



## A NEW ASSEMBLAGE OF LARGE-SIZED MICROFOSSILS FROM THE SALKHAN LIMESTONE (>1600 MA), SEMRI GROUP, VINDHYAN SUPERGROUP, INDIA

BANDANA SHUKLA and MUKUND SHARMA\*

BIRBAL SAHNI INSTITUTE OF PALAEOSCIENCES, 53 UNIVERSITY ROAD, LUCKNOW 226007, INDIA

\*CORRESPONDING AUTHOR E-MAIL: mukund\_sharma@bsip.res.in

TEL: +91-522-2742922; FAX: +91-522-2740485

### ABSTRACT

The Salkhan microbiota of the Vindhyan Supergroup is stratigraphically very important to understand the evolution of life forms during the Late Palaeoproterozoic to Early Mesoproterozoic time period. Well-preserved, large-sized coccoidal microfossils are being reported in the present study from the Salkhan Limestone (>1600 Ma) of the Semri Group of the Vindhyan Supergroup, India. These coccoidal microfossils have been recovered from the sporadically found black cherts in the Salkhan Limestone. More than 200 specimens are studied. The assemblage comprises three genera and five species. Four species are being recorded for the first time from the Salkhan Limestone, namely, *Gloeodiniopsis lamellosa*, *G. mikros*, *Phanerospherops capitaneus*, and *P. magnicellularis*. The large-sized coccoids, *Kheinjuasphaera vulgaris*, *Phanerospherops capitaneus* and *P. magnicellularis*, are grouped under *incertae sedis* and their taxonomic positions are reconsidered. *Gloeodiniopsis lamellosa* and *Gloeodiniopsis mikros* are grouped under cyanobacteria. The biggest ever size of *Gloeodiniopsis mikros* has been recorded from the Salkhan Limestone. Morphology and size criteria have been discussed to consider the nature of these large-sized cells and their affinity. The coccoidal microfossils have been assigned to large-sized prokaryotes that got preserved during the Late Palaeoproterozoic to Early Mesoproterozoic sediments of the Salkhan Limestone. Palaeobiological implications of the assemblage are also provided.

**Keywords:** Large size coccoids, Salkhan Limestone, Semri Group, Palaeoproterozoic-Mesoproterozoic, Vindhyan Supergroup, India

### INTRODUCTION

Both prokaryotic and eukaryotic microfossils show demonstrable changes in the morphology around Late Palaeoproterozoic-Early Mesoproterozoic time interval (Javaux *et al.*, 2001, 2003, 2004; Sharma and Shukla, 2009a). Sedimentary successions of this interval are important target of investigations for such microfossil evidence. The Salkhan Limestone of the Vindhyan Supergroup of India is a well established unit for its microfossil content (Kumar, 1978a; McMenamin *et al.*, 1983; Venkatachala *et al.*, 1990; Kumar and Srivastava, 1992a, b, 1995; Srivastava, 2005; Prasad *et al.*, 2005; Sharma and Sergeev, 2004; Sharma, 2006a, b; Sergeev *et al.*, 2008; Srivastava and Tewari, 2011). Well-preserved microfossils were recorded from the black bedded cherts and were attributed to cyanobacteria, akinetes and eukaryotes. The wide variation in size of prokaryotic forms are prominently recorded in these cherts including the solitary coccoid microfossil *Kheinjuasphaera vulgaris* (size ~ 35 µm) (McMenamin *et al.*, 1983) as well as millimetric prokaryote *Grypania spiralis* (Sharma and Shukla, 2009a, b). The Semri Group (> 1600 Ma old) of the Vindhyan Supergroup in central India has revealed the presence of some advanced palaeobiological entities which are inconsistent with comparative biological perspective on Protista evolution. This is evident with the records of some rudimentary small shelly fossils (SSF- multicellular in nature) from the uppermost unit of the Semri Group which have been viewed as a challenge (Azmi, 1998; Bengtson *et al.*, 2009). Similarly, the eukaryotic forms were also recorded from the Semri Group that show distinct wall structures, wall ornamentations, processes extending from the vesicle walls, prominent ex-cystment structure and wall chemistry (Kumar and Srivastava, 1997; Prasad *et al.*, 2005; Sharma, 2006a, Sharma *et al.*, 2009; Singh and Sharma, 2014). These microfossils, including those assigned to group acritarcha, were recorded from different facies and geological formations

of the Semri Group and were recovered from the macerated residues as well as in the petrographic thin sections of black cherts. Results of some of these studies are contradictory and therefore require further investigations to explore the occurrence of prokaryotic algae and/or cyanobacterial forms during the Late Palaeoproterozoic to Early Mesoproterozoic time period, the most important time period for understanding the evolution of life forms and associated oxygen level in the early atmosphere. We document the results of a study on the relatively large-sized coccoidal microfossils recorded from the petrographic thin sections of the black cherts from the Salkhan Limestone of the Vindhyan Supergroup. Further, we discuss the affinities of these large-sized coccoidal microfossils and ascertain their position as prokaryotic forms.

### GENERAL GEOLOGY AND AGE

The Vindhyan Basin, located in central India, is a ca. 4500-5000 m thick sedimentary succession belonging to the Proterozoic age. It is exposed over a large area extending from Sasaram, Bihar in the east to Chittorgarh, Rajasthan in the west and Dholpur, Rajasthan in the north to Hoshangabad (M.P.) in the south west (Fig. 1a). In most of the regions, it is an undeformed and unmetamorphosed sequence (Auden, 1933). Sickle-shaped basin outcrops between the Archaean Aravalli-Bundelkhand province to the north and east and the Cretaceous Deccan Traps to the south and bounded by the Great Boundary Fault to the west (Mazumdar *et al.*, 2000). It occupies an area of 1,20,000 sq km in central India besides considerable area (80,000 sq km) covered by the Deccan traps and about 10,000 sq km lies hidden under the Gangetic alluvium in the north (Mathur, 1987). The thick succession is represented by the sequence of sandstone, shale, limestone, dolomite with minor conglomerate and volcanoclastic rocks. Lithostratigraphically the Vindhyan Supergroup

