



MORPHOLOGICALLY COMPLEX ORGANIC-WALLED MICROFOSSILS (OWM) FROM THE LATE PALAEOPROTEROZOIC - EARLY MESOPROTEROZOIC CHITRAKUT FORMATION, VINDHYAN SUPERGROUP, CENTRAL INDIA AND THEIR IMPLICATIONS ON THE ANTIQUITY OF EUKARYOTES

VEERU KANT SINGH and MUKUND SHARMA

BIRBAL SAHNI INSTITUTE OF PALAEOBOTANY, 53 UNIVERSITY ROAD, LUCKNOW-226007, INDIA

E-mail: veerukantsingh@bsip.res.in;

Corresponding author E- mail: sharmamukund1@rediffmail.com

ABSTRACT

Three complex Organic-Walled Microfossils (OWM) viz. *Shuiyousphaeridium echinulatum* Yin and Gao, 1999; *Cymatiosphaeroides kullingii* Knoll *et al.*, 1991 and *Trachysphaeridium* sp. are recorded from the chert streaks of the Chittrakut Formation of the Semri Group, Vindhyan Supergroup. This assemblage has been attributed to eukaryotic remains and discussed on various possible criteria to establish their affinity. The present record is the third occurrence of such eukaryotic forms from the Late Palaeoproterozoic – Early Mesoproterozoic succession after the report of the Roper Group, Australia and the Ruyang Group, China. The Chittrakut assemblage represents the first comprehensive report of the acritarchs including *Shuiyousphaeridium* type acritarch from the Vindhyan Supergroup.

Keywords: *Shuiyousphaeridium*, eukaryotes, Chittrakut Formation, Vindhyan Supergroup, India

INTRODUCTION

Presence of eukaryotes in the Meso and Neo-Proterozoic Era is fairly established but their origin, evolution and antiquity in deep Proterozoic Eon are debatable (see Xiao, 2013; Knoll, 2014). Understanding of the distinction between extant eukaryotic and prokaryotic forms helps identify the characteristics of two distinct types of entities in early history of Earth. Morphological and anatomical characters found in living forms, however, rarely survive fossilization and therefore not available for documentation to the palaeontologists (Xiao, 2013; Knoll, 2014). In recent years, interest in recording eukaryotic forms in the geological past specifically during the Proterozoic has considerably increased. Discovery of an urn shaped hollow structure *Diskagma buttonii* from the 2.2 Ga old Palaeosols of South Africa is claimed to be the oldest likely eukaryote and earliest evidence for life on land (Retallack *et al.*, 2013) however, its biological affinity is still unknown and not well established. Size and complexity suggest that *Diskagma* had the degree of cytoskeletal complexity which is found in eukaryotes. Among the carbonaceous fossils, *Grypania* the oldest coiled megascopic fossil recorded from marine realm, described from 1.87 Ga old Negaunee Iron Formation, Michigan (Han and Runnegar, 1992; Schneider *et al.*, 2002), is considered as the oldest eukaryote. Similar fossils were also recorded from the Mesoproterozoic rocks in North China, Montana and India (Walter *et al.*, 1990; Kumar, 1995; Sharma and Shukla, 2009a,b). However, Sharma and Shukla (2009a) established that the *Grypania* was prokaryotic in nature. Many other fossils that appeared after Great Oxidation Event (2.3 Ga) are claimed to be eukaryotes (Knoll *et al.*, 2006). Reviews highlight that most convincing fossil eukaryotes, however, come from the micropalaeontological records that were radiated in the oxygenated surface water of Proterozoic oceans which otherwise were commonly anoxia at depth (Knoll *et al.*, 2006). Besides various other Proterozoic fossils, the acritarchs — a group of decay-resistant organic-walled vesicular microfossils, interpreted as unicelled photosynthetic protists-

are considered as eukaryotic candidates during Precambrian time span, though some may represent multicellular algae (Mendelson, 1987; Butterfield, 2004), and a few have been tentatively interpreted as fungi (Butterfield, 2005). Although the biological affinities of acritarchs are quite uncertain (Yin *et al.*, 2007), their distinct complex morphological features and size are very helpful in their taxonomic divisions which are commonly used both in biostratigraphic and palaeoecological ranges (Evitt, 1963; Volkova, 1965; Grey and Willman, 2009). These records provide an earliest adequate data to assess the history of protistan biodiversity (Knoll, 1994; Vidal and Moczydlowska, 1997; Huntley *et al.*, 2006). Processed acritarchs are generally found in Neoproterozoic successions with the two exceptions, one in the Roper Group in Australia and the other is from the Ruyang Group in China.

We report an assemblage constituting third occurrence and first from India and discuss their eukaryotic affinity and implications in geological history of the Vindhyan Supergroup. Large acritarchs in the chert bands occurring close to the basement of the Vindhyan Supergroup - the Bundelkhand Granitic Complex from the Chittrakut Formation (> 1.64 Ga) were reported (Kumar and Srivastava, 1991; Anbarasu, 2001a; Singh *et al.*, 2008). These authors did not explain the unusual occurrence of the large-sized acritarchs in older strata. The present paper describes in detail the large-sized, morphologically complex Organic-Walled Microfossils assemblage from the Chittrakut Formation and discusses their affinity and significance.

GENERAL GEOLOGY

The Vindhyan Basin is the largest intracratonic Proterozoic sedimentary basin in Peninsular India. Sedimentary successions range from Late Palaeoproterozoic to Neoproterozoic. About ~ 4000-5000 meter thick pile of tectonically less disturbed and un-metamorphosed Vindhyan Supergroup has been lithostratigraphically subdivided into four groups in stratigraphic order, the Semri, the Kaimur, the Rewa and the Bhandar

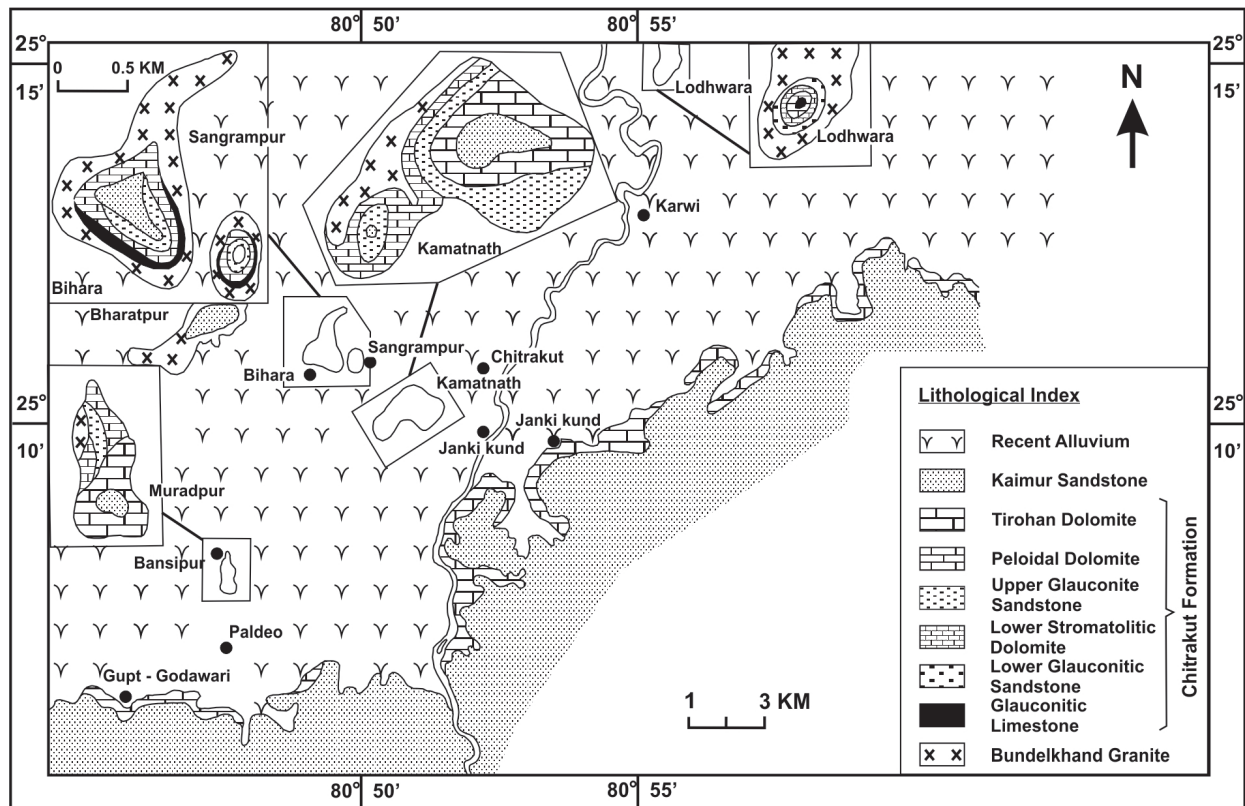


Fig. 1. Generalize geological map of the Chitrakut Formation (redrawn after Singh and Pal, 1970; Anbarasu, 2001b) showing the location of the study area.

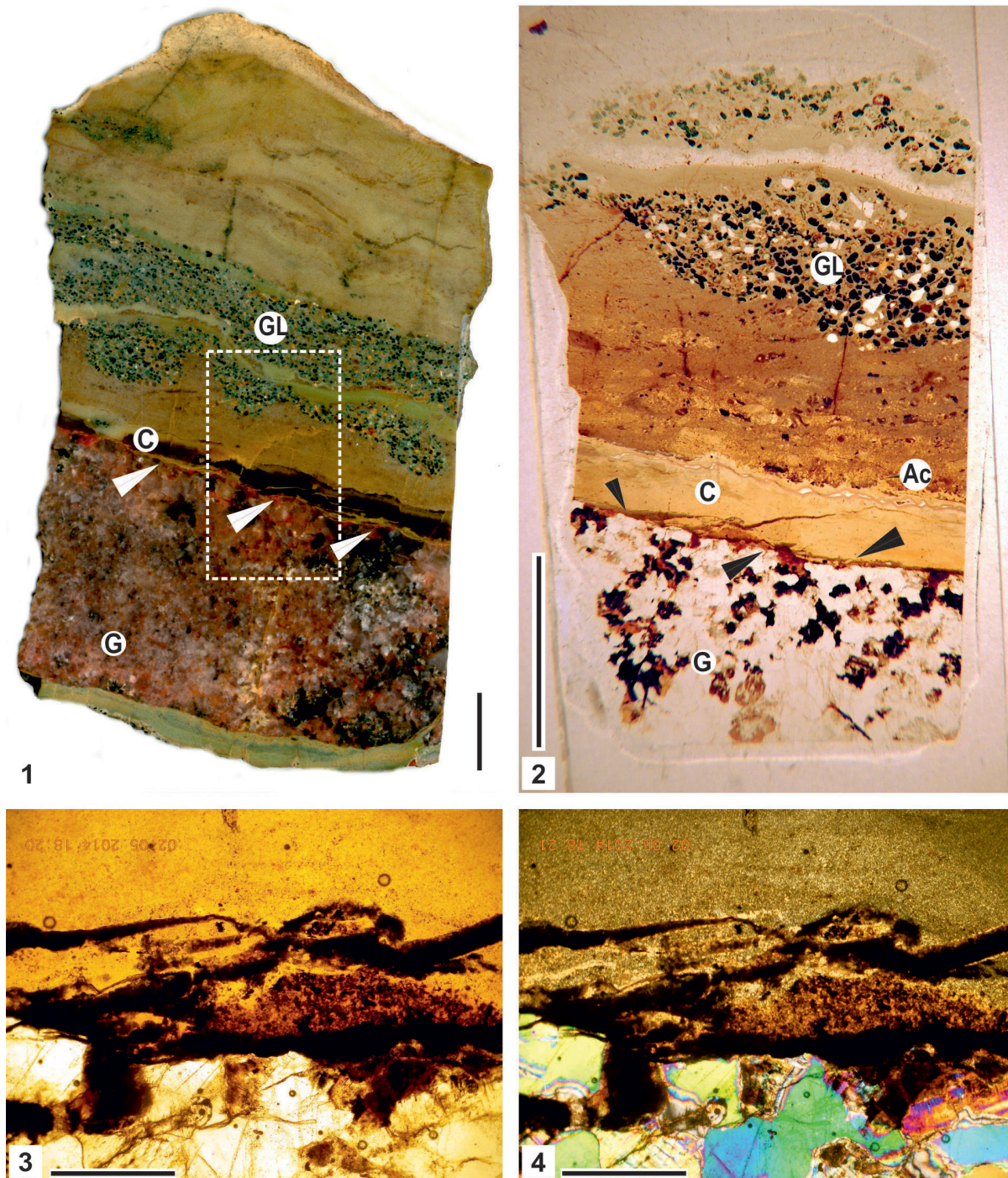
(Auden, 1933). The sedimentary sequences of this basin are extensively exposed in Bundelkhand, Son Valley region of Bihar, Uttar Pradesh and Madhya Pradesh and Chambal Valley of Rajasthan sectors (Chakraborty, 2006) and show much facies variations. The Semri Group is the oldest group of the Vindhyan Supergroup, comprising thick deposits of argilo-arenaceous sediments exposed in both Son and Chambal Valley sections (Sastri and Moitra, 1984).

