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Petsamomyces, a New Genus of Organic-Walled Microfossils from the Coal-Bearing Deposits of the Early Proterozoic, Kola Peninsula

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Abstract—A new genus of organic-walled microfossils of supposed fungal origin, *Petsamomyces* Belova gen. nov., is described from the black shales of the Pechenga complex of the Early Proterozoic (Kola Peninsula). The find testifies to the development of eukaryotic heterotrophic microorganisms as early as 2 Ga ago.

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Key words: Kola Peninsula, Precambrian, Paleoproterozoic, Pechenga complex, microfossils.

INTRODUCTION

Finds of organic remains in Early Proterozoic complexes are relatively rare in comparison with the younger Riphean and Vendian deposits. The respective numbers of localities with organic remains differ by almost an order of magnitude: microfossils are described from slightly more than 30 Early Proterozoic formations (*The Proterozoic* …, 1992). Among them, there are two main types of biota differing in both the mode of preservation and taxonomic composition, which, to a great extent, reflects environmental differences. The first, most common, type of Early Precambrian biota includes organic-walled microfossils of mostly spherical acritarchs and is restricted to terrigenous deposits. The overwhelming majority of these microbiota were revealed by Timofeev as early as the 1960s–1970s in the former Soviet Union. The other, so-called Gunflint type (after the Gunflint Formation, Canada), comprises microbiota of siliceous microfossils with more morphologically complex forms, unknown in younger deposits. Such biota are described from several Paleoproterozoic formations of the United States, Canada, and Australia (Barghoorn and Tyler, 1965; Walter et al., 1976; Cloud and Morrison, 1979; and others).

The presence of microfossils resembling lower fungi was repeatedly reported from both types of Early Proterozoic biota. Darby (1974), who studied a comprehensive material from flints of the iron Gunflint Formation of one of the previously described localities (Shriberry region, Ontario; Barghoorn and Tyler, 1965), hypothesized that some specimens of coccoid microfossils of *Huroniospora microreticulata* Barghoorn might be comparable with sprout forms of Mucorales fungi. Timofeev (1979, 1982) reported the presence of fungal-like remains from the Early Proterozoic of the Karelia–Kola Peninsula region. Hofmann and Grotzinger (1985) described a pear-shaped form (unnamed form B) from the carbonate stromatolites of the Rocknest Formation, northwestern Canada, 1.89 Ga, and compared it with sprout forms from the Gunflint Formation described by Darby (1974).

In the Late Precambrian, microfossils of supposed fungal affinity were relatively common (Herman, 1979; Mikhailova, 1986; Allison, 1988; Burzin, 1993; Weiss and Petrov, 1994; and others). Nonetheless, reports of eukaryotic heterotrophic microorganisms from about 2-Ga-old deposits are often considered as doubtful, and these remains are interpreted as deformed acritarchs or modern contaminants (*The Proterozoic* …, pl. 22.1, 22.3). It was repeatedly emphasized that lower fungi, along with bacteria, are able to decompose organic matter and return it into the nutrient cycle. Their presence is necessary in any biogeocenosis starting from the origin of the biosphere (Vernadsky, 1965; Popov, 1973; etc.).

Non-mineralized microfossils were first recorded from the deposits of Pechenga complex by Timofeev (1979), who studied core samples from the Kola ultradeep borehole, 5800–764 m and found at different levels mostly small spherical acritarchs of *Protosphaeridium* Timofeev (~*Leiosphaeridia*). Among them, solitary pear-shaped microfossils are present, determined by Timofeev as spores of *Phycomycetes*.

Our study of a representative material from the core samples (including ultradeep borehole-3) and quarry exposures (Figs. 1, 2) revealed numerous diverse microfossils comparable with vegetative and reproductive organs of lower fungi.