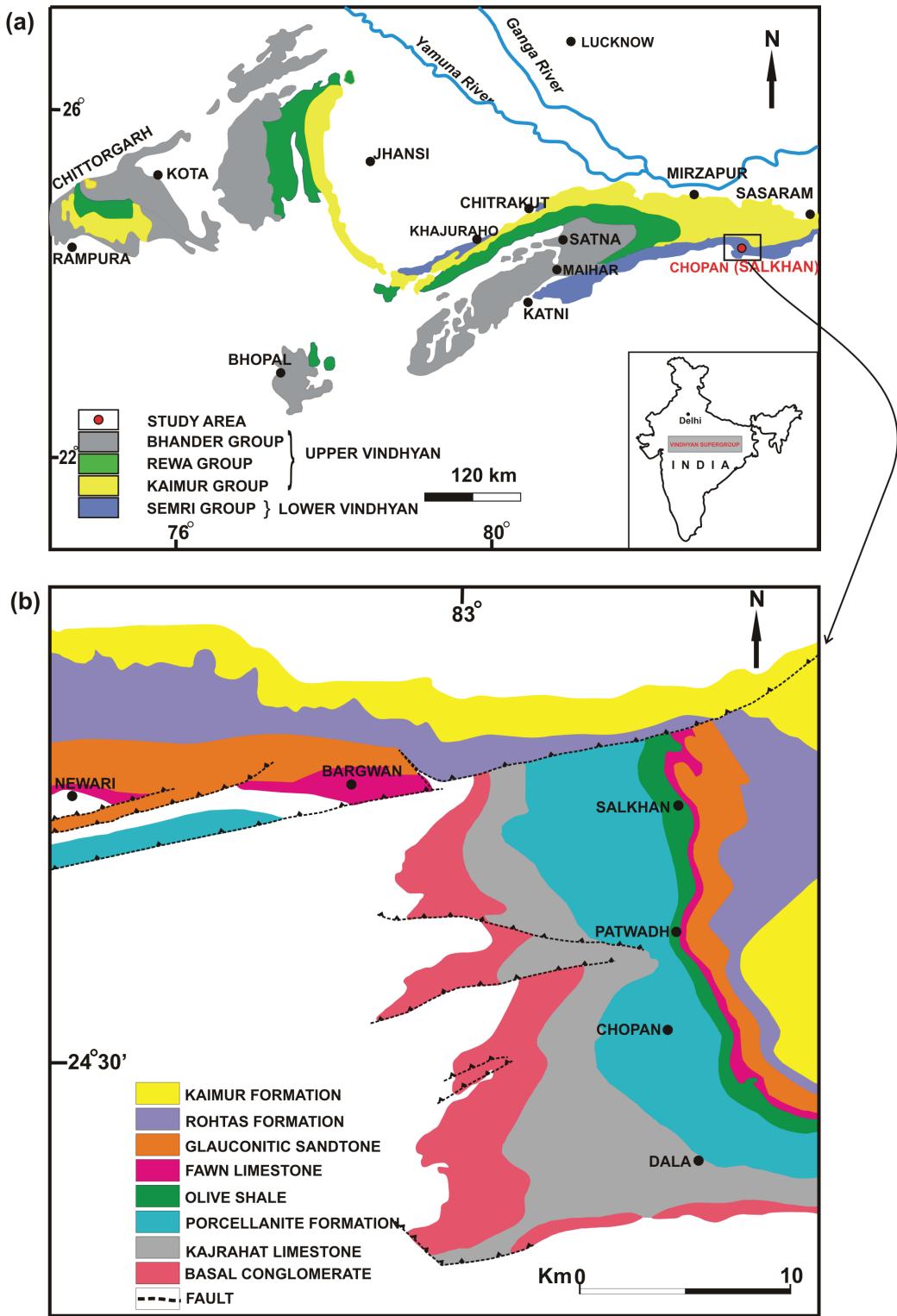
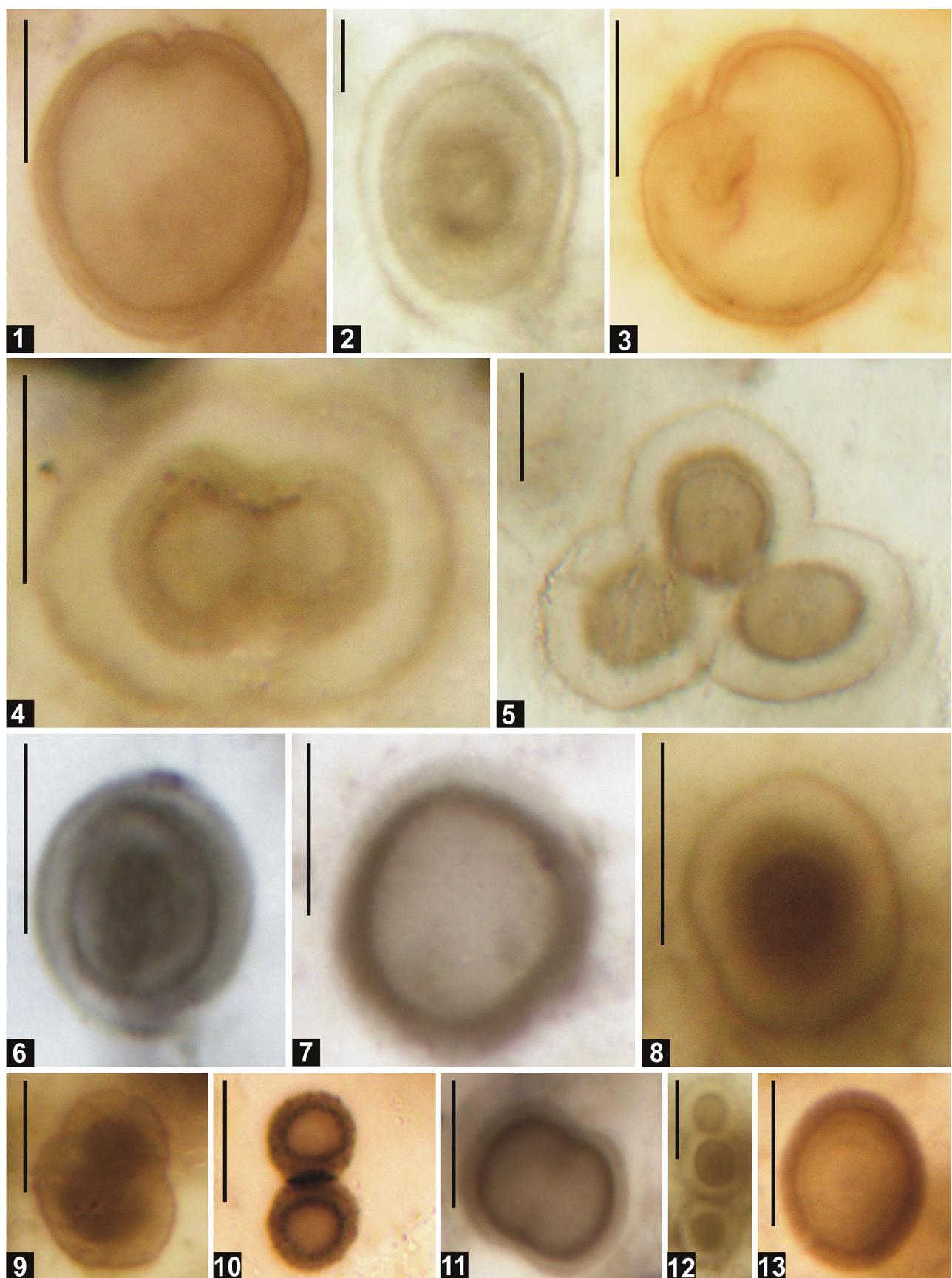


Fig. 1. Generalized geological map of Vindhyan Basin, Inset map of India showing position of the Vindhyan Supergroup (after Krishnan and Swaminath, 1959) (a), and geological map showing lithostratigraphic units of the Son Valley Section with the details of sample locations denoted with black dots (after Auden, 1933) (b).

