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Radiolarians and Their Role in the Study of Stratigraphy and Paleogeography of Shale Oil Basins (Based on the Example of the Bazhenovo Formation in Western Siberia and the Arctic)

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Abstract—Radiolarians are rock-forming constituents of siliceous beds of the Bazhenovo Formation in Western Siberia. Studying radiolarians is necessary for stratigraphy and correlation of the organic-rich Bazhenovo Formation, as they provide reliable dating of productive intervals of the section and detailed stratigraphy and zonation, which is especially important when data on other fossils groups are absent or insufficient. The evolution of the radiolarian fauna in the Bazhenovo Basin of Western Siberia is briefly reviewed. At different times radiolarian paleocommunities were dominated by different morphotypes. Two new species, *Orbiculiforma sibirica* sp. nov. and *Emiluvia retorta* sp. nov. are described.

Keywords: Nassellaria, Spumellaria, Upper Jurassic, Lower Cretaceous, paleogeography, new species

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INTRODUCTION

Current interest in radiolarians of the Bazhenovo Formation in Western Siberia is caused by the demand because of its resource potential. In the last two to three decades, the global oil and gas industry has seen a sharp increase in the development of unconventional sources of hydrocarbons (HC) from shale strata, which has received the resounding name of the "shale revolution." It is believed that it is this enormous resource potential that will make it possible to saturate the world economy with hydrocarbon raw materials. The so-called "shale oil" (also known as "tight oil") belongs to the category of hard-to-recover reserves from organic-rich, low-permeability sedimentary reservoirs (Vysotsky et al., 2023). Shale strata are rocks consisting mainly of organic-rich carbonate-argillaceous-siliceous rocks.

Russia owns approximately 20% of the world's hard-to-recover hydrocarbon reserves. Such global hydrocarbon resources are estimated to include 10.2 billion tons of Russian shale oil reserves and 8.1 billion tons of Russian shale gas reserves (Vysotsky et al., 2023). On the territory of the Russian Federation, promising high-carbon shale strata are confined to: the Khadum (Lower–Middle Oligocene) and Batalpasha formations (Upper Oligocene) of the North Caucasus oil and gas province (PGP): the Domanik formation (Upper Devonian) of the Volga–Ural and Timan–Pechora oil and gas provinces; Bazhenovo Formation (Upper Jurassic) of the West Siberian Oil and Gas Province; Kuonamka Formation (Lower–Middle Cambrian) Leno-Tunguska oil and gas basin, etc. (Vysotsky et al., 2023).

Of the objects listed above, the Bazhenovo Formation found in Western Siberia and in its Arctic margin is of greatest importance. The Bazhenovo Formation contains the majority of Russian oil shale, containing both solid organic matter (kerogen) and liquid light oil in low-permeability reservoirs (Brekhuntsov et al., 2017; Khartukov, 2020).

In recent years, the Mesozoic high-bituminous clayey-carbonate-siliceous strata of Western Siberia have attracted increasing attention from specialists. The Bazhenovo Formation is of particular interest, since it is considered as one of the important objects for replenishing the resource base of the Russian oil industry (Kalmykov and Balushkina, 2017; Kontorovich, 2019; Nemova, 2021; Eder et al., 2022; Panchenko, 2023).

Currently, when oil production in traditional deposits in the West Siberian Basin is declining, this formation is becoming the main target for potential increases in reserves and oil production. The productive potential of the Bazhenovo Formation is 0.7 billion tons of technically recoverable reserves, while the Domanik Formation is 0.1, and the Khadum Formation is 0.02 billion tons (Rogovaya, 2019). 600–800 thousand tons of oil are produced annually from the Bazhenovo formation, production could increase to 10 million tons per year by 2025 and reach an annual maximum of 50 million tons (almost 10% of total Russian oil production) by 2030 (Khartukov, 2020). The territory of distribution of bituminous deposits of the Bazhenovo Horizon occupies a huge space of Western Siberia from Omsk to the coast of the Yamal Peninsula. According to various estimates, the hydrocarbon content in the formation could reach up to 2 trillion barrels, and according to some estimates, the rocks could contain 180–360 billion barrels of recoverable reserves (Brekhuntsov et al., 2017).

The Bazhenovo Formation is found Western Siberia occupying an area of over 1000000 km^2, as well as on the Yamal Peninsula and on a significant area of the bottom of the Kara Sea. For comparison, the area of the largest Bakken Shale Formation in North America is half the size, 520000 km^2 (Rogovaya, 2019). The Bazhenovo Formation is represented by dark gray to black bituminous carbonate-argillaceous-siliceous rocks 10 to 40 m thick. Rocks throughout most of the formation have low storage capacity and flow characteristics and occur under abnormally high reservoir pressure. The depth ranges from 650 m in marginal zones to 3700 m in the most submerged parts of the basin (Afanasiev et al., 2010). The age of the Bazhenovo Formation is still interpreted ambiguously: as the Volgian–Lower Berriasian (*Reshenie*..., 2004), Volgian–Berriasian (Zakharov, 2006), from Tithonian to Hauterivian (Afanasiev et al., 2010), Upper Jurassic (Bazhenova, 2015; Rogovaya, 2019), from the Upper Kimmeridgian to the Hauterivian (Bolshannik, 2021), Volgian (Fomin et al., 2023), Lower Volgian–Lower Valanginian (Vishnevskaya et al., 2020; Panchenko et al., 2021; Panchenko, 2023).

It has been also shown that the age of the six main members is not always determined based on the macrofossils, and there is a disagreement or even a discrepancy on their dating (Dzyuba et al., 2022). The rarity of identifiable macrofossils in cores from the Bazhenovo Formation (see text-figs. 7 and 8 in Panchenko, 2023) or even their complete absence in high-carbon siliceous intervals (see text-fig. 4 in Panchenko, 2023) may have been the basis for the assumption of the presence of numerous long gaps (up to nine ammonite zones) in deposition (see text-fig. 9 in Panchenko, 2023).

MATERIAL AND METHODS

Radiolarian assemblages were studied from 12 of the most complete sections of boreholes (Vishnevskaya et al., 2020) drilled in the Latitudinal Ob region, Salym, Frolov, Gubkin, Radonezh and Yamal regions of Western Siberia (Fig. 1), with sampling at 1 m intervals. Radiolarian associations originate from five biozones and beds (Vishnevskaya, 2016; Vishnevskaya et al., 2020), which correlate well with the five regional cyclites proposed for the Bazhenovo Horizon by V.D. Nemovaya (2021).

Collection no. 2018 "Radiolaria of Western Siberia" is housed at the Geological Institute of the Russian Academy of Sciences (GIN RAS).

Collection no. 2019 "Radiolaria of Western Siberia" is housed at the Department of Paleontology, Faculty of Geology, M.V. Lomonosov Moscow State University.

The method of chemical maceration using acetic and hydrofluoric acids was used to extract radiolarians from siliceous-carbonate rocks and radiolarites of the Bazhenovo Formation (Vishnevskaya, 2013; Vishnevskaya and Gatovsky, 2020; Vishnevskaya et al., 2019, 2020).

Three-dimensional radiolarian skeletons were examined using a scanning electron microscope (SEM) (Plate 1). Radiolarians were photographed using a VEGA2 TESCAN SEM at the Borissiak Paleontological Institute of the Russian Academy of Sciences (PIN RAS) by E.A. Zhegallo. Radiolarian specimens were attached to cylindrical metal stubs using pre-applied double-sided carbon tape. In total 3 stubs were prepared: two with radiolarian skeletons (500 specimens) extracted from the rock, and the third with fragments of rock (13 pieces) containing radiolarians.

In thin sections (more than 1500 petrographic thin sections), various sections of radiolarian skeletons were studied in an optical light (transmitted-light) microscope in order to determine the internal structure of the shells (Pl. 4, figs. 3, 4, 7, 9, 17, 19, 21). To identify the structure of three-dimensional forms in high-bituminous varieties of rocks of the Bazhenovo Formation, from which it is impossible to extract microfossils using chemical preparation with acids, the method of X-ray microtomography was used (Plate 4, figs. 2, 5, 12).

THE ROCK FORMING ROLE OF RADIOLARIANS

In the Bazhenovo Formation, radiolarians are common and, most likely, they are rock-forming fossils (Fig. 2). Almost all siliceous rocks of the Bazhenovo Formation are biogenic, which is supported by most authors (Nemova, 2021; Eder et al., 2022). Biogenic silica is observed in the skeletons of radiolarian shells and their fragments. The rock-forming role of

