Palaeobiology of Mesoproterozoic Salkhan Limestone, Semri Group, Rohtas, Bihar, India: Systematics and significance

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Mesoproterozoic (~1600 Ma old) Salkhan Limestone (Semri Group) of the Vindhyan Supergroup, exposed in Rohtas district of Bihar, India, preserves an abundant and varied ancient microbial assemblage. These microfossils are recorded in three distinctly occurring cherts viz., bedded chert, stromatolitic chert and cherty stromatolites. 27 morphoforms belonging to 14 genera and 21 species have been recognized. Six unnamed forms are also described.

The microbial assemblage, almost exclusively composed of the remnants of cyanobacteria, is dominated by entophysalidacean members and short trichomes and can be termed as 'typical Mesoproterozoic microbiotas'. The assemblage includes characteristic mat-forming scytonematacean and entophysalidacean cyanobacteria. *Eoentophysalis* is the dominant organism in the assemblage. Ellipsoidal akinetes of nostocalean cyanobacteria (*Archaeoellipsoides*) and spherical unicells also occur; both are distinct from mat forming assemblage, allochthonous and possibly planktic. Co-occurrence of the microbiotas and precipitates is related to the depositional environment of the Mesoproterozoic tidal flats with high carbonate saturation.

1. Introduction

A number of publications have appeared in past years on the palaeobiological remains of the Proterozoic Vindhyan Supergroup, viz., the microfossils (Kumar and Srivastava 1992a, b, 1995; Anbarasu 2001), carbonaceous megaremain (Kumar 1995, 2001; Rai and Guatam 1998; Azmi 1998), and trace fossils (Sarkar *et al* 1996; Seilacher *et al* 1998; Chakraborty 2001) reflecting the renewed attempts to understand the palaeobiology of the basin. The interest and importance lie in tracing the antiquity of the life forms and the age of the fossil bearing Vindhyan sediments that have long been an enigma (see Venkatachala *et al* 1996; Sharma 2003 for comprehensive reviews). The recent radiometric datings of various horizons of the Semri Group (Kumar *et al* 2001; Rasmussen

et al 2002; Ray *et al* 2002, 2003; Sarangi *et al* 2004) have thrown a challenge in the understanding of the evolution of life in Vindhyan.

The Vindhyan Supergroup is well exposed in central India (figure 1). There are a few reports of palaeobiological remains from the easternmost part of the basin (Beer 1919; Maithy 1989; Azmi 1998). Except a brief account of microfossils (Venkatachala *et al* 1990) no detailed systematic account of the microfossils is available from the eastern most fringe of the basin.

In the present paper diverse Mesoproterozoic microbial assemblage recorded from the Salkhan Limestone of the Vindhyan basin exposed in the Rohtas District, Bihar is being reported (see figures 1 and 2). Palaeoenvironmental interpretation of the assemblage and significance of the microfossils have also been discussed.

Keywords. Palaeobiology; cyanobacteria; microfossils; Semri Group; Vindhyan Supergroup; India.

Figure 1. Regional geological map of the Vindhyan basin (after Ahmad 1962).

Figure 2. Geographic and stratigraphic location of fossiliferous cherts from the Salkhan Limestone. (A) Index map of India with position of Bihar state. (B) Outline map of Bihar showing position of Rohtas District where microfossiliferous outcrops of the Salkhan Limestone occur. (C) Generalized stratigraphic column of the Semri and Kaimur Groups exposed in Rohtas. (D) Detailed litholog of Salkhan Limestone, showing location of fossiliferous horizons (after Sharma and Sergeev 2004).

Table 1. Generalized lithostratigraphic succession of Vindhyan Supergroup (modified after Auden 1933 and Bhattacharyya 1996).

		After Auden (1933)	After Bhattacharyya (1996)
Vindhyan Supergroup	Kaimur Group	Dhandraul quartzite	Dhandraul Sandstone
		Scarp sandstone and shale	Mangesar Formation
		Bijaigarh Shale	Bijaigarh Shale
		Upper quartzite and sandstone	Ghaghar Sandstone
		Susnai Breccia	Susnai Breccia
		Lower quartzite and shale	Sasaram Formation
	----- Unconformity -----		
	Semri Group	Nodular limestone and shale	Bhagwar Shale
		Banded shale and limestone	
		Nodular limestone	Rohtasgarh Limestone
		Glauconite beds	Rampur Formation
		Fawn Limestone	Salkhan Limestone
		Olive Shale	Koldaha Shale
		Porcellanite	Deonar Formation
		Kajrahat Limestone	Kajrahat Limestone
			Arangi Formation
		Basal conglomerate	Deoland Formation

2. General geological setting

The Vindhayan Supergroup unconformably overlies the slightly metamorphosed Bijawar Group of rocks with an Rb–Sr age of ~2500 Ma (Crawford and Compston 1970). It is constituted of a thick

pile of rocks occupying a large area extending from Sasaram (Bihar) in the east to Chittorgarh (Rajasthan) in the west and Dholpur (Rajasthan) in the north to Hoshangabad (Madhya Pradesh) in southwest comprising sandstones, shales and limestones (figure 1). In general, the Vindhyan

Supergroup is considered to be unmetamorphosed, tectonically less disturbed in most of the areas and one of the best-preserved Proterozoic sedimentary sequences in India. The entire thickness of the Vindhyan Supergroup is divided into four equal groups namely Semri, Kaimur, Rewa and Bhander in ascending order. The Semri Group is best exposed in Son valley area Sonbhadra District, Uttar Pradesh, where it is divided into different formations (Auden 1933). The eastern most fringe of Vindhyan basin is exposed in the Rohtas District of Bihar. In this locality, only the Semri and Kaimur Groups of rocks are developed. Geology of the eastern part of the basin and general lithostratigraphic succession of the Vindhyan Supergroup in the central part of the basin is given in table 1. The lithostratigraphy of the area has been studied in detail (Sarkar 1981; Sharma 1993; Das Gupta 1997). Here, the estimated thickness of the different formations is 935 m (Prakash and Kumar 1980).

Salkhan Limestone, overlying the Olive Shales (earlier reported as Nauhatta Limestone Formation by Venkatachala *et al* 1990) is well-developed, thickly bedded and fawn coloured. It is extremely fine grained, dolomitic and cherty at places, in nature. The gradational to sharp contact have been observed at Jaradag and Nauhatta. The chert bands present in the dolostone stands out on weathering. The chert is typically black to dark greenish black, and its nature gradually changes from the massive, bedded, stromatolitic to again bedded chert in a lithological column.

3. Age

The Vindhyan Supergroup unconformably overlies the Bijawar Group of Rocks which are slightly metamorphosed with an Rb–Sr age of ~ 2500 Ma (Crawford and Compston 1970). The age of the new assemblage of microbiota reported from the Salkhan Limestone is poorly constrained in the locality. The only radiometric data available for the Bijaigarh Shale in the study area are based on the U/Pb isotope studies of the galena collected at the contact of Bijaigarh Shale and Amjhore Sandstone of Kaimur Group. The lead isotope ratio suggests an age of 725 Ma, probably indicating the age of galena mineralisation, which is distinctly syngentic (Balasubramanian and Chandy 1976).

Recently Rasmussen *et al* (2002) have provided a robust data set for the Semri Group by using SHRIMP U–Pb Zircon geochronology dating the silicified tuffs. Their studies have shown that the sediments were deposited between 1628 ± 8 Ma and 1599 ± 8 Ma. Ray *et al* (2002) dated the rhyolitic volcanic horizons from the

Deonar Formation between the Kajrahat and Rohtas Formation that yield U–Pb zircon ages of 1631 ± 5 Ma and 1631 ± 1 Ma. Sarangi *et al* (2004) reported a Pb–Pb isochron age of 1599 ± 48 Ma for the *Grypania* bearing Rohtas Formation of Vindhyan Supergroup, central India. These results suggest that the Kajrahat Limestone is of the latest Palaeoproterozoic age and the Rohtas Formation is of Mesoproterozoic age. The fossil-yielding horizon of Salkhan Limestone occurring in between is therefore early Mesoproterozoic.

Thus, the comparison and correlation of central Indian Vindhyan sediments indicate that the age of Semri Group of sediments exposed on the eastern-most fringe of the Vindhyan basin range in age from >1600 – 1000 Ma. The fossiliferous strata – Salkhan Limestone – is considered older than 1400 Ma and about 1600 Ma old.

4. Previous studies

The first record of the microfossils from the black-bedded chert of the Salkhan Limestone exposed in the Salkhan area of Uttar Pradesh was reported by Kumar (1978), which was later described in detail by McMenamin *et al* (1983). In this report ten species belonging to nine genera were reported. In a subsequent publication Kumar and Srivastava (1995) reported a new assemblage of microfossils from Salkhan Limestone exposed in Newari area (Newari is 30 km west of Salkhan) also in Uttar Pradesh. This report included 28 species belonging to 18 genera representing both coccoid and filamentous forms. The Salkhan Limestone facies extends further east and is well exposed on the easternmost fringe of the Vindhyan basin. The black-bedded chert and other varieties of chert have yielded the well-preserved microbial assemblages that are described and compared in the present paper.

5. Fossiliferous chert

Chert is a natural archive of well-preserved microorganisms the world over (Knoll 1985). It provides an insight into the early life and evolutionary trends subsequently opted by these organisms (Knoll and Sergeev 1995; Knoll 1996). The process of preservation is still to be completely understood, yet the cherts where these microfossils are well preserved are most sought after lithology to find an insight into the Precambrian biosphere (Leo and Barghoorn 1976; Maliva *et al* 1989). Salkhan Limestone exposed in Rohtas District of Bihar shows three main forms of chert, i.e., bedded chert, stromatolitic chert and cherty stromatolites in the field, and all of them proved to be fossiliferous.

Figure 3. Different types of cherts from the Salkhan Limestone. Note the variations as observed in thin sections. Slide number, bar scale and nature of light used for exposing the thin sections are given in parenthesis. (a) A transitional portion of the section of bedded to stromatolitic chert (BSIP-10903; bar scale = 2 mm, slide exposed under diffused light). (b) A section of stromatolitic chert showing fine stromatolitic columns (BSIP-10911; bar scale = 2.2 mm, slide exposed under diffused light). (c) and (f) A section of bedded chert in thin section. Note the presence of alternate dark and light laminae. The dark laminae invariably contain varied microfossils. Vugs replaced by chert are present in the light coloured laminae. (BSIP-10908; bar scale = 2 mm, slide exposed under reflected light); (f) bar scale = 1.2 mm. (d) A section of bedded chert in thin section showing ripped up clasts (BSIP-10905; bar scale = 2.2 mm, slide exposed under diffused light). (e) A section of bedded chert in thin section showing tabular nature of stromatolite (BSIP-10906; bar scale = 2.2 mm, slide exposed under diffused light).

