

The Jurassic-Cretaceous boundary in Boreal Russia: radiolarian and calcareous dinoflagellate potential biomarkers

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The International Berriasian Working Group (ISCS) suggested primary and secondary marker “datums” to fix the basal Berriasian boundary and thus to define the Jurassic-Cretaceous boundary (Wimbledon et al., 2011, 2013). Two primary markers *Calpionella*, as well as calcareous nannoplankton, are practically unknown in the Boreal Realm. Testing and calibration of these markers, as well as of fossils of radiolarians and other signals, in the most complete sections, were declared as an important task for the near future. In the Tethys, the Jurassic-Cretaceous boundary based on radiolarians falls inside zone UAZ 13 of Baumgartner et al. (1995), whereas in the palaeo-Pacific it corresponds to the boundary between zones 4 and 5 of Pessagno et al. (2009), and in boreal Siberia it probably falls between the biohorizons of *Parvicingula haeckeli* and *P. khabakovi*. The radiolarian events at the Jurassic-Cretaceous boundary in the boreal successions of Russia can be proposed to be used as an additional biomarker to help develop new integrated boundary criteria. Thus, as the first appearance of the zonal species *Calpionella alpina*, which defines the Jurassic and Cretaceous boundary, coincides with the first occurrence of the calcareous dinocyst zonal species *Stomiosphaerina proxima* (Reháková, 2000), it is logical to propose a calcareous dinoflagellate, widely represented in the Upper Jurassic-Lower Cretaceous Bazhenovo Formation of Siberia, as a secondary marker.

Key words: Tithonian and Berriasian stages, radiolarians, calcareous dinoflagellates, Tethys, boreal, Volgian.

INTRODUCTION

The Jurassic-Cretaceous boundary interval has been problematic since the start of stratigraphic study, as reflected in different stage names being employed in the Tethyan realm and below and above the putative boundary (Wimbledon, 2008). Due to magnetostratigraphy there has been some progress in the correlation of the Jurassic-Cretaceous boundary interval from Tethys to Siberia (Nordvik) (Wimbledon et al., 2011). Moreover, Upper Jurassic to Lower Cretaceous highly bituminous shale and siliceous sequences of Western Siberia draw increasing attention, especially the Bazhenovo suite. Now it is considered as a strategically important asset in terms of prospects for the Russian oil industry (Afanasev et al., 2010). There are question marks over the lower and upper limits of deposits of the Bazhenovo suite and also over the location of the Jurassic and Cretaceous boundary within it.

In the 29th issue of ISC *Decisions* (1997) a resolution was published to specify the position of the Jurassic-Cretaceous boundary in the Boreal Realm and the status of the Volgian Stage, accepted at the Extended Meeting of the ISC Bureau on February 2, 1996. The accepted position of the Jurassic-Cretaceous boundary in the Boreal Realm of the Russian sector was

between the Middle and Upper Volgian substages. It was accepted to re-classify the Volgian Stage in the same volume from the category of a general unit into the category of a regional stratigraphic unit as a horizon (regional stage), leaving in the General Stratigraphic Scale of Russia only the Tithonian and Berriasian stages in the boundary interval (Vasileva, 2015).

The international Berriasian WG (ISCS) proposed primary markers and secondary constraining datums (Fig. 1) in order to fix a base for the Berriasian and the Jurassic-Cretaceous boundary (Wimbledon et al., 2011, 2013; Schnabl et al., 2015). The testing and calibration of these markers, as well as foraminiferal, radiolarian and other signals in the most complete and fossiliferous sections, was promoted as an important task for the near future.

The Russian Commission on the Jurassic system is working on the restoration of the inclusion of the Volgian Stage into the Jurassic System, based on new magnetostratigraphic and biostratigraphic data. The commission (on 3 April 2012) decided to recommend to ISC to replace the Tithonian Stage by the Volgian in the General Stratigraphic Scale of Russia, preserving the latter in the volume, accepted before 1996 (from the base of the Ilowaiskya klimovi Zone to the top of the Craspedites nodiger Zone) and to discuss this issue at a joint meeting of the commissions on the Jurassic and Cretaceous systems of the ISC (Baraboshkin et al., 2015).

The main points of this paper are:

- to examine the potential of radiolarians as additional biological markers to help define a boundary;
- to propose calcareous dinocysts as a secondary marker.

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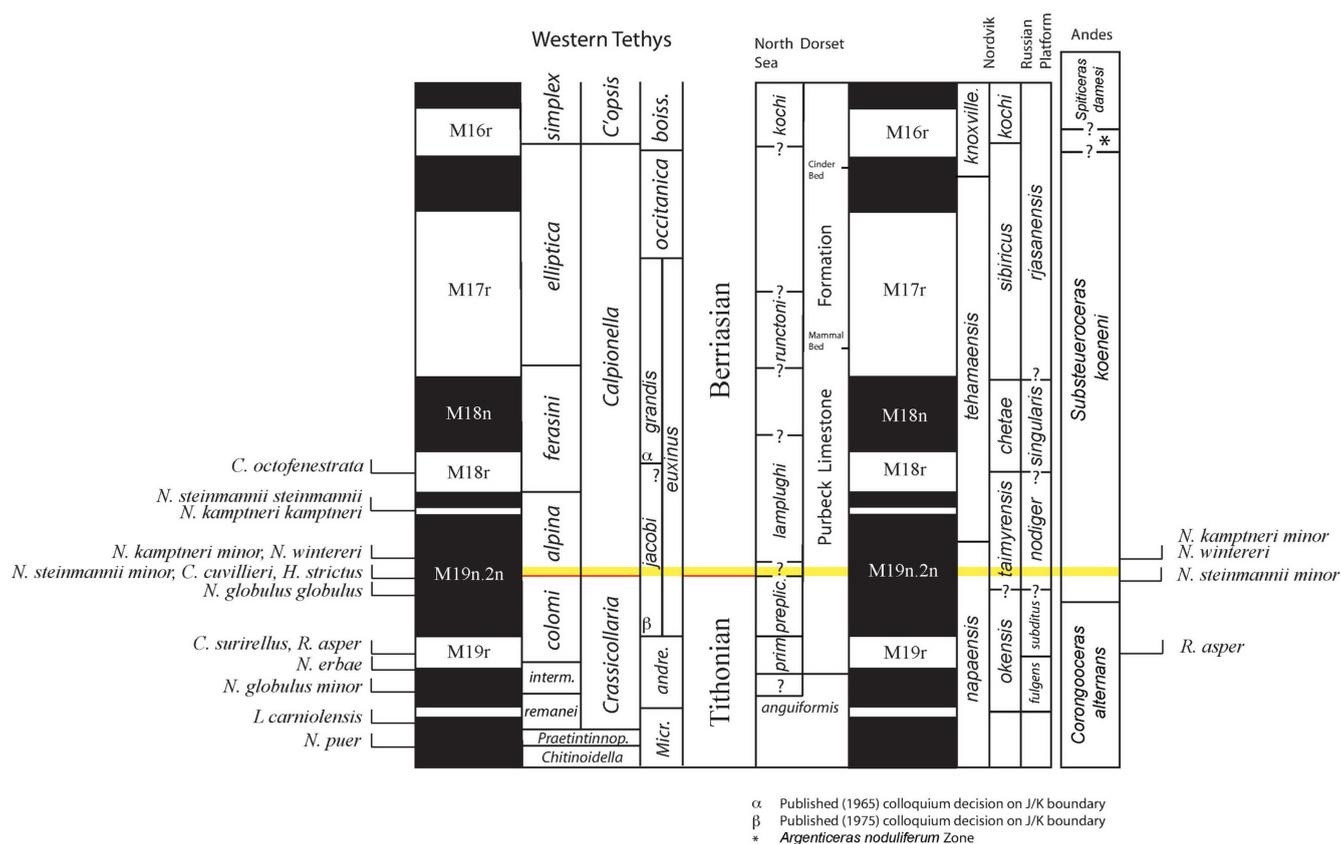


Fig. 1. Markers under examination as potentially useful in defining the Jurassic/Cretaceous interval in the Tethyan and Boreal realms (Wimbledon et al., 2011, 2013; Schnabl et al., 2015)

MATERIALS AND METHODS

Radiolarian collections were taken from 6 sections of the Russian Arctic (Vishnevskaya and Kozlova, 2012), 7 sections in the Siberian Bashenovo Formation (Panchenko et al., 2016), as well as the Lena Delta section (Vishnevskaya et al., 2014) and 24 profiles in NE Asia (Vishnevskaya and Filatova, 2012, 2016). The number of specimens examined exceeds one thousand: 44 samples come from 6 sections of the Russian Arctic, 700 samples from 7 sections in the Siberian Bashenovo Suite and the Lena Delta section, and 300 samples from 24 profiles in NE Asia. The collections are housed at the Geological Institute of the Russian Academy of Sciences.

The samples (all chert, shale, or jasper) were crushed and processed with hydrofluoric acid (5–10%), while clay, shale and carbonate concretions were processed with acetic acid in the palaeontology laboratory of the Geological Institute, Moscow. Radiolarians were picked, mounted on cardboard slides fixed with special glue on metal stubs, and identified using a binocular microscope and a scanning electron microscope (SEM). All photographs were taken with SEM, as well as with an optical microscope.

