

MICROBIAL FOSSILS FROM THE KHEINJUA FORMATION, MIDDLE PROTEROZOIC SEMRI GROUP (LOWER VINDHYAN), SON VALLEY AREA, CENTRAL INDIA

DIANNA SCHULTE McMENAMIN

Department of Geological Sciences, Preston Cloud Research Laboratory, University of California, Santa Barbara, California 93106 (U.S.A.)

SURENDRA KUMAR

Department of Geology, Lucknow University, Lucknow, 226007, U.P. (India)

STANLEY M. AWRAMIK

Department of Geological Sciences, Preston Cloud Research Laboratory, University of California, Santa Barbara, California 93106 (U.S.A.)

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ABSTRACT

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Abundant coccoid and filamentous microfossils are found in petrographic thin sections of stratiform stromatolitic cherts from the ≈ 1200 Ma-old Fawn Limestone of the Kheinjua Formation, lower Vindhyan Supergroup, central India. The assemblages is dominated by coccoid forms of probable chroococcacean and entophysalidacean affinities; most filaments closely resemble the oscillatoriacean *Gunflintia minuta*.

Unlike other Middle to Late Proterozoic stromatolitic microbiotas, the Kheinjua is dominated by microfossils $< 10 \mu\text{m}$ in diameter. Another notable feature of the assemblage is that its microfossils are found in extensive sheets of amorphous organic matrix, which also contains rare bizarre morphs unique to this formation.

Taxonomically, the Kheinjua microbiota most closely resembles Proterozoic microbiotas described from the Belcher Islands (Kasegalik Formation), McArthur Group, Bitter Springs Formation, and the Yudoma Suite.

The following taxa are formally described: Chroococcaceae — *Myxococcoides minor* Schopf, *Eosynechococcus isolatus* n.sp., *Tetraphycus congregatus* n.sp., *Kheinjua-sphaera vulgaris* n.gen., n.sp., *Glenobotrydion aenigmatis* Schopf, *Melasmatosphaera media* Hofmann; Entophysalidaceae — *Eoentophysalis belcherensis* Hofmann, *E. magna* n. sp.; Oscillatoriaceae — cf. *Gunflintia minuta* Barghoorn, *Eomycetopsis? siberiensis* Lo.

INTRODUCTION

The Middle to Late Proterozoic Vindhyan Supergroup covers an area of $\sim 104\,000 \text{ km}^2$ (Fig. 1) between Bihar in the east and Rajasthan to the west.

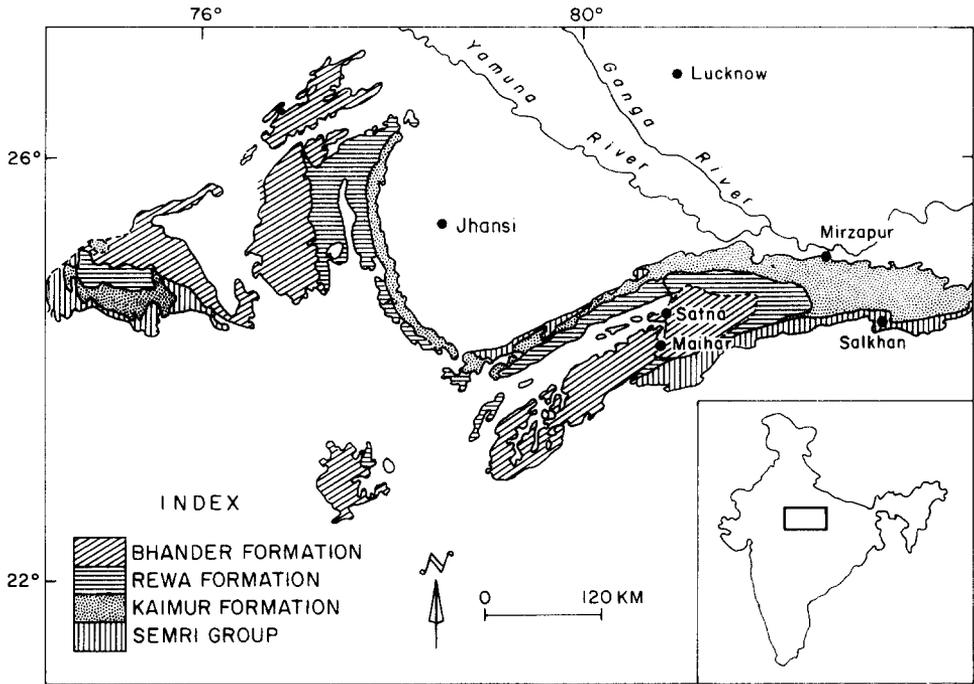


Fig. 1. The location and extent of the Vindhyan Supergroup (after Krishnan and Swaminath, 1959).

The Vindhyan has a maximum thickness of ≈ 4000 m and a lithology dominated by sandstone, shale, and limestone. As a whole the Vindhyan Supergroup is unmetamorphosed, has not undergone much tectonism, and is one of the best preserved Proterozoic sedimentary sequences in India.

The earliest report of fossils from the Vindhyan appears to be that of Auden (1933) who first recognized the structures now known to be stromatolites in a few strata of the sequence. Misra and Bhatnager (1950) reported carbonaceous disc-like bodies a few millimeters in diameter which are probably the acritarch *Chuarina*. Reports on acritarch microfossils are rare. Sitholey et al. (1953), Salujha (1971), Salujha et al. (1971), Salujha and Rehman (1972), and Maithi and Shukla (1977) have all described acritarchs from Vindhyan rocks, but the syngenecity of these microfossils is open to question. Caution must be exercised in acritarch research in order to convincingly demonstrate that the acritarch is not a post-depositional contaminant (Schopf and Prasad, 1978), a laboratory contaminant (Cloud and Morrison, 1979), or a micropseudofossil produced in the laboratory (Wang and Lo, 1983).

Kumar (1978a) reported on microfossils from thin sections of stratiform stromatolitic black chert from the Fawn Limestone of the Kheinjua Formation (Lower Vindhyan). These microfossils differ from acritarchs in that

they are found in petrographic thin section and have affinities among modern cyanobacterial groups, whereas the category 'acritarch' is generally reserved for *incertae sedis* microfossils found in acid residues.

Overall, the taxonomic composition of the microbiota from the Kheinjua Formation resembles other Proterozoic stratiform stromatolitic microbiotas, such as those from the ≈ 1900 Ma-old Belcher Islands (Hofmann, 1976), the ≈ 1500 Ma-old McArthur Group (Muir, 1976; D.Z. Oehler, 1978), the ≈ 850 Ma-old Bitter Springs Formation (Schopf and Blacic, 1971), and the ≈ 650 Ma-old Yudoma Suite (Lo, 1980). However, this microbiota is unusual and differs significantly from these and many other stromatolitic microbiotas in that: (1) it is dominated by small-sized ($< 10 \mu\text{m}$ diameter) individuals; (2) many of the microfossils are found in an abundant organic matrix which partly defines the stromatolitic lamination; and (3) there are some bizarre, multicomponent morphs present that defy placement in any known taxonomic category.

GEOLOGIC SETTING

The Vindhyan Supergroup has been recognized as an important stratigraphic unit since its establishment by Oldham (1856). The Supergroup is relatively thick (≈ 4000 m), extensive (outcrops cover $\sim 104\,000$ km²), and unmetamorphosed in most areas, but its stratigraphic position and age have been subject to debate for many years (Gupta, 1977).

Following the studies of Auden (1933), the Vindhyan is divided into two lithostratigraphic units; the lower unit, the Semri Group or Lower Vindhyan, is unconformably overlain by the Upper Vindhyan Group (Fig. 1). The Semri Group is best exposed in the Son Valley where it crops out in small hillocks and scarps. Here, four lithostratigraphic units are distinguished; the Basal Formation, the Porcellanite Formation, the Kheinjua Formation and the Rohtas Formation (Fig. 2). The Rohtas Formation is unconformably overlain by argillaceous-arenaceous rocks of the Upper Vindhyan Kaimur Formation. Stromatolite occurrences have been recorded from the Basal, Kheinjua and Rohtas Formations (Kumar, 1978b).

The Kheinjua Formation is further subdivided into three conformable lithological members. These are, in ascending stratigraphic order, the Olive Shale Member, the Fawn Limestone Member and the Glauconitic Sandstone Member. The Fawn Limestone contains the microfossiliferous cherts.