#### EXPLANATION OF PLATE I

Photomicrographs of thick and double cell-walled cocoids forms in thin petrographic sections of black chert. 1 to 5. *Gloeodiniopsis lamellosa* Schopf, 1968 and 6 to 13. *Gloeodiniopsis mikros* Knoll, 1982. Scale bar = 10 µm. 1- BSIP- 14999 (Q/48-4); 2- BSIP- 14996 (Q/27-4); 3- BSIP- 14993 (O/49-4); 4- BSIP- 14994 (G/46-3); 5- BSIP- 14994 (J/41-3); 6- BSIP- 14993 (K/59-2); 7- BSIP- 14993 (J/56-1); 8- BSIP- 14994 (L/30-4); 9- BSIP- 14994 (L/31-3); 10- BSIP- 15100 (K/33-4); 11- BSIP- 14993 (B/34-4); 12- BSIP- 14994 (I/29-1); 13- BSIP- 14995 (T/34-4).

Plate I



has been divided into four subgroups, i.e. the Semri Group, the Kaimur Group, the Rewa Group, and the Bhander Group. The Semri Group is considered as the Lower Vindhyan, whereas Kaimur, Rewa and Bhander constitute the Upper Vindhyan. On the basis of the lithological dissimilarity noted in the successions exposed east and west, the Vindhyan Basin is further divided into two parts: the eastern part is known as the Son Valley Section and the western part is designated as the Chambal Valley Section. The Semri Group is best exposed in the Son Valley area, Sonbhadra district, Uttar Pradesh (Fig. 1b), Rohtas district, Bihar and Satna district, Madhya Pradesh. The lithostratigraphic succession of the Semri Group, as recoded in the Son Valley, is given in Table 1. In the stratigraphic order, these are Mirzapur Subgroup, Kheinjua Subgroup and Rohtas Subgroup. The

**Table 1.** Lithostratigraphic subdivisions of the Semri Group (after Sastry and Moitra, 1984).

Son Valley (After Sastry and Moitra, 1984)	
Subgroup	Formation
Rohtas Subgroup	Bhagwar Shale
	Rohtasgarh Limestone
Kheinjua Subgroup	Rampur Formation
	Salkhan Limestone
	Koldaha Shale
Mirzapur Subgroup	Deonar Formation
(Basal Subgroup)	Kajrahat Limestone
	Arangi Formation
Deoland Formation	
-----Unconformity-----	
Bijawar Phyllites/Bundelkhand Granite	

Kheinjua Subgroup is further divided into three Formations: the Koldaha Shale (Olive Shale), the Salkhan Limestone and the Rampur Formation. In the study area, the Salkhan Limestone is a 90 m thick, fawn and dark grayish coloured lithounit comprising dolomitic and siliceous limestone with intermittent chert bands. The microfossil-bearing chert was collected from different localities of the Salkhan Limestone exposed in the Sonbhadra district and Sasaram district. Chertification, confined to certain regions, has conspicuously not affected the entire unit of the Salkhan Limestone. It is considered to have been deposited under the supratidal to intertidal environment and also shows extensive development of columnar and stratified stromatolites (Kumar, 1978b). Of these, some stromatolites are chertified. Pockets of early diagenetic chert commonly found in carbonate sequences are store house of microfossils (Knoll, 1985). It is a good indicator of depositional environment. In the Salkhan Limestone, three types of cherts are found, i.e. bedded chert, stromatolitic chert, chertified stromatolite; all these cherts are invariably well to poorly fossiliferous. Bedded chert is black in colour and shows waxy lustre. It is rich in both coccoids and filamentous forms. Stromatolitic chert shows the alternation of white and grayish black colour and probably experienced

early to late diagenetic changes. Poorly preserved filamentous forms are mainly found in this kind of chert. Presence of well-preserved microfossils in these stromatolites suggested that replacement was early diagenetic. Fossiliferous chert under microscope shows yellowish brown colour due to the extensive presence of organic matter.

In the Son Valley, the Vindhyan Supergroup overlies the slightly metamorphosed Bijawar Group of rocks. Crawford and Compston (1970) dated the Bijawar lava by Rb-Sr method and provided the age  $2780 \pm 365$  Ma. A dolerite dyke piercing into Pre-Vindhyan rocks at Chopan was also dated by (Crawford and Compston, 1970) which yielded an age of  $2370 \pm 590$  Ma. The Deonar Formation, chiefly constituted of Porcellanites, underlies the Salkhan Limestone and Koldaha Shale which has yielded Late Palaeoproterozoic ages ( $1628 \pm 8$  Ma - Rasmussen *et al.*, 2002, SHRIMP, zircon U-Pb method;  $1631 \pm 1$  Ma and  $1631 \pm 5$  Ma - Ray *et al.*, 2002, U-Pb, zircon and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope). The Rampur Formation immediately overlying the Salkhan Limestone has been dated as  $1599 \pm 8$  Ma and  $1602 \pm 10$  Ma (Rasmussen *et al.*, 2002, SHRIMP - U-Pb). The Rohtasgarh Limestone, another unit of the Semri Group, overlying the Rampur Formation has been dated at different places in Madhya Pradesh, Rajasthan and Uttar Pradesh by Pb-Pb isochron method. These ages range between  $1599 \pm 48$  Ma (Sarangi *et al.*, 2004);  $1601 \pm 130$  Ma (Ray *et al.*, 2003);  $1650 \pm 89$  Ma (Bengtson *et al.*, 2009). A number of the age determinations have been made on the Rohtasgarh Limestone and Chorhat Sandstone which overlie the Salkhan Limestone where the age comes between >1600 to 1400 Ma (Ray *et al.*, 2003; Sarangi *et al.*, 2004; Bengtson *et al.*, 2009; McKenzie *et al.*, 2011). These dates were obtained by Pb-Pb, isochron and LA ICPMS methods. Thus, the calibrations of the ages of different units of the Semri Group suggest that the Salkhan Limestone may be Late Palaeoproterozoic to Early Mesoproterozoic in age. The age data of both the overlying formations designate that the Salkhan Limestone is older than >1600 Ma (Palaeoproterozoic). A summary of the geochronological dates is provided for the Semri Group (Fig. 2). We attribute the Late Palaeoproterozoic to Early Mesoproterozoic age for the Salkhan Limestone on the basis of new geochronological data presented in the last decade.