With bituminous radiolaria-bearing sequences, we used the method of tomography, which allows one to investigate the inner and external structure of radiolarian skeletons in rocks (Fig. 2) and in thin-sections. Tomography was firstly applied in radiolarian analysis. The advantage of the tomographic method is that it allows to examine the object while rotating around both vertical axis and horizontal axes.

The calcareous dinocysts were investigated under an optical microscope.

CORRELATION OF NORTH AMERICAN RADIOLARIAN ZONES WITH TETHYAN UNITARY ASSOCIATION ZONES

Starting in the Late Jurassic there are three distinct climatic radiolarian associations. These are: Tethyan, Pacific, and Boreal. The Tethyan or Mediterranean Tethyan radiolarian fauna represents the first association with an abundance of *Andromeda* Baumgartner, *Emiluvia* Foreman, *Pantanellium* Pessagno (Baumgartner, 1984; Baumgartner et al., 1995; Hardenbol et al., 1998) and *Ristola* Pessagno and Whalen (Alps, Carpathians and Caucasus). This association is very diverse and represents low-latitude radiolarian faunas. Tethyan Unitary Association Zones (Tethyan Zones) were developed by the International Jurassic-Lower Cretaceous Group: all data published in Baumgartner et al. (1995). The second radiolarian fauna (North Pacific bioprovince) is dominantly non-Tethyan with some input of Tethyan species: the base of site 305 of DSDP in the Pacific Ocean (Vishnevskaya, 2001), California (Pessagno et al., 2000), and Mexico (Yang, 1993). North American Radiolarian Zones (Pacific Zones) were established by Pessagno (1977) Pessagno et al. (1993, 2000, 2009; cf. Yang, 1993) based on the genera *Parvicingula*, *Mirifusus*, *Ristola*, *Caneta* of the family Parvicingulidae (Fig. 3). The last occurrence of *Parvicingula colemani* and *Ristola altissima* was fixed in Zone 4 (Pessagno et al., 1993), the first appearance of *Williriedellum ruesti* and *Obesacapsula rotundata* was recorded in Zone 5 (Kiesling et al., 1999; Pessagno et al., 2009). The third climatic radiolarian association, a Boreal one, is characterized by the prevalence of *Parvicingula* and is more typical of high latitudes (Pacific Rim, Argentina,

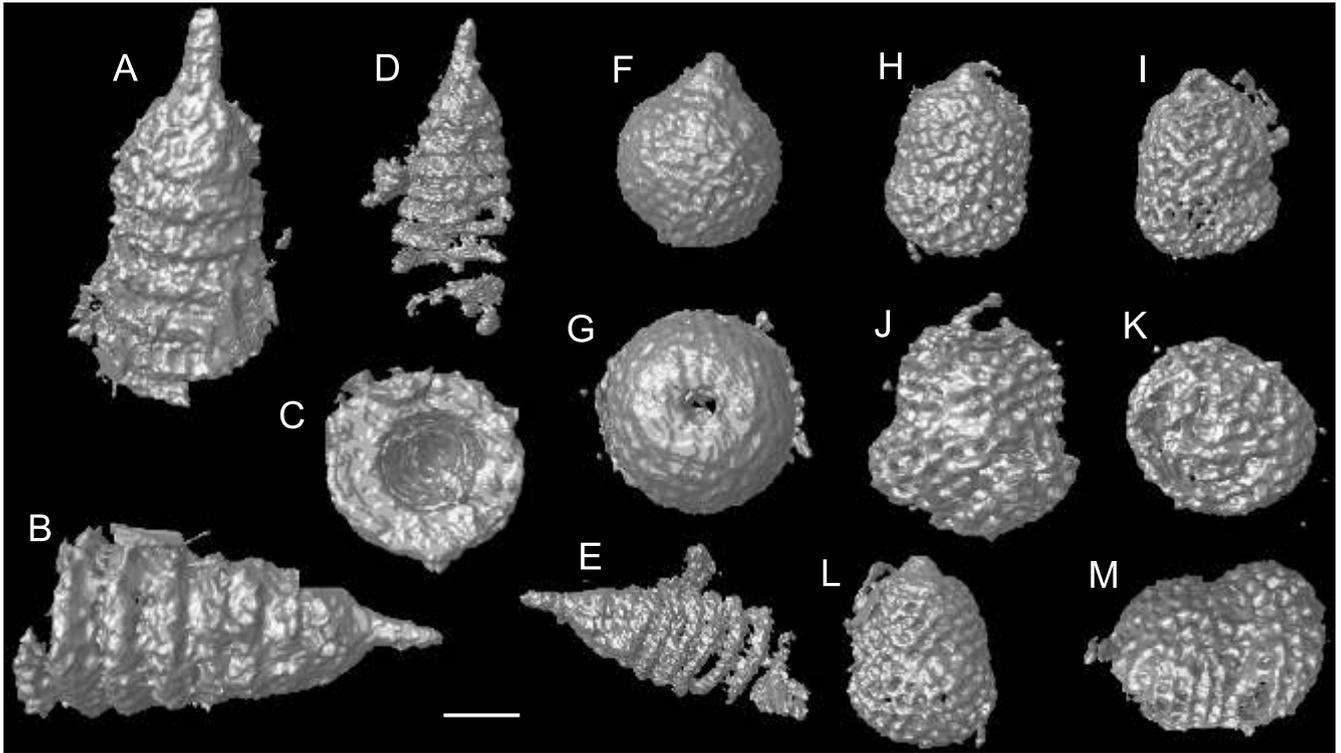


Fig. 2. Radiolarian skeletons as X-ray microtomographic images

A–C – *Parvicingula haeckeli* (Pantanelli); D, E – *Parvicingula* sp.; F, G – *Willriedellum salymicum* (Kozlova);
 H–M – *Tricolocapsa campana* Kiesling; A–E, sample 2–35, Western Siberia, Upper Volgian;
 F–M, sample 11–22, Western Siberia, Berriasian; scale bar 100 µm

| | | | | Primary taxa | Secondary taxa | Corporeal taxa |
|--------------|--------|-------------|---------------------------------|--------------------------------|-----------------------------|----------------------------------|
| BERR. | early | Zo. 5 | Subzone 5A | <i>Parvicingula jonesi</i> | | <i>Obesacapsula rotunda</i> |
| | late | | Zone 4 | <i>Ristola altissima</i> | <i>Parvicingula excelsa</i> | <i>Parvicingula colemani</i> |
| TITHONIAN | early | Subzone 4 α | | <i>Vallupus hopsoni</i> | <i>Hsuum mclaughlini</i> | <i>Orbiculiforma lowreyensis</i> |
| | late | Subzone 4 β | <i>Acanthoc. dicranacanthos</i> | <i>P. colemani</i> | <i>Parvicingula jonesi</i> | |
| KIMMERIDGIAN | early | Zone 3 | Subzone 3 α | <i>Napora burckhardti</i> | | <i>Turanta</i> |
| | late | | Subzone 3 β | <i>Mirifusus guadalupensis</i> | | <i>Hsuum maxwelli</i> |
| | early | | Subzone 3 γ | <i>Mirifusus baileyi</i> | <i>Caneta hsui</i> | |
| OXFORDIAN | middle | Zo. 2 | Subzone 2 α ₁ | <i>Loopus</i> | <i>Parvicingula blowi</i> | |
| | late | | Subzone 2 α ₂ | <i>Parvicingula s.s.</i> | | |

Fig. 3. Upper Jurassic and Lower Cretaceous radiolarian zonation of Pessagno et al. (1993, 2009)

northern European and Siberian platforms). This association is widespread in the Volga River Basin of the Russian Platform (Vishnevskaya and Baraboshkin, 2001; Vishnevskaya and Kozlova, 2012) and many areas of Western Siberia (Vishnevskaya, 1998, 2013; Bragin, 2009; Vishnevskaya et al., 2014). The genus *Parvicingula* is also widespread in the Arcto-Boreal province (Spitsbergen, Timan-Pechora Basin, Norway Sea and northern Siberia; Vishnevskaya and Kozlova, 2012) and Austral province of Antarctica and the Indian Ocean (site 765, 766 and DSDP site 261, Argo Abyssal Plain and Lower Exmouth Plateau; Kiessling, 1999).

Based on correlation with the first appearance of nannofossils the Jurassic-Cretaceous boundary in the Tethys (for instance, in Turkey) corresponds to first occurrences of the radiolarians *Becus nodulosus* (Dumitrica), *Diceratosaturnalis dicranacanthos* (Squinabol), *Deviatus diamphidius* (Foreman), *Pyramispongia bormsteinensis* (Steiger), *Acaeniotyle diaphorogona* Foreman, *Emiluvia pessagnoii* Foreman, *Archaeodictyomitra apiarium* (Rüst) sensu Kocher, as well as *Thanarla sensu lato* (Mekik et al., 1999; Mekik, 2000).

Due to radiolarian provincialism the correlation of radiolarian biozones between the Boreal (north of Eurasia and America) and Sub-Boreal Pacific and Tethyan realms (Mediterranean area, southern Europe) is hampered during the Late Jurassic-Early Cretaceous interval. The Jurassic-Cretaceous boundary of the Tethyan zonal scheme sits within UAZ 13 of Baumgartner et al. (1995), whereas the J/K boundary in the Pacific North American zonal scheme (Pessagno et al., 1993, 2009) is between zones 4 and 5 (Fig. 4). These differences are likely due to the predominance of boreal faunas in North America and may be explained by different methodologies and chronostratigraphic calibration of radiolarian data in the successions.

