Close-up view of *Arumberia banksi*, Sonia Sandstone, Marwar Supergroup (Diameter of coin = 2.0 cm); (e) *Beltanelliformis minuta*, Sonia Sandstone, Marwar Supergroup (Diameter of coin = 2.5 cm); (f) *Beltanelliformis minuta* associated with microbial mats on the bedding plane of the Maihar Sandstone, Bhander Group, Vindhyan Supergroup. (Diameter of coin = 2.2 cm)

succession. Microbial mats are well developed in the hypersaline coastal plains of the Gulf of Khambhat and offer an opportunity to compare similar features in Precambrian (see also Sarkar & Banerjee, 2007). Banerjee *et al*. (2010) reported many enigmatic features from the shallow marine sandstones of the ~1.6 Ga old Semri Group of the Vindhyan basin bearing uncanny resemblance to metazoan burrows, tracks and trails and metazoan body fossil impressions. Microbial mat origin of these features was confirmed on the basis of the modern examples. Further, Banerjee *et al*. (2010) reported perfectly circular varieties of wrinkle structures on modern coastal sands with sharp outline (commonly known as discoidal microbial colony) resembling medusoid type of Ediacaran fossils found in Terminal Precambrian sedimentary successions (see also Banerjee, 2012). The study of modern mat-related structures thus, provides alternative and more readily acceptable explanations of features resembling traces of advanced organisms in considerably older rocks besides high-resolution environmental interpretations in Precambrian shallow marine environments.

Pre-Ediacaran-Ediacaran Fossils

Sudden occurrence of complex life forms in the Cambrian puzzled Charles Darwin and subsequent discoveries close to the PC-C boundary have helped in propounding the theory of 'Cambrian Explosion'. Several of recorded fossil life forms are assigned to known phylum of the animal kingdom. These discoveries at global level in certain time period led to the establishment of a new geological period-the Ediacaran Period (635-542 Ma: Knoll *et al*., 2006). With a little larger time span, the Vendian, a favourable period with Russian researchers, is another time period which almost corresponds to the Ediacaran is teeming with complex life forms. The complexity of Ediacaran fossils led to the postulation of pre-Ediacaran animals as well as metaphytes. Sun *et al*. (1986) demonstrated the possibility of the occurrence of pre-Ediacaran animals from China. Affinity of these remains as pre-Ediacaran metazoan or metaphyte is debatable. (Fig. 6 & 7: Dong *et al*., 2009; Sharma & Shukla, 2012a). In addition to several previous reports, pre-Ediacaran fauna has been again described in recent time (Sharma & Shukla, 2012a). All previously described Ediacaran metazoan forms are devoid of any hard part but retained their carbonaceous contents and therefore, paved the way for the study of evolutionary tendencies in these life forms. In India, a small number sedimentary successions show Precambrian to Cambrian transition. Hence, the possibility of deposition of the Ediacaran period sediments is restricted only to these successions. Krol belt and the Spiti sections in the Himalaya and the Marwar Supergroup in the Western India, therefore, expose the Ediacaran successions. Occurrence of *Twitya*-discs, *Cyclomedusa*, *Obruchevella* and burrow structures in the Kurnool Group make it another Ediacaran succession in the Peninsular India (Sharma, 2008b; Sharma & Shukla, 2012b).

Up to 2006, several workers reported Ediacaran fossils in the Vindhyan Supergroup, but most of these have now been discarded as artifacts (Kumar & Sharma, 2012). The Ediacaran assemblage of the Himalaya include *Pteridinium simplex*, *Charniodiscus*, *Zolotystia*, *Beltanelliformis*, *Kimberella*, *Conomedusites* sp., *Cyclomedusa davidi*, *Sekwia, Irridinites* (Mathur, 2008; Maithy & Kumar, 2007). Morphologically differentiated calcified sponges. *Mussooriell kroli* and *Maldeotania composita* have been described from Krol E' of Mussoorie Hill (Flügel and Singh, 2003). Varied trace fossils have been reported from the Upper Tal Formation of Mussoorie Syncline (Tiwari & Parcha, 2006). From the Marwar Supergroup in Rajasthan several Ediacaran forms and Lower Cambrian trace fossils have been reported (Raghav *et al*., 2005; Kumar & Pandey, 2008b, 2010; Kumar *et al*., 2009; Kumar *et al*., 2012).