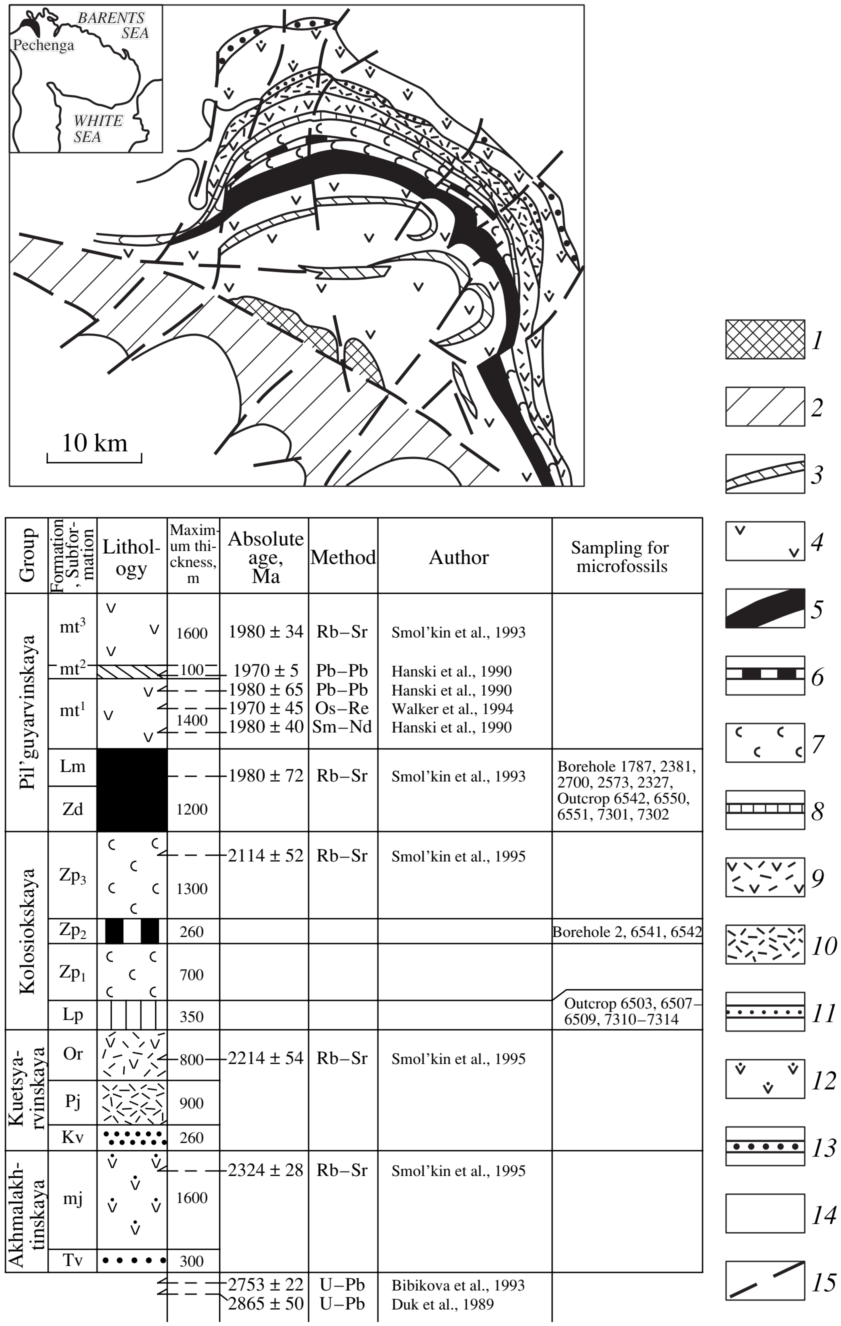


Fig. 1. Geological scheme of the Pechenga Trough and the composite section of the Pechenga complex: (*1*) andesite-dacites; (*2*) deposits of the southern shaly Pechenga Subzone; (*3*) quartz porphyries; (*4*) tholeiites of the Matert Formation; (*5*) productive strata; (*6*) black shales of the Zapolyarnyi Formation; (*7*) tholeiites of the Zapolyarnyi Formation; (*8*) metasediments of the Luchlompolo Formation; (*9*) trachybasalts of the Pirtiyarvi Formation; (*10*) trachyandesites of the Orshoaivi Formation; (*11*) metasediments of the Kuvernerin-ioki Formation; (*12*) andesite-basalts of the Mayarvi Formation; (*13*) polymictic conglomerates of the Televi Formation; (*14*) Archean deposits; (*15*) ruptured zones.

Geological Position and the Age of the Black Shales

The Pechenga structure is a relict of the rift trough, the formation of which started during the Sarioli Stage, 2.4–2.3 Ga (Fig. 1). The Pechenga section is characterized by cyclic interstratification of sedimentary and volcanogenic successions. There are four groups (Fig. 1), the upper of which, Pil'guyarvi, represents beds of complicated structure of various black shales (Zhdanovskoe and Lammas formations), forming so-called productive beds, and overlying volcanites of the Matert Formation.

According to different isochrones (Pb-Pb method), the ages of tholeiitic and ferropicritic lavas of the