PARVICINGULIDAE AS A UNIQUE FAMILY, USED IN ALL ZONATIONS

The family Parvicingulidae Pessagno, 1977 includes 17 genera, 11 of which originated in the Pacific palaeogeographic province. Probably *Proparvicingula* Carter, 1993 was the pre-

| | NORTH AMERICAN ZONES | TETHYAN ZONES (UAZ 95) | ARCTIC SIBERIA (Vishnevskaya, 2016) |
|--------------|----------------------|------------------------|-------------------------------------|
| BERRIASIAN | 5 | 13 | <i>P. khabakovi</i> |
| TITHONIAN | 4 α | | 12 |
| | 4 β | 11 | |
| KIMMERIDGIAN | 3 α | 10 | <i>P. blowi</i> |
| | | | <i>P. elegans</i> |

Fig. 4. Correlation of North American, Tethyan and Russian Arctic Siberian radiolarian zones after Kiessling et al. (1999)

cursor of three lines within the family Parvicingulidae Pessagno (Fig. 5):

- conical-subsphaerical representatives without an apical horn and spine,
- high-conical representatives with an apical horn,
- high-conical representatives with a long apical spine.

Thus, an analysis of the geographical distribution of the Parvicingulidae showed that its high-conical representatives (*Parvicingula*, *Proparvicingula*, *Praeparvicingula*, *Atalantria*, *Canelonus*, *Elodium*, *Darvelus*, *Nitrader*, *Pseudoristola* and *Triversus*) come from the Pacific palaeogeographic province and have a mass development in boreal and natal (=Austral or southernmost Antarctic-related Zone) areas, and their areas of distribution often coincide with areas with cold-water *Buchia*, whereas the conical-subsphaerical group (*Mirifusus*, *Ristola*, *Tethysetta*, *Caneta*, *Svinitzium*, *Pseudocrocolanium*, *Wrangelium*) has a primary distribution in Tethys.

It is possible that the appearance of the genus *Proparvicingula* Carter (and family Parvicingulidae Pessagno) was connected with cooling which began 210 Ma (Fig. 6A). The earliest representatives of this family, excepting *Proparvicingula* Carter, with their first occurrence in the Rhaetian (Late Triassic), are the genera *Nitrader* Cordey and Carter (Hettangian-Sinemurian) and *Atalantria* Cordey and Carter (Hettangian-Pliensbachian) probably derived from *Proparvicingula* during a temperature minimum at the Triassic-Jurassic boundary (Zakharov, 2010).

At the end of prolonged Early Jurassic cooling in boreal regions, the new genera *Praeparvicingula* Pessagno, Blome and Hull (Middle Toarcian-Barremian) *Parvicingula* Pessagno and *Elodium* Carter (Middle Toarcian-Aalenian) made their first appearance.

The genus *Proparvicingula* Carter is a possible ancestor of *Praeparvicingula* Pessagno, Blome and Hull (Middle Toarcian-Barremian) and *Parvicingula* Pessagno.

The high-conical representatives of the family Parvicingulidae Pessagno also have principal stratigraphic significance (*Parvicingula* and *Praeparvicingula* alone contain together 77 species) and can be used for subdivision and correlation of sequences around the Jurassic-Cretaceous boundary.

Many species of the Parvicingulidae, such as *Parvicingula blowi*, *P. colemani*, *P. jonesi*, *P. vera*, *Ristola turpicula*, *R. cretacea*, *R. altissima*, *Tethysetta depressa*, *Caneta hsui*, *Mirifusus baileui*, *M. guadalupensis* and *M. mediodilatatus* are zonal markers (see Fig. 3) for the Jurassic and Lower Cretaceous (Pessagno, 1993; De Wever et al., 2001). The phylogenetic lines of the Parvicingulidae have allowed the compilation of stratigraphical zonal schemes for the Jurassic to Lower Cretaceous sequences of California (Pessagno, 1977; Hull, 1997), Argentina and Antarctica (Kiessling, 1999), as well as northern Russia (Vishnevskaya, 2001; Vishnevskaya and Murchey, 2002; Vishnevskaya and Kozlova, 2012) and the Russian Far East (Popova et al., 1999).

The ubiquitous presence of the Jurassic-Early Cretaceous genera *Parvicingula* and *Praeparvicingula* [*Parvicingula blowi* Pessagno, *P. jonesi* Pessagno, *P. excelsa* Pessagno and Blome, *P. blomei* Yang, *Praeparvicingula holdsworthi* (Yang), *Praeparvicingula* aff. *sencilla* Hull] in radiolarian associations of the Anyui Ocean (Vishnevskaya and Filatova, 2012, 2016), Bazhenovo (Panchenko et al., 2015), Pechora and Russian seas (Vishnevskaya and Kozlova, 2012) supports the presence of the northern seaway bringing a large number of species of these genera from the Pacific palaeoclimatic province to the

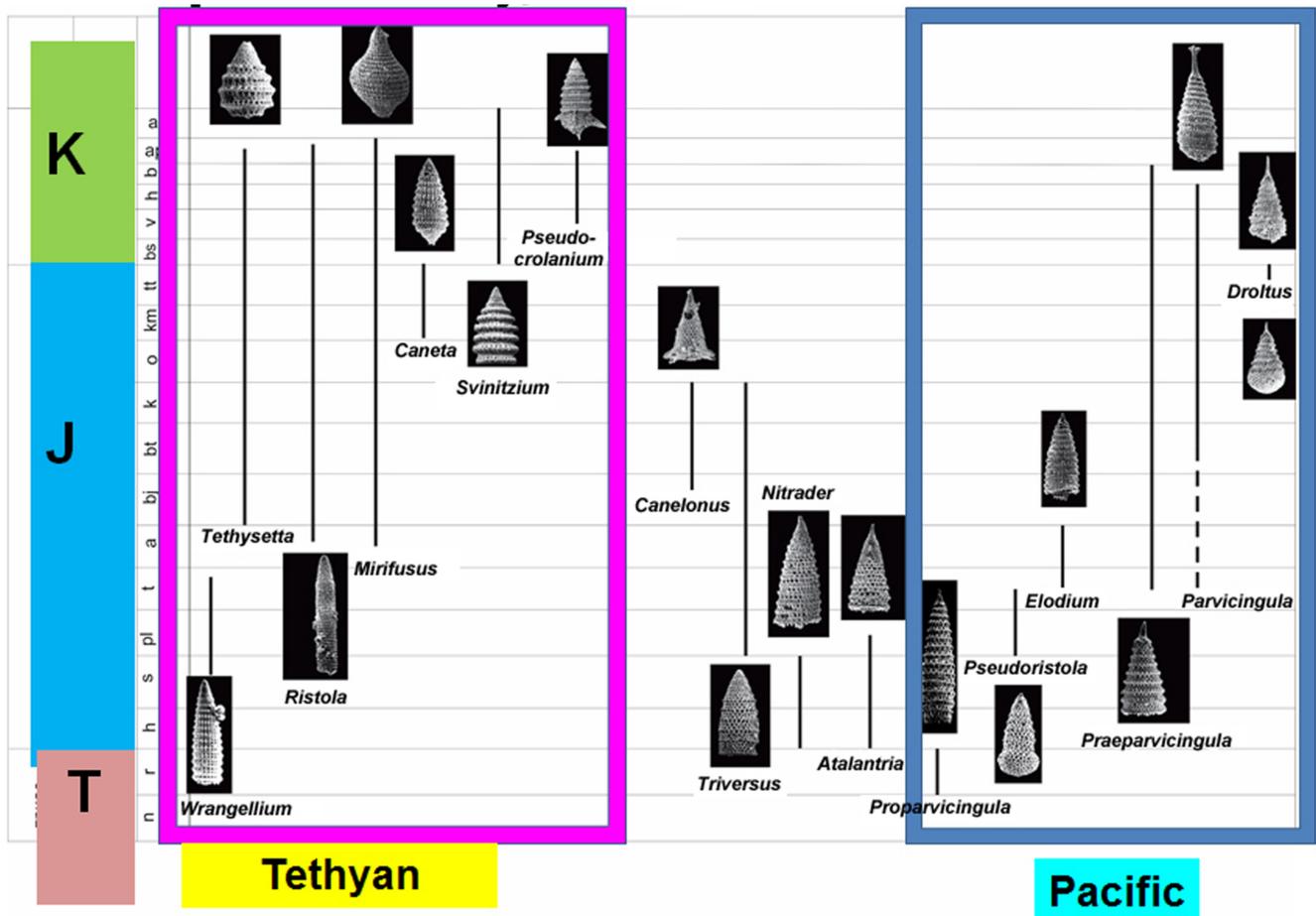


Fig. 5. The stratigraphic ranges and possible phyletic relationships of genera of the family Parvincingulidae

Boreal, Arctic (Bragin, 2011; Vishnevskaya et al., 2014) and Arcto-Boreal of the north Atlantic (Vishnevskaya and Kozlova, 2012). Only in the later Berriasian (at the end of the Volgian) time, new specialized genera – *Arctocapsula*, *Echinocampe*, *Nordvikella* and *Spincingula* – appeared in radiolarian associations (Bragin, 2011; Vishnevskaya and Kozlova, 2012).