A condensed section of the Semri Group of rocks (~80 meter) is exposed in a few isolated hillocks in and around Chitrakut area situated on the territory of Madhya Pradesh and Uttar Pradesh (Singh and Kumar, 1978) (Fig. 1). The sedimentary history of the area has been studied in detail by various workers (Auden, 1933; Narain 1970; Singh and Pal 1969; Singh and Kumar, 1978; Safaya, 1975; Nautiyal, 1986; Nautiyal and Singh, 1990; Kumar

and Srivastava, 1991; Anbarasu, 2001b). Sedimentary succession of the Semri Group in the Chitrakut area unconformably exposed over the rocks of 2.5 Ga old Bundelkhand Granite-Gneissic Complex (BGGC) which forms the northern limb of Vindhyan syncline (Auden, 1933; Narain, 1970; Singh and Pal, 1970; Singh and Kumar, 1978; Safaya, 1975) and designated as the Chitrakut Formation (Singh and Pal, 1970). In the southern and southeastern part of the area, the Tirohan Limestone and the Kaimur Sandstone form a NE-SW running escarpment which is a prominent geomorphic feature of the area. Litho-stratigraphically, the Chitrakut Formation has been classified into seven members in stratigraphic order (Anbarasu, 2001b) (Table 1). The Bundelkhand Granitic Complex is a coarse grained pink, porphyritic and medium grained non porphyritic granite exposed as inliers surrounded by pedi plain deposits of

Table 1: Generalized Lithostratigraphy of the Chitrakut area (after Singh and Pal, 1970; Anbarasu, 2001b).