AGE

The Vindhyan Supergroup unconformably overlies the slightly metamorphosed Bijawar Group with a Rb-Sr age of ≈ 2500 Ma (Crawford and Compston, 1970). Despite the research activity on the Vindhyan Supergroup during the last 15 years (see Singh, 1973; Sahni, 1975; Kumar, 1978b), most radiometric age data are K-Ar dates of a mid-1960's vintage.

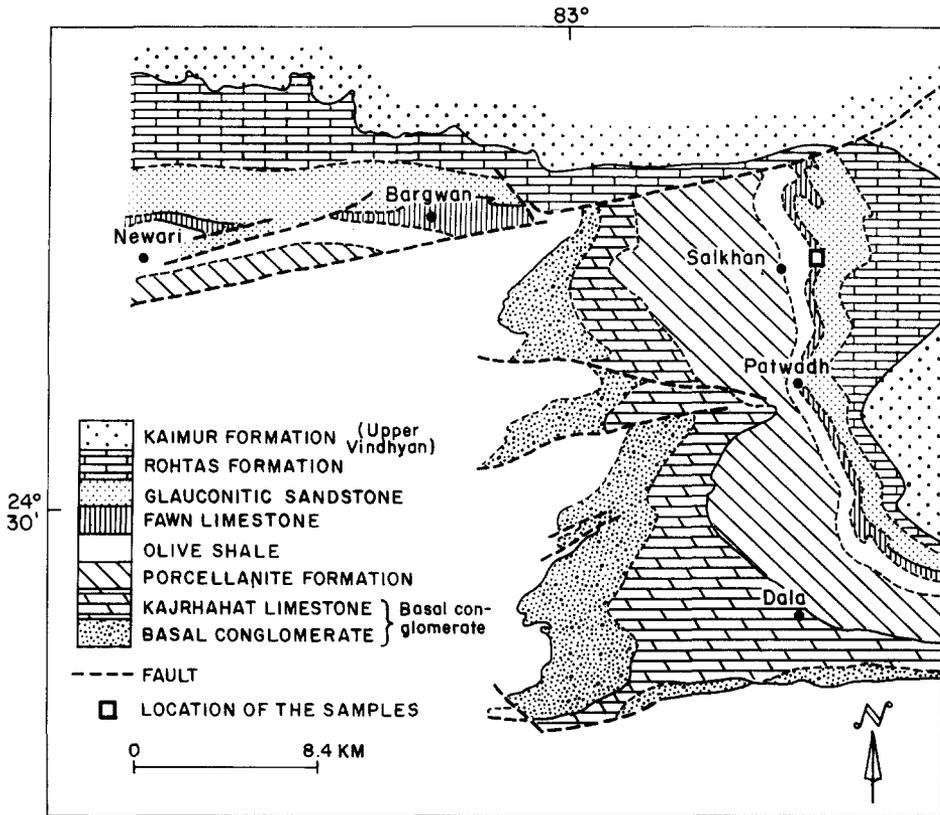


Fig. 2. The occurrence of the Semri Group in the Son Valley (after Auden, 1933).

The Glauconitic Sandstone Member that conformably overlies the Fawn Limestone is an important glauconite-bearing horizon in the Son Valley. The most quoted age for these glauconites is a K—Ar age of 1100 ± 60 Ma (Vinogradov et al., 1964). This has been recalculated with later recommended decay constants to 1080 ± 40 Ma (Kreuzer et al., 1977). Glauconite-bearing layers in the Kaimur Formation (Upper Vindhyan) have K—Ar ages of 940–910 Ma (Vinogradov et al., 1964) which have been recalculated to 890 ± 40 Ma (Kreuzer et al., 1977).

Ages based on biostratigraphically characteristic stromatolites are in general agreement with the K—Ar dates on glauconites. In the Kheinjua Formation (K—Ar age >1100 Ma), the Fawn Limestone contains the typical Middle Riphean (1350–950 Ma) stromatolite *Conophyton garganicum* (Kumar, 1976). Additional Middle Riphean stromatolites (*Tungussia* and *Baicalia*) are found in the Rhotas Formation (Kumar, 1980). However, as in most stromatolite work of this type, some of the data are inconsistent: *Boxonia* (an Upper Riphean to Lower Cambrian group) has been reported from the Upper Vindhyan Bhandar Formation (Rao et al., 1977).

The age of the Fawn Limestone, Kheinjua Formation, seems to be between 1300 and 1100 Ma-old (Kumar, 1978b) or ≈ 1200 Ma-old.

THE MICROFOSSILIFEROUS CHERT

The Fawn Limestone averages ≈ 35 m thick, and is a tan to gray-colored siliceous limestone with characteristic chert lenticles (Auden, 1933). Kumar (1978b) identified two facies of the Fawn Limestone Member in the Son Valley area: a lagoonal facies extending south from near Patwadh and an intertidal-supratidal carbonate tidal flat facies from Salkhan to the west (Fig. 2).

Near Salkhan, where the microfossil-bearing cherts were collected, the Fawn Limestone is only ≈ 10 – 12 m thick (Fig. 3) and the rocks are more or less horizontal. Here, *Conophyton garganicum* is profusely developed, up to 1.6 m thick. The entire Fawn Limestone, including the *Conophyton*-bearing zone, is characterized by ≈ 3 cm-thick dark gray to black bedded

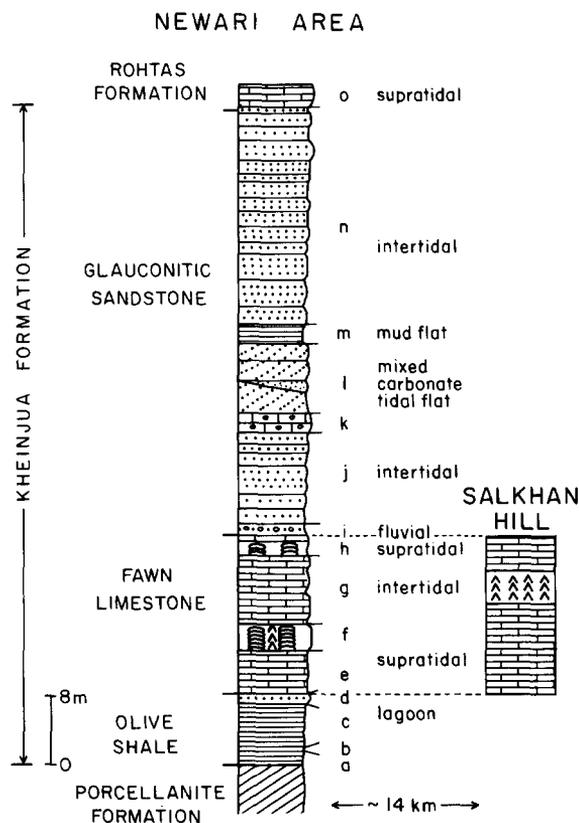


Fig. 3. Stratigraphy of the Kheinjua Formation in the Son Valley. The microfossiliferous cherts are just above the *Conophyton*-bearing bed, in the vicinity of Salkhan Hill.

chert. In places chert lenticles can be traced laterally for several meters. Near Patwadh, these black bedded cherts, as well as *Conophyton*, are absent.

Microfossiliferous cherts have only been found in strata just above the *Conophyton*-bearing bed near Salkhan (Fig. 4). Chert associated with *Conophyton* was also searched for microfossils, but only poorly preserved filaments, possibly sheaths of some cyanobacteria, could be found (Kumar, 1980a). The microbiota described here is found within stratiform stromatolitic chert laminae 0.4–2.5 mm thick (averaging ≈ 0.8 mm; Fig. 5A). The chert consists of cryptocrystalline quartz ($\approx 73\%$), opal ($\approx 19\%$) and pockets of fibrous chalcedony ($\approx 2\%$). The remaining $\approx 6\%$ is pyrite grains (some framboids) plus other opaque minerals, dolomite and organic material.