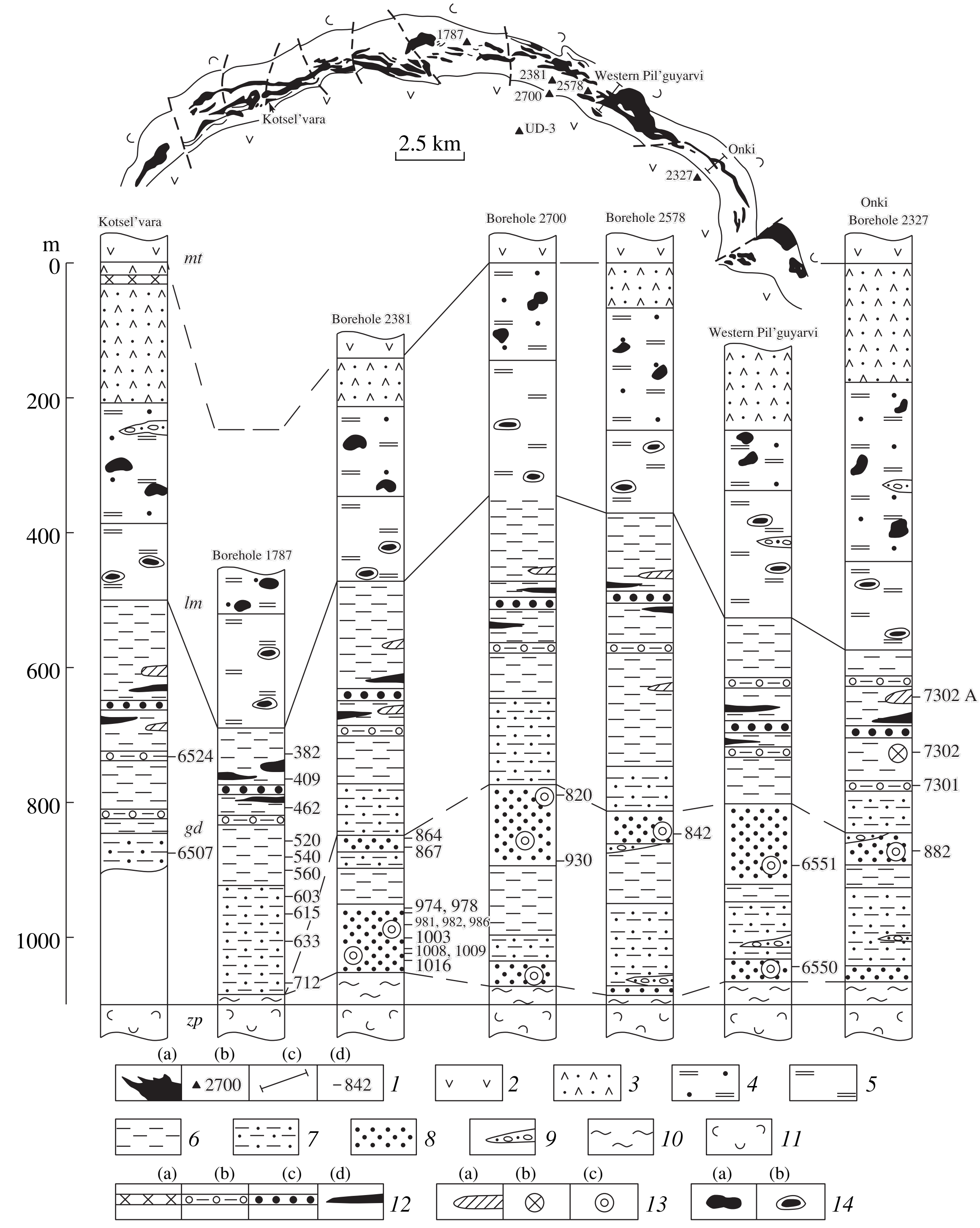


Fig. 2. Position of boreholes and sections and the structure of the productive strata of the Pechenga complex in different facial subzones: (*1*) field of the productive strata; (*1*a) nickel-bearing intrusions; (*1*b) boreholes and their numbers; (*1*c) sections; (*1*d) numbers of samples; (*2*) lavas of the Matert Formation; (*3*) tuff-sandstones; (*4*) tuffaceous sandstones; (*5*) flyschoid carbonaceous aleuropelites; (*6*) tuffaceous siltstones; (*7*) tuffaceous aleuropsammites; (*8*) gritstones and gravelly sandstones; (*9*) small-pebbled conglomerates; (*10*) high-carbonaceous pelites; (*11*) spherulitic lavas; (*12*) levels with concretions; (*12*a) siliceous concretions; (*12*b) carbonaceous concretions; (*12*c) pyritic concretions; (*12*d) massive pyritic ores; (*13*) separated concretions; (*13*a) calcareous concretions; (*13*b) manganese concretions; (*13*c) phosphate concretions; (*14*) sulfide deposits; (*14*a) pyrrhotite sulfides; (*14*b) carbonaceous pyrrhotite sulfides.

Matert Formation is 1980 ± 65 Ma and 1980 ± 40 Ma (Smol'kin et al., 1993; Hanski et al., 1990). According to the Sm-Nd isochrone, the age of the ferropicrites is 1990 ± 43 Ma. The tholeiitic basalts of the Matert Formation is 1980 ± 40 Ma by the $^{87}Sr/^{86}Sr$ method (*Magmatism* …, 1995). The productive beds are situated on tholeiitic basalts of the Zapolyarnyi Formation, 2114 ± 52 Ma according to the Rb/Sr method (*Magmatism* …, 1995). Therefore, the formation of the black shales took place about 2 Ga ago.

The lower formation of the productive beds, Zhdanovskoe Formation, is up to 900 m thick and is constituted by rhythmic layered carbonaceous siltstones and silt sandstones of the turbidite type, with the presence of pyritic, manganous-carbonaceous, and phosphate diagenetic concretions. The number and composition of the concretions vary laterally depending on the facial conditions. Most microfossils were found in gritstones and gravelly sandstones, which form a member (150 m) in the lower portion of the Zhdanovskoe Formation and include carbonaceous phosphate macro- and microconcretions. The lithologic-and-facial study of the productive beds showed that carbonaceous sediments were deposited in a sea basin under turbidite sedimentary conditions, and phosphates were related to shelf facies (Akhmedov and Krupenik, 1990).

MATERIALS AND METHODS

The organic remains from the deposits of the Zhdanovskoe Formation were extracted via conventional palynological maceration without crushing the samples. In total, we analyzed about 50 core samples and samples from outcrops of Onki, Zapadnoye Pil'guyarvi, and Kotsel'vara open mines (Fig. 2). The occurrence of numerous microfossils in the core samples (at depths of about 1000 m) excludes the possibility of older or younger contamination, including modern inwash of organic matter into deposits. To check the possibility of laboratory contamination, some samples were re-macerated. These samples showed a good correspondence: qualitative and quantitative characteristics microfossils were similar.

The microbiota of the Zhdanovskoe Formation differs from most of the biota known from the Early and Late Proterozoic in the following parameters.

