NEOPROTEROZOIC (VENDIAN) PHYTOPLANKTON FROM THE SIBERIAN PLATFORM, YAKUTIA

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ABSTRACT. Seven new species of comparatively large Neoproterozoic organic-walled acritarchs (*Appendisphaera grandis*, *A. fragilis*, *A. tenuis*, *A.*? *tabifica*, *Cavaspina basiconica*, *Tanarium irregulare*, *T. tuberosum*) are reported from two drilling sites in Yakutia, eastern Siberia. Two previously known form-species (*Cavaspina acuminata* comb. nov. and *Tanarium conoideum*) are also emended. The acritarchs derive from siliciclastic rocks of the Khamaka Formation, the lowermost part of the Vendian to Cambrian sedimentary succession in the central part of the Siberian Platform. By comparison with assemblages from the Ediacaran Pertatataka Formation, the acritarchs in the Khamaka Formation are considered to indicate an Ediacaran age. The study confirms the broad environmental and geographical distribution of Neoproterozoic (late Vendian) plankton, and that they are diverse in rocks reflecting a range of depositional settings.

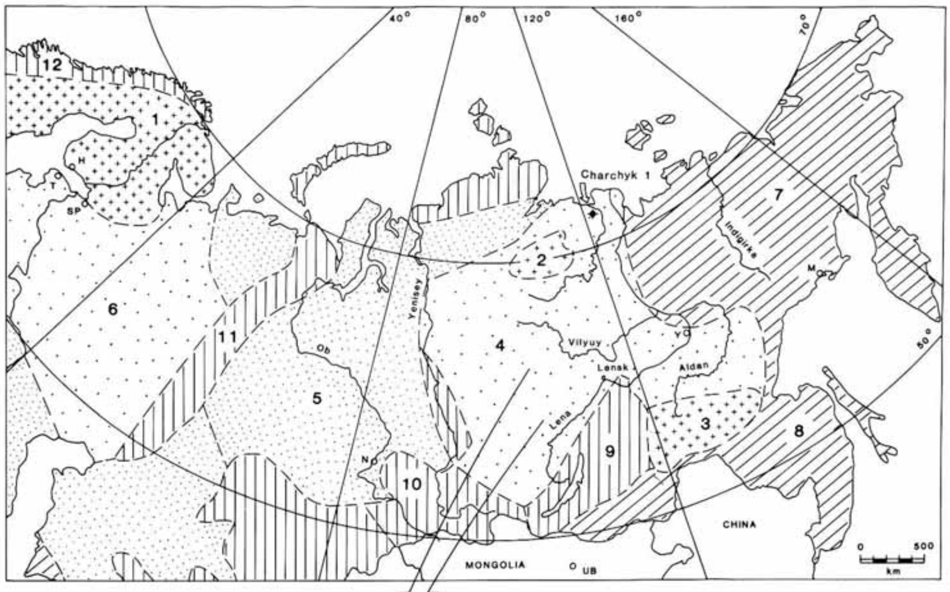
THE biotic changes near the Proterozoic–Phanerozoic boundary are currently the subject of intense debate (Cowie and Brasier 1989; Brasier 1990, 1992). While the causes and effects of these changes remain problematic (Brasier 1992; Kaufman *et al.* 1992), their magnitude is being revealed with increasing clarity by a steadily growing record of well-preserved, diagnostic acritarchs from strata straddling the Neoproterozoic/Lower Cambrian boundary (Awramik *et al.* 1985; Yin 1985*a*, 1985*b*, 1987; Zang 1988, 1992; Zang and Walter 1989, 1992; Moczydłowska 1991; Vidal and Moczydłowska 1992). Here we report on Neoproterozoic organic-walled phytoplankton (acritarchs) from two drilling sites in Yakutia, eastern Siberia, including seven new species and two previously described form-species that are emended.

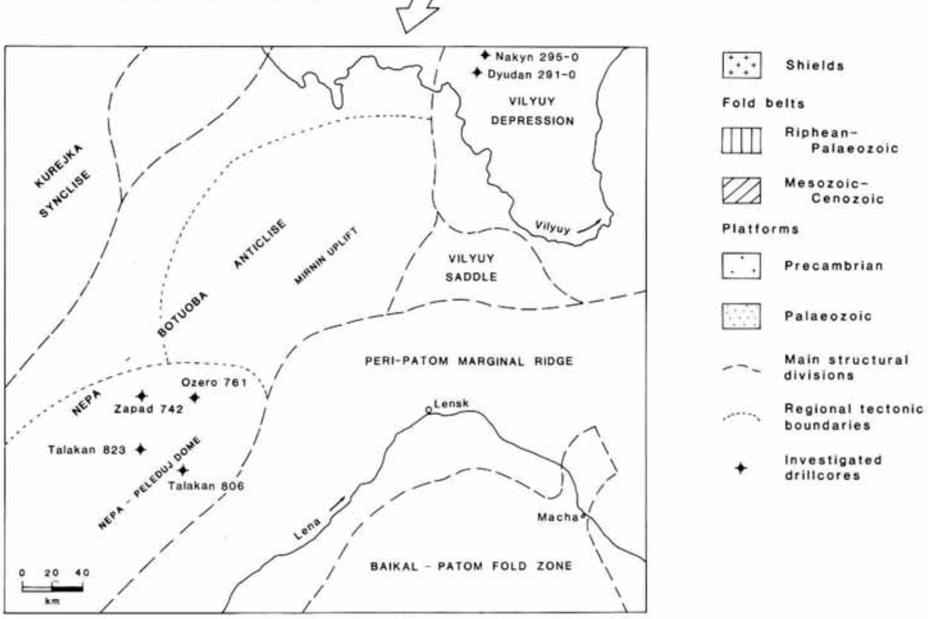
GEOLOGICAL FRAMEWORK

Eastern Siberia offers exceptionally well-developed Neoproterozoic to Lower Cambrian successions that contribute substantially to the understanding of Neoproterozoic and early Cambrian biotic change (Sokolov and Ivanovskij 1985). Proterozoic sedimentary rocks overlie the crystalline basement with major disconformity. The lower part of the Mesoproterozoic to Cambrian sedimentary succession formed on a carbonate platform that developed above siliciclastic deposits. It is well exposed along the rivers Lena, Aldan, Maya, Olenek, Kotuj, Kotujkan, Nemakit-Daldyn, Khorbusuonka and Miroedikha (Rozanov *et al.* 1969; Rozanov and Sokolov 1984; Khomentovski 1985) and is also widely known from subsurface borehole sections on the Siberian Platform. During Riphean time, detrital and carbonate deposition was largely in troughs and pericratonic basins. The Neoproterozoic (Yudomian or Vendian) succession developed on a stable carbonate platform and lies unconformably or disconformably on Riphean strata and/or basement rocks. From more or less reliable biostratigraphical evidence, Yudomian strata are generally interpreted as time-equivalent to the Vendian of the East European Platform (Khomentovski 1985). By comparison with the East European successions, recent chemostratigraphical data indicate that lower Yudomian rocks are of latest Neoproterozoic age (Knoll, pers. comm. 1992).

Irrespective of their depositional settings, a general feature of these deposits is the almost total lack of metamorphism. This has resulted in the generally excellent preservation of organic-walled fossils.

[Palaeontology, Vol. 36, Part 3, 1993, pp. 495–521, 1 pl.]





TEXT-FIG. 1. Simplified geological sketch-map of Siberia showing main structural units and location of investigated drillholes within regional tectonic units. H, Helsinki; T, Tallinn; SP, St Petersburg; N, Novosibirsk; Y, Yakutsk; M, Magadan; UB, Ulan Bator. Figures indicate: 1, Baltic Shield; 2, Anabar

This paper is concerned with assemblages from the lowermost part of the sedimentary succession in the Nepa-Botuoba region (Text-fig. 1) in the central part of the Siberian Platform. Rocks in this region have been dated as Vendian and Early Cambrian. This subsurface sequence was penetrated by numerous hydrocarbon exploration boreholes, resulting in the geology of the area being relatively well documented, largely in internal company reports.

The lower part of the succession in the study area (Text-fig. 2) consists of siliciclastic rocks of variable thickness succeeded by thick carbonates, which are, in turn, overlain by evaporites. The siliciclastic deposits consist of sandstones, mudstones and shales ranging in thickness from approximately 30 to 300 m (Rudavskaya and Vasileva 1989). Occasionally, conglomerates occur at the base of the sequence (Borehole V-Ch 96; Rudavskaya and Vasileva 1989). Sandstones are predominant, forming thick units with numerous discontinuity surfaces and unconformities. Mudstones occur as thin intercalations in the sandstones or as discrete beds reaching 20 to 40 m in thickness (for example, boreholes 845 and 611; Rudavskaya and Vasileva 1989). Carbonates overlying the siliciclastic portion of the sequence range in thickness from 170 to 400 m. They consist largely of dolostones or more rarely limestones, and clayey dolostones (Grausman and Zhernovskij 1989; Rudavskaya and Vasileva 1989). The carbonate succession is overlain by thick (250 m) evaporites, comprising mainly of halite, with lesser amounts of anhydrite.

Although variably complete in different parts of the basin, the succession constitutes a single transgressive–regressive depositional cycle. At its greatest development, the succession is more than 700 m thick (Borehole 606; Rudavskaya and Vasileva 1989). Detailed facies reconstruction and basin analysis is not yet possible, since drillcores are available for only a limited portion of the sequence, and some of the data are not accessible. As a consequence, the present level of knowledge is not enough to allow comparison with other depositional grand cycles (Aitken 1978). However, from the available evidence it is clear that the sequence was deposited under shallow marine conditions on a stable platform, on which almost exclusively fine-grained detrital deposits and carbonates accumulated. The depositional cycle began with a transgression over the extensively peneplained crystalline basement, and extended through late Vendian–early Cambrian times.

The overlying carbonates represent a thick sequence that formed part of an extensive carbonate platform occupying a vast area of present-day Siberia. Shallowing-up interrupted carbonate sedimentation on the platform, which was followed by accumulation of evaporites (Text-fig. 2).

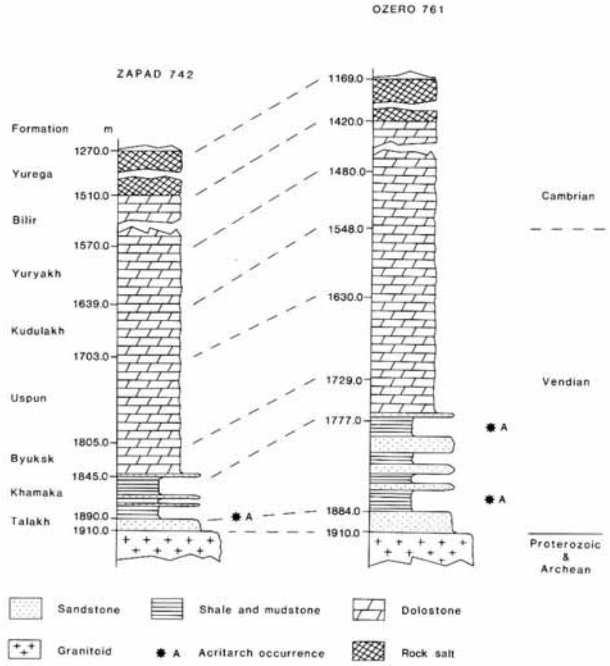
FOSSIL RECORD

The fossil record in the studied sequence comprises abundant acritarchs, abandoned cyanobacterial sheaths and small shelly fossils. The lowermost recorded occurrence of small shelly fossils, including hyolithids (*Conotheca mammilata* Missarzhevskij, *Turcutheca* sp.), problematic shells resembling obolellid brachiopods and possible archaeocyathans, is in the upper part of the Yuryakh Formation (Text-fig. 2; Grausman and Zhernovskij 1989; Rudavskaya and Vasileva 1989); these fossils were considered by the latter authors to indicate an early Cambrian age. However, their taxonomic assignment and age are uncertain; thus, the chronostratigraphical position of the Yuryakh Formation remains questionable (Grausman and Zhernovskij 1989; Text-fig. 2).

