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Upper Jurassic Volgian Stage and Lower Cretaceous Ryazanian Stage of the Panboreal Biogeographic Superrealm

M. A. Rogov[a], *, V. A. Zakharov[a], E. B. Pestchevitskaya[b], V. S. Vishenvskaya[a], N. G. Zverkov[a], and E. Yu. Baraboshkin[a, c]

[a] *Geological Institute, Russian Academy of Sciences, Moscow, 119017 Russia*

[b] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*

[c] *Moscow State University, Moscow, 119991 Russia*

**e-mail: rogov@ginras.ru*

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Abstract—The history of study of the Upper Jurassic Volgian Stage and Lower Cretaceous Ryazanian Stage, their geographic occurrence, and use in world practice, subdivision, and correlation are considered. The data on the occurrence of various groups of macro- and microfossils (ammonites, bivalves, radiolarians, dinocysts, and marine vertebrates) in the Volgian and Ryazanian are reviewed. In spite of significantly different lifestyle of all these groups, the Volgian and Ryazanian assemblages are highly similar in the entire Panboreal Superrealm, on one hand, and significantly different from coeval Tethyan fauna, on the other hand. The biostratigraphic scales of these stages based on successions of ammonites, bivalves, radiolarians, and dinocysts are analyzed. It is shown that the substage boundaries of the Volgian are reliably traced along the entire Panboreal Superrealm. None of the boundaries, except for the base of the Volgian, corresponds even to a zonal boundary of the Tethys–Pantalassa Superrealm. A similar situation is also observed in the Ryazanian: its lower boundary, as well as the Lower–Upper Ryazanian boundary, does not coincide with any well-traced boundary in the Tethys–Pantalassa Superrealm. The necessity of using the Volgian and Ryazanian in geological studies is substantiated for all Russian regions with abundant Boreal deposits, as well as inclusion of these stages to the General Stratigraphic Scale in parallel with the Tithonian and Berriasian. We suggest the cancellation of the Decree of the Interdepartmental Stratigraphic Committee of Russia about the transition of the Volgian into regional stratigraphic subdivisions, as well as the reconsideration of the correlation scheme of the Volgian and Ryazanian accepted in the same decree.

Keywords: biostratigraphy, Upper Jurassic, Lower Cretaceous, stage, mollusks, dinocysts, radiolarians, marine reptiles

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INTRODUCTION

The Volgian and Ryazanian stages are the only stages of the Jurassic and Cretaceous whose type locality occurs at the territory of the Russian Federation. Over a long period, the Volgian had been part of the General Stratigraphic Scale (GSS) ubiquitously applied at the territory of the Soviet Union and Russia for the subdivision of Boreal deposits. It lasted until 1996, when the Interdepartmental Stratigraphic Committee (ISC) of Russia issued a decree (Zhamoida and Prozorovskaya, 1997) according to which the Volgian was converted to a regional stratigraphic subdivision, whereas the Upper Volgian Substage was equated to the lower Berriasian. Although Mitta (2011, 2004) and Zakharov (2003) just after showed the controversy of this comparison and failure of the ISC decision, as well as the fallacy of this correlation based on paleomagnetic data (Houša et al., 2007; Bragin et al., 2013; Schnabl et al., 2015), the employees of industrial organizations (first of all, prospecting geologists) must be guided by the ISC Decree and use the names "Tithonian Stage" and "Berriasian Stage" in study of the Jurassic–Cretaceous boundary deposits. The ambiguities of the comparison of the Volgian with its Tethyan equivalents and uncertain position of the Tithonian–Berriasian boundary of the International Chronostratigraphic Chart (ICC) lead to permanent confusion and errors, which have been hampering the work of researchers for more than 35 years, including the composing the State Geological Map on scales of 1 : 1000000 and 1 : 200000.

The Ryazanian as the lower stage of the Cretaceous was proposed at the beginning of the 1950s, but it was not accepted as the GSS stage until now in spite of regular use in scientific publications. At the same time, the Volgian and Ryazanian are widely being used for more than 50 years in study of Boreal deposits of Arctic