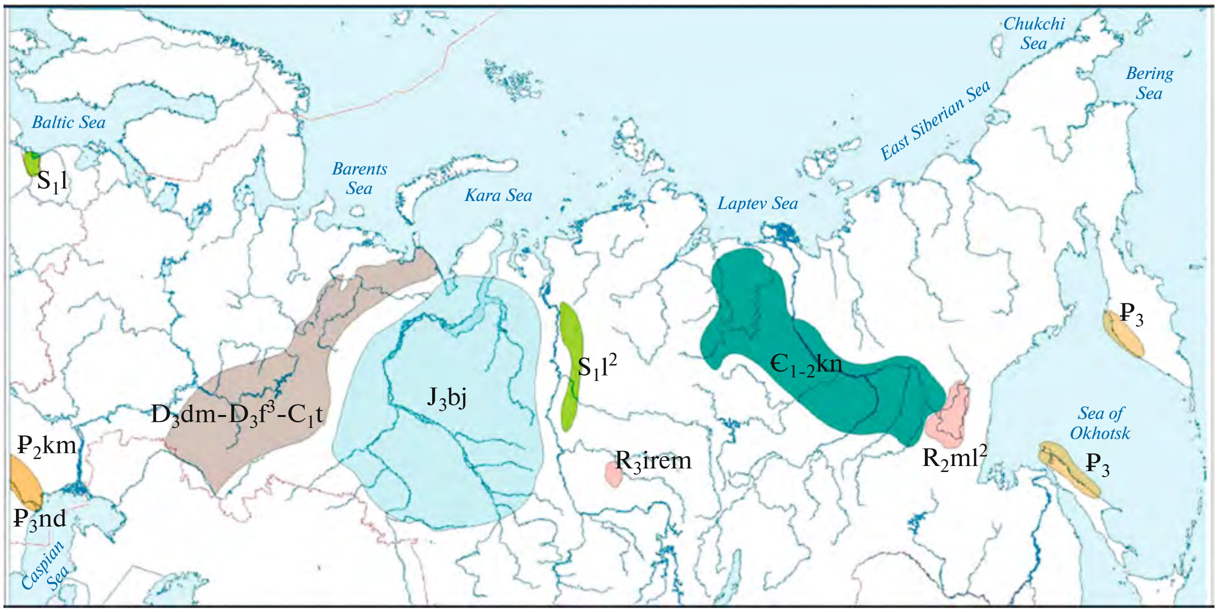

Fig. 1. Distribution of the main shale formations in Russia (according to Bazhenova, 2015). Designations: ₽$_2$ km—Kum Formation; ₽$_3$_Pilenga Formation; ₽$_3$ nd—Khadum Horizon; D_3dm-D_3f_3-C_1t—Domanik Formation; J_3 bj—Bazhenovo Formation; S_1 l—Llandovery Formation; $Є_{1-2}$ kn—Kuonam Formation; R_2 ml_2—Malga Formation; R_3 irem—Iremeken Formation. The age of the Bazhenovo Formation is indicated as Upper Jurassic; according to the Decision of the 6th Interdepartmental Stratigraphic Meeting, its range is generally considered to be within the Volgian Stage—Lower Berriasian (*Reshenie*..., 2004), and in recent years it has been specified as the Lower Volgian Substage–Lower Valanginian (Vishnevskaya et al. ., 2020; Panchenko et al., 2021).

radiolarians is clearly visible both in petrographic thin sections and in SEM, where juvenile skeletons of radiolarians are clearly visible, as well as relics of the biomorphic radiolarian structure (Fig. 3). The participation of radiolarians as rock-forming microorganisms is manifested even in recrystallized form when they are replaced by calcite or dolomite. The preservation of radiolarian skeletons varies, from perfectly preserved to highly dissolved, then becoming microlenticular siliceous forms without signs of a biogenic structure.

Radiolarians in the rocks of the Bazhenovo Formation have been known to researchers for more than half a century, based on which Kozlova (1983, 1994; *Bazhenovsky*..., 1986) proposed to identify biostratigraphically significant Middle Volgian, middle Upper Volgian, Upper Volgian and Berriasian assemblages.

These assemblages identifying the "Beds with fauna", are accepted in the stratigraphic practice of the Upper Jurassic of Western Siberia (*Reshenie*..., 2004). Later, a slightly different biozonation was proposed, distinguishing three assemblages: the new Middle Volgian, middle Volgian sensu Kozlova (1983), and the Upper Volgian, combining two previously proposed assemblages (Amon, 2011). At the same time, the above-mentioned schemes of biostratigraphic division of the Bazhenovo Formation suffered from the main drawback that all types of radiolarians were identified and described from petrographic thin sections. The inaccuracy of species identification from random sections of forms in thin sections significantly reduced the value of biostratigraphic conclusions; in particular, their index species were not recognized as valid (O'Dogherty et al., 2009). It is necessary use new research methods and techniques for thorough study of radiolarians from new borehole core material (Vishnevskaya et al., 2020; Isaeva and Gatovsky, 2023; Isaeva et al., 2023).

The use of X-ray microtomography and chemical extraction of three-dimensional radiolarians from carbonate-siliceous rocks made it possible to more fully and accurately characterize the index species and characteristic species of zonal radiolarian assemblages (Plate 4). This made it possible to identify five stratigraphic units in the rank of zones and layers (Vishnevskaya et al., 2020; etc.). In recent years, a new version of the scheme has begun to be used both for biostratigraphic subdivision and for correlation of sections of the Bazhenovo Horizon (Panchenko et al., 2013, 2015, 2021; Amon et al., 2021, 2022; Panchenko, 2023). Based on radiolarians, it was possible to confirm the presence of Lower Cretaceous, namely, Berriasian beds in the Bazhenovo Formation, which is still shown on many maps as Upper Jurassic (Fig. 1).

Thus, it is shown that radiolarians are one of the significant tools for stratigraphy and correlation of sections of the region. It is important to keep in mind

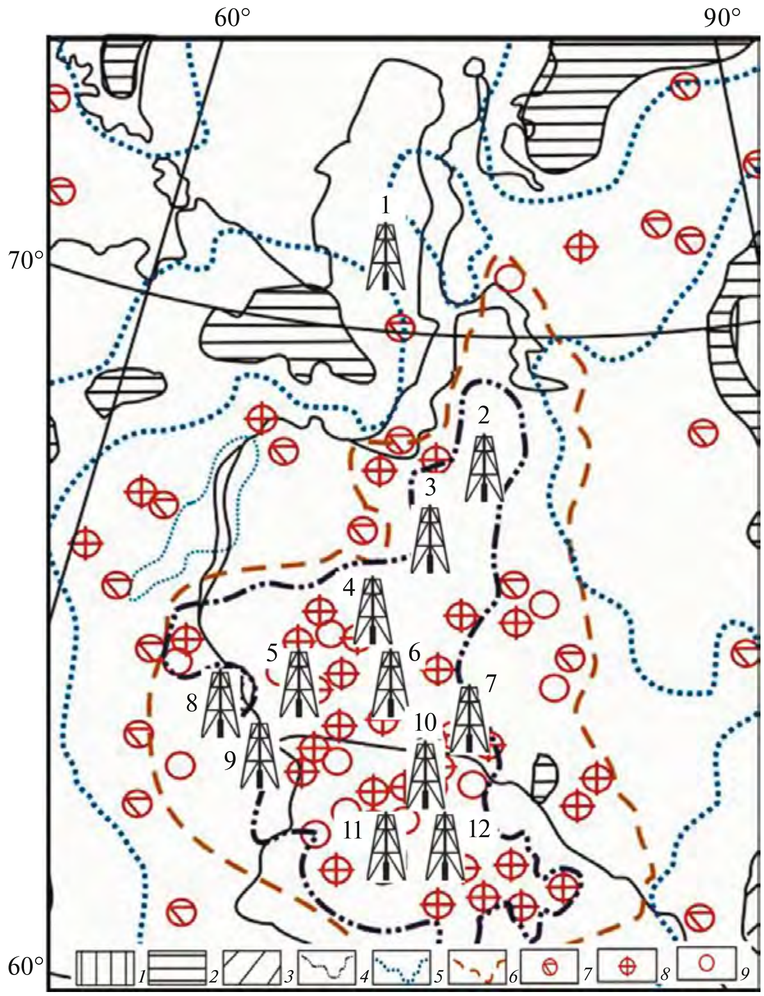

Fig. 2. Distribution of radiolarians and accompanying microfauna in the West Siberian basin in the Bazhenovo time (Tithonian–Berriasian) (Predtechenskaya et al., 2006, with modifications and additions). Location of the main fields from which radiolarians were studied: (1) Yuzhnyi Tambey or Yamal, (2) Gubkin, (3) Imilor, (4) Novoortyagun, (5) Pravdinskaya, (6) Aprelskaya, (7) Sredne-Shapkinskaya, (8) Molodezhnaya, (9) Nizhne-Yanlotskaya, (10) Verkhne-Salyms, (11) Radonezh, (12) Malobalykskaya. Designations: (*1*) plateau, mountain areas; (*2*) areas of denudation (hilly plateaus); (*3*) lagoons, marshes, alluvial-lacustrine-marsh plains; (*4–6*) boundaries of distribution areas: (*4*) greatest depths (pseudo-abyssal); (*5*) relatively deep waters (middle and lower sublittoral); (*6*) bituminous deposits; (*7–9*) microfossils: (*7*) foraminifers, (*8*) radiolarians, (*9*) coccolithophores.

that the Bazhenovo Formation of Western Siberia does not reach the surface anywhere, it is studied only from borehole cores, and, in this regard, microfossils are especially significant, since the probability of their detection in the borehole core is much higher than that of the index macrofossils.

