Review Article

Palaeobiology of Indian Proterozoic and Early Cambrian Successions — Recent Developments

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Many facets of the early biosphere preserved in the Proterozoic and Early Cambrian successions, recorded during 2011-2015, are reviewed. Recent advancements made in the Precambrian palaeobiology and newer steps recognized in the organismal evolution in the global perspective *vis-a-vis* significance of Indian records are discussed. The palaeobiological evidence reported from India are chronicled and grouped under seven categories: MISS (Microbially Induced Sedimentary Structure) & stromatolites, acritarchs, OWM (Organic Walled Microfossils), carbonaceous remains, trace-fossils & Ediacaran fossils, stable isotope studies and organic geochemistry. Present article is a continuum of Sharma *et al.* (2012), provides the status of Precambrian palaeobiological studies in the country, enumerates the importance of Indian records, and enlist unsolved problems and future research directions.

Keywords: Precambrian; Palaeobiology; Carbonaceous Fossils; Acritarchs; Trace Fossils; India

Introduction

Precambrian Eon is the longest geological subdivision (4200-541 Ma) in the Earth's history. During this period the atmosphere, lithosphere, hydrosphere, and biosphere evolved and transformed towards stabilization. Steps involved in the formation and changes in these four spheres are the subject matter of numerous studies. The Proterozoic Eon represents almost four fold time duration but satisfactory geological divisions are by far exponentially less than the Phanerozoic Eon due to lack of differentiable biotic entities suitable for biostratigraphic divisions of Proterozoic Eon. International Sub-commissions on Stratigraphy related to Cryogenian, Ediacaran and Cambrian are concentrating their efforts on documenting newer biotic forms, morphologies and events to further sub-divide these time durations and Indian researchers are actively participating in this endeavour. In the present review, we discuss the

advancements made in the understanding of the biosphere and summarize the Indian contributions essentially made during 2011-2015 and their impact on the global evolutionary understanding. Proterozoic sedimentary successions are well exposed both in peninsular and extra-peninsular regions of India but there are very few and restricted occurrences of the Cambrian exposures in the peninsular region of western India and in Himalayas (Valdiya, 2015) (Fig. 1).

Recent studies documented unprecedented biotic diversity during the Proterozoic successions especially from the Neoproterozoic and Cambrian successions. Records of evidence are mainly drawn from the Proterozoic and Early Cambrian successions of India; however, a few important contributions from Archaean are also discussed. Understanding of the morphological diversity of biotic forms has considerably increased (Liu *et al.*, 2014; Tang *et al.*, 2013, 2015).

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

Advancements in analytical facilities and their access have helped fathom the hitherto unknown world of the biosphere (Schopf *et al.*, 2016; Porter *et al.*, 2016; Cole *et al.*, 2016). These studies have shown newer ecological niches adopted by the biotic communities with sudden or gradual changes in the hydrosphere/atmosphere or lithosphere (Ye *et al.*, 2015; Wang *et al.*, 2015b; Yuan *et al.*, 2011, 2013; Zhu *et al.*, 2016). Molecular phylogenetic studies and cladistic analysis are new dimensions of the Precambrian palaeobiology (Pawloska *et al.*, 2013; Schirrmeister *et al.*, 2013;

Butterfield 2015). Most of these studies are aimed to understand and establish the early evolutionary pathways in the biotic realm and also co-relate their distribution in time and space so that they would be effectively used in biostratigraphic endeavours. In the present paper, we have discussed various aspects of Precambrian palaeobiology and salient contributions made by the Indian researchers in recent years. It also enlists the gaps in our knowledge base and charts the path of future studies.

Proterozoic and Early Cambrian Biosphere

MISS and Stromatolites

Stromatolites are one of the oldest recognizable Precambrian organosedimentary structures which are considered as an indicator of the presence of life in the Archaean and Proterozoic successions. Many aspects of these organosedimentary structures were extensively studied, classified and used in intra-basinal and inter-basinal correlations in the last century, yet scientific curiosity and interest in understanding the stromatolitic structures received less attention in the last two decades. Researchers showed more interest in recognizing Microbially Induced Sedimentary Structures (MISS), their formation and usefulness in delineating the depositional environment. Although both these structures are result of microbial activity yet they are distinct in morphological expressions. In this connection, advancements made on these aspects in the country during 2011-2015 are discussed in the following paragraphs.

Sarkar *et al.* (2011a) reported the “setulf” or inverted flute cast in growth and fossilized stages from the Sonia Sandstone and the Upper Bhandar Sandstone which helped in interpreting the depositional palaeoenvironment of the sequences as a high-littoral to supra-littoral zone and stands for syndepositional with microbial growth. Banerjee (2012) demonstrated the presence of ‘Discoidal Microbial Colonies’ flourishing in an intertidal hypersaline sand flats of the Gulf of Cambay, north of Mumbai, which has remarkable similarities with an Ediacaran fossil forms often described as ‘medusoid’ and used in delineating the ‘end Precambrian stratigraphic succession’. Therefore, he suggested to use caution whilst describing such fossil forms. From Chhattisgarh (Mesoproterozoic age) and Khariar basins, Chakraborty and Das (2013) reported various types of bedding plane structures, such as palimpsest and patchy ripples, spindle-shaped and sub-circular microbial shrinkage cracks, wrinkle structures, fragments of torn mat spreads, etc. These structures suggest unequivocal influence and interplay of mat induced biophysical interactions during the shallow marine clastic sedimentation in the Proterozoic basins of India. Sarkar *et al.* (2014) described the genetic aspects, and palaeoenvironmental affinity of the microbial mat related structures noted in the

Proterozoic successions viz., the Marwar Supergroup, the Vindhyan Supergroup, the Chhattisgarh Supergroup and the Khariar Supergroup. It has been noted that the diagenetic alteration of microbial mat produced pyrite that enhances the preservation of microbial remains (Samanta *et al.*, 2011). Kumar and Ahmad (2014) reported 14 types of miscellaneous morphologies grouped under three headings depending upon the role of possible microorganisms in their formation (Fig. 2A-B). Samanta *et al.* (2015) described body impressions and burrow like trails which possibly represented the bioturbation produced by some higher organism in the Sonia Sandstone during Proterozoic time. These morphological features were closely associated with microbial mat features. The palaeobiological implication of MISS lie in the fact that sub-mat benthic lifestyle originated and evolved during the Ediacaran Period.