In the Bilir Formation, which overlies the Yuryakh Formation, there is a rich association of various shelly fossils, including hyolithids, hyolithelmintids, brachiopods, gastropods, chancellorids, tommotids and archaeocyathans. These fossils are more convincingly early Cambrian (Tommotian to early Atdabanian; Grausman and Zhernovskij 1989).

Acritarchs and cyanobacterial microfossils occur at specific levels in the siliciclastic and carbonate succession and numerous taxonomically and stratigraphically undiagnostic cyanobacterial sheaths

Shield; 3, Aldan Shield; 4, Siberian Platform; 5, West Siberian Platform; 6, East European Platform; 7, Verkhoyansk–Chukotka–Kamchatka area; 8, Primorye area; 9, Baikal fold zone; 10, Altaj-Sayan fold zone; 11, Urals; 12, Scandinavian Caledonides. Compiled after Rundquist (1984) and Geological-Prospecting Oil and Gas Review Map of Yakutian ASSR 1:1000000, Ministry of Geology of the USSR, 1990.



TEXT-FIG. 2. Generalized stratigraphical sections of the investigated sequences penetrated at the Zapad 742 and Ozero 761 drilling sites in the Siberian Platform, Yakutia.

and spheromorphic microfossils occur throughout (Rudavskaya and Vasileva 1989; Grausman and Zhernovskij 1989; Text-fig. 2).

MATERIAL AND TAPHONOMY

Microfossils were studied in permanent strew slides prepared by conventional palynological maceration techniques. The samples investigated are from dark-grey, thin-bedded, kerogen-rich mudstones and shales of the Khamaka Formation at depths between 1887 and 1894 m in Borehole Zapad 742, and between 1876 and 1884 and 1770 and 1790 m in Borehole Ozero 761 (Text-fig. 2). Additional specimens of acritarchs from the earlier collections of one of us (V. A. R.) marked with the acronym VNIGRI have been re-examined and taxonomically re-assigned. These additional specimens originated from boreholes Talakan 806, Talakan 823 and Zapad 844 in the principal study region, from Dyudan 291-0 and Nakyn 295-0 boreholes situated in the Syugdzher Saddle to the northeast of the Nepa-Botuoba region, and from the Borehole Charchyk 1 from the Lena-Anabar Depression (near the mouth of the Olenek River; Text-fig. 1). Microfossils from the Zapad 742 and Ozero 761 successions are exceptionally well-preserved, showing particularly well morphological elements such as processes. Nevertheless, rare instances of corrosion (Text-figs 6A–B, 16) occur, and vesicle collapse following the loss of cell turgescence and ensuing sediment compaction has resulted in the formation of folds and wrinkles.

The colour of organic vesicles ranges from pale yellow to very light brown, a feature that indicates low-grade thermal alteration. The palaeotemperature to which the host rocks were heated is inferred to have been approximately 50–70 °C, corresponding to the diagenesis and protokatagenesis stages of lithogenesis (Rovnina 1981; Hayes *et al.* 1983). However, no induced fluorescence is observed in the organic residues, which could indicate thermal alteration beyond the oil generation window (*c.* 90 °C). While the large acanthomorphic acritarchs are light yellow, spheromorphs are darker (brown).

PALAEOBIOLOGY

Siliclastic and carbonate rocks were initially thought to represent different environmental or taphonomic settings yielding different microfossils. However, the occurrence of encysted or motile life stages of planktonic protists in both silicified carbonate and detrital shelf deposits is now amply documented (Knoll 1984, 1992; Zhang 1984; Awramik *et al.* 1985; Yin 1985*a*, 1985*b*; Knoll and Ohta 1988). Despite the extensive literature dealing with environmental and climatological factors affecting the lateral and vertical distribution of acritarchs (see Moczydłowska and Vidal 1992, pp. 30–36 for a comprehensive review), few conclusions have been generated. The distribution of extant marine planktic protists responds to the complex interaction of water masses of different temperatures, salinity and nutrient-availability. In contrast, populations of early Palaeozoic cyst-forming protists appear to have displayed remarkable taxonomic homogeneity during relatively short intervals of time, a feature that has made them so useful in biostratigraphy (Moczydłowska and Vidal 1992). It could be argued that the unevenness observed in the populations of modern marine environments does not apply to the populations in the fossil record, due to the compression inherent in geological data making them appear substantially more stable and constant. On the basis of previous studies (e.g. Knoll 1992) and the present material, the wide environmental (Vidal and Nystuen 1990*a*) and geographical distribution of late Vendian (Ediacaran) plankton parallels the above observations on early Palaeozoic acritarchs. However, while early Cambrian acritarchs are generally abundant (Moczydłowska 1991) in standard palynological preparations, their late Neoproterozoic lavishly ornamented counterparts are by comparison quite rare. Hence, acid-resistant residues of organic-rich standard 50 g rock samples yield only modest numbers of large acanthomorphic acritarchs accompanied by numerous sphaeromorphs and cyanobacterial sheaths, in contrast to the hundreds of specimens commonly recovered from Cambrian rocks in comparable facies associations. This circumstance was not previously noted but, in our experience, it certainly applies also to the Ediacaran Pertatataka Formation in the Amadeus Basin of Australia. It is, however, difficult to relate such observations to assemblages from cherts of the late Neoproterozoic Doushantuo Formation in China, since microfossils from this unit were generally studied in petrographic thin sections (Zhang 1984; Yin 1985*a*, 1985*b*, 1987).

BIOSTRATIGRAPHY

Acritarchs attributed here to *Appendisphaera grandis* sp. nov., *Cavaspina acuminata* (Kolosova, 1991) comb. nov., *C. basiconica* sp. nov., *Tanarium conoideum* Kolosova, 1991 emend., *T. irregulare* sp. nov., and *T. tuberosum* sp. nov. were formerly assigned to the generally Early Palaeozoic genus *Baltisphaeridium* (Pyatiletov and Rudavskaya 1985; Rudavskaya and Vasileva 1989; Kolosova 1991). They were considered as evidence of an Early Cambrian age by Rudavskaya and Vasileva (1989), but Kolosova (1991) regarded them as indicating a late Riphean age. Acritarchs attributed here to *T. irregulare* sp. nov. were recently reported from the undoubtedly Neoproterozoic (Ediacaran) Pertatataka Formation in the Amadeus Basin of Australia (Zang 1988, p. 282). Other acritarchs reported by Zang (1988) are described here as *A. grandis* sp. nov. and *A. tenuis* sp. nov. (see below).

Recently, Knoll (1992) reported large acanthomorph acritarchs from a metamorphic rock succession in Prins Karls Foreland (Svalbard), including a taxon that he attributed to *Briareus borealis*. He also pointed out the resemblance between this taxon and acritarchs attributed by Rudavskaya and Vasileva (1989) to *Baltisphaeridium varium* (= *T. irregulare* sp. nov.; see below), whereas acritarchs described as ?*Asterocapsoides sinensis* were considered to resemble *B. primarium*

(Rudavskaya and Vasileva 1989; = *T. conoideum* (Kolosova) comb. nov.; see below). Furthermore, he noted that *B. strigosum* (in Rudavskaya and Vasileva 1989; see below) resembles *C. magnum* from the Neoproterozoic Doushantuo Formation in China (Zhang 1984). Unfortunately the markedly different state of preservation of the material from the Prins Karls Foreland adds some uncertainty to their identification.

The lower age limit of the present acritarch assemblage from the Khamaka Formation and time-equivalent beds cannot be established independently with absolute certainty, due to the absence of underlying fossiliferous beds. However, an upper limit is clearly provided by the Tommotian to early Atdabanian shelly fossils in the Bilir Formation (see above). Morphologically complex, age-diagnostic phytoplanktic microfossils occur consistently within an interval of shales and thin-bedded mudstones in the upper part of the siliciclastic unit, and dolostones of the lower part of the carbonate unit. This diagnostic assemblage was recorded in twenty boreholes in the region (Rudavskaya and Vasileva 1989; Kolosova 1991; and this paper).

Comparable associations of microfossils and isolated occurrences of individual species of microfossils are known from a number of localities in other regions of the Siberian Platform (Pyatiletov and Rudavskaya 1985; Kolosova 1991). However, these associations have not been described in detail. Kolosova (1991) concluded that the presence of acritarchs identified as *Trachyhystrichosphaera* aff. *aimica* Hermann in the rock interval 53·8 to 103·7 m of Borehole Torgo G-2 is in agreement with a late Riphean age. *Trachyhystrichosphaera* is indeed typically late Riphean (Hermann, 1990; Vidal *et al.* in press), but the identification of *T.* aff. *aimica* by Kolosova (1991, fig. 3, 1–3) appears extremely uncertain. They are associated with acritarchs attributed to *Cavaspina acuminata* (Kolosova) comb. nov., which also occurs abundantly in Borehole Talakan 806 at 1467·0 to 1473·9 m, between the Khamaka Formation and the clearly early Cambrian Bilir Formation (Grausman and Zhernovskij 1989; Rudavskaya and Vasileva 1989). These observations could suggest a post-late Riphean age for the material described by Kolosova (1991).

In summary, the acritarch evidence is here taken to indicate that, by comparison with acritarchs from the Ediacaran Pertatataka Formation from Australia (Zang, 1988; Zang and Walter, 1992), the age of acritarchs in the Khamaka Formation is late Vendian (Ediacaran). This conclusion also accords with evidence presented by Knoll (1992) for comparable microfossils from Svalbard, which he also interpreted as Vendian.

SYSTEMATIC PALAEONTOLOGY

Microscopic slides containing all figured specimens are kept in the collections of the Institute of Palaeontology, Uppsala University, Uppsala (with prefix PMU-Sib.) and at the All-Union Scientific Research Geological Prospecting Institute, St Petersburg (VNIGRI). The location of specimens on the microscopic slides is given by England Finder coordinates.

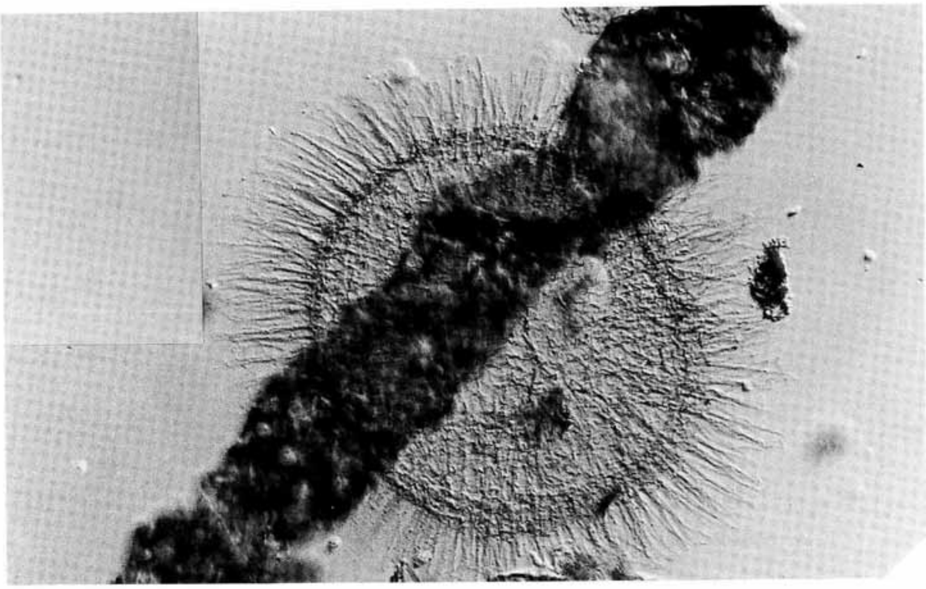
The problems resulting from incorrect taxonomic assignation of certain Neoproterozoic taxa were extensively discussed by Vidal and Nystuen (1990*b*). Some acritarch taxa reported in this paper were initially attributed to primarily Palaeozoic genera such as *Baltisphaeridium*, but are transferred here to new genera. Diagnostic morphological features and dimensional parameters are shown in Text-figs 3–4, 8–9, 12–13.