CHARACTERISTIC AND ZONAL RADIOLARIAN SPECIES OF THE BAZHENOVO FORMATION

At the base of the Bazhenovo Formation, the *Parvicingula antoshkinae–P. blowi* Zone is recognized (lower–middle substage of the Volgian Stage = Lower Tithonian), the index species of which are represented by highly conical cyrtoid Nassellaria with a large number of chambers. One of the index species, *P. blowi* Pessagno, 1977 (Pl. 4, fig. 17, SEM and Pl. 4, fig. 18 in an optical light (transmitted-light) microscope) is interesting in that it entries at the base of bituminous beds. Higher up in the Bazhenovo Formation, the index species of the Middle Volgian *Parvicingula jonesi–P. excelsa* Zone, to which the maximum oil occurrences are confined, are of significant interest (Kalmykov and Balushkina, 2017). The skeletons of these species are usually represented by the largest number of chambers and are well diagnosed both in SEM (Pl. 4, figs. 16, 19) and in an optical light microscope (Pl. 4, figs. 20, 21). It is this interval of the Bazhenovo Formation, composed of kerogen-siliceous rocks, that has the highest flow and storage properties and could serve as the main natural reservoir of mobile oil (Kalmykov and Balushkina, 2017). The appearance higher up the section (Vishnevskaya

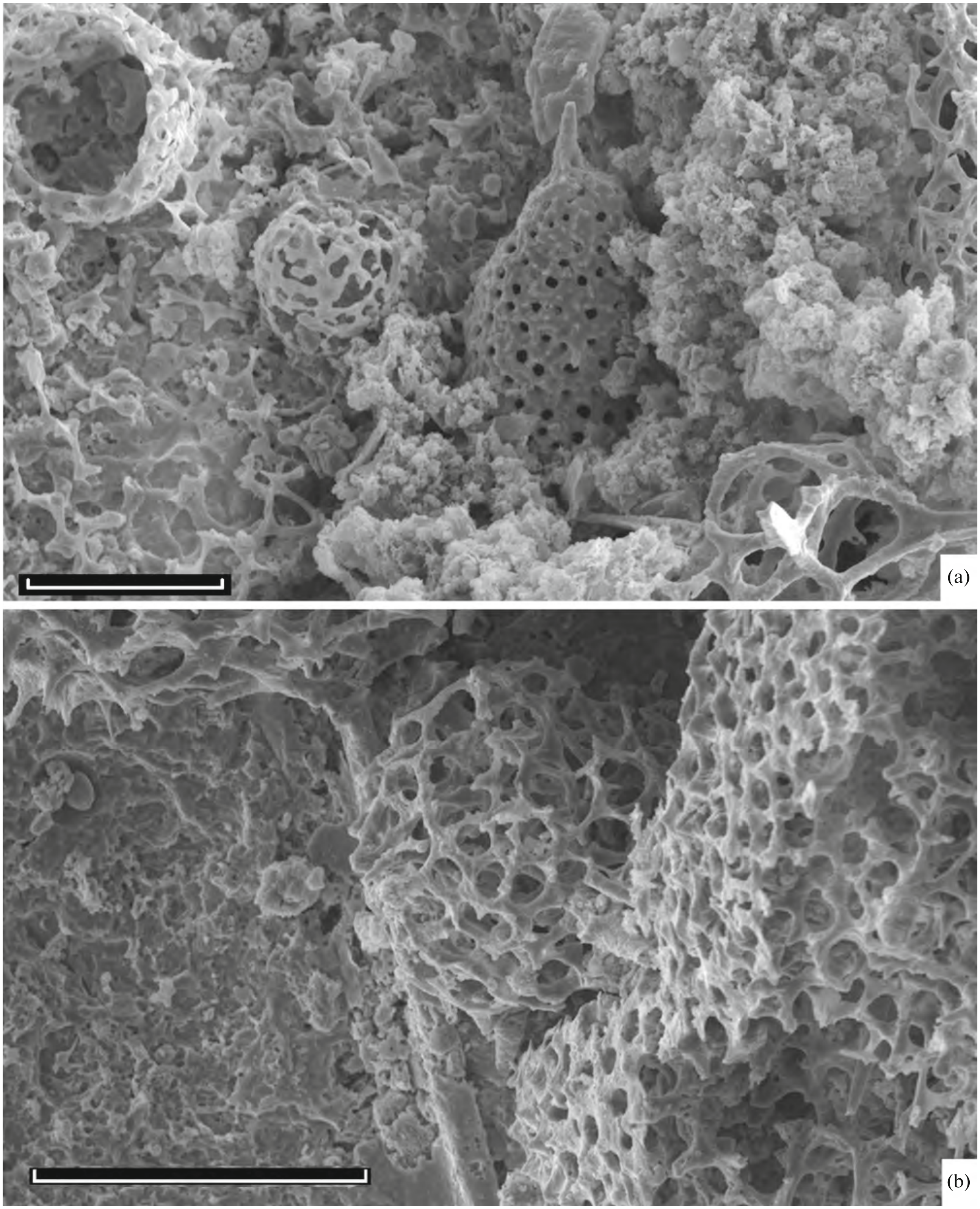

Fig. 3. Rock-forming significance of radiolarians in the Bazhenovo Formation: (a) specimen GIN, no. 170/1-Y3-004, juvenile forms from different orders of radiolarians among decayed skeletal elements: in the lower right corner there are fragments of lattice skeletons of the family Poulpidae; Yuzhno-Tambey Field, Lower Volga Substage; scale bar 30 μm; (b) specimen GIN, no. 170/1-Y3-005, radiolarian skeletons form both the basis and matrix of the rock: in the center there is a small spherical shape with a cellular skeletal structure—this is a representative of Spumellaria, at the top left there is a large sphere, the long spine of which divides the image into two parts; on the right there is a destroyed skeleton of a large spongy shape; Yuzhno-Tambey Field, Lower Volgian Substage; scale bar 50 μm.

et al., 2020) of the zonal species *Parvicingula rotunda* (Hull, 1977) (SEM, Pl. 2, figs. 11, 13, and in an transmitted light microscope—Pl. 4, fig. 12) and *P. alata* Kozlova et Vishnevskaya, 2012 (Vishnevskaya and Kozlova, 2012) allows us to recognize the Upper Volgian *Parvicingula rotunda—P. alata* Zone, and marks a general decrease in the height of cyrtoid shells, as well as the disappearance of highly conical forms of radiolarians. The upper part of the section of the Bazhenovo Formation is characterized by a sudden increased in the number of radiolarians of the genus *Williriedellum* (Vishnevskaya, 2019), representatives of which are clearly recognizable both in SEM (Pl. 4, figs. 1, 6), and in X-ray microtomography (Pl. 4, fig. 2) and in light microscope (Pl. 4, figs. 3, 7). The index species *Williriedellum salymicum* Kozlova, 1983 allows us to identify the base of the *Parvicingula khabakovi—Williriedellum salymicum* Zone, which can be correlated with the previously proposed Beds with *Quasicrolanium planocephala*. The uppermost Upper Volgian and Berriasian dating of these beds is confirmed by associated finds with ammonites of the *kochi* and *analogus* zones (*Reshenie*..., 2004). The most characteristic marker species of this zonal radiolarian assemblage are *Tricolocapsa campana* Kiessling, 1995 (X-ray microtomography Pl. 4, fig. 5, and transmitted light microscope—Pl. 2, fig. 4), first described from the Berriasian of Oman (Kiessling, 1995) and *Arctocapsula perforata* Bragin, 2009 (SEM—Pl. 4, figs. 8, 10, and light microscope—Pl. 4, fig. 9), described from the Upper Volgian *chetae* Zone and the Lower Berriasian *sibiricus* Zone) of the Nordvik Peninsula. The interval of the *Parvicingula khabakovi—Williriedellum salymicum* zone contains the second productive horizon of the Bazhenovo Formation, composed of kerogen-argillaceous-siliceous rocks (Kalmykov and Balushkina, 2017). Here the rocks contain numerous spherical Nassellaria of the genus *Williriedellum* (Pl. 4, figs. 1, 3, 6, 7), which has a large abdomen and aperture, providing a joint open pore space, thereby creating high flow-storage properties. Thus, in the Radonezh Field, within the *Parvicingula khabakovi—Williriedellum salymicum* Zone, with an organics content of up to 26% (Vishnevskaya, 2024). The zonal assemblage contains numerous representatives of the genus *Arctocapsula*, which, in addition to the aperture, in the area of the first and second abdominal sections, have a lateral pseudo-opening, lowered down into the internal porous layer or cavity of the test (Pl. 4, fig. 8), which could also serve as a natural reservoir of mobile oil. Microphotographs of thin sections and microtomographic 3D images (Balushkina et al., 2014), clearly shows the variants of void space in the radiolarites of the Sredne-Nazym Field, which belong to pore-type reservoirs. Thus, numerous finds of radiolarians throughout the entire thickness of the Bazhenovo Formation (as opposed to macrofauna), enabled stratification of its sections into actual biostratigraphic zones (Vishnevskaya et al., 2020) and determine the age of productive high-carbon horizons using radiolarians even in those intervals of the section where no other fossils are found.

The time of deposition of the unique Bazhenovo Formation, which is considered the main oil and gas productive series of the West Siberian Basin, is Early Volgian—Early Valanginian, and not Late Jurassic, as is sometimes proposed (Bazhenova, 2015; Rezvaya, 2019).

RADIOLARIANS AND PALEOGEOGRAPHY OF THE BAZHENOVO SEA BASIN

Radiolarians also make it possible to reconstruct some characteristic features and the paleobiogeography and paleobionomy of the Bazhenovo Late Jurassic-Early Cretaceous marine basin. Data on radiolarians confirm the presence of its free connections in the north and northeast with the Paleo-Arctic and Paleo-Pacific oceans (Fig. 4). The widespread presence of the genus *Parvicingula* (Pl. 4, figs. 11–21) in radiolarian associations of the Bazhenovo Sea confirms the presence of a northern current, which brought many representatives of this genus from the Pacific Province to the Boreal Region (Arctic and North Atlantic provinces). The mass occurrences of Late Jurassic highly conical parvicingulids (Pl. 4, figs. 16–21) would have been impossible without upwelling (Vishnevskaya, 1993, 2017; Vishnevskaya, 2001; Zakharov, 2006; Khotylev et al., 2021). According to most authors, the Bazhenovo Formation accumulated in a relatively deep-water (up to 500 m) subepicontinental sea (Zakharov, 2006; Kontorovich et al., 2013, 2014). The abundance of radiolarians at the base of the bituminous deposits of the Bazhenovo Formation indicates that at the beginning of the Volgian time a fairly deep-water basin with paleoenvironments suitable for the existence and evolution of siliceous plankton had already been formed (Fig. 4). The presence of all mor-

Fig. 4. Paleogeographical scheme of Western Siberia, Volgian Age—Berriasian Age (according to Kontorovich et al., 2013, 2014; Amon et al., 2021 with modifications and additions): (a) Early Volgian Age; (b) Middle Volgian Age; (c) Late Volgian Age; (d) Berriasian (=Ryazan) age. Designations: A—D—morphological groups of radiolarians: A—spheroid, B—discoid, C—cyrtoid, D—prunoid; Cc—multi-spined cyrtoids; Ci—wall of cyrtoids with irregular arrangement of pores; Co—wall of cyrtoids with pores placed in a regular checkerboard pattern; K—calcareous cysts; N—calcareous nannoplankton; (*1–11*) paleogeographic areas: areas of marine sedimentation: (*1*) deep sea, more than 400 m; (*2*) deep sea, 200–400 m; (*3*) shallow sea, 100–200 m; (*4*) shallow sea, 25–100 m; (*5*) shallow sea, less than 25 m; (*6*) areas of transitional sedimentation, areas of continental sedimentation: (*7*) internal reservoirs, (*8*) lowland plain, (*9*) denudation-accumulative plain; (*10*) elevated plain (denudation land); (*11*) low mountains; (*12*) main directions of demolition of clastic material; (*13*) state border.