5.1 Bedded chert

(Figures 3a, 3c–d, 3f; 4a–f, 4i, 4j)

5.1a Description

The bedded fossiliferous chert is dense, black, waxy lustrous on freshly broken conchoidal faces. It lies

below the stromatolites in the area of study. In the thin section, the chalcedonic grains form an interlocking mosaic pattern and vary from less than $1\mu\text{m}$ to more than $100\mu\text{m}$ in diameter with almost amorphous nature tending to be localized in the more fossiliferous areas of the matrix. Quartz grains sometime more than $150\mu\text{m}$ in

Figure 4.

diameter are locally present. Varied well-preserved, randomly distributed sphaeroidal and filamentous microfossils are preserved in a matrix of primary chalcedonic chert with kerogen (*microfossils are separately described under systematics section*). Multilamellated sheaths, various unnamed forms and sheaths are also recorded. None of these members have any tendency to form organic laminae, or specific preferences for association among the members of assemblage.

5.1b Interpretation

The presence of micro-organisms in irregular kerogenic brown patches indicate that these microfossils had no role in the formation of overlying stromatolite. The general distribution of micro-organisms within the chert matrix and dominance of cyanobacterial elements, strongly suggests that these organisms were present in nearby localities and got entrapped in the zone of silica precipitation. The presence of spherulitic chalcedony (figure 4f) at certain places in the thin section suggests minor alternation in the chert. Except zebraic chalcedony, other elements of replacing chert as suggested by Milliken (1979) are absent in this unit. Therefore it cannot be conclusively considered as a criterion for the replacement nature of the entire chert.

5.2 Stromatolitic chert

(Figures 3e; 4g, 4h, 4k, 4l, 4m)

5.2a Description

The other form of the chert in Salkhan Limestone is associated with the stromatolites in the locality. Generally, either it is underlying or overlying the stromatolites. Except alternation of dark and light bands of chert no typical stromatolites have been observed in the hand specimens. The dark and light band varies in thickness from few millimeters to centimeter. In thin sections, however, these

bands show a variety of stromatolite fabric and texture with varied shapes of precipitates (see Sharma and Sergeev 2004 for precipitate patterns). At few places broken tufted mats, oncoïd and oncoïdal kerogen and ripped up clasts are also noticed. Sometimes microspar and silica vein impregnations are also noticed in the chert. Fossils are invariably present in dark bands. The white bands show chalcedonic grains of interlocking mosaic patterns from less than 1 μm to more than 100 μm in diameter. The voids present in light bands are generally constituted of megaquartz, flamboyant quartz, spherulitic chalcedony and zebraic chalcedony and those present in the tufted broken mats are filled with microcrystalline silica. Voids assume a variety of shapes from tear, ovoidal, rounded, polygonal to irregular and devoid of any microbial remains.

5.2b Interpretation

It is likely that the thin veneer of cyanobacterial blooms or mats present in the open sea got deposited over the regular mats of stromatolitic chert as broken tufted mats, or assumed shapes of oncoïd and oncoïdal kerogen. The organic matter and kerogen present in the chert impart the black colour to the dark bands of the chert. Like the bedded chert all the elements of evaporite replacing chert have not been recorded in each void. There is a possibility of chert being primary in nature.

5.3 Cherty stromatolites

(Figures 4l, 4m)

5.3a Description

Different stromatolitic forms are noticed in the field and their study shows that they are invariably constituted of cherts rather than carbonates (for details of stromatolites see Sharma 1996). In cherty stromatolites, ghosts of carbonate are noted at several places. Proper orientation of lamination could not be noticed in thin sections. Clasts of

Figure 4 caption

Figure 4. Replacement features of vugs and voids as observed in thin section of bedded and stromatolitic cherts. (a) Note various shapes of vugs and voids observed in dark lamina of bedded chert (BSIP-10910; bar scale = 1.2 mm, slide exposed under diffused light). (b) and (c) Void observed in bedded chert, (b) in plane polarized light and the same void under cross polarized light (BSIP-10910; bar scale = 1.5 mm). (d) and (e) Elongated upside down voids in bedded chert, (d) under polarized light and the same void under cross polarized light (BSIP-10910; bar scale = 1.5 mm). (f) Fine bedded chert showing selective growth of spherulitic chalcedony under cross polarized light (BSIP-13138; bar scale = 1.5 mm). (g) and (h) Void observed in stromatolitic chert in light coloured laminae, (g) under plane polarized light and (h) same void under cross polarized light (BSIP-13145; bar scale = 1.25 mm). (i) and (j) Tear shaped upside down void in bedded chert with very thin rim of spherulitic quartzite and mega quartz, (i) under plane polarized light, (j) same void under cross polarized light (BSIP-10910; bar scale = 1.5 mm). (k) Note the spherulitic chalcedony in stromatolitic chert (BSIP-13145; bar scale = 1.10 mm). (l) and (m) Enlargements of voids in lighter laminae of cherty stromatolites. Note that voids are constituted of spherulitic chalcedony, megaquartz and flamboyant quartz, (l) under plane polarized light and (m) under cross polarized light (BSIP-13145; bar scale = 1.25 mm).

kerogen are floating in amorphous silica. Voids are scattered in stromatolites. Void fillings, spherulitic chalcedony, zebraic chalcedony and flamboyant quartz are present in the voids. Microfossils content in these cherts are poor and only some filamentous forms are observed.

5.3b Interpretation

Presence of ghosts of carbonate in the chert thin section as well as microtexture and fabric studies indicate that stromatolitic carbonate has been replaced with chert and most of the cherty stromatolites are formed by the replacement of carbonate rocks or sediments. The stromatolitic laminae and kerogen have also contributed towards the black colour stromatolites. The presence of voids in between the stromatolitic laminae and spatial relationships of void and replacement features suggest that prior to lithification of the mats, there was a short phase of desiccation and an evaporite development. Thus it is reasonably clear to conclude that the microbial assemblage of Salkhan Limestone grew in arid, intertidal to supratidal environment where some evaporitic minerals could have formed contemporaneously with the mat formation or very likely soon thereafter.

6. Palaeoenvironmental interpretation of microfossils

The microfossils of Salkhan Limestone are three dimensionally preserved in a structurally little altered condition as organic residue within the bedded, stromatolitic as well as chertified stromatolites. The dark brown colour imparted to the chert by the organic residue testifies that the original organic compounds have been a little altered except for the thermal alteration. In different types of cherts, solitary, planktic and randomly occurring microfossils are considered mat dwellers as inferred by the orientation and density of microfossils. Those occurring in groups in organized fashion and benthic in nature are termed as mat builders. Similar association of taxa in a structured pattern of community occurs in Bahamania environment and in the Proterozoic succession of the East Greenland (Green *et al* 1987).

It is likely that the microbial assemblage of the Salkhan Limestone grew in shallow, relatively saline water. This is suggested by analogy with modern entophysalidacean mats that occur in arid, shallow-water environments often in intertidal to supratidal flats (Logan *et al* 1974; Horodyski and Von der Haar 1975; Golubic 1973, 1976; Kinsman and Park 1976; Playford and Cockbain 1976; Walter 1976; Horodyski *et al* 1977; Margulis *et al*

1980; Sergeev *et al* 1995, 1997). No relicts of evaporite minerals are so far found in the Salkhan Limestone yet the voids, vugs and replacement sequence of carbonates to chert suggest their formation and successive replacement in some cases. The other parameter is the evidence for the original pigment concentrations in the upper parts of the microbial mats constituted by *E. belcherensis*. Analogous conditions of colouring in modern *Entophysalis* is apparently a response to highlight intensity and is characteristic of cyanobacteria that live in areas of high salt content (Fritsch 1945; Drouet 1968; Fogg *et al* 1973; Walsby 1974).

The noticeable difference in the composition and level of preservation of the biota in different types of cherts suggests that each one of them represents a different zone of carbonate tidal flat of intertidal to supratidal region. Similar assemblages are reported in various Proterozoic basins from different parts of the world (Knoll *et al* 1989, 1991; Sergeev *et al* 1997). It is presumed that the biological communities preserved in different cherts may be analogous to those described from several extant environmental niches such as in the Hamelin Pool, Shark Bay (Logan *et al* 1974), Coastal lagoon, lagoon Mormona, Baja California, Mexico (Horodyski *et al* 1977; Margulis *et al* 1980; Green *et al* 1987). The well-preserved mats of *Eoentophysalis* recorded in the stromatolitic cherts seem to be analogous with the 'pustular mats' built by *Entophysalis major* in the middle to upper intertidal zones of the Hamelin Pool. The compressed mats of *Eoentophysalis* in the same chert forming organic laminae may be compared with the 'film mats' (desiccated ecomorphs of pustular mat; see Logan *et al* 1974, p. 146 for their discussion of film mat) reported from the upper intertidal to supratidal zones of the Hamelin Pool. The microbial assemblage consisting of *Tetraphycus* and *Sphaerophycus* resembles the population reported from 'gelatinous mat' in the lower to middle intertidal zones of Hamelin Pool.

Stratiform stromatolites particularly the *Stratiferia irregularis* and *Irregularia* sp. occurring in Salkhan Limestone appear to have been built by *Eoentophysalis belcherensis*, a coccoidal, entophysalidacean cyanobacteria which are well preserved and very abundant in the stromatolitic chert. Coccoid unicells of the genus *Myxococcoides* are common in the assemblage and probably represent fossilized chroococcean cyanobacteria. Different species of *Myxococcoides* either occur along with the *Eoentophysalis* mats or are dispersed freely in organic mass/kerogen. This spatial relationship suggests that *Myxococcoides* were mat dwellers rather than actually having contributed to the building of the organic laminae. The other important constituents of stromatolitic

chert include *Eosynechococcus grandis*, *E. moorei*, *Palaeoanacystis vulgaris*, some species of *Sphaerophycus* and *Tetraphycus*. Of these the species of *Eosynechococcus* and *Palaeoanacystis* along with a large amount of mucilaginous sheath suggest their growth in arid and harsh conditions. Their isolated and patchy distribution above the *Eoentophysalis* mat/layers in darker laminae, sometimes even transgressing into the lighter laminae, suggests that these forms were free floating.

Numerous solitary sporangia like spheroids of *Clonophycus elegans*, *C. ostiolum*, *Conhemisphaera pendulua* occur in the stromatolitic chert. These fossils resemble endosporangia of cyanobacteria or sporangia of the type that contain asexual, non-motile spores. Members of *Clonophycus* and *Conhemisphaera*, occur as solitary and in isolation with other cyanobacterial assemblage of the chert in part of dark organic laminae and precipitates. This spatial distribution suggests that these organisms lived unattached to substrate. Number of cells have been recorded in the stromatolitic chert but have not been detected in the bedded chert as well as in the cherty stromatolites. It is likely, therefore, that the restricted occurrences of these forms may be due to the biological relationship among *Clonophycus*, *Conhemisphaera* and *Eoentophysalis*, common in the same locality. These fossils present interesting details of the mode of reproduction through endospores or akinetes, which have rarely been found preserved in fossil record (e.g., Sergeev *et al* 1995; Kumar and Srivastava 1995; Srivastava 2005). These are identified with the help of extant genera, to which they are remarkably similar.

Conhemisphaera shows formation of 8 endospores in each small spherical cell, which apparently are dispersed by the rupture of cell walls. Some of the specimens have large smooth walled 'Spherical Cells'. They do not show cell division. It is probable that these may represent isolated instances of smooth walled akinetes bereft of vegetative cells. Preservation of a germling of a few cell lengths inside a large spore provides support to the aforesaid interpretation. Probably it is a homocystous *anabaenoid* alga.