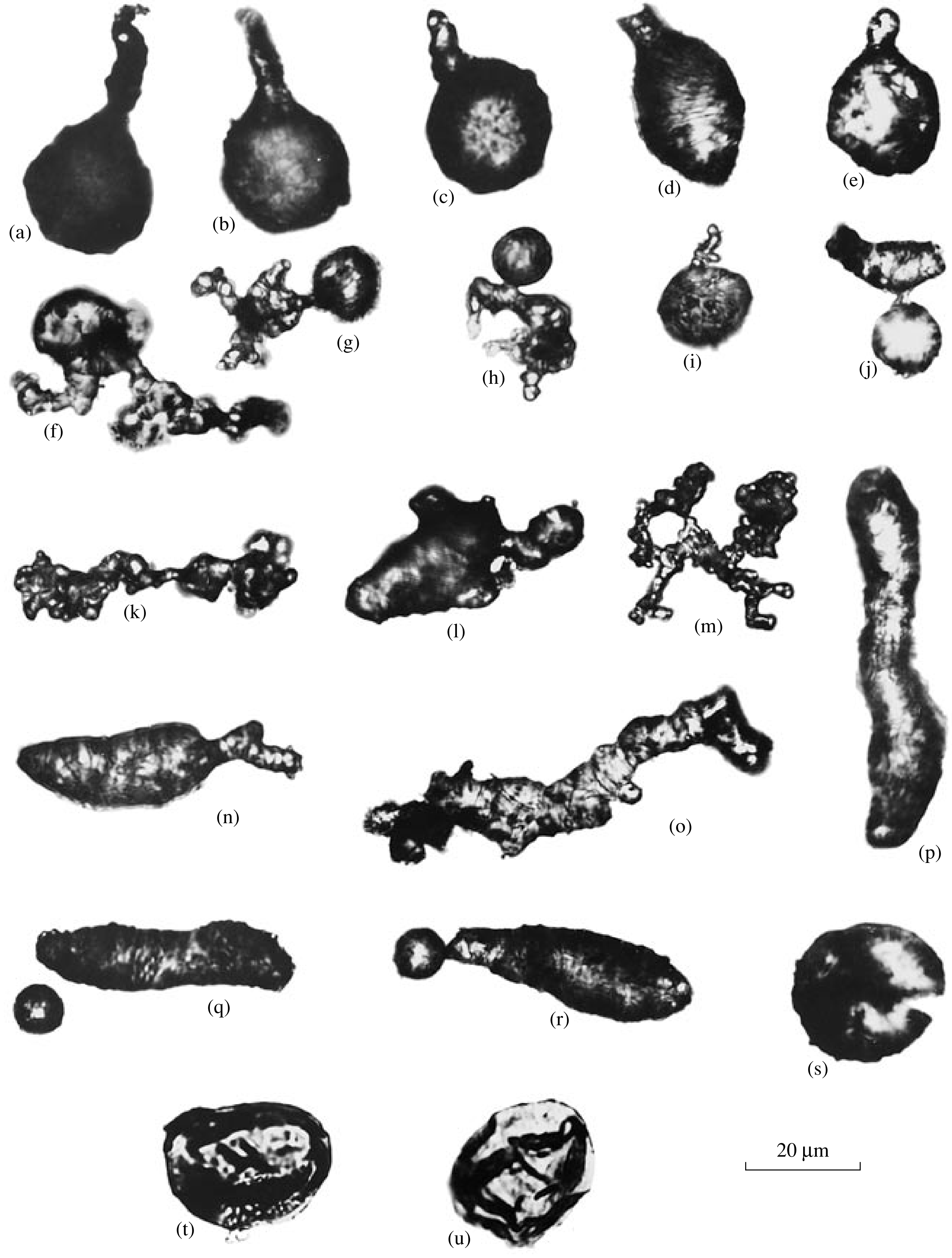
(1) The remains of microorganisms have a solid organic coat (supposedly chitinous) and a three-dimensional shape. Three-dimensional organic-walled microfossils have been recorded from some sections of the Late Precambrian of eastern Siberia (*Microfossils* …, 1989; Stanevich and Faizulina, 1992). No 3-D microfossils are known from the Early Proterozoic. Faizullin (1996) believes that the type of preservation (3-D or flattened) of fossil microorganisms is determined not by their biological characteristics, but by various abiogenic factors: metamorphism, sedimentation rate, and the correspondence between the sizes of microfossils and sediment particles. The last factor obviously affected the microfossils from the Zhdanovskoe Formation, which are restricted to gravelly sandstones and gritstones. Relatively small sizes and solid coats of the microfossils facilitated their 3-D preservation. Solitary specimens of thin-walled acritarchs of *Leiosphaeridia* (Eisenack) Downie et Sarjeant recorded from the same samples are flattened and folded (Figs. 3s–3u).

(2) The microfossils of the Zhdanovskoe Formation include several morphological types, co-occurring in the overwhelming majority of the samples (table). Relationships are often observed between particular morphological types, suggesting that we are observing disintegrated parts of an entire organism, and that the microbiota of the Zhdanovskoe Formation is virtually a monospecific population.

(3) The polymorphism of the microfossils found, their morphological peculiarities, sizes, and interrelations between particular morphotypes testify to the lower fungal affinity of these ancient microorganisms. However, it is impossible to estimate all of the diagnostic characters of families and genera based on the available fossil material; therefore, we assign the new genus to Fungi incertae sedis.

Below the description of the microfossils from the Zhdanovskoe Formation is given. The material is kept at the department of Precambrian Geology of Federal State Unitary Enterprise *Karpinskii All-Russia Research Institute of Geology* (VSEGEI).