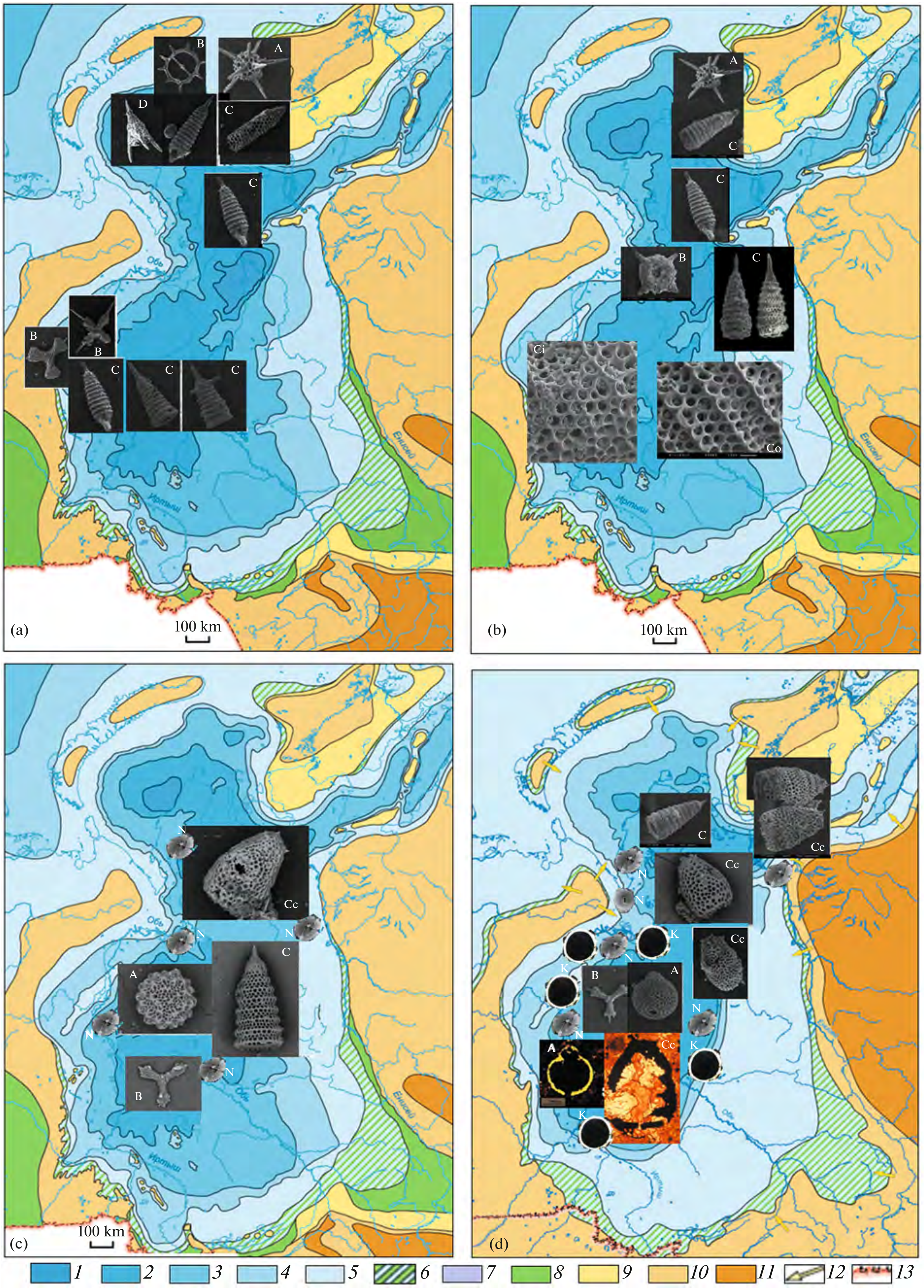
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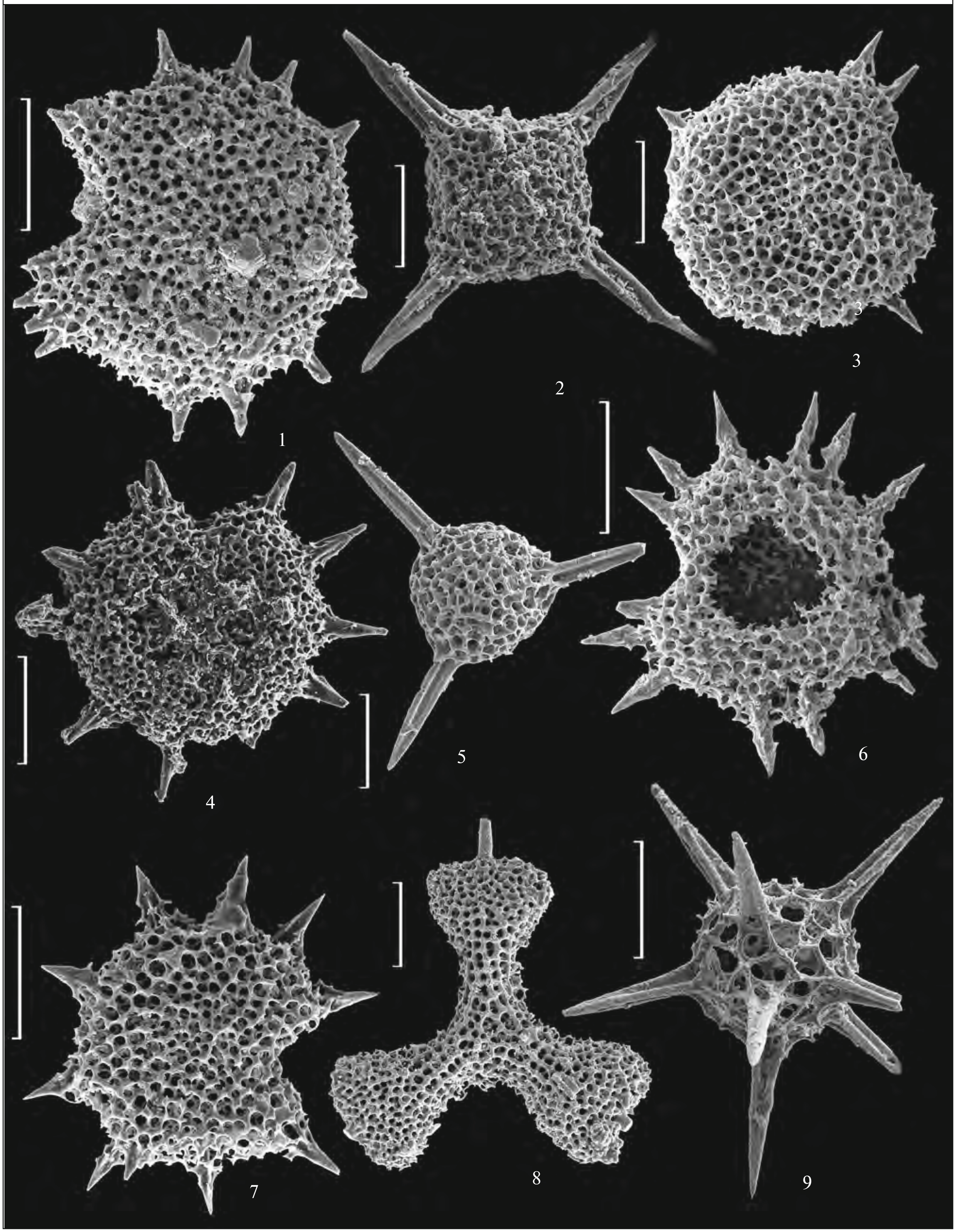
Plate 3



phological groups of radiolarians in the assemblage (Pls. 1, 2) suggests the open marine nature of the basin, and the presence of 20–40% *Parvicingula* indicates a possible upwelling zone in the areas controlled by contrasting depths or the proximity of uplifts (islands).

The main feature of the associations of radiolarians of the Bazhenovo Formation is the vast number of spiny Nassellaria tests among them. It has been shown that in modern basins, near upwelling there are often nassellarian species with a pattern of long spines on the cephalis, which were not observed in pelagic areas (Kruglikova, 2013). Indeed, extant spumellarians prefer the surface water layers, while nassellarians inhabit deep waters enriched with nutrients, which occurs in zones of ascending water flows such as upwelling (Lazarus et al., 2021). Consequently, for Arctic Siberia (Bragin, 2011; Vishnevskaya et al., 2014), where spiny nassellarians are widely represented, the presence of zones of upwelling directed to the west can be assumed. The Bazhenovo regional fauna of radiolarians was formed by migrants from various water areas of the boreal and Arctic basins (Fig. 4a). The introduction of radiolarians of the genus *Parvicingula* into the Bazhenovo Sea most likely took place before or at the time of the formation of the radiolarian association of the *Parvicingula antoshkinae–P. blowi* Zone. At this time, the association was represented by all morphological groups—spheroid, cyrtoid, prunoid, discoid, including ring-shaped Entactinaria from the family Saturnalidae, which could immigrate from the Paleo-Pacific.