Cellularly preserved, filamentous organisms are rare in this assemblage. Only some multilamellated sheaths and unnamed organic forms have been observed. Absence of cellular details in filamentous forms and patchy organic mass dispersed in the chert support the view that these forms may also have washed into the realm of precipitating chert. However, the possibility of preferential preservation of coccoid forms over the filamentous forms cannot be ruled out. Cherty stromatolites show preferential preservation of filamentous forms over coccoid forms in the stromatolitic chert. Microfossils are confined to darker laminae of the

stromatolites. Some of them are parallel to the laminae, where as *Oscillatorioopsis* and *Siphonophycus* cut across the darker and lighter laminae. Tussocky texture of the stromatolite is probably due to the overgrowth of filamentous forms showing their gliding movement for sunlight. Broken and small-scale texture suggest agitation environment, which prohibited the growth of large size columnar stromatolites leading to the formation of a new type of stromatolite *Rohtasia harnaensis* (Sharma 1996).

7. Comparison with other Proterozoic microfossils

7.1 Kheinjua Formation microfossils

The microfossils of the Salkhan Limestone are quite similar to those described by (Kumar 1978; McMenamin *et al* 1983; Kumar and Srivastava 1995) from Fawn Limestone of Kheinjua Formation (~1600 Ma) Semri Group, Vindhyan Supergroup, India. Five genera including a minimum of two species are common to both assemblages. In both the deposits *Eoentophysalis belcherensis* dominates the preserved microbes and appears to have formed stratiform stromatolites in shallow arid environments. *E. belcherensis* in the two localities has darkly coloured margins and many of the same degradational forms of this and other species occur in each assemblage. Both biotas contain few well preserved filamentous microfossils and it is possible that some of the unicells from Kheinjua Formation assigned to *Khienjuasphaera vulgaris*, *Melasmatosphaera media* may be conspecific with the unicells described as *Clonophycus*, *Conhemisphaera* from the Salkhan Limestone.

Nevertheless, the Salkhan assemblage includes numerous genera and species that appear to be absent from Kheinjua deposits and Kheinjua microbiota includes distinctive forms such as *Gunflintia minuta*, *Khienjuasphaera vulgaris*, *Melasmatosphaera media* and *Glenobotrydion aenigmatis*, besides different species of *Myxococcoides*, *Eosynechococcus*, *Tetraphycus* and *Eoentophysalis*.

7.2 Microfossils of the Chitrakut area

Kumar and Srivastava (1992a) in a preliminary report described the two microfossils from the chert present in the basal most part of the Semri Group. Recently, Anabarasu (2001) recorded acritarch *Cymatospheroides kullingii* and unnamed form 'A' from the non-stromatolitic Glauconitic Limestone Member of Chitrakut Formation. The chert occurs as thin specks and lens. The unnamed filamentous

Figure 5.

form and an acritarch *Trachysphaeridium* noticed in Chitrakut chert are absent in the Salkhan assemblage. No conclusive comparison is possible except that microbial assemblage grew at several localities at various stratigraphic levels in Vindhyan Supergroup, and in Semri Group in particular.

7.3 Comparison with other Mesoproterozoic formations of the world

The microbiota of the Salkhan Limestone is quite similar to that described from other Mesoproterozoic localities of the world, viz., Balbirini Dolomite, McArthur Group of Australia (~1500 Ma) by Oehler (1978); the Dismal Lakes Group (1250 Ma) of Arctic Canada by Horodyski and Donaldson (1980); Cliffs Formation and Victor Bay Formation of Uluksan Group (~1250 Ma), Bylot Supergroup, Canada by Hofmann and Jackson (1991). *Eoentophysalis* is conspicuously absent in Uluksan Group. The Salkhan Limestone, can therefore be termed 'typical Mesoproterozoic microbiota'.

8. Significance of the microfossils

With 27 morphotypes belonging to fourteen genera, twenty-one species and six unnamed forms, the Salkhan microbiota exhibit considerable taxonomic diversity. The biological affinities of many of the taxa remain uncertain, although they can be considered prokaryotic benthic and planktic forms (cyanobacteria) (compare with assemblages described by Hofmann and Schopf 1983, p. 349–359).

The most common mat forming benthic form is *Eoentophysalis* and to some extent *Eosynechococcus* a coccoid cyanobacteria and *Siphonophycus* is the individual filamentous form. The assemblage includes several planktonic forms washed into the stromatolitic environment. The *Eoentophysalis* dominated assemblage of the Salkhan Limestone provides probably the best biological point of comparison between the modern and ancient environment in totality. Salkhan Limestone is strikingly similar to the modern environment for the

consideration of microbial morphologies, taxonomy, morphology of the associated stromatolites and position within the carbonate intertidal zone.

Entophysalid-dominated mat association is a characteristic of a number of Proterozoic Formations, the oldest being the 2000 Ma old cherts of the Kasegalik and McLeary Formations, Belcher Islands Canada (Hofmann 1976) and the youngest being the 570 Ma old Yudoma Suit, Eastern Siberia (Lo 1980). The other younger and older *Eoentophysalis* dominated assemblages have been reported from 1500 Ma Amelia Dolomite, Australia (Muir 1976), the slightly younger Balbirini Dolomite, also of Australia (Oehler 1978), 1400–1500 Ma old Gaoyuzhuang Formation, China (Zhang 1981), the 1200 Ma old Dismal Lakes Group, Canada (Horodyski and Donaldson 1980) and the 750–790 Ma old Bitter Springs Formation, Australia (Knoll and Golubic 1979), 1500 Ma old Debengda Formation, Siberia (Sergeev *et al* 1994), 1500–1250 Ma old Billyakh Group (Sergeev *et al* 1995). Depositional environment and ecological parameters seem to be similar in all the instances testifying the persistence of a unique community type in a single environment throughout some 2000 Ma of the earth history fighting and winning for its existence. Most of the taxa of the Salkhan Limestone assemblage are long ranging prokaryotes, the overall character of the assemblage is characteristically Mesoproterozoic with its major features comparable to the coeval floras of Australia, Canada, China and Russia.

The biostratigraphic significance of Salkhan microbiota is very limited. Most of the taxa including the rarely occurring nonseptate filaments and small coccoids are long ranging in age. They are abundant in the Proterozoic and even continue into the Phanerozoic. However, the Salkhan assemblage contains taxa such as *Clonophycus* which is characteristic of the Mesoproterozoic microbiotas such as 1500 Ma old Balbirini Dolomite (Oehler 1978). The other forms show a long range extending into the Neoproterozoic. In comparison with known palaeobiological records, silicified biota of Salkhan assemblage can be dated ~1600 Ma, consistent with the age for the Semri Group based on radiometric and stromatolite biostratigraphic data.

Figure 5 caption

Figure 5. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. In this and all following figures, slide catalogue number for the Birbal Sahni Institute of Palaeobotany Museum (BSIP) and co-ordinates for each fossil or population illustrated are given in brackets. X and Y slide co-ordinates given are for Leitz Diaplan Microscope. (a–e) *Coniunctiophycus majorinum* Knoll *et al* (a) (BSIP-10907; 40.3/100.0), (b) (BSIP-10907; 40.3/103.5), (c) (BSIP-10907; 40.2/100.0), (d) (BSIP-10907; 40.0/101.8), (e) (BSIP-10906; 33.4/98.3). (f–i) *Diplococcus* sp. (f) (BSIP-10905; 38.5/108.3), (g) (BSIP-10906; 36.5/108.6), (h) (BSIP-13145; 37.0/97.0), (i) (BSIP-10907; 34.4/105.1). (j, k, m, n) *Sphaerophycus medium* Horodyski and Donaldson, (j) (BSIP-10905; 29.0/105.4), (k) (BSIP-13140; 39.3/102.1), (m) (BSIP-13142; 26.4/96.9), (n) (BSIP-10906; 34.6/99.3). (l) *Sphaerophycus parvum* Schopf (BSIP-13142; 49.0/107.4). Single scale bars = 10 µm; double bars = 50 µm.

The Salkhan microfossils add significant data on the habit of cyanobacteria during Precambrian Eon. The colonial habit of cyanobacteria as represented by five genera of colonial coccoid microfossils in the Salkhan assemblage is a testimony of regular colonial morphologies and polarity of organisation as exhibited by *Eoentophysalis*, *Myxococcoides*, *Eosynechococcus* and *Palaeoanacystis*.

The occurrence of *Clonophycus* and *Archaeolipsoidea* in the Salkhan assemblage representing algal sporangia/akinetes suggests that the sexual mode of reproduction through endospores/akinetes/sporangia may have developed by the close of Mesoproterozoic at least 1200 Ma ago. The *Eoentophysalis*, which is an endospore forming cyanobacteria, is wide spread in the Salkhan assemblage. The occurrences of this cyanobacteria from 2000 Ma to 700 Ma old sediments from Belcher Island Formation to Narssarssuk Formation provides circumstantial evidences for the earlier development of the process of endospore formation. The other apparent examples of Precambrian sporangia or sexual mode of reproduction include 700 Ma old endosporangia of *Sphaerocongregus variabilis* Moorman (Moorman 1974; Cloud *et al* 1975) and the type species of *Clonophycus* (Oehler 1977) from the H.Y.C. microbiota the *C. elegans* and other species of the same genera *C. ostiolum*, *C. refreingens*, *C. vulgaris* and *Clonophycus* sp. from Balbirini Dolomite (Oehler 1978). Recently well-preserved akinetes of heterocystous cyanobacteria have been recorded from several Mesoproterozoic localities (Golubic *et al* 1995; Sergeev *et al* 1995; Knoll and Sergeev 1995; Srivastava 2005).

9. Samples, method and repository

The material for the present investigation was collected during 1988 and 1990 field visits. Outcrop samples of black-bedded chert, stromatolitic chert and cherty stromatolites were collected from the Nauhatta, Harna and Sihaldeh localities. Cutting samples from dug wells of stromatolitic chert were collected from Harna locality. All the localities are in the Rohtas district of Bihar in India. The microbiota of the Salkhan Limestone are studied in petrographic thin sections by optical microscopy using transmitted light. The mineralogy of the samples was studied in petrographic thin sections by optical microscopy using transmitted and polarised light. The sizes of microfossils were measured in thin sections using an eyepiece micrometer. All the relevant slides are housed in the repository of Birbal Sahni Institute of Palaeobotany Museum bearing slide nos. BSIP-10903, 10905, 10906, 10907, 10908, 10910, 10911, and 13138-13145.

10. Systematic palaeontology

On the basis of comparable size, morphology and colony shape, it has been attempted to place microfossils in the extant groups of cyanobacteria. There is no agreement to adopt a single classification scheme for taxonomic dealing of organic-walled microfossils and a general consensus agreement is still to be developed. Presently most of the existing systems of extant cyanobacteria classification consider the following features: nature of any sheath or gelatinous matrix surrounding the cells; presence of specialised cells such as akinetes, heterocysts, and the trichomes of filamentous species; size and characteristics of vegetative cells; presence of pseudovacuoles; presence and types of branching of filamentous species and ultimately the ecological role. Some of these features are taken into account while dealing with the systematics of fossils cyanobacteria of the Salkhan assemblage of Rohtas District, Bihar. The role of preservation and its effect on changes in morphology cannot be negated and is taken into account while describing the chroococcacean members. The fossils described here can be divided into two broad categories: filamentous forms and coccoidal forms.