The group of high-conical representatives of the Parvincingulidae evolved rapidly in the course of the Late Jurassic and Early Cretaceous, spreading through the high palaeolatitudes of the entire Pacific palaeogeographic province, and even penetrating into the Arctic and Antarctic regions: whereas the conical-sub-sphaerical group, related to warmer episodes, coincides with Tethys, and sometimes with the ecotone zones of “greenhouse” periods (Fig. 6B).

RADIOLARIAN ASSOCIATIONS AT THE J/K BOUNDARY IN BOREAL REGIONS

So far data on the Late Jurassic–Early Cretaceous radiolarian associations of the Russian sector of northern Asia (Vishnevskaya and Pralnikova, 1999; Vishnevskaya and Filatova, 2012, 2016), as well as eastern Europe and Western Siberia (Vishnevskaya, 1993, 1997, 1998; Vishnevskaya and Pralnikova, 1999; Vishnevskaya and Baraboshkin, 2001; Vishnevskaya and Kozlova, 2012), and the Norway Sea

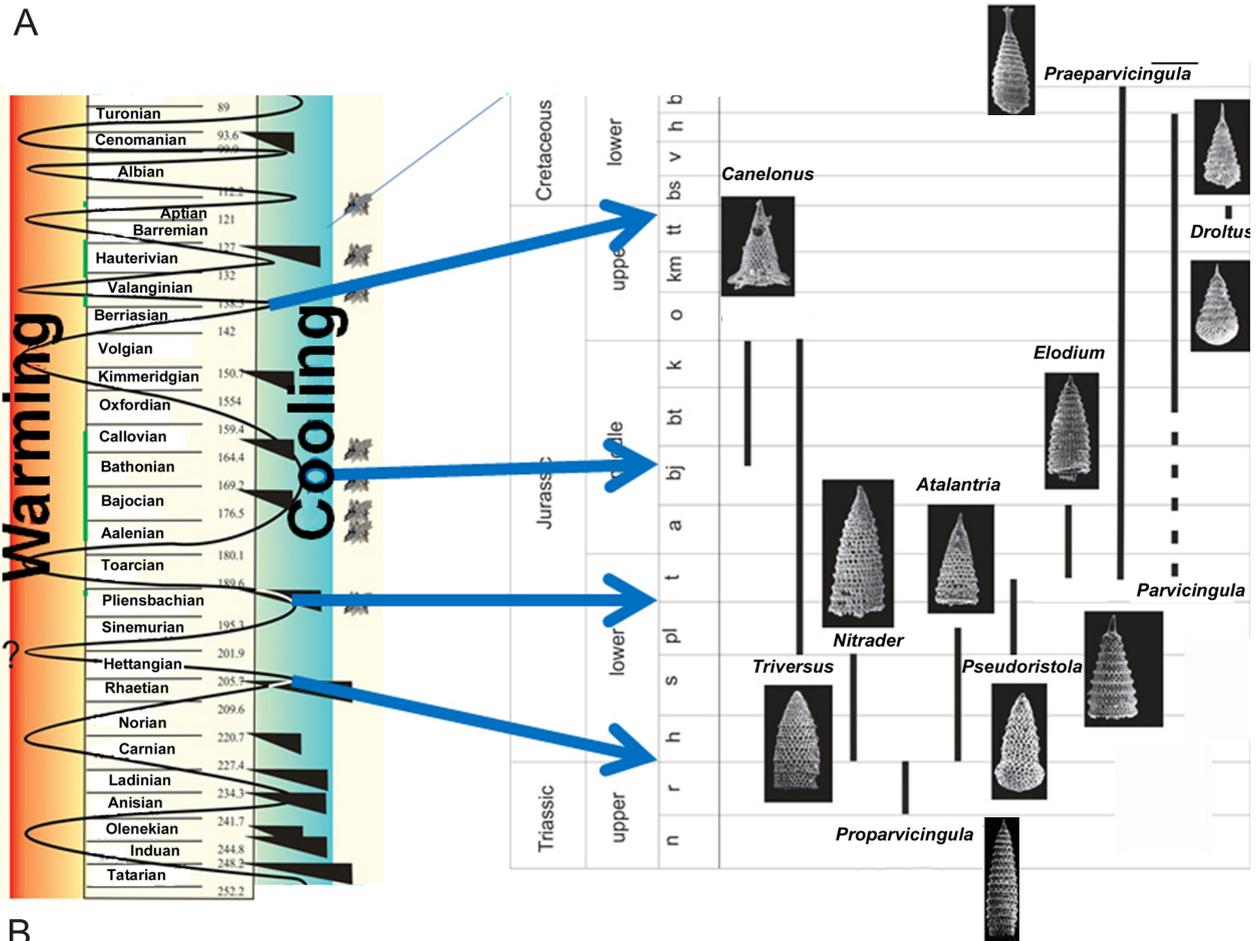
(Nakrem and Kiessling, 2012) with abundant Parvincingulidae (Fig. 7) have been published.

The high-conical representatives with apical horns (Fig. 8L, O, P), high-conical representatives with long apical spines (Fig. 8Q) together with conical-sub-sphaerical representatives without an apical horn and spine of the genera *Mirifusus* and *Ristola* (Fig. 8N, R–T) of the Parvincingulidae are well-known from sites on the Pacific Rim of Russia.

Typical Middle–Late Volgian (Middle Tithonian–Berriasian) radiolarians have been described from Nordvik of the Arctic coast of eastern Siberia (Zakharov and Rogov, 2006; Bragin, 2011) and Lena River Delta area (Vishnevskaya et al., 2014), where species of the endemic family Echinocampidae Bragin prevail in the Lower Cretaceous (Fig. 8).

The Middle Volgian (Middle–Upper Tithonian) radiolarian association of the ammonite Variabilis Zone includes *Arctocapsula magna* Bragin, *A. congelata* Bragin, *A. constantia* Bragin, *Archaeospongoprunum* sp. cf. *A. klingi* Pessagno, *Higumastra turgida* Bragin, *Orbiculiforma* sp. aff. *O. teres* Hull, *Parvincingula* sp., *Praeconocaryomma* sp. cf. *P. spinosa* Yang, *Praeparvincingula* sp. cf. *P. sencilla* Hull, *P. cappa* (Cortese), whereas the Upper Volgian (Uppermost Tithonian–Lower Berriasian) Chetae and Sibiricus ammonite zones contain *Arctocapsula incompta* Bragin, *A. perforata* Bragin, *Echinocampe aliferum* Bragin, *E. cristatum* Bragin, *E. aculeatum* Bragin, *Nordvikella elegans* Bragin, *N. improcera* Bragin, *Glomeropyle polygonium* Bragin, *Napora pyramidalis reticulatus* Bragin, *Orbiculiforma* sp. aff. *O.*

A



B

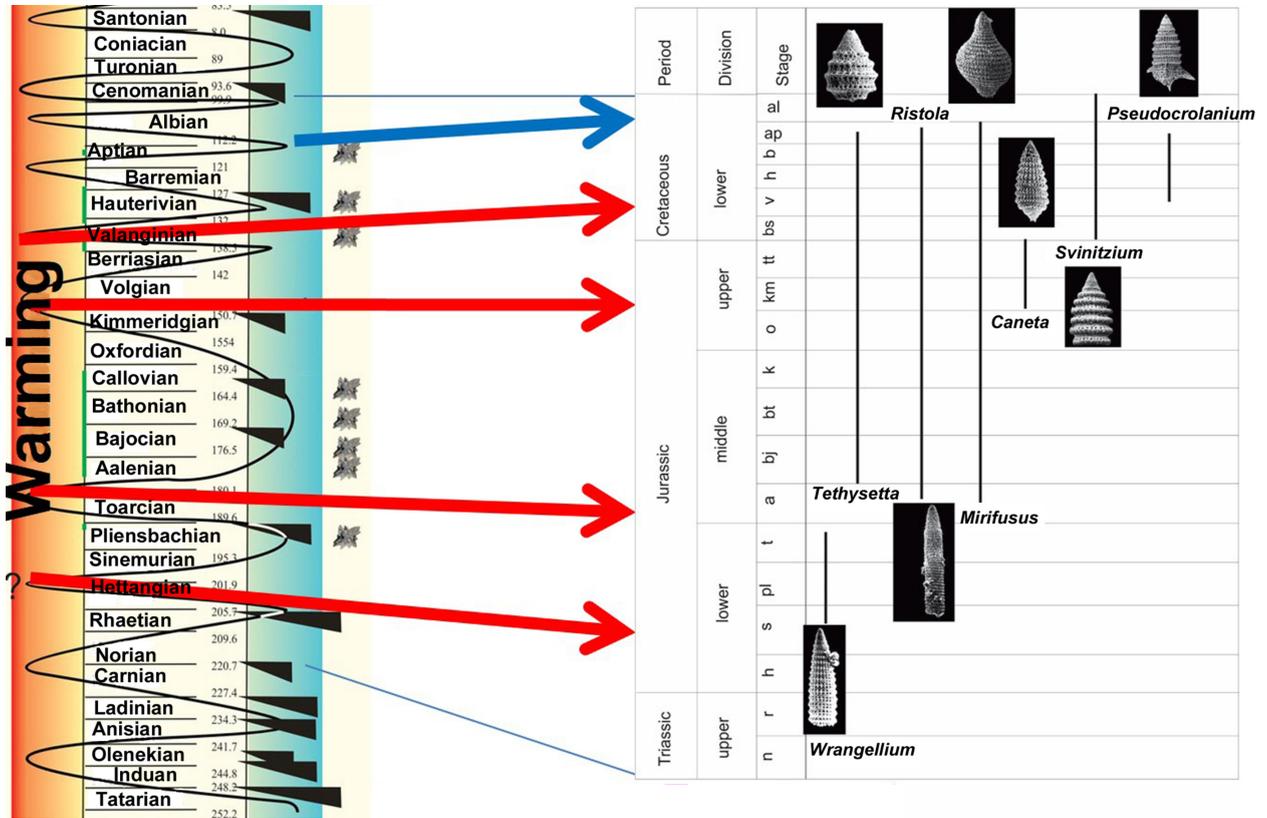


Fig. 6. The evolution of the family Parvicungulidae and the possible relationship with climate