Group ACRITARCHA Evitt, 1963
Genus APPENDISPHAERA gen. nov.

Type species. Appendisphaera grandis sp. nov.

EXPLANATION OF PLATE 1

Figs 1–2. *Appendisphaera grandis* sp. nov. PMU-Sib.1-L/27/1, paratype; Borehole Zapad 742; depth 1887 to 1894 m. 1, specimen partly covered by superposed tubular, probably cyanobacterial sheath, ×570. 2, enlarged part of the same specimen showing detail view of processes, ×2400.



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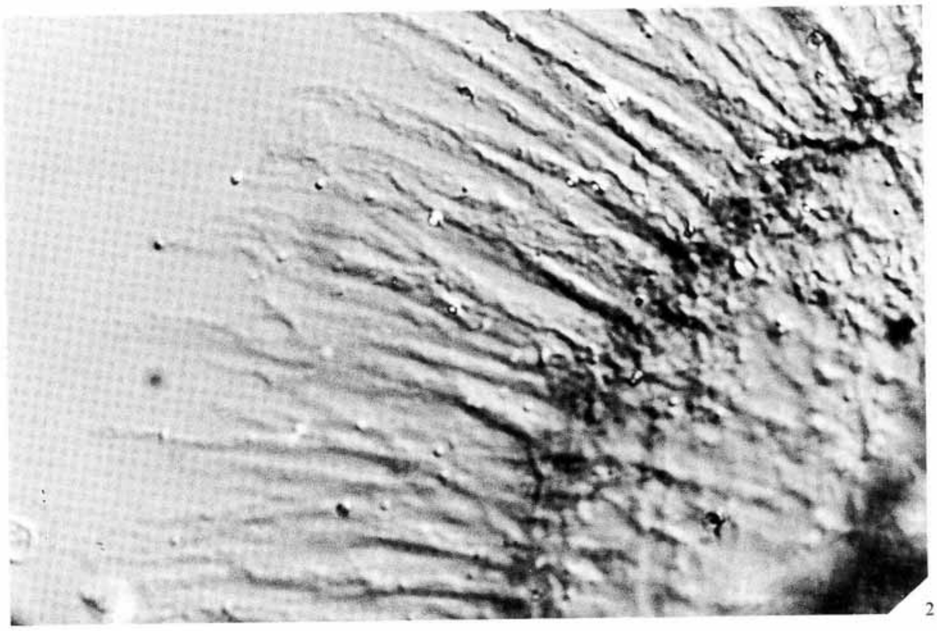

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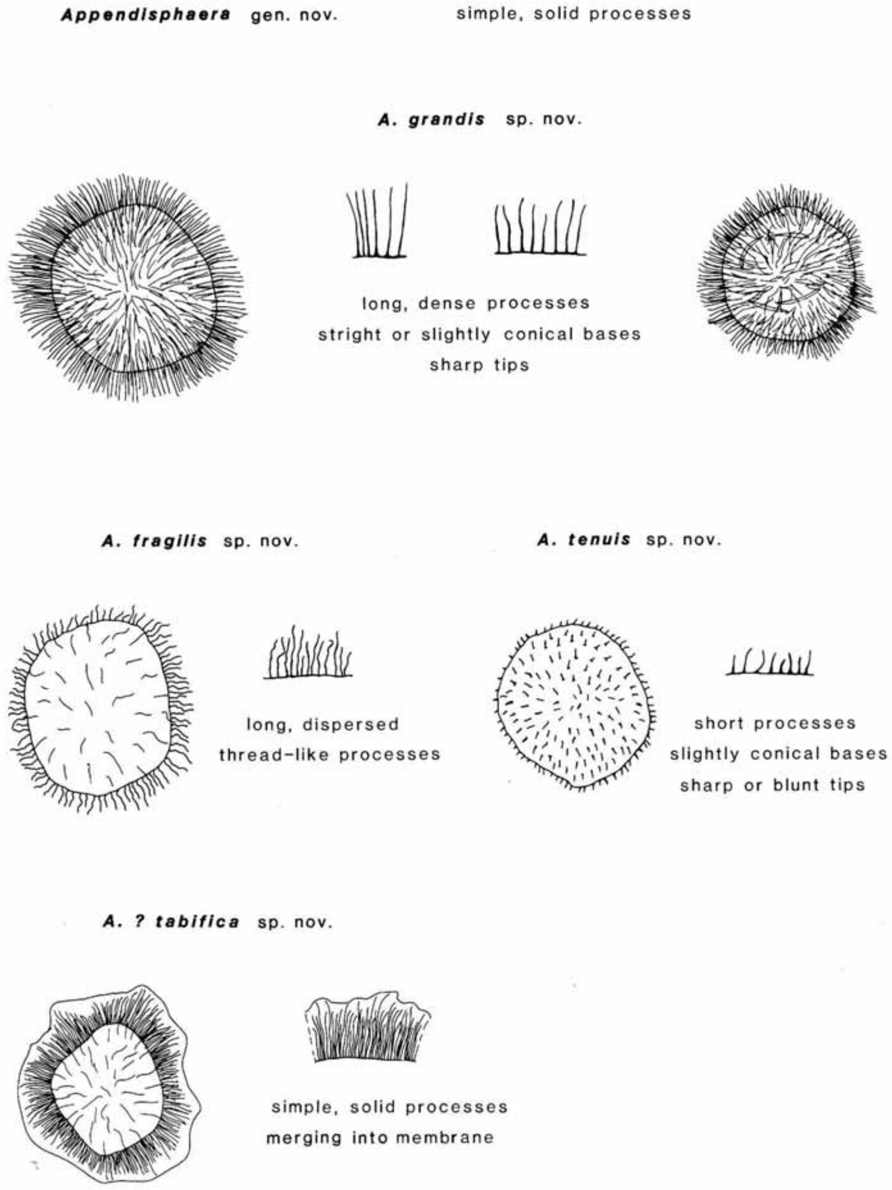
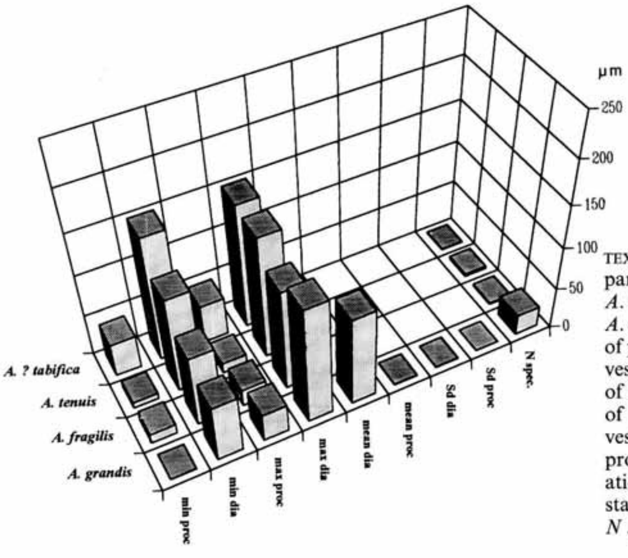


TEXT-FIG. 3. Generalized features of species of *Appendisphaera* gen. nov. showing diagnostic features of *A. grandis* sp. nov., *A. fragilis* sp. nov., *A. tenuis* sp. nov. and *A.* ?*tabifica* sp. nov.



TEXT-FIG. 4. Distribution of dimensional parameters of *A. ?tabifica* sp. nov., *A. tenuis* sp. nov., *A. fragilis* sp. nov. and *A. grandis* sp. nov. *Min proc*, lower range of process length; *min dia*, lower range of vesicle diameter; *max proc*, upper range of process length; *max dia*, upper range of vesicle diameter; *mean dia*, mean of vesicle diameter; *mean proc*, mean of process length; *Sd dia*, standard deviation of vesicle diameter; *Sd proc*, standard deviation of process length; *N spec*, number of measured specimens.

Derivation of name. From Latin *appendix* – outgrowth, process, appendage; and Latin *sphaera* – sphere, ball. The name refers to the spherical shape of the central vesicle and the processes that it bears.

Diagnosis. Organic-walled, acid-resistant microfossils consisting of medium to large circular to oval vesicles (originally spherical) bearing relatively long processes evenly distributed on the vesicle wall. The processes are simple and solid.

Remarks. Under transmitted-light microscopy, the processes appear to be solid, although they may have slightly widened proximal attachment areas. The morphological and dimensional characters of individual species are shown in Text-figs 3–4.

Appendisphaera grandis sp. nov.