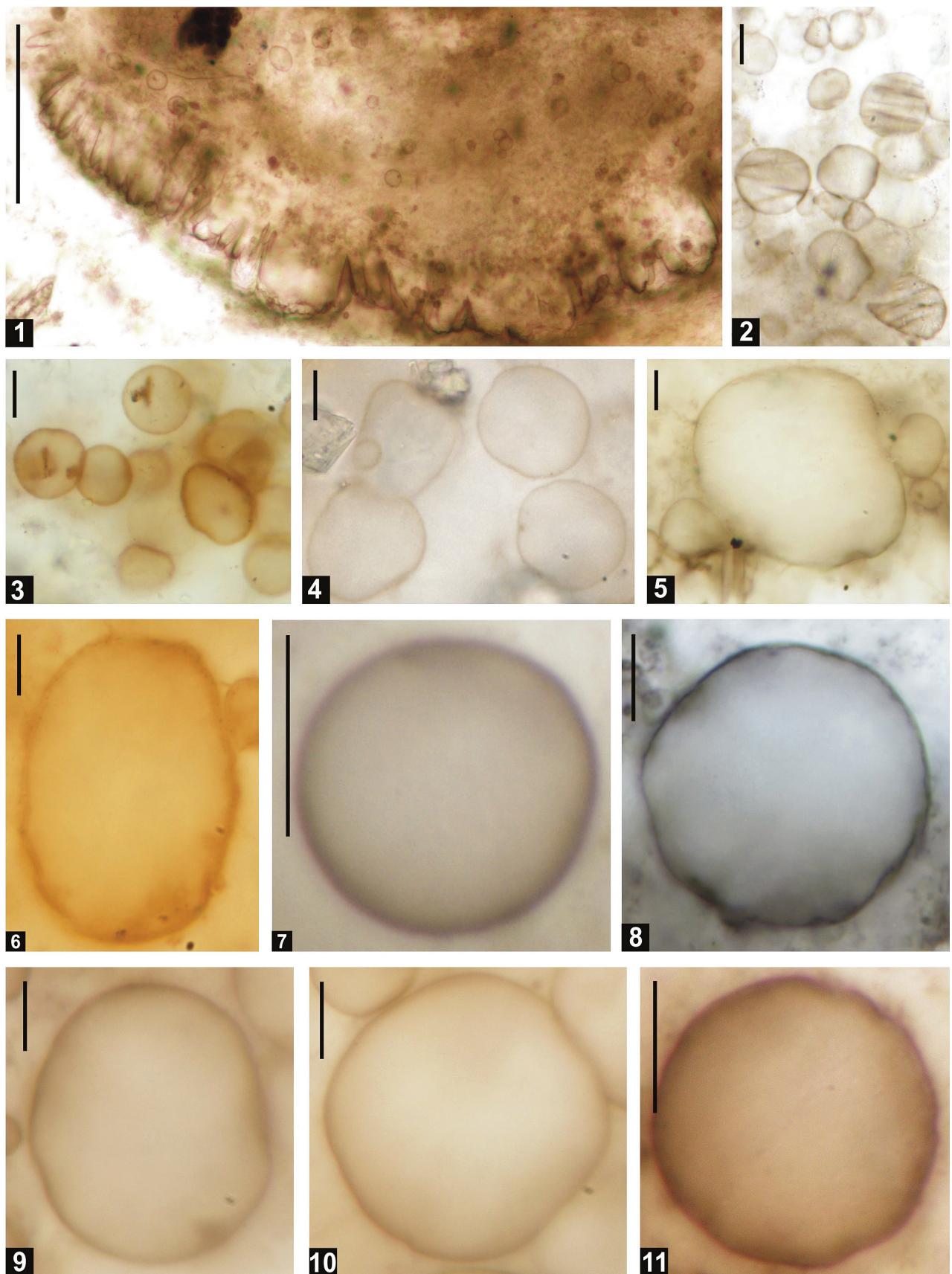
## MATERIAL AND METHODS

The present study is based on the samples previously collected by one of us (MS) in 1988 and also on new chert samples (black bedded chert and stromatolitic chert - Fig. 3a and 3b, respectively) collected by both the authors (BS and MS) during the field work conducted in March, 2013 from the Salkhan Limestone of the Semri Group exposed in the Uttar Pradesh (Sonbhadra district) and Bihar (Sasaram district) states of India. Outcrops at six different localities, i.e. Nauhatta, Newari, Bargawan, Jatashankar Pahari, Barwadih and Salkhan Fossil Park were sampled for the chert collection (Fig. 1b). All the microfossils reported in this paper were examined using petrographic thin sections and photographed under transmitted

## EXPLANATION OF PLATE II

Photomicrographs of coccoids forms in petrographic thin sections of black chert. 1 to 11. *Kheinjuasphearea vulgaris* McMenamin *et al.*, 1983. Scale bar 1=100  $\mu\text{m}$  and 2 to 11 = 10  $\mu\text{m}$ . 1- BSIP- 14994 (H/29-4); 2 - BSIP- 14995 (X/55-1); 3- BSIP- 15104 (Q/46-1); 4 - BSIP- 15103 (K/39-3); 5- BSIP- 14994 (M/29-3); 6 - BSIP- 15106 (D/46-1); 7- BSIP- 14997 (H/45-2); 8- BSIP- 14997 (H/41-2); 9- BSIP- 14999 (F/49-4); 10- BSIP- 14999 (F/49-4); 11- BSIP- 14996 (P/42-4).

Plate II



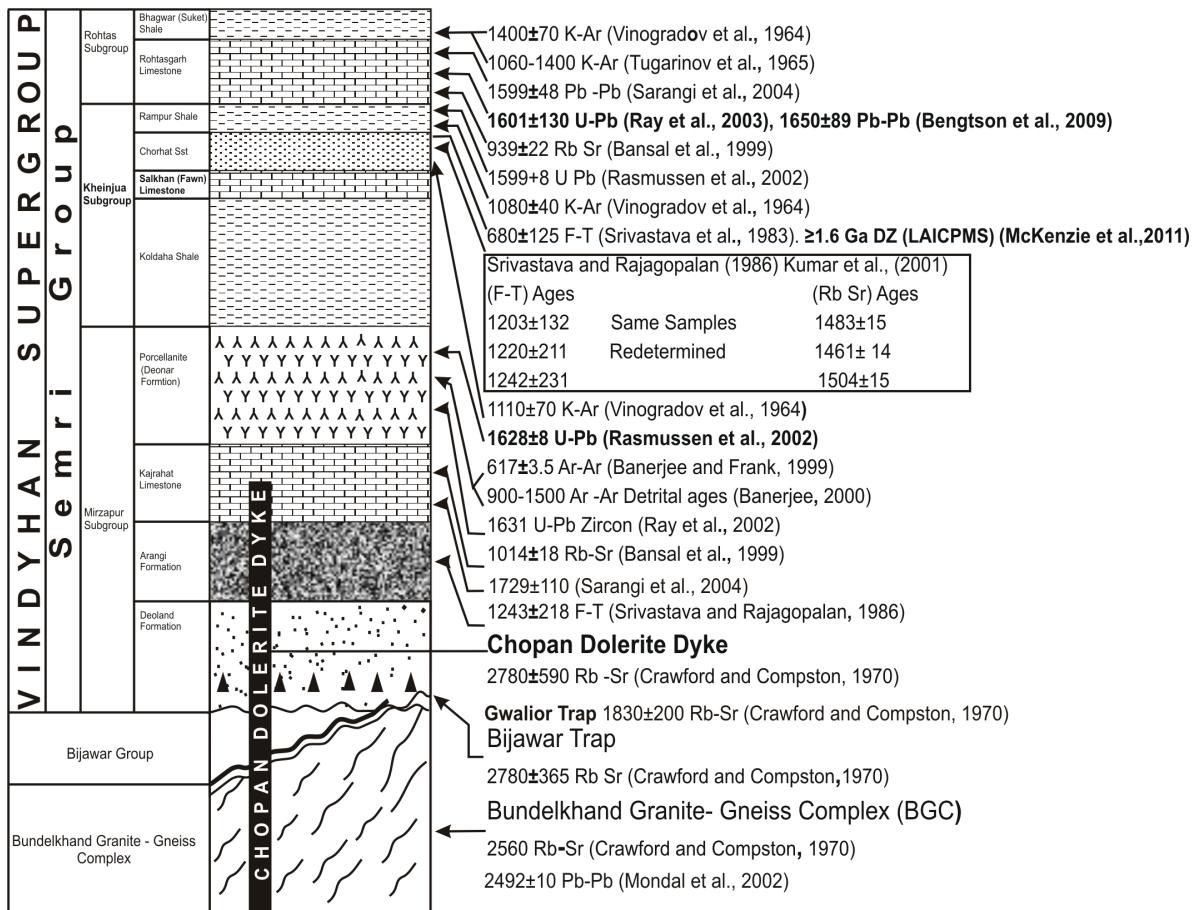


Fig. 2. A summary of the geochronological data on the Semri Group (modified after Azmi *et al.*, 2007).