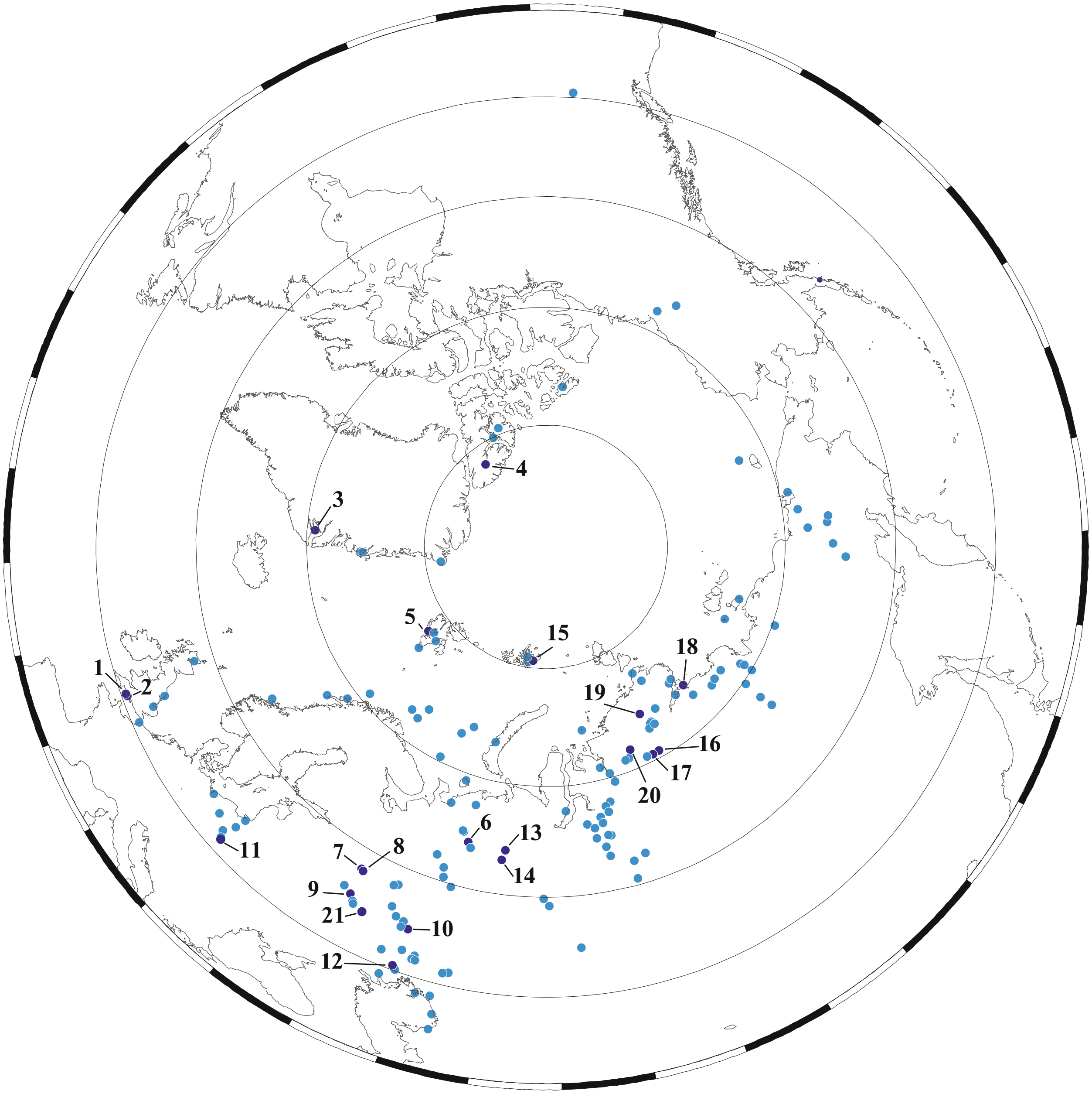


Fig. 1. Key and reference Volgian sections. Numbers show the sections important for the elaboration of zonal scales of various regions. 1, Portland Peninsula (stratotype of the Portlandian Stage); 2, Kimmeridge Bay (stratotype of the Kimmeridgian Stage); 3, Milne Land; 4, Rollrock, Ellesmere Island; 5, Festningen Cape, Spitsbergen; 6, Izhma River; 7, Glebovo; 8, Vasil'evskoe; 9, quarries of the Lopatino phosphorite mine (an additional section of the Middle and Upper Volgian substages); 10, Gorodishchi (lectostratotype of the Volgian Stage); 11, Owadów-Brzezinki; 12, Berdyanka (an additional section of the Lower Volgian substage); 13, Yatriya River; 14, Mauryn'ya River; 15, Lamon Cape, Wilczek Land; 16, Levaya Boyarka River; 17, Kheta River; 18, Urdyuk-Khaya Cape, Nordvik Peninsula; 19, Dyabyaka-Tari River; 20, Novoyakomovskaya 1 borehole; 21, Nikitino–Shatrishchi (reference sections of the Ryazanian Stage of type region).

Canada, East and North Greenland, Spitsbergen, and shelf of North, Norwegian, and Barents seas (Fig. 1).

In this work, we substantiate the necessary comeback of the Volgian to the GSS of Russia and suggest its use in study of the Boreal deposits in both our country and abroad. The Ryazanian is recommended for use as the lower stage of the Cretaceous of the Boreal basins and also for inclusion in the GSS of Russia.

HISTORY OF STUDY OF THE VOLGIAN AND RYAZANIAN STAGES

A peculiarity of marine fauna of the end of the Jurassic and the beginning of the Cretaceous and the high degree of biogeographic differentiation of mollusks, which were the basis for the subdivision and correlations of these deposits, led to the fact that three stages were suggested as the upper stage of the Jurassic for various regions: Portlandian (d'Orbigny, 1842–1850; Northwest France and England are a type area), Tithonian (Oppel, 1865; no type area is indicated; the stage is suggested for Southern Europe), and Volgian (Nikitin, 1881; the Upper Volga region is a type area; now is Yaroslavl region). The peculiarities of fauna of the terminal Jurassic of the European part of Russia was established earlier, when C. Rouillier (Rouillier, 1845; Rouillier and Frears, 1845) suggested "the stage with Ammonites virgatus" and "the stage with Ammonites catenulatus," which correspond to the middle and upper Volgian substages in current understanding, for the vicinity of Moscow. In 1884, S.N. Nikitin subdivided the Volgian into the Lower and Upper Volgian stages, but he simultaneously used all these subdivisions in the same publications for some time (Nikitin, 1884, 1885, 1888): Volgian, Lower Volgian, and Upper Volgian stages. First, he suggested that the Volgian terminates the Jurassic. Later, mainly because of the erroneous correlation of the Ryazanian Horizon with Volgian deposits, he came to consider the Volgian stages to be the Jurassic–Cretaceous boundary units marking them as JCra and JCrb (Nikitin, 1887, 1888). In contrast to S.N. Nikitin, who noted that the Volgian is difficult to compare with West European stratigraphic subdivisions, his contemporary and opponent in many questions A.P. Pavlow argued his point, according to which the stages previously identified in England (Kimmeridgian and overlying Portlandian) could be traced in the European part of Russia. For the "Upper Portlandian," which is approximately equivalent to the Upper Volgian Stage of S.N. Nikitin (in his expanded understanding together with the Ryazanian Horizon), A.P. Pavlow suggested the presence of the Aquilonian Stage (or Substage). First, an interval from the Upper Volgian Substage to the lower part of the Valanginian was referred to as the Aquilonian Substage (Pavlow and Lamplugh, 1892). Further, A.P. Pavlow considered the Aquilonian as a stage which is equivalent to the upper Tithonian and Purbeckian and left there only analogs of the Upper Volgian Substage and the lower parts of the Ryazanian in the modern range (Pavlow, 1895, 1896). At the end of the 19th and the first half of the 20th century, the Volgian stages, Portlandian, and Aquilonian were used for the Boreal deposits approximately equally.

At the beginning of the 20th century, D.N. Sokolov established a new stratigraphic interval transitional from the Kimmeridgian to the Lower Volgian based on the study of material from the Orenburg Jurassic. He wrote the following (Sokolov, 1901, p. 56): "Fauna found by me in the Vetlyanian sandstone confirms the presence of a horizon ..., which is a transition from the Kimmeridgian to the Lower Volgian. If this horizon requires a specific name, I suggest the Vetlyanian Horizon." Soon the "Vetlyanian Horizon" became widely used for the interval above the Kimmeridgian, but below the Volgian also in the Volga region (Zonov, 1937, 1939). At this time, one used the zonal scale of the "Vetlyanian Horizon" which was elaborated by D.I. Ilovaisky at the beginning of the 1930s, but which was fully published only six years after his death (Ilovaisky and Florensky, 1941). D.I. Ilovaisky also suggested that the "Vetlyanian Horizon" should be raised to the "Vetlyanian Stage," which was supported by Sazonov (1953, 1956). At the same time, Bodylevsky (1956) suggested that these deposits should be ascribed to the Volgian, and the "Vetlyanian Horizon" was included in the Lower Volgian Stage in the decision of the All-Union Meeting on Elaboration of a Unified Correlation Scheme of the Mesozoic Deposits of the Russian Platform (*Resheniya...*, 1955).