Fig. 3. Proterozoic organic-walled microfossils: (a–e) reproductive organs of *Petsamomyces polymorphus* gen. et sp. nov.; (a) VSEGEI, no. 2381-867-1/1; (b) VSEGEI, no. 2381-867-4/1; (c) VSEGEI, no. 2381-867-4/2; Kierdzhipor area, borehole 2381, depth 986 m; (d) VSEGEI, no. 1885-1047-2/1; Kierdzhipor area, borehole 2381, depth 1047 m; (f–r) vegetative organs of *P. polymorphus* gen. et sp. nov.; (f) VSEGEI, no. 2381-867-1/2; (g) VSEGEI, no. 2381-867-4/4, Kierdzhipor area, borehole 2381, depth 867 m; (h) 2381-986-2/3; Kierdzhipor area, borehole 2381, depth 986 m; (i) VSEGEI, no. 1885-1047-2/2; Kierdzhipor area, borehole 2381, depth 1047 m; (j) VSEGEI, no. 2381-986-2/4; Kierdzhipor area, borehole 2381, depth 986 m; (k) VSEGEI, no. 1885-1011-1/1; Kierdzhipor area, borehole 2381, depth 1011 m; (l) VSEGEI, no. 1885-1047-2/3; Kierdzhipor area, borehole 2381, depth 1047 m; (m) VSEGEI, no. 7302-2/1; Onki area, outcrop no. 7302; (n) VSEGEI, no. 9082-1/1; (o) VSEGEI, no. 9082-1/2; Kola ultradeep borehole UD-3, depth 9082 m; (p) VSEGEI, no. 9770-2/1; Kola ultradeep borehole UD-3, depth 9770 m; (q) VSEGEI, no. 2381-867-1/3; Kierdzhipor area, borehole 2381, depth 986 m; (s–u) acritarchs of the genus *Leiosphaeridia*; (s) VSEGEI, no. 9770-2/2; Kola ultradeep borehole UD-3, depth 9770 m; (t) VSEGEI, no. 2381-867-4/5; Kierdzhipor area, borehole 2381, depth 867 m; (u) VSEGEI, no. 2381-986-2/6; Kierdzhipor area, borehole 2381, depth 986 m; Kola Peninsula, Pechenga Region; Early Proterozoic, Zhdanovskoe Formation.


(a)
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20 μm

Morphological types of microfossils of the Zhdanovskoe Formation

Facial subzones	Western		Central																				Eastern				Kola ultradeep borehole UD-3 depth, m		
Areas	Kotsel'-vara		Souker	Kierdzhipor																Pil'guyarvi			Onki						
Nos. outcrops, boreholes, depth, m			borehole 1787	borehole 2381											borehole 1885		borehole 886		borehole 2700				borehole 2578				borehole 2327			
Morphotypes of microfossils	outcrop 6507	outcrop 6524	712	864	867	974	978	981	982	986	1003	1008	1009	1016	1011	1047	853	1567	820	930	outcrop 6550	outcrop 6551	842	outcrop 7301	outcrop 7302	outcrop 7302a	882	8429	9082	9770
1. Spherical forms	⬤	•	⬤	●	⬤	•	⬤	⬤	⬤	⬤	•	•	⬤	•	⬤	⬤	⬤	•	•	●	●	⬤	●	●	⬤	⬤	●	●	⬤	⬤
2. Forms with appendages	●		●	•	●		⬤	●	●	●	•	•	•	•	●	•	•		•		●	•	•	•	•	•	•	●	●	●
3. Amoeboid forms	•	•	⬤	•	●		●	●	•	⬤					●	●	●	•		•		●	•	•	●	⬤	●	●	●	•
4. Filaments		⬤	•	⬤	⬤	•	⬤	•	⬤	⬤		•	•	●		•	●		●	●	•	•		•	•			⬤		

Note: Number of specimens: • several, ● several tens, ⬤ several hundreds.

SYSTEMATIC PALEONTOLOGY
FUNGI INCERTAE SEDIS

Genus *Petsamomyces* Belova, gen. nov.

E t y m o l o g y. From the Finnish place name *Petsamo* (Russian name Pechenga) and the Greek *myces* (fungus).

T y p e s p e c i e s. *Petsamomyces polymorphus* Belova, sp. nov.

D i a g n o s i s. Three-dimensional microfossils of variable morphology: spherical, oval with appendages, irregularly amoeboid coats, and thin branching filaments. Thalli of two types: amoeboid bodies of irregular, elongate, occasionally complicated shape, with solid coat, occasionally with appendages, and short thin branching hyphalike filaments. Morphotypes are interrelated: the amoeboid bodies obviously had thickened and/or densely interlaced hyphae. Reproductive organs: spherical structures with solid and apparently resistant coats ("cysts"), spherical structures with appendages ("germinating cysts"), and drop-shaped or oval structures with appendages ("sporangia").

S p e c i e s c o m p o s i t i o n. Type species.

C o m p a r i s o n. The new genus does not show direct similarities to any known genera of Precambrian microfossils (see *Remarks in the description of the type species*).

Petsamomyces polymorphus Belova, sp. nov.

Plate 1, figs. 2–20; Plate 2, figs. 1–10

E t y m o l o g y. From the Greek *polymorphus* (many shaped).

H o l o t y p e. Department of Precambrian Geology of Federal State Unitary Enterprise *Karpinskii All-Russia Research Institute of Geology,* no. 2381-986-3/1; Kola Peninsula, Pechenga Region, Kierdzhipor, borehole, no. 2381, depth 986 m; Early Proterozoic, Pil'guyarvi Group, Zhdanovskoe Formation.

D e s c r i p t i o n (Figs. 3a–3r). The outlines of amoeboid thalli vary from irregularly oval, sac-shaped to complicated (Figs. 3l, 3n–3r; Pl. 2, figs. 6, 7). The thalli have a solid, somewhat transparent coat; they occur isolated or attached to "hyphae" (Pl. 2, fig. 6). Occasionally, they have appendages (Fig. 3n). The sizes of the bodies vary broadly from 10×17 up to 39×83 μm (20.3×48.7 μm on average, $n = 198$). "Hyphae" are 3–6 μm wide, with shallow constrictions, branching repeatedly. The branching is monopodial with short lateral processes. The length of hyphae without processes does not exceed 50 μm. Irregular thickenings are common, supposedly representing incipient amoeboid thalli (Fig. 3f).