light on Nikon Eclipse 80*i* Microscope. The size measurements of microfossils were carried out using an eyepiece micrometer. Slide No (S. No.) and England Finder co-ordinates (EF) are also provided for all the reported microfossils. Microfossils can be located keeping the BSIP slide label on left hand side. All the slides are deposited in the repository of the Birbal Sahni Institute of Palaeosciences, Lucknow, India vide statement No. -1386.

#### SYSTEMATIC DESCRIPTION

**Kingdom** Eubacteria Woese and Fox, 1977  
**Phylum** Cyanobacteria Stanier *et al.*, 1978  
**Class** Coccogoneae Thuret, 1875  
**Order** Chroococcales Wettstein, 1924  
**Family** Chroococcaceae Nägeli, 1849  
**Genus** *Gloeodiniopsis* Schopf, 1968,  
emend. Knoll and Golubic, 1979

*Gloeodiniopsis lamellosa* Schopf, 1968, emend. Knoll and Golubic, 1979, emend. Sergeev, 1992a.  
(Pl. I, figs. 1-5)

**Description:** Vesicles spheroidal, sometimes oblong in shape, with multilayered envelopes. Cells are arranged in monads, dyads and triads; the envelope comprises one or more thin and thick layers. Cell walls finely granular and about 1-2 µm thick, lamellae in outer portion are curved occasionally solitary in nature but some times found in colonies also. Diameter of vesicles ranges from 5-35 µm. (long axis  $\bar{x} = 17.83 \sigma 8.16$  µm and short axis  $\bar{x} = 15.94 \sigma 7.63$  µm, N = 52).

**Remarks:** *Gloeodiniopsis lamellosa* was reported from the silicified coastal playa lake carbonate of the ca. 800 Ma from Bitter Springs Formation, Australia (Schopf 1968). Knoll and Golubic (1979) emended this taxon to include species of the genera *Bigeminococcus*, *Eozygion*, *Eotetrahedron* and *Caryosphaeroides* (in part), recognizing that earlier described taxa reflect a cell division cycle and variable post-mortem decay within a single population. Many species of *Gloeodiniopsis* have been described but their size ranges overlap. Earlier, *Gloeodiniopsis lamellosa* commonly occurring with large vesicles were described as *G. magna* (Nyberg and Schopf, 1984). The type specimen *G. lamellosa* had of diameter 35 µm (Sergeev *et al.*, 1997). In our study, about 52 specimens were

#### EXPLANATION OF PLATE III

Photomicrographs of coccoids forms in petrographic thin sections of black chert. 1 to 4. *Phanerospherops capitaneus* Schopf and Blacic 1971 and 5 to 12- *Phanerospherops magnicellularis* Yakschin, 1991. Scale bar = 10 µm. 1- BSIP- 14998 (V/37-3); 2- BSIP- 15102 (P/35-2); 3- BSIP- 15101 (O/39-4); 4- BSIP- 15101 (O/39-4); 5- BSIP- 14993 (O/50-3); 6- BSIP- 14995 (U/43-1); 7- BSIP- 15107 (S/45-2); 8- BSIP- 15105 (P/53-2); 9- BSIP- 15107 (U/42-2); 10- BSIP- 15106 (G/46-2); 11- BSIP- 15104 (L/37-4); 12- BSIP- 14998 (H/44-1).