Kingdom: Eubacteria, Woese and Fox 1977

Phylum: Cyanobacteria, Stainer *et al* 1978

Class: Coccogoneae, Thuret 1875

Order: Chroococcales, Wettstein 1924, emend. Rippka *et al* 1979

Family: Chroococcaceae, Nägeli 1849

Genus: *Coniunctiophycus*, Zhang 1981

Type species: *Coniunctiophycus gaoyuzhuangense* Zhang 1981

Stratum typicum: Gaoyuzhuang Formation, China.

Coniunctiophycus majorinum Knoll *et al* 1991 (Figures 5a–5e)

Coniunctiophycus majorinum Knoll *et al* 1991, p. 554, 557, figures 16.1–16.4.

Description: Sphaeroidal to elongated organic walled cells, occasionally polygonal, walls thin, finely granular, arranged in packets of 50–100 cells, 20–100 μm long and 30–50 μm wide. Unit cells of pluricellular colonies range in size 2–5 μm (2.4 μm , wall 0.5 μm , 100 cells measured), no external mucilage is apparent. Generally clumped in more or less globular colonies composed of more than 400 cells. Larger packets of cells form distinct lobes, generally accentuated due to post preservation changes. Colonies elongated parallel to bedding. No differentiation of cells within colonies. Surface texture psilate. Cells not individually covered but colonies are encompassed by organic mucilaginous sheath. Cells randomly and compactly arranged

in the colonies. Reproduction by fission in three mutually perpendicular planes. Compactness of the colonies is probably due to daughter cells remaining aggregated. New colonies are probably formed by the fragmentation of the pre-existing colonies.

Discussion: *Coniunctiophycus majorinum* colonies occur in stromatolitic cherts. Their colonial habit compares closely with certain pleurocapsalean cyanobacteria like *Myxosarcina* and *Chroococcidiopsis* (Waterbury and Stainer 1978). But other cyanobacteria (e.g., *Entophysalis* sp.) and other Eubacteria and certain protists (like *Chlorosarcina*) may assume such shape. Zhang (1981) described the genus *Coniunctiophycus* as complex aggregated colonies of a number of spheroidal cells. He compared this habit to the living planktonic chroococcoid cyanobacteria *Microcystis*, *Coelosphaeridium* and *Aphanotheca*. The Salkhan assemblage of *Coniunctiophycus* conforms in all salient features to Zhang's (1981) generic diagnosis. In specific diagnosis it is also closely comparable to Draken population of *C. majorinum* (Knoll *et al* 1991). Zhang (1981) assigned the *Coniunctiophycus gaoyuzhuangense* to the family Chroococcaceae, close similarity of the present specimens with *Coniunctiophycus* and in absence of any reproductive body no firm systematic assignment is possible. Although Knoll *et al* (1991) placed *Coniunctiophycus* under incertae sedis but considering Zhang's (1981) proposition it has been grouped in Chroococcaceae.

Distribution: Mesoproterozoic: the Gaoyuzhuang Formation, China; the Kotuikan and Yusmastakh Formations, Anabar Uplift, northern Siberia; the Salkhan Limestone, Semri Group, Vindhyan Supergroup.

Material: More than a dozen colonies from Salkhan Limestone.

Genus: *Diplococcus* sp.

Type Species: *Diplococcus* sp.

Stratum typicum: Salkhan Limestone.

***Diplococcus* sp.**

(Figures 5f–5i)

Diplococcus shaped Microstructures Lo 1980, p. 160, Pl. IV, figures 12–15.

Description: Spherical to hemispherical cells, solitary or in pairs, occasionally forming planar colonies. Surface of cells smooth to thickly granular, cell range in size from 2–5 μm (average 2.8 μm , 125 cell measured). Paired cells are 3–5 μm long (average 4.0 μm , 10 specimens measured).

Discussion: These forms are common in bedded and stromatolitic chert assemblage and are distributed in the chert along the bedding plane. *Diplococcus* is similar to several living Chroococcalean members and resemble dividing Chroococcaceae cells representing binary fission. Some of the cells,

which are larger in size noted in the assemblage of bedded chert, do not commonly have dividing line across the cell, yet all other characters like mode of occurrence, surface structure, etc. are similar. Hence they have been categorized under *Diplococcus* like cells. Similar cell like units have been reported from Bitter Springs assemblage as *Sphaerophycus* Schopf (1968), in Belcher Island assemblage as *Eoentophysalis* Hofmann (1976) but they differ only in size parameter.

Distribution: Palaeoproterozoic: Belcher Islands, Canada; Mesoproterozoic: Salkhan Limestone of Semri Group, India; Neoproterozoic: Yodoma Suite, Siberia; Bitter Springs, Australia.

Material: More than hundred specimens noticed.

Genus: *Eosynechococcus* Hofmann 1976 emend. Golovenok and Belova 1984

Type species: *Eosynechococcus grandis* Hofmann 1976 emend. Golovenok and Belova 1984

Stratum typicum: McLeary Formation, Canada.

***Eosynechococcus grandis* Hofmann 1976**

(Figures 7e–7g, 7l)

Eosynechococcus grandis Hofmann 1976, p. 1058, Pl. 2, figures 11–14. emend.; Golovenok and Belova 1984, p. 28 (p. 24 english version), Pl. 2, figure 1; Hofmann and Jackson 1991, p. 372, figures 7.18, 7.19, 9 (partim).

Description: Cells long, ellipsoidal, rod shaped to barrel shaped, sometimes rounded. Envelope not distinct. Cells solitary, due to clumping some of the cells are adpressed and aggregated in irregular clumps, slightly constricted. Division by transverse fission. No dark inclusions found. 10–18 μm long and 5–7.0 μm across, averaging $14.5 \times 6.0 \mu\text{m}$ (10 specimens measured).

Discussion: Salkhan population of *Eosynechococcus grandis* confirms in all salient features to the specimens described by Hofmann (1976) emended by Golovenok and Belova (1984). They have considered these forms as akinetes. It has been noticed in the stromatolitic chert of the Salkhan Limestone occurring above the dark laminae of the stromatolites.

Distribution: Palaeoproterozoic: the McLeary Formation, Belcher Supergroup, Canada; Mesoproterozoic: the Ulukhan Group, Bylot Supergroup, Canada; the Salkhan Limestone, Semri Group, Vindhyan Supergroup.

Material: Several specimens in Salkhan Limestone.

Type species: *Eosynechococcus moorei* Hofmann 1976

Stratum typicum: Kasegalik Formation, Belcher Supergroup, Canada.

***Eosynechococcus moorei* Hofmann 1976**

(Figures 7h–7k)

Figure 6.

Category 1 microfossils Hofmann 1974, p. 88, figures 1b, c; Category 2 microfossils Hofmann 1974 (partim), p. 88, figure 1g.

Eosynechococcus moorei Hofmann 1976, p. 1057, 1058, Pl. 2, figures 1–7, 8?; Knoll *et al* 1991, p. 557, figure 17.16–17.22.

Description: Cells oblong, ellipsoidal to long rod shaped, sometimes curved to slightly constricted on one side. No covering envelope observed. Occurring solitary and loosely or closely aggregated forming irregular clumps or bowl shaped. Constriction probably representing transverse cell division can be seen. Centrally or eccentrically positioned, no dark object noticed. Dimension of cells 3–8 μm long and 2–3 μm across (average $5 \times 2.3 \mu\text{m}$; 50 cells measured).

Discussion: Population of *Eosynechococcus moorei* in the Salkhan assemblage have been found in stromatolitic chert. It loosely occurs over the dark laminae, probably they may not have any role in the formation of stromatolitic laminae. Salkhan population of *Eosynechococcus* confirm in all salient features with the diagnosis provided by Hofmann (1976). But contrary to the Salkhan population, specimens described from Kasegalik Formation have occasional occurrence of dark inclusion and are slightly larger in size. Knoll *et al* (1991) argued that these could be remains of chroococcalean cyanobacteria, but all could alternatively be the remains of physiologically dissimilar eubacteria and treated them as incertae sedis.

Distribution: Palaeoproterozoic: the Kasegalik Formation, Belcher Supergroup, Canada; Mesoproterozoic: the Salkhan Limestone, Semri Group, Vindhyan Supergroup; Neoproterozoic: the Draken Conglomerate Formation, Spitsbergen.

Material: A few dozens of specimens in the Salkhan Limestone.

Genus: *Myxococcoides* Schopf 1968

Type species: *Myxococcoides minor* Schopf 1968

Stratum typicum: Bitter Springs Formation, Australia.

Myxococcoides minor Schopf 1968

(Figures 6g, 6i, 6k, 6m; 7m)

Myxococcoides minor Schopf 1968, p. 676, Pl. 81, figure 1, Pl. 83, figure 10, table 4; Hofmann 1976, p. 1061, Pl. 7, figures 4–8; Knoll 1982b, p. 784–785, Pl. 8, figures 3, 4; McMenamin *et al* 1983, p. 258,

figure 5B, C; Zhang and Gu 1986, p. 326 (p. 18 english version), Pl. II-2, 5; Hofmann and Jackson 1991, p. 374, figures 8.1–8.5, 11; Kumar and Srivastava 1992c, p. 300, figure 8A, Text figures 4, 5, 11.

Description: Cells commonly sub-spherical to ellipsoidal somewhat flattened by compression against the adjacent cells. Clubbed into globular colonies. Surface structure smooth to finely granular. Cell dimension 6 μm –13 μm (averaging 10.5 μm ; 50 cells measured). Cells are enveloped in a granular to non-lamellated organic matrix; number of cells per colony varies from 40–60. Cells randomly oriented in the colony. Occasionally distorted due to mutual compression.

Discussion: Cells of this species are common in the stromatolitic cherts. The form *Myxococcoides minor* Schopf is morphologically similar to the ones described by Schopf (1968) except for the smaller size of Salkhan population. It is also comparable to *M. minor* described by McMenamin *et al* (1983). Specimens of *Myxococcoides ovata* have been noted in the bedded chert. In general morphology these specimens resemble the *Myxococcoides ovata* Knoll recorded from Akademikerbreen Group, Svalbard.

Distribution: Mesoproterozoic: the Ulukhan Group, Bylot Supergroup, Canada; the Kheinjua Formation, Semri Group, Vindhyan Supergroup, India; Neoproterozoic: the Bitter Springs Formation, Australia.

Material: A few dozen specimens are recorded in Salkhan Limestone.

Genus: *Palaeoanacystis* Schopf 1968

Type species: *Palaeoanacystis vulgaris* Schopf 1968

Stratum typicum: Bitter Springs Formation, Australia.

Palaeoanacystis vulgaris Schopf 1968

(Figures 6a–6e)

Palaeoanacystis vulgaris Schopf 1968, p. 672–675, Pl. 82, figures 5–7, table 4; Hofmann 1976, p. 1061, pl. 5, figures 1–2.