Reproductive organs are spherical "cysts" and "sporangia." Dominating "dormant cysts" have a solid resistant coat and a smooth or weakly shagreened surface (Pl. 1, figs. 3–5; Pl. 2, fig. 3). They are 7–14 μm in diameter (12.7 μm on average, $n = 1439$). The "cysts" germinated either vegetatively, by "hyphae" (Figs. 3g–3i), or by a germinating tube (Pl. 1, figs. 13, 14; Pl. 2, fig. 3). In the latter case "cysts" are larger: 10–33 μm in diameter (15.4 μm on average, n = 118); the germinating tube is 3–5 μm wide, its length does not exceed the cell diameter, the extremity is closed and rounded (Pl. 1, fig. 14). "Cysts" with broken appendages occur more often (Pl. 1, fig. 13; Pl. 2, fig. 3).

"Sporangia" are oval or tear-shaped, with excretory necks that are closed (Pl. 1, fig. 18; Pl. 2, fig. 5) or open in the "sporangial" cavity (Pl. 1, figs. 7, 10, 16). Their sizes vary from 10×13 to 36×66 μm (16.9×33.0 μm on average, $n = 108$).

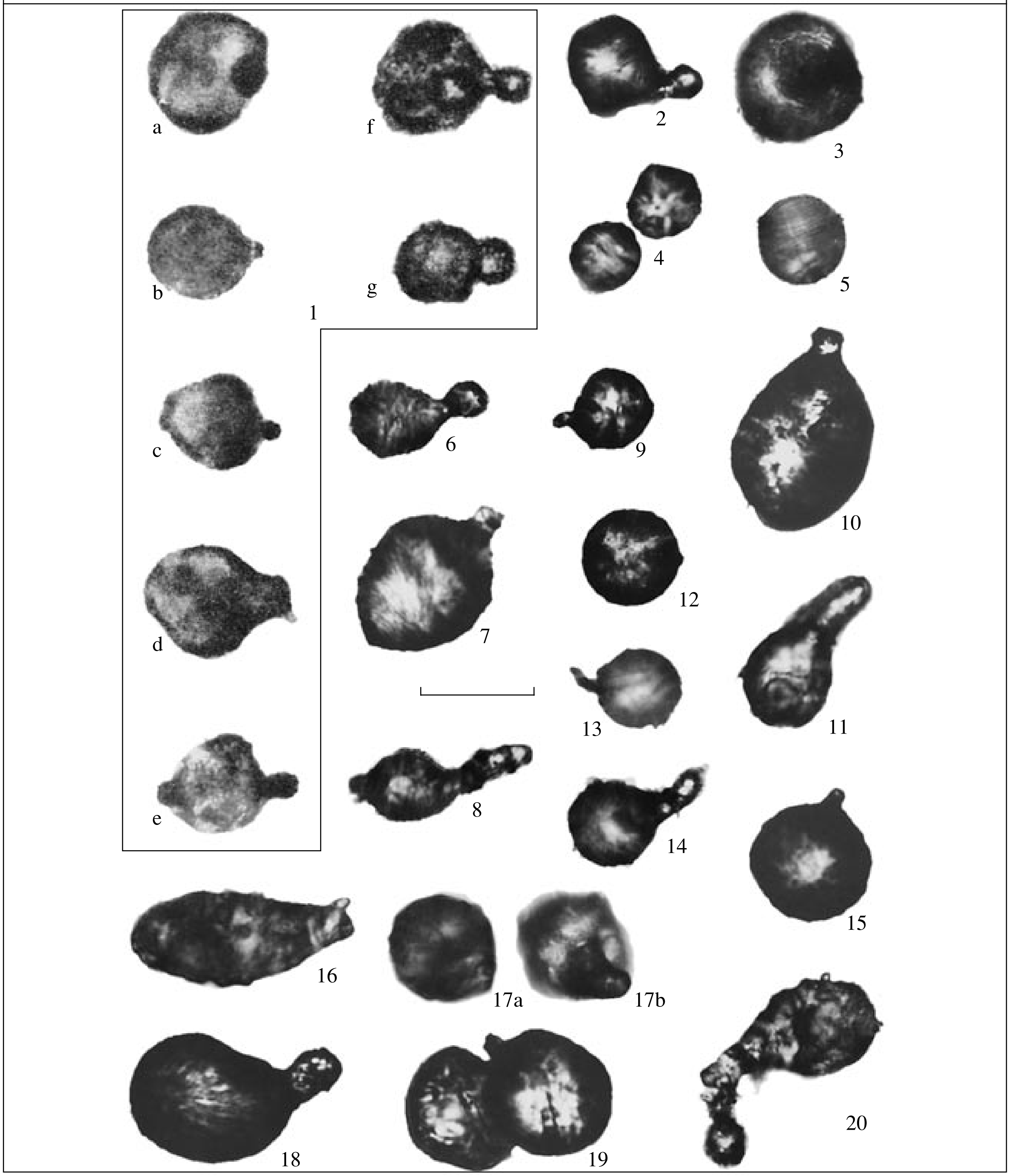
All the microfossils are brownish-gray to black. Examination by electron microscope, at high magnification (up to ×10 000) revealed that the surface of both types of thalli, "cysts" and "sporangia," is transpierced with identical pores (Pl. 2), thus implying a common origin of all these morphotypes. In places, the porate upper coat 1–2 μm thick is detached exposing a smooth surface (Pl. 2, figs. 6–8). It is possible that the coats of the microfossils described have a complex morphology and include at least two layers.