A – stratigraphic ranges and possible phyletic relationships of the high-conical genera of the Parvicungulidae, and climatic fluctuations;
 B – stratigraphic ranges, possible phyletic relationships of the conical-subsphearical group of the Parvicungulidae, and climatic fluctuations

railensis Pessagno, *Parvicingula khabakovi* (Zhamoida), *Præparvicingula rotunda* Hull, and *Pyramotertonium planocephalum* (Kozlova) (Bragin, 2011). The last species was of boreal origin, and it has also been described from the Upper Volgian deposits of the Barents Sea Region and Timan-Pechora Plate (Vishnevskaya and Kozlova, 2012).

The radiolarian assemblage from the Berriasian Buchia *okensis* Zone in the Lena River delta (Ystannakh Khocho locality) includes *Arctocapsula devorata arctica* (Vishnevskaya and Murchey), *A. cf. constantia* Bragin, *A. incompta* Bragin, *Echinocampe* aff. *aculeatum* Bragin, *Parvicingula alata* Kozlova and Vishnevskaya, *P. papulata* Kozlova and Vishnevskaya, *Præparvicingula rotunda* Hull, and *Spinicingula cf. ceratina* Kozlova and Vishnevskaya (Vishnevskaya et al., 2014).

The subspecies *Arctocapsula devorata arctica* (Vishnevskaya and Murchey) was recorded in Upper Volgian clays (ammonite Subditus Zone/Buchia *piochii* Zone) of the Gorodishche section on the River Volga and in the uppermost Volgian shale of the Bazhenovo Formation in Western Siberia (Vishnevskaya and Murchey, 2002; Vishnevskaya and Kozlova, 2012).

According to Baraboshkin et al. (2015) the base of the Upper Volgian (uppermost Tithonian-Lower Berriasian) in the Russian Platform should be defined by the appearance of the genus *Kachpurites*. Thus, the first appearance of species of the endemic family Echinocampidae Bragin is fixed at the *Craspedites* subditus Zone of the Gorodishche section (Vishnevskaya and Baraboshkin, 2001). The Tithonian/Berriasian boundary falls somewhere in M19n, perhaps in the local Taimyrensis ammonite Zone (Schnabl et al., 2015), where radiolarians were described below and above in the Nordvik section (Bragin, 2011) and thus, in terms of international stages, part of the "Upper Volgian" is Tithonian and part is Berriasian (Wimbledon et al., 2011, 2013).

Episodes of significant decrease in taxonomic diversity of radiolarians and ammonites in the Late Jurassic within boreal regions were synchronous in both groups (Mitta and Vishnevskaya, 2006). The Late Volgian crisis coincided with significant changes in the morphotypes of ammonite and radiolarian skeletons. A typical Lilliput effect of the latest Middle Volgian boreal ammonite faunas was described by Rogov (2015). The specimens of the latest Middle Volgian/Late Volgian cyrtoidal Nassellaria (*Parvicingula*, *Spinicingula*) also have lilliput size, small reticular pores, weak distinct ridges or almost no external circumferential ridges. Also, the decrease in the number of chambers was fixed among the Nassellaria in Late Volgian representatives of the genera *Parvicingula*, *Spinicingula* and *Stichocapsa*. Some extinction of radiolarians began at the end of the Jurassic and most likely resulted from a marine regression and climatic cooling. This is supported by the predominance of cold-water representatives of the genus *Parvicingula* in radiolarian associations and of the boreal ammonite family *Craspeditidae* at that time in the Middle Russian, Timan-Pechora and West Siberian Seas (Mitta and Vishnevskaya, 2006; Vishnevskaya and Kozlova, 2012). The rapid evolution of *Radiolaria* and a bloom of morphological diversity of *Parvicingula* with the development of numerous abnormal skeletons may have been caused by stress conditions, as was proposed for the "Lilliput effect" in ammonites Rogov (2015). Probably, only the more accommodated, often-primitive, vulgar forms of *Parvicingula* and *Stichocapsa* survived to give rise to new trends (*Spinicingula* and others) and provide evolutionary progress.

The change of the Jurassic *Parvicingula*-rich assemblage into *Echinocampe*, *Nordvikella* and *Spinicingula*-rich assemblages is observed at the Jurassic-Cretaceous boundary. Just

at the Jurassic-Cretaceous boundary (base of the Berriasian), the occurrence of *Thanarla*, *Mita*, *Dictyomitra*, *Neorelumbra*, *Quasicrolanium-Pyramotertonium* groups has been recorded among radiolarians.

The degree of endemism in high conical Parvicingulidae Pessagno and Echinocampidae Bragin is related to a great abundance of morphotypes with external cephalic spines and apophyses (Vishnevskaya and Kozlova, 2012) at the Jurassic-Cretaceous boundary in boreal regions.

As radiolarians are so common as to be rock formers in the Bazhenovo shale, and other fauna is practically absent, biostratigraphic subdivision is possible only using radiolarians. Because all radiolarian assemblages, used before in the regional scheme of Western Siberia, have been described on the basis of thin section study only, local zonal indices were recognized as not valid (O'Dogherty et al., 2009), and there is a need for the application of a new technique. Application of the tomography method has allowed the recognition of 5 stratigraphic divisions, named as radiolarian biohorizons. All biohorizons are founded on evolutionary changes in the genus *Parvicingula*.

The lower biohorizon in the Abalak suite (of Siberia) with *Parvicingula elegans* is Kimmeridgian. The biohorizon of *Parvicingula blowi* (Lower Tithonian) is established in a siliceous and carbonate interval at the bottom of the Bazhenovo shale with rare *Dorsoplanites ilovaiskii* Mesezhnikov (Panchenko et al., 2016). Top: last occurrence of *Zhamoidellum ovum* Dumitrica in the Lower Tithonian (Fig. 9) and *Parvicingula blowi* as corporeal taxa in the Lower Tithonian (Vennari and Pujana, 2017).

The biohorizon of *Parvicingula jonesi* (Middle Tithonian) is established in clays and siliceous radiolarites with rare *Laugeites groenlandicus* Spath and *Epilaugeites cf. vogulicus* (Ilovaisky). Bottom: first appearance of *Parvicingula jonesi* Pessagno, *P. excelsa* Pessagno and Blome. Top: last occurrence of *Praeparvicingula gracila* Hull in the Middle Tithonian.

The *Parvicingula haeckeli* biohorizon (Upper Tithonian) lies in the Bazhenovo shale in carbonate and siliceous radiolarites with *Praechetaites exoticus* (Schulgina, 1967) (Panchenko et al., 2016). Bottom: first appearance of *Parvicingula haeckeli* (Pantanelli), *P. rothwelli* Pessagno. Top: last occurrence of *Parvicingula blomei* Yang, *P. colemani* Pessagno et Blome in the Tithonian.

The *Parvicingula khabakovi* biohorizon (Lower Berriasian) with Echinocampidae are identified at the limestone and clay chert level in the Bazhenovo shale with *Craspedites taimyrensis* (Bodyl.), *Chetaites chetae* Schulgina (Panchenko et al., 2015, 2016). Bottom: first appearance of *Parvicingula khabakovi* (Zhamoida), *Arctocapsula incompta* Bragin, *A. perforata* Bragin, *Echinocampe? aculeatum* Bragin, *Pyramotertonium planocephalum* (Kozlova).

The *Williriedellum salymicum* biohorizon (Upper Berriasian-Valanginian) with *Williriedellum*, Echinocampidae are identified at the highest level in the Bazhenovo shale with *Buchia okensis* (Pavlov) and *B. volgensis* (Lahusen) (Panchenko et al., 2015, 2016).

The radiolarian biohorizons may be considered as biozones (Vishnevskaya, 2013, 2016). Bottom: first appearance of *Tricolocapsa campana* Kiessling, *Williriedellum salymicum salymicum* Kozlova. Top: last occurrence of *Parvicingula khabakovi* (Zhamoida). The *Williriedellum* species amount to 70% within this biohorizon.