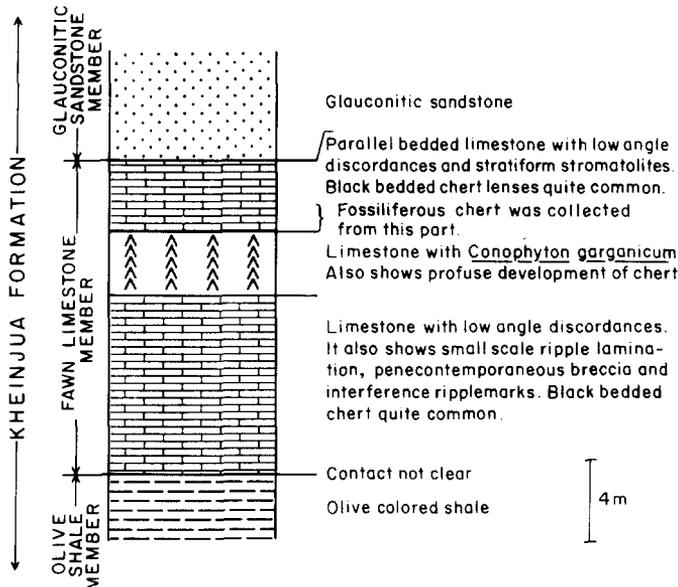
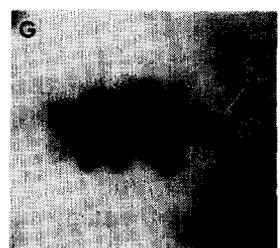
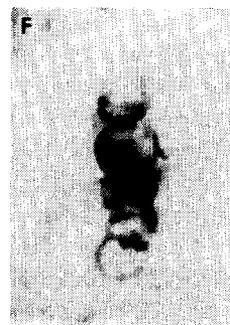
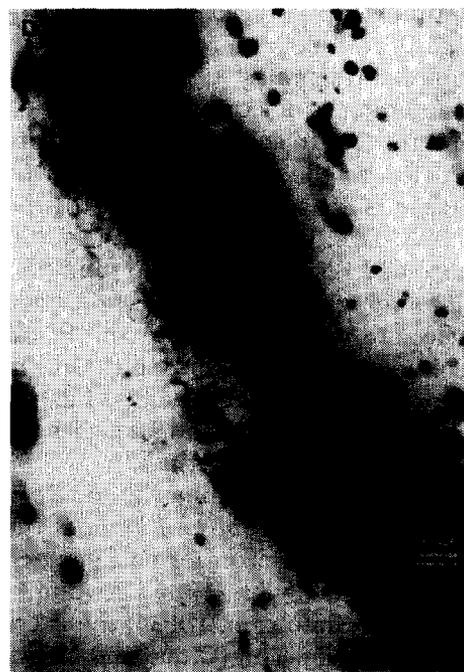
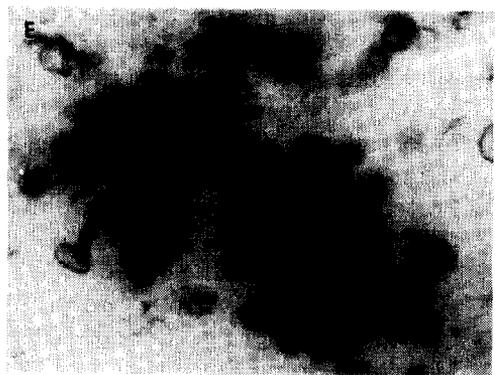
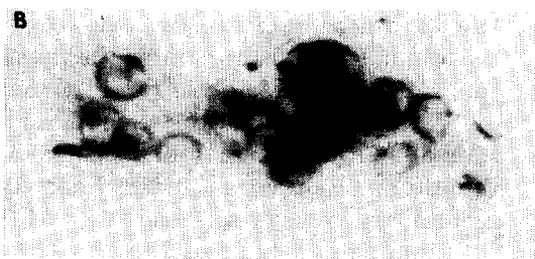


Fig. 4. Lithology of the Fawn Limestone member of the Kheinjua Formation at Salkhan Hill.

SUMMARY AND SIGNIFICANCE

Despite the fact that many unmetamorphosed Proterozoic sedimentary sequences are exposed in India, there are few convincing reports of well-

Fig. 5. Microstructure of the fossiliferous chert, and examples of the Kheinjua microbiota. (All at the same magnification except A and D.) Arrow indicates type specimens. (A) The fine structure of the microfossiliferous chert in thin section. (B) *Myxococcoides minor* Schopf (1968): thin section SB029-2; coordinates 28.5/1.6. (C) *Myxococcoides minor*: thin section SB029-2; coordinates 33.2/0.2. (D) *Glenobotrydion aenigmatis* Schopf (1968): thin section SB029-3; coordinates 36.2/1.0. (E) *Eosynechococcus isolatus* n. sp.: thin section SB029-2; coordinates 33.0/-1.7. (F) *Glenobotrydion aenigmatis*: thin section SB039-2; coordinates 28.5/1.6. (G) *Eosynechococcus isolatus* type specimen: thin section SB029-2; coordinates 33.4/0.7.



10 μ m

preserved microfossils. Based on studies of petrographic thin sections, convincing Indian microfossils have been reported from the 1700–2000 Ma-old Babadudan Iron Formation (Viswanathiah and Venkatachalapathy, 1980); the 1100–2500 Ma-old Aravalli Group (Bannerjee, 1973); the \approx 1400 Ma-old Vempalle Formation (Schopf and Prasad, 1978); the \approx 1100 Ma-old Deoban Group (Kumar and Singh, 1979); and the \approx 970 Ma-old Jammu Limestone (Raha et al., 1978; Raha, 1980). Kumar (1978a; 1980) published preliminary reports on this 1100–1300 Ma-old Kheinjua microbiota which we examine here in greater detail. This report significantly expands the available information on stromatolite-building microorganisms from the Proterozoic of India.

One of the most striking features of the Kheinjua microbiota is the generally small size of the microfossils. Though two of the new species described here are larger than related species described elsewhere, the modal size distribution of both coccoids and filaments is \approx 7 μ m. Coccoids range from 2.6 to 33.6 μ m in diameter, averaging 5.2 μ m, with a mode between 3 and 6 μ m. Filamentous microfossils are similarly small, having a range from 0.57 to 7.5 μ m (average 2.03 μ m), and a modal distribution from 0.6 to 2.3 μ m. These sizes are unusually small for a microbiota of this age when compared to the size data given by Schopf (1977): for microbiotas younger than 1400 Ma, the average size of coccoids is 13 μ m, and acellular filaments range from 2 to 20 μ m in diameter (no mean calculated). Hence, the Kheinjua microbiota deviates from the tendency noted by Schopf (1977) for microfossils to increase in mean diameter through Proterozoic time.

Taxonomically, the Kheinjua microbiota resembles other stratiform stromatolitic microbiotas. Taxonomic similarity is a common feature of Proterozoic stratiform stromatolites from intertidal to subtidal environments (Hofmann, 1976; Awramik, 1981). In particular, the Kheinjua is similar to microbiotas from the \approx 1900 Ma-old Belcher Islands (Hofmann, 1976); the \approx 1500 Ma-old McArthur Group (Muir, 1976; D.Z. Oehler, 1978); the \approx 850 Ma-old Bitter Springs (Schopf, 1968; Schopf and Blacic, 1971); and the \approx 650 Ma-old Yudoma Suite (Lo, 1980). Of the 9 genera and 10 species described from the Kheinjua, 5 genera and 3 species are in common with the Bitter Springs, 5 genera and 4 species are in common with the McArthur Group, and 6 genera and 3 species are in common with the Belcher Islands (Fig. 6). When compared to the Yudoma microbiota, only 4 genera and 1 species are in common. All these deposits share similar environmental settings.

Anomalously, the filaments of the Kheinjua are predominantly cf. *Gunflintia minuta*. The only other microbiotas where *Gunflintia minuta* is the major filamentous component are in Early Proterozoic iron-formations such as the Gunflint Iron Formation (Barghoorn and Tyler, 1965; Awramik, 1976); the Sokoman Iron Formation (Knoll and Simonson, 1981); the Frere Formation (Walter et al., 1976); and the Tyler Formation (Cloud and Morrison, 1980). Unlike these formations, the Kheinjua microbiota is not associated with iron, is found only in stratiform stromatolites, and is significantly younger.