R e m a r k s. Formally, each of the morphological types described could be considered as a separate taxon, as, for example, in Herman's (1979) study of fungal microfossils from the Late Riphean Neryuen Formation of the Uchur-Maya Region, eastern Siberia. Thus, 3-D spherical remains, which are interpreted here as encysted spores, most closely resemble the mineralized forms of the genus *Huroniospora* Barghoorn from the flints of the iron Gunflint Formation of the Early Proterozoic age, Canada (Barghoorn and Tyler, 1965; Awramik and Barghoorn, 1977). They are also comparable to small acritarchs of the genus *Leiosphaeridia* (*Microfossils* …, 1989), differing in their 3-D preservation and, because of this, lacking folds.

Among living microorganisms such forms occur commonly and may be unicellular cyanobacteria or algal or fungal spores. The presence of a solid coat and the relationship between spherical microfossils and hyphalike filaments (Figs. 3g–3i), which was repeatedly observed, allow us to hypothesize that the remains under study may represent cysts of lower fungi. It is known that encysted spores are able to germinate vegetatively, by hyphae (*Life* …, 1976; Müller and Leffler, 1995).

The spherical or oval fossils with a solid coat and short appendages are similar to remains described by Mikhailova (1986) from the Late Riphean terrigenous deposits of the Dashka Formation, Yenisei Ridge, as members of *Germinosphaera* Mikhailova and compared with reproductive organs of algae or fungi. Members of *Germinosphaera* differ from the Pechenga microfossils in having a thinner, folded coat. A striking similarity should be pointed out between microfossils of this morphological type and some forms of *Huroniospora microreticulata* from the Gunflint Formation

Plate 1

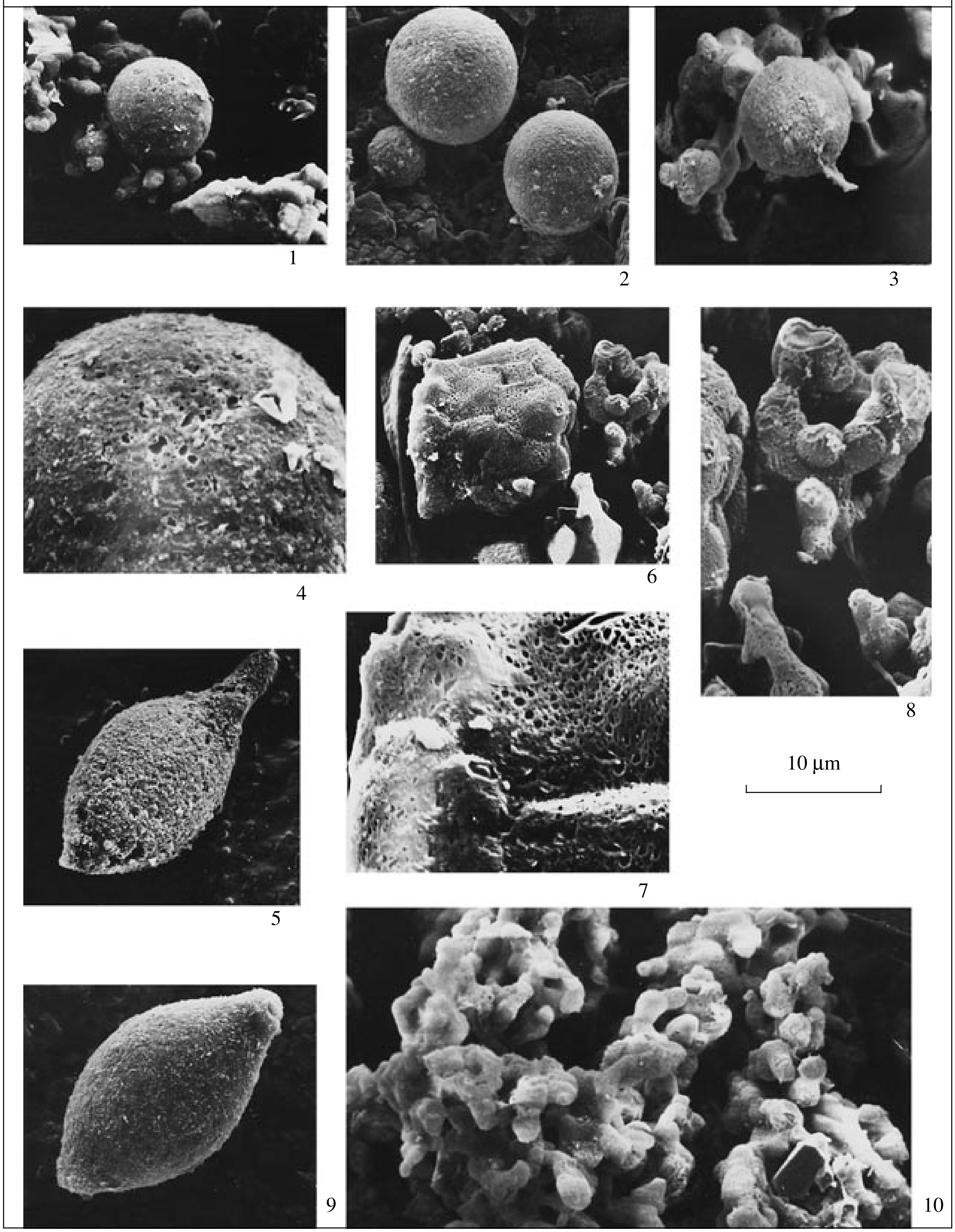


Explanation of Plate 1

Fig. 1. *Huroniospora microreticulata* Barghoorn (redrawn from Darby, 1974).