The decrease in diversity of the Parvicingulidae at about the Jurassic-Cretaceous boundary, as well as the bloom of the Williriedellidae, with their hyper-thick skeletal wall and submerged cephalothorax, coincides with and probably reflect environmental or hydrological stress.



| Stage | Substage | Ammonite zones (Zakharov et al., 1997) | Bichias zones (Zakharov et al., 1997) | Beds | Lithology | Thickness, m | 8 | Thickness |
|-------------|----------|--|---------------------------------------|------|-----------|--------------|---|-----------|
| Valanginian | Lower | Klimovskiensis | Buchia inflata | XVII | | 17.5 | 8 | > 4.2 m |
| | | | | XVI | | 17.4 | | |
| Berriasian | | Tollia tolli | Buchia toimatschow | XV | | 10.7 | 8 | 15.0 |
| | | | | XIV | | 7.8 | | |
| | | | | XIII | | 4.7 | | |
| | | | | XII | | 2.7 | | |
| | | | | XI | | 3.6 | | |
| | | | | X | | 3.4 | | |
| Volgian | Upper | Chetae | Buchia unshensis | IX | | 4.0 | 8 | |
| | | | | VIII | | 1.2 | | |
| | | | | | | | | |

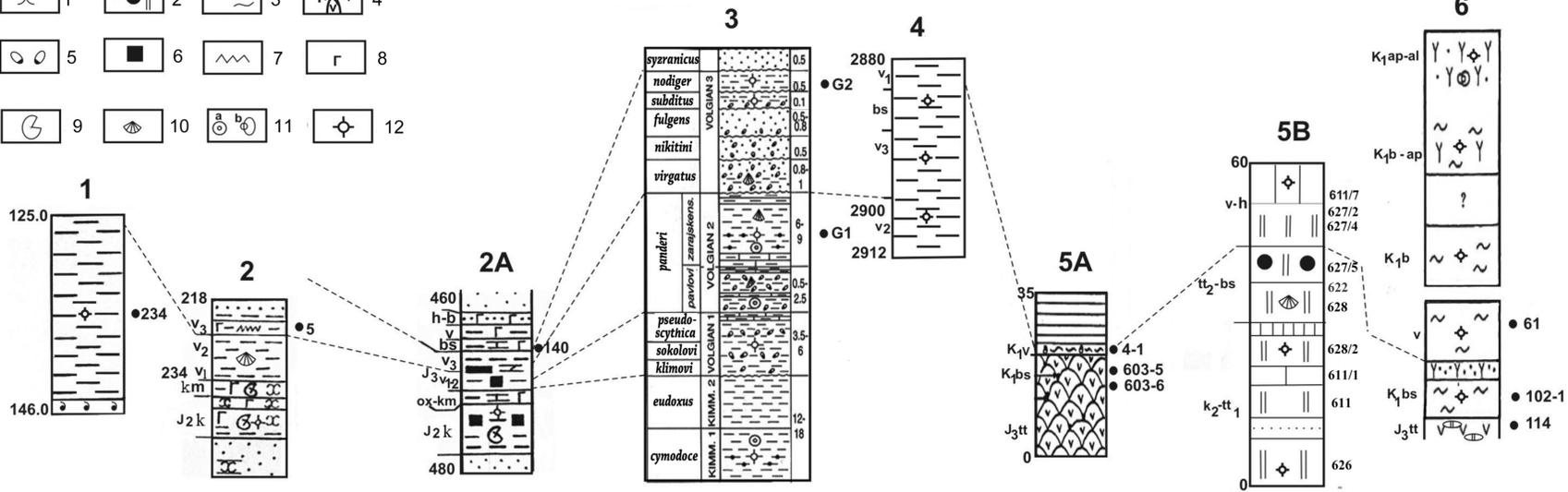
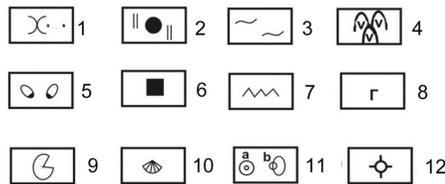


Fig. 7. Correlation of Upper Jurassic and Cretaceous sequences from the Barents-Pechora region to Sakhalin in the far east of the Pacific Margin

Localities: 1 – Mezen Basin, Pesh section; 2 – southeastern Barents-Pechora Basin (2 – Narjan-Mar, borehole 5; 2A – Kolguev, borehole 140); 3 – Volga-Pre-Ural Basin (3 – Gorodishche section, Uljanovsk region); 4 – northern and Western Siberian basins (4 – Upper Salym, borehole 17); 5 – western Kamchatka and Chukotka (5A – Omgon; 5B – Semiglawaya Mountains); 6 – Sakhalin; 7 – Nordvik (after [Bragin, 2011](#); [Marinov, 2014](#)); 8 – Lena Delta (after [Vishnevskaya et al., 2014](#)). Abbreviations for Jurassic: k – Callovian; km – Kimmeridgian; ox – Oxfordian; tt – Tithonian; v – Volgian regional stage. Abbreviations for Cretaceous: al – Albian; ap – Aptian; b – Barremian; bs – Berriasian; h – Hauterivian; v – Valanginian. Age and depths indicate at the left and samples numbers at the right of the column; 1–5, 7, 8 – radiolaria-bearing Boreal sequences with predominance of *Parvicingula*; 6 – Tethyan affinity with *Ristola*. Legend: 1 – sand and sandstone, 2 – chert and chert concretion, 3 – jasper, 4 – basalt, 5 – phosphatic pebbles, 6 – pyrite, 7 – trace of fossil, 8 – organic detritus, 9 – ammonite, 10 – Bichias, 11 – foraminifera: a – benthic, b – planktonic, 12 – radiolarians. For other explanations see [Figure 9](#)

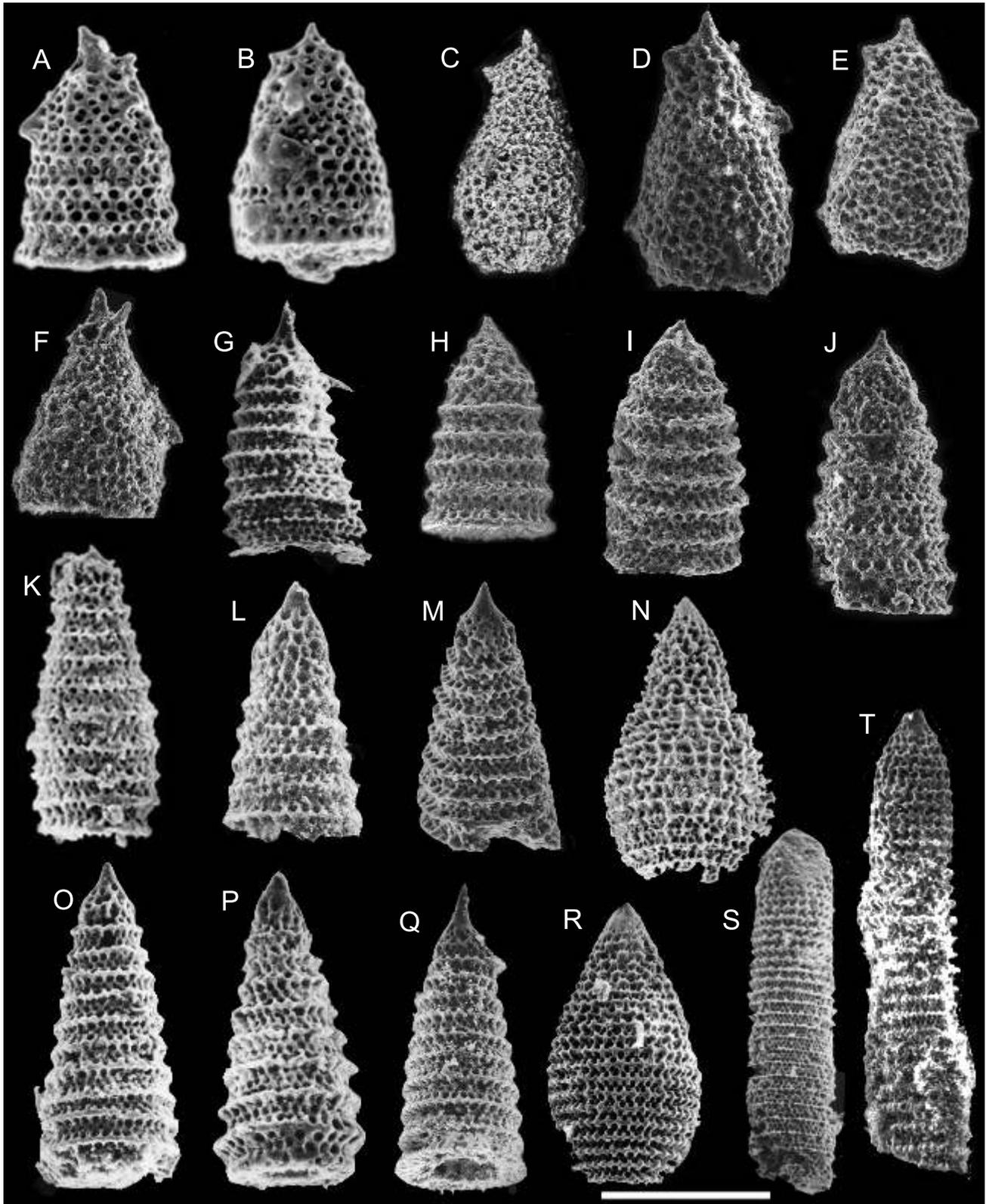


Fig. 8. Scanning electron photomicrographs of Late Jurassic to Early Cretaceous radiolarians from siliceous clay rocks (A, B, K, M – Barents Sea region, C–F, H–J – Lena Delta), tuffaceous jaspers (G, L, N–T – Bering Sea region) in northern Russia