GROUP	FORMATION	MEMBER	AGE	
VINDHYAN SUPERGROUP	Kaimur Group	Kaimur Sandstone		
		Arkosic Sandstone		
	~~~~~~ Erosional Unconformity ~~~~~~			
	Semri Group	Chitrakut Formation	Tirohan Dolomite	1650±89 Ma Pb-Pb (Bengtson <i>et al.</i> , 2009)
			Oolitic Dolomite	
			Upper Glauconitic Sandstone	1409±14 Ma ⁸⁷ Rb/ ⁸⁶ Sr
			Peloidal Dolomite	(Kumar <i>et al.</i> , 2001)
Lower Stromatolitic Dolomite				
		Lower Glauconitic Sandstone		
		Glauconitic Limestone	1483±15 Ma ⁸⁷ Rb/ ⁸⁶ Sr (Kumar <i>et al.</i> , 2001)	
<b>Bundelkhand Granite Gneissic Complex</b>				



SINGH AND SHARMA

#### EXPLANATION OF PLATE I

1. Polished slab showing the contact between Bundelkhand Granite and Glauconitic Limestone Member of the Chitrakut Formation, Specimen No. BSIP 40288;
  2. Photomicrograph of fossiliferous rock showing the contact between Bundelkhand Granite and Glauconitic Limestone Member of the Chitrakut Formation, Slide No. BSIP 14144. Abbreviations : G- Granite; C- Chert; GL- Glauconite; Ac- Acritarch;
  3. Photomicrograph of fossiliferous chert under plain polarized light, Slide No. BSIP 14144; 4. Photomicrograph of fossiliferous chert under cross polars showing amorphous chert and granite, Slide No. BSIP 14144.
- Scale bar for figs. 1- 2 = 10 mm; figs. 3-4 = 100  $\mu$ m.

Banda alluvium. Rocks overlying the Chitrakut Formation are known as the Kaimur Sandstone and are not much in thickness. Lateral juxtaposition of environmental belt proposed for the rocks of Chitrakut Formation (Safaya, 1975). However, Singh (1985) suggested fluctuation in depositional environment due to syn-sedimentary sinking of the basin and lateral shifting of the shallow marine environments. Anbarasu (2001b) studied the Chitrakut Formation in detail and proposed shallow subtidal – peritidal environmental complex, dominantly in peritidal setting.

## AGE

Like other Purana basins of India, age of the Vindhyan sedimentation is still the subject of considerable controversy (Gregory *et al.*, 2006; Azmi *et al.*, 2007; Basu and Bickford, 2014; Basu *et al.*, 2008; Malone *et al.*, 2008). Most of the published dates are based on different geochronological systematics (U–Pb TIMS, Ray *et al.*, 2002; U–Pb SHRIMP, Rasmussen *et al.*, 2002; Pb–Pb dating of carbonate, Sarangi *et al.*, 2004; Sr isotope, Ray *et al.*, 2003) that range from latest Palaeoproterozoic– Early Mesoproterozoic age for the Semri Group (Ray, 2006). The Chitrakut sediments are characterized by rich occurrence of glauconite. Rb–Sr isotope dates of the glauconite range between  $1531 \pm 15$  Ma to  $1409 \pm 14$  Ma suggesting that the onset of earliest Vindhyan sedimentation should not be later than 1600 Ma (Kumar *et al.*, 2001). Recently, direct Pb–Pb isochron age  $1650 \pm 89$  Ma of the Tirohan phosphorite - a dolomite unit just above the Chitrakut Formation (Bengtson *et al.* 2009) and U–Pb Zircon dates of the Deonar Porcellanite have yielded 1632 Ma (Ray *et al.*, 2002), confirmed the Late Palaeoproterozoic age of the Lower Vindhyan.

## PREVIOUS STUDIES

Several palaeobiological studies have been conducted on the Semri Group. The report of triploblastic animal traces (Seilacher *et al.*, 1998) and Small Shelly Fossils of Cambrian age (Azmi, 1998) have drawn global attention. These discoveries challenged several established biotic evolutionary understanding and thereby implied the existence of metazoan life further deeper in geological time. The subsequent studies (Hofmann, 2005; Prasad *et al.*, 2005; Sharma, 2006) did not corroborate these findings and interpretations; reinvestigation of 1.6 Ga old phosphatic chert of the Tirohan Limestone of the Semri Group of the Vindhyan Supergroup (Bengtson *et al.*, 2009) suggested the presence of shelly remains. Although enigmatic palaeobiological remains are abundantly recorded from the entire Vindhyan sediments (Venkatachala *et al.*, 1996; Prasad *et al.*, 2005; Sharma 2006; Sharma and Shukla, 2009a and Singh *et al.*, 2009, 2011), yet very few reports are available from the sediments of the Chitrakut Formation. Kumar and Srivastava (1991), Anbarasu (2001a) and Singh *et al.* (2008) have recorded microbiota (acritarchs) from the chert veins associated with glauconitic limestone at the base of the Chitrakut Formation but have not discussed their occurrence and significance. Microstructures comparable to filamentous cyanobacteria from the intraclasts associated with the phosphatic stromatolites (Kumar, 1993) and calcareous algae of earliest Cambrian age (?) were reported from the Tirohan Limestone (Joshi *et al.*, 2006, Azmi *et al.*, 2007). Bengtson *et al.* (2009) restudied the fossils and demonstrated that the skeletal fossils of Cambrian taxa are real but more than one billion year old.

## MATERIAL AND METHODS

To adjust the significance of the earlier reported Organic-

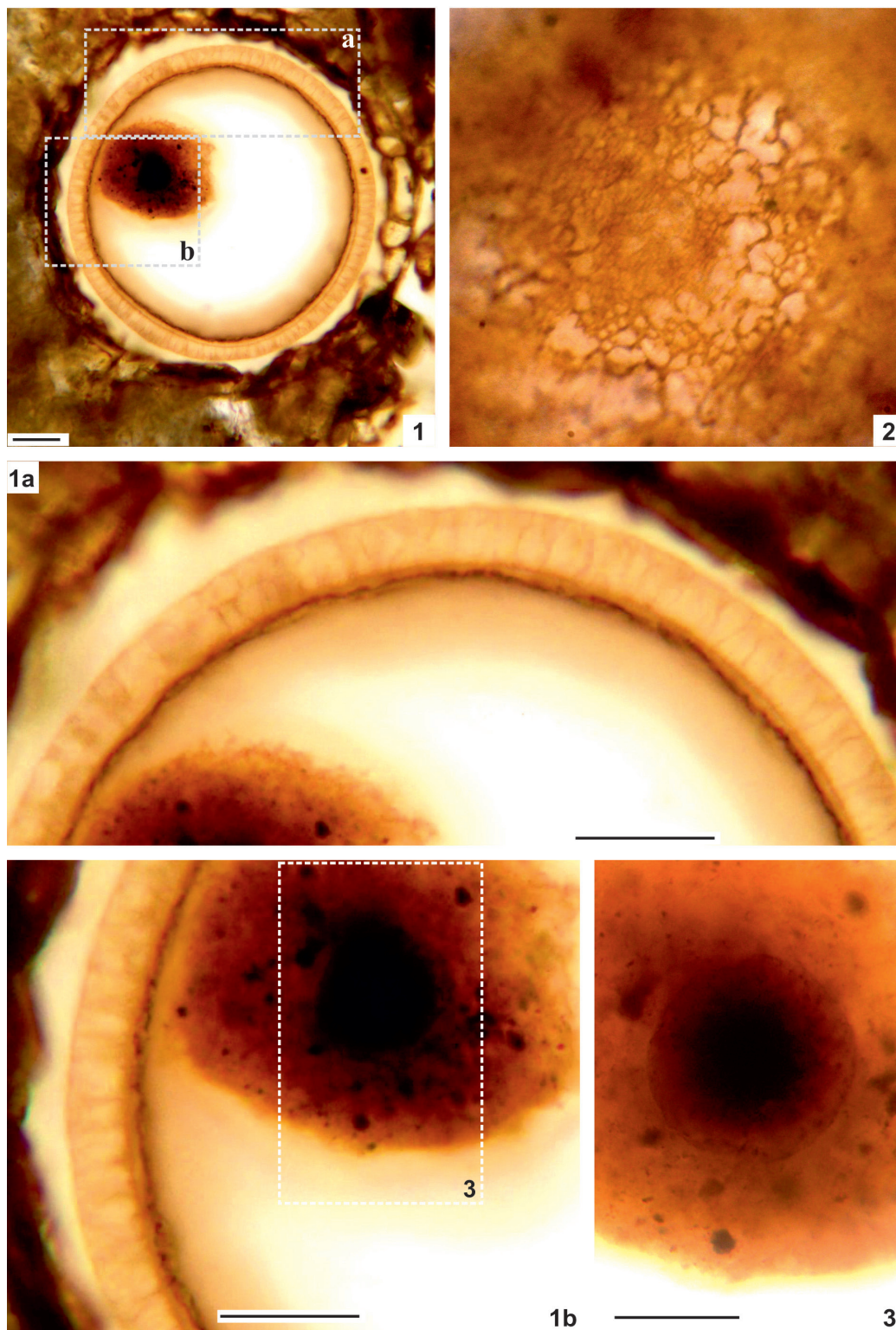
Walled Microfossils, fresh samples were studied from the non-stromatolitic chert bands occurring within the glauconitic limestone of the Chitrakut Formation, a stratigraphic unit lying below the well-dated Tirohan Limestone ( $1650 \pm 89$  Ma old) of the Semri Group. The chert samples were collected from the sections exposed on isolated hillocks of Bihar (Long:  $25^{\circ}11'01.1''$  N; Lat:  $80^{\circ}49'23.6''$  E) and Sangrampur (Long:  $25^{\circ}10'45.2''$  N; Lat:  $80^{\circ}49'30.4''$  E) hillocks in Chitrakoot district, Uttar Pradesh. The lithostratigraphic succession of the Semri Group exposed over the weathered profile of Bundelkhand Granite at these locations is: Glauconitic Limestone, Pelloidal Limestone, Glauconitic Sandstone, Tirohan Dolomite followed by the Kaimur Group in order of superposition (Plate I). The microfossils bearing silicified carbonaceous chert band/lenses (maximum thickness 0.5– 2.0 cm) are sandwiched between Bundelkhand Granite and the Glauconite-bearing Limestone (see Fig. 2). The present paper is based on the collections made by VKS and late Manoj Shukla in 2006. Sharma, along with a team of scientists, also made a collection of samples from Sangrampur hillock during the International Field Workshop organized by the Palaeontological Society of India in 2010.

Extensive Light Microscopic (LM) studies were conducted on petrographic thin sections of the black silicified cherts. The standard and modified palynological protocols of chemical digestion of rocks (maceration), using 40% hydrofluoric acid following (Grey, 1999) were applied and organic residue was mounted on permanent strew slide through Canada Balsam (R. I. = 1.5) on microscopic slides. Forty petrographic and palynological slides were examined under transmitted light at 40X or 100X (under oil immersion lens) magnifications for documenting the finer morphological details of microorganisms. Size measurements were taken through eye piece micrometer. Specimens were photographed on software supported digital cameras Olympus DP 26 and Nikon DS-Fi1 respectively mounted on Olympus BH2 and Nikon Eclipse 80i microscopes.

A few specimens from the macerated residue were hand-picked for Scanning Electron Microscopic - SEM (Leo 430) studies. The selected specimens were coated with a layer of 22 nm thick gold palladium. Many specimens are encrusted by pyrite framboids and crystal growths, which sometimes obscure observation of primary morphological features. All the petrographic thin sections and palynological slides, associated samples and photomicrographs have been deposited in the repository of Birbal Sahni Institute of Palaeobotany, Lucknow (BSIP) vide statement no. BSIP-1367.

## MICROPALAEONTOLOGY

The chert streaks from the Chitrakut Formation have yielded majority of exceptionally well preserved Organic Walled Microfossils (OWMs). These are chiefly constituted of acanthomorphs followed by sphaeromorphic acritarch belonging to Sphaeromorphida and Sphaerohystrichomorphida subgroups. In taxonomic composition, the organic- walled microfossils are excellent/good, three-dimensionally preserved, slightly compressed due to mutual compressions and display light brown to dark amber coloration of organic matter. The yellowish brown to brown color of the microfossils is attributed to the absence of severe geochemical degradation of organic constituents (Staplin, 1961). On the size parameters, vesicles are large ( $>100 \mu\text{m}$ ), ornamented, thick to thin walled, single to multilayered, surface sculptures ranging from reticulate to polygonal, honey comb like mesh. Sometimes compression and



SINGH AND SHARMA

EXPLANATION OF PLATE II

1 – 3. Morphology and wall structure of *Shuiyousphaeridium echinulatum* Yin and Gao, 1999 from the Chitrukut Formation.  