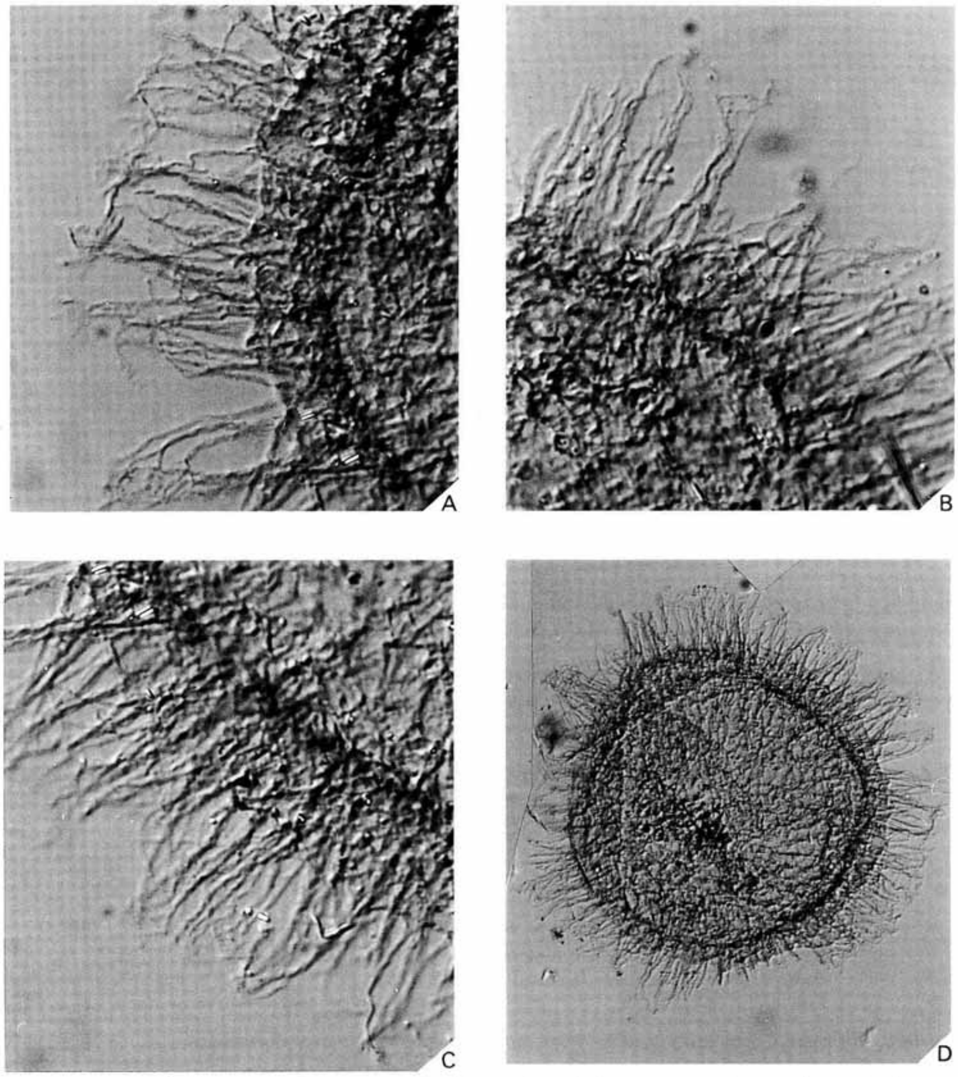
Plate 1, figs 1–2, Text-fig. 5

1985 *Baltisphaeridium* (?) *strigosum* Jankauskas; Pyatiletov and Rudavskaya, p. 152, pl. 63, figs 7, 9.
1989 *Baltisphaeridium strigosum* Jankauskas; Rudavskaya and Vasileva, pl. 1, figs 2–4, 6; pl. 2, figs 1–2.

Derivation of name. From Latin *grandis* – large, great. It refers to the large dimensions.

Types. Holotype specimen PMU-Sib.1-R/63/2 (Text-fig. 5A–D); paratype specimen PMU-Sib.1-L/27/1 (Pl. 1, figs 1–2). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887 to 1894 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

Diagnosis. Vesicle circular in outline, originally spherical, bearing very abundant long processes evenly distributed over its surface. The processes are homomorphic, simple and solid, proximally slightly widened and distally tapering. Their tips are sharp-pointed. The processes are densely distributed but clearly separated from each other and attached to the vesicle without clearly defined basal structures.



TEXT-FIG. 5. *Appendisphaera grandis* sp. nov. PMV-Sib.1-R/63/2, holotype; Borehole Zapad 742; depth 1887 to 1894 m. A–C, enlarged part of the vesicle displaying details of processes, × 2000. D, full specimen, × 500.

Material. Thirty-one specimens, including twenty-four that are very well preserved.

Dimensions. $N = 24$. Diameter of central body 68–140 μm (holotype 105–108 μm), $\bar{x} = 106{\cdot}1$ μm, $\delta = 10{\cdot}0$ μm; length of processes 9–33 μm (holotype 18–23 μm), $\bar{x} = 17{\cdot}4$ μm, $\delta = 6{\cdot}0$ μm. Length of processes varies within a range of 15–25% of the vesicle diameter.

Remarks. Kolosova (1990) proposed a new acritarch species *T. perfectum*. Despite attempts at obtaining the original publication, there is substantial doubt as to whether it was validly published, since only a preprint with submission number is available at the moment. In a later paper Kolosova (1991) figured a specimen under this name, but without providing a description or indicating the taxonomic status of the taxon. We suspect the taxonomic identity of *T. perfectum* with the presently erected *A. grandis*. However, the poor illustration of the equally poorly preserved holotype of *T. perfectum* in Kolosova (1990, 1991) does not allow certain identification. For these reasons, *T. perfectum* is not included in the formal synonymy.

In the present material, the vesicle wall is most probably smooth, but it is difficult to confirm this due to the very dense arrangement of the processes. The processes, although thin, seem to be relatively stiff and straight. As a result, they are commonly very well preserved and display a considerable regularity in shape and distribution.

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region: boreholes Zapad 742, depth 1887 to 1894 m, Ozero 761, depth 1876 to 1884 m, and Talakan 823, depth 1534 to 1539 m; Khamaka Formation. Syugdzher Saddle (NE of the Nepa-Botuoba region): boreholes Dyudan 291-0, depth 3414·3 to 3420·3 m and Nakyn 295-0, depth 3062 to 3068 m (this paper). Boreholes Ozero 750 (also known as Peleduj 750), depth 1835 to 1837 m and Byuk 715, depth 1964·8 m; Kursov Formation (Pyatiletov and Rudavskaya 1985).

Appendisphaera fragilis sp. nov.

Text-fig. 6A–B

Derivation of name. From Latin *fragilis* – fragile, thin, referring to the nature of the processes.

Holotype. Specimen PMU-Sib. 1-Y/37/3 (Text-fig. 6A–B). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887·0–1894·0 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

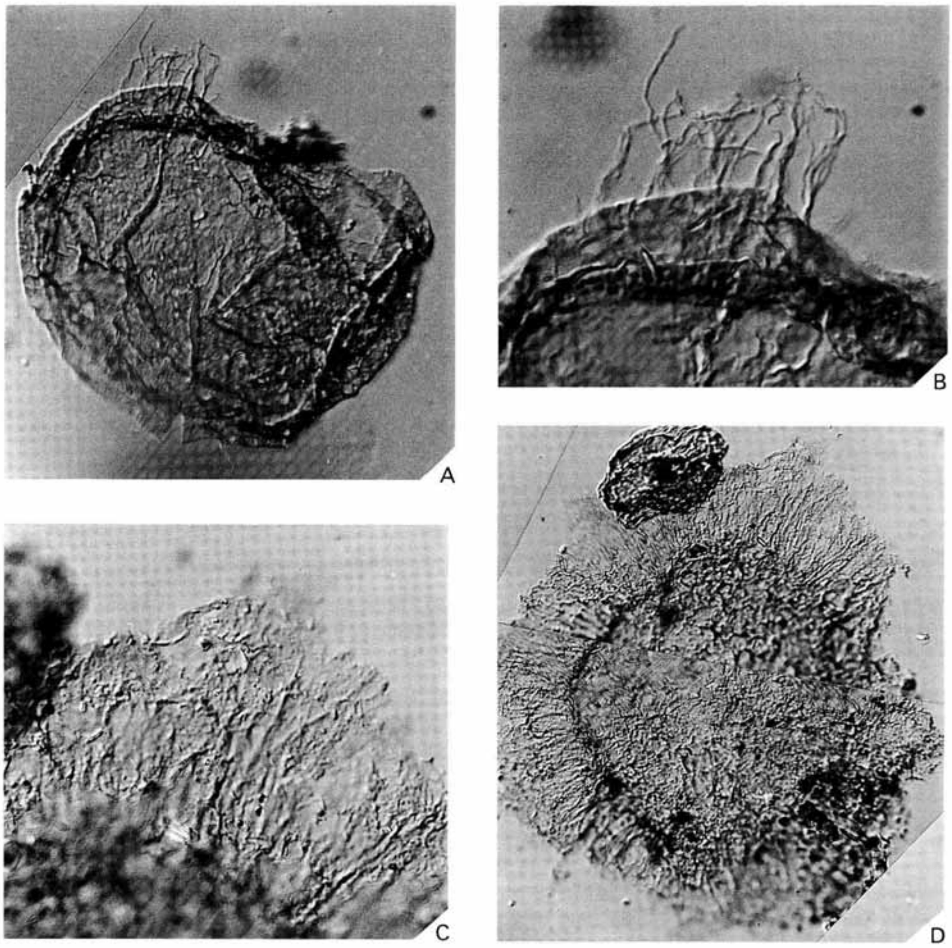
Diagnosis. Vesicle oval in outline, originally spherical, bearing long, slender and fragile processes. The wall of the vesicle is smooth as shown by the vesicle outline. The processes are of approximately equal length, thin and thread-like and have blunt tips. They are widely spaced.

Material. Three poorly preserved specimens.

Dimensions. $N = 3$. Diameter of central body is 57–121 μm, length of processes is 11–20 μm.

Remarks. The processes are only preserved on a small portion of the vesicle. Thus, their numbers and distribution is uncertain. The part of the vesicle wall that bears processes does not differ morphologically from the portions where processes are absent. The processes appear attached to the wall without additional basal structures. It is possible that, if they were broken during deposition and burial, they would not leave any traces on the surface of the vesicle. It is also possible that processes may have been both numerous and distributed over the complete surface of the vesicle. On the other hand, it is also conceivable that extremely poorly preserved specimens with a vesicle totally lacking processes could be easily mistaken as spheromorphs. Thus, some of the thin-walled spheromorph microfossils frequently found in Upper Proterozoic rocks could perhaps be in reality poorly preserved specimens of process-bearing species.

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region: Borehole Zapad 742, depth 1887 to 1894 m; Khamaka Formation. Syugdzher Saddle (NE of the Nepa-Botuoba region), Borehole Dyudan 291-0, depth 3414·3 to 3420·3 m (this paper).



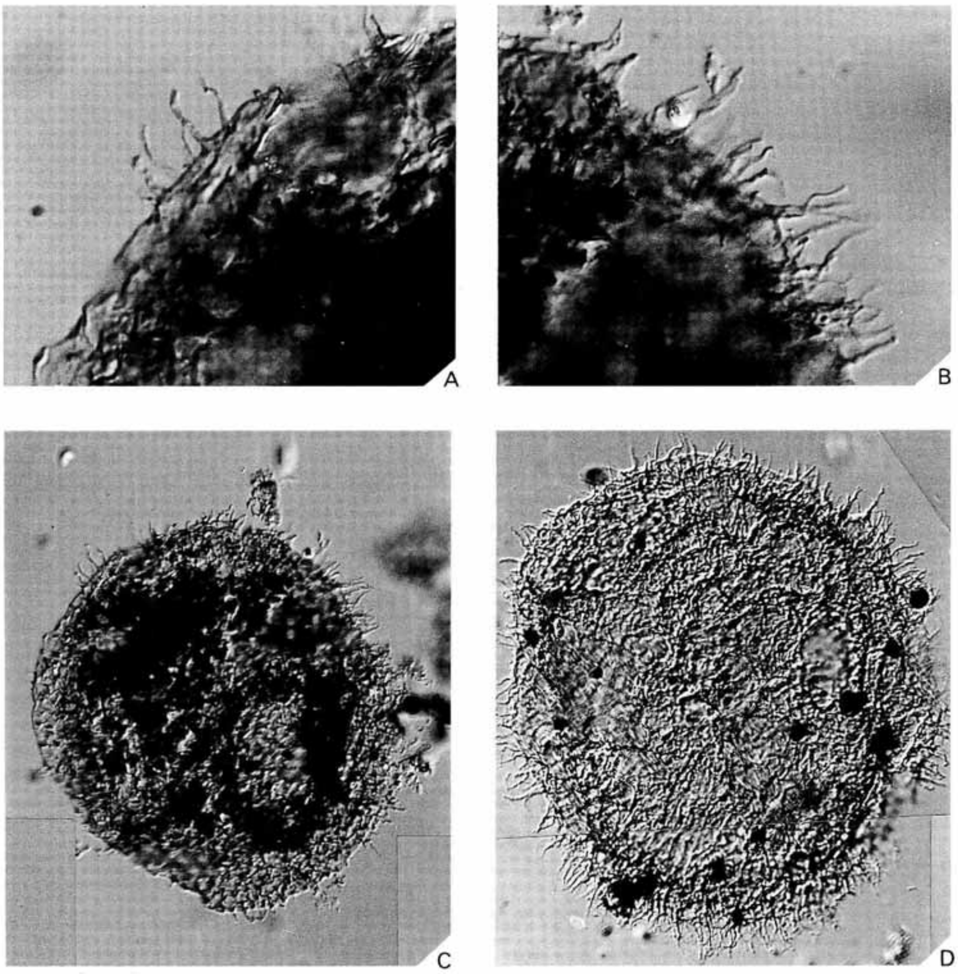
TEXT-FIG. 6A–B, *Appendisphaera fragilis* sp. nov. PMU-Sib.1-Y/37/3, holotype; Borehole Zapad 742; depth 1887 to 1894 m. A, complete specimen, × 600. B, enlarged portion of the vesicle and processes, × 1350. C–D, *Appendisphaera ?tabifica* sp. nov. PMU-Sib.2-H/33/4, holotype; Borehole Zapad 742; depth 1887 to 1894 m. D, full specimen, × 400. C, magnified part of the vesicle showing details of processes and membrane, × 850.