Oldest microbe-sediment system was documented from Archaean (3.33 Ga old) Josefsdal chert, Barberton greenstone belt, South Africa (Westall *et al.*, 2015). This study shows that the intricate microbe-sediment systems are deep-rooted in time and recognized the syngenetic diversity of Archaean microbial palaeocommunities-both phototrophs and chemotrophs-which were present within the sedimentary realm. Most important aspects of this study were to define the role of hydrothermal processes in preserving biosignatures and as an energy supplier for biomass production. Josefsdal chert is a testimony of diverse microbial population consisting of phototrophic, chemo-organotrophic, and chemolithotrophic microorganisms that co-existed in a coastal, volcanogenic sedimentary environment. This study has opened a new vista for organosedimentary structures. From another central Indian Proterozoic succession of India, Guhey *et al.* (2011) recorded stromatolitic assemblage from the Indravati basin, Chhattisgarh. The assemblage includes *Colonnella laminate*, *Gymnosolen furcatus*, *Kussiella enigmatica*, *Boxonia pertaknurra*. Sharma and Pandey (2012) reported an assemblage of stromatolites from the Bagalkot Group of Kaladgi Supergroup viz., *Asperia digitata*, *Ephyaltes edingunnensis*, *Eucapsiphora leakensis*, *Kussoidella karalundiensis*, *Pilbaria deverella*, and *Yandilla meekatharrensensis* etc. Based on this assemblage, the Bagalkot Group is assigned the Late Palaeoproterozoic to Early Mesoproterozoic age.

Fig. 2: MISS, Stromatolites and trace fossils reported from the different horizons of Marwar Supergroup bracketing the age from Ediacaran to Lower Cambrian. A: Well preserved *Aristophycus* around a large sandstone clast showing primary, secondary and tertiary bifurcations recorded from Jodhpur Group (specimen no. BSIP- 41038) (coin diameter = 2.4cm); B: Close up of *Jodhpuria circularis* from Jodhpur Sandstone; C: *Colonnella columnaris* recorded from the Bilara Group (scale bar = 2cm) and D: *Coniform* stromatolites also described from the Bilara Group (lens cap = 5.6cm)

Stromatolites are invariably found in carbonate sequences (Fig. 2C-D). In recent years, features akin to stromatolites have been documented in some of the siliciclastic rocks and inferred to have formed by the biogenic activity of microscopic organisms. Loon and Mazumder (2013) described fine laminated structures which were probably formed due to accumulation of fine siliciclastic particles on top of biofilm from the Late Palaeoproterozoic Chaibasa Formation of Singhbhum Craton. Contrary to the formation of traditional stromatolitic structures, which were formed by trapping and binding of sediments

Chaibasa laminated structures (another form of stromatolite) are thought to be formed by accumulation of sediments over the biofilms. Pandey (2013) reported clotted fabric of thrombolite from the Upper Vindhya. Thrombolites are restricted in the Proterozoic and are reported mostly from the upper Neoproterozoic and Cambrian. During this intervening period, detailed accounts of stromatolites were also provided from a few new stratigraphic horizons of the Precambrian strata.

Acritarchs

The latest Palaeoproterozoic–Early Mesoproterozoic Chitrakut Formation (>1600 Ma old) of the Vindhyan Supergroup revealed the oldest morphologically complex organic-walled eukaryotic microfossils (Fig. 3A–C) (Singh and Sharma, 2014). This report predates the oldest record of eukaryotic fossils known from ~1500 Ma (Javaux *et al.*, 2003) and takes the antiquity of eukaryotes further back deep in time. Recently, Shukla and Tiwari (2014) also reported a well developed and diverse assemblage of Ediacaran large size acanthomorphic acritarchs from the cherts of the Krol Belt of Lesser Himalaya. This assemblage helps correlate the microfossil-bearing Krol Formation with other known global occurrences and also highlights the sudden advent of large acanthomorphic acritarchs in Ediacaran horizons (Tang *et al.*, 2013, 2015; Liu *et al.*, 2014; Vorob'eva *et al.*, 2015). Both molecular and palaeontological data across the world suggest that fossil records from the Proterozoic basins of India can play a vital role in understanding the advent, evolution and diversification of eukaryotes on the Earth's earliest biosphere.