1a. Short membranous hairy processes on the periphery of the vesicle; 2 – Honey comb like reticulations on vesicle surface; 1b. Dark circular intracellular inclusion (ICI) in vesicle; 3. Enhanced view of ICI showing nucleus covered by thin membrane. Scale = 50 μm for each. Slide No. BSIP 14137, England Finder No. Z30/4.

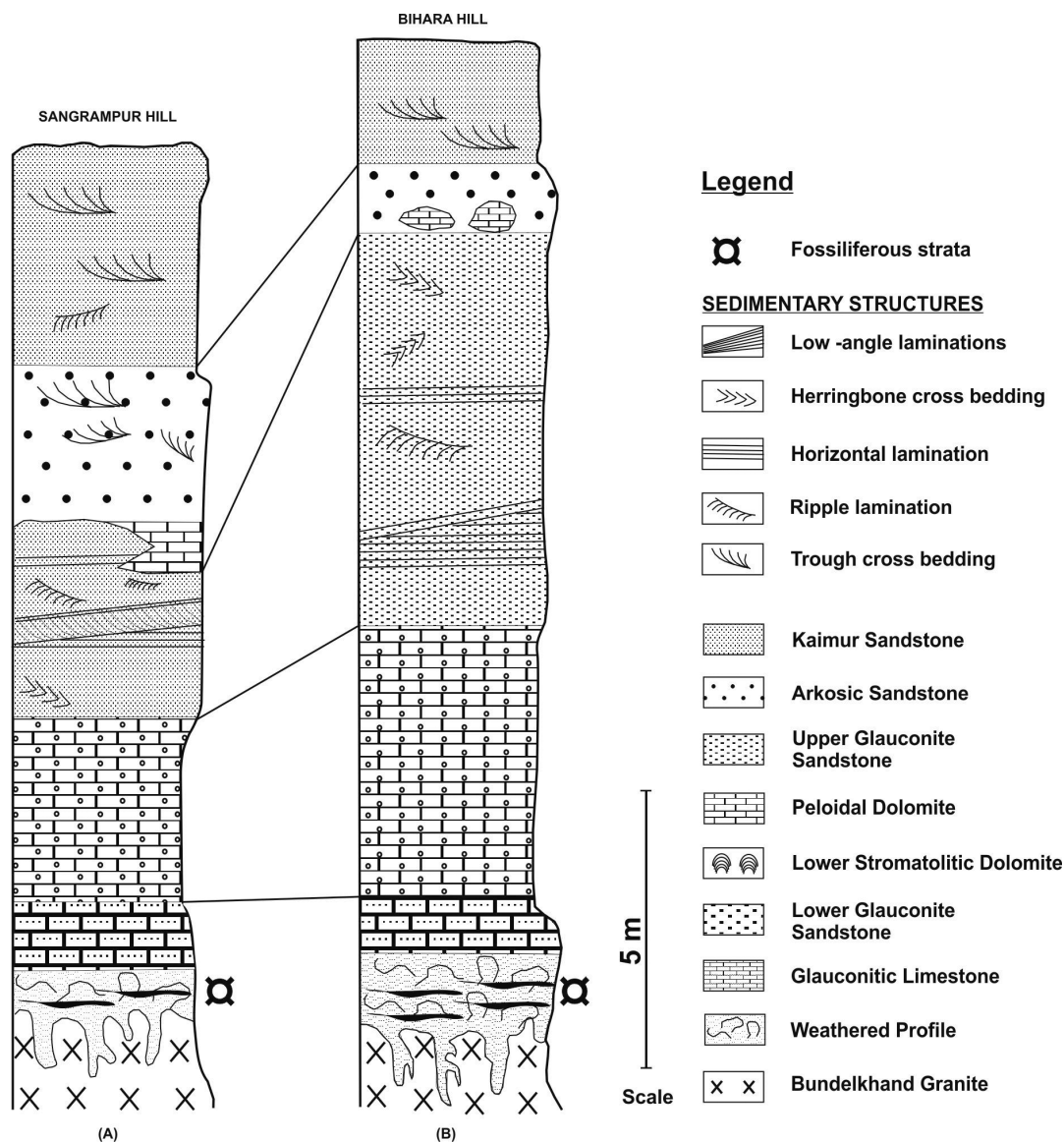


Fig. 2. Lithostratigraphic columns of the Chitrakut Formation at Sangrampur (A) and Biara hills (redrawn after Anbarasu, 2001b) showing sample locations.

compaction folds are observed on the vesicle wall and some loss of process or deformation in specimens. Some vesicles hold inclusion of well developed pyrite framboids ranging 5- 10  $\mu\text{m}$ . A detailed microscopic observation of the cherts characterizes a pale yellow colour matrix including excellent preservation of microbial assemblage. Earlier, these OWMs were identified as *Trachysphaeridium* sp. (Kumar and Srivastava, 1991) and *Cymatiosphaeroides kullingii* (Anbarasu, 2001a).

*Group Acritarcha* Evitt, 1963

*Subgroup Herkomorphytæ* Downie, Evitt and Sarjeant, 1963

*Genus Shuiyousphaeridium* (Du, 1988) Yan, 1992 emend. Yin, 1997

(Type species *Shuiyousphaeridium macroreticulatum* Yan in Yan and Zhu, 1992 emend. Yin, 1997.)

*Shuiyousphaeridium echinulatum* Yin and Gao, 1999

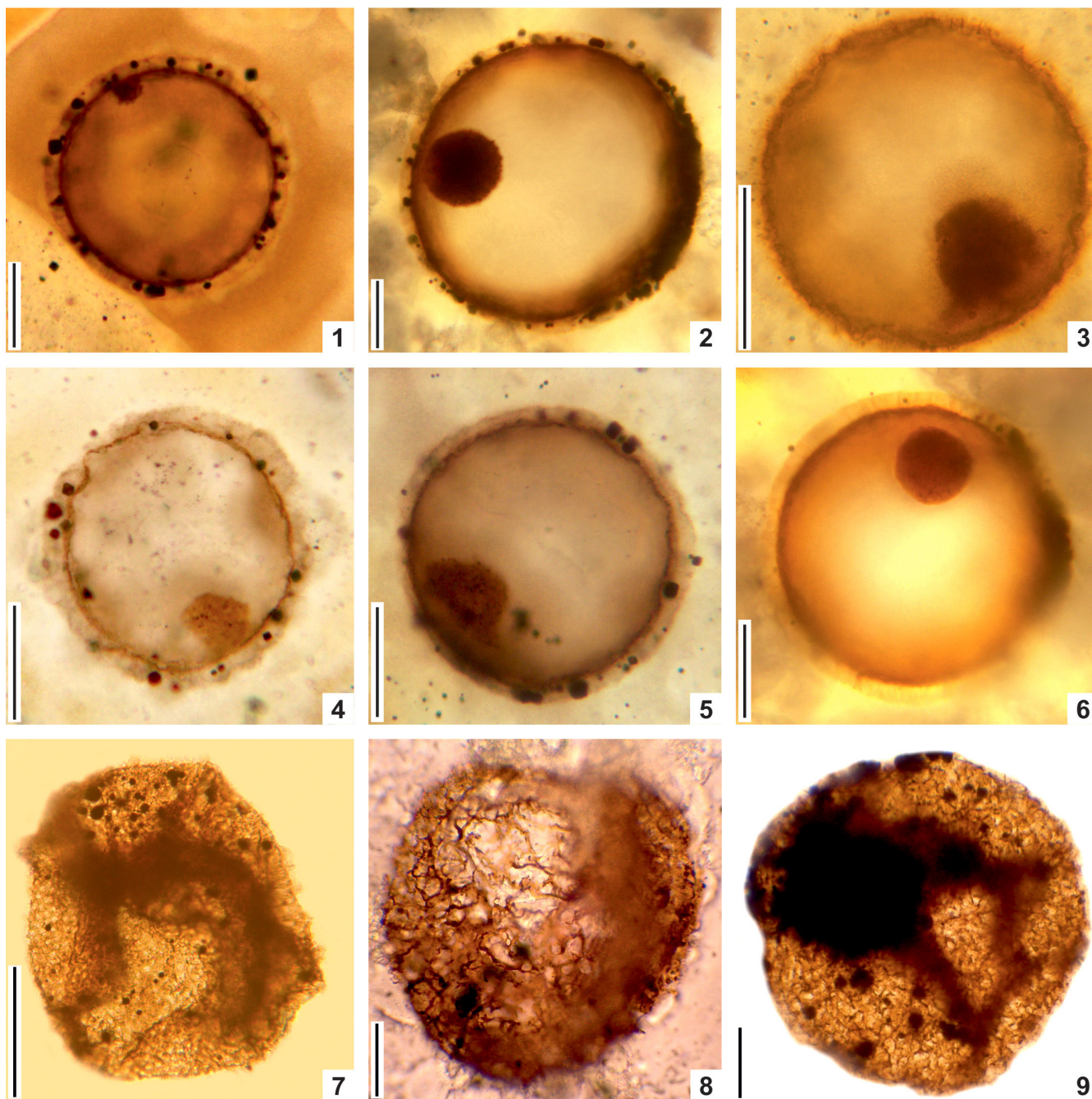
(Pl. II, figs. 1-3; Pl. III, figs. 1-9; Pl. IV, figs. 4, 4a;

Pl. V, figs. 1, 4)

*Description:* Vesicle sphaeroidal to ovoidal, circular in

cross section, covered by multilaminated wall, inner wall robust, outer wall hyaline relatively thin, compact, with honey comb like organization of short membrane like simple or fractured hairy processes, vesicle surface reticulate, vesicle hollow or containing a dark circular intra-cellular inclusion engulfed within light coloured mucilaginous material close to the vesicle wall. Vesicle diameter 128 - 286  $\mu\text{m}$ , processes 5 - 20  $\mu\text{m}$  and 1 - 2  $\mu\text{m}$ , intracellular inclusions range between 18 - 59  $\mu\text{m}$  (n=17). Processes numerous hollow, wide on distal end and interconnected with adjacent process but not connecting with the vesicle cavity.

*Remarks:* The present specimens are more or less similar in morphology to the specimens of 1602 Ma old Ruyang Group, China. Originally two species of *Shuiyousphaeridium* were described from Baicaoping Formation of the Ruyang Group: *S. macroreticulatum* and *S. membraniferum* (Yan and Zhu, 1992). Later, Yin (1997) emended the diagnosis and merged the species keeping *S. macroreticulatum* as the sole species of the genus because membranous material was also incorporated in the



SINGH AND SHARMA

EXPLANATION OF PLATE III

1 – 9. *Shuiyosphaeridium echinulatum* Yin and Gao in Petrographic thin sections (1 - 6) and macerated residue (7 - 9). Note that the pyrite framboid are confined in the outer membrane. Scale bar for each figure is 50  $\mu$ m.

1. Slide No. BSIP 14138, England Finder No. M39/2; 2. Slide No. BSIP 14144, England Finder No. G39; 3. Slide No. BSIP 14139, England Finder No. Q29; 4. Slide No. BSIP 14140, England Finder No. K54/4; 5. Slide No. BSIP 14138, England Finder No. K42/1; 6. Slide No. BSIP 14144, England Finder No. D38; 7. Slide No. BSIP 14146, England Finder No. V52/3; 8. Slide No. BSIP 14143, England Finder No. F42; 9. Slide No. BSIP 14143, England Finder No. O24/3.

holotype. Another species of *Shuiyousphaeridium echinulatum* was described by Yin and Gao (1999) from the same formation. This species was having shorter unbranched processes and devoid of outside membrane, conspicuously some of the vesicles contain dark inclusion which was not reported from *S. macroreticulatum*. Chittrakut acritarchs are closely comparable with *S. echinulatum* except the outer membrane. Pyrite framboids are conspicuously associated with processes on vesicle wall. Exceptional preservation of pyrite framboids, confined in the outer membranous region, suggest that these acritarchs were flourishing in euxinic environment probably a lagoonal setting where sulfur bacteria prompted the formation of pyrite in the peripheral zones where exchange of dissolved mineral was taking place. Presence of intracellular inclusion in the vesicle and multilayered wall differentiate *Shuiyousphaeridium* from the *Cymatiosphaeroides*. Knoll (1984) reported such types of fossils, as unidentified form, from the 700- 800 Ma old Hunnberg Formation, Svalbard and compared with *Chuarina circularis*. The nature of intracellular inclusion may be of biological origin as proposed for the Ruyang acritarchs (Pang *et al.*, 2013).

**Stratigraphic distribution:** *Shuiyousphaeridium* is widely recorded from Palaeoproterozoic sediments of Ruyang Group, China (Yan and Zhu, 1992; Yin, 1997; Yin and Gao, 1999) also found in the Late Palaeoproterozoic to Early Mesoproterozoic Chittrakut Formation, Vindhyan Supergroup.

**Genus *Cymatiosphaeroides*** Knoll, 1984 emend.

Knoll in Knoll *et al.*, 1991

(Type species *Cymatiosphaeroides kullingii* Knoll, 1984, emend. Knoll in Knoll *et al.*, 1991)

*Cymatiosphaeroides kullingii* Knoll, 1984, emend.

Knoll in Knoll *et al.*, 1991

(Pl. IV, figs. 9–11; Pl. V, figs. 2, 5)

**Description:** Vesicle originally spheroidal in shape, circular to sub-circular in cross section; vesicle wall thin, unilayered; surface finely reticulated, covered with mesh of thin solid cylindrical processes arising from the vesicle, 1-2  $\mu\text{m}$  in diameter, processes uniformly distributed over vesicle, appears as membrane; intracellular inclusion absent. Inner wall diameter 96 - 187  $\mu\text{m}$ ; process 8-11  $\mu\text{m}$  long (n = 15).

**Remarks:** The present specimen is similar in morphology with *Cymatiosphaeroides kullingii* recorded from Neoproterozoic carbonate deposits of Svalbard (Knoll, 1984). However, specimens in the macerated residue are more or less morphologically comparable with the > 742 Ma old Chuar Group, Grand Canyon, Arizona (Nagy *et al.*, 2009) and Lower Vendian Vychegda Formation of East European Platform, Russian (Veis *et al.*, 2006). The *Cymatiosphaeroides kullingii* has been widely recorded from the Neoproterozoic deposits (800 – 700 Ma) of Hunnberg and Ryssö Formation, Nordaustlandet, Svalbard (Knoll, 1984); Canada (Allison and Awramik, 1989), Tidal lagoon complex of Draken Conglomerate Formation,

Spitsbergen (Knoll *et al.*, 1991; Butterfield *et al.*, 1994); Alinya Formation, Officers Basin, Australia (Zang, 1995); Deoban Limestone Formation (Srivastava and Kumar, 2003); Lower Vendian Vychegda Formation, East European Platform, Russia (Veis *et al.*, 2006) and Tidal influenced Kwagunt Formation, Chuar Group, Arizona, USA (Vidal and Ford, 1985, Nagy *et al.*, 2009) and rarely reported from the Mesoproterozoic/Palaeoproterozoic deposits of India (Anbarasu, 2001a). Pyrite crystals interlocked with the processes.

**Stratigraphic distribution:** Based on present fossil records it can be considered a long ranging form which appeared in Late Palaeoproterozoic and continued up to the Neoproterozoic.

**Subgroup Sphaeromorphitae** Downie *et al.*, 1963

**Genus *Trachysphaeridium*** Timofeev (1959), 1969

(Type Species *Trachysphaeridium attenuatum* Timofeev, 1959)

*Trachysphaeridium* sp.

(Pl. IV, figs. 1–3, 5–8; Pl. 5, figs. 3, 6)

**Description:** Single, thin walled, compressed, hollow, originally spherical vesicle; psilate or finely granular surface texture with curvilinear folds; variable sized circular to polygonal pores present on the vesicle, processes not present, vesicle diameter 90 -210  $\mu\text{m}$ . Pores 3 - 4  $\mu\text{m}$  in diameter, (n = 12), occurs as solitary isolated in matrix, extracellular mucilage not present.

**Remarks:** Specimens of *Trachysphaeridium* are common acritarch of many Neoproterozoic microfossils assemblages. Morphological characteristics and vesicle diameter of the described species are more or less similar to the reported specimens of Neoproterozoic (700-800 Ma) Hunnberg Formation of Svalbard (Knoll, 1984); Ryssö Formation of Nordaustlandet, Svalbard (Knoll and Calder, 1983) and from the Vindhyan Supergroup, India (Prasad *et al.*, 2005). Specimens recorded from the Chittrakut Formation are larger in size that fit with the description of *Trachysphaeridium* sp. A and *Trachysphaeridium* sp. B. of Knoll (1984) and Knoll and Calder (1983).

**Stratigraphic distribution:** Widely reported from the Neoproterozoic (700- 800 Ma) sediments, also noted in the Late Palaeoproterozoic Chittrakut Formation.

## DISCUSSION

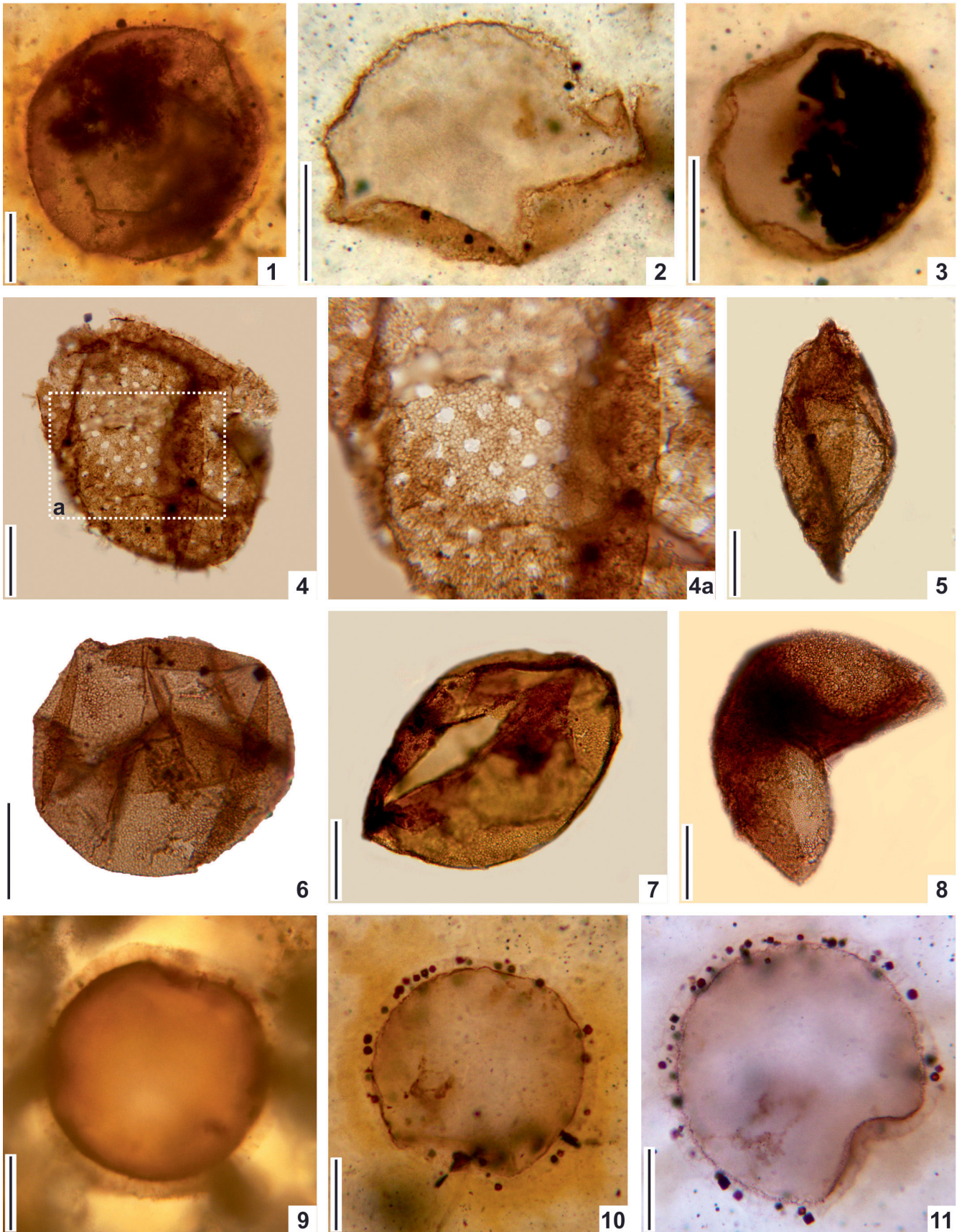