		KHEINJUA											
		Yudoma ≈ 650	Bitter Springs ≈ 850	Dismal Lake ≈ 1200	Beck Spring < 1300	Balbirini	HYC	1375-1550 McArthur Gp.	Amelia	Gaoyuzhuang ≈ 1450	Kasegalik	McLeary	Belcher Gp. ≈ 1900
COCCOIDS													
<u>Myxococcoides minor</u> Schopf 1968		G	S	G		G	G	S		S	S		
<u>Eosynechococcus isolatus</u> n. sp.			G							G			
<u>Tetraphycus congregatus</u> n. sp.		G				G							
<u>Kheinjuasphaera vulgaris</u> n. gen., n. sp.													
<u>Glenobotrydion aenigmatis</u> Schopf 1968			S							G		G	
<u>Melasmatosphaera media</u> Hofmann 1976											S	S	
<u>Eoentophysalis belcherensis</u> Barghoorn 1976		G	G	G	G	S				S	S	G	
<u>E. magna</u> n. sp.													
FILAMENTS													
cf. <u>Gunflintia minuta</u> Barghoorn 1965								S				S	
<u>Eomycetopsis? siberiensis</u> Lo 1980		S	S			G		S			G	G	

G = genus present S = species present

Fig. 6. A comparison of the Kheinjua microbiota with some other Proterozoic microbiotas: Yudoma (Lo, 1980), Bitter Springs (Schopf, 1968; Schopf and Blacic, 1971), Dismal Lake (Horodyski and Donaldson, 1980), Beck Spring (Licari, 1978), McArthur Group (Muir, 1976; J.H. Oehler, 1977; D.Z. Oehler, 1978), Gaoyuzhuang (Zhang, 1981), Belcher Group (Hofmann, 1976), and Gunflint (Barghoorn and Tyler, 1965; Awramik and Barghoorn, 1977).

Another peculiar aspect of this microbiota is the presence and abundance of the microfossils in an extensive organic matrix (Figs. 5, 7). If this substance was an extracellular mucus secretion, there is no evidence or suggestion that it was pigmented. Prolonged exposure in the intertidal to subtidal environment could have triggered gel production, producing the organic matrix.

No convincing eukaryotic morphs have been detected among the Kheinjua microfossils. The larger morphs, those above 10 μm in diameter, contain no inclusions of any kind, whereas a few of the smaller cells contain centrally located dots or granules, which are interpreted here as remnants of cytoplasmic degradation (see Awramik et al., 1972; Knoll and Barghoorn, 1975; Francis et al., 1978).

If the ≈1200 Ma age of the Kheinjua is correct, eukaryotes were already in existence (Cloud, 1976, p. 353; Schopf and Oehler, 1976; Hofmann and

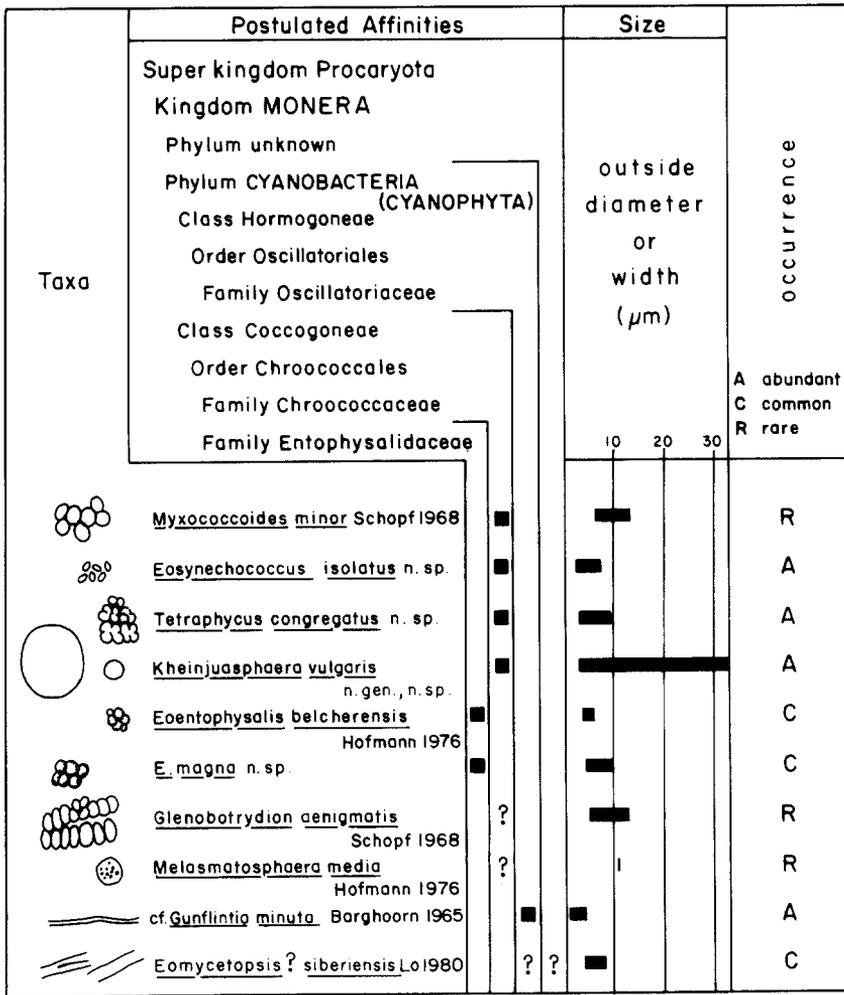


Fig. 7. Affinities and relative abundances of species in the Kheinjua microbiota.

Chen, 1980; Awramik, 1981). By analogy with modern stromatolitic communities, environments like that of the Fawn Limestone in the Kheinjua Formation are unlikely places for proctostistan eukaryotes. Eukaryotes would more likely be found in offshore, permanently submerged stromatolitic, or non-stromatolitic clastic facies.

The similarity of the Kheinjua microfossils to older microbiotas in size and taxonomic composition may reflect environmental conditions which favored small microorganisms and excluded large microbes. The details of these environmental conditions are uncertain. Alternatively, there might be peculiarities in the diagenetic and taphonomic history of the Kheinjua that destroyed most of the larger, possibly more delicate morphs. Another explanation for the anachronistic characteristics of the microbiota is the possibility of an error in the age assignment of the Kheinjua.

Like a few other Proterozoic microbiotas (e.g., the Gunflint microbiota, Awramik and Barghoorn, 1977), the Kheinjua contains some morphologically complex microfossils which have no modern or other fossil analogs. Though such morphs are rare members of the Kheinjua it is important for the completeness of this report to illustrate these curious, well-preserved microfossils. At present, we have no opinion as to their affinities, evolutionary significance, or role in microbial mat construction.

TAXONOMY

Method of study

The Kheinjua Formation microbiota was studied in petrographic thin section using transmitted light. Thin sections cut perpendicular to stromatolite lamination were ground to $\approx 50 \mu\text{m}$ in thickness. Such thick sections afford maximum three-dimensional viewing of objects, and assist in the understanding of spatial relationships between the microfossils and their enclosing matrix. Size data were obtained by direct measurement using an eyepiece micrometer. Photomicrographs were made with a Zeiss Photomicroscope II and Leitz Orthomat using Kodak technical pan film 2415. In most photomicrographs, a xenon light source with neutral density and green filters was used.

Holotypes and other illustrated specimens are noted by slide number and cartesian coordinates. Coordinates are measured in millimeters to the right (x coordinate) and above (y coordinate) of an inscribed x located in the lower left-hand corner of the thin section with the inscribed slide number to the right of the viewer. Thin sections containing type specimens are deposited in the Preston Cloud Research Laboratory Collection at the University of California, Santa Barbara and additional thin sections are on deposit at the Department of Geology, Lucknow University.

Note on terminology

Rarely is it possible to determine whether the microfossils studied are the preserved cell wall, cell envelope, or, in the case of multiple-layered fossils, combinations of these. Thus, we use the term 'cell-like unit' in each introduction, but then use 'cell' in the remainder of each description for simplicity.

SYSTEMATIC PALEONTOLOGY

Superkingdom Prokaryota

Kingdom Monera

Phylum Cyanobacteria (Cyanophyta)

Class Coccogoneae
 Order Chroococcales
 Family Chroococcaceae
 Genus *Myxococcoides* Schopf (1968)

Type species. *Myxococcoides minor* Schopf (Schopf, 1968; pp. 183 and 676, Plate 81, Figs. 1 and 10, and Table 4), Bitter Springs Formation, Northern Territory, Australia.

Myxococcoides minor Schopf (1968) (Fig. 5B, C)

Description. Single-walled cell-like units, spheroidal to ellipsoidal; often deformed by mutual compression when in groups. Habit solitary or clustered in groups of up to 30 cells. Groups vary in shape from roughly spheroidal to elongate. Cell unit diameter 6.3–12.75 μm , average 8.2 μm (38 cells measured). Few cells contain an inclusion. Long axes of ellipsoids have no preferred orientation with respect to bedding or stromatolite lamination.