Large acanthomorphic acritarchs, characteristic of Ediacaran Period, radiated and diversified during ~635–551 Ma (Liu *et al.*, 2013). Although this radiation is noted as a global phenomenon (Vidal and Moczydlowska, 1997; Grey, 2005) yet most of them disappeared before the end of the Ediacaran Period. These Ediacaran large acanthomorphic acritarchs have been reported worldwide from several basins, namely South China, South Australia, East European

Platform, Siberia, northern India, and Svalbard (see references in Shukla and Tiwari, 2014). Based on the age of the Ediacaran metazoan in the Amadeus Basin of Australia, the minimum age of these acritarchs are considered as around 550 Ma (Zang and Walter, 1992b; Grey *et al.*, 2003; Grey, 2005). Acritarchs have emerged as the most suitable proxies for biostratigraphic zonation of Ediacaran sequences globally. Although the occurrences and distribution of the acritarchs are controlled by the facies and many of them have taxonomic constraints with taphonomic biases, (Grey *et al.*, 2003; Grey, 2005; Willman and Moczydlowska, 2008; McFadden *et al.*, 2009; Vorob'eva *et al.*, 2009a; Yin *et al.*, 2009), yet their potential for biostratigraphic subdivision and global correlation is becoming increasingly important. Due to differences in the mode of preservation in shale and chert facies and extraction techniques, it is difficult to accurately correlate the acritarch assemblages recovered from these two distinctly different facies.

In India, the Krol Belt in Lesser Himalaya, exposed as a series of synclines from Solan in the north-west to Nainital in the south-east, represents a thick, uninterrupted sedimentary sequence of the Ediacaran–Lower Cambrian interval. The Outer Krol Belt in Lesser Himalaya, consists of Blaini and Krol Groups. The Krol Group is further divided into Infra-Krol, Krol Sandstone, Krol 'A', Krol 'B', Krol 'C', Krol 'D' and Krol 'E' (Srikantia and Bhargava, 1998). The Blaini Group is identified by its characteristic lithology of diamictites, grading upwards into pink carbonate beds or 'cap carbonates'. Petrographic thin

Fig. 3: Morphologically complex acritarchs from the Chitrakoot Formation, Semri Group, Vindhyan Supergroup, India. A: *Shuiyousphaeridium echinulatum* Yin and Gao, 1999. (slide no. BSIP 14137); B: *Cymatiosphaeroides kullingii* Knoll 1984 (slide no. BSIP 14144); C: *Trachysphaeridium* sp. (slide no. BSIP 14141). (scale bar = 50 μ m for a, and 25 μ m for b, c)

sections of chert samples collected from Krol 'A' revealed a highly fossiliferous microbial assemblage with abundant, permineralized, large acanthomorphic acritarchs, which are yellowish-brown to dark brown in colour and are preserved within a light to dark brown coloured organic mass. These acritarchs exhibit diverse morphologies, mainly occurring as compressed, folded forms with very few preserved as complete circular vesicles. The presence of dark organic matter within the vesicle cavity is characteristic of these acritarchs. This organic matter occurs as particulate coccoidal clusters, as a mesh, or as dark, clotted mass within the vesicle cavity. It is also found within the matrix. The Rock Eval study of a few shale and chert samples indicates high thermal maturity of these rocks, which is echoed in the dark colour of the acritarchs. The surface textures of the acritarchs are psilate, granular, shagrenate or reticulate. Large acanthomorphic acritarchs have previously been reported from the Infra-Krol Formation in the Pachmunda and Krol Hill Synclines of the Outer Krol Belt and Nainital Syncline of the Inner Krol Belt (Tiwari and Knoll, 1994; Tiwari, 1996; Tiwari and Pant, 2004). Thin sections of chert from Krol 'A' in Khanog and Rajgarh Synclines of Outer Krol Belt record an equally well developed and diversified assemblage of Ediacaran large acanthomorphic acritarchs (Shukla and Tiwari, 2014). This assemblage contains: *Appendisphaera fragilis*, *A. grandis*, *Asterocapsoides* sp., *Cavaspina acuminata*, *C. basiconica*, *Eotylotopalla dactylos*, *Knollisphaeridium* sp., *Papillomembrana* sp. and *Weissiella* cf. *grandistella* (Fig. 4A-K).

The Krol acritarch assemblage shows a close resemblance with the Upper Doushantuo or *Tanarium anozos*–*Tanarium conoideum* assemblage of China. However, the absence of biostratigraphically important markers such as *Tanarium anozos* and *T. conoideum* from the Krol assemblage, so far, makes it difficult to establish a definite biostratigraphic correlation between the two assemblages. Systematic comparison of the Krol acritarchs suggests their remarkable similarity to approximately contemporaneous assemblages preserved in the Doushantuo Formation exposed in Guizhou Province Weng'an Phosphate Mine, Yangtze Gorges Region and Hubei Province of South China (Yin and Li, 1978; Awramik et al., 1985; Yin, 1985, 1987; Yuan and Hofmann, 1998; Zhang et al., 1998; Liu et al., 2013, 2014; Xiao et al., 2014);