Beginning in the 1960s, the Volgian became widely used for study of high-latitude sections of the Northern Hemisphere (Różycki, 1959; Frebold, 1961; Donovan, 1964; Jeletzky, 1965; Parker, 1967). Moreover, two significant events related to the acknowledgment of the international status of the Volgian occurred in 1963. The Mediterranean Mesozoic Committee recommended the Volgian as a single stage of the International Chronostratigraphic Chart (ICC) and encouraged everybody to avoid using the Tithonian (Sazonov, 1964), whereas the British Mesozoic Committee recommended the Volgian as the upper stage of the Jurassic System during the discussion on the range and boundaries of the Kimmeridgian (Ager, 1964). By that time, some foreign researchers already mentioned a single Volgian in correlation schemes (Enay, 1963). The resolution on the Jurassic nomenclature approved by the Mediterranean Mesozoic Committee was considered at an expanded meeting of the Bureau of the Commission on Jurassic System of the ISC on October 28–29, 1964. A unanimous decision was adopted at the meeting for the reasonable consideration of the deposits previously distinguished as the Lower Volgian and Upper Volgian stages as a single Volgian Stage (Krymgolts, 1966; The resolution..., 1966). A section located at the right bank of the Volga River 1 km south of the settlement of Gorodishchi was suggested as a lectostratotype of the Volgian at this meeting, as well as an outcrop in the Berdyanka River as an additional section. The soon published paper of Gerasimov and Mikhailov (1966) characterized the Volgian as a subdivision of the GSC and described the lectostratotype and additional sections except for the section at the Berdyanka River (the section of the Lopatino phosphorite mine was described as an additional section for the middle and upper substages). The recommendations of the International Symposium on the Upper Jurassic Stratigraphic hold in Moscow in June 1967 included the following: "... it is reasonable to keep two stages: the Tithonian and Volgian for the Mediterranean and Boreal realms, respectively" (*Rekomendatsii...*, 1974, p. 150), which matched the Decision of the Plenary Session of the Regular Stratigraphic Commission of the ISC on the USSR Jurassic concerning the question on the recommendations of the First International Colloquium on the Jurassic System

(February 21, 1963; Krymgolts, 1965). It was considered that the range of the Volgian corresponds to that of the Tithonian; therefore, the Soviet researchers recognized the Berriasian at the base of the Cretaceous, whereas the Ryazanian proposed by Sazonov (1953) was mainly used abroad over a long period of time.

At the same time, more arguments in favor of the inconsistency between the Volgian and Tithonian stages have appeared since the 1970s. A large part of the evidence, as a rule, was based on the traditional comparison of the uppermost zone of the Berriasian Boissieri Zone with the Ryazanian Horizon, on one hand, and the analysis of Pacific fauna, where the Boreal *Buchia* occur together with Tethyan ammonites, on the other hand. This correlation, to a lesser extent, relied on data on the Berriasian of the North Caucasus, Tithonian of Austria and South Germany, and Volgian deposits of Poland. Although these arguments were indirect or based on debatable determinations and the analysis of the same findings locally led various researchers to significantly different scenarios of the Boreal–Tethyan correlation (Jeletzky, 1984; Zeiss, 1984), the viewpoint according to which the Middle–Upper Volgian boundary corresponds to the Tithonian–Berriasian boundary and the Lower–Middle Volgian boundary is correlated with the middle–upper Tithonian boundary (Zeiss, 1977) gradually attracted more followers, including in Russia. The most complete arguments of this correlation scenario were formulated by I.I. Sei and E.D. Kalacheva. These arguments were first published as a preprint (Sei and Kalacheva, 1993) and later as a paper (Sei and Kalacheva, 1997; the manuscript was submitted to the journal in the middle of 1994). At the beginning of 1995, the Jurassic–Cretaceous boundary of the Boreal Realm was a matter of debate at the session of the Bureau of the Commissions on Jurassic and Cretaceous systems and was brought for the consideration of the expanded Bureau of the ISC. Most members of the Commissions on Jurassic and Cretaceous systems voted for the suggested movement of the Jurassic–Cretaceous boundary to the base of the Upper Volgian and for the change in the status of the Volgian to a regional stage, which was finally enshrined in a decree accepted at the expanded session of the Bureau of the ISC on February 2, 1996 (Zhamoida and Prozorovskaya, 1997). The Volgian became regional and was excluded from the GSS, which retained only the Tithonian and Berriasian, whereas the Upper Volgian was equated in the volume to the lower Berriasian. This information was operatively reported to the Subcommission on Jurassic Stratigraphy (Rostovtsev and Prozorowsky, 1997). Henceforth, the application of the Tithonian and Berriasian during geological survey became obligatory and this hasty decision directly led to confusion. In some cases, because the Volgian and Berriasian were previously mapped in contrast to the currently adopted Tithonian and Berriasian, the entire Volgian in a full range continued to ascribe to the "Tithonian" (*Gosudarstvennaya*..., 2000; Burguto et al., 2016; Shkarubo et al., 2017). In other cases (often on adjacent sheets of the State Geological Map), the "Tithonian" and "Berriasian" were recognized according to the Decree of the ISC (*Gosudarstvennaya*..., 2008) or the Volgian and Berriasian were applied (*Gosudarstvennaya*..., 2006; Proskurnin et al., 2015, 2016). It is obvious that this confusion affected the papers. For example, it was often unclear during the discussion of the Bazhenovo Formation of Western Siberia what is "Tithonian" and "Berriasian" to the authors (Stafeev et al., 2017). Although until the very last time the Berriasian was subdivided into three substages, it became two-member in the Boreal sections of Russia. The "lower Berriasian" included the Upper Volgian, whereas the overlying deposits to the base of the Valanginian were considered the "upper Berriasian," which did not make it clear in understanding these subdivisions and their interrelations with the Berriasian substages of the Tethys–Pantalassa Superrealm.[1]

The Decree of the ISC, which actually removed the Volgian, was strongly criticized by specialists in Boreal deposits (Mitta, 2001, 2004; Zakharov, 2003), who considered the rejection of the Volgian erroneous. This was supported by new biostratigraphic data on ammonites, according to which the correlation of the Lower Volgian and the lower part of the Middle Volgian substages with the Tithonian and the Ryazanian with the upper Berriasian accepted by the ISC was incorrect (Rogov, 2002, 2004; Mitta, 2005).