Discussion. Though the Kheinjua form has a somewhat wider size range and an average diameter slightly less than the type material described from the Bitter Springs Formation (Fig. 8), it conforms to all other diagnostic features of *M. minor* Schopf (1968). The Kheinjua *Myxococcoides* differs in size from other described species of *Myxococcoides* (Fig. 8). *Myxococcoides minor* may also be compared to *Glenobotrydion aenigmatis* Schopf (1968). As noted by Hofmann (1976), *M. minor* and *G. aenigmatis* overlap in group organization, dimensions, and appearance. In the Kheinjua, *M. minor* and *G. aenigmatis* are differentiated on the basis of colonial organization; *G. aenigmatis* forms pseudofilamentous colonies, sometimes containing very large numbers of cells (Fig. 5D, F). Intracellular inclusions are not considered taxonomically diagnostic.

Genus *Eosynechococcus* Hofmann (1976)

Type species. *Eosynechococcus moorei* Hofmann (Hofmann, 1976; pp. 1057–1058 Plate 2, Figs. 1–7), Kasegalik Formation, Belcher Islands, Canada.

Eosynechococcus isolatus n. sp. (Fig. 5E, G).

Diagnosis. Cell-like units, rod-shaped to ellipsoidal, occasionally slightly curved. Cells found loosely associated in groups of 30–60 cells; cells rarely touch and lack individual sheaths, but are usually in a common organic matrix. Cells measure 1.7–6.8 μm in the short dimension and 1.7–8.5 μm in the long dimension, averaging 2.7 μm by 4.07 μm (91 specimens measured). Cells are organized into ovoidal groups, 10–30 μm by 20–60 μm (4 measured).

Etymology: *isolatus*, Latin, with reference to the isolated nature of individuals within a group.

Glenobotrydion

<i>G. majorinum</i>	Schopf & Blacic 1971 Hofmann 1976
<i>G. varioforme</i>	Zhang 1981
<i>G. aenigmatis</i>	Schopf 1968 present paper

Myxococcoides

<i>M. minor</i>	Schopf 1968 Muir 1976 Hofmann 1976 present paper
<i>M. cracens</i>	D. Z. Oehler 1978
<i>M. kingii</i>	Muir 1976 J. H. Oehler 1977 D. Z. Oehler 1978
<i>M. minuta</i>	Muir 1976 D. Z. Oehler 1978
<i>M. reticulata</i>	Schopf 1968
<i>M. inornata</i>	Schopf 1968 Hofmann 1976
<i>M. konzalovae</i>	Muir 1974
<i>M. staphilydion</i>	Lo 1980
<i>M. quyangensis</i>	Yin 1981
<i>M. reniformis</i>	Muir 1974
<i>M. sp.</i>	Hofmann 1976
<i>M. sp.</i>	D. Z. Oehler 1978
species	Report

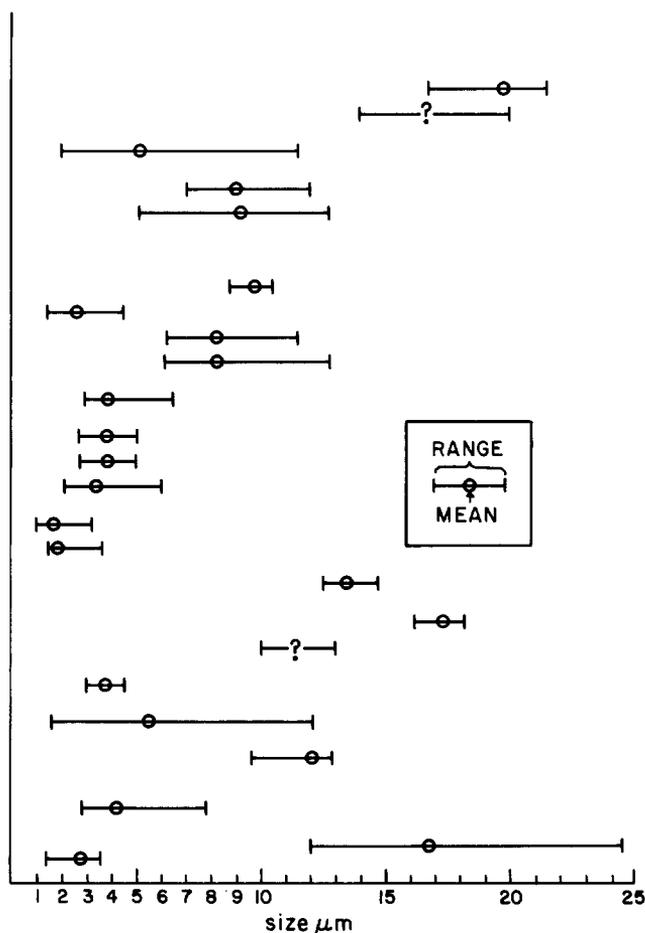


Fig. 8. The sizes of *Glenobotrydion* and *Myxococcoides* individuals in several micro-biotas.

Type locality. Upper Fawn Limestone, Kheinjua Formation, above *Conophyton garganicum*, Salkhan Hill, Son Valley area, Mirzapur district, Uttar Pradesh, India.

Type specimen. 33.4/0.7 in thin section SB029-2, illustrated in Fig. 5G.

Discussion. Although the dimensions of *E. isolatus* are similar to *E. moorei* Hofmann (1976), the Kheinjua species differs in the arrangement of cells. *Eosynechococcus isolatus* is not grouped in small stacks and chains, and cells are not in contact with one another. *Eosynechococcus isolatus* shows more size variation within a group and individuals tend to be rounder (Fig. 9). Groups of *E. isolatus* are occasionally surrounded by an amorphous organic matrix. Individuals of *E. isolatus* resemble the solitary *Pilavia maculata* Oehler (1978), which does not form groups. Occasionally, *E. isolatus* contains a single centrally or eccentrically positioned inclusion.

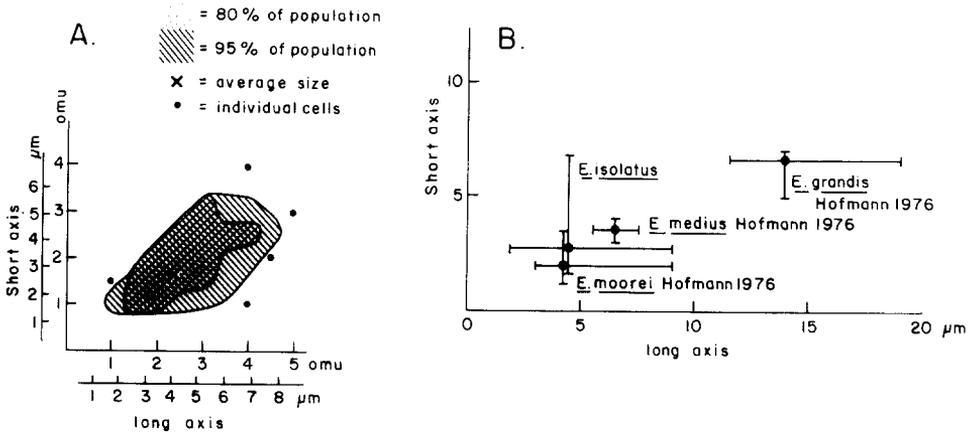


Fig. 9. (A) Size distribution of *Eosynechococcus isolatus* n. sp. Measured population is 101 individuals (omu = ocular micrometer units; raw data). (B) Comparison with other described species of *Eosynechococcus*.

Genus *Glenobotrydion* Schopf (1968)

Type species. Glenobotrydion aenigmatis Schopf (Schopf, 1968; pp. 681–683, Plate 83, Fig. 9; Plate 84, Figs. 4 and 5; text—Fig. 6, and Table 4), Bitter Springs Formation, Northern Territory, Australia.

Glenobotrydion aenigmatis Schopf (1968) (Fig. 5D, F)

Description. Cell-like units, spheroidal to discoidal; 5.1–12.75 μm in diameter, average 9.3 μm (43 individuals measured); usually arranged in pseudofilamentous colonies containing from 7 to over 100 cells. Colony dimensions range from 10 × 35 μm to 50 × 300 μm (3 colonies measured); long axes of colonies are roughly parallel to stromatolitic lamination. Short axis of compressed or flattened cells is parallel to pseudofilament. Reproduction by fission observed in one or two planes.