Proterozoic early digenetic cherts are considered as storehouse of varied types of micro and macrofossils that play a key role in understanding the evolution of eukaryotic life in deep time (Sergeev, 2009). The earliest eukaryotes are considered to be morphologically simple and single celled organisms (Xiao, 2013). In the present study, three species of well-preserved large, ornamented acritarchs *Shuiyousphaeridium echinulatum*; *Cymatiosphaeroides kullingii* and *Trachysphaeridium* sp. are described from the Late Palaeoproterozoic chert of the Chittrakut Formation of the Semri Group, Vindhyan Supergroup. Although *Cymatiosphaeroides kullingii* and *Trachysphaeridium*

## EXPLANATION OF PLATE IV

1 – 3, 5 - 8. *Trachysphaeridium* sp. population in thin sections (1 - 3) and macerated residue (5- 8); 4. *Shuiyousphaeridium echinulatum* Yin and Gao; 4a. Circular pits and reticulate ornamentations on the vesicle; 5–8. Medial splitting in the vesicle; 9–11. *Cymatiosphaeroides kullingii* Knoll. 10, 11. Note that the Pyrite framboid confined in the outer membrane. Scale bar for each figure is 50  $\mu\text{m}$ .

1. Slide No. BSIP 14141, England Finder No. N29; 2. Slide No. BSIP 14138, England Finder No. N45; 3. Slide No. BSIP 14142, England Finder No. C43/4; 4. Slide No. BSIP 14145, England Finder No. O40/1; 5. Slide No. BSIP 14147, England Finder No. G45/4; 6. Slide No. BSIP 14148, England Finder No. V37/4; 7. Slide No. BSIP 14145, England Finder No. N57; 8. Slide No. BSIP 14147, England Finder No. W26; 9. Slide No. BSIP 14144, England Finder No. P35; 10. Slide No. BSIP 14139, England Finder No. Z38/4; 11. Slide No. BSIP 14138, England Finder No. K42.





sp. were earlier reported from the Chitrukut Formation (Kumar and Srivastava, 1991; Anbarasu, 2001a) yet their antiquity and affinity, were not discussed. Both the taxa are common in various Neoproterozoic successions across the world (Knoll, 1984; Allison and Awramik, 1989). Several morphotypes recorded from the Proterozoic successions are claimed as having eukaryotic affinities but among them the acritarchs have indisputably considered as best eukaryotic candidate. If the Chitrukut OWMs are indeed acritarchs and not the characteristic Neoproterozoic forms than what are the reasons for their occurrence in Palaeoproterozoic sediments and significance thereof. In the following text we discuss these aspects of the Chitrukut acritarch assemblage in the context of three broad Proterozoic time divisions: Palaeoproterozoic, Mesoproterozoic and Neoproterozoic.

In recent years, exceptionally well-preserved structurally complex ornamented acritarchs assemblages, bearing irregularly distributed processes of varying shape with complex ultrastructure, are recorded from the Ediacaran (late Neoproterozoic) sediments of Australia, China, Siberia, Russia and India (Zhang *et al.*, 1998; Knoll *et al.*, 2006; Willman and Moczyłowska, 2008; McFadden *et al.*, 2008; Sergeev *et al.*, 2011). These are known as Ediacaran Complex of Acanthomorphic Palynoflora (ECAP) – some of which have alternatively been related to be the egg cysts of invertebrate metazoans (Cohen *et al.*, 2009). The assemblages of this time period show extraordinary taxonomic diversity that represent pronounced diversification of major eukaryotic clade in late Neoproterozoic biosphere after global cooling (Nagy *et al.*, 2009). Compilation of total diversity (Vidal and Moczyłowska, 1997), assemblage diversity (Knoll *et al.*, 2006) and morphospace occupation (Huntley *et al.*, 2006) indicates that the acritarchs were moderately diverse and wide spread (Knoll *et al.*, 2006) in older sediments (Meso-Palaeoproterozoic). Based on higher acritarchs diversity in the Neoproterozoic time palaeontologist contended that eukaryotes did not evolve until 850 Ma (Cavelier-Smith, 2010). This time period includes richness of unornamented sphaeromorphs and process bearing acritarchs (Javaux and Marshall, 2006).

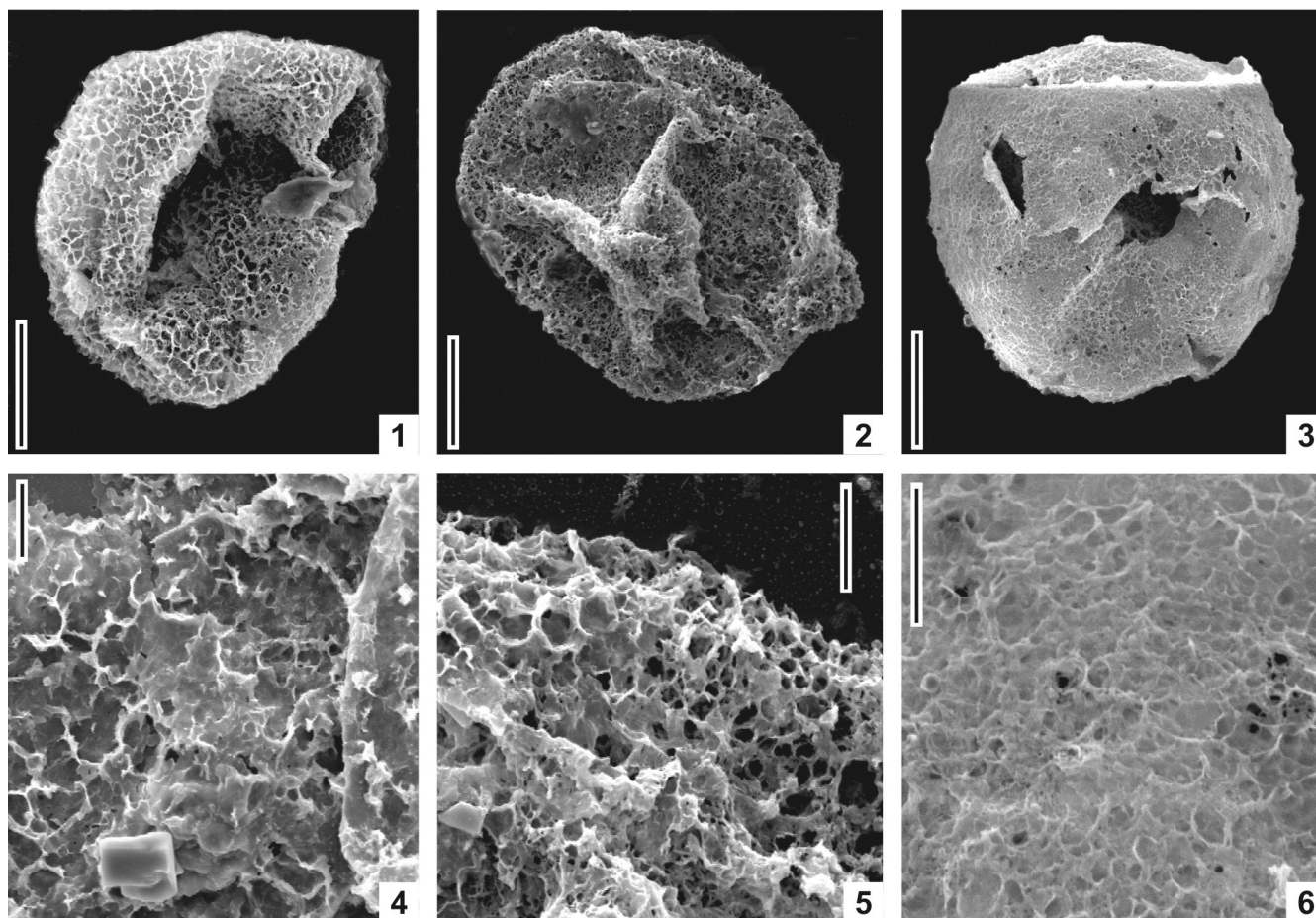
Mesoproterozoic sedimentary rocks contain abundant, but modest diverse fossils of probable eukaryotic origin (Javaux, 2011). Shales occurring in ~1600 Ma and younger sequences contain microfossils that combine large size (> 100 µm) with complex ultrastructure, structurally complex ornamented cell wall and surface processes of varying forms (Yin *et al.*, 2005). Various sphaeromorphic, acanthomorphic and netromorphic acritarchs have been reported from the sediments of this time span. Large cell size, once considered as pointer of eukaryote's existence is only suggestive evidence and not unequivocally accepted because most of the modern single celled eukaryotes are >10 – 20 µm in diameter while most of the prokaryotic cells are also > 50 - 100 µm in diameter (Javaux *et al.*, 2003; Buick, 2010). Ornamented acritarch *Shuiyousphaeridium* is one of the oldest best preserved and morphologically complex acritarch that existed in anoxic and sulfidic Palaeoproterozoic oceans. Yan (1995) described *Shuiyousphaeridium* (size 50 – 250 µm) with ridged walls, made up of regularly packed hexagonal plates from the 1.6 Ga Ruyang Group (Pang *et al.*, 2013). Three species *viz.* *S. macroreticulatum* (Yin, 1997), *S. echinulatum* (Yin and Gao, 1999), *S. pilatum* (Meng *et al.*, 2012) have been differentiated from each other by their vesicle size and processes arrangement. Chitrukut OWMs include abundance of *Shuiyousphaeridium*

*echinulatum*, which is morphologically characterized by large size vesicle (128 - 286 µm), having short unbranched processes (5 - 20 µm) and intracellular inclusions (18 - 59 µm) within the vesicle. This form was originally reported from the Baicaooping Formation of Ruyang Group exposed in southern margin of North China (Yin and Gao, 1999). *Shuiyousphaeridium* contains nucleus like dark, circular intra-cellular inclusion.

Besides large size, there are other features which are considered important in establishing an entity as eukaryote *viz.*, complex surface ornamentation, spiny processes extending from the surface, excystment ruptures, complex wall ultrastructure, or specific hydrocarbon biomarker geochemistry (Buick, 2010). In modern biology, the nucleus is the characteristic feature of eukaryotes on which basis they are differentiated from prokaryotes. Are these nuclei similar to modern eukaryotes? What is their origin? In a study of Ruyang Group acritarchs, Pang *et al.* (2013) have suggested the biological origin for the intracellular inclusion present in *Shuiyousphaeridium* and *Dictyosphaera*. The comparison suggests that the morphological complexity and the presence of intracellular inclusions, which may represent a nucleus in the *Shuiyousphaeridium*, denote the presence of eukaryote in the Proterozoic strata.

In addition, the Chitrukut Organic-Walled Microfossils include two other ornamented acritarchs *Cymatiosphaeroides* and *Trachysphaeridium*. Such ornamented acritarchs are generally found in the Neoproterozoic successions (800-700 Ma) of Canada, Spitsbergen, USA (Arizona), Sweden and Russia (Vidal, 1976; Knoll, 1984; Allison and Awramik, 1989; Knoll *et al.*, 1991; Butterfield *et al.*, 1994; Zang, 1995; Veis *et al.*, 2006; Voroveba *et al.*, 2009; Nagy *et al.*, 2009). They have also been found in Palaeoproterozoic Ruyang Group, China (Yin and Gao, 1999) and India (Kumar and Srivastava, 1991; Anbarasu, 2001a; Singh *et al.*, 2008). A rare occurrence of *Trachysphaeridium* has also been noted from the Archaean sediments of northern Karelia (Astafieva *et al.*, 2005). Herkomorphic acritarch *Cymatiosphaeroides kullingii* is second most abundant elements in the Chitrukut OWMs. It is a common constituent of shallow marine Neoproterozoic OWM assemblage (Knoll, 1984; Knoll *et al.*, 1991; Allison and Awramik, 1989; Nagy *et al.*, 2009) but also known from the Mesoproterozoic sediments (Anbarasu, 2001a). Yin and Gao (1999) have reported *Cymatiosphaeroides pilatopilum* and *Cymatiosphaeroides* sp. from the Mesoproterozoic Baicaooping Formation of Ruyang Group of North China. *C. pilatopilum* was originally reported from the Neoproterozoic Amadeus Basin, Australia (Zang and Walter, 1992). If these are, in fact, the Neoproterozoic fossils occurring in Late Palaeoproterozoic to Early Mesoproterozoic strata, then their presence in the Chitrukut Formation has a great significance in terms of understanding of the advent and antiquity of eukaryotes. On the basis of present occurrence and earlier reports (Yin and Gao, 1999) we suggest their origin in the Late Palaeoproterozoic and their subsequent diversification in the Neoproterozoic.