Bizzare Forms

Palaeobiological forms recovered from the Precambrian sediments have generally been assigned to some particular group, phylum/family of the living world. Differences are there in the opinion of researchers about the assignment of certain forms with regard to their grouping into three principle domains, viz. the Bacteria, the Archaea and the Eukarya. Still there are some biological forms which cannot be grouped or assigned to any domain of the living forms of the present day. These forms, however, are described as bizzare forms. Morphology, form and function of these bizzare forms are not completely understood, but they have found place in literature with a view that in future these enigmatic forms may prove to be some link in the evolutionary chain. Such forms are reported from many Precambrian basins of India, particularly from the Vindhyan and the Marwar Supergroups and the Deoban Limestone Belt (Sharma, 2006b, Srivastava, 2011; Srivastava, 2012).

Chemostratigraphy

Carbonate rock successions in various Precambrian basins of India have been analyzed for stable isotopes of carbon, oxygen and sulphur for assessment of their excursions across the Pc-C boundary. Such studies helped in understanding the changes in the depositional conditions and organic-inorganic interactions through time. These studies also helped in establishing the onset of cold glacial environment at particular period of the earth history. In recent years, comprehensive and robust data sets have been generated on the Krol carbonate rock succession (Kaufman *et al*., 2006) in the Lesser Himalaya; Vindhyan Supergroup (Kumar *et al*., 2005; Banerjee *et al*., 2006a); Marwar Supergroup (Mazumdar & Bhattacharya, 2004; Mazumdar & Strauss, 2006). Collectively, these studies have demonstrated the usefulness of the isotopic signatures in demarcating the Precambrian-Cambrian boundary and understand the palaeoclimatic changes.