Plate III

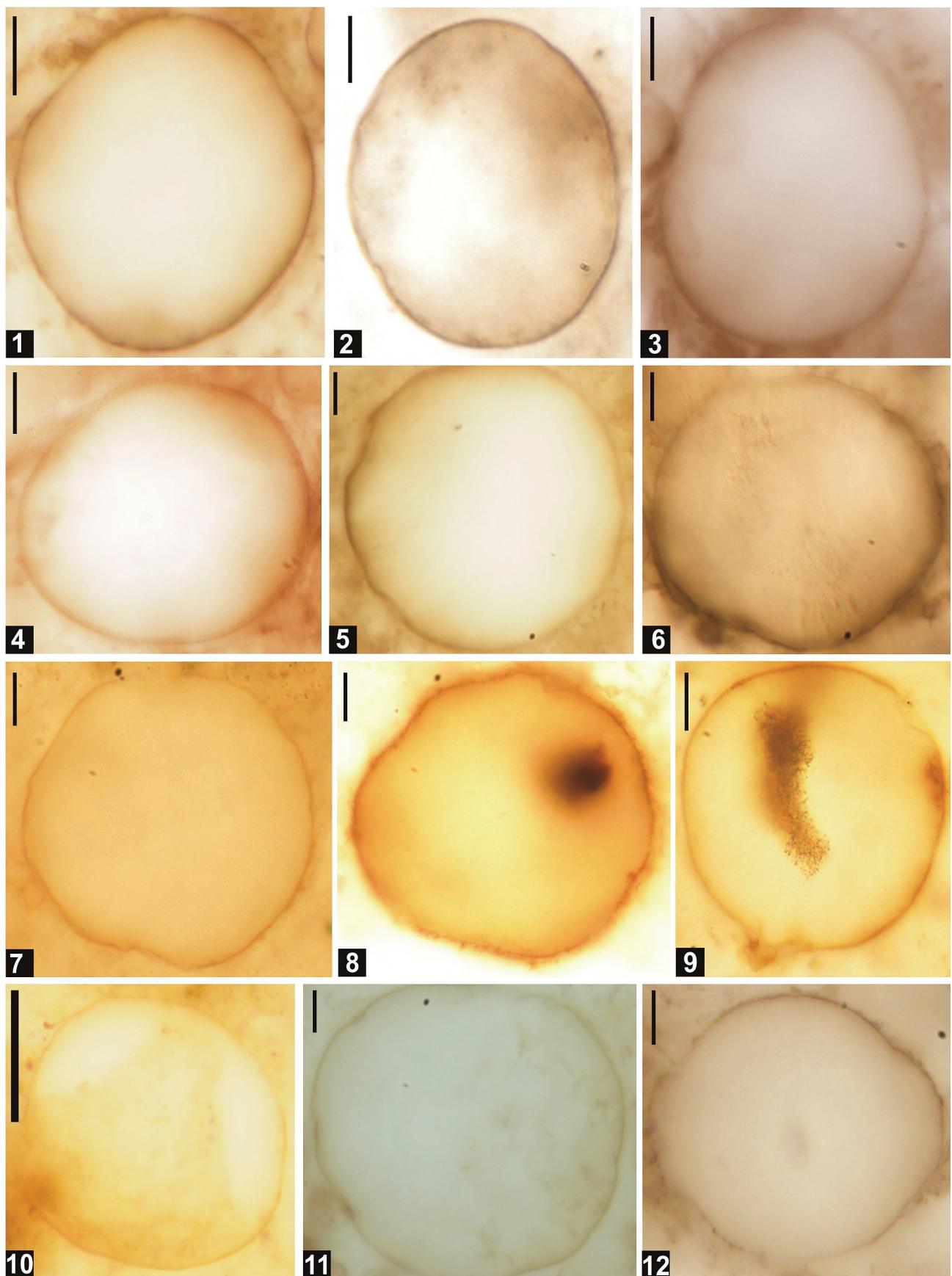




Fig. 3. Field photographs showing different varieties of chert from the Salkhan Limestone, Son Valley section, Vindhyan Supergroup. (a) Bedded Chert and (b) Stromatolitic Chert.

studied from the chert samples of the Salkhan Limestone and most of them fall in the same range of diameter.

**Age:** Late Palaeoproterozoic to Mesoproterozoic.

*Gloeodiniopsis mikros*, Knoll, 1982b  
(Pl. I, figs. 6-13)

**Description:** Relatively thick walled spheroidal vesicles, diameter of cells ranges from 2-15  $\mu\text{m}$ , vesicle solitary with double layered, outer layer is relatively thin and light in colour, inner wall is thick and darker in colour. Dyads are more common than single vesicles. (long axis  $\bar{x} = 8.79 \sigma 3.89 \mu\text{m}$  and short axis  $\bar{x} = 7.97 \sigma 3.59 \mu\text{m}$ , N= 60).

**Remarks:** Based on size parameters this species can be differentiated from *Gloeodiniopsis lamellosa*. The inner part of *G. mikros* is inferred as the preservational remnants of cells, while the external boundary is interpreted as a polysaccharoidal envelope. Monads, dyads and tetrads point out the various stage of cell division. It closely resembles modern cyanobacteria of the family Chroococcaceae, species of *Chroococcus*, *C. minutes* Kützing (Geitler, 1932: P. 232-233) and *Gloeocapsa*.

**Age:** Commonly Neoproterozoic but also found in Meso- and Palaeoproterozoic.

### *Incertae sedis*

Genus *Kheinjuaspharea* McMenamin et al., 1983

*Kheinjuaspharea vulgaris* McMenamin et al., 1983  
(Pl. II, figs. 1-11)

**Description:** Spheroidal to ellipsoidal, slightly deformed cell, single walled, solitary and generally occurring in colony also. Surface texture is smooth; cell wall is smooth, granular to psilate. No envelop and internal inclusions found. Diameter of cells ranges between 10-35  $\mu\text{m}$ . (long axis  $\bar{x} = 27.45 \sigma 5.56 \mu\text{m}$  and short axis  $\bar{x} = 24.29 \sigma 5.02 \mu\text{m}$ , N = 117).

**Remarks:** McMenamin et al. (1983) described this monospecific genus from the Salkhan Limestone. This genus differs from the other coccoidal forms based on its diameter and cell wall texture. In this paper we report large population of *Kheinjuaspharea vulgaris*. It is having large size and is slightly granular in nature and mostly found above the layers of aragonite

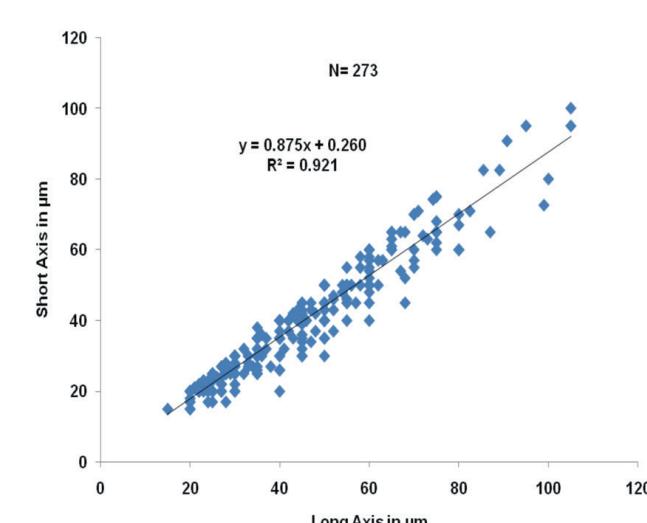
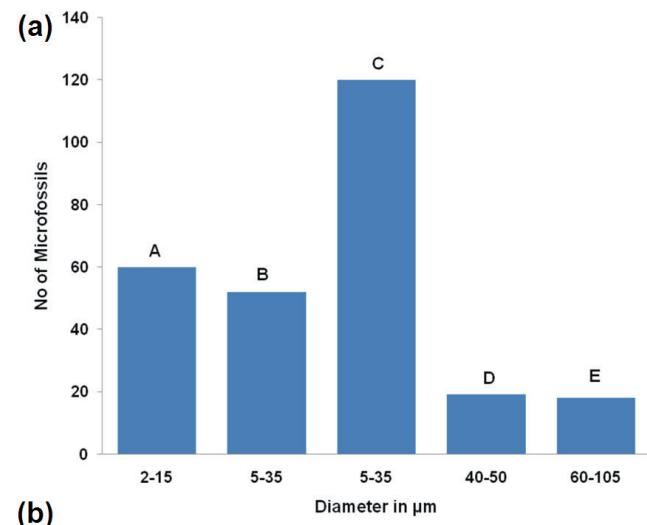


Fig. 4. Statistical data representation of microfossils found in the Salkhan Limestone (a): *Gloeodiniopsis mikros* (A), *G. lamellosa* (B), *Kheinjuaspharea vulgaris* (C), *Phanerospherop capitaneus* (D), and *P. magnicellularis* (E). The scatter diagram of large sized coccoids microfossils occurring in the Salkhan Limestone showing strong linear correlation between the two axes, short and long, of the microfossils (b).

and gypsum crystal pseudomorphs (Pl. II, fig. 1). McMenamin *et al.* (1983) placed *Kheinjuaspheara vulgaris* in *incertae sedis*. We are inclined to place it under the genus *Myxococcoides* but due to the insufficient material, we are grouping it under *incertae sedis*.

*Age:* Late Palaeoproterozoic to Early Mesoproterozoic.

*Genus Phanerospherops* Schopf and Blacic, 1971

*Phanerospherops capitaneus* Schopf and Blacic, 1971  
(Pl. III, figs. 1-4)

*Description:* Mostly spheroidal to elongate in shape. Cell wall is translucent and about 1 $\mu\text{m}$  thick, vesicles are solitary, surface texture is finely granular to smooth. Diameter ranges between 40-50  $\mu\text{m}$ . (long axis  $\bar{x} = 51.53 \pm 2.23 \mu\text{m}$  and short axis  $\bar{x} = 45.48 \pm 3.40 \mu\text{m}$ , N= 19).