Other convincing eukaryotic fossil includes *Tappania plana*, a vesicle with numerous spiny processes in the Mesoproterozoic. It was also described from the coastal facies of the Ruyang Group, China (Yin, 1997), subsequently reported from the Bahraich Group in India (Prasad and Asher, 2001), Siberia (Nagovitsin, 2009) and Roper Group in Australia (Javaux *et al.* 2001, 2003) and also found in the Wynniatt Formation, Arctic Canada (Butterfield, 2005). *Tappania* extends up to 160 µm in diameter and is characterized by hollow cylindrical processes



SINGH AND SHARMA

#### EXPLANATION OF PLATE V

Scanning Electron Microscopic (SEM) images showing ultrastructure of the Chitrukut OWMs.

1. *Shuiyosphaeridium echinulatum* Yin and Gao; 2. *Cymatiosphaeroides kullingii* Knoll; 3. *Trachysphaeridium* sp.; 4. Enlarge view of *S. echinulatum* showing the reticulate vesicle wall; 5. Vesicle surface of *C. kullingii* showing processes arrangement; 6. Details of *Trachysphaeridium* sp. vesicle surface. Scale bar for figs. 1-3 = 50  $\mu$ m; figs. 4-6 = 10  $\mu$ m.

with extended tips. They are considered as eukaryotes based on Light Microscopy (LM) and Transmission Electron Microscopy (TEM) investigations (Javaux *et al.*, 2004). *Tappania* has also been recorded from the Neoproterozoic (~ 850 Ma) sediments, however, they show complex multicellularity and assigned as precursor of fungi (Butterfield, 2005; Nagovitsin, 2009) but its affinity is still viewed as uncertain because of the limited number of systematically informative characters (Knoll *et al.*, 2006). Additional OWMs of Mesoproterozoic includes *Valeria lophostriata* - a spherical vesicle with concentric striations - is one of the examples which is found in the sediments of ~ 1650 Ma (Javaux *et al.*, 2004) to ~700 Ma (Hofmann, 1999); *Navifusa segmentatus* - is a form having elliptic outline having linear transverse striations on the surface, these are recorded extensively from the various Mesoproterozoic successions in Australia, north China, Siberia, Greenland, and North America (Hofmann and Jackson, 1994, 1996; Javaux *et al.*, 2001, 2004; Nagovitsin, 2009). Two other ornamented acritarchs taxa viz., *Sipromorpha segmentata* and *Discityosphaera delicata* with complex morphology were also recorded from the Mesoproterozoic sediments and their affinity were assigned as eukaryotes

(Knoll *et al.*, 2006). In addition, the sphaeromorphic acritarchs *Dictyosphaera* and *Tasmanites* includes complex morphological features, such as rounded opening and striated ornamentation on the vesicle surface which can be attributed to eukaryotic affiliation. Recent studies indicate that the Palaeoproterozoic acritarchs had low diversity from the first occurrence. Most of the recorded species are known from the shales of shallow marine depositional environment. Yan and Liu (1997) have reported acritarchs and multicellular microfossils assemblages comprising dominantly of *Qingshania magnifica*, *Thecatovalvia annulata* and *Valvimorpha annulata* from the Chuanlinggou Formation of China. They suggested the eukaryotic affinity for these acritarchs on the basis of concentric striations and cytoskeleton system. Additionally, Lamb *et al.* (2009) have reported large sphaeromorphic acritarchs assemblages from the ~1800 Ma old Changzhougou Formation of north China, as oldest possible eukaryotic attributes on the basis of medial split, variation in cell wall structure and wall flexibility. Additional Organic-Walled Microfossils *Tappania*, *Cymatiosphaeroides* and *Trachyhystrichosphaera* have also been recorded from the

Beidajian Formation of the Palaeoproterozoic Ruyang Group, China (Yin *et al.*, 2005).

The overall fossilized features that are consistent with eukaryotic affinity include a combination of a large size, the presence of complex morphological features, wall structures or ornamentation, or typical excystment structures unknown in Prokaryotic organisms (Buick, 2010; Strother *et al.*, 2011). The Chittrakut microfossils are characterized by abundance of *Shuiyousphaeridium echinulatum*. It was originally reported as large circular to sub-circular vesicle (170 µm), having densely arranged short cylindrical processes, containing dark circular inclusion. Together with other members of the assemblage, the Chittrakut OWMs are large in size having complex morphological features and ornamentation on the basis of which these can be attributed to eukaryotic affinity. Record of *Shuiyousphaeridium* from the Chittrakut Formation represents third and possibly the oldest occurrence of acanthomorphic acritarchs during Palaeoproterozoic outside China and Australia.

## CONCLUSIONS

The discovery of Ruyang type microbiota from the Chittrakut Formation of the Semri Group represents an evolutionary innovation in the early eukaryotes in the Proterozoic biosphere. Morphological complexity suggests eukaryotic affinity for the Chittrakut microfossils. Most of the species found in the Chittrakut Formation are more or less similar to those found in Neoproterozoic but their occurrence in deep time suggests their origin in latest Palaeoproterozoic time and subsequent diversity in Neoproterozoic through Mesoproterozoic. The Chittrakut assemblage represents first occurrence of *Shuiyousphaeridium* type acritarch assemblage in the Vindhyan Supergroup.

## ACKNOWLEDGEMENTS

The authors are grateful to Prof. Sunil Bajpai, Director, Birbal Sahni Institute of Palaeobotany, Lucknow for providing necessary facilities during the progress of this work and permission to publish it. The paper is dedicated to the memory of our colleague, the late Dr. Manoj Shukla. We are thankful to Prof. Shuhai Xiao for helpful discussions and to Prof. S. Kumar for constructive suggestions and criticism.

## REFERENCES

- Allison, C. W. and Awramik, S. M. 1989. Organic-walled microfossils from earliest Cambrian or latest Proterozoic Tindir Group rocks, northwest Canada. *Precambrian Research*, **43**: 253–294.
- Anbarasu, K. 2001a. Acritarchs from the Mesoproterozoic, Chittrakoot Formation, Semri Group, Chittrakoot area, Central India. *Journal of the Geological Society of India*, **57**: 179–183.
- Anbarasu, K. 2001b. Facies variation and depositional environment of Mesoproterozoic Vindhyan sediments of Chittrakut Area, Central India. *Journal of the Geological Society of India*, **58**: 341–350.
- Astafieva, M. M., Hoover, R. B., Rozanov, A. Y. and Vrevskiy, A. B. 2005. Fossil microorganisms in Archaean deposits of Northern Karelia., *Proc. SPIE 5906, Astrobiology and Planetary Missions*: 590–606. doi:10.1117/12.646847.
- Auden, J. B. 1933. Vindhyan sedimentation in the Son Valley Mirzapur district. *Memoir Geological Survey of India*, **62**(2): 141–250.
- Azmi, R. J. 1998. Discovery of Lower Cambrian small shelly fossils and brachiopods from the lower Vindhyan of Son Valley, Central India. *Journal of the Geological Society of India*, **52**(4): 381–389.
- Azmi, R. J., Joshi, D., Tiwari, B. N., Joshi, M. N., Mohan, K. and Srivastava, S. S. 2007. Age of the Vindhyan Supergroup of Central India: An exposition of biochronology vs radiochronology, p. 29–62. In: *Micropaleontology: Application in Stratigraphy and Paleooceanography*, (Ed. Sinha, D.), Narosa Publishing House, New Delhi.
- Basu, A. and Bickford, M. E. 2014. Contributions of zircon U–Pb geochronology to understanding the volcanic and sedimentary history of some Purāna basin. *Journal of Asian Earth Sciences*. <http://dx.doi.org/10.1016/j.jseae.2013.06.018>.
- Basu, A., Patranabis-Deb, S., Schieber, J. and Dhang, P. C. 2008. Stratigraphic position of the ~1000 ma Sukhda Tuff (Chhattisgarh Supergroup, India) and the 500 Ma question. *Precambrian Research*, **167**: 383–388.
- Bengtson, S., Belivanova, V., Rasmussen, B. and Whitehouse, M. 2009. The controversial “Cambrian” fossils of the Vindhyan are real but more than a billion years older. *Proceedings of National Academy of Sciences, USA*, **106**(19): 7729–7734.
- Buick, R. 2010. Ancient Acritarchs. *Nature* **463**: 885–886.
- Butterfield, N. J. 2004. A vaucherian alga from the Middle Neoproterozoic of Spitsbergen: Implications for the evolution of Proterozoic eukaryotes and the Cambrian explosion. *Paleobiology*, **30**: 231–252.
- Butterfield, N. J. 2005. Probable Proterozoic fungi. *Paleobiology*, **31**: 165–182.
- Butterfield, N. J., Knoll, A. H. and Swett, K. 1994. Paleobiology of the Upper Proterozoic Svanbergfjället Formation, Spitsbergen. *Fossils and Strata*, **34**: 1–84.
- Cavalier-Smith, T. 2010. Deep phylogeny, ancestral groups and the four ages of life. *Philosophical Transactions Royal Society London*, **36**(5): 111–132.