Appendisphaera tenuis sp. nov.

Text-fig. 7

Derivation of name. From Latin *tenuis* – thin, fine, delicate; with reference to the morphology of the processes.

Holotype. Specimen PMU-Sib.1-M/33 (Text-Fig. 7A–C). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887 to 1894 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.



TEXT-FIG. 7. *Appendisphaera tenuis* sp. nov. A–C, PMU-Sib.1-M/33, holotype; Borehole Zapad 742; depth 1887 to 1894 m. A–B, enlarged part of the vesicle with processes, ×1500; C, complete specimen, ×500. D, VNIGRI.3758/2-U/55/1; Borehole Dyudan 291-0; depth 3413·3 to 3420·3 m, ×500.

Diagnosis. Vesicle circular in outline, with smooth or psilate wall surface bearing numerous, evenly distributed, short spiny processes. The processes are solid, thin, and have sharp-pointed to blunt tips and slightly expanded, conical bases.

Material. Three well preserved specimens.

Dimensions. $N = 3$. Diameter of central body is 115–147 μm and length of processes 7–12 μm.

Remarks. The present species differs from the Neoproterozoic (late Riphean) species *Ericiasphaera* *spjeldnaesii* Vidal, 1990 through the more dense distribution of processes and by the lack of ciliar distal portions in the processes (Vidal 1990, p. 291).

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region: Borehole Zapad 742, depth 1887 to 1894 m; Khamaka Formation. Syugdzher Saddle (NE of the Nepa Botuoba region), Borehole Dyudan 291-0, depth 3414·3 to 3420·3 m (this paper).

Appendisphaera? *tabifica* sp. nov.

Text-fig. 6C–D

Derivation of name. From Latin *tabificus* – melting. It refers to distal portions of processes merging into the membrane.

Holotype. Specimen PMU-Sib.2-H/33/4 (Text-fig. 6C, D). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887 to 1894 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

Diagnosis. Vesicle circular in outline, originally spherical, having very abundant, extremely thin processes that coalesce and acquire the appearance of a membrane in the equatorial zone. The processes are simple, thin, solid and evenly distributed around the vesicle; they are supported by intervening organic matter and are welded to it distally.

Material. A single very well-preserved specimen.

Dimensions. The vesicle diameter is 115 μm and the length of processes 40–46 μm.

Remarks. The present material consists of a single specimen bearing processes, and embedded in a membrane that seems to be formed or supported by the processes. However, the membrane-like material is restricted to the equatorial zone, despite the fact that processes are evenly distributed around the vesicle. Since only one specimen is available, it is difficult to establish whether this is a diagnostic feature or a preservational artefact (e.g. due to the accumulation of organic matter trapped between very densely arranged processes). The species is assigned provisionally to *Appendisphaera*. Future finds may provide evidence as to whether the equatorial membrane is a diagnostic morphological character and thus require erection of a new genus.

Occurrence. As for the holotype.

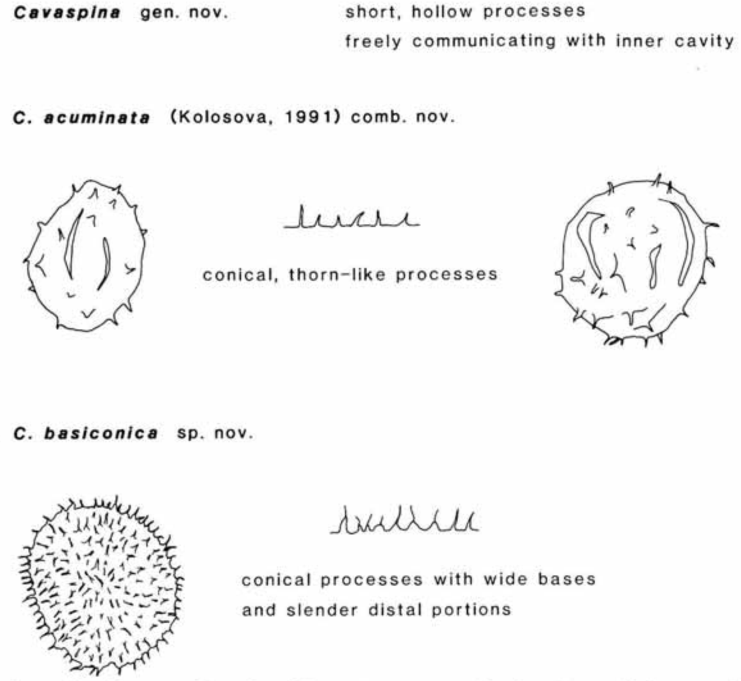
Genus CAVASPINA gen. nov.

Type species. *Cavaspina acuminata* (Kolosova, 1991) comb. nov.

Derivation of name. From Latin *cavus* – hollow, and Latin *spina* – spine. The name refers to the hollow processes, the cavities of which communicate with the vesicle cavity.

Diagnosis. Organic-walled, acid-resistant microfossils consisting of medium to large vesicles, circular to oval in outline, originally spherical, bearing evenly distributed processes. The processes are short and simple, cylindrical or conical, and hollow. The process cavities freely communicate with the vesicle cavity.

Remarks. The general morphology and dimensions of the species attributed to this genus are shown in Text-figs 8–9. *Cavaspina* superficially resembles *Goniosphaeridium*, but species attributed to *Cavaspina* are generally much larger. The ratio of vesicle diameter to process length in species of *Cavaspina* is substantially larger than in most species of *Goniosphaeridium*.



TEXT-FIG. 8. Generalized features of species of *Cavaspina* gen. nov. showing diagnostic features of *C. acuminata* (Kolosova 1991) comb. nov., and *C. basiconica* sp. nov.

Cavaspina acuminata (Kolosova, 1991) comb. nov.

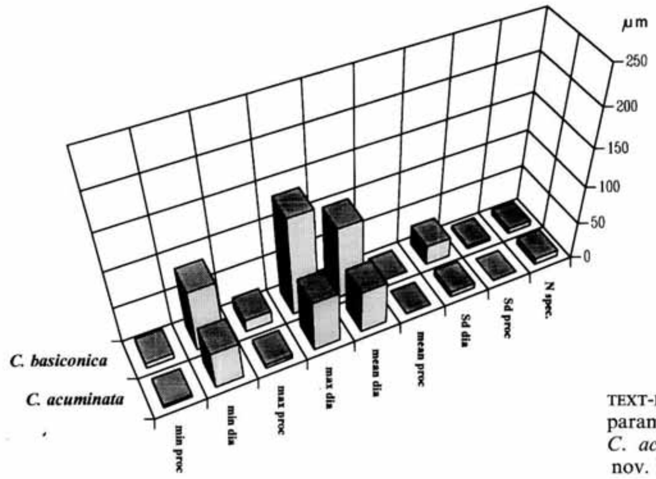
Text-fig. 10A–B

1989 Rudavskaya and Vasileva, pl. 1, fig. 5.
1989 *Baltisphaeridium pilosiusculum* Jankauskas; Rudavskaya and Vasileva, pl. 2, figs 4–6.
1989 *Baltisphaeridium* sp.; Rudavskaya and Vasileva, pl. 2, fig. 7.
1991 *Baltisphaeridium* (?) *acuminatum* Kolosova, p. 57, fig. 4: 1–3.

Holotype. Specimen YIGS Nr 87–123 (Kolosova 1991, fig. 4: 1). Yakutia, Siberian Platform, Borehole Torgo G-2 depth 70 to 74 m, Torgo Formation, Upper Proterozoic (Upper Riphean according to Kolosova 1991).

Translated original description. Microfossils (diameter 35–50 μm) more or less spherical, with slightly ribbed surface, having abundant folds. Processes (length 3–6 μm) conical, with sharp tips, of unequal length, unevenly distributed. Their number varies. Some processes have convex and the others straight surface. They differ in size and shape within the same specimen. Some processes have thick basis and regular conical shape, the others are sharply tapering in the distal portion. (Kolosova 1991, p. 57; translation by the authors.)

Remarks. The original description of the species does not provide information as to whether the processes are hollow or solid. Moreover, the species was only doubtfully referred to the genus *Baltisphaeridium*. However, the micrograph of the holotype (Kolosova 1991, fig. 4: 1), as well as the other figured specimens, shows that the processes are hollow and have free communication with the interior of the vesicle; diagnostically, *Baltisphaeridium* (a predominantly Ordovician genus) does not include species in which the processes and vesicle cavities interconnect.



TEXT-FIG. 9. Distribution of dimensional parameters of *C. basiconica* sp. nov. and *C. acuminata* (Kolosova, 1991) comb. nov. For abbreviations, see Text-fig. 4.

Emended diagnosis. Vesicle circular to oval in outline, spherical before compaction, bearing numerous simple processes. The processes are short, conical, acuminate and hollow, their cavities freely interconnecting with the vesicle cavity.

Material. Eight well-preserved specimens.

Dimensions. $N = 8$. The diameter of central body is 50–68 μm, $\bar{x} = 57{\cdot}0$ μm, $\delta = 6{\cdot}9$ μm. Length of processes is 3–5 μm, $\bar{x} = 4{\cdot}5$ μm, $\delta = 0{\cdot}7$ μm.

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region, Borehole Talakan 806, depth 1467.0 to 1473·9 m; Khamaka Formation. Lena-Anabar Depression (Mouth of Olenek River), Borehole Charchyk 1, depth 2683·0 to 2712·3 m (this paper). Berezov Depression (western slope of Aldan Shield), Borehole Torgo G-2, depth 70 to 74 m; Torgo Formation (Kolosova 1991).

Cavaspina basiconica sp. nov.