Description: Cells sphaeroidal to ellipsoidal, seldom angular due to mutual compression, aggregated in more or less sphaeroidal colonies, rarely solitary, clumped into mass of more than 300–400 cells. Cells diameter varies between 2 and 5 μm , with an average diameter of 4.0 μm , cell walls

Figure 6 caption

Figure 6. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a–e) *Palaeoanacystis vulgaris* Schopf, (a) (BSIP-10906; 34.0/99.7), (b) (BSIP-10907; 40.3/100.0), (c) (BSIP-10906; 31.2/96.4), (d) (BSIP-10906; 34.0/99.7), (e) (BSIP-10907; 40.2/100.0). (f, h, j, l, n, o) *Palaeoanacystis minor* sp. nov. (f) (BSIP-10906; 27.0/97.6), (h) (BSIP-13142; 48.9/106.3), (j) (BSIP-13142; 37.6/92.5), (l) (BSIP-13141; 43.0/104.6), (n) (BSIP-13141; 33.4/97.1), (o) (BSIP-13141; 43.1/103.6). (g, i, k, m) *Myxococcoides minor* Schopf, (g) (BSIP-13142; 42.4/96.5), (i) (BSIP-10906; 38.8/103.2), (k) (BSIP-13142; 42.4/96.5), (m) (BSIP-13139; 33.1/95.6). Single scale bars = 10 μm .

Figure 7.

robust and psilate, $1\text{ }\mu\text{m}$ thick. Individual cells are not surrounded by sheath. Reproduction by fission. It is observed that daughter cells remain aggregated, new colonies are formed by the fragmentation of the daughter colonies.

Discussion: Salkhan population of *Palaeoanacystis vulgaris* has been noted in stromatolitic chert of Salkhan Limestone. It confirms in all the diagnostic characters of Schopf's (1968) specimen. *P. vulgaris* is one of the more frequently occurring members of Salkhan assemblage and it is characterised by the well developed colonial habit and by the size of component cells. Undifferentiated cells in the colony are difficult to make out the characters of individual cell, indicate the compactness of colony and amount of organic matter. This is further proved by the maceration techniques where they remain attached in spite of their being released from the rock matrix. *P. vulgaris* is quite similar to modern Chroococcacean cyanobacteria of the genus *Anacystis*.

Distribution: Palaeoproterozoic: the Kasegalik and McLeary Formations Belcher Supergroup, Canada; Mesoproterozoic: the Salkhan Limestone, Semri Group, Vindhyan Supergroup; Neoproterozoic: the Bitter Springs Formation, Australia.

Material: Several hundred specimens.

Type species: *Palaeoanacystis minor*, nov. sp.

Palaeoanacystis minor nov. sp.

(Figures 6f, 6h, 6j, 6l, 6n, 6o, 8a, 8b, 8d, 8e)

Diagnosis: Cells spheroidal to ellipsoidal, cells forming small aggregate of 16–32 cells, walls robust, smooth to psilate, seldom occurring solitary, enclosed in amorphous organic matter.

Etymology: With reference to the small size of the cells.

Type locality: Harna village, Rohtas District, Bihar.

Stratum typicum: Salkhan Limestone, India.

Type specimen: Figure 6f.

Description: Pluricellular aggregate of cells forming the compact small colonies, size of each colony ranges between 15 and $30\text{ }\mu\text{m}$, average $20\text{ }\mu\text{m}$ with 16–32 cells in each colony. Cells robust walled, small $2\text{--}3\text{ }\mu\text{m}$ diameter (average $2.5\text{ }\mu\text{m}$, 25 cells measured) and enclosed in amorphous organic matter. Reproduction by fission in three mutually perpendicular planes with the resulting daughter cells

remaining attached to parent body. New colonies are formed by fragmentation.

Discussion: *Palaeoanacystis minor* is also a frequently occurring specimen in the Salkhan assemblage. They are found in abundance in the stromatolitic chert. *P. minor* has been noticed in the dark stromatolitic laminae, where *Eoentophysalis* form the base of laminae. No relationship in this order of occurrence could be established, but it seems that they are members of the same biotope occurring in Salkhan Limestone. Salkhan population of *P. minor* confirms in nearly all the salient features to generic diagnosis of *Palaeoanacystis* Schopf (1968) but differ in the size range and small colonial habit. It seems that fragmentation takes place at the early stage, so that the colony size remains small.

Distribution: Noted in the stromatolitic cherts of the Salkhan Limestone.

Material: A number of specimens are recorded in the Salkhan Limestone.

Genus: *Sphaerophycus* Schopf 1968

Type species: *Sphaerophycus parvum* Schopf 1968

Stratum typicum: Bitter Springs Formation, Australia.

Sphaerophycus parvum Schopf 1968

(Figure 5l)

Sphaerophycus parvum Schopf 1968, p. 672, Pl. 80, figures 4–10, table 4; Hofmann 1976, p. 1058, 1061, Pl. 2, figure 8?, Pl. 3, figures 1–6; Oehler 1977, p. 343, figure 12 H, I; Oehler 1978, p. 293, figure 10R, S; Horodyski and Donaldson 1980, p. 140, figures 5A–E, F?, G?, H?, I?, 6A, B; Horodyski and Donaldson 1983, figure 5A, B; Knoll 1982b, p. 783, Pl. 6, figures 3, 4; Hofmann and Jackson 1991, p. 374, figures 8.9, 8.10, 8.11, 10.1–10.3, 11 (Partim); Schopf 1992, p. 1070, Pl. 9, figure G, and p. 1097, Pl. 33, figure F; Kumar and Srivastava 1992c, p. 310, figure 8D; Kumar and Srivastava 1995, p. 107, figure 8L; Sergeev *et al* 1997, p. 222, figure 13A, C; Amrad and Bertrand-Sarfati 1997, p. 209, figure 7G.

“Smaller Chroococcacean cyanobacteria” Mendelson and Schopf 1982, p. 71, Pl. 1, figure 11.

Description: Cells, small spheroids to ellipsoidal, solitary or in pairs. Sometimes loosely associated, some specimens angulated, surface texture psilate.

Figure 7 caption

Figure 7. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a–d) *Sphaerophycus medium* Horodyski and Donaldson, (a) (BSIP-10906; 34.6/104.3), (b) (BSIP-10905; 29.0/105.4), (c) (BSIP-13142; 47.6/107.5) (d) (BSIP-13142; 41.8/105.1). (e–g, l) *Eosynechococcus grandis* Hofmann, (e) (BSIP-13141; 50.5/106.4), (f) (BSIP-13139; 31.1/94.5), (g) (BSIP-10906; 37.8/99.8), (l) (BSIP-10907; 44.2/97.2). (h–k) *Eosynechococcus moorei* Hofmann, (h) (BSIP-10906; 31.5/98.7), (i) (BSIP-13139; 42.2/94.8), (j) (BSIP-10907; 34.8/94.8), (k) (BSIP-10907; 44.2/97.2). (m) *Myxococcoides minor* Schopf (BSIP-10906; 28.8/99.5). Single scale bars = $10\text{ }\mu\text{m}$; double bars = $50\text{ }\mu\text{m}$.

Figure 8.

Cell diameter ranges between 2 and 3 μm (average 2.5 μm ; 25 cells measured). Sheath encompassing cells present, typically hyaline, 0.4–0.5 μm thick. Reproduction by fission. Daughter cells do not remain attached to the parent cell.

Discussion: The size of the Salkhan population overlaps with that of the type species in the Bitter Springs Formation. On the basis of their characteristic features like small size, shape their solitary/paired occurrence they are differentiated from *Huroniospora psilata*, *Eosynechococcus isolatus*, etc. Knoll (1982b) described *S. wilsonii* from Draken Conglomerate, Spitsbergen but subsequently on the suggestion of Hofmann put into *S. medium* (Knoll *et al* 1991).

Distribution: Palaeoproterozoic: Kasegalik and McLeary Formations Belcher Supergroup, Canada; Franceville Group, Gabon; Mesoproterozoic: Amelia Dolomite Formation, Australia; Balbirini Dolomite, McArthur Group, Australia; Dismal Lakes Group, Canada; Kheinjua Formation, Semri Group, India; Salkhan Limestone, Vindhyan Supergroup, India; Sukhaya Tunguska Formation, Siberia; Neoproterozoic: Draken Conglomerate, Spitsbergen; Bitter Springs Formation, Australia.

Material: Several hundred specimens.

Type species: *Sphaerophycus medium* Horodyski and Donaldson 1980

Stratum typicum: Dismal Lakes Group.

Sphaerophycus medium Horodyski and Donaldson 1980

(Figures 5j, 5k, 5m, 5n; figures 7a–7d)

Sphaerophycus medium Horodyski and Donaldson 1980, p. 140–141, figures 5J, K?, L?, M?, N?, O?, P?, 6C, 6D; Horodyski and Donaldson 1983, figures 5C, D?–H?; Green *et al* 1987, figure 5J, Knoll *et al* 1991, p. 553, figure 19.3; Schopf and Klein 1992, p. 9, figures F?–H?; Sergeev *et al* 1995, p. 27, figures 9.6–9.7; Kumar and Srivastava 1995, p. 107, figures 8M, 12F.

Sphaerophycus wilsonii Knoll 1982b, p. 783, Pl. 9, figures 5–9.

Description: Cells sphaeroidal, 4–6 μm in diameter (average 4.6 μm total cells measured 100). Wall robust, 0.75 μm granular to smooth, found in diad, tetrad or in linear clusters rare unicells. Cell division by binary fission, daughter cells are not attached with the parent cell.

Discussion: *Sphaerophycus medium* is abundant in the Salkhan population and are found in stromatolitic cherts and cherty stromatolites. These are randomly distributed in the amorphous organic matter. Their occurrence in diad, tetrad and linear clusters differentiates from the *S. parvum*. These are also distinguished by the slightly larger size. The diameter of both the species overlap somewhat as they do in Akademikerbreen Group of Svalbard (Horodyski and Donaldson 1983). As suggested by the Hofmann and Jackson (1991) *S. wilsonii* may be considered junior synonym of *S. medium* on the arguments put forth by them. But in our collection there are no solitary specimens as in Knoll's collection (1982b, figure 5) and are always found as diad and tetrad.

Distribution: Mesoproterozoic: the Dismal Lakes Group, Canada; Kotuikan and especially, Yusmakh Formations, Northern Siberia; Kheinjua Formation, Semri Group, India; Neoproterozoic: the Draken Conglomerate Formation, Spitsbergen and the Limestone–Dolomite “Series”, East Greenland.

Material: A few hundred specimens.

Genus: *Tetraphycus* Oehler 1978

Type species: *Tetraphycus hebeiensis* Liu 1982

Stratum typicum: Wumishan Formation, China.

Tetraphycus hebeiensis Liu 1982

(Figures 8c, 8h)

Tetraphycus hebeiensis Liu 1982, p. 152–153, Pl. 7, figures 1, 2, Pl. 8, figures 12, 13; Liu *et al* 1984, p. 179, Pl. 2, figures 9–11; Hofmann and Jackson 1991, p. 375–376, figures 10.7, 10.9–10.13.

Description: Solitary or clumped tetrads common. Compressed on one side. Cell dimension 5–7 μm long and 2–3 μm wide (average 4.5 $\times$ 2.6 μm ; 100 cells measured) dark black in colour, no covering envelope noticed, diads, planar and cross tetrads are not noticed. Set in an amorphous organic matrix.