meta-sedimentary chert of the Baklia and Scotia Groups, Prins Karls Foreland, Svalbard (Knoll, 1992); Pertatataka Formation, Amadeus Basin and Tanana Formation, Officers Basin, Australia (Zang, 1988; Zang and Walter, 1989; Grey, 2005; Willman, 2006; Willman and Moczydlowska, 2008, 2011); Khamaka and Kursov Formations of Yakutia and Nepa-Botuoba region, Siberia (Pyatiletov and Rudavskaya, 1985; Pyatiletov, 1988; Kolosova, 1991; Moczydlowska et al., 1993; Moczydlowska, 2005) and the Ura Formation, the Baikal-Patom Uplift, Siberia (Sergeev et al., 2011; Moczydlowska and Nagovitsin, 2012). Although the Krol Ediacaran acritarch assemblage shows similarity with the assemblages mentioned above, the mode of preservation and occurrence is comparable to the Ediacaran acritarch assemblage from the Doushantuo Formation in the Yangtze Gorges section of China. The Ediacaran Doushantuo Formation in the Yangtze Gorges region of China has been lithostratigraphically divided into four members (Liu et al., 2013). Two acanthomorphic acritarch biozones, the Lower biozone and the Upper biozone corresponding to Member II and Member III respectively have been recognized in this area (McFadden et al., 2009; Yin et al., 2009, 2011; Liu et al., 2013, 2014; Xiao et al., 2014). Lithologically, the lower part of Krol 'A', showing alternations of black shale and carbonate bands, corresponds to the intercalations of bedded or muddy dolostone within black shale which characterize Member II of the Doushantuo Formation. The upper part of Krol 'A' with its bedded and massive carbonates is lithologically similar to Member III of the Doushantuo Formation. The assemblage from the lower part of Krol 'A' however, shows greater similarity with the Upper Doushantuo biozone. The Ediacaran Complex Acanthomorph Palynoflora (ECAP) of South Australia has been divided into four zones by Grey (2005). Other than *Appendisphaera grandis* and *Eotylotopalla dactylos*, no other species from the present study occurs in these zones of Australia. Lithological differences, methods of processing, taphonomic biases and differences in identification of same species make it difficult to compare the present assemblage with that from Australia.

The Krol Group can be bracketed within two significant global events: the glacial event and the biotic explosion event. Diamictites of the Blaini Group, which are equated with the Marinoan glacial event globally,

Fig. 4: Acritarchs recorded from the Krol Group, Lesser Himalaya India. A: *Appendisphaera fragilis*, WIMF/A-3951; B: *A. grandis*, WIMF/A-3954; C: *Asterocapsoides* sp. B, WIMF/A-3958; D: *Asterocapsoides* sp. B, WIMF/A-3959; E: *Cavaspina acuminata*, WIMF/A-3962; F: *Cavaspina basiconica*, WIMF/A-3962; G: *Eotylotopalla dactylos*, WIMF/A-3964; H: *Knollisphaeridium* sp., WIMF/A-3967; I: *Papillomembrana* sp., completely compressed and folded vesicle WIMF/A-3969; J: detailed view of processes; K: *Weissella* cf. *W. grandistella*, WIMF/A-3973 complete vesicle, with heteromorphic processes filled with organic matter (scale bar = A & F-5 μ m, B, E, G, H-20 μ m, C, D & J-10 μ m, I & K-50 μ m)

are overlain by another globally conspicuous unit, the 'cap carbonates'. Based on the 'cap carbonates' which are globally conspicuous and correlatable with similar lithology in Australia (Nuccaleena Formation) and China (Nantuo Formation) the upper part of Blaini Formation has been equated with the end of Marinoan (early Varanger) glaciation. The Marinoan age for the Nantuo Formation in China has been constrained between 663 ± 4 Ma and 635.2 ± 0.6 Ma (Jiang *et al.*, 2003; Zhou *et al.*, 2004; Condon *et al.*, 2005) and is consistent with the youngest zircon age of 643 ± 7 Ma given by Hofmann *et al.* (2011) for the tillites of Blaini Group. The base of the 'cap carbonates' marks the base of the Ediacaran Period (Grey, 2005), which is currently taken to extend from 635.2 ± 0.6 Ma (Condon *et al.*, 2005) up to the Precambrian–Cambrian boundary at ~ 541 Ma (Bowring *et al.*, 1993; Grotzinger *et al.*, 1995; Amthor *et al.*, 2003). The above facts thus constrain the age of the Krol Group within the Ediacaran time span. In China, the Doushantuo Formation is overlain by massive dolostone of the Dengying Formation which can be correlated with the Upper part of the Krol Group (Krol 'C', 'D' and 'E') on the basis of lithological similarity. The Dengying Formation is overlain by basal Cambrian chert and phosphorites, which are again similar to the lower Shaliyan Formation of the Tal Group, overlying the Krol 'E' Formation in the Inner Krol Belt (Jiang *et al.*, 2003). The stratigraphic similarities suggest a coeval deposition of the Krol 'A' and Doushantuo Formation. With better documentation of the acritarch assemblage from Krol, a definite biostratigraphic correlation between the Ediacaran successions of Krol Belt in India and Yangtze Gorges region in China may become feasible. Absence of *Tanarium*, the marker acritarch taxon of the Upper Doushantuo assemblage, in the Krol Group is very peculiar. Taphonomic variations and method of sample preparation may be the reasons for different kinds of preservation and hence, different identification of the same form. The direct correlation of the Krol acritarch assemblage with that from South Australia (Grey, 2005) is not feasible at present.

Organic Walled Microfossils

Organic Walled Microfossils (OWM), largely consisting of cyanobacterial fossils and eukaryotic remains, occur extensively in the silicified cherts and carbonaceous shales. Among the Precambrian