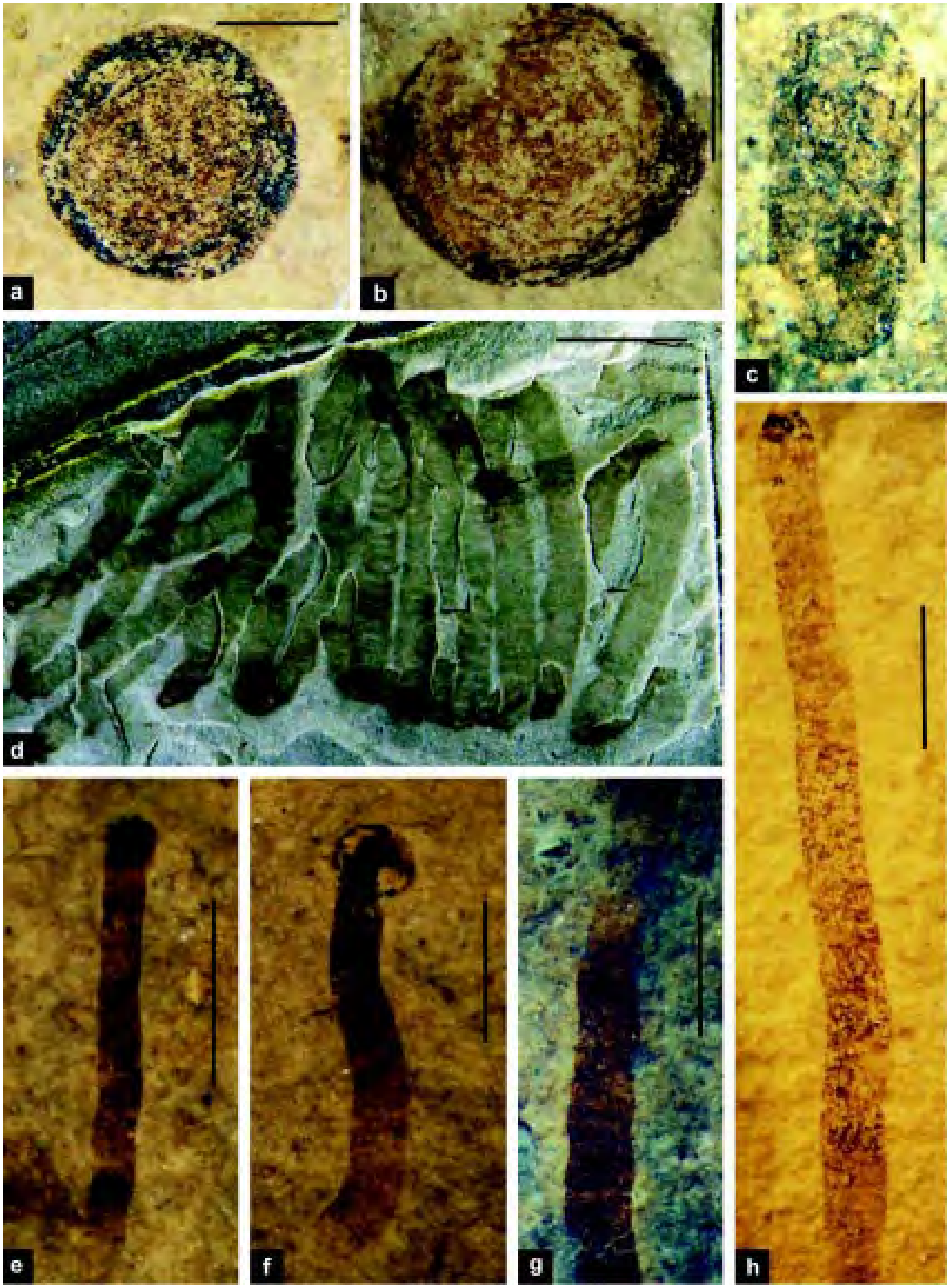

Fig. 6: Varied carbonaceous remains recovered from the Proterozoic sedimentary basins of peninsular India. (a-b) *Chuaria circularis*; *C. circularis* showing thick rim on the periphery of specimen noted in the Halkal Formation of the Bhima basin; (c) *Tawuia dalensis* recorded from the Halkal Formation of the Bhima basin; (d) *Katnia singhii* preserved on the parting surfaces of grey shale from the Rohtas Formation, Vindhyan basin; (e-f) *Protoarenicola baiguashanensis;* (g) *Sinosabellidites huainanensis;* (h) *Pararenicola huaiyuanensis* all recorded from the Halkal Formation of the Bhima Group. Scale bar for (a) = 1mm; for (d) =5mm and for rest of the specimen = 2 mm