*Remarks:* *Phanerospherops capitaneus* differ from *P. magnicellularis* on the basis of their small size range. *P. capitaneus* was reported from the Bitter Springs chert at Ellery Creek. Schopf and Blacic (1971) assigned this taxon to the blue green algae (cyanobacteria) Chroococcaceae; size of the vesicles ranges between (43.3-46.3  $\mu\text{m}$ ). It is sheathless and well rounded in nature. However, the same species was also reported from Hunnberg Formation which is bigger in size range (37-93  $\mu\text{m}$ ) and shows some unequal division (Knoll, 1984). The chances cannot be negated that these monotonous smooth species are merely envelopes of multicellular colonies of *Microcystis*-like coccoidal cyanobacteria.

*Age:* Meso-Neoproterozoic.

*Phanerospherops magnicellularis* Yakschin, 1991.  
(Pl. III, figs. 5-12)

*Description:* Large spheroidal vesicles, single walled, cell walls commonly rather distorted, depressed or broken. Walls translucent, medium grained and about 1 $\mu\text{m}$  thick. Solitary, non colonial, surface texture smooth, diameter of spheroids ranges between 60-105  $\mu\text{m}$ . (long axis  $\bar{x} = 84.57 \pm 11.04 \mu\text{m}$  and short axis  $\bar{x} = 78.95 \pm 10.04 \mu\text{m}$ , N= 18).

*Remarks:* Yakschin (1991) described three additional species of genera *Phanerospherops* which were later merged with species of genera *Myxococcoides* or *Eoentophysalis* by Sergeev *et al.* (1995, 2012). *Phanerospherops magnicellularis* is different from other large-sized coccoidal forms like *Myxococcoides*, *Leiosphaeridia*. Based on the large size, spheroids of this genus could be either eukaryotic unicellular or empty envelopes surrounding colonies of cyanobacteria. The argument given above that these may be envelopes of multicellular colonies of *Microcystis*-like coccoidal cyanobacteria or *Myxococcoides* holds true for this species as well.

*Age:* Late Palaeoproterozoic to Mesoproterozoic.

## DISCUSSION

Presently, all the living entities are grouped under the three domains of life: Archaea, Bacteria and Eukarya (Woese *et al.*, 1990). Eukaryotes belong to Eukarya. In comparison to prokaryotes, eukaryotes generally have larger cell size, advanced complex cell structure; membrane-bound nucleus, cytoskeleton, complex endomembrane and organelles such as mitochondria and plastids (Porter, 2004). The steranes - a part

of molecular fossil - reported from ~2700 Ma old shales of the Fortescue and Hamersley groups of the Pilbara Craton, Western Australia were considered as the first evidence of the presence of eukaryotes (Brocks *et al.*, 1999). However, using the carotenoid biomarker okenane, the occurrence of eukaryotic algae was ascertained at 1.64 Ga from northern Australia (Brocks *et al.*, 2005). In the geological records, it was once considered as a vast age gap (~1000 Ma) between the occurrence of molecular fossil and the occurrence of true eukaryotic fossil remnants. In the restudy, however, the Pilbara block biomarkers were established as contaminants (Rasmussen *et al.*, 2008). In the Precambrian palaeobiology, researchers enumerated various parameters to distinguish the eukaryotic nature among the simple morphologies, yet no single unequivocally acceptable criterion has been agreed to establish their existence in the geological records. Initially, cell size was suggested as a main criterion for the identification of eukaryotes (Schopf and Oheler, 1976; Schopf, 1977, 1992). Several researchers, however, do not consider the cell size alone as a satisfactory criterion for considering any vesicle or coccoid microfossil as eukaryote (Samuelsson and Butterfield, 2001; Javaux *et al.*, 2003; Sharma and Shukla, 2009a); but the presence of spines and ornamentation on the vesicle and cell wall ultrastructure together with cell size can be considered for establishing the presence of eukaryotic cells in the fossil records. Simple large-sized tubular coiled forms reported from Negaunee Iron Formation USA (> 1800 Ma) were also suggested to be eukaryotic in nature (Han and Runnegar, 1992; Schneider *et al.*, 2002). Similar, large size coiled forms were also reported from China, India and USA (Walter *et al.*, 1976, 1990; Kumar, 1995; Sharma and Shukla, 2009a, b). Megascopic large coiled forms reported from India were attributed as prokaryotic remains (Sharma and Shukla, 2009a, b). The ultrastructure studies conducted on the large-sized microfossils provide another parameter to determine the differences between prokaryotic and eukaryotic cells: TEM studies of the acritarchs of the Roper and Ruyang groups revealed the complex cell wall ultrastructure (Javaux *et al.*, 2004). These studies indicated the moderate diversity of eukaryotes found in the Early Mesoproterozoic. Likewise, studies by Moczdłowska and Willman (2009) demonstrated the ultrastructures (SEM and TEM) of the walls of sphaero-and acanthomorphic acritarchs of the Proterozoic and the Cambrian age. *Tappania plana* reported from the shales of the Early Mesoproterozoic Roper Group of Australia (1500 Ma old), was believed to be the earliest true eukaryotic fossil (Javaux *et al.* 2001). Recently, Peng *et al.* (2013) reported large-sized acritarchs *Dictyosphaera delicata* and *Shuiyousphaeridium macroreticulatum* from the shale and siltstone of the Baicaoping and Beidajian formations of the Ruyang Group, China (1611 ± 8 Ma old). The Ruyang and Luoyu groups are considered to have been deposited during the period of 1750-1400 Ma based on the detrital zircon and diagenetic xenotimes dating (Lan *et al.*, 2014). With the discovery of the Palaeoproterozoic ornamented acritarchs from the Ruyang Group, North China, the antiquity of eukaryotes has gone further deep in the geological past. The organic-walled microfossils reported from the chert streaks of the Chitrakut Formation of the Semri Group ( $\geq 1600$  Ma), namely, *Shuiyousphaeridium echinulatum*, *Cymatiosphaeroides kullingii*, and *Trachysphaeridium* sp. are also considered as eukaryotes due to the presence of their complex nature, ornamentation and processes along with the large size (Kumar and Srivastava, 1997; Anbarasu, 2001; Singh and Sharma, 2014). These organic-walled microfossils recorded from the Late

Palaeoproterozoic and Early Mesoproterozoic sediments of the Vindhyan Supergroup demonstrate the existence of eukaryotes during this time period. Another possible precursor of the eukaryotic form is multicellular *Diskagma buttonii* reported from the Hekpoort Formation of Palaeoproterozoic (2200 Ma) palaeosols in South Africa (Retallack *et al.*, 2013). It indicates still older antiquity of the eukaryotes. Considering these points, it is explicit that there are several parameters on which any organic vesicle can be assessed for its prokaryotic and eukaryotic nature. The presence of complex cytoskeleton in the body may be a prime factor for assigning any vesicle as a eukaryotic form. Therefore, various additional parameters viz. wall morphology, cell-wall ultrastructure, wall chemistry; ornamentation and presence of processes have been recommended to differentiate the eukaryotic remains from the prokaryotic ones in the fossils conditions (Gundersen *et al.*, 1992; Javaux, 2007; Javaux *et al.*, 2003, 2004, 2010; Knoll *et al.*, 2006; Mocdłowska and Willman, 2009).