Discussion. In the Bitter Springs, *G. aenigmatis* is characterized by an inclusion which has been used as evidence for a eukaryotic affinity (Schopf, 1968). However, such inclusions are more likely the result of cytoplasmic degradation (Awramik et al., 1972) and should not be used as a diagnostic taxonomic feature. The Kheinjua form is similar in size and morphology to the Bitter Springs *G. aenigmatis* (Schopf, 1968, Plate 84, Fig. 5), except that Kheinjua cells generally lack inclusions.

Individual cells of *G. aenigmatis* and *Myxococcoides minor* are indistinguishable; we refer to cells organized into pseudofilaments as *G. aenigmatis*. Also, solitary spheroids of the correct size found closely associated with *G. aenigmatis* colonies are assigned to that species on the assumption that they may have broken off from the parent colony. Single-walled, solitary

spheroids not closely associated with any colony are grouped in the new genus *Kheinjuasphaera* (see below). Based on the size and shape of individuals and mode of reproduction, *G. aenigmatis* may be a member of the Chroococcaceae, but a pseudofilamentous arrangement is a common feature in the Entophysalidaceae (Geitler, 1932).

Genus *Melasmatosphaera* Hofmann (1976)

Type species. *Melasmatosphaera magna* Hofmann (Hofmann, 1976; p. 1066, Plate 8, Figs. 1–2), Mc Leary Formation, Belcher Islands, Canada.

Melasmatosphaera media Hofmann (1976)

Description. Solitary, dark spheroid 11.4 μm across, containing numerous clustered and scattered granules of sub-micron size.

Discussion. Only one specimen has been found, but it is identical to the diagnosis and illustrations of Hofmann (1976, Plate 8, Fig. 5). Following Hofmann (1976), we recognize that *Melasmatosphaera* may represent a degradational morph of other taxa; in this assemblage, possible candidates include *Kheinjuasphaera vulgaris*, or solitary individuals of *Myxococcoides minor* or *Glenobotrydion aenigmatis*.

Family Entophysalidaceae

Genus *Eoentophysalis* Hofmann (1976)

Type species. *Eoentophysalis belcherensis* Hofmann (Hofmann, 1976; pp. 1070–1072, Figs. 1–5; Plate 5, Figs. 3–6; Plate 6, Figs. 1–14), Kasegalik Formation, Belcher Islands, Canada.

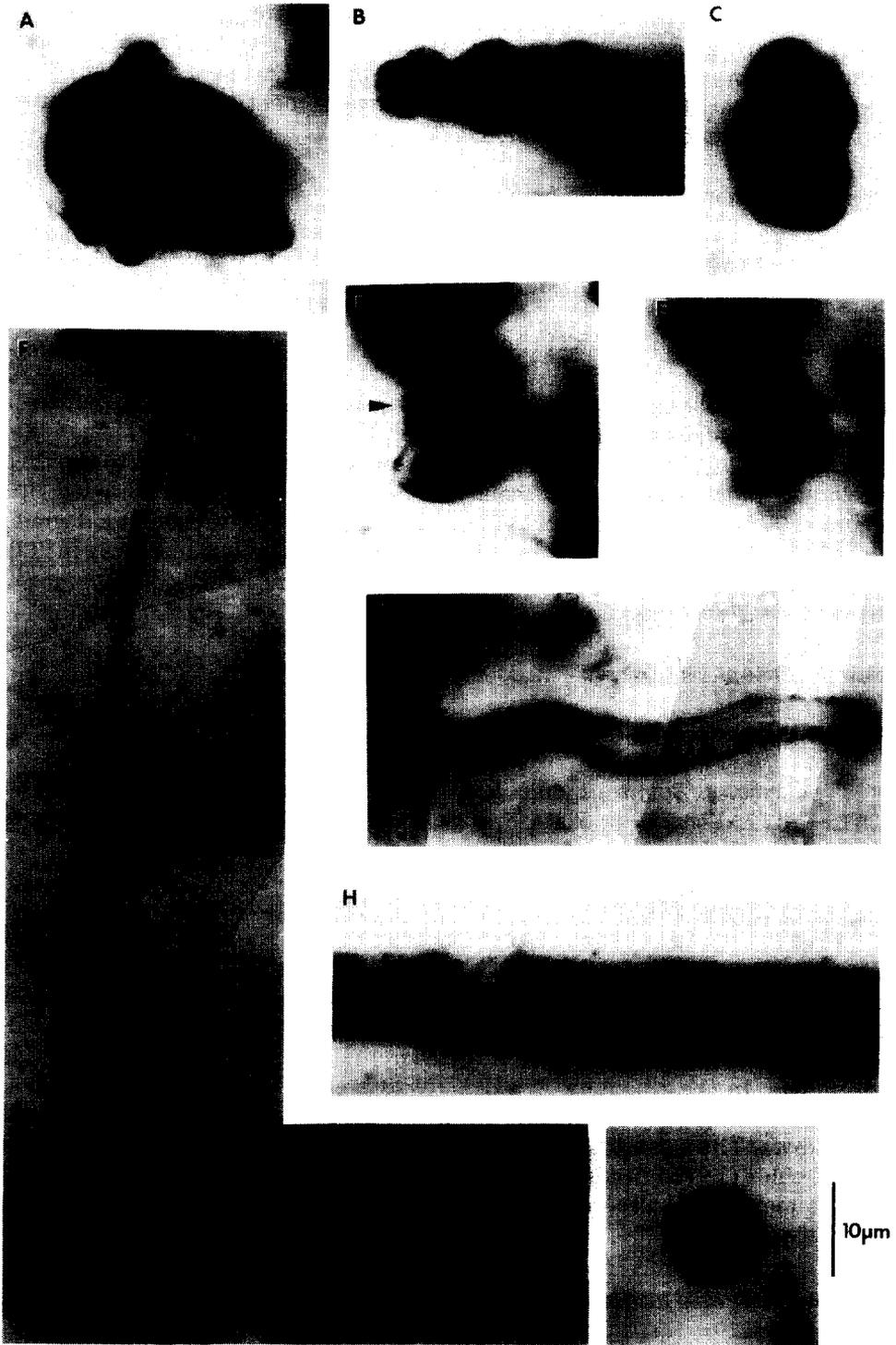
Eoentophysalis belcherensis Hofmann (1976) (Fig. 10A–C)

Description. Cell-like units, spheroidal to polyhedral, often deformed by mutual compression. Found in spheroidal or roughly linear clumps of 5–25 cells with a diameter of 3.99–5.7 μm , averaging 4.89 μm (10 cells measured).

Discussion. The type material of *E. belcherensis* occurs in extensive monospecific mats. In the Kheinjua, *E. belcherensis* is only found in small clusters associated with other members of the microbiota; nowhere was it observed to form mats. The aggregation in Fig. 10B illustrates the sub-linear organization that Oehler (1978) has interpreted as indicative of a young colony. Such an arrangement could also be viewed as an isolated, detached remnant of a more extensive colony.

Eoentophysalis magna n. sp. (Fig. 10D, E)

Diagnosis. Cell-like units, spheroidal, ellipsoidal, or subpolyhedral; diameter 4.25–9.12 μm , average 5.41 μm (22 specimens measured). Occurs in irregular



clumps from 4 or 5 to 40 cells, each possessing a distinctly particulate envelope with no lamellations.

Etymology: *magna*, Latin, in reference to the large size of cells.

Type locality. Upper Fawn Limestone, Kheinjua Formation above *Conophyton garganicum*, Salkhan Hill, Son Valley, Mirzapur district, Uttar Pradesh, India.

Type specimen. 33.0/0.1 in thin section SB029-2; illustrated in Fig. 10D.

Discussion. *Eoentophysalis magna* differs from the Kheinjua *E. belcherensis* in its larger size. Morphologically, it most closely resembles the *capsulata* degradational form of *E. belcherensis* from the Kasegalik Formation (Hofmann, 1976, (text—Figs. 5–6) (Fig. 11). *Eoentophysalis magna* is not considered a degradational variant of *E. belcherensis*, as the cell-like units in *E. magna* colonies are substantially larger, and only these larger individuals are found in clusters of more than 25 in the Kheinjua.