The immigration flow reached its maximum in the second half of the Middle Volgian time (Fig. 4b) at the time of *Parvicingula jonesi–P. excelsa* (=middle Tithonian—lower Upper Tithonian). In the Middle Volgian assemblage, there is a sharp increase in the number of cyrtoids (from 40 to 75%) and the diversity of highly conical forms of the genus *Parvicingula* (Vishnevskaya, 2013), which gravitated to significant depths, which is in good agreement with the disappearance of the benthic fauna (Zakharov, 2006). In some places, the thin sections show a pile up of skeletal remains of only the genus *Parvicingula*, of radiolarian spines oriented in one direction, which indicates a contrasting seafloor topography or a difference in depth and removal by currents and redeposition in an adjacent depression. The great depths of the Bazhenovo Sea are indicated by the achievement of the maximum number of chambers (up to 15–20) in representatives of the genus *Parvicingula* (Pl. 4, figs. 18, 21), which was previously known only for *Parvicingula* from synchronous deposits of the Pacific Province (Vishnevskaya and Filatova, 2017).

The radiolarian fauna flourished until the end of the Late Volgian time in the *Parvicingula rotunda–P. alata* Phase and in the Early Berriasian *Parvicingula khabakovi–Williriedellum salymicum* Phase. However the number of highly conical multi-chambered forms, which gravitate to great depths, is decreasing, and many low-conical and tricyrtid skeletons appear. The gradual disappearance of highly conical spindle-shaped forms and a general decrease in shell height in cyrtoids in the penultimate phase indicates changes in the depth of the basin towards shallowing, and, possibly, flattening of the relief (Fig. 4c). The presence of common taxa, direct connections are suggested between the Western and Northern Siberian associations of the Volgian radiolarians (Fig. 4c) with associations of the Arctic (areas of the Lena estuary, Nordvik), basins of the Russian Platform, Pechora Province, Barents Sea shelf, North Sea, Northern California and Oregon, as well as the Pacific frame of Russia (Koryak Highlands, Kamchatka, Sakhalin) and the Northwestern Pacific (Amon et al., 2021, 2022; Vishnevskaya, 2024). These connections with the above areas and their adjacent seas, in fact, may indicate possible migration routes and the exchange of elements of regional radiolarian faunas.

At the very end of the Volgian time, highly specialized morphotypes appeared in families Williriedellidae and Echinocampidae, indicating that in the ecosystem of the Bazhenovo Sea during the Ryazanian time, all possible and previously unoccupied ecological niches were occupied. Finally, another feature is that the closest connections are established between three regional radiolarian faunas—the West Siberian fauna proper and the fauna from the Paleoatlantic (Vishnevskaya and Pralnikova, 1999; Nakrem and Kiessling, 2012), as well as the Paleopacific (Bragin, 2011).

Explanation of Plate 3

Late Jurassic radiolarians of the Yamal Peninsula: (1–4, 6–8) discoid morphological group of radiolarians, (5, 9) spheroid. Yuzhno Tambey area, Bazhenovo Formation, Lower Volgian Substage, *Parvicingula antoshkinae–P. blowi* Zone. Scale bar 100 μm.

Figs. 1, 3, 4, 6, 7. *Orbiculiforma sibirica* Vishnevskaya, sp. nov.: (1) specimen MSU, no. 2019-170/061; (3) specimen MSU, no. 2019-4-170/063; (4) holotype, MSU, no. 2019-4-170/094; (6) specimen MSU, no. 2019-4-170/064, (7) specimen MSU, no. 2019-4-170/062.

Fig. 2. *Emiluvia retorta* Vishnevskaya, sp. nov., holotype, MSU, no. 2019-4-170/111.

Fig. 5. *Tripocyclia trigonum* Rüst, 1885, specimen MSU, no. 2019-Y-3-170/007.

Fig. 8. *Santonaella* cf. *obesa* Yang, 1993, specimen MSU, no. 2019-Y-3-170/012.

Fig. 9. *Actinomma frigida* Kiessling, 1999, specimen MSU, no. 2019-Y-3-170/007.

At the very end of the Berriasian, radiolarians became declined, which corresponds to the time of deposition of the Beds with *Williriedellum*, the upper part of the Ryazanian Stage–Valanginian (Berriasian–Valanginian), and then the radiolarian fauna experienced a stressful state and ceased to exist in the Valanginian.

Palaeogeographical disturbances and stresses led to a sharp change in the parameters of the radiolarian habitat, and traces of their influence can be observed in the response of their radiolarian faunas. In particular, irregularities of the hexagonal pattern were recorded in the skeletons of radiolarians of the genus *Parvicingula*, which indicates a change/deterioration of the habitat. This is especially true for Berriasian cyrtoids (Fig. 4D). In addition, the low coefficient of taxonomic diversity of the radiolarian association, the predominance of two or three morphotypes with the dominance of cryptocephalic radiolarians indicates the neritic nature of the environment.

Thus, both the Late Jurassic and Late Jurassic–Early Cretaceous radiolarian associations of the Bazhenovo Formation are dominated by nassellarians. In the Late Jurassic, the nassellarian association was dominated by a cyrtoid morphological group, consisting predominantly of highly conical forms of the family Parvicingulidae, while the Early Cretaceous association was dominated by the spheroid group, represented by the family Williriedellidae, followed by the cyrtoid morphological group, represented by the spiny Echinocampidae.

In addition to significant biostratigraphic and paleogeographic contributions, the study of radiolarians has brought new data on the systematics and distribution of radiolarians. In particular, representatives of the families Saturnalidae and Echinocampidae, previously unknown in Western Siberia, were identified for the first time (Vishnevskaya, 2021, 2024), two new species were described: *Orbiculiforma sibirica* Vishnevskaya, sp. nov. from the family Orbiculiformidae and *Emiluvia retorta* Vishnevskaya, sp. nov. from the family Staurolonchidae.

SYSTEMATIC PALEONTOLOGY

CLASS RADIOLARIA

SUBCLASS POLYCYSTINA

Order Spumellaria

Family Orbiculiformidae Pessagno, 1973

Genus *Orbiculiforma* Pessagno, 1973

***Orbiculiforma sibirica* Vishnevskaya, sp. nov.**

Plate 3, figs. 1, 3, 4, 6, 7

Orbiculiforma sp. aff. *O. teres*: Bragin, 2011, pl. 1, figs. 9–11.

Orbiculiforma cf. *teres*: Vishnevskayaet al., 2020, p. 115, pl. 2, figs. 9, 13; Amon et al., 2022, text-fig. 2, figs. 1, 3, 6, 7.

E t y m o l o g y. From the Latin *sibirica* (Siberian; from geographical location).

H o l o t y p e. MSU, no. 2019-4-170/094; Russia, Yamalo-Nenets Autonomous Okrug, Yamal Peninsula, South Tambeyskaya Field, Borehole 170, depth 3352.90 m; Upper Jurassic, Lower Volgian Substage, *Parvicingula antoshkinae–P. blowi* Zone.

E x p l a n a t i o n o f P l a t e 4

Index species and characteristic species of radiolarians of the Bazhenovo Formation (Late Jurassic–Early Cretaceous, Western Siberia, Russia): spheroid (1–3, 6, 6) and cyrtoid (4, 5, 8–21) radiolarian morphogroups. (1, 6, 8, 10, 11, 13–17, 19) SEM photographs; (2, 5, 12) images taken using X-ray microtomography; (3, 4, 7, 9, 18, 20, 21) images taken with an optical light microscope. Scale bar 100 μm.

Figs. 1–3, 6, 7. *Williriedellum salymicum* (Kozlova, 1983), Lower Cretaceous, Berriasian, *Parvicingula khabakovi–Williriedellum salymicum* Zone; (1) specimen MSU, no. 2018-651/5-4-068, Gubkin Field; (2) specimen GIN, no. 11-22/4-1, Aprelevskaya Field; (3) specimen GIN, no. 4004-75-3, Pravdinskaya Field; (6) specimen GIN, no. 2018-651/5-4-073, Gubkin Field; (7) specimen GIN, no. 4004-125-2, Pravdinskaya Field.

Figs. 4, 5. *Tricolocapsa campana* Kiessling, 1995, Lower Cretaceous, Berriasian, *Parvicingula khabakovi–Williriedellum salymicum* Zone: (4) specimen MSU, no. 2024-E-1P/2870.41-3, Endyr Field; (5) specimen GIN, no. 11-22-1, Aprelevskaya Field.

Figs. 8–10. *Arctocapsula perforata* Bragin, 2009, Lower Cretaceous, Berriasian: (8) specimen MSU, no. 2018-126/1-074, Gubkin Field; (9) specimen GIN, no. 2015/2-31-1, Nizhne-Yanlotskaya Field; (10) specimen GIN, no. 2018-V-3-126/059, Radonezh Field.

Figs. 11–13. *Parvicingula rotunda* (Hull, 1997), Upper Jurassic, Upper Volgian Substage, *Parvicingula rotunda–P. alata* Zone: (11) specimen MSU, no. 2018-651/5-4-096, Gubkin Field Gubkin Field; (12) specimen GIN, no. 2015/2-35, Nizhne-Yanlotskaya Field; (13) specimen GIN, no. 2018-1-126/002, Radonezh Field.