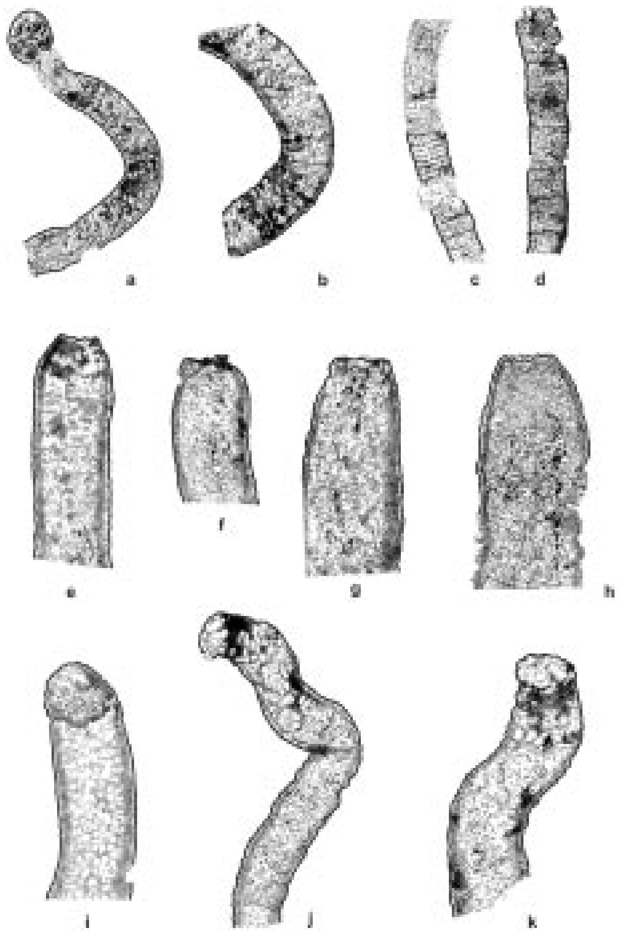

Fig. 7: Line diagrams of the carbonaceous remains recovered from the Halkal Formation of the Bhima Group. (a) Line diagram of representative geometrical shape of *Protoarenicola* & (b-d) Line diagrams of representative geometrical shapes of *Sinosabellidites* based on specimens recorded from the Halkal Formation of Bhima basin; (e-k) Line diagrams of representative geometrical shapes of *Pararenicola* from the Halkal Formation of the Bhima basin (after Shukla, 2011)

Molecular Biology

Following the molecular phylogenetic studies, the two kingdom divisions, the Plantae and Animalia, of the living world grossly changed its scientific complexion. It was suggested that all living forms can be grouped into three principle domains, viz. the Bacteria, the Archaea and the Eukarya (Woese *et al*., 1990) or two empires, viz. the Prokaryota and the Eukaryota (Mayr, 1998). Incidentally, molecular phylogenetic studies also established that these domains diverged from one another during the Archaean. Molecular biology, also known as organic geochemical studies, has helped understand the advent of different group of animals and plants as well as the pathways of metabolism adopted by different organisms. Many of the biomarker molecular studies and recorded fossil evidence are not conformable. It is more so evident with the example of *Tappania plana* from the Roper Group which is considered as the oldest known fossil eukaryote (Javux *et al*., 2003), whereas the molecular studies indicate existence of eukaryotes around 2.7 Ga (Brocks *et al*., 1999). In spite of such inconsistencies biomarkers as well as molecular biological studies are drawing attention of researchers (Sharma *et al*., 2009; Shukla, 2011; Dutta *et al*., 2006; Sharma *et al*., 2010).

Astrobiology

Human curiosity to find life beyond the Earth has led to development of several programmes on the global scale. SETI (Search for Extraterrestrial Intelligence), Astrobiology etc. are ambitious programmes of some of the leading scientific societies. Experimental studies to understand the '*Origin of Life*' and nature of primitive life in the evolutionary chain have a link with the Precambrian palaeobiology. Several space missions are probing the universe for intelligent life and life forms that may be different from the earth. Precambrian, particularly the Archaean rocks and several unusual niches on the continents and in the marine realms provide clues to such investigations. Scientific journals like, *Origins of Life*, *Geobiology* and *Astrobiology* are the careers of research results and ideas on the varied possible life forms. In the last few years, India has embarked on the ambitious space programme including the lunar mission *Chandrayan*. To remain in the fore-front of the scientific investigations it would be appropriate for the country to join the leading scientific societies like Australia, Canada, China, France, Russia, UK, USA in the astrobiology programme. Scientists involved in the Precambrian palaeobiology can provide the much needed expertise in the field of astrobiology.

Gaps and Goals

Our understanding of the Precambrian palaeobiology has increased several folds in the last two decades. Many patterns and nature of evolution are better defined. Palaeobiological studies have seen phases of lean interest as well as surge of research involvement (Fig. 2). Some of the main impediments in the Precambrian palaeobiological studies are the poor preservation of fossils and large number of unproductive samples. The time devoted in investigations does not commensurate with the academic rewards. Therefore, few researchers venture into the domain of the Precambrian palaeobiology. In spite of more than hundred years of history of the Precambrian palaeobiological investigations in India some clear-cut gaps can be identified in our understanding of early life *vis-a-vis* global records. Some of them are enumerated below.