microfossils records, cyanobacteria are by far the most prominent and diverse prokaryotic phyla. Morphologically they range from unicellular coccoidal forms to multicellular filamentous forms. Although indirect evidence of their presence is noted in the form of stromatolites in the Archaean but it is believed that they raised the oxygen levels in the atmosphere around 2.45–2.32 Ga during the Great Oxidation Event (GOE) which changed the pace of life on the planet Earth (Schirrmeister *et al.*, 2013). It is also believed that cyanobacteria arose before the GOE and diversified during GOE. It was demonstrated that multicellularity most likely played an important role in cyanobacterial evolution around GOE and their three clades E1, E2 and AC evolved shortly after the rise of atmospheric oxygen (Schirrmeister *et al.*, 2011, 2013). OWMs have been recorded from the Mesoproterozoic Vindhyan, Chhattisgarh, Kurnool and Ediacaran sediments of the Lesser Himalaya, India (Singh *et al.*, 2011; Sharma and Shukla, 2012a b; Pandey and Kumar 2013; Shukla and Tiwari, 2014; Singh and Sharma, 2014). In a monographic account published by an Indo-Russian team, Sergeev *et al.* (2012) reviewed 50 genera and 90 species of fossil cyanobacteria from petrographic thin sections of different Proterozoic formations across the world. To date, this study provides the most exhaustive account of the morphology, palaeobiology, palaeoecology and geological history of cyanobacterial microfossils. Singh *et al.* (2011) reported an assemblage of cyanobacterial microfossils of endolithic habitats from the carbonate facies of Bhandar Group, Vindhyan Supergroup. In another important work, Sharma and Shukla (2012a) reported helically coiled microfossils *Obruchevella*, a Vendian marker, from the Owk Shale of the Kurnool Group which suggests an Ediacaran rather than a Mesoproterozoic age for this sequence. Singh and Babu (2013) and Babu *et al.* (2014) reported a diverse assemblage of Neoproterozoic chert permineralized microbiota from the carbonate facies of Raipur Group (Chhattisgarh Supergroup) and discussed their biostratigraphic significance.

Carbonaceous Remains

Carbonaceous fossils found in the Precambrian sedimentary successions of India continue to provide important insights into the evolutionary history of early life ranging from single-celled prokaryotes to nucleated eukaryotic cells and multicellular life forms

that appeared and evolved during the first three billion years of earth's history. After cyanobacterial microfossils, the carbonaceous remains are the morphologically most diversified fossil assemblage of the Precambrian successions. From simple form, such as *Chuaria circularis* to complex Lantian biota constitute the assemblage of carbonaceous remains (Fig. 5A-R and Fig. 6A-G). On the global scale, several studies demonstrated the existence of earliest multicellular megascopic benthic algal life during and immediately preceding the Ediacaran Period. Complex multicellular carbonaceous megascopic forms, recorded from the black shales of the Ediacaran Lantian Formation, South China are grouped as an algal form (seaweed) (Yuan *et al.*, 2011, 2013). Wang *et al.* (2015a) described a body fossil of Ediacara carbonaceous compression fossil *Zhongaodaphyton* Chen *et al.* from the black shale of the Upper Doushantuo Formation, south China as a macroalgal form comparable to the members of phaeophyta. On the basis of Upper Doushantuo biotic assemblage, Wang *et al.* (2015b) suggested the existence of three tiered palaeoecosystem of macroalgal forms and established a multilayered ecological pyramid in the biosphere with increasing demand of oxygen which pinnacle at Pc-C boundary. Ye *et al.* (2015) reported carbonaceous compression fossils (benthic macroalgae) from the Marinoan-age Nantuo Formation in South China. Study suggests that these open waters system were the 'refugia' where macroscopic phototrophs survived the Marinoan glaciation and subsequently diversified in the early Ediacaran Period. Recent discovery of *Grypania spiralis* from the Ediacaran Doushantuo Formation, Guizhou, south China suggest that its habit endowed great competitiveness for sunlight and it remained unchanged in size or morphology over more than 1200 Ma (Wang *et al.*, 2016). Like many other cyanobacterial fossils, it retained its morphological attributes and also evolutionary conservatism for more than billion years and proves its prokaryotic nature.

Carbonaceous compression fossils are generally preserved on the bedding plane of an arenosargillaceous sediments. Well preserved and diversified carbonaceous fossils have been recorded in Indian Proterozoic successions of the Vindhyan, Kurnool, Bhima and Chhattisgarh basins. *Chuaria circularis* and *Tawuia dalensis* are the most well documented carbonaceous remains from several basins. They are

Fig. 5: Line diagram of carbonaceous remains recorded from various geological units; A and B: *Chuaria circularis*; C: *Ellipsophysa*; D: *Beltanelliformis brunsa*; E: *Grypania spiralis*; F: *Katnia singhii*; G: *Vendotaenia antiqua*; H: *Tyrasotaenia podolica*; I: *Sinocylindra yunnanensis*; J: *Tawuia dalensis*; K: *Longfengshania ovalis*; L: *Protoarenicola baiguashanensis*; M: *Pararenicola huaiyuanensis*; N: *Baculiphyca taeniata*; O: *Gesinella hunanensis*; P: *Sinosabellidites huainanensis*; Q: *Doushantuophyton cometa*; R: *Flabelliphyton lantianensis*. (scale bars = 1 mm for A, B, C, J, L, M, P; 2 mm for E, K and 10 mm in H, Q)

Fig. 6: Line diagram of carbonaceous remains recorded from various geological units; A: *Konglingiphyton*, B: *Enteromorphytes*; C: *Wenghuiphyton erecta*; D: *Parallelphyton*; E: *Huangshanophyton fluticulosum*; F: *Anhuiphyton lineatum*; G: *Orbisiana* (scale bar = 3mm in D, 5mm for F, 10 mm in C and 1 cm for E)