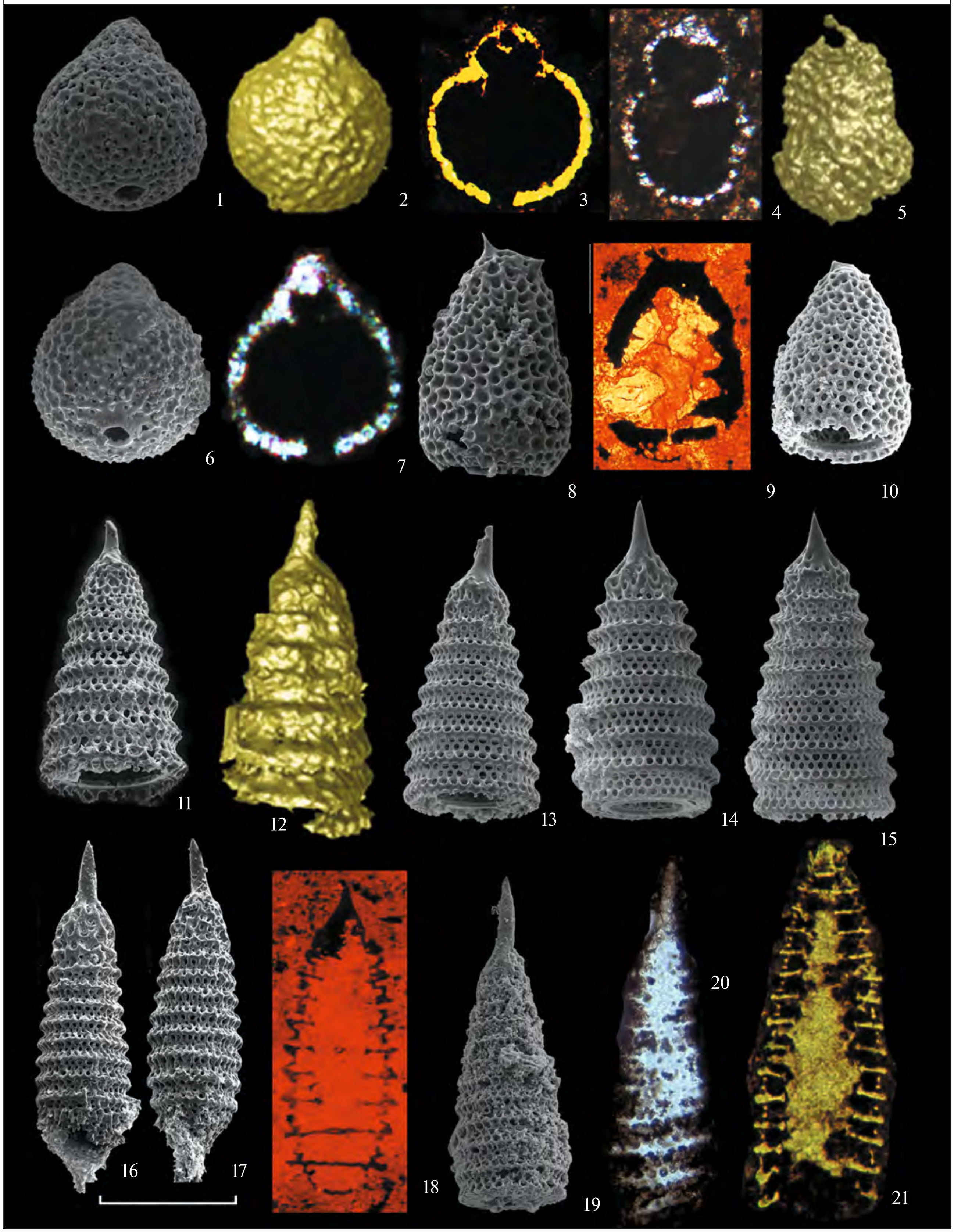
Figs. 14, 15. *Parvicingula khabakovi* (Zhamoida, 1963): (14) specimen GIN, no. 2018-1-126/049, Radonezh Field, Upper Jurassic, Upper Volgian Substage, *Parvicingula rotunda–P. alata* Zone; (15) specimen GIN, no. 2018-4-126/039, Radonezh Field, Lower Cretaceous, Berriasian, *Parvicingula khabakovi–Williriedellum salymicum* Zone.

Fig. 16. *Parvicingula jonesi Pessagno*, 1997, specimen MSU no. 2019-Y-3-170/124, Yuzhno-Tambey Field, Upper Jurassic, Lower Volgian Substage, *Parvicingula antoshkinae–P. blowi* Zone.

Figs. 17, 18. *Parvicingula blowi* Pessagno, 1997, Upper Jurassic: (17) specimen MSU, no. 2019-Y-3-170/007, Yuzhno-Tambey Field, Lower Volgian Substage, *Parvicingula antoshkinae–P. blowi* Zone; (18) specimen GIN no. SP3-14, Sredne-Pamutskaya Field, Middle Volgian Substage, *Parvicingula jonesi–P. excelsa* Zone.

Figs. 19–21. *Parvicingula excelsa* Pessagno et Blome, Upper Jurassic, Middle Volgian Substage, *Parvicingula jonesi–P. excelsa* Zone; (19) specimen MSU, no. 2018-651/016-1, Gubkin Field; (20) specimen GIN, no. 4004-83-5, Pravdinskaya Field; (21) specimen GIN, no. 4004-93-1, Pravdinskaya Field.

Plate 4



D e s c r i p t i o n. The test is in the form of a slightly flattened disk, has 10–13 radial peripheral spines in the equatorial plane. The structure of the disc is spongy-porous, uneven, consists of quadrangular and pentagonal small pore frames, the number of which is about 10 per half shell diameter. The central depression is absent. The primary peripheral spines are triradiate in axial section, with wide grooves and narrow ridges at the points of attachment to the disk, pointed, and round in cross section at the ends. Inside the shell, the bars of spines cannot be traced. In the peripheral part of the disk there is a depression in the form of a V-shaped notch, amounting to one third to half the diameter of the disk; it is recorded on all specimens and, most likely, is a pylome. Sometimes, in addition to the main spines, short thin secondary spines may be developed along the disk margin.

D i m e n s i o n s i n μm. The diameter of the disk with peripheral spines is 355, the diameter of the disk without spines is 255, the length of the spines is 50, their diameter at the base is about 25–27, the thickness of the disk is 30–35.

C o m p a r i s o n. The new species is distinguished from *Orbiculiforma teres* (Hull, 1997, pl. 1, figs. 10, 11, 15, 19), which has a shallow central cavity, about 20 pores per half shell diameter and bearing twelve to eighteen short spines, by the absence of central depression and half the number of pores per half shell diameter.

O c c u r r e n c e. Yamal Peninsula on the Arctic periphery of Western Siberia, Russia; Upper Jurassic, Lower Volgian Substage (=Lower Tithonian).

M a t e r i a l. Ten well-preserved specimens from the type locality.

Family Staurolonchidae Haeckel, 1881; emend. Pessagno, 1977

Genus *Emiluvia* Foreman, 1973; emend. Pessagno, 1977

Emiluvia retorta Vishnevskaya, sp. nov.

Plate 3, fig. 2

E t y m o l o g y. From the Latin *retortus* (twisted, turned, bent).

H o l o t y p e. MSU, no. 2019-4-170/111; Russia, Yamalo-Nenets Autonomous Okrug, Yamal Peninsula, South Tambeyskaya Field, Borehole 170, depth 3352.90 m; Upper Jurassic, Lower Volgian Substage, *Parvicingula antoshkinae–P. blowi* Zone.

D e s c r i p t i o n. A spongy, cushion-shaped disk with a square outline, the corners of which bear thin long spines. There is no central depression. The spines at the corners of the square are four-rayed. The ridges and grooves of the spines are approximately the same width. Towards the distal ends the spines are slightly twisted and pointed. The disk is spongy-porous, uneven, formed predominantly by thin tetragonal and pentagonal pore frames. There are no nodes at the vertices of the pore frames.

D i m e n s i o n s i n μm. Shell diameter 176, disc thickness 35–40, maximum length with spines 490, spine length 137–156, thickness at the point of attachment to the disc 36.

C o m p a r i s o n. The new species is distinguished from the closest *Emiluvia* sp. B (Hull, 1997, pl. 27, fig. 5) from the upper part of the Lower–Upper Tithonian of California, which is characterized by straight spines, triradiate in the proximal half, cylindrical distally, by the four-rayed spines, in which the rays gradually curl towards the ends. From *E. lowercoonensis polaris* (Kiessling, 1999, pl. 5, figs. 14–16, 20–22), which has rounded outline and many small stellate nodes over the entire surface of the test, as well as triradiate spines of different lengths, the new species is distinguished by its subquadrate shape tests, the absence of a knotted wall structure and the four-ray shape of the spines, slightly twisted towards the ends.

O c c u r r e n c e. Yamal Peninsula on the Arctic periphery of Western Siberia, Russia; Upper Jurassic, Lower Volgian Substage (=Lower Tithonian).

M a t e r i a l. Six well-preserved specimens from the type locality.

CONCLUSIONS

Our study shows that radiolarians can be effectively used for stratigraphy and correlation of high-carbon rocks, providing detail down to the biostratigraphic zone, which is especially important in the context of a lack of data on other groups of fossils. The use of chemical maceration and tomography methods in addition to optical microscopy for the Bazhenovo Formation, where the rock-forming role of radiolarians is high, makes it possible to date even those productive high-carbon intervals of the section where other fauna is not found.