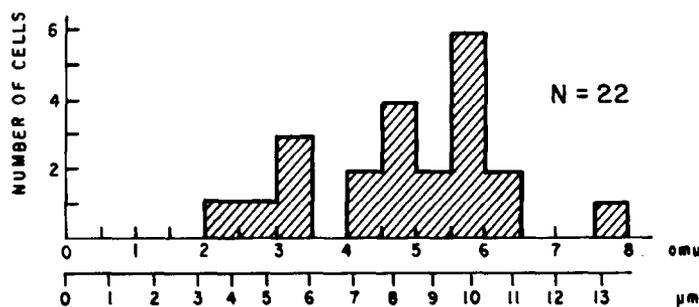


Fig. 11. Histogram of *Eoentophysalis magna* n. sp. (omu = ocular micrometer units; raw data).

Class Hormogoneae

Order Oscillatoriales

Family Oscillatoriaceae

Genus *Gunflintia* Barghoorn (1965)

Fig. 10. Microfossils from the Kheinjua microbiota; all at the same magnification. Arrow indicates type specimens. F and G are composite photomicrographs. (A) *Eoentophysalis belcherensis* (Hofmann, 1976): thin section SB029-2; coordinates 33.0/0.1. (B) *Eoentophysalis belcherensis*: thin section SB029-2; coordinates 37.1/–1.7. (C) *Eoentophysalis belcherensis*: thin section SB029-2; coordinates 26.0/–1.7. (D) *Eoentophysalis magna* n. sp. type specimen: thin section SB029-2; coordinates 33.0/0.1. (E) *Eoentophysalis magna*. Same colony as in D, but at a different focal depth: thin section SB029-2; coordinates 33.0/0.1. (F) cf. *Gunflintia minuta* Barghoorn (1965): thin section SB029-2; coordinates 22.8/0.5. (G) *Eomycetopsis? siberiensis* Lo (1980); thin section SB029-2; coordinates 30.6/0.1. (H) *Eomycetopsis? siberiensis*: thin section SB029-2; coordinates 36.2/1.0. (I) *Melasmatosphaera media* Hofmann (1976); thin section SB029-2; coordinates 33.6/103.9.

Type species. Gunflintia minuta Barghoorn (Barghoorn and Tyler, 1965; Fig. 4, parts 6, 8; Fig. 6, part 1), Gunflint Iron Formation, Ontario, Canada.

Comparable to Gunflintia minuta Barghoorn (1965) (Fig. 10F)

Description. Unbranched uniseriate, straight or somewhat curved filaments 0.57–3.99 μm in diameter (average 1.6 μm , 64 specimens measured) and up to 375 μm long; no septations visible. Filaments unoriented with respect to stromatolitic lamination or bedding.

Discussion. Based on size and morphology, Kheinjua filaments < 4 μm in diameter strongly resemble *G. minuta* from the Early Proterozoic Gunflint Iron Formation. However, based on the experience of one of us (S.M.A.), these filaments differ from *G. minuta* in their growth habit and relation to stromatolitic laminations, and the Gunflint *G. minuta* has a very narrow modal diameter, unlike the Kheinjua filaments. As pointed out by Muir (1976), *Gunflintia* is in need of further study. Filaments > 4 μm across form a second population of Kheinjua filaments which are assigned to *E.?* *siberiensis* Lo (1980) (Fig. 12).

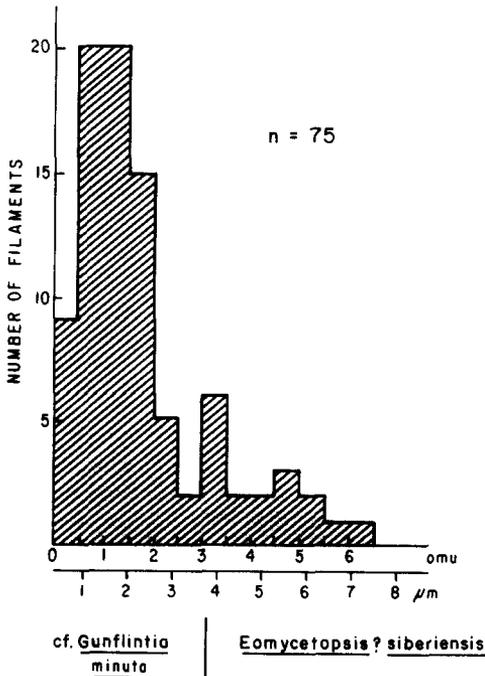


Fig. 12. Histogram of Kheinjua filamentous forms. (omu = ocular micrometer units; raw data).

Genus *Eomycetopsis* Schopf (1968) em. Knoll and Gobulic (1979)

Type species. Eomycetopsis robustis Schopf (1968) em. Knoll and Golubic (1979) (Schopf, 1968; pp. 684–686, including *E. filiformis* Schopf), Bitter Springs Formation, Northern Territory, Australia.

Eomycetopsis? siberiensis Lo (1980) (Fig. 10G–H)

Description. Large non-septate filaments, occasionally containing a line or lines resembling trichome remnants. Diameter 3.99–7.12 μm , average 5.23 μm (11 specimens measured).

Discussion. Occasional linear inclusions representing trichome or sheath remnants place this species within *Eomycetopsis* as emended by Knoll and Golubic (1979); inclusions are lacking in filaments smaller than 3.99 μm which are referred to as cf. *Gunflintia minuta*. Filaments larger than 3.99 μm most closely resemble *E.? siberiensis* described from the Yudoma Suite (Lo, 1980).

Order Chroococcales (?)

Family Chroococcaceae (?) or,

Order Pleurocapsales (?)

Family Chroococciaceae (?)

Genus *Tetraphycus* D.Z. Oehler (1978)

Type species. Tetraphycus gregalis D.Z. Oehler (Oehler, 1978; p. 294; Fig. 9I–K), Balbirini Dolomite, Northern Territory, Australia.

Tetraphycus congregatus n. sp. (Fig. 13A, B)

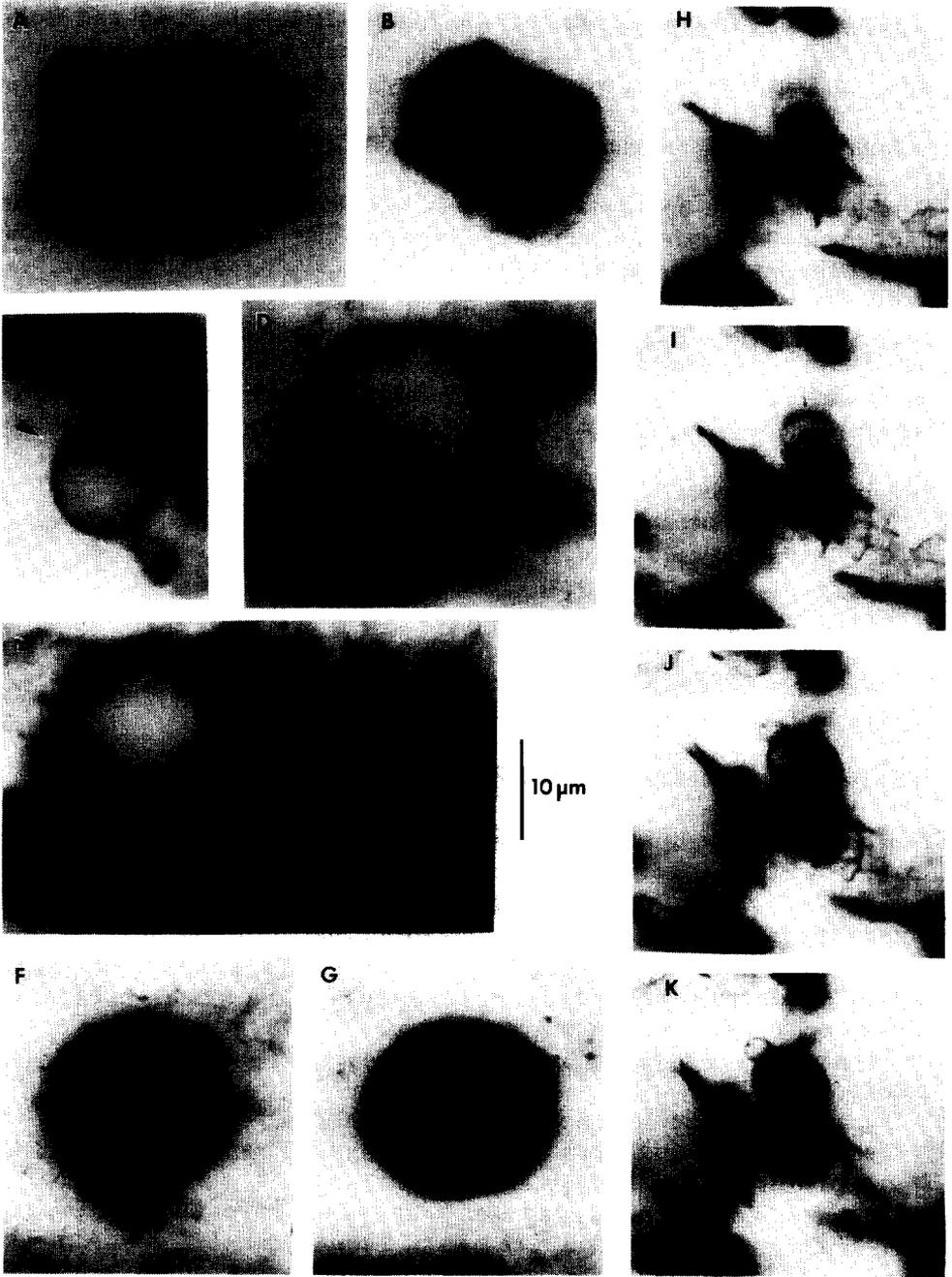
Diagnosis. Cell-like units, subspherical or slightly elongate along one or two axes; longest dimension 4.6–9.1 μm ; shortest dimension 3.4–6.8 μm ; average size 6.7 \times 3.8 μm (37 specimens measured within 3 colonies). Cells commonly in planar tetrads: occasional dyads and triads also found; grouped in roughly rectangular colonies of 15–25 cells. Amorphous organic matrix occasionally visible as an envelope surrounding tetrads, but not observed enclosing an entire colony.