Unlike other continents, Indian Precambrian successions (Archaean-Proterozoic) are well exposed and easily accessible; Proterozoic successions are less deformed and show varied well developed stromatolite morphoforms. Taxonomy of the stromatolites is one such area which demands serious attention of the Precambrian palaeobiologists. Intra-basinal and inter-basinal correlation can easily be attempted in different basins which can establish their utility in biostratigraphy. Diversity in coniform stromatolites offers another area of investigation. The question of their confinement in the Palaeoproterozoic and Mesoproterozoic and absence in the Neoproterozoic needs to be addressed. Is there anything like time controlled morphogenesis of stromatolites? It is also an attractive research problem. The Vindhyan Supergroup (from the Olive Shale to the Dholpura Shale) is a good rock repository for tracing the evolutionary history of the carbonaceous remains, as extensive occurrences of carbonaceous remains have been reported from the Vindhyans. Abundance of microbial mats in the Ediacaran Period, as exemplified, in the Marwar Supergroup needs suitable explanation. Their genesis, environment of deposition and relationship with mineralogy and grain size are yet to be fully understood.

In spite of extensive Neoproterozoic exposures in India we do not have properly identified Ediacaran successions, and in turn not able to record varied Ediacaran metaphytes and metazoans. Serious geochemical investigations have not been carried out to study the organic matter, kerogen and maturation studies of Precambrian organic remains.

In case of microfossils and macrofossils, some of the unsolved questions are related to the taphonomy, palaeoecology, microbiology and taxonomy. Assessment of evolutionary paradigms and diversity of forms in the Precambrian are other related aspects for study. Studies in the field of taphonomy would help in interpreting the true diversity of the micro-macrofossils. Study of the extant organisms and their behavior during the simulated fossilization processes would help in drawing parallels between varied fossilized morphologies found in the rock sequences and true biological affinities. Results of the palaeobiological studies help in deciphering the occurrences of various types of acritarchs in variety of depositional niches. Modern microbiological studies encompassing the vertical and horizontal distribution of microbes and phytoplanktons provide analogs for the Precambrian specially the Proterozoic microbial mat communities. There is a vast scope of the modern microbiological studies.

Taxonomic diversity has been recorded in the chert-facies microbiota which shows excellent preservation and varied assemblage in various stratigraphic units. This diversity needs to be filtered through the lenses of taphonomy and preservational biases to adjudge the true diversity. Taxonomy of the micro and macrofossils itself is another area which needs immediate attention and requires the standardization so that meaningful evolutionary information is gathered from the published literature. Several attempts were made in this direction in the past (Culver *et al*., 1987; Herman *et al*., 1989) for the Precambrian microfossils. A more comprehensive step in this direction has been taken for the Proterozoic fossil cyanobacteria (Sergeev *et al*., 2012).

The C, H, N and S analyses of the kerogen provide excellent markers of the biological processes. With a vast expanse of Precambrian rocks in India, greater involvement of geochemists and isotope geologists are required to unravel various chemical signatures of life. Geological sections of the Marwar Supergroup, the Kurnool, Bhima and Badami Groups in the peninsular India and Spiti section of the extra-peninsular region need to be rigorously investigated for identification of the Neoproterozoic isotopic records as many of the Proterozoic basins are considered to be coeval (Singh, 1980).

There are several questions in the evolutionary studies for which no easy answer is yet available. One such probing question is: How old are the eukaryotes? What is the relationship between the sizes of the eukaryotes found in the open coastal water and those phytoplanktons found in the deep waters? Which criterion, the size of the cells or branching habit is more important in differentiating the eukaryotes in filamentous forms? Answers to these questions are important for evolutionary biologists as well as palaeobiologists. Known occurrences of chert-facies microfossils from the Precambrian of India can be helpful in obtaining these answers.

The role of the Precambrian palaeobiology is increasing in understanding the dynamic earth and its evolution. Over the years, it has become interdisciplinary, more innovative and insightful than before. Advanced instruments and analytical techniques available to the researchers have opened several new vistas of investigations. Strong support available to the programmes at global level has infused a great interest among the researchers. Beginning with simple optical microscope, the Precambrian palaeobiology is now being pursued with Raman imagery and CLSM, Atomic Force Microscopy (AFM), Synchrotron X-ray microtomography (SR-µCT), mass spectroscopy (MS), Secondary Ion Mass Spectroscopy (SIMS and nano SIMS), Fourier Transform Infrared Spectroscopy (µXANES). Presently, a few Indian researchers are involved in some of these investigations on collaborative basis. With gradual advancements in the Precambrian palaeobiology these instrumentation based analytical techniques will be more readily accessible to Indian reviewers.

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