Radiolarians can serve as an important tool in understanding the paleogeographic conditions of the formation of oil source and oil-bearing strata of shale oil basins, as has been shown in a number of examples of studies of sections of the Bazhenovo Formation in Western Siberia and its Arctic coast. The presence of the genus *Parvicingula* in radiolarian associations of the Bazhenovo Formation is an indicator of a northern current that could bring many representatives of this genus from the Pacific or Arctic paleoclimatic province.

Two new species were described: *Orbiculiforma sibirica* Vishnevskaya, sp. nov. from the family Orbiculiformidae Pessagno 1973; *Emiluvia retorta* Vishnevskaya, sp. nov. from the family Staurolonchidae Haeckel, 1881; emend. Pessagno, 1977.

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AUTHOR CONTRIBUTION

A historical review and critical analysis of the research process of radiolarians of the Bazhenovo Formation was prepared by E.O. Amon; analysis of the geological structure was provided by G.A. Kalmykov; selection of stone material, examination of thin sections and chemical preparation of radiolarians with subsequent SEM imaging were carried out by V.S. Vishnevskaya and Yu.A. Gatovsky; definitions of radiolarians and establishment of the age of radiolarian zones, descriptions of new species were made by V.S. Vishnevskaya; paleogeographical findings and conclusions were made by E.O. Amon and V.S. Vishnevskaya.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human or animal subjects.

CONFLICT OF INTEREST

The author of this work declares that she has no conflict of interest.

REFERENCES

Afanasiev, I.S., Gavrilova, E.V., Birun, E.M., et al., The Bazhenovo Formation. General overview, unsolved problems, *Nauch.-Tekh. Vestn. OAO "NK "Rosneft",* 2010, no. 4, pp. 20–25.

Amon, E.O., Radiolarians in the ecosystem of the Bazhenovo Sea (Late Jurassic–beginning of the Early Cretaceous, Western Siberia), *Litologiya i Geologiya Goryuchikh Iskopayemykh*, 2011, no. V (21), pp. 145–169.

Amon, E.O., Vishnevskaya, V.S., and Gatovsky, Yu.A., On some features of habitation of radiolarians in the Late Jurassic–Early Cretaceous Bazhenovo basin of Western Siberia, *Bull. Mosk. Obshch. Ispyt. Prir., Otd. Geol.*, 2021, vol. 96, no. 2, pp. 3–38.

Amon, E.O., Vishnevskaya, V.S., and Gatovsky, Yu.A., Morphotypes of radiolarians and some features of paleogeography of Arctic periphery of Western Siberia (Yamal Peninsula) during Late Jurassic, *Bull. Mosk. Obshch. Ispyt. Prir., Otd. Geol.*, 2022, vol. 97, no. 1, pp. 15–45.

Balushkina, N.S., Kalmykov, G.A., Belokhin, V.S., Khamidullin, R.A., and Korost, D.V. Siliceous reservoirs of the Bazhenovo Formation, the Sredny Nazym Oil Field, and the structure of their pore space, *Moscow Univ. Geol. Bull.*, 2014, vol. 69, no. 2, pp. 91–100.
https://doi.org/10.3103/S0145875214020033

Bazhenova, T.K., Bituminous strata of Russia and assessment of hydrocarbon resources, in *Trudnoizvlekayemyye zapasy i netraditsionnyye istochniki uglevodorodnogo syr'ya. Problemy, perspektivy, prognozy: sbornik dokladov konferentsii* (Hard-to-Recover Petroleum Reserves and Unconventional Hydrocarbon Resources. Problems, Prospects, Forecasts. Coll. Conf. Reports), St. Petersburg: Vseross. Neft. Nauchno-Issled. Geol. Inst., 2015. 1 CD-R.

Bazhenovsky gorizont Zapadnoy Sibiri (stratigrafiya, paleogeografiya, ekosistema, neftenosnost') (Bazhenov Horizon of Western Siberia (Stratigraphy, Paleogeography, Ecosystem, Oil Content), Novosibirsk: Nauka, 1986.

Bolshanik, P.V. History of the discovery of the Bazhenovo Formation in the Omsk Region, *Natsional'nyye Prioritety Rossii*, 2021, no. 4 (43), pp. 79–82.

Bragin, N.Yu., Radiolarians of the Volgian and Berriasian stages of the North of Central Siberia, *Stratigr. Geol. Correl.*, 2011, vol. 19, no. 2, 173–187.

Brekhuntsov, A.M., Nesterov, I.I., Jr., and Nechiporuk, L.A., Tight reserves and unconventional hydrocarbon raw material objects in Western Siberia, *Nedropol'zovaniye XXI vek*, 2017, no. 3 (66), pp. 54–63.

Dzyuba, O.S., Alifirov, A.S., Igolnikov, A.E., Zakharov, V.A., Shurygin, B.N., Eder, V.G., Ryzhkova, S.V., and Zamirailova, A.G., Stratigraphic ranges of members of the Bazhenovo Formation in Western Siberia based on macrofauna, *Cretaceous System of Russia and Neighboring Countries: Problems of Stratigraphy and Paleogeography: Materials of the 11th All-Russian Meeting, Tomsk, September 19–24, 2022*, Baraboshkin, E.Yu., Ed., Tomsk: TSU, 2022, pp. 103–109.

Eder, V.G., Ryzhkova, S.V., Dzyuba, O.S., and Zamirailova, A.G., Lithostratigraphy and sedimentation conditions of the Bazhenovo Formation (Western Siberia) in the central, southeastern, and northern regions of its occurrence, *Stratigr. Geol. Correl.*, 2022, vol. 30, no. 5, pp. 46–74.
https://doi.org/10.1134/S0869593822050021

Fomin, M.A., Saitov, R.M., and Zamirailova, A.G., Lithology and oil content of the Bazhenov Formation in the central part of the Mansi Syneclise, *Georesources*, 2023, vol. 25, no. 4, pp. 176–191.

Hull, D., Upper Jurassic Tethyan and southern Boreal radiolarians from western North America, *Micropaleontology*, 1997, vol. 43, no. 2, pp. 1–202.

Isaeva, A.V. and Gatovsky, Yu.A., New data on the internal structure of some species of Mesozoic radiolarians from the genera *Parvicingula* and *Takemuraella*, in *Mikropaleontologiya: fundamental'nyye problemy i vklad v regional'noye geologicheskoye izucheniye nedr. Trudy XVIII Vseross. mikropaleontol. soveshch. (Sankt-Peterburg, 2023 g.)* (Micropaleontology: Fundamental Problems and Contribution to the Regional Geological Study of the Subsoil. Proc. XVIII All-Russ. Micropaleontol. Meet. (St. Petersburg, 2023)), St. Petersburg: VSEGEI, 2023, pp. 210–213.

Isaeva, A.V., Vishnevskaya, V.S., and Gatovsky, Yu.A., New data on the internal structure of some species of radiolarians of the genera *Parvicingula* and *Takemuraella* (Late Jurassic–Early Cretaceous, Bazhenovo Formation, Western Siberia), in Bio- i geosobytiya v istorii Zemli. Etapnost' evolyutsii i stratigraficheskaya korrelyatsiya, *Mater. LXIX sessii Paleontol. o-va Ross. Akad. Nauk* (Bio- and Geoevents in the History of the Earth. Stages of Evolution and Stratigraphic Correlation. Proc. LXIX Sess. Paleontol. Soc. Russ. Acad. Sci.), St. Petersburg: Kartfabrika Vseross. Nauchno-Issled. Geol. Inst., 2023, pp. 51–52.

Kalmykov, G.A. and Balushkina, N.S., *Model' neftenasyshchennosti porovogo prostranstva porod bazhenovskoy svity Zapadnoy Sibiri i yeye ispol'zovaniye dlya otsenki resursnogo potentsiala* (Model of Oil Saturation in the Pore Space of Rocks of the Bazhenovo Formation in Western Siberia and its Use for Assessing Resource Potential), Moscow: GEOS, 2017.

Khartukov, E.M., "Shale oil" in Russia: Today and tomorrow, *Sfera. Neft Gaz*, 2020, nos. 3–4, pp. 104–111.

Khotylev, O.V., Gatovsky, Yu.A., Balushkina, N.S., etc. Models of sedimentation of the Bazhenov high-carbon formation in the development zone of the Tutleim and Bazhenov formations, *Georesources*, 2021, vol. 23, no. 2, pp. 120–131. https://doi.org/10.18599/grs.2021.2.11

Kiessling, W., New radiolarians from the earliest Cretaceous of the Sultanate of Oman (Wahrah Formation, Jebel Buwaydah), *Paläontol. Z.*, 1995, vol. 69, pp. 321–342.

Kiessling, W., Late Jurassic radiolarians from the Antarctic Peninsula, *Micropaleontology*, 1999, vol. 45, no. 1, pp. 1–96.

Kontorovich, A.E., We should go to the Arctic for oil and gas to the Bazhenov Formation and to the small fields, *Neftegazovaya Vertical*, 2019, no. 14, pp. 12–17.

Kontorovich, A.E., Kontorovich, V.A., Ryzhkova, S.V., et al., Jurassic paleogeography of the West Siberian sedimentary basin, *Russ. Geol. Geophys.*, 2013, vol. 54. no. 8, pp. 747–779.

Kontorovich, A.E., Ershov, S.V., and Kazanenkov, V.A., Cretaceous paleogeography of the West Siberian sedimentary basin, *Russ. Geol. Geophys.*, 2014, vol. 55, nos. 5–6, pp. 582–609.

Kozlova, G.E., Distribution of radiolarians in the Bazhenovo Formation of Western Siberia, in *Paleobiogeografiya i biostratigrafiya yury i mela Sibiri* (Paleobiogeography and Biostratigraphy of the Jurassic and Cretaceous of Siberia), Moscow: Nauka, 1983, pp. 47–55.