Etymology: congregatus, Latin, with reference to tight clusters within the colony.

Type specimen. 24.4/–2.6 in thin section SB029-2.

Type locality. Upper Fawn Limestone, Kheinjua Formation, Salkhan Hill, Mirzapur district, Uttar Pradesh, India.

Discussion. The cells of *T. congregatus* are slightly larger and less spherical than the 5 previously described species of *Tetraphycus* (Fig. 14). Although tetrads within the *T. congregatus* colony resemble the lone tetrads of *T.*



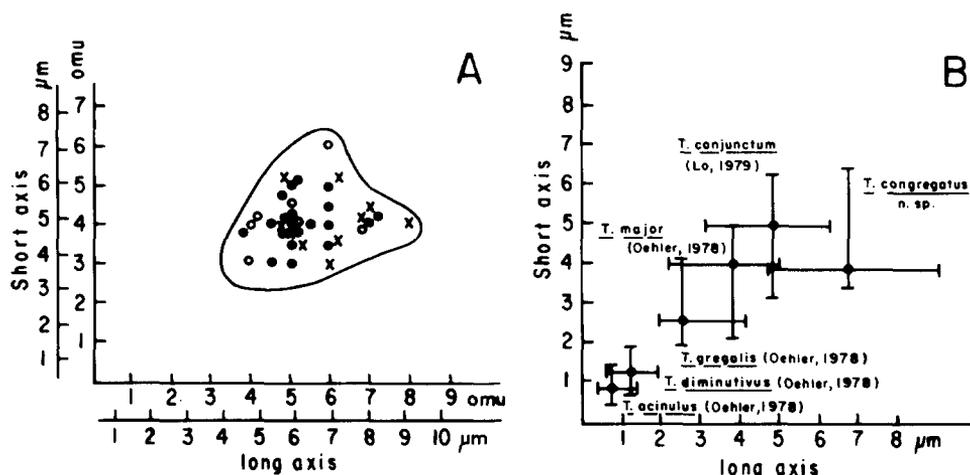


Fig. 14. (A) Size distribution of *Tetraphycus congregatus* individuals. Open and closed circles and X's indicate individuals from different colonies (omu = ocular micrometer units; raw data). (B) Comparison with other species of *Tetraphycus*.

major D.Z. Oehler (1978), no isolated tetrads of *Tetraphycus* have been found in the Kheinjua. The slight elongation or flattening of many of the cells is probably due to mutual compression within the tetrad's organic matrix. Colonies appear roughly rectangular in two dimensions. It is uncertain whether the individual microfossil is the preserved cell wall or cell capsule (envelope). Oehler (1978) mentions the resemblance this genus has to modern chroococcacean cyanobacteria and halophytic bacteria, as well as certain chlorococcacean algae. Here, we note the similarity of *T. congregatus* to cell aggregates of the modern pleurocapsaleans *Myxosarcina* and *Chroococidiopsis* (see Waterbury, 1979). Because of the lack of unequivocal eukaryotic morphological characteristics, we favor a cyanobacterial affinity for this morph.

Incertae sedis

Kheinjuasphaera n. gen.

Type species. Kheinjuasphaera vulgaris n. sp.

Fig. 13. Kheinjua microfossils; all at the same magnification. Arrows indicate type specimens. (A) *Tetraphycus congregatus* n. sp. type specimen: thin section SB029-2; coordinates 34.7/1.4. (B) *Tetraphycus congregatus*: thin section SB029-2; coordinates 28.3/-1.8. (C) *Kheinjuasphaera vulgaris* n. gen. et n. sp. type specimen: thin section SB029-2; coordinates 30.2/-1.0. (D) *Kheinjuasphaera vulgaris*: thin section SB029-2; coordinates 30.2/-0.8. (E) *Kheinjuasphaera vulgaris*: thin section SB029-2; coordinates 30.2/-0.8. (F) A possible example of endosporulation: thin section SB029-2; coordinates 33.3/-2.0. Surface texture. (G) A possible example of endosporulation: thin section SB029-2; coordinates 33.3/-2.0. Internal structure. (H-K) An enigmatic, complex structure, shown in focus-through series: thin section SB029-2; coordinates 37.0/-2.0.

Type locality. Upper Fawn Limestone, Kheinjua Formation, Salkhan Hill, Son Valley area, Mirzapur District, Uttar Pradesh, India.

Etymology. With reference to its occurrence in the Kheinjua Formation; *sphaera*, Latin, spherical shape.

Diagnosis. Cell-like units, solitary; spherical or slightly distorted, with a well-defined single wall $< 1 \mu\text{m}$ thick. Diameter of cells $2.8\text{--}35 \mu\text{m}$, averaging $11.7 \mu\text{m}$ (173 cells measured). No envelopes or internal inclusions. Found scattered throughout a medium brown colored organic matrix, or in small populations (2 or 3, up to 8 cells) in pockets of clear light brown colored chert.

Discussion. The wide range in cell size of closely associated units is the main feature differentiating this genus from other genera, in particular *Huroniospora microreticulata* Barghoorn (1965), to which most of the smaller spheroids would be assigned if they were not so consistently associated with larger spheroids.

Kheinjua-sphaera vulgaris n. gen., n. sp. (Fig. 13C–E)

Etymology: *vulgaris*, Latin, common.

Type locality. As for genus.

Type specimen. 30.2/1.0 in thin section SB029-2. Illustrated in Fig. 13C.

Diagnosis. As for genus.

Discussion. These solitary, simple spheroids, quite common in the Kheinjua microbiota, exhibit a wide range in size (Fig. 15), and the smallest cells are nearly always found in the same vicinity as the largest cells (Fig. 13D, E). We cannot rule out the possibility that *K. vulgaris* is polytaxonomic and composed of *Myxococcoides* and *Glenobotrydion* cells which became isolated

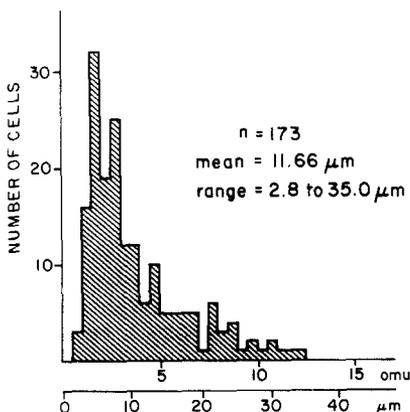


Fig. 15. Histogram for *Kheinjua-sphaera vulgaris* n. sp.

from their parent colonies. However, the lack of prominent breaks in the size distribution of closely associated cells and the uniformity of morphology make this a relatively well defined species.

Kheinjaesphaera vulgaris is associated with the enigmatic microfossil illustrated in Fig. 13F, G. This association suggests that *K. vulgaris* may be derived from the complex microfossil and represents spores, fruiting bodies, or some other type of developmental morph. We place *K. vulgaris* in *Insertae sedis*.

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