The study of the Jurassic–Cretaceous boundary deposits in the section on Nordvik Peninsula (Northern Siberia) soon yielded convincing paleomagnetic data, according to which the most part of the Upper Volgian is compared with the upper part of the Tithonian and only the uppermost part of the substage must be correlated with the lower Berriasian (Houša et al., 2007). This section was further independently studied by another group of researchers, who confirmed the position of the Jurassic–Cretaceous boundary in this section from paleomagnetic data (Bragin et al., 2013). Already in 2012, the ISC commissions on the Jurassic and Cretaceous systems jointly decided to include the Volgian and Ryazanian to the GSS in parallel with the Tithonian and Berriasian (The protocol..., 2013). The question of repealing the ISC Decree was further discussed at the session of the Commission on Cretaceous System (2018) and was brought to the Bureau of the ISC (2019); however, an idea about the cancellation of the ISC Decree was not supported by the members of the Bureau. In 2019, the Commission on Cretaceous System proceeded to an online vote on the following questions: (1) fixation of the Volgian/Ryazanian boundary and (2) the choice of the reference section of this boundary. Most voting members supported the fixa-

[1] Hereinafter, the names of biochorems are given after (Westermann, 2000; Zakharov et al., 2003).

tion of the boundary by the appearance of ammonites of the species *Praetollia maynci* and the choice of the Nordvik section as a reference.

It has been proven by now that none of the substage boundary of the Tithonian coincides even with zonal or subzonal boundaries of the Volgian (Rogov, 2014, 2021), and the recognition of strict analogs of the Tithonian substages (both at its three- and two-member structure) is almost impossible in the Boreal deposits.

All these years after the "liquidation" of the Volgian, this unit was used by specialists from various countries who study the Jurassic–Cretaceous boundary beds of the Boreal regions. The Volgian is applied as the terminal Jurassic stage in Arctic Canada (Galloway et al., 2020; Schneider et al., 2020; Ingrams et al., 2021; Bringué et al., 2022), East and North Greenland (Kelly et al., 2015; Hovikoski et al., 2018; Alsen et al., 2023), Spitsbergen (Wierzbowski et al., 2011; Hammer et al., 2012; Koevoets et al., 2016, 2018a; Vickers et al., 2023), the shelf of the Norwegian, Barents, and North seas (Ineson et al., 2003; Lipinski et al., 2003; Mutterlose et al., 2003; Bruhn and Vagle, 2005; Rokoengen et al., 2005; Jackson et al., 2011; Petersen and Jacobsen, 2021), and England (Gallois, 2011, 2012). Obviously, the use of the Volgian is continued by Russian stratigraphers who study the Boreal sections. The same also concerns the Ryazanian. Its use continues both abroad (Alsen, 2006; Koevoets et al., 2019; Frau et al., 2021; Janssen et al., 2022) and in Russia.

The Boreal marine fauna of the basal part of the Cretaceous, which are currently ascribed to the Ryazanian, were primarily described in Central Russia by Nikitin (1888). He assigned these deposits to the Lower Volgian Stage, considering they are the analogs of the beds with *Olcostephanus virgatus*, but he noted the similarity of ammonites to taxa known from the lower part of the Cretaceous of Western Europe. Describing the species *Hoplites rjasanensis* (now *Riasanites rjasanensis*, an index species of the lower zone of the Ryazanian of European Russia), he noted: "I consider *Ammonites privasensis*, which is described and shown by Pictet ... from the Berrias limestone and marls with *Belemnites latus*, thus from the very basement of the Neocomian, the most similar to *Hoplites rjasanensis*" (Nikitin, 1888, p. 92).

Soon, Krishtafovich (1892a, 1892b) and A.P. Pavlow (Pavlow and Lamplugh, 1892) showed that the beds with *Hoplites rjasanensis* occur above the uppermost horizons of the Volgian, whereas Bogoslowsky (1895) proposed to name these deposits the "Ryazanian Horizon." In an extensive monograph dedicated to the Ryazanian Horizon, Bogoslowsky (1897) described the key sections of this stratigraphic interval, which are still important now, as well as its ammonites. All these researchers compared the Ryazanian Horizon with the "upper Tithonian," i.e., with the most part of the Berriasian in the current understanding.

Sazonov (1953) suggested that this stratigraphic unit should be considered a stage. He wrote (Sazonov, 1953, p. 94): "We consider that the independent stratigraphic significance of the Ryazanian is questionless. The introduction of a new stratigraphic unit (stage) did not complicate the stratigraphic scale of the Lower Cretaceous deposits, but, on the contrary, it will fill a missing gap in the evolution of fauna over the Lower Cretaceous and, what is most important, will emphasize the presence of a specific zoogeographic province." This suggestion in the Soviet Union, however, found no support, and the use of the Berriasian continued in both the GSS and publications of specialists, while the Ryazanian was mentioned only occasionally (Egoyan, 1971; Casey et al., 1977; Mesezhnikov, 1984). Only in the 2000s did the Ryazanian become widely used in publications (Mitta, 2005, 2007, 2017, 2021; Urman et al., 2019) for the lower part of the Cretaceous of the European part of Russia, whereas its analog ("Boreal Berriasian") was more often used in Siberia (Zakharov et al., 1996). At the same time, the foreign researchers who studied the Jurassic–Cretaceous boundary interval of the Boreal regions began to apply the Ryazanian as early as the end of the 1950s (Różycki, 1959) and especially intensely after the publication of a paper by Casey (1973), where he proposed the zonal scales of the Upper Volgian and Ryazanian of England, which are currently applied for Northwest Europe (Janssen et al., 2022). At present, the Ryazanian is widely used as a lower stage of the Cretaceous in study of shelf of the North, Norwegian, and Barents seas, Spitsbergen, Arctic Canada, and East Greenland.

In contrast to the Volgian, which occurs in the full range in type region, the Ryazanian is present in the European part of Russia probably without the lower part (the analogs of the Arctic Praetollia maynci Zone are fully or partly absent), is ubiquitously condensed, and has a low thickness (Mitta, 2017).

TITHONIAN–BERRIASIAN BOUNDARY

In the 1990s, when the ISC issued a decree on the Volgian, the Tithonian–Berriasian boundary was accepted by most specialists at the base of the Berriasella jacobi ammonite Zone. Exactly this version of the boundary was shown in correlations published by Sei and Kalacheva (1993, 1995, 1997), as well as the Decree of the ISC (Zhamoida and Prozorovskaya, 1997). The same level of the boundary was considered main by the Berriasian Working Group (Zakharov et al., 1996).