Discussion: Of the different species known, the present specimen compares with *T. hebeiensis* in all its salient diagnostic features described from Wumishan Formation, China (Liu 1982) with cells in the range of 5–8 μm . It differs from *Tetraphycus congregatus* described from Kheinjua Formation (McMenamin *et al* 1983) which contain large number of cells forming colonies. It is possible that some of the specimens may be the earliest stages of *E. belcherensis* colonies.

Figure 8 caption

Figure 8. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a, b, d, e) *Palaeoanacystis minor* sp. nov., (a) (BSIP-13141; 30.0/96.6), (b) (BSIP-13141; 37.2/99.5), (d) (BSIP-13142; 38.9/93.0), (e) (BSIP-10906; 34.6/104.3). (f, i, m, n) *Tetraphycus major* Oehler, (f) (BSIP-10906; 32.5/98.3), (i) (BSIP-10906; 34.3/102.8), (m) (BSIP-13142; 49.7/106.5), (n) (BSIP-13143; 34.0/104.4). (c, h) *Tetraphycus hebeiensis* Liu, (c) (BSIP-10907; 35.0/103.4), (h) (BSIP-10906; 34.3/102.8). (j–l) *Eoentophysalis belcherensis* Hofmann, (j) (BSIP-10906; 36.8/97.3), (k) (BSIP-10905; 32.4/105.0), (l) (BSIP-10907; 35.0/102.0). Single scale bars = 10 μm .

Figure 9. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a–g) *Eoentophysalis belcherensis* Hofmann, (a) (BSIP-13142; 39.4/96.5), (b) (BSIP-13142; 42.3/96.5), (c) (BSIP-13142; 39.3/95.5), (d) (BSIP-13143; 32.4/105.0), (e) (BSIP-10906; 36.2/98.8), (f) (BSIP-13139; 38.8/95.0), (g) (BSIP-13142; 41.8/96.8). Single scale bars = 10 μm .

Distribution: Mesoproterozoic: Wumishan Formation, China; Ulukhan Group, Bylot Supergroup, Canada.

Material: A few hundred specimens.

Type species: *Tetraphycus major* Oehler 1978

Stratum typicum: Balbirini Dolomite, McArthur Group, Australia.

Tetraphycus major Oehler 1978

Figure 10. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a, b) *Huroniospora psilata* Barghoorn, (a) (BSIP-10907; 34.7/94.7), (b) (BSIP-10907; 24.3/95.3). (c) *Siphonophycus robustum* Knoll *et al* (BSIP-10906; 37.1/95.3). (d) *Eomicrocoleus crassus* Horodyski and Donaldson (BSIP-10906; 36.1/108.4). (e, f) *Conhemisphaera pendulua* Luo and Wang, (e) (BSIP-13141; 37.4/97.7), (f) (BSIP-10907; 26.5/99.9). (g) *Clonophycus ostiolum* Oehler (BSIP-13141; 52.5/106.5). Single scale bars = 10 μm ; double bars = 50 μm .

(Figures 8f, 8i, 8m, 8n)

Tetraphycus major Oehler 1978, p. 296, figures 10L–10Q; Kumar and Srivastava 1995, p. 107–108, figures 11E, 12G

Description: Cells spheroidal to slightly polygonal due to compression. Cells diameter 3–5 μm (average 3.4 μm , 100 cells measured). Cell walls psilate to granular, no cellular inclusion found. Cells commonly occur in planar tetrad, cross tetrad, diads and clusters of eight may be present. This mode of arrangement can be observed at one place

or at different places, set within a common amorphous organic matrix.

Discussion: This species abundantly occurs in Salkhan bedded chert. It confirms in all salient features to the generic diagnosis of Oehler's (1978) specimens. Of at least 11 described species of *Tetraphycus*, distinguished chiefly on the basis of cell diameter, the present species compares with the *T. major* from the Balbirini Dolomite of McArthur Group, Australia (Oehler 1978) with the cells size in range of 2.2–5.0 μm (with the average diameter

Figure 11. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a) Unnamed Form F- (BSIP-13140; 41.6/105.6). (b) Unnamed Form E- (BSIP-10907; 40.0/106.0). (c) Unnamed Form C- (BSIP-10906; 37.9/104.0). (d) Unnamed Form A- (BSIP-13144; 37.8/109.5). (e) *Clonophycus elegans* Oehler (BSIP-13142; 40.2/98.0). (f) *Clonophycus ostiolum* Oehler (BSIP-13141; 35.8/99.3). (g) Unnamed Form D- (BSIP-10906; 38.2/102.0) Single scale bars = 10 μm ; double bars = 50 μm .

3.9 μm). The other species are either smaller or larger in size with the overlapping cell diameter but they do not have the average cell diameter, equal to that of *T. major*.

Distribution: Mesoproterozoic: the Kheinjua Formation, Semri Group, Vindhyan Supergroup, India; the Balbirini Dolomite, McArthur Group, Australia.

Figure 12. Microbial assemblage recorded from Salkhan Limestone of the Semri Group. (a, d, f) *Siphonophycus robustum* Knoll *et al* (a) (BSIP-13142; 26.7/100.6), (d) (BSIP-13142; 26.8/99.0), (f) (BSIP-13142; 27.0/100.5). (c) *Oscillatoriopsis media* Mendelson and Schopf (BSIP-10906; 38.1/98.5). (b, h) *Siphonophycus septatum* Knoll *et al* (b) (BSIP-10906; 33.5/99.4), (h) (BSIP-10906; 30.0/97.0). (e) Unnamed Form B- (BSIP-10906; 37.4/103.6). (g, i) *Oscillatoriopsis longa* Timofeev and Hermann, (g) (BSIP-10907; 43.2/98.8), (i) (BSIP-10906; 36.8/98.2). Single scale bars = 10 μm ; double bars = 50 μm .

Material: A few hundred cells.

Family: Eoentophysalidaceae Geitler 1932

Genus: *Eoentophysalis* Hofmann 1976 emend. Mendelson and Schopf 1982

Type species: *Eoentophysalis belcherensis* Hofmann 1976 emend. Mendelson and Schopf 1982

Stratum typicum: Kasegalik Formation, Canada.

Eoentophysalis belcherensis Hofmann 1976 emend. Mendelson and Schopf 1982.

(Figures 8j–8l; 9a–9g)

Eoentophysalis belcherensis Hofmann 1976, p. 1070, 1072, Pl. 4, figures 1–5, pl. 5, figures 3–6, pl. 6, figures 1–14;

Eoentophysalis cumulus Butterfield *et al* revised 1994.

Description: Cells polygonal, sphaeroidal, ellipsoidal, occur in solitary or in pairs, planar tetrads, irregular clusters and colonies, occasionally distorted due to mutual compression. The size of cells varies from 3–10 μm across (with the average of 4 μm , 100 cells measured). Pleuricellular aggregate of cells forming the thick sheet. Dark stromatolitic laminae are formed by these cellular aggregates. Maximum length of sheet noticed is 800 μm and breadth 200 μm . Generally 100–150 μm long and 60–80 μm broad sheets are noticed. Sometimes form pustulose laminae or palmelloid colonies. Dark-brown in colour. Sometimes dark black micron sized inclusions are present. Cells are enveloped by thin walls, which are sometimes weakly or darkly pigmented. Some of the enveloped double or paired ellipsoids contain spheroids (dark bleb of less than a micron size) as inclusion.

Discussion: *Eoentophysalis belcherensis* has been noted in stromatolitic chert. It occurs along the dark stromatolitic laminae pointing its role in the formation of stromatolite. These specimens are in conformity with the specimen described from the Kasegalik Formation of Canada both in generic and specific diagnosis. Yakschin (1990, 1991) described similar fossils from the Mesoproterozoic Kutungda Formation of Olenek Uplift as the new genera *Eoxenococcus* Yakschin and *Corynophycus* Yakschin. Sergeev in Sergeev *et al* (1995) interpreted the Kutungda population as *E. belcherensis*. *Palaeoanancystis vulgaris* Schopf 1968 (partim) described by Yakschin (1991, pl. VI, figures 3, 5, 6, 8, pl. VII, figure 6), *Palaeoanancystis parvicellularis* Yakschin (1991, pl. VI, figures 2, 4, 9), *Tortiliphycus bifilamentosus* Yakschin (1991, Pl. XV, figure 3), *Phanerosphaerops tenuichalmis* Yakschin (1991, Pl. III, figures 9, 11) are also placed in the synonymy list of *E. belcherensis*. Besides *Myxococcoides minor* Schopf (partim) Yakschin (1991, Pl. IX, figures 1, 2, 4, 5),

Archaeophycus venustus Wang *et al* 1983 (partim) Yakschin (1991, Pl. III, figure 10, Pl. VIII, figures 1, 6, Pl. IX, figure 3), *Bulbiphycus sectilis* Yakschin (1991, Pl. VIII, figure 2) are also considered as synonymy list of *E. belcherensis*. *Entophysalis* is commonly found in the regions, which are frequently exposed to atmosphere. The extensive mucilage helps them withstand harsh light and exposure. They regenerate as soon as the environment is favourable.

Distribution: Widely distributed in Palaeo- and Mesoproterozoic chert; much less abundant in Neoproterozoic assemblage.

Material: Several hundred colonies from the Salkhan Limestone.

Class: Hormogoneae Thuret 1875

Order: Oscillatoriales Elinkin 1949

Family: Oscillatoriaceae (Gray) Kirchner 1898

Genus: *Oscillatoriopsis* Schopf 1968 emend. Mendelson and Schopf 1982 emend. Butterfield (in Butterfield *et al* 1994)

Type species: *Oscillatoriopsis media* Mendelson and Schopf 1982

Stratum typicum: Sukhaya Tunguska Formation, Russia.

Oscillatoriopsis media Mendelson and Schopf 1982

(Figure 12c)

Oscillatoriopsis media Mendelson and Schopf 1982, p. 64–65, pl. 4, figures 3, 5, 6; Ogurtsova and Sergeev 1987, pl. 9, figures 1, 2; Sergeev 1992, p. 87–88, pl. 26, figure 4, pl. 27, figures 1, 2; Schopf 1992, pl. 10, figures F, H; Sharma and Sergeev 2004, figures 5E, 7D.

Description: Trichomes multicellular, uniseriate, unbranched, not constricted at the septa. Cross wall distinct, not granular, sheath absent. Trichomes solitary, slightly curved near the apices. Trichomes are 70–100 μm long. Medial cells of trichomes short, cylindrical, approximately rectangular. 2–3 μm long and 10–12 μm wide, with average dimension of $2.5 \times 10.7 \mu\text{m}$ (30 cells measured in the two trichomes). Structural features could not be observed near the apices due to amorphous organic matter. Reproductive structures unknown.

Discussion: The genus *Oscillatoriopsis* was erected by Schopf (1968) to include the sheathless trichomes of oscillatoriacean cyanobacteria similar to modern genus *Oscillatoria* Vaucher. Later, Mendelson and Schopf (1982) emended it to include all *Oscillatoria* or *Lyngbya*-like trichomes encompassed by a sheath less than 1 μm thick. Subsequently, Butterfield (in Butterfield *et al* 1994) emended this genus to include unbranched, uniseriate, cellular trichomes with cell length less or equal to cell diameter. Sergeev (2001), however,

did not agree to this proposal. In general morphology *Oscillatorioopsis* is similar to all the characters to *Oscillatorioopsis media* described by Mendelson and Schopf (1982) except that Salkhan specimens are larger and thicker in size. Only two trichomes of *Oscillatorioopsis media* have been reported one each in stromatolitic chert and cherty stromatolites. These are comparable to several extant Oscillatoriacean species. Lack of constriction at the septa and nature of apices are distinctive of *Oscillatorioopsis media*.