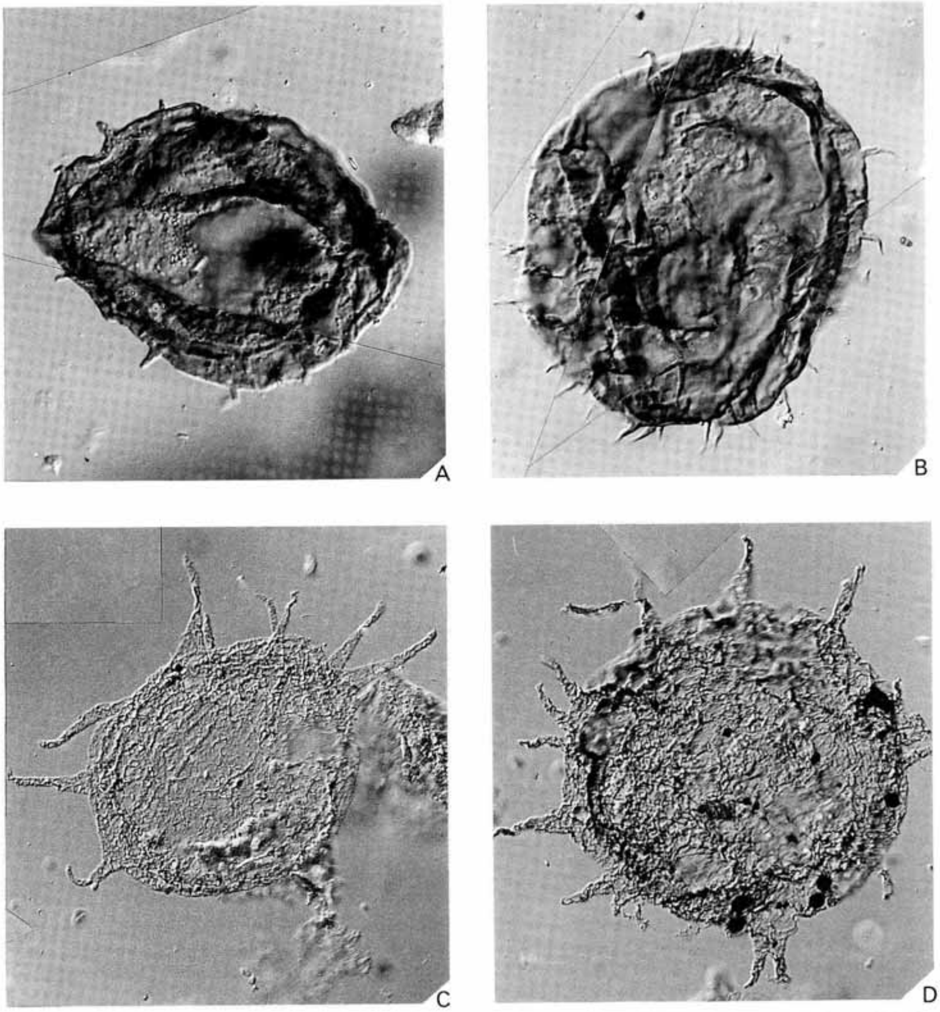
Text-fig. 11

1985 *Baltisphaeridium* (?) *strigosum* Jankauskas, 1976; Pyatiletov and Rudavskaya, p. 152, pl. 63, fig. 8.

Derivation of name. From Latin *basis* – base; and Latin *conicus* – conical. The name refers to the quasi-conical shape of the process base.

Types. Holotype specimen PMU-Sib.1-Y/55/2 (Text-fig. 11A–B, D); paratype specimen PMU-Sib.1-O/56-2 (Text-fig. 11C). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887 to 1894 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

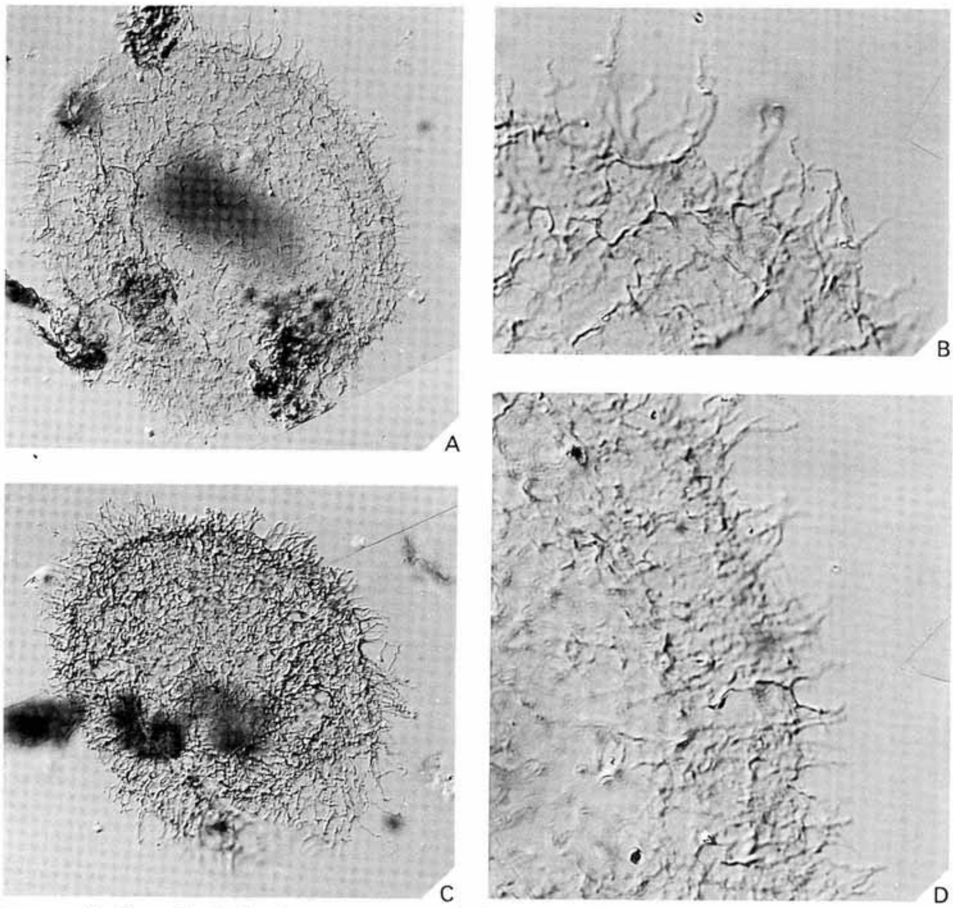
Diagnosis. Vesicle circular to oval in outline, originally spherical, having numerous and evenly distributed processes. The processes are approximately equal in length and have distinctive conical, swollen bases that grade into thin, slender and twisting distal portions. The process bases form a slightly wavy outline. The tips of the processes are tapering or blunt. The processes are hollow proximally, their cavities communicating with the vesicle cavity.



TEXT-FIG. 10. A–B, *Cavaspina acuminata* (Kolosova, 1991) comb. nov.; Borehole Talakan 806; depth 1467·0 to 1473·9 m. A, VNIGRI.1091/1-N/32, ×950; B, VNIGRI.1091/1-M/32/3, ×950. C–D, *Tanarium conoideum* Kolosova, 1991 emend.; Borehole Dyudan 291-0; depth 3414·3 to 3420·3 m. C, VNIGRI.3758/3-N/27/3, ×420; D, VNIGRI.3758/3-J/20/1, ×480.

Material. Seven well-preserved specimens.

Dimensions. $N = 6$. Diameter of central body is 83–133 μm (holotype 115–133 μm), $\bar{x} = 96{\cdot}9$ μm, $\delta = 26{\cdot}5$ μm. Length of processes 7–16 μm (holotype 11 μm), $\bar{x} = 10{\cdot}6$ μm, $\delta = 3{\cdot}9$ μm. One additional specimen displays much smaller dimensions, i.e. 32–43 μm in diameter and the length of processes is 3–5 μm.



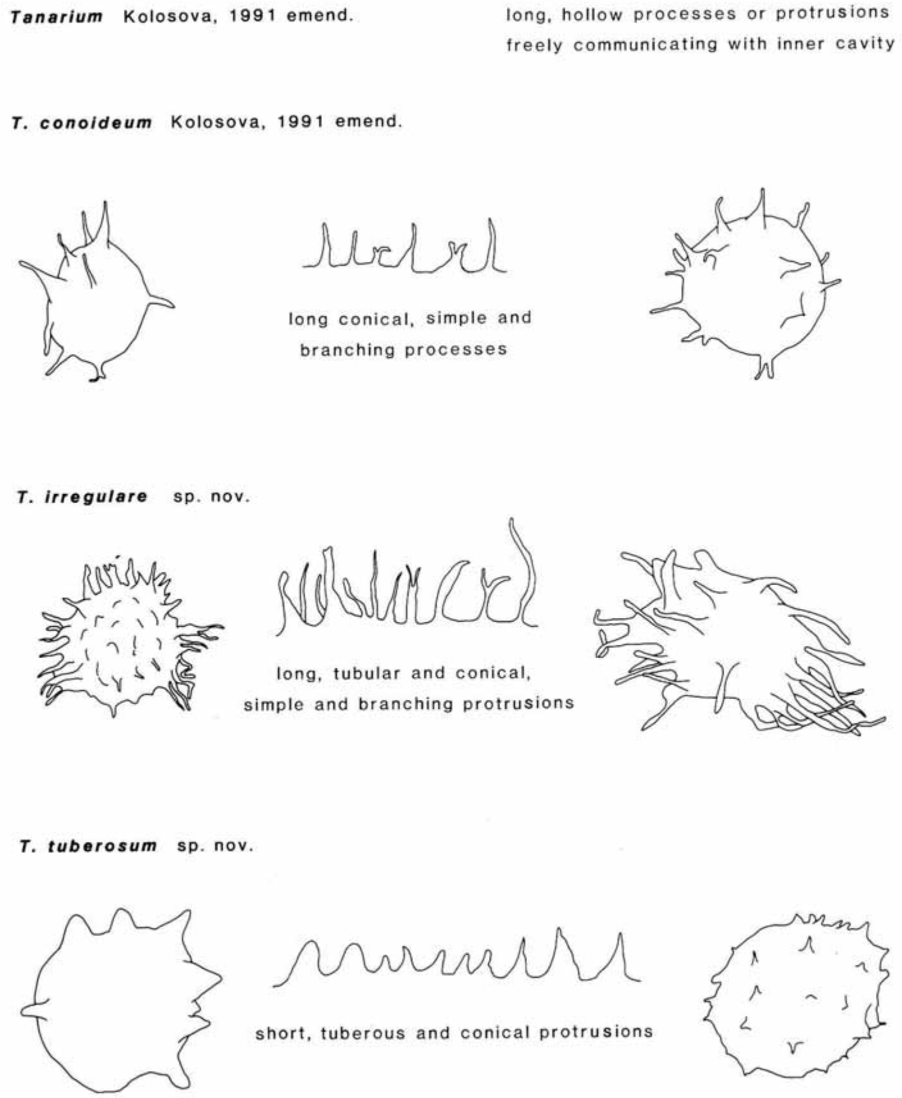
TEXT-FIG. 11. *Cavaspina basiconica* sp. nov. A–B and D, PMU-Sib.1-Y/55/2, holotype; Borehole Zapad 742; depth 1887 to 1894 m. A, complete specimen, × 480; B, D, magnified part of the same specimen showing conical bases of the processes (B) and slender distal portions of processes (D), × 1350. C, PMU-Sib.1-O/56/2, paratype; Borehole Zapad 742; depth 1887 to 1894 m, × 500.

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region: boreholes Zapad 742, depth 1887 to 1894 m and Talakan 823, depth 1534 to 1539 m; Khamaka Formation (this paper). Borehole Byuk 715, depth 1964·8 m; Kursov Formation (Pyatiletov and Rudavskaya 1985).

Genus TANARIUM Kolosova, 1991 emend.

Type species. *Tanarium conoideum* Kolosova, 1991.