known for more than 100 years, yet affinities of many of them remained enigmatic. Sharma *et al.* (2009) resolved this conundrum and presented a model which is known as 'hybrid model'. Morphological diversity of *C. circularis* and *T. dalensis* have been recorded from Late Palaeoproterozoic to Late Neoproterozoic successions (Fig. 7A-K). Helically coiled carbonaceous remains have been recorded from Late Palaeoproterozoic and Early Mesoproterozoic successions. These are variously described as *Katnia singhii*, *Grypania spiralis* and *Spiroichnus beerii* (Figs. 8A-E). Debate continued with regard to their nature whether these represent eukaryotes or prokaryotes. Sharma and Shukla (2009) firmly established them as prokaryotic remains. These are probably the earliest large size prokaryotes known in the earth's history. Studies on these remains from India have led to a better understanding of the evolutionary pathways adopted by life forms during the Neoproterozoic Era (1000-541 Ma). All such remains have been investigated for their biogenicity, syngenecity and age because of possible errors in distinguishing the true fossils from pseudofossils. As number of such reports increased over the year and there is a need for comprehensive review from time to time. Sharma *et al.* (2012) reviewed carbonaceous compression fossils recorded from the various Precambrian basins of India. Sharma and Shukla (2012b) reported annulated compression/impression fossils from the Hulkal Formation of Bhima Basin of India (~750 Ma) and established the existence of Pre-Ediacaran epi-benthic organisms. Elsewhere, earliest multicellular megascopic benthic algal life has been documented from the Ediacara and slightly older periods (~635-541 Ma) and includes complex multicellular carbonaceous megascopic forms (seaweed) (Yuan *et al.*, 2011, 2013). Significance of carbonaceous fossils from Bhima basin of India lies in their antiquity, which suggests that these forms survived the glaciation events and passed into the Ediacaran time. Babu and Singh (2013) reported diversified carbonaceous remains occurring on the Early Mesoproterozoic grey shales of the Saraipali Formation, Singhora Group of the Chhattisgarh Supergroup. Babu and Singh (2013) recovered some peculiar compression and impression fossils of multicellular benthic and planktic eukaryotic forms from the Latest Palaeoproterozoic to Early Mesoproterozoic age (Figs. 9A-B).

Trace Fossils and Ediacaran Fossils

Early trace fossils have invariably been documented from Precambrian-Cambrian boundary successions. These are one of the important parameters to explore the metazoan activities of the past life. In the Early Cambrian successions, ichno-fossils were considered as an important palaeoenvironmental indicators and help trace the evolution of lifestyles of marine benthic organisms particularly in areas dominated by siliciclastic sediments (Conway-Morris, 1993, 1998; Erwin *et al.*, 1997; Droser *et al.*, 1999; Jensen *et al.*, 2000). In the Indian scenario, the Himalaya region and Marwar Supergroup have revealed the presence of various trace fossils. During the last five years, a variety of trace fossils such as *Rusophycus*, *Cruziana*, *Treptichnus*, *Dimorphichnus*, etc. have been reported from Lesser Himalayan sedimentary successions of the Tal and Kumzum La Formations (Desai *et al.*, 2010; Parcha and Pandey, 2011; Tiwari *et al.*, 2013; Singh *et al.*, 2014b; Joshi and Tiwari, 2014). These reports are mostly on the taxonomical aspects of trace fossils. In Mussoorie syncline area, the topmost lithostratigraphic unit of the Krol Belt, the Tal Group, is very well exposed, from this group Singh *et al.* (2014b) reported *Bergaueria*, *Cruziana*, *Phycodes*, etc. The Arenaceous member of Deoka-Tibba Formation has yielded considerable number of ichnofossils. These ichnofossils mainly belong to *Skolithos* and *Cruziana* ichnofacies with an abundance of arthropod traces like *Aulichnites*, *Diplichnites*, *Merostomichnites*, *Dimorphichnus*, *Monomorphichnus*, *Protichnites* and *Tasmanadia*. *Psammichnites gigas* is a product of a burrowing slug-like animal that bulldozed the sediment and collected food from the surface with a pendulum like siphon. It is reported from the lowermost Cambrian shallow-marine deposits of Sweden, Australia, Greenland, Spain, France, Canada, United States, Sardinia and South Australia (Hofmann and Patel, 1989; Walter *et al.*, 1989; Pickerill and Peel, 1990; Zhu, 1997; Alvaro and Vizcaino, 1999; Jensen *et al.*, 2002; Dzik, 2005; Jago and Gatehouse, 2007). In contrast, there are limited reports of ichnofossil from Dhaulagiri Formation. Recently, Tiwari *et al.* (2013) reported nine new ichnotaxa from Member B of Dhaulagiri Formation which are *Dimorphichnus* isp., *?Diplichnites* isp., *Monomorphichnus* isp., *Nereites* isp., *Palaeopasichnus* isp., *Palaeophycus* isp.,

Fig. 7: Morphological variations noted in the carbonaceous specimens recorded from Sirbu Shale and Bhandar Limestone, Bhandar Group, Vindhyan Supergroup and Deoban Limestone, Lesser Himalaya, India. A, B, C: Exceptionally long elongated straight, slight curved specimens of *Tawuia dalensis* with rounded terminal end; D: Curved *Tawuia dalensis* with circular terminal end; E: Overlapped *Tawuia dalensis*; F-G: Dumbbell shaped *Tawuia dalensis*; H, I: *Glossophyton mucronatus*; J: 'c' shaped curved enigmatic carbonaceous specimen with tapering end and blur septation noted (see inset); K: Another curved enigmatic carbonaceous specimen with tapering end on one side only. (specimens A-E & K from Deoban Limestone and F-J from Sirbu Shale and Bhandar Limestone, India). Specimen nos. for Figs. A-D. BSIP-41033; Fig. E. BSIP-41034; Fig. F. BSIP-41037; Fig. G. BSIP-41041; Fig. H. BSIP-41039; Fig. I. BSIP-41040; Fig. J. BSIP-39621; Fig. K. BSIP-41042 (scale bar = A-E-1cm; F-K-1mm)