Distribution: Widely distributed in Proterozoic cherts and organic walled assemblages. Mesoproterozoic Sukhaya Tunguska Formation, Russia; Salkhan Limestone, Semri Group, India.

Material: Only two trichomes.

Type species: *Oscillatorioopsis longa* Timofeev and German 1979, emend. Butterfield (in Butterfield *et al* 1994)

Stratum typicum: Lakhandha Formation, Russia.

Oscillatorioopsis longa

(Figures 12g, 12i)

Unnamed microfossil Zhang Z 1981a, p. 793, figure 3a.

Doushantuonema peatii Zhang Z 1981b, p. 204, pl. 1a–c; Zhang Z 1982, p. 1255, pl. 1, figure 5.

Palaeolynghya sp., Zhang Z 1982, p. 1225, pl. 1, figure 12.

Hyalothecopsis nanshanensis Zhang P 1982, pp. 35–36, pl. 1, figure 2.

Hyalothecopsis sinica Zhang P 1982, pp. 35, 39, pl. 1, figure 1.

Oscillatorioopsis major Liu 1982, p. 139, pl. 29, figures 3, 4.

Halysirix leningradica Schenfil 1983, p. 473, pl. 1, figure 1.

Oscillatorioopsis variabilis Strother *et al* 1983, p. 26, pl. 3, figures 3–6, 11.

Oscillatorioopsis princeps Zhang and Yan 1984, pp. 198, 203, pl. 1, figure 6.

Oscillatorioopsis aculeata Zhang and Yan 1984, pp. 199, 203, pl. 1, figure 7.

Oscillatorioopsis maxima (Zhang Y) Zhang Z (1986), p. 83, pl. 2, figure 3.

Oscillatorioopsis connectens Zhang and Gu 1986, pp. 323–324, 329, pl. 1, figure 10.

Oscillatorioopsis strictura Zhang and Gu 1986, pp. 324, 329–330, pl. 1, figure 8.

Oscillatorioopsis valida Zhang and Gu 1986, pp. 324, 330, pl. 1, figure 9.

Oscillatorioopsis planaris Zhang and Gu 1986, pp. 324, 330, pl. 1, figure 12.

Partitofilum tungusum Jankauskas *et al* 1989, p. 118, pl. 27, figure 4.

Filiconstrictosus magnus, Yakschin 1991, pp. 32–33, pl. 11, figure 2.

Description: Trichomes multicellular, uniseriate, unbranched, not constricted at the septa. Cross wall distinct, not granular, sheath absent. Trichomes solitary, slightly curved near the apices. Trichomes are $\sim 80\ \mu\text{m}$ long. Medial cells of trichomes short, cylindrical, approximately rectangular. $2\text{--}3\ \mu\text{m}$ long and $13\text{--}14\ \mu\text{m}$ wide, with average dimension of $2.5 \times 10.7\ \mu\text{m}$ (30 cells measured in the two trichomes). Reproductive structures unknown.

Discussion: In a major restudy, Butterfield *et al* (1994) merged many species of *Oscillatorioopsis* to include only those filamentous microfossils that can be confidently identified as cellular trichomes, lack enveloping sheath and have a cell length: width ratio less than or equal to 1. More than 75 species of *Oscillatorioopsis* have been considered and 54 have been put as synonymy or merged with one or the other species. It has been noted that all the species are known from unique or few specimens and derived from few localized assemblages. They recognized four basic species of *Oscillatorioopsis* with diameter less than $25\ \mu\text{m}$: *O. vermiformis*, $1\text{--}3\ \mu\text{m}$ wide; *O. obtusa*, $3\text{--}8\ \mu\text{m}$ wide; *O. amadeus* $8\text{--}14\ \mu\text{m}$ wide and *O. longa* $14\text{--}25\ \mu\text{m}$.

Distribution: Mesoproterozoic: Salkhan Limestone, Semri Group, India; Neoproterozoic: Lakhandha Formation, Russia; Doushantuo Formation, China.

Material: Two specimens in Salkhan Limestone.

Genus: *Eomicrocoleus* Horodyski and Donaldson 1980

Type species: *Eomicrocoleus crassus* Horodyski and Donaldson 1980

Stratum typicum: Dismal Lakes Group, Arctic Canada.

Eomicrocoleus crassus Horodyski and Donaldson 1980

(Figure 10d)

Eomicrocoleus crassus Horodyski and Donaldson 1980, p. 154, figure 15A, 15B; Sergeev 2001, p. 442, figure 9.5.

Description: Multilamellated trichomes are common component of Salkhan population. These are $3\ \mu\text{m}$ broad and $40\text{--}60\ \mu\text{m}$ long sheaths. Bundles are constituted of $20\text{--}30$ such sheaths. Dark brown in colour. Set in the organic matrix. These bundles are generally underlain by the coccoid cyanobacteria.

Discussion: Occurrence of such bundles of sheath in bedded chert and stromatolitic chert of Salkhan assemblage in the areas where degraded organic matter is present in plenty suggests that these are remnants of cyanobacterial sheath. Since no cellular remains are observed in bundles, affinity of these sheaths could not be established. Seong-Joo and Golubic (1998) have interpreted

these remains as polytrichomatous cyanobacterial filaments, comparable to species of the modern genera *Microcoleus*, *Hydrocoleum* and *Schizothrix*. Specimens without common envelope are assigned to *Polythrighoides* German but some specimens with sheaths have been referred to this genus (Jankauskas 1982, pl. 48, figure 16). Hofmann and Jackson (1991) opined that *Eomicrocoleus* may thus be a junior synonym of *Polythrighoides*.

Distribution: Widely distributed in Proterozoic chert assemblages.

Material: A dozen preserved filaments have been noted in Salkhan Limestone.

Order: Nostocales? or Oscillatoriales

Genus: *Siphonophycus*, Schopf 1968 emend. Knoll and Golubic 1979, emend. Knoll *et al* 1991

Type species: *Siphonophycus robustum* (Schopf 1968) comb. nov. Knoll *et al* 1991, emend. Butterfield (in Butterfield *et al* 1994)

Stratum typicum: Bitter Springs Formation, Australia.

Siphonophycus robustum Knoll *et al* 1991.

(Figure 10c; figures 12a, 12d, 12f)

Eomycetopsis robusta Schopf 1968, p. 685, pl. 82, figures 2, 3, pl. 83, figures 1–4; Knoll and Golubic 1979, p. 149, figure 4A, B; Mendelson and Schopf 1982, 59, 60, 62, pl. 1, figures 9, 10; in Zhang Z 1982, p. 1254, pl. 1, figures 8, 11; Zhang Z 1984, p. 138, pl. 2, figure 10; Sergeev 1984, p. 436, figure 2a–2r; Cao 1985, p. 186, pl. 1, figure 4a, b; Golovenok and Belova 1993, pl. 2, figure e.

Eomycetopsis filiformis Schopf 1968, p. 685, 686, pl. 82, figure 1, 4, pl. 83, figures 5–8.

Eomycetopsis ex gr. *obtusa* Yakschin 1991, p. 36, pl. XII, figure 4.

Eomycetopsis spp. (partim) Mendelson and Schopf 1982, p. 62, pl. 4, figure 2.

Rhiconema antiquum Hofmann, in Zhang Z 1982, p. 1255, pl. 1, figure 1; in Zhang Z 1984, p. 138, pl. 1, figure 1.

Cyanonema attenuata (partim) Yakschin 1991, p. 36, pl. XII, figure 1.

Empty algal tubes Schenfil 1983, p. 471, figure 1.4, 1.5.

Siphonophycus robustum Knoll *et al* 1991, p. 565, figure 10.3, 10.5; Sergeev 1994, p. 250–251, figure 8F; Kumar and Srivastava 1995, p. 114, figure 14C; Sergeev *et al* 1997, p. 230, figure 14A; Zhang *et al* 1998, p. 22, figure 4.11; Srivastava and Kumar 2003, p. 26, pl. 7.2, pl. 10.10.

Description: Filaments tubular, curved, unbranched non-septate, more than 100 µm long (incomplete). Surface is smooth to finely granular due to diagenetic effect, occur solitary or interwoven, forming mat. Width 3–4.5 µm (average 3.7 µm, 50 specimens measured). Dense masses of

filaments align parallel or perpendicular to bedding lamination.

Discussion: *Siphonophycus* is the predominantly mat forming microbe in many Proterozoic benthic assemblages, sometimes occurs solitarily. This species is common in stromatolitic cherts and cherty stromatolites of Salkhan Limestone. The sheaths may occur vertically or parallel to the lamination. Tubes of *Siphonophycus robustum* are considered as empty cyanobacterial (oscillatoriacean or nostocacean) sheaths (Knoll and Golubic 1979; Mendelson and Schopf 1982; Knoll *et al* 1991). Knoll *et al* (1991) discussed the genus *Siphonophycus* described from Bitter Springs Formation, Australia and after the study of three form genera viz. *Siphonophycus kestron*, *Eomycetopsis robusta* and *Tenuofilum septatum* placed them in synonymy as *S. kestron*, *S. robustum*, *S. septatum*. Earlier Pjatiletov (1988) synonymized *Leiothrighoides* German (1974) with *Eomycetopsis* that was later put under the *Siphonophycus* by Knoll *et al* (1991). They further argued that the larger populations of the *Siphonophycus* are presumably cyanobacterial, but *S. septatum* and *S. robustum* could be flexi-bacterial in origin (Aizenshtat *et al* 1984). Many cyanobacterial species could have similar morphology and some may assume this morphology taphonomically. Zhang *et al* (1998) therefore proposed that the taxonomy of the microbial sheath is a form taxonomy.

Distribution: Widely distributed in Proterozoic cherts, and Phanerozoic deposits and organic walled assemblages.

Material: A few hundred specimens.

Type species: *Siphonophycus septatum* Knoll *et al* 1991

Stratum typicum: Bitter Springs Formation, Australia.

Siphonophycus septatum Knoll *et al* 1991

(Figures 12b, 12h)

Tenuofilum septatum Schopf 1968, p. 679, pl. 86, figures 10–12; not *Tenuofilum septatum* Schopf, Schopf and Blacic, 1971, pl. 108, figures 11, 13.

Archaeotrichion contortum Schopf 1968, p. 686, Pl. 86, figures 1–2; Wang *et al* 1983, p. 170, figures 8, 4–8.

Eomycetopsis campylomitus Lo 1980, pp. 143–144, pl. 1, figures 9–11.

Allachjunica tenuiuscula Kolosov 1982, p. 80, pl. 14, figure 1.

Judomophyton microscopiocum Kolosov 1982, p. 75, pl. 11, figure 1.

Siphonophycus chuii Liu 1982, p. 148, pl. 11, figure 5, 8, 11.