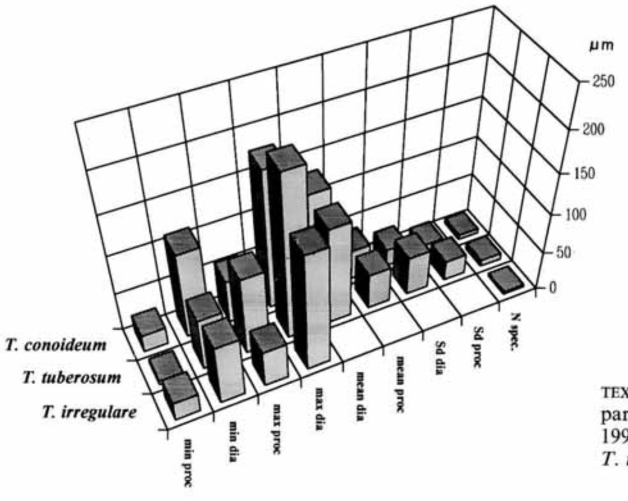
Translated original diagnosis. Microfossils dominantly of spheroidal form, diameter 80–200 μm. They possess processes of more or less equal size (in a single specimen), differing in number between specimens and not very



TEXT-FIG. 12. Generalized features of species of *Tanarium* Kolosova, 1991 emend., showing diagnostic features of *T. conoideum* Kolosova, 1991 emend., *T. irregulare* sp. nov., and *T. tuberosum* sp. nov.

evenly distributed; processes are unbranching, conical, solid and have straight or indented sides or they are needle-shaped thorns with greatly thickened bases. (Kolosova 1991, p. 56; translation by the authors).

Emended diagnosis. Organic-walled, acid-resistant microfossils consisting of a medium to large



TEXT-FIG. 13. Distribution of dimensional parameters of *T. conoideum* Kolosova, 1991 emend., *T. tuberosum* sp. nov., *T. irregulare* sp. nov. For abbreviations, see Text-fig. 4.

vesicle; the vesicle is circular, oval or irregular in outline, originally spherical or sub-spherical. Processes and protrusions of various shapes arise from the vesicle. The processes and protrusions are hollow and communicate with the vesicle cavity. They are conical or cylindrical, and tapering or rounded distally. Simple or branching processes may occur in the same specimen.

Remarks. According to the original diagnosis, *Tanarium* possesses solid processes. This feature is inconsistent with photo-micrographs of the type species, *T. conoideum* (Kolosova 1991, fig. 5: 1–3), which clearly show that the processes have inner cavities communicating with the vesicle cavity. Morphological criteria and dimensional parameters of species of *Tanarium* are shown in Text-figures 12 and 13.

The most salient feature distinguishing species of *Tanarium* from acritarchs attributed to *Goniosphaeridium* is the heteromorphic nature of their processes, a feature absent in *Goniosphaeridium*. Moreover, as with *Cavaspina* (see above), the observed ratio between vesicle diameter and process length seems generally larger in species of *Tanarium* than in the morphologically related *Goniosphaeridium*.

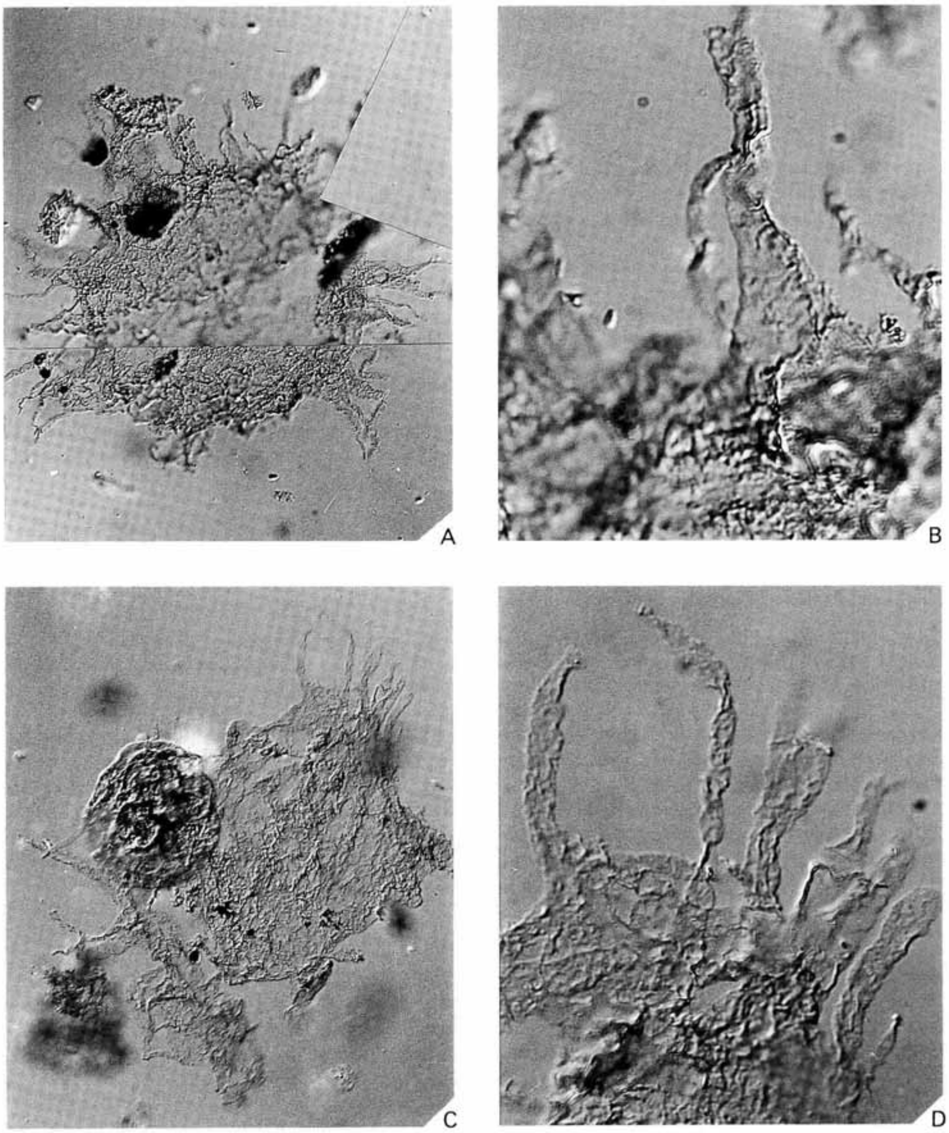
Tanarium conoideum Kolosova, 1991 emend.

Text-fig. 10C–D

1985 *Baltisphaeridium primarium* Jankauskas; Pyatiletov and Rudavskaya, p. 152, pl. 63, figs 1–4.
1989 *Baltisphaeridium primarium* Jankauskas; Rudavskaya and Vasileva, pl. 1, fig. 7.
1991 *Tanarium conoideum* Kolosova, p. 57, fig. 5: 1–3.

Holotype. Specimen YIGS Nr 87-115 (Kolosova, 1991, fig. 5: 1–2). Yakutia, Siberian Platform, Borehole Byuk-Tanar 715 (= Byuk 715), depth 1964·0 to 1970·6 m, Kursov Formation, Upper Proterozoic, Vendian.

Translated original description. Diameter of spheres 109–120 μm. Processes conical with straight sides. Their length is up to 40 μm and width at the base is 16 μm. Their number varies, relatively few in holotype and more numerous in other specimens. Due to their number, the distance between processes is variable. It varies between 7·2 and 90 μm (as stated in original publication) between different specimens. Some processes are broken. Microfossils are light yellow and darker in colour around the outline and, thus, they seem to be spheroidal, having narrow peripheral dark zone (Kolosova 1991, p. 57; translation by the authors).



TEXT-FIG. 14. *Tanarium irregulare* sp. nov. A, PMU-Sib.2-J/57/1, holotype; Borehole Zapad 742; depth 1887 to 1894 m, ×300. B, magnified part of the same specimen showing tubular processes with widened bases, ×1650. C, PMU-Sib.1-Q/51/3-4, paratype, Borehole Zapad 742; depth 1887 to 1894 m, ×280. D, enlarged part of the same specimen showing the vesicle with tubular process having free communication with the inner cavity, ×1000.

Emended diagnosis. Vesicle circular to oval in outline, originally spherical or spheroidal, possessing randomly distributed heteromorphic processes. The processes are conical or cylindrical with tapering or rounded tips. Occasionally the processes are bifurcated distally. The bases of the processes are often conspicuously widened. The processes are hollow and their cavities communicate with interior of vesicle.

Remarks. The holotype of *T. conoideum* was selected by Kolosova (1991) from the same locality and stratum as Pyatiletov and Rudavskaya (1985) recorded *Baltisphaeridium primarium* Jankauskas. The latter species is here considered conspecific with *T. conoideum*.

Material. Six very well-preserved specimens.

Dimensions. $N = 6$. Diameter of central body is 110–176 μm, $\bar{x} = 130{\cdot}2$ μm, $\delta = 22{\cdot}4$ μm. Length of processes is 22–55 μm, $\bar{x} = 38{\cdot}5$ μm, $\delta = 10{\cdot}5$ μm. Width of process bases is 7–22 μm.

Occurrence. Yakutia, the Siberian Platform, Syugdzher Saddle (NE of the Nepa-Botuoba region): Borehole Dyudan 291-0, depth 3414·3 to 3420·3 m; Lena-Anabar Depression (Mouth of Olenek River), Borehole Charchyk 1, depth 2703·0 to 2712·3 m (this paper). Nepa-Botuoba region: boreholes Byuk 715, depth 1968·8 m, Kursov Formation (Pyatiletov and Rudavskaya 1985) and Ozero 761, depth 1876·3 to 1884·6 m (Kolosova 1991).

Tanarium irregulare sp. nov.

Text-fig. 14

1989 *Baltisphaeridium varium* Volkova; Rudavskaya and Vasileva, pl. 2, fig. 8.

Derivation of name. From Latin *irregularis* – irregular, referring to the shape of processes.

Types. Holotype specimen PMU-Sib.2-J/57/1 (Text-fig. 14A–B); paratype specimen PMU-Sib.1-Q/51/3-4 (Text-fig. 14C–D). Borehole Zapad 742, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1887·0 to 1894·0 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

Diagnosis. Vesicle irregular in outline with a general oval shape, originally probably sub-spherical. The vesicle extends into long processes that are hollow, their cavities communicating freely with the vesicle cavity. The wall of the vesicle and processes is smooth or psilate. The processes are heteromorphic, simple or branched. They are tubular and of equal diameter along their complete length. Alternatively, they may gradually taper towards the distal portion or be conical. Their tips are sharply pointed to rounded. Some processes are distally bifurcated. Proximally the processes arise abruptly from the vesicle wall, or have widened conical bases.

Material. Three well-preserved specimens.

Dimensions. $N = 3$. Diameter of central part of vesicle is 75–115 μm. Length of processes is 23–46 μm.

Remarks. Microfossils of comparable shape and symmetry of the vesicle were reported by Zang (1988, p. 282) from the Neoproterozoic Pertatataka Formation in the Amadeus Basin, Australia.