In the 2000s, mostly owing to the predominance of specialists on microfossils in the Berriasian Working Group, calcareous nannoplankton or calpionellids were discussed as the best candidates for this boundary rather than ammonites. In 2008–2020, the head of the Berriasian Working Group W. Wimbledon proposed a scenario of the position of the boundary in the basement of the Calpionella alpina Zone, which is well recognized in the Mediterranean Tethyan sections, but which mismatches the striking boundaries traced in other regions, as well as the boundaries established by ammonites. In 2020, the working group under the leadership of W. Wimbledon proposed a GSSP (Global Stratotype Section and Point) section of the Berriasian near the village of Tré Maroua in Southeast France (Wimbledon et al., 2020a, 2020b) with the lower boundary of the Berriasian at the base of the Calpionella alpina Zone. This conclusion was not supported by the Subcommission on Cretaceous Stratigraphy and the working group was disbanded. It should be noted that not only the position of the lower boundary of the Berriasian and Cretaceous at the base of the C. alpina Zone raises numerous questions because of the low correlation potential of this event, but also the suggested section does not meet the GSSP requirements. For example, the level of the suggested boundary is faulted and the Tithonian and Berriasian parts of the section contain numerous interlayers of breccias with redeposited microfossils. Most zonal boundaries according to microfossils near the Tithonian–Berriasian boundary are related to hiatuses and coincide with erosion surfaces (Granier et al., 2020, 2023). At the beginning of 2021, a new Berriasian Working Group was organized and headed by J. Grabowski. Several possible scenarios of the Tithonian–Berriasian boundary located in an interval from the upper Tithonian to the middle part of the Berriasian are currently being discussed. None of these intervals garnered an absolute majority of the vote of the members of the working group. A key event for the identification of this boundary (biotic, paleomagnetic, isotopic, etc.) also remains undetermined. At present, the Tithonian–Berriasian boundary in the GSS can thus be shown only conditionally.

BIOTA AND ZONAL SCALES OF THE VOLGIAN AND RYAZANIAN STAGES

Over the entire Mesozoic, marine fauna of high latitudes preserved its diversity and included a significant amount of endemic taxa (including those of high rank) that evolved in this region (Zakharov et al., 2002). At the Jurassic–Cretaceous boundary, this feature of the high latitude fauna became especially striking because of the reduced ecotone zones (Zakharov and Rogov, 2008) and almost full termination of the faunal exchange between the high- and low-latitude basins. Therefore, the zonal scales created on the basis of various groups of marine organisms for the Volgian and Ryazanian significantly differ from the coeval Tithonian and Berriasian scales and are based on the representatives of various genera and families. Below, we consider only some typical groups of the Boreal fauna. Other groups significant for stratigraphy include, first of all, foraminifers and belemnites. High-resolution zonal scales, which are similar in most regions, were proposed for the Volgian and Ryazanian with respect to foraminifers (Nikitenko, 2009). The Subboreal scales of the Volgian with respect to foraminifers are similar to each other (Kuznetsova, 1979). The scales of the Ryazanian are less detailed and, as a rule, include two incomplete zones (Nagy and Basov, 1998; Nikitenko et al., 2013). The zonal scales with respect to belemnites for the Jurassic–Cretaceous boundary have been actively being developed for the Siberian sections in the last 20 years (Dzyuba, 2004, 2012). Although they are based on the Boreal genera, for the boundary beds of the Volgian and Ryazanian, Dzyuba (2012) used the species which were first described in California and which could potentially be applied for interregional correlation.

Ammonites

Ammonites played a key role for the subdivision and correlation of the Volgian from the beginning of its study. In spite of noticeable differences of ammonite fauna in various regions of the deposition of the Volgian and a large amount of existing zonal scales, the ammonite assemblages of the entire Panboreal Superrealm are very similar and all substage boundaries of the Volgian are unambiguously traced by ammonites (Fig. 2). The degree of unity of the ammonite fauna and stratigraphic scales gradually increases from the Lower Volgian to the Upper Volgian. The Volgian was characterized by a gradual decrease in taxonomic diversity of ammonites with a minimum during the Late Volgian time, which is related to the full termination of the link with Tethyan regions at the beginning of the Middle Volgian time, as well as to the gradual unification of the Boreal fauna (Rogov, 2021).

The lower boundary of the Volgian coincides with that of the Tithonian. It is well recognized by the appearance of new species of virgatitids (*Ilowaiskya*) and dorsoplanitids (*Virgatosphinctoides*) and also coincides with disappearance of aulacostephanids in the sections of Central Poland, European part of Russia, Northwest Europe, and South Germany (Rogov, 2010, 2021). In the Early Volgian time, the basins of the Russian Plate and the regions of the Turan Plate adjacent from the south and southeast were characterized by the predominance of virgatitids (genera *Ilowaiskya* and *Michailoviceras*) and the constant presence of Tethyan taxa (*Neochetoceras*, *Paralingulaticeras*, *Sutneria*, *Schaireria*, etc.), whereas the Boreal dorsoplanitids were relatively rare (Rogov, 2017, 2021). The Boreal Realm in the Early Volgian time was almost inclusively inhabited by Dorsoplanitidae, which mostly include the subfamily Pectinatitinae, and they were accompanied by Gravesiinae in Northwest Europe and Siberia. In spite of the straits which connected the Boreal and Subboreal basins, the faunal exchange between them in the Early Volgian time was very weak and one-sided: only a few Boreal Gravesiinae penetrated the Subboreal Realm (Rogov, 2021).

The Lower–Middle Volgian boundary is defined by the appearance of new genera of dorsoplanitids