- Chakraborty, C. 2006. Proterozoic intercontinental basin the Vindhyan example. *Journal of Earth System Sciences*, **115**: 13–22.
- Cohen, P. A., Knoll, A. H., Kodner, R. B. 2009. Large spinose microfossils in Ediacaran rocks as resting stages of early animals. *Proceedings of National Academy Sciences*, **16**, 6519–6524.
- Downie, C., Evitt, W. R. and Sarjient, W. A. S. 1963. Dinoflagellates, hystrichospheres, and the classification of the acritarchs. *Stanford University Publication Geological Science*, **7**(3): 1–16.
- Evitt, W. R. 1963. A discussion and proposals concerning fossil Dinoflagellates, Hystrichospheres and Acritarchs. *U. S. National Academy Sciences Proceedings*, **49**, 158–164, 298–302.
- Gregory, L. C., Meert, J. G., Pradhan, V., Pandit, M. K., Tamrat, E. and Malone, S. J. 2006. A paleomagnetic and geochronologic study of the Majhgawan kimberlite, India: Implications for the age of the Upper Vindhyan Supergroup. *Precambrian Research*, **149**: 65–75.
- Grey, K. 1999. A modified palynological preparation technique for the extraction of large Neoproterozoic acanthomorph acritarchs and other acid insoluble microfossils. *Record of Geological Survey of Western Australia*, **1999/10**: 1–23.
- Grey, K. and Willman, S. 2009. Taphonomy of Ediacaran Acritarchs from Australia: significance for taxonomy and biostratigraphy. *Palaios*, **24**: 239–256.
- Han, T.-M., and Runnegar, B. 1992. Megascopic Eukaryotic Algae from the 2.1-Billion-Year-Old Negaunee Iron-Formation, Michigan. *Science*, **257**: 232–235.
- Hofmann, H. J. 1999. Global distribution of the Proterozoic sphaeromorph acritarch *Valeria lophostriata* (Jankauskas). *Acta Micropalaeontologica Sinica*, **16**: 215–224.
- Hofmann, H. J. 2005. Palaeoproterozoic Dubiofossils from India Revisited - Vindhyan Triploblastic Animal Burrows or Pseudofossils? *Journal of the Palaeontological Society of India*, **50**(2): 113–120.
- Hofmann, H. J. and Jackson, G. D. 1994. Shale facies microfossils from the Proterozoic Bylot Supergroup, Baffin Island, Canada. *Memoir Paleontological Society*, **37**: 1–35.
- Hofmann, H. J. and Jackson, G. D. 1996. Notes on the geology and micropaleontology of the Proterozoic Thule Group, Ellesmere Island, Canada and North-West Greenland. *Geological Survey of Canada Bulletin*, **495**: 1–26.
- Huntley, J. W., Xiao, S. and Kowalewski, M. 2006. 1.3 Billion years of acritarch history: an empirical morphospace approach. *Precambrian Research*, **144**: 52–68.
- Javaux, E. 2011. Early eukaryotes in Precambrian oceans. In *Origins and evolution of life: An astrobiological perspective* (ed. Gargaud M., *et al.*), Cambridge University Press, Cambridge, UK: 414–449.
- Javaux, E. J. and Marshal, C. P. 2006. A new approach in deciphering early protest paleobiology and evolution: Combined microscopy

- and microchemistry of single Proterozoic acritarchs. *Review of Palaeobotany and Palynology*, **139**(1-4): 1-15.
- Javaux, E., Knoll, A. H., and Walter, M. R.** 2001. Morphological and ecological complexity in early eukaryotic ecosystems. *Nature*, **412**: 66-69.
- Javaux, E., Knoll, A. H., and Walter, M. R.** 2003. Recognizing and interpreting the fossils of early eukaryotes. *Origin of Life and Evolutionary Biosphere*, **33**: 75-94.
- Javaux, E., Knoll, A. H., and Walter, M. R.** 2004. TEM evidence for eukaryotic diversity in mid-Proterozoic oceans. *Geobiology*, **2**: 121-132.
- Joshi, D., Azmi, R. J. and Srivastava, S. S.** 2006. Earliest Cambrian calcareous skeletal algae from Tirohan Dolomite, Chitrakoot, Central India: A new age constraint for the Lower Vindhyan. *Gondwana Geology Magazine*, **21**: 73-82.
- Knoll, A. H.** 1984. Microbiotas of the Late Precambrian Hunnberg Formation, Nordaustlandet, Svalbard. *Journal of Paleontology*, **58**: 131-162.
- Knoll, A. H.** 1994. Proterozoic and Early Cambrian protists: evidence for accelerating evolutionary tempo. *Proceedings of the National Academy of Sciences USA*, **91**: 6743-6750.
- Knoll, A. H.** 2014. Paleobiological Perspectives on Early Eukaryotic Evolution, p. 1-14. In: *Additional Perspectives on the Origin and Evolution of Eukaryotes* (Eds. Keeling, P. J. and Koonin, E. V.), Cold Spring Harbor Perspectives in Biology, **6**.
- Knoll, A. H. and Calder, S.** 1983. Microbiota of the Late Precambrian Ryssö Formation, Nordaustlandet, Svalbard. *Palaentology*, **26**: 467-496.
- Knoll, A. H., Javaux, E. J., Hewitt, D. and Cohen, P.** 2006. Eukaryotic organisms in Proterozoic oceans. *Philosophical Transactions Royal Society London*, **361B**: 1023-1038.
- Knoll, A. H., Swett, K. and Mark, J.** 1991. Paleobiology of a Neoproterozoic tidal flat/lagoonal complex: the Draken Conglomerate Formation, Spitsbergen. *Journal of Paleontology*, **65**: 531-570.
- Kumar, A., Gopalan, K. and Rajagopalan, G.** 2001. Age of the Lower Vindhyan Sediments, Central India. *Current Science*, **81**(7): 806-809.
- Kumar, S.** 1993. Mineralogy, geochemistry and genesis of middle Riphean phosphatic carbonates, Tirohan Limestone (Lower Vindhyan Supergroup), Chitrakut area, central India. *Journal of the Geological Society of India*, **41**: 133-143.
- Kumar, S.** 1995. Megafossils from the Mesoproterozoic Rohtas Formation (the Vindhyan Supergroup), Katni area, central India. *Precambrian Research*, **72**(12): 171-184.
- Kumar, S. and Srivastava, P.** 1991. Microfossils from the nonstromatolitic Middle Proterozoic Vindhyan Chert, Chitrakut area, Uttar Pradesh. *Journal of the Geological Society of India*, **38**: 511-515.
- Lamb, D. M., Awramik, S. M., Chapman, D. J. and Zhu, S.** 2009. Evidence for eukaryotic diversification in the ~1800 million-year-old Changzhougou Formation, North China. *Precambrian Research*, **173**: 93-104.
- Malone, S. J., Meert, J. G., Banerjee, D. M., Pandit, M. K., Tamrat, E., Kamenov, G. D., Pradhan, V. R. and Sohl, L. E.** 2008. Paleomagnetism and detrital Zircon geochronology of the Upper Vindhyan sequence, Son Valley and Rajasthan, India: A ca. 1000Ma Closure age for the Purana Basins?. *Precambrian Research*, **164**: 137-159.
- McFadden, K. A., Huang, J., Chu, X., Jiang, G., Kaufman, A. J., Zhou, C., Yuan, X., Xiao, S.** 2008. Pulsed oxidation and biological evolution in the Ediacaran Doushantuo Formation. *Proceedings of the National Academy of Sciences of the United States of America*, **105**: 3197-3202.
- Mendelson, C. V.** 1987. Acritarchs In: *Fossil Prokaryotes and Protists*, p. 62-86 (Ed., Lipps, J.), University of Tennessee, Knoxville.
- Meng, Li., Peng-jiu Liu, Yin, C., Tang, F., Gao, L. and Chen, S.** 2012. Acritarchs from the Baicaooping Formation (Ruyang Group) of Henan. *Acta Palaeontologica Sinica*, **51**(1): 78 -87 (in Chinese with English abstract).
- Nagovitsin, K.** 2009. *Tappania*-bearing association of the Siberian platform: biodiversity, stratigraphic position and geochronological constraints. *Precambrian Research*, **173**:137-145.
- Nagy, R. M., Porter, S. M., Dehler, C. M. and Shen, Y.** 2009. Biotic turnover driven by eutrophication before the Sturtian low-latitude glaciation. *Nature Geoscience*, **2**: 415-418.
- Narain, K.** 1970. Vindhyan sedimentation in the Karvi area, Uttar Pradesh. *Records of the Geological Survey of India*, **98**(2): 96-106.
- Nautiyal, A. C. and Singh, S.** 1990. Petrography and tectonic significance of lower Vindhyan arenites (Proterozoic) of Sangrampur Hill (Banda District), Northern India. *Proceedings of Indian National Science Academy*, **57A**(3): 437-454.
- Nautiyal, A. C.** 1986. Lower Vindhyan (Algonkian) microflora (microbiota) and biostratigraphy of Sangrampur hill, Banda district, Northern India. *Geoscience Journal*, **7**: 1-22.
- Pang, K., Tang, Q., Schiffbauer, J. D., Yao, J., Yuan, X., Wan, B., Chen, L., Ou, Z. and Xiao, S.** 2013. The nature and origin of nucleus-like intracellular inclusions in Paleoproterozoic eukaryote microfossils. *Geobiology*, **11**: 499-510.
- Prasad, B. and Asher, R.** 2001. Acritarch biostratigraphy and lithostratigraphic classification of Proterozoic and lower Paleozoic sediments (pre-unconformity sequence) of Ganga Basin. *India Paleontographica Indica*, **5**:1-151.
- Prasad, B., Uniyal, S. N. and Asher, R.** 2005. Organic walled microfossils from the Proterozoic Vindhyan sediments of Son Valley, Madhya Pradesh, India. *Palaebotaniat*, **54**: 13-60.
- Rasmussen, B., Bose, P. K., Sarkar, S., Banerjee, S., Fletcher, I. R. and McNaughton, N. J.** 2002. 1.6 Ga U-Pb Zircon age for Chorhat Sandstone, Lower Vindhyan, India: possible implications for early evolution of animals. *Geology*, **30**: 103-106.