Fig. 8: Helically coiled carbonaceous megascopic fossils from the Rohtas Formation, Vindhyan Supergroup, India. **A:** *Katnia singhii* (specimen no. BSIP-39346); **B:** *Grypania spiralis* (specimen no. BSIP-39327); **C:** *Katnia singhii* (specimen no. BSIP-39349); **D:** *Spiroichnus beerii* Mathur (1983) (specimen no. BSIP-39335); **E:** *Grypania spiralis* (specimen no. BSIP-40813)

Planolites montanus, *Planolites* isp., *Skolithos* isp., *Treptichnus* isp. and some meandering trails. The detailed analysis of ichnofossil assemblage indicates that there exist two distinct levels of trace fossils, one in the Arenaceous Member of the Deo-ka-Tibba Formation and the other in the A and B Members of the Dhaulagiri Formation. Similar ichnofossils have been reported from the Lower Cambrian successions of the Tethyan Himalayan sequences exposed in Parahio section of Spiti and in Zaskar basins (Parcha and Singh, 2010; Parcha and Pandey, 2011). Many of these traces are interpreted to be dwelling traces made by filter feeding organisms. Besides, the traces are moderately crowded on bedding plane and are restricted to the thinly laminated sandy and silty layers only, thereby indicating substrate preference of the trace making organisms. The dominance of deposit feeding traces indicates presence of abundant food resources along with low to moderate energy and low turbidity conditions. The detailed analysis of the trace fossils indicates fluctuating energy conditions with fluxes of turbid water. The studied ichno-fossils indicate shallow marine depositional conditions for the entire succession of the Tal Group.

Similarly, the Marwar Supergroup in western India yielded varied fossils known from the Ediacaran to Cambrian successions. The lowermost unit of the

Marwar Supergroup, the Jodhpur Group, yields fossils of the Late Neoproterozoic Era comprising possible body fossils *Marsonia artiyansis* (Kumar and Ahmad, 2012) and plant fossil (Kumar and Ahmad, 2016), five-armed body fossil (Kumar et al., 2012), fourteen types of well-preserved microbial mats (Kumar and Ahmad, 2014), Ediacaran Discs (Srivastava, 2012a) and (?) non-vascular megaplant fossils (Srivastava, 2015; Kumar and Ahmad, 2016). The other contributions also helped in documenting biodiversity of different Ediacaran litho-units from the Jodhpur Sandstone (Sharma and Pandey 2011; Kumar and Ahmad, 2012, 2014, 2016; Kumar et al., 2012). From the Nagaur Group, trace fossils (Ahmad and Kumar, 2014), *Treptichnus pedum* (Srivastava, 2012b), priapulid worms (Srivastava, 2012c), burrows and scratch marks of arthropods and poorly preserved burrows have been documented from fine to medium grained sandstone (Ahmad and Kumar, 2014). Singh et al. (2014a) recorded various trace fossils from the Lower Cambrian Nagaur Sandstone, Marwar Supergroup. They reported *Rusophycus*, *Diplichnites*, *Monomorphichnus*, *Bergaueria*, *Cruziana*, etc. from the Mohra Member (Nagaur Sandstone). On the basis of presence of graded rip-up clasts, current ripples, dune cross-stratification with mud drapes and tidal bundles they considered the subtidal palaeoenvironment for the deposition of Nagaur Sandstone. These trace fossil are assigned to Cambrian Stage 2 (upper part of Terreneuvian Series) (Fig. 10A-B).

From the Tunkliyan Sandstone, organic activity in terms of scratch marks of arthropod and poorly preserved burrows in the fine to medium grained sandstone (Ahmad and Kumar, 2014) are recorded. These finds have enriched our knowledge of the diversity of Ediacaran biosphere and also help in further refining the stratigraphic divisions of Ediacara and Lower Cambrian intervals.

Stable Isotope Studies

In the recent past, more extensive high resolution carbon, oxygen and sulphur stable isotopes investigations on various Precambrian geological settings have been performed. Many of these investigations have been coupled with other geological parameters i.e. oxygen isotopic variations (Chakrabarti et al., 2011); REE (Mohanty et al.,

Fig. 9: Carbonaceous remains from the Sirbu Shale, Bhandar Group, Vindhyan Supergroup. A: Early Ediacaran carbonaceous remain *Doushantuophyton cometa* (specimen no. BSIP-39615); B: *Sitaulia minor* large filamentous form noted on the surface of Sirbu Shale (specimen no. BSIP-39229). (scale bar = A, B-1mm)

Fig. 10: A: *Treptichnus pedum* recorded from the Nagaur Sandstone, Dulmera area, Rajasthan (specimen no. BSIP- 41036) (scale bar = 2cm); B: *Chondrites* isp. described from the Nagaur Sandstone (specimen no. BSIP- 41035) (scale bar = 2mm)

2015); Trace elements (Johnston *et al.*, 2013; Kurzweil *et al.*, 2015; Wood *et al.*, 2015; Zhao and Zheng, 2013); heavier stable isotopes (Etemad-Saeed *et al.*, 2015; Nagarajan *et al.*, 2013); lipid biomarkers (Lee *et al.*, 2013) to achieve an improved understanding on palaeoenvironmental conditions and evolution of life. For example, in a recent study by Planavsky *et al.* (2012) on Lomagundi interval, coupled stable isotope data for carbonate carbon and

carbonate-associated sulfate (CAS) demonstrated their importance to explain the mechanism behind Earth's most dramatic carbon isotope events along with associated evolution of seawater sulphate and pyrite burial.