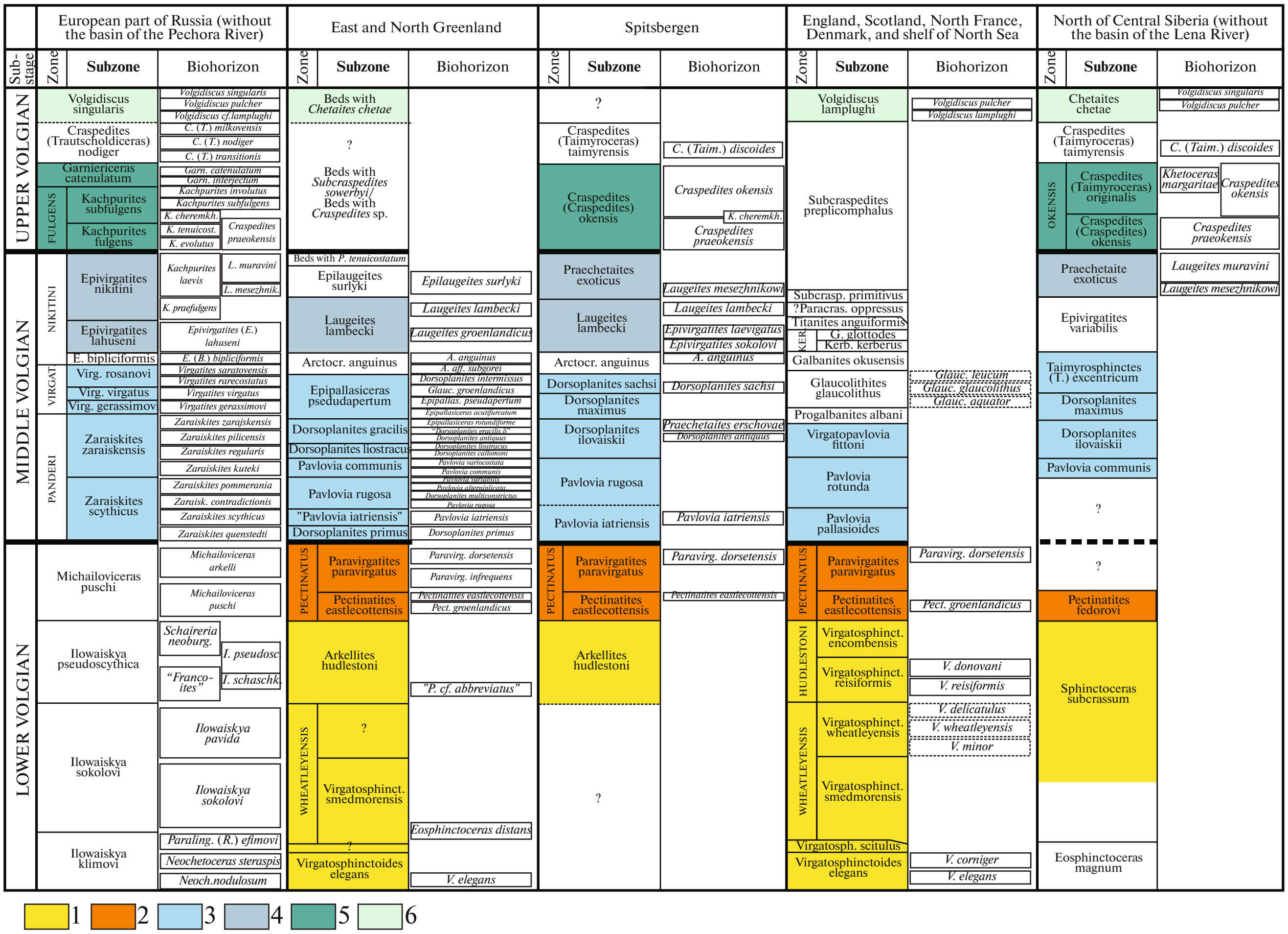


Fig. 2. Zonal and infrazonal subdivision of the Volgian by ammonites, after (Rogov, 2021; Kiselev and Rogov, 2023). The same color shows the intervals of the occurrence of key genera and subgenera of ammonites that are the most important for the intra-Boreal correlation: (1) *Virgatosphinctoides*; (2) *Pectinatites* + *Paravirgatites*; (3) *Pavlovia* + *Dorsoplanites*; (4) *Laugeites*; (5) *Craspedites* (*Craspedites*); (6) *Volgidiscus* + *Chetaites*.

abundant along the entire Panboreal Superrealm (*Dorsoplanites* and *Pavlovia*; Fig. 2). In spite of the significant differences in the dorsoplanitid assemblages of various regions, some genera (first of all, *Dorsoplanites* and *Pavlovia*) were widely distributed in the Middle Volgian time, providing a reliable Panboreal correlation. The first craspeditids (Laugeitinae) appear in the end of the Middle Volgian time, became ubiquitous in the Arctic, and include the same species succession in most cases (Rogov, 2021). In the Middle Volgian time, the most specific ammonite fauna was typical of the basins of the Central Russian Sea and adjacent basins (Poland basin from the west and Caspian basin from the southeast), as well as in Northwest Europe. Virgatitidae were dominant in the first half of the Middle Volgian time in the Central Russian Sea and adjacent basins and were absent in other basins. It should be noted that the Middle Volgian virgatitids and dorsoplanitids were often very large (0.5 to 1.0 m and more in diameter), and this trend was characteristic of various (including indirectly related) species, which inhabited the various parts of the Panboreal Superrealm. Northwest Europe that time was dominated by large and giant dorsoplanitids, which mostly belong to the species of the genera *Crendonites*, *Kerberites*, *Glaucolithites*, and *Titanites* (Casey, 1973; Wimbledon, 1984). The end of the Middle Volgian time, the second half of Nikitini chron and its correlatives, was characterized by a strong turnover of the Boreal ammonite assemblages, the so-called the Late Volgian crisis, which was related to the reduction in taxonomic diversity, the decrease in average and maximum shell sizes, weakening of sculpture, and the change in the type of development of septal suture at the late stages of ontogenesis (Rogov, 2013, 2021; Figs. 8, 11). At this time, the dorsoplanitids had become almost extinct except for *Praechetaites* which existed in the highest latitudes, and the ammonite assemblages were ubiquitously dominated by Craspeditidae, which include the subfamily Subcraspeditinae in the basins of Northwest Europe, mostly Laugeitinae and first Garniericeratinae

(*Kachpurites*) in Russia, and Laugeitinae in the Arctic (Rogov, 2021).

At the beginning of the Late Volgian time, the principal character of the Boreal ammonite fauna remained unchanged, but the important event was related to the appearance of the first *Craspedites* (*Craspedites*), which were abundant from the beginning of the Late Volgian time everywhere in the Panboreal Superrealm with the exception of Northwest Europe (Rogov, 2021). During the Late Volgian time, Subcraspeditinae were dominant in this basin, Garniericeratinae (except for the terminal part of this period) prevailed in the Central Russian Sea, and Craspeditidae preponderated in the other part of the superrealm (Rogov, 2020). At the same time, the fauna exchange between the different parts of the Panboreal Superrealm continued: *Kachpurites* penetrated the West Siberian basin and Spitsbergen, whereas Subcraspeditinae entered the Central Russian Sea (Rogov, 2020). Subcraspeditins *Volgidiscus* widely settled in the Arctic at the very end of the Late Volgian time (Lamplughi/Singularis chron) (Kiselev and Rogov, 2023). In Northwest Europe and the Central Russian Sea, they formed monospecies communities, whereas other Arctic areas contained dominant *Craspedites* (*Taimyroceras*) or dorsoplanitids *Chetaites*. At the Volgian–Ryazanian boundary, the most significant event in the Boreal basins included the change of *Volgidiscus* by *Praetollia*, whereas the genera *Chetaites* and *Craspedites* were known both below and above the boundary (Rogov, 2021). Exactly for this reason, most members of the Commission on Cretaceous Stratigraphy of the ISC supported the drawing of the Volgian/Ryazanian boundary by the appearance of ammonites of the species *Praetollia maynci* during the discussion of the lower boundary of the Ryazanian.