Figs. 2–20. *Petsamomyces polymorphus* gen. et sp. nov., reproductive organs; Early Proterozoic, Zhdanovskoe Formation; Kola Peninsula, Pechenga Region: (2) VSEGEI, no. 2381-867-4/1; (3) VSEGEI, no. 2381-867-4/2; (4) VSEGEI, no. 2381-867-4/3; Kierdzhipor area, borehole 2381, depth 867 m; (5) VSEGEI, no. 2381-864-3/1; (6) VSEGEI, no. 2381-864-3/2; Kierdzhipor area, borehole 2381, depth 864 m; (7) VSEGEI, no. 2381-986-1/1; (8) VSEGEI, no. 2381-986-1/2; (9) VSEGEI, no. 2381-986-2/1; (10) VSEGEI, holotype, no. 2381-986-3/1; (11) VSEGEI, no. 2381-986-5/1; (12) VSEGEI, no. 2381-986-5/2;; Kierdzhipor area, borehole 2381, depth 986 m (13) VSEGEI, no. 6551-1/1; (14) VSEGEI, no. 6551-2/1; Pil'guyarvi area, outcrop no. 6551; (15) VSEGEI, no. 7302-3/1; Onki area, outcrop no. 7302; (16) VSEGEI, no. 7302a-2/1; (17) VSEGEI, no. 7302a-2/2; Onki area, outcrop, no. 7302a; (18) VSEGEI, no. 2381-986-2/2; (19) VSEGEI, no. 6551-1/2; (20) VSEGEI, no. 6551-1/3; Pil'guyarvi area, outcrop, no. 6551. Scale bar 20 μm.

Plate 2



E x p l a n a t i o n   o f   P l a t e   2

Figs. 1–10. *Petsamomyces polymorphus* gen. et sp. nov., reproductive and vegetative forms; Early Proterozoic, Zhdanovskoe Formation; Kola Peninsula; Pechenga Region; Kierdzhipor area, borehole, no. 2381, depth 986 m: (1) VSEGEI, no. 2381-986/1; (2) VSEGEI, no. 2381-986/2; (3) VSEGEI, no. 2381-986/3; (4) VSEGEI, no. 2381-986/4; (5) VSEGEI, no. 2381-986/5; (6) VSEGEI, no. 2381-986/6; (7) VSEGEI, no. 2381-986/7; (8) VSEGEI, no. 2381-986/8; (9) VSEGEI, no. 2381-986/9; (10) VSEGEI, no. 2381-986/10. Scale bar (1–7, 9) 20 μm and (8, 10) 10 μm.

(Darby, 1974), which were compared with Mucorales fungi (Pl. 1, fig. 1).

The most probable living analogues of these microfossils are cysts and sporangia of chytrids and oomycetes (*Illustrated Key* …, 1954; *Life* …, 1976).

Coats of irregular shape resemble in some respects members of *Amoeboidium* Timofeev and Herman from the Neryuen Formation of the Uchur-Maya Region, eastern Siberia, which were compared with plasmodia of myxomycetes (Timofeev and Herman, 1979). The Pechenga microfossils differ from members of *Amoeboidium* in having a thick coat and much smaller size.

Similar structures are known in members of different classes of modern lower fungi. An irregular amoeboid shape is observed in plasmodia of myxomycetes or their dormant form, sclerotia. The vegetative body of the simplest chytrids is also a plasmodium that, after coating with a solid coat, may transform into a fructification. More evolved chytrids form thickenings on the hyphae, so-called collecting cells, which usually have regular oval shapes. In perenosporalean and lagenidialean oomycetes the sac-shaped mycelium of irregular (or, occasionally, intricate) shape is known that transforms into sclerotium under unfavorable conditions (*Lagenidium* and *Pythium*). On hyphae of some Zygomycetes, thickenings (hyphagenic bodies) may appear, on which fructifications develop (*Life* …, 1976; Müller and Leffler, 1995). This morphotype is impossible to interpret unequivocally in fossil state.

The branching filaments that are comparable to hyphae and occur in intimate association with amoeboid bodies and cysts do not show close similarity to any known taxa of Precambrian microfossils. The abundantly branching hyphae with short lateral appendages and a weak constriction of the filament is characteristic of some living chytrids (e.g., *Allomyces*; *Illustrated Key* …, 1954; *Life* …, 1976).

The cooccurrence of the forms described in all samples studied, their general morphology, surface structure, sizes, and, most important of all, interrelations between particular morphotypes lead us to the conclusion that they belong to an entire organism, representing its vegetative and generative organs. The diversity of the Pechenga microfossils and the peculiarities of their morphology testify their fungal origin. Fungal polymorphism does not allow us to establish eutaxa without revealing all stages of the life cycle. This difficult task is rarely solved on the basis of fossil material, even those not as ancient as the microfossils under study. Therefore, the taxonomic assignment of *Petsamomyces polymorphus* gen. et sp. nov. based on the analysis of the available material and its comparison with modern and fossil lower fungi is purely hypothetical.

Occurrence. Kola Peninsula; Early Proterozoic, Pechenga complex, Pil'guyarvi Group, Zhdanovskoe Formation.

Material. Several hundred specimens (Fig. 1) of good preservation in 149 slides from 47 samples.

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