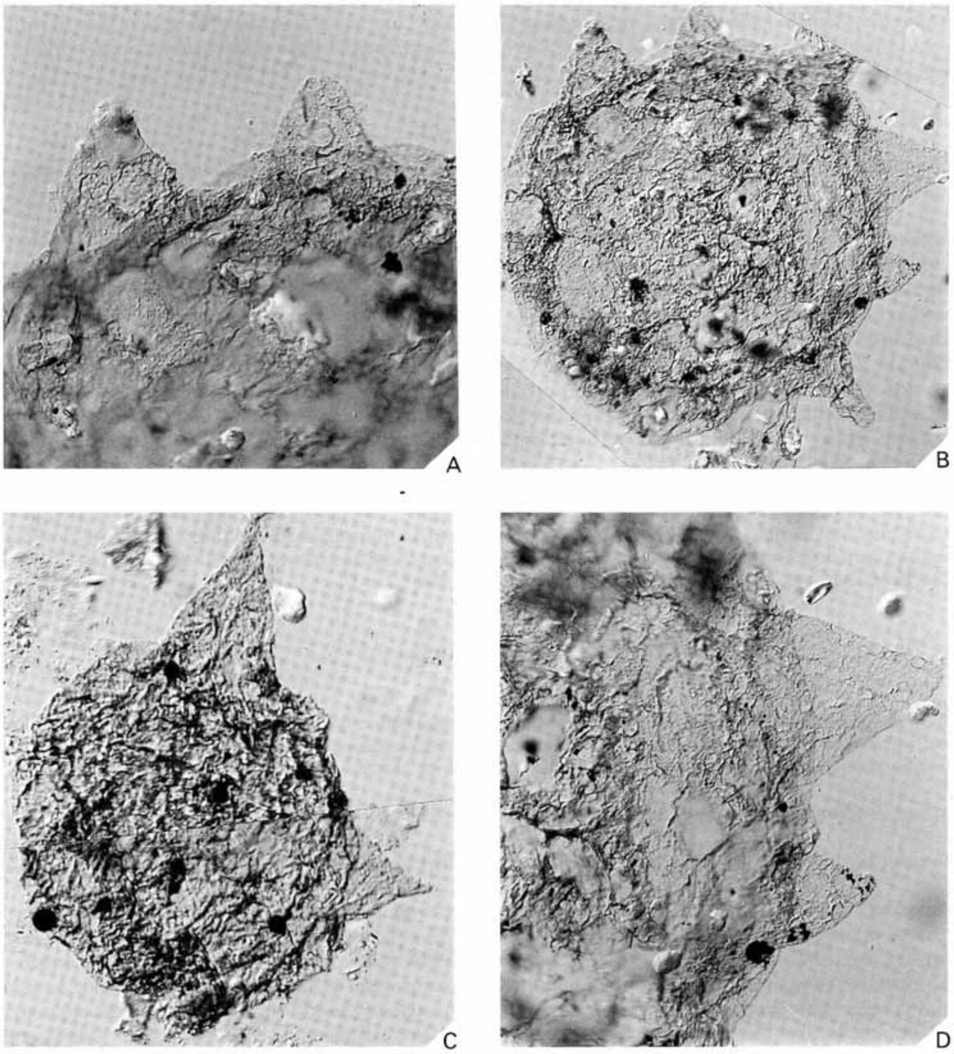
Occurrence. As for the holotype.

Tanarium tuberosum sp. nov.

Text-fig. 15

1989 *Baltisphaeridium primarium* Jankauskas; Rudavskaya and Vasileva, pl. 2, fig. 3.

Derivation of name. From Latin *tuberosus* – full of protuberances or lumps. It refers to the shape of the morphological elements.



TEXT-FIG. 15. *Tanarium tuberosum* sp. nov. A–B and D, PMU-Sib.4-J.30/3, holotype; Borehole Ozero 761; depth 1876 to 1884 m. A, D, enlarged part of the vesicle with hollow protuberances freely communicating with the inner cavity of vesicle, × 560. B, the same specimen in full, × 280. C, VNIGRI.3142/2-W/56/3; Borehole Nakyn 295-0; depth 3062 to 3068 m, × 550.

Holotype. Specimen PMU-Sib.4-J/30/3 (Text-fig. 15A–B, D). Borehole Ozero 761, Nepa-Botuoba region, Yakutia. Thinly bedded mudstones at 1876 to 1884 m, lowermost Khamaka Formation, Neoproterozoic, Upper Vendian.

Diagnosis. Vesicle circular, oval or irregular in outline, originally spherical to sub-spherical, and possessing wide or conical protrusions. The protrusions are hollow and communicate with the vesicle cavity.

Material. Eight well-preserved specimens.

Dimensions. $N = 8$. Diameter of central body is 66–207 μm, $\bar{x} = 124{\cdot}3$ μm, $\delta = 49{\cdot}4$ μm. Length of protrusions is 5–99 μm, $\bar{x} = 45{\cdot}6$ μm, $\delta = 25{\cdot}4$ μm. Width of protrusions is 6–46 μm.

Remarks. Chen and Liu (1986) described structurally preserved microfossils from the Neoproterozoic (Sinian) Doushantuo Formation in China that they attributed to *Megasphaera inornata*, *Meghystrichosphaeridium wengaensis* and *M. chadianensis*. The taxa in question appear to represent three-dimensionally preserved large acritarchs, 200–800 μm in diameter. In particular, illustrated specimens of *Meghystrichosphaeridium wengaensis* and *M. chadianensis* (Chen and Liu 1986, pl. 2, figs 1–4) undoubtedly resemble some acritarch specimens attributed here to *T. tuberosum* sp. nov. However, the different preservation of these phosphatized specimens renders identification difficult. Furthermore, specimens of *T. tuberosum* are substantially smaller, with overall dimensions ranging from *c*. 70–300 μm (see above). Safe identification demands direct examination of the Doushantuo microfossils.

Occurrence. Yakutia, Siberian Platform, Nepa-Botuoba region: boreholes Ozero 761, depth 1876 to 1884 m and Zapad 844, depth 1700·0 to 1715·6 m; Khamaka Formation. Syugdzher Saddle (NE of the Nepa-Botuoba region), Borehole Nakyn 295-0, depth 3062 to 3068 m. Lena-Anabar Depression (Mouth of River Olenek), Borehole Charchyk 1, depth 2703·0 to 2712·3 m (this paper).

Spheromorphs

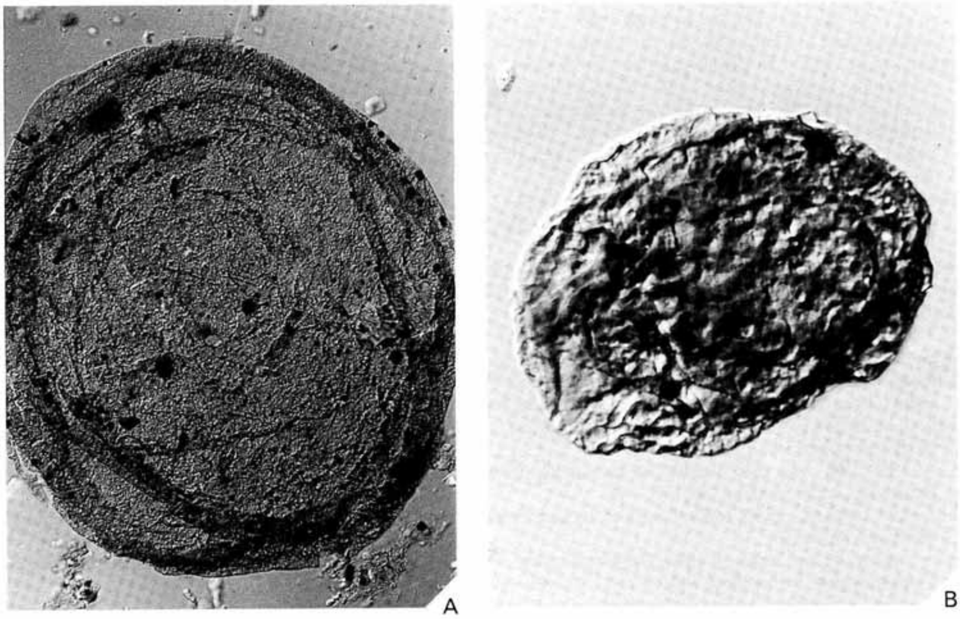
Text-fig. 16

Description. Acritarchs with circular to oval outline, spherical before compaction. The thickness of the vesicle wall varies from thin to thick, a feature not related to the vesicle diameter. The surface of the wall is smooth, psilate or chagrinate, and is often deformed into irregular or arcuate compression wrinkles.

Material. Abundant specimens in variable states of preservation.

Dimensions. $N = 20$. Diameter of vesicle varies between 46–118 μm and 250–424 μm.

Remarks. The taxonomy of spheromorphic organic-walled microfossils has been the subject of several taxonomic reviews (Volkova 1964; Vidal 1976; Lindgren 1982; Vidal and Siedlecka, 1983; Jankauskas 1989; Knoll *et al*. 1991; Moczydłowska 1991; Knoll 1992) that reflect the small number of available morphological features. Diagnostic features used to subdivide the group into genera and species have been essentially arbitrarily and inconsistently used. Features such as the diameter of the vesicle, and thickness and surface sculpture of the wall, seem open to subjective judgement. In the case of dimensional limits chosen to distinguish various taxa (e.g. within the genus *Leiosphaeridia* Jankauskas, 1989) the criteria are purely arbitrary. In many taxa, the apparent ornamentation of the wall seems to be a preservational feature introduced by corrosion, biodegradation or mineral growth (Vidal 1974, 1976). Different states of preservation of the vesicle wall have been used to recognize species. With the exception of a few diagnostically ornamented taxa, the taxonomic attribution of unornamented spheromorphs remains problematic. Possibly, more 'objective' characters could be provided by studies on the chemical composition and ultrastructure. However, few such studies have been undertaken and in view of the present lack of other evidence we refrain from attempting a more precise taxonomic attribution of these microfossils.



TEXT-FIG. 16. Spheromorphic, organic-walled microfossils displaying corroded vesicle walls and compaction wrinkles. A, PMU-Sib.4-V/32; Borehole Ozero 761; depth 1876 to 1884 m, ×240. B, PMU-Sib.1-J/49/4; Zapad 742; depth 1887 to 1894 m, ×800.

Occurrence. Common in all investigated successions.

Acknowledgements. For support connected with logistics, field work and collecting of material we are most grateful to Mrs Valentina V. Grausman and Dr Valeri E. Bakin (Geological Production Corporation, Lena Gas and Oil Geology, Yakutsk, P. G. O., Lena, Yakutsk), Dr Genady Novikov (V.N.G.R.E., Kysyl-Syr, Yakutia) and the Swedish Arctic Research Programme, Stockholm. G. Vidal and M. Moczydłowska wish to acknowledge generous grant support from the Natural Science Research Council (NFR) that defrayed field work in Yakutia, laboratory research and the work of V. A. Rudavskaya at the Micropalaeontological Laboratory (Uppsala University). Our initially submitted manuscript was substantially improved through constructive reviews by Drs Robert A. Fensome and Andrew H. Knoll.

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Typescript received 9 June 1992
Revised typescript received 21 December 1992

Note added in proof. In a recent monograph, Zang and Walter (1992) described similar acritarchs. *Solisphaeridium*? sp. in Zang and Walter (1992, p. 100, fig. 32H, I) is conspecific with *Tanarium irregulare* sp. nov. *Appendisphaera grandis* sp. nov. is similar to *Comasphaeridium* sp. B (Zang and Walter 1992, fig. 28F, G). *A. tenuis* sp. nov. differs from *Baltisphaeridium plerusente* Zang, 1992 and *B. rarusente* Zang, 1992 by having solid processes. The latter two species are considered conspecific and the generic attribution incorrect. *A.*? *tabifica* differs from *C. dilutopilum*. *A.*? *tabifica* processes are more even in length and longer than *C. dilutopilum*. The generic attribution of the latter species is incorrect given that *Cymatiosphaeroides* possesses an outer membrane enclosing the vesicle and processes (Knoll 1984; Knoll *et al.* 1991).