- Ray, J. S.** 2006. Age of the Vindhyan Supergroup: a review of recent findings. *Journal of Earth System Science*, **115**: 149-160.
- Ray, J. S., Martin, M. W., Veizer, J. and Bowring, S. A.** 2002. U-Pb zircon dating and Sr isotope systematics of the Vindhyan Supergroup, India. *Geology*, **30**: 131-134.
- Ray, J. S., Veizer, J. and Davis, W. J.** 2003. C, O, Sr and Pb isotope systematics of carbonate sequences of the Vindhyan Supergroup, India: age diagenesis correlations and implications for global events. *Precambrian Research*, **121**: 103-140.
- Retallack, G. J., Krull, E. S., Thackray, G. D., and Parkinson, D.** 2013. Problematic urn-shaped fossils from a Paleoproterozoic (2.2 Ga) paleosol in South Africa. *Precambrian Research* **235**: 71-87.
- Safaya, H. L.** 1975. Microfacies and depositional history of Strandline carbonates of Semri Series. Lower Vindhyan System. Banda Dist., U.P. *Journal of the Geological Society of India*, **16**(3): 294-303.
- Sarangi, S., Gopalan, K. and Kumar, S.** 2004. Pb-Pb age of earliest megascopic, eukaryotic alga bearing Rhotas Formation, Vindhyan Supergroup, India: implications for Precambrian atmospheric oxygen evolution. *Precambrian Research*, **132**: 107-121.
- Sastri, M. V. A. and Moitra, A. K.** 1984. Vindhyan Stratigraphy— A review. *Memoir Geological Society of India*, **16**: 109-148.
- Schneider, D. A., Bickford, M. E., Cannon, W. F., Schulz, K. J. and Hamilton, M. A.** 2002. Age of volcanic rocks and syndepositional iron formations, Marquette Range Supergroup: implications for the tectonic setting of Paleoproterozoic iron formations of the Lake Superior region. *Canadian Journal of Earth Sciences* **39** (6): 999-1012.
- Seilacher, A., Bose, P. K., and Pfluger, F.** 1998. Triploblastic animals more than 1 billion years old: Trace fossil evidence from India. *Science*, **282**: 80-83.
- Sergeev, V. N.** 2009. The distribution of microfossil assemblages in Proterozoic rocks. *Precambrian Research*, **173**: 212-222.
- Sergeev, V. N., Knoll, A. H. and Vorob'eva, N. G.** 2011. Ediacaran microfossils from the Ura Formation, Baikal-Patom Uplift, Siberia: Taxonomy and Biostratigraphic significance. *Journal of Paleontology*, **85**(5): 987-1011.
- Sharma, M.** 2006. Palaeobiology of Mesoproterozoic Salkhan Limestone, Semri Group, Rohtas, Bihar, India: Systematic and significance. *Journal of Earth System Science*, **115**(1): 67-98.
- Sharma, M. and Shukla, Y.** 2009a. Taxonomy and affinity of Early Mesoproterozoic megascopic helically coiled and related fossils from the Rohtas Formation, the Vindhyan Supergroup, India. *Precambrian Research*, **193**:105-122.
- Sharma, M. and Shukla, Y.** 2009b. Mesoproterozoic coiled Megascopic fossil *Grypania spiralis* from the Rohtas Formation, Semri Group, Bihar, India. *Current Science*, **96**(12): 1636-1640.

- Singh, I. B.** 1985. Palaeogeography of Vindhyan Basin and its relationship with other late Proterozoic basins of India. *Journal of the Palaeontological Society of India*, **30**: 35-41.
- Singh, I. B. and Kumar, S.** 1978. On the stratigraphy and sedimentation of the Vindhyan sediments in the Chitrakut area, Banda District (U. P.), Satna District (M. P.). *Journal of the Geological Society of India*, **19**(8): 359-367.
- Singh, S. N. and Pal, O. P.** 1970. Geology around Chitrakoot area, District Banda, U. P. *Journal of the Palaeontological Society of India*, **14**: 77-85.
- Singh, V. K., Babu, R. and Shukla, M.** 2008. Mesoproterozoic microbiotic fossil assemblage from the Chitrakut Formation, Semri Group, Vindhyan Supergroup. Conference *On Plant life through the ages*, BSIP, Lucknow, 16-17 November, 2008, 170-171. (Abstract).
- Singh, V. K., Babu, R. and Shukla, M.** 2009. Discovery of carbonaceous remains from the Neoproterozoic shales of Vindhyan Supergroup, India. *Journal of Evolutionary Biology Research*, **1**(1): 1-17.
- Singh, V. K., Babu, R. and Shukla, M.** 2011. Heterolithic prokaryotes from the coated grains bearing carbonate facies of Bhandar Group, Madhya Pradesh, India. *Journal of Applied Bioscience*, **37**(2): 80-90.
- Srivastava, P. and Kumar, S.** 2003. New microfossils from the Meso-Neoproterozoic Deoban Limestone, Garhwal Lesser Himalaya, India. *Palaeobotanist*, **52**: 13-47.
- Staplin, F. L.** 1961. Reef controlled distribution of Devonian microplankton in Alberta. *Palaeontology*, **4**(3): 394-424.
- Strother, P. K., Battison, L., Brasier, M. D. and Wellman, C. H.** 2011. Earth's earliest non-marine eukaryotes. *Nature*, **473**: 505-509.
- Timofeev, B. V.** 1959. Drevneishaya flora prebaltiki I ee stratigraficheskoe znachenie, Leningrad. Vsesoyuznyi neftyanoi Nauchno-Issledovatel'skii Geologorazvedochnyi Institut (VNIGRI) Trudy 129: 1-36 (in Russian).
- Timofeev, B. V.** 1969. *Spheromorphids of the Proterozoic*. (Nauka, Leningrad. [in Russian]).
- Veis, A. F., Vorob'eva, N. G. and Golubkova, E. Yu.** 2006. The early Vendian microfossils first found in the Russian Plate: taxonomic composition and biostratigraphic significance. *Stratigraphy Geological Correlation*, **14**: 368-385.
- Venkatachala, B. S., Sharma, M. and Shukla, M.** 1996. Age and life of Vindhyan—facts and conjectures. *Memoir Geological Society of India*, **36**: 137-165.
- Vidal, G.** 1976. Late Precambrian microfossils from the Visingsö beds in Southern Sweden. *Fossil and Strata*, **9**: 1-57.
- Vidal, G. and Ford, T. D.** 1985. Microbiotas from the Late Proterozoic Chuar Group Northern Arizona and Uinta Mountains Group Utah and their chronostratigraphic implications. *Precambrian Research*, **28**: 349-389.
- Vidal, G., and Moczydlowska-Vidal, M.** 1997. Biodiversity, speciation, and extinction trends of Proterozoic and Cambrian phytoplankton. *Paleobiology* **23**: 230-246.
- Volkova, N. A.** 1965. On the nature and classification of the Precambrian and Lower Paleozoic plant microfossils. *Paleontologicheskii zhurnal*, **1**: 1-13. (in Russian).
- Vorob'eva, N. G., Sergeev, V. N. and Knoll, A. H.** 2009. Neoproterozoic microfossils from the northeastern margin of the East European Platform. *Journal of Paleontology*, **83**:161-196.
- Walter, M. R., Du, R. and Horodyski, R. J.** 1990. Coiled carbonaceous megafossils from the middle Proterozoic of Jixian (Tianjin) and Montana. *American Journal of Science*, **290-A**: 133-148.
- Willman, S. and Moczydlowska, M.** 2008. Ediacaran acritarch biota from the Giles 1 drillhole, Officer Basin, Australia, and its potential for biostratigraphic correlation. *Precambrian Research*, **162**: 498-530.
- Xiao, S.** 2013. Written in Stone: The Fossil Record of Early Eukaryotes, p. 107-124. In: *Evolution from the Galapagos* (Eds. Trueba, G. and Montúfar, C.), *Social and Ecological Interactions in the Galapagos Islands*, **2**.
- Yan, Y. and Zhu, S.** 1992. Discovery of acanthomorphic acritarchs from the Baicaoping Formation in Yongji, Shanxi and its geological significance. *Acta Micropalaeontologica Sinica*, **9**(3): 267-282.
- Yan, Y. Z.** 1995. Discovery and preliminary study of megascopic algae (1,700 Ma) from the Tuanshanzi Formation in Jixian, Hebei. *Acta Micropalaeontologica Sinica*, **12**(2): 107-126 (in Chinese).
- Yan, Yu. and Liu- Zhi- Li.** 1997. Tuanshanzian macroscopic algae of 1700 Ma B. P. from the Changcheng System of Jinxian China. *Acta Palaeontologica Sinica*, **36**(1): 18-41.
- Yin, Chong-yu and Gao, Lin-zhi.** 1999. Microflora in Baicaoping Formation of Ruyang Group in southern margin of north China platform and discussion. *Professional Papers of Stratigraphy and Palaeontology*, **27**: 81-94 (in Chinese with English abstract).
- Yin, L.** 1997. Acanthomorphic acritarchs from Meso-Neoproterozoic shales of the Ruyang Group, Shanxi, China. *Review of Palaeobotany and Palynology*, **98**: 15-25.
- Yin, L., Zhu, M., Knoll, A. H., Yuan, X., Zhang, J. and Hu, J.** 2007. Doushantuo embryos preserved inside diapause egg cysts. *Nature*, **446**: 661-663
- Yin, L., Yuan, X., Meng, F. and Hu, J.** 2005. Protists of the upper Mesoproterozoic Ruyang Group in Shanxi Province, China. *Precambrian Research*, **141**: 49-66
- Zang, W. L. and Walter, M. R.** 1992. Late Proterozoic and Early Cambrian microfossils and biostratigraphy, Amadeus Basin, central Australia. *Memoirs Association of Australasian Palaeontologists*, **12**: 1-132.
- Zang, W. L.** 1995. Early Neoproterozoic sequence stratigraphy and acritarch biostratigraphy, eastern Officer Basin, South Australia. *Precambrian Research*, **74**: 119-175.
- Zhang, Y., Lei-ming, Y., Xiao, S. and Knoll, A.H.** 1998. Permineralized fossils from the terminal Proterozoic Doushantuo Formation, South China. *Palaeontological Society Memoir*, **50**: 1-52.