Eophormidium capitatum Xu 1984, pp. 219, 314, p. 1, figure 5.

Archaeotrichion lacerum Jankauskas *et al* 1989, p. 88, pl. 39, figures 4a–b.

Siphonophycus septatum Knoll *et al* 1991, p. 565, figure 10.2; Kumar and Srivastava 1995, p. 114–115, figure 14D.

Description: Fine thread like filament, sinuously wounded, non-septate, unbranched and more or less uniform in diameter, commonly $1/2\ \mu\text{m} \sim 1\ \mu\text{m}$ broad and $80\ \mu\text{m}$ or large in length. They are composed of dark brown organic matter. Occur solitary or in groups, sometimes broken into segments tens of microns long.

Discussion: Sharma (1993) described *Archaeotrichion contortum* from Salkhan Limestone. Filaments compare well with the Australian specimens ($1/2$ – $2/3\ \mu\text{m}$, mean $<1\ \mu\text{m}$). Morphological features are similar to the *Archaeotrichion*, *Eomycetopsis* and *Siphonophycus*. As discussed above, Knoll *et al* (1991) merged *Eomycetopsis* into *Siphonophycus*. Subsequently, Butterfield (in Butterfield *et al* 1994) put the *Archaeotrichion contortum* as junior synonymy of *Siphonophycus septatum*. Therefore the *Archaeotrichion contortum* described by Sharma (1993) has been placed as *Siphonophycus kestron*. The smaller size diameter and non-septate nature suggest their bacterial affinity.

Distribution: Widely distributed in Proterozoic and Phanerozoic deposits.

Material: Several specimens.

Order: Insertae sedis

Family: Insertae sedis

Genus: *Huroniospora* Barghoorn 1965 in Barghoorn and Tyler 1965, p. 563–577, pl. 2, figure 5.

Type species: *Huroniospora psilata*, Barghoorn 1965, in Barghoorn and Tyler 1965

Stratum typicum: Gunflint Iron Formation, Canada.

Huroniospora psilata Barghoorn 1965, in Barghoorn and Tyler 1965

(Figures 10a, 10b).

Huroniospora psilata Barghoorn 1965, in Barghoorn and Tyler 1965, Kumar and Srivastava 1992c, p. 304, figure 8I.

Description: Cells sphaeroidal to ellipsoidal, occur solitary and loosely in the assemblage. No envelope or mucilage covering noticed. Walls granular to psilate. Some of the specimens show smooth margin. The size range of cells 3 – $7\ \mu\text{m}$ with an average of 3 – $4\ \mu\text{m}$.

Discussion: These cells are found in bedded chert and stromatolitic chert of the Salkhan population and often confined to areas where no other biota occur. They are often set in a matrix of amorphous organic matter, which may represent uncrushed

remains of mucilage. Intracellular dense mass is absent. The Salkhan population confirms in all the salient features with the specimens described by Barghoorn and Tyler (1965). Cells generally occur in the area where no other member of the Salkhan population is found.

Distribution: Most of the Proterozoic cherts of the world.

Material: A few dozen specimens.

Genus: *Conhemisphaera* Luo and Wang in Luo *et al* 1983

Type species: *Conhemisphaera pendulua* Luo and Wang in Luo *et al* 1983

Stratum typicum: Not mentioned (Chinese publication) in english version.

Conhemisphaera pendulua Luo and Wang in Luo *et al* 1983

(Figures 10e, 10f)

Conhemisphaera pendulua; Luo *et al* 1983, p. 38, Pl. II, figures 7, 8.

Description: Spherical colonies composed of more than ten hemispherical cells arranged loosely on the periphery of thick colonial envelope. Individual cells are without sheath. The diameter of the colony ranges from 20 – $25\ \mu\text{m}$ (average $23\ \mu\text{m}$, 25 colonies measured). Peripheral cells are ellipsoidal, sometimes overlapping each other; 2 – $3\ \mu\text{m}$ long and $1.4\ \mu\text{m}$ broad. Central portion of the colony is hollow.

Discussion: It is an enigmatic form recorded in the stromatolitic chert of Salkhan population. The typical arrangement of cells and their association with cyanobacterial elements indicate their cyanobacterial affinity. It could as well be a preservational feature. A colonial form may assume such shape if it is present in a plane parallel to the grinding surface. The other possibility is that a *Volvox* like algal ball (not the *Volvox*) cut in any plane may assume such morphology. It is difficult to assess the nature of this microorganism at present.

Distribution: Mesoproterozoic: Found in the Salkhan Limestone; Neoproterozoic: (Uppermost Sinian-lowermost Cambrian age microfossils) from Qingshen-Zhijin County, Guizhou Province, China.

Material: About two dozens specimens recorded.

Genus: *Clonophycus* Oehler 1977 emended D Z Oehler 1978

Type species: *Clonophycus elegans* Oehler 1977

Stratum typicum: H. Y. C. Pyritic Shale Member of Barney Creek Formation (McArthur Group), Australia.

Clonophycus elegans Oehler 1977

(Figure 11e)

Clonophycus elegans: Oehler 1977, p. 346, figure 11A–D, J, K. emended Oehler 1978

Description: Cells spheroidal to ellipsoidal, sometimes adpressed by mutual compression of cells, cells thin walled, smooth to granular, generally single walled, may be double layered. Cells are densely packed within a thin walled sac of 25–30 μm diameters. Number of cells varies in each sac but generally in multiples of two. Internal cells are released through the opening on the margin, it may be rounded to slit/cleavage like, sometimes a small dot of black coloured matter is noticed on the cells which may be less than 1 μm in size.

Discussion: *Clonophycus elegans* is a distinct micro-organism and is confined to only stromatolitic cherts. *C. elegans* and other four species *C. biattina*, *C. ostiolum*, *C. refringens* and *C. vulgaris* are known from Balbirini Dolomites (McArthur Group) of Australia. A single species *C. elegans* has been recorded from the H. Y. C. Pyritic Shale. The pattern of rupture and association of cells in an enclosed sheath indicate that this fossil could be a sporangium. It is not determined whether the specimens belong to prokaryote or eukaryote. In both the algae breaking pattern of sporangia is similar (Fritsch 1935, 1945; Starr 1955). Possibly *Clonophycus* is Gloecapsoid colonies of *Eoentophysalis* or *Gloecapsa*.

Distribution: Mesoproterozoic cherts of Australia and India.

Material: About ten specimens.

Type species: *Clonophycus ostiolum* D Z Oehler 1978

Stratum typicum: Balbirini Dolomite, Australia.

Clonophycus ostiolum Oehler 1978

(Figure 10g; Figure 11f)

Clonophycus ostiolum Oehler 1978, p. 303, figures 4R–4T.

Description: Cells spheroidal, thin walled and pressed due to mutual compression enclosed in a sac-like body (or sporangia) spheroids range in size from 6–15 μm in diameter (average 10 μm ; 25 cells measured), smooth walled, characterized by a large opening on one side, rounded opening or ruptured wall 5–7 μm through which spores or cells are released. Individual cells are 2–3 μm (average 2.75 μm , 10 cells measured) finely to coarsely granular. No sheath and black inclusion observed.

Discussion: Tightly clustered cells encapsulated in a sac like body give an impression of sporangia. The pattern of rupture and release of cells suggest that the cells may belong to prokaryote/eukaryote since the manner of dispersal of cells is same in both. The specimen *C. ostiolum* was reported from Balbirini Dolomite and interpreted to be sporangia like body considering that sporangia commonly break open in this manner (Fritsch 1935, 1945; Starr 1955).

Distribution: Mesoproterozoic cherts of Australia and India.

Material: About ten specimens.

Unnamed Form A

(Figure 11d)

Description: Solitary double walled spheroidal specimen with knuckle shaped protuberance, which has continuous outer wall with parent body. Several fine villi like protruding structures are noticed on the inner wall. Outer wall granular, inner wall robust. The outer diameter of sphaeroidal structure is 40 μm whereas the inner diameter is 30 μm .

Discussion: It is a rare specimen in the Salkhan assemblage found in bedded chert. A spheroid of such a dimension with knuckle shaped protuberance has not been recorded anywhere. Since it occurs in the cyanobacteria dominant assemblage it may be accorded a cyanobacterial affinity but not kept in any group and presently placed in *Incertae sedis*. It is probable that these may represent isolated instances of smooth walled akinetes bereft of vegetative cells. "Probably it is a homocystous anabenoid alga".

Unnamed Form B

(Figure 12e)

Description: Multilamellated sphaeroidal sheaths. Solitary, occurring freely. Diameter of sphaeroidal structure 200 μm . Each enveloping sheath is 2–3 μm thick, light brown in colour, robust. Outermost sheath is made-up of diffused organic matter. Subsequent inner sheaths are psilate to granular.

Discussion: This specimen is found in the bedded cherts of Salkhan Limestone. Due to its association with microbial assemblage of cyanobacterial affinity these are considered produce of cyanobacteria. Since there are no cells inside to distinguish or characterise, it is difficult to understand to which specific species this sheath genera belongs. Its large size indicates that some larger colonial forms were in existence in the Salkhan population. It is also possible that it may be a degradation feature of amorphous organic matter/precipitate pattern.

Unnamed Form C

(Figure 11c)

Description: Multilamellated bilobate sheath. Solitary specimen occurring freely. It is an extraordinary large size specimen – 800 μm long and 200 μm broad. Curvature in the middle part leads to form bilobate structure. 5–7 layers of successive covering forms this specimen. Outer wall diffuse while the inner walls are psilate to granular and light brown in colour.

Discussion: Solitary specimen is found in Salkhan bedded chert. Its association with microbial

assemblage of cyanobacterial affinity is considered akin to cyanobacteria. It is also possible that the specimen may be only a degradation feature of amorphous organic matter, since sheath genera of cyanobacteria of such dimension are not known; it is placed under unnamed category.

Unnamed Form D

(Figure 11g)

Description: Ellipsoidal to polygonal organic mass. Dark black in colour. $15\mu\text{m}$ long to $20\mu\text{m}$ wide, outer texture granular. No internal structure observed.

Discussion: This is a rare component of bedded and stromatolitic chert. Probably formed by the degraded mucilaginous sheaths of encompassing coccoidal cells. No definite mode of origin can be assigned to these structures.

Unnamed Form E

(Figure 11b)

Description: Uniseriate, unbranched, slightly constricted at the septa, gradually tapering, length of the filament $15\mu\text{m}$, individual cell demarcation at $2\mu\text{m}$ interval. No cells are observed, their impression only noticed on the sheaths.

Discussion: This form occurs in bedded chert and stromatolitic chert. Rare occurrence of this form does not allow any meaningful interpretation except that it is a microbial component of Salkhan population.

Unnamed Form F

(Figure 11a)

Description: Extraordinary large bilobate structure composed of fine radial fabric in the centre. Outer wall/sheath is robust, granular $3\mu\text{m}$ thick, dark brown in colour, central portion hyaline. Set in amorphous organic matrix, $1500\text{--}2000\mu\text{m}$ long and $850\mu\text{m}$ broad.

Discussion: These are found in the bedded and stromatolitic chert. Such large structured sheath may be degraded organic mass of sheaths left by the extra large *Chroococcacean* colony. No other meaningful information obtained by the study of these sheaths.

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