At present, the zonal and infrazonal scales by ammonites are constructed for all large regions of the Panboreal biogeographic superrealm (Rogov, 2021, Fig. 107). In spite of different zonal and infrazonal scales, the presence of a significant amount of interregionally correlated levels in the Volgian (22 if counted from the boundary with the Kimmeridgian to the boundary with the Ryazanian) allows the reliable comparison of scales of various regions of the occurrence of the Volgian, including ubiquitous unambiguous determination of the position of the substage boundaries. The infrazonal scale of the Volgian of the type region (central regions of the European part of Russia) is first of all based on phylogenetic biohorizons, which reflect the evolution of virgatitids (the Lower Volgian and the lower parts of the Middle Volgian), dorsoplanitids (the upper part of the Middle Volgian), and craspeditids (the terminal part of the Middle Volgian–Upper Volgian), providing the high reliability of the scale and its significant correlation potential in the case of the occurrence of individual elements of infrazonal succession outside the reviewed region (Rogov, 2013, 2017, 2021). In other regions, the infrazonal scales are less detailed; the most complete infrazonal successions are established to date in East Greenland (Callomon and Birkelund, 1982; Rogov, 2021) and Spitsbergen (Rogov et al., 2023b); in other areas of the occurrence of the Volgian, only individual biohorizons or their short successions can be identified as a rule. The zonal scales by ammonites provide the most detailed subdivision and the high-resolution correlation of the Volgian deposits for the entire Panboreal Superrealm (Fig. 2). In contrast to the zonal scales of the Volgian, which are highly diverse (caused by the high degree in biogeographic differentiation of fauna), the scale primarily created for the sections of Northern Siberia (Saks and Shulgina, 1962, 1964, 1969; Alekseev, 1984) can be used for the Ryazanian of the entire Arctic (Fig. 3). Significantly distinct scales (Fig. 3) are proposed only for Northwest Europe (Casey, 1973), where, in spite of different index species, the principal succession of the zones is similar to that of the Arctic scale, as well as the type region (East European Platform; Rogov et al., 2015a; Mitta, 2017, 2019a, 2019b, 2021), where the scale is mostly based on Tethyan ammonites (Himalayitidae), although the entire Ryazanian contains the Boreal ammonites, which belong to widely distributed Arctic species (Mitta, 2019a, 2019b). The degree of the resolution of the subdivision of the Ryazanian deposits is significantly below those of the Volgian: only zones without more detailed units are used in the Ryazanian (Casey, 1973; Igolnikov, 2019; Mitta, 2021). This is related to both the lower degree of knowledge of the Ryazanian deposits and ammonite fauna in comparison with the Volgian ones and, probably, to the shorter duration of the Ryazanian. An additional unfavorable factor, which hampered further detailed subdivision of the scale by ammonites in the European part of Russian, includes a low thickness of the deposits, numerous hiatuses, and condensed horizons. In spite of numerous new data over the last 20 years mainly owing to the studies of V.V. Mitta (a review in Mitta, 2017; Mitta, 2019a, 2019b, 2021), the zonal scale remained almost unchanged over this time, whereas no infrazonal subdivisions proposed (Mitta, 2007) were further used.

In spite of the presence of common genera and, to a lesser extent, species in the Ryazanian of the European part of Russia, Northwest Europe, and Siberia, the comparison of scales of these regions remains more or less conditional. The Hectoroceras kochi Zone is the most important widely tracing interval, which can be recognized in all these regions (in the type region, it corresponds to the Riasanites rjasanensis Zone, which also contains *Hectoroceras*). The comparison of the higher intervals of the Ryazanian is first of all based on data on the change of *Surites* by *Bojarkia*, which remains ambiguous outside Siberia (Janssen et al., 2022).

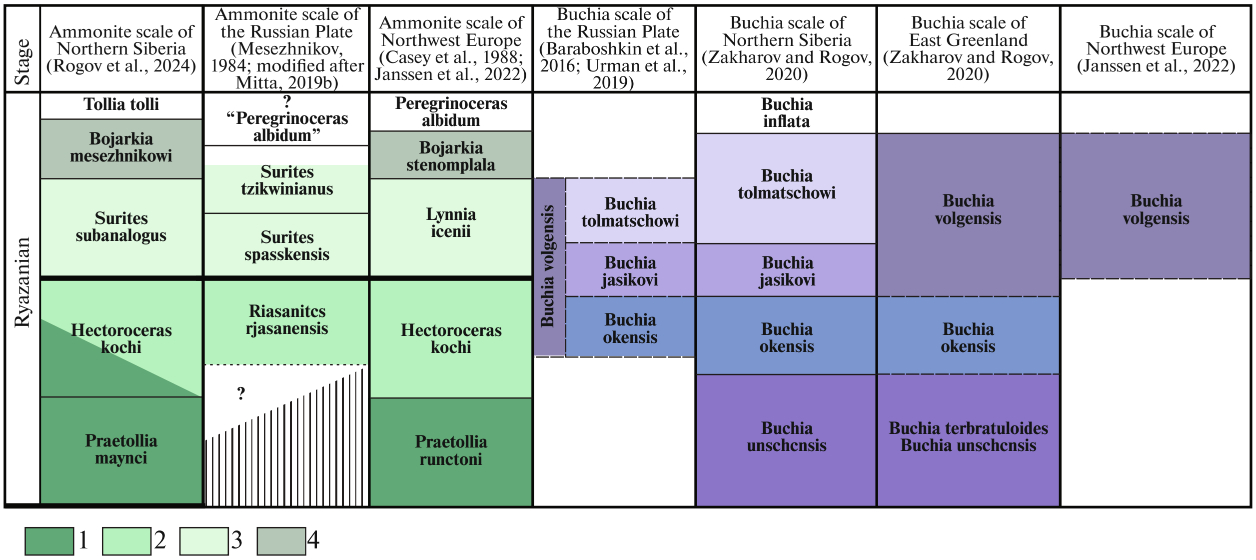


Fig. 3. Zonal and infrazonal subdivision of the Ryazanian by ammonites and bivalves. The same color show the zones and beds with identical index species for *Buchia* (see also Figs. 4 and 5) and intervals of occurrence of key genera for ammonites: (1) *Praetollia*; (2) *Hectoroceras*; (3) *Surites*; (4) *Bojarkia*.

Bivalves (Family Buchiidae)