A, B – *Spinicingula ceratina* Kozlova and Vishnevskaya, Narjan-Mar, borehole 5, Upper Volgian; C – *Arctocapsula incompta* Bragin; D, E – *A. devorata arctica* (Vishnevskaya et Murchey); F – *Echinocampe* aff. *aculeatum* Bragin; G – *Parvicungula* aff. *projecta* Kiessling; H – *P. papulata* Kozlova et Vishnevskaya; I – *P. alata* Kozlova et Vishnevskaya; J – *Praeparvicungula rotunda* Hull; K – *P. jonesi* Pessagno, L – *P. gemmata* Hull; M – *P. rothwelli* Pessagno; N – *Mirifusus guadalupensis* Pessagno; O–Q – *P. colemani* Pessagno et Blome; R – *Mirifusus mediodilatatus* (Rüst); S, T – *Ristola altissima* (Rüst). Scale bar 100 μ m. A, B – Narjan-Mar, borehole 5, Upper Volgian; C–F, H–J – locality Lena Delta, Berriasian; G – Koryak Mountains, Nauchiranay, Tithonian; K, M – Mezen Basin, Pesha River section, borehole 234, Middle Volgian; L, N–T – Koryak Mountains, Nauchiranay, Tithonian

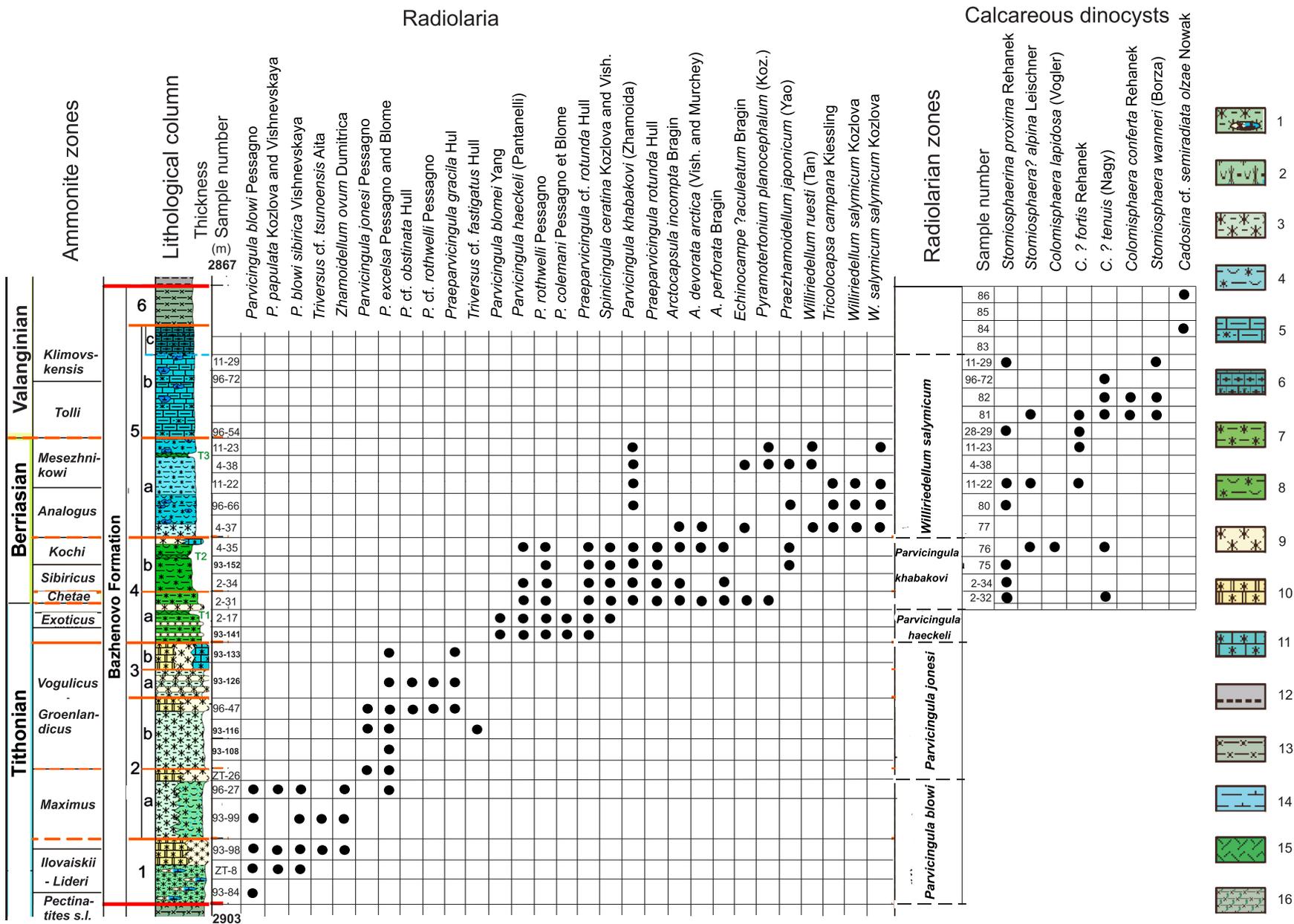


Fig. 9. Range chart of radiolarians and calcareous dinoflagellate cysts in the Bazhenovo Formation of Western Siberia

1 – bituminous clay with radiolarite lens, 2 – clay with calcareous detritus, 3 – bituminous clay, 4 – bituminous clayey limestone with bivalves, 5 – clayey limestone, 6 – clayey limestone with pyrite, 7 – high bituminous clay, 8 – bituminous clay with bivalves, 9 – radiolarite, 10 – radiolarite partly replaced by dolomite, 11 – radiolarite partly replaced by calcite, 12 – clay, 13 – siliceous clay, 14 – marl, 15 – tuff, tuffite, 16 – siliceous clay with glauconite, T1, T2, T3 – tuffic horizons

Thus, an abundance of *Parvicingula* within the oil shale sequences of the Arctic Margin (Dyer and Copestake, 1989; Vishnevskaya and Kozlova, 2012; Vishnevskaya et al., 2014; Vishnevskaya, 2016) provides a basis for establishing a preliminary boreal zonation at the Tithonian-Berriasian boundary: that is, the *P. haeckeli* (Tithonian), and *Parvicingula khabakovi* (Lower Berriasian) Zones.

CALCAREOUS DINOFLAGELLATES AS POSSIBLE SECONDARY MARKERS

Zonal schemes using calcareous dinoflagellate cyst have been widely proposed in the Tethys realm (Balkans, Carpathians, Spain, Indian Ocean) within an Upper Jurassic (from Oxfordian) to Lower Cretaceous (up to Albian) interval (Reháková, 2000; Michalík and Reháková, 2011) and applied to other regions (Lakova et al., 1999; Petrova et al., 2012).

Calcareous dinoflagellate cysts (before named as “calci-sphaerulides”) are common (Figs. 9–13) in the above-described *Parvicingula khabakovi* biohorizon (Berriasian) and *Williriedellum salymicum* biohorizon (Upper Berriasian-Valanginian) of the Bazhenovo Formation. They co-occur together with *Williriedellum*, Echinocampidae, where rare finds of nannoplankton have also been recorded. The abundant representatives of *Pithonella* occur in the limestone and shale of Berriasian age (Figs. 10 and 11). *Pithonella* cf. *ovalis* (Kaufmann) and *Stomiosphaerina proxima* Rehánek (Fig. 12) have been observed in the *Parvicingula khabakovi* biohorizon (Berriasian).