Kozlova, G.E., Assemblages of Mesozoic radiolarians of the Timan-Pechora oil and gas region, in *Poiski, razvedka i dobycha nefti i gaza v Timano-Pechorskom basseyne i Barentsevom more* (Search, Exploration and Production of Oil and Gas in the Timan-Pechora Basin and the Barents Sea), St. Petersburg: Vseross. Neft. Nauchno-Issled. Geol. Inst., 1994, pp. 60–81.

Kruglikova, S.B., *Radiolyarii Polycystina iz donnykh otlozheniy Mirovogo okeana kak bioindikatory izmeneniy okruzhayushchey sredy* (Radiolarians Polycystina from Bottom Sediments of the World Ocean as Bioindicators of Environmental Changes), Moscow: GEOS, 2013.

Lazarus, D., Suzuki, N., Ishitani, Y., and Takahashi, K., *Paleobiology of the Polycystine Radiolaria*, Wiley Blackwell, 2021.

Nakrem, H.A. and Kiessling, W., Late Jurassic (Volgian) radiolarians from Central Spitsbergen—a preliminary study, *Norwegian J. Geol.*, 2012, vol. 92, pp. 149–155.

Nemova, V.D., Lithogenetic classification of rocks and technomorphism of sediments of the Bazhenovo Formation of the West Siberian oil and gas province, *Doct. Sci. (Geol.–Mineral.) Dissertation*, Moscow, 2021.

O'Dogherty, L., Carter, E.S., Dumitrica, P., et al., Catalogue of Mesozoic radiolarian genera. Part 2: Jurassic–Cretaceous, *Geodiversitas*, 2009, vol. 31, no. 2, pp. 271–356.

Panchenko I.V. Event-stratigraphic levels of the Upper Jurassic–Lower Cretaceous black shale strata of Western Siberia, *Cand. Sci. (Geol.–Mineral.) Dissertation*, Moscow, 2023.

Panchenko, I.V., Vishnevskaya, V.S., Kalmykov, G.A., and Baraboshkin, E.Yu., New data on the biostratigraphy of the Abalak and Bazhenov formations, obtained based on a comprehensive study of macro- and microfaunal remains, in *Yurskaya sistema Rossii: problemy stratigrafii i paleogeografii* (Jurassic System of Russia: Problems of Stratigraphy and Paleogeography), Yekaterinburg: LLC Publishing House "IzdatNaukaServis", 2013, pp. 162–165.

Panchenko, I.V., Balushkina, N.S., Baraboshkin, E.Yu., etc., Assemblages of paleobiota in the Abalak-Bazhenov deposits of the central part of Western Siberia, *Neftegaz. Geol. Teoriya Praktika*, 2015, vol. 10, no. 2, pp. 1–29. http://www.ngtp.ru/rub/2/24_2015.pdf.

Panchenko, I.V., Sobolev, I.D., Rogov, M.A., and Latyshev, A.V., Volcanic tuffs and tuffites in Jurassic–Cretaceous (Volgian–Ryazanian) boundary rocks of Western Siberia, *Lithol. Miner. Resour.*, 2021, vol. 56, no. 2, pp. 152–188.

R*esheniye 6-go Mezhvedomstvennogo stratigraficheskogo soveshchaniya po rassmotreniyu i prinyatiyu utochnennykh stratigraficheskikh skhem mezozoyskikh otlozheniy Zapadnoy Sibiri (Novosibirsk, 2003 g.)* (Decision of the 6th Interdepartmental Stratigraphic Meeting on the Consideration and Adoption of Refined Stratigraphic Schemes of Mesozoic Deposits of Western Siberia (Novosibirsk, 2003)). Novosibirsk: Sib. Nauchno-Issled. Inst. Geol. Geofiz. Miner. Syr'ya, 2004.

Rogovaya, I., Khadum Formation: Caucasian oil and gas shales are also waiting for their technologies, *Neft' Kapital*, 2019, nos. 7–8, pp. 21–26.

Vishnevskaya, V., Jurassic and Cretaceous radiolarian biostratigraphy in Russia, Radiolaria of giant and subgiant fields in Asia, *Micropaleontology. Spec. Publ.*, 1993, vol. 6, pp. 175–200.

Vishnevskaya, V.S., *Radiolyariyevaya biostratigrafiya yury i mela Rossii* (Radiolarian Biostratigraphy of the Jurassic and Cretaceous of Russia), Moscow: GEOS, 2001.

Vishnevskaya, V.S., Biostratigraphy and paleogeography of the Bazhenovo Formation according to radiolarian analysis, in *Yurskaya sistema Rossii: problemy stratigrafii i paleogeografii* (Jurassic System of Russia: Problems of Stratigraphy and Paleogeography), Yekaterinburg: IzdatNaukaServis, 2013, pp. 34–37.

Vishnevskaya, V.S., Age of oil source siliceous-carbonate strata of the Bazhenovo Formation of Western Siberia based on radiolarian analysis, in *Problemy regional'noy geologii Severnoy Yevrazii* (Problems of Regional Geology of Northern Eurasia), Moscow: MGRI-RGGRU, 2016, pp. 22–24.

Vishnevskaya, V.S., The Jurassic–Cretaceous boundary in Boreal Russia: radiolarian and calcareous dinoflagellate potential biomarkers, *Geol. Quart.*, 2017, vol. 61, no. 3, pp. 641–654.

Vishnevskaya, V.S., Revision of the Early Cretaceous radiolarian species *Williriedellum salymicum* Kozlova, *Paleontol. J.,* 2019, vol. 53, no. 4, pp. 334–340.

Vishnevskaya, V.S., New Late Jurassic Saturnalidae (Radiolaria) of the Arctic and Pacific margins (Russia), *Paleontol. J.*, 2021, vol. 55, no. 12, pp. 1511–1524. https://doi.org/10.1134/S0031030121120078

Vishnevskaya, V.S., Echinocampidae (Radiolaria) of the Upper Jurassic and Lower Cretaceous of Western Siberia, in *PALEOSTRAT-2024. Godichnoye sobraniye (nauchnaya konf.) Sektsii Paleontologii Mosk. Obshch. Ispyt. Prir. i Mosk, Otd. Paleontol. Obsch. RAN. Tez. Dokl.* (PALEOSTRAT-2023. Annu. Meet. (Sci. Conf.) Paleontol. Sect. MOIP, Moscow Branch, Paleontol. Soc., Russ. Acad. Sci. Abstracts of Reports), Moscow: Paleontol. Inst. Ross. Akad. Nauk, 2024, p. 14.

Vishnevskaya, V.S. and Gatovsky, Yu.A., Late Jurassic Saturnalidae (Radiolaria) Yamal (Arctic Siberia), *Mater. VIII Vseross. soveshch. s mezhdunarodnym uchastiyem. Onlayn-konferentsiya, 7–10 sentyabrya 2020 g.* (Proc. VIII All-Russ. Conf. with Int. Participation. Online-conf., September 7–10, 2020), Syktyvkar: IG Komi Nauhn. Tsentr. Ross. Akad. Nauk, 2020, pp. 46–48.

Vishnevskaya, V.S. and Filatova, N.I., Paleoclimatic and paleolatitude settings of accumulation of radiolarian siliceous–volcanogenic sequences in the middle Mesozoic Pacific: Evidence from allochthons of East Asia, *Oceanology*, 2017, vol. 57, no. 5, pp. 685–699. https://doi.org/10.1134/S0001437017050186

Vishnevskaya, V.S., and Kozlova, G.E., Volgian and Santonian–Campanian radiolarian events from the Russian Arctic and Pacific Rim, *Acta Palaeontol. Pol.,* 2012, vol. 57, no. 4, pp. 773–790.

Vishnevskaya, V.S. and Pral'nikova, I.E., Jurassic radiolarians from northern Russia, *Stratigr. Geol. Correl.*, 1999, vol. 7, no. 5, pp. 473–491.

Vishnevskaya, V.S., Amon, E.O., Marinov, V.A., and Shurygin, B.N., A new finds of Early Cretaceous radiolarians on the Arctic coast of East Siberia (Lena River delta area), *Dokl. Earth Sci.*, 2014, vol. 458, no. 1, pp. 1047–1051.

Vishnevskaya, V.S., Amon, E.O., and Gatovsky, Yu.A., Radiolarian Biostratigraphy of the Bazhenovo Regional Substage (Upper Jurassic–Lower Cretaceous) of Western Siberia, *Stratigr. Geol. Correl.*, 2020, vol. 28, no. 6, pp. 665–683. https://doi.org/10.31857/S0869592X20060101

Vishnevskaya, V.S., Ovechkina, M.N., and Ustinova, M.A., Biostratigraphy and paleogeography of the Bazhenovo Formation (Upper Jurassic and Lower Cretaceous) based on radiolarians, nannoplankton and calcareous dinocysts, *Paleontol. J.*, 2019, vol. 53, no. 9, pp. 916–921. https://doi.org/10.1134/S003103011909017X

Vysotsky, V.I., Merkulov, O.I., and Sizintsev, S.V., Shale hydrocarbons and heavy oil as the main promising directions for the development of global oil and gas production in the medium and long term, Mi*ner. Resour. Rossii. Ekon. Uprav*., 2023, no. 2, pp. 19–28.

Zakharov, V.A., Conditions for the formation of the Volgian–Berriasian high-carbon Bazhenovo Formation in Western Siberia according to paleoecology data, in *Evolyutsiya biosfery i bioraznoobraziya* (Evolution of the Biosphere and Biodiversity) Moscow: KMK, 2006, pp. 552–568.

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