In addition to the ammonite zonal scales, the scales based on a succession of bivalves of the genera *Buchia* and *Praebuchia* of the family Buchiidae are very important for the subdivision of the Boreal sections at the Jurassic–Cretaceous boundary (Zakharov, 1981, 1987). The dispersal of these bivalves was not controlled by facies; thus, the same species of buchiids occurred in the Northern Hemisphere throughout the entire of the Panboreal Superrealm and, in some periods, they penetrated outside and were present in those regions where the findings of Boreal or Subboreal ammonites are unknown, e.g., Mexico, Cuba, Crimea, Transcaspian region, Caucasus, or Transcaucasia (Yanin, 1970; Tovbina, 1988; Zakharov and Rogov, 2020; Zakharov 2022). The buchiid-based regional scales are thus predominated by Buchia zones with the same index species, whereas the findings of *Buchia* with Tethyan ammonites are very important for the Boreal–Tethyan correlation of the terminal Jurassic. The rate of the evolution of buchiids at the Jurassic–Cretaceous boundary was very high, and the duration of Buchia zones is comparable with that of ammonite zones. The zonal scales by buchiids were created beginning from the end of the 19th century (Lahusen, 1888). The most complete and high-resolution succession of buchiids is established in the upper Bathonian–lower Hauterivian interval of Eastern Siberia (Zakharov, 1981). The advantage of the Siberian scale over the North American scale, which was proposed in the same years, is related to the fact that the Siberian sections contain the ammonites, which allowed the detailed correlation of Buchia zones with ammonite zones and subzones. The insufficiently precise correlation of the ammonite and Buchia zones is typical only of the Lower Volgian and the lower parts of the Middle Volgian, because this interval in the north of Eastern Siberia is incomplete and is strongly condensed. Outside Siberia, the sections, which are well characterized by *Buchia* and ammonites and intensely studied, are few in number. Relatively complete *Buchia* successions well-correlated with the ammonite zonal scale are identified in Subpolar Urals and the Pechora River basin (Mesezhnikov et al., 1979), as well as Western Siberia (Mesezhnikov et al., 1984; Zakharov and Lebedev, 1986). At the same time, the Volgian *Buchia* in the Volga region, which is a type area of the Volgian and Ryazanian, require revision. There are new data only on a *Buchia* succession of the Ryazanian (Urman et al., 2019), but the different composition of the assemblages of various sections actually allow us to distinguish only the beds with *Buchia volgensis*. A succession of *B. okensis–B. jasikovi–B. tolmatschowi* inside the interval with *B. volgensis* can be recognized in the Kashpir section (Baraboshkin et al., 2016), but it is difficult to predict its tracing in other sections of this region.

At present, the zonal scales by *Buchia* are established for all regions of the Panboreal biogeographic superrealm, but the position of the boundaries of the Buchia zones relative to the ammonite zones and even substages is often imprecise, especially there where the findings of ammonites are rare (e.g., Northeast Russia). The boundaries of the Buchia zones are identified either by the appearance of the index species or by numerous findings of the index species, which can occur also outside its zone (Zakharov, 1987). The identical stratigraphic succession of *Buchia* on a vast territory of North Eurasia and North America allows

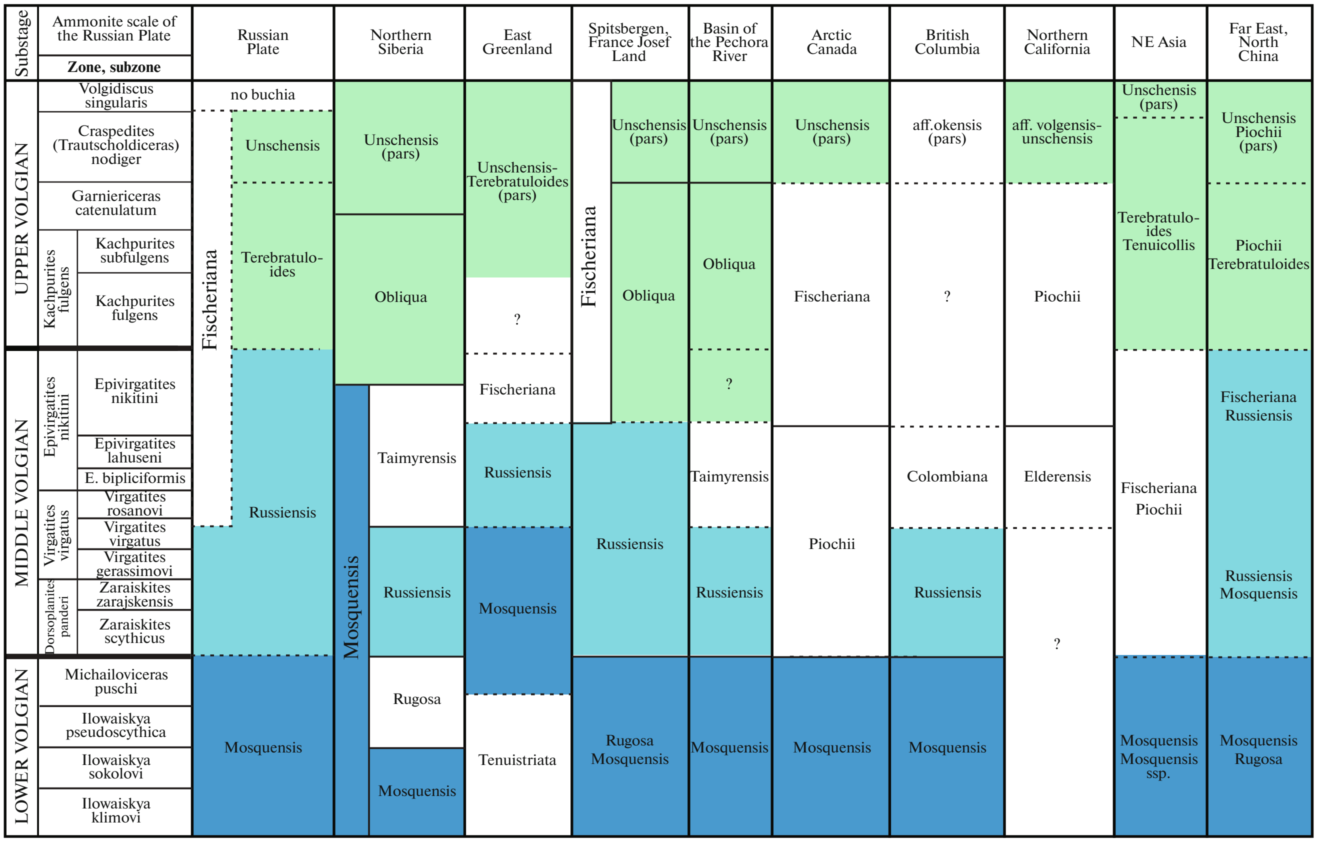


Fig. 4. Zonal subdivision of the Volgian by bivalves of the genus *Buchia*, modified after (Rogov and Zakharov, 2009; Zakharov and Rogov, 2020), and its comparison with scales of the Pacific region.

us to consider geologically coeval the beds containing the same or vicariant species (Figs. 3, 4). Unfortunately, the Buchia zones do not allow the recognition of the Volgian–Ryazanian boundary, because the *Unschensis* Buchia Zone spans the top of the Jurassic System and the base of the Cretaceous.

The Panboreal correlation of the Volgian and Ryazanian Buchia zones was recently published by (Rogov and Zakharov, 2009; Zakharov and Rogov, 2020) and is presented here almost intact (Figs. 3, 4). Only the boundary of the *Jasikovi* and *Tolmatschowi* Buchia zones is lowered in the present work to the lower part of the Subanalogus ammonite Zone judging from the occurrence of the index species of the zones (Zakharov, 1981).

Radiolarians

The radiolarians in the Volgian deposits of Russia have been known long ago. Their presence in Volgian phosphorites of the Vyatka River basin was noted by Kassin (1928) and his materials were later described in thin sections by Khabakov (1937). The Volgian radiolarians of the