The assemblage of coccoidal microfossils is very distinct in the population of the Salkhan Limestone. Affinities of these coccoids are not clearly discernible owing to non-diagnostic simple morphology. There could be three possibilities with regard to their nature and affinity: first, although remote, yet on the basis of large size they could represent eukaryotic remnants; second, they may represent empty envelops of cyanobacteria; and third, they may represent comparatively large size prokaryotic (cyanobacterial) cells. We discuss below these propositions of the large-sized coccoidal fossils of the Salkhan population. No cytoskeleton is recorded in the microfossils of the Salkhan Limestone. These forms are completely devoid of any type of complex structures, spines, ornamentation and processes. Comparison of the Salkhan large-sized coccoidal fossils placed under *incertae sedis* in the present paper lacks any distinguishing parameter to place them under eukaryotes and, therefore, cannot be considered as eukaryote merely on the basis of their size and appearance.

The eukaryotic cells are generally larger in size than the bacteria and archaea but some of the extra cellular sheaths and envelops encompassing numerous cells of cyanobacteria are also large in size (Knoll, 2014). A few prokaryotes like modern sulfur oxidizing "megabacterium" *Thiomargarita*, typically of 100-300  $\mu\text{m}$  in size and may range up to 750  $\mu\text{m}$  in diameter. Their large size is due to presence of large vacuoles inside the cells but the volume of cytoplasm is restricted (Schulz and Schulz, 2005; Bailey *et al.*, 2007). The population of these thick-walled and large-sized microfossils found in the Salkhan chert demonstrates variable size distribution (Table 2). Variation in both single and double walled microfossils species on the basis of their diameter and number of specimens is shown in the histogram (Fig. 4a). The scatter plot of coccoidal microfossils display that all coccoidal forms show a linear pattern (Fig. 4b). Therefore, the growth of coccoidal forms in long and short axis was in a constant ratio (long axis = 0.875 short axis,  $R^2 = 0.921$ ,  $P = 0.00$ ).

The Salkhan coccoidal forms are morphologically differentiated, taxonomically described and identified on the basis of size. Three genera have been documented from the different localities of the Salkhan Limestone. We discuss below the distribution and size range of the different species recorded:

*Gloeodiniopsis lamellosa* reported from different Neoproterozoic successions of India, such as Deoban Limestone Formation (Srivastava and Kumar, 2003), and Vaishnodevi

Limestone Formation, India (Kumar and Venkatachala, 1998) show large size variation (18-34  $\mu\text{m}$ , Kumar and Srivastava, 1992c and 8-18  $\mu\text{m}$ , Srivastava and Kumar, 2003). However, the size of *G. lamellosa* recorded from the Salkhan Limestone (Late Palaeoproterozoic to Early Mesoproterozoic) and those recorded from the Bitter Springs Formation, Australia (Neoproterozoic) are identical 5 to 35  $\mu\text{m}$  (Sergeev *et al.*, 1997). Slightly larger (13-42  $\mu\text{m}$ ) *G. lamellosa* has been reported from the Sukhaya Tunguska Formation, Turukhansk Uplift, Siberia (Sergeev *et al.*, 1997). Knoll (1982) reported *Gloeodiniopsis mikros* from Darken conglomerate Ny Friesland Svalbard which range in size from 3-6  $\mu\text{m}$ . The Salkhan specimens range between 2-15  $\mu\text{m}$  which are comparatively larger than the specimens reported from the Darken conglomerate.

*Phanerospherops capitaneus* reported from the Bitter Springs Formation, Australia (Schopf and Blacic, 1971) were in the size range of 43.3 to 46.3  $\mu\text{m}$ , whereas the Salkhan specimens range between 40 and 50  $\mu\text{m}$  which is slightly larger; however, bigger specimens (37 to 93  $\mu\text{m}$ ) have been recorded from the Hunnberg Formation, Spitsbergen (Knoll, 1984). The data on the size distribution of *P. capitaneus* from the Proterozoic successions of India are poorly constrained. Therefore, we assign this species with its size variation as a new addition from the Salkhan Limestone as well as from the Proterozoic successions of India. *Phanerospherops magnicellularis* was reported from the Koutikan Formation, Anabar Uplift, Siberia where it ranges between 55 to 300  $\mu\text{m}$  (Yakschin, 1991; Sergeev *et al.*, 1995). In the present study, specimens of *P. magnicellularis* range between 60 to 105  $\mu\text{m}$ . The coccoidal microfossils *Gloeodiniopsis lamellosa*, *G. mikros*, *Phanerospherop capitaneus* and *P. magnicellularis* have been recorded for the first time from the Salkhan Limestone, India and described taxonomically as prokaryotes based on the present state of knowledge (Sergeev *et al.*, 2012 and references therein). The age of these relatively large-sized prokaryotes has been assigned as Late Palaeoproterozoic to Early Mesoproterozoic. Generally, the size range of coccoidal prokaryotes in the modern environments is up to 60  $\mu\text{m}$  (Hofmann and Schopf, 1983); however, larger specimens have been recorded in the geological successions (Sergeev, 1992a, b, 1994, 2006). *Grypania spiralis* and *Katnia singhii* reported from the Early Mesoproterozoic Rohtas Limestone, Vindhyan Supergroup are other example of large-sized prokaryotes (Sharma and Shukla, 2009 a, b). The occurrence of relatively large-sized coccoidal prokaryote *Phanerospherops magnicellularis* from the Salkhan Limestone, India are correlatable with other previous studies from Koutikan Formation, Anabar Uplift, Siberia (Yakschin, 1991; Sergeev *et al.*, 1995).

## CONCLUSIONS

Large-sized microfossils are recovered from the Late Palaeoproterozoic-Early Mesoproterozoic Salkhan Limestone of the Vindhyan Supergroup, India. Present assemblage of chert-entombed microfossils are large sized, thick to thin, single and double walled and assigned to prokaryotes due to the complete lack of complex cytoskeleton, spines, ornamentation and processes. Interestingly, two genera and four species of the microfossils, namely, *Gloeodiniopsis lamellosa*, *G. mikros*, *Phanerospherop capitaneus* and *P. magnicellularis*, are reported for the first time from the Late Palaeoproterozoic to Early Mesoproterozoic age Salkhan Limestone, India. The biggest

**Table 2.** A list of microfossils recorded from the Salkhan Limestone in the present study showing size range and population density.

Species	Diameter	No of Microfossils
<i>Gloeodiniopsis mikros</i>	2-15	60
<i>Gloeodiniopsis lamelloosa</i>	5-35	52
<i>Kheinjuasphaera vulgaris</i>	15-40	120
<i>Phanerospherops capitaneus</i>	40-50	19
<i>Phanerospherop magnicellularis</i>	60-105	18

ever size of *Gloeodiniopsis mikros* has been recorded from the Salkhan Limestone.

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