Probably, it will be possible to recognize calcareous dinocyst zones of *Colomisphaera tenuis* and *C. fortis* in the Upper Tithonian and *Stomiosphaerina proxima* and *Stomiosphaera wanneri* in the Berriasian, as well as *Colomisphaera conferta* in the Valanginian of the Bazhenovo Formation (Fig. 13) with progress in new investigations of calcareous dinoflagellate cysts. The comparison with Jurassic to Cretaceous boundary sequences of the European part of Russia indicates some biohorizons in the Gorodishche section of the Volga-Pre-Ural Basin (Vishnevskaya and Baraboshkin, 2001). The Jurassic to Cretaceous boundary sequences of central Europe (e.g., the

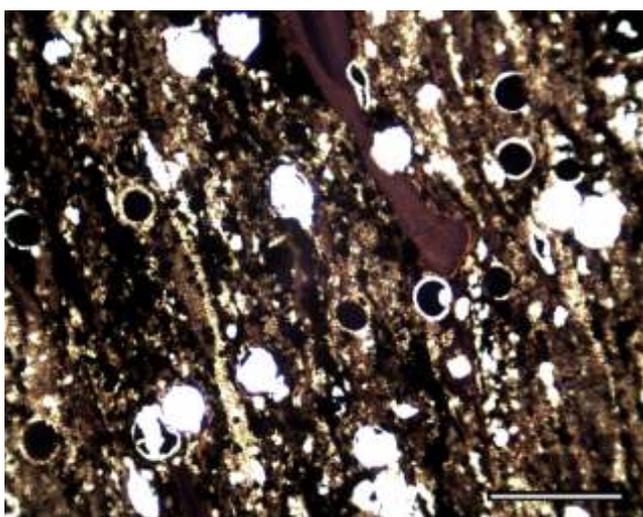


Fig. 10. Calcareous dinoflagellate cysts of the *Williriedellum salymicum* biohorizon of the Bazhenovo Formation together with Williriedellidae; sample 11-29, Western Siberia, Berriasian-Valanginian; scale bar 100 μ m

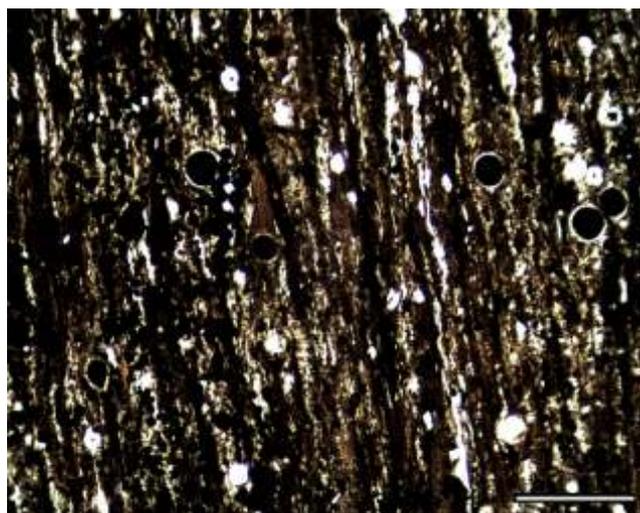


Fig. 11. Calcareous dinoflagellate cysts in *Williriedellum salymicum* biohorizon of the Bazhenovo Formation; sample 11-23, Western Siberia, Berriasian; scale bar 100 μ m

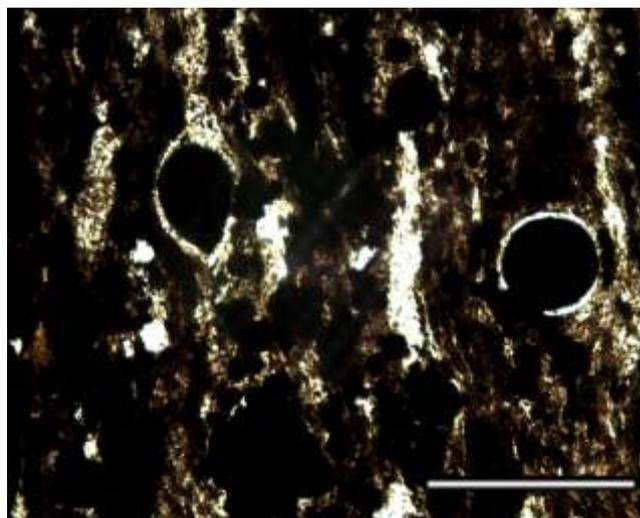


Fig. 12. Calcareous dinoflagellate cysts *Pithonella* cf. *ovalis* (Kaufmann) (left side) and *Stomiosphaerina proxima* Rehánek (right side) in *Williriedellum salymicum* biohorizon of the Bazhenovo Formation; sample 11-22, Western Siberia, Berriasian; scale bar 100 μ m

Strapkova section; Michalík et al., 2016) are also characterized by a change from limestone containing radiolarians belonging to the Parvicingulidae into limestone with pithonellids and radiolarians of the Williriedellidae (Vishnevskaya, 2016).

CONCLUSIONS

Due to radiolarian provincialism the correlation of radiolarian biozones between boreal (northern Eurasia and America) and Tethyan regions (southern Europe: Baumgartner et al., 1995; Hardenbol et al., 1998) is hampered in the Late Jurassic-Early Cretaceous interval. Nevertheless, it is possible to use the Pacific zonation (where the boreal *Parvicingula* occurs to-

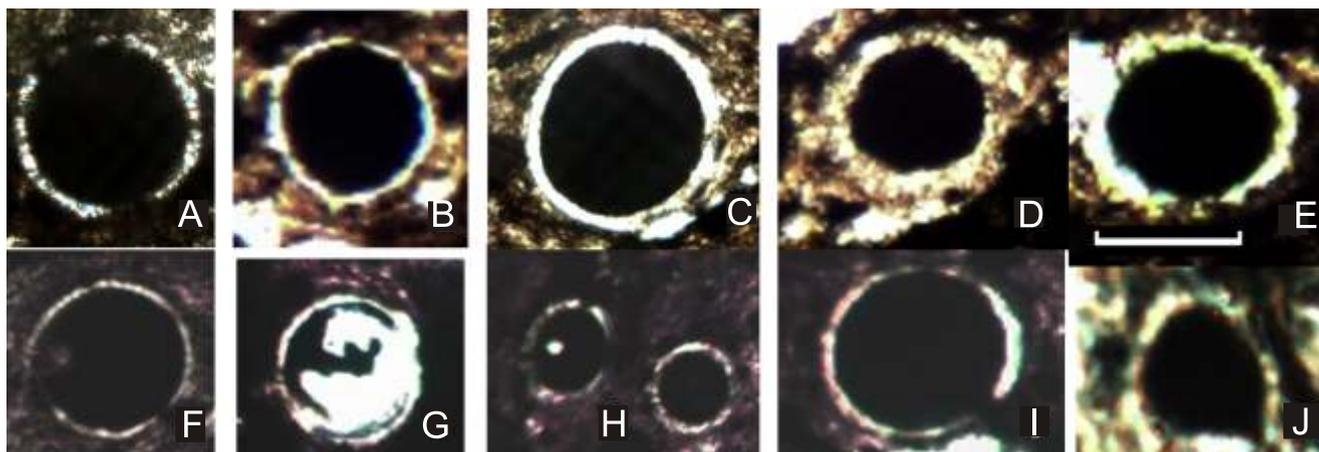


Fig. 13. Calcareous dinoflagellate cysts

A, B – *Stomiosphaerina* cf. *proxima* Rehánek (A – sample ZU-308-30, Western Siberia, Berriasian-Valanginian; B – sample 96-72, Western Siberia, Berriasian-Valanginian); **C** – *Colomisphaera* ?*fortis* Rehanek, sample 11-23, Western Siberia, Berriasian; **D** – *Stomiosphaera wanneri* (Borza), sample 11-29, Western Siberia, Berriasian-Valanginian; **E** – *Colomisphaera* ?*tenuis* (Nagy), sample 2-32-2, western Siberia, Berriasian; **F, G** – *Stomiosphaera*? *alpina* Leischner (F – sample 76, Western Siberia, Berriasian; G – sample 81, Western Siberia, Berriasian-Valanginian); **H, I** – *Colomisphaera conferta* Rehanek, sample 81, Western Siberia, Berriasian-Valanginian; **J** – *Calpionella*? sp., sample 2-32-2, Western Siberia, Berriasian; scale bar 30 μ m

gether with the Tethyan genera *Mirifusus* and *Ristola*) as the link to correlate Tethyan and boreal scales.

The high-conical representatives of the families Parvicin- gulidae and Echinocapsidae have key stratigraphic significance at the Jurassic-Cretaceous boundary. The appearance of a group of high-conical parvicin- gulids at the Triassic-Jurassic boundary in high latitudes of the Northern Hemisphere was most likely due to global cooling. In the course of the Jurassic to the beginning of the Early Cretaceous, this group evolved, spreading across the high latitudes of the entire Pacific palaeo- geographic province, and even penetrating into the Arctic and Antarctic regions.

We prove the ubiquitous presence of the Jurassic-Early Cretaceous radiolarian genus *Parvicingula* in the Bazhenovo, Pechora and the Russian seas, which supports the existence of the northern pathway, bringing a large number of members of this genus from the Pacific palaeoclimatic province into the Arctic and the North Atlantic and South Boreal up to Gorodishche section of the Volga-Pre-Ural Basin.

The abundant presence of *Parvicingula* within the oil shale sequences of the Russian Arctic margin and the application of tomographic methods provides a basis for establishing a preliminary boreal zonation: *Parvicingula elegans* (Lower Kimme- ridgian), *P. blowi* (Lower Tithonian), *P. jonesi* (Middle Titho- nian), *P. haeckeli* (Upper Tithonian), *P. khabakovi* (Berriasian) and *Williriedellum salymicum* biohorizon (Upper Berriasian- Valanginian) zones.

The radiolarian events at the Jurassic-Cretaceous bound- ary in the Russian boreal region can be used as an additional biomarker to help develop new integrated boundary criteria. In addition, sections through the Bazhenovo Formation are often characterized by a range of calcareous dinocysts previously re- peatedly recorded as “calcisphaerulides”. According to the Tethyan calcareous dinocyst zonal scheme (Reháková, 2000), in which the first occurrence of the zonal species *Stomio- sphaerina proxima* coincides with the first appearance of *Calpionella alpina*, it is logical to propose calcareous dinocysts as a secondary marker.

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