Since last one decades carbon, oxygen and sulphur stable isotope study for Precambrian has largely been focused on Ediacaran period because of

two main reasons: (1) the discovery of largest (both in magnitude and duration) negative carbon isotope excursion of Earth's geological history (also known as Shuram/Wonoka excursion) from Oman, Australia, North America, and China etc. (2) Radiation of metazoa is considered to have a root in Ediacaran Period. The cause and coverage of Shuram excursion and its possible link with the radiation of metazoa is still under debate (Gamper *et al.*, 2015; Loyd *et al.*, 2015; Macdonald *et al.*, 2013; Osburn *et al.*, 2015; Schrag *et al.*, 2013; Tahata *et al.*, 2015). Trace elements and sulphur stable isotope studies suggest that severe glaciation in Cryogenian led to oxidation of Earth's surface which induced the radiation of metazoa during Ediacaran Period (Sahoo *et al.*, 2016; Wood *et al.*, 2015). Recent development in stable isotope studies of carbonate-C, O, organic-C, sulphate-S, pyrite-S and Fe speciation have provided the framework for reconstruction dissolved oxygen history of Precambrian/Ediacaran ocean (Chang *et al.*, 2016; Cui *et al.*, 2015; Kurzweil *et al.*, 2015). According to these multiproxy studies, Ediacaran ocean water column was stratified in which surface water was oxic whereas bottom water was anoxic to sulphidic (Spangenberg *et al.*, 2014). Parallel studies of lipid biomarker helped to understand the biological community shifts during this period (Lee *et al.*, 2013).

In this context, Indian Precambrian settings have received little attention in the recent past. A study on Palaeoproterozoic Aravali Supergroup used phosphate organic content and stable isotopes of C to understand the role of phosphate as a nutrient on GOE oxidation event and subsequent $\delta^{13}\text{C}_{\text{carb}}$ (Papineau *et al.*, 2013). Purohit *et al.* (2012) tried oxygen and carbon isotopes across three different sections of Neoproterozoic Sirohi Group to understand their relationship with contemporaneous global events. C and O isotope along with $^{87}\text{Sr}/^{86}\text{Sr}$ ratio were studied in carbonate rocks of shallow marine Proterozoic Bhima Basin to identify diagenetic signature in carbonate rocks (Nagarajan *et al.*, 2013). In Palaeoproterozoic Sausar Group of central India C and O isotopes together with Sr and Ba and REE studies indicated the glaciogenic origin for diamictite and its primary origin. Chemostratigraphy allowed the comparison of this group with other similar geological settings of the world (Mohanty *et al.*, 2015).

Organic Geochemistry

In India, Precambrian organic geochemical study is largely limited to hydrocarbon exploration for example, Dutta *et al.* (2013) conducted a biomarker and carbon isotope study of oil from Bikaner-Nagaur Basin and compared those of other infra Cambrian oils like Huqf oils from Oman and Baykit High oils from eastern Siberia. Furthermore, using organic geochemical tools, Raju *et al.* (2014) indicated that oil of Bikaner-Ganganagar basin was generated in anoxic hypersaline from marine clastic source rock and undergone some degree of biodegradation. Gaseous hydrocarbon study by Dayal *et al.* (2014) in Vindhyan Basin demonstrated conducive pathways for migration of the hydrocarbons towards the surface soil. Biomarker study was also conducted in the Chattishgarh Basin that indicated this Proterozoic basin had little eukaryotic abundance relative to prokaryotic bacteria (Patranabis-Deb *et al.*, 2016).

Unsolved Problems and Future Research Directions

In the last five years, Precambrian palaeobiological investigations have increased manifold. Researchers from China, Russia and Sweden have contributed a lot in the domain of palaeobiology of Proterozoic and Early Cambrian successions. Antiquity of earliest life forms, advent of various metabolic pathways in use and conversion of energy, advent of different living forms of three principle domains, *viz.*, the Bacteria, the Archaea and Eukarya (Woese 2002, Woese *et al.*, 1990) or belonging to two different empires, *viz.*, the Prokaryota and Eukaryota (Mayr, 1998) are major areas of investigations. Advancement in analytical instrumentation have helped in acquiring even the weakest or feeble signature of life forms entombed in the Precambrian sedimentary successions. In spite of the development of sensitive facilities, the most convincing answers for Precambrian palaeobiology are those which demonstrate morphologically differentiated forms which could be associated with distinct depositional environment.

Oxygenation events in the Precambrian, acquisition of plastids/photo-endosymbionts to evolve into eukaryotes, ecological takeover of oxygenic cyanobacteria are some inter-related questions which are being investigated. Ediacaran and early Cambrian successions in India are important to test the two

contrary view points such as redox-static Ediacaran ocean verses multiple oceanic oxygenation events in a predominantly anoxic global Ediacaran-early Cambrian ocean and their impact on biotic innovations/mass extinctions. To test these hypothesis multi-proxy palaeoredox studies are conducted involving major and trace element concentrations, iron speciation, sulfur isotopes, Mo and U enrichment factors. Though such studies are conducted in many other parts of the world but no data are available for any of the Indian successions. Estimation of oxygen level during Proterozoic is vigorously pursued and generally believed to have increased from trace levels ($<10^5$) present atmospheric level (PAL) near Archaean-Proterozoic boundary, great oxidation event (Ca 2.4 Ga) (Lyons *et al.*, 2014) but its level during mid-Proterozoic remained debated. In a recent pursuit, Cr isotope data from marine black shale suggest very low background oxygen levels ($<1\%$ of present atmospheric level) that would be the reason for inhibiting the diversification of animals until 800 Ma (Planavasky *et al.*, 2014; Cole *et al.*, 2016). Black shales occurring in Indian Proterozoic successions are better target to verify these data and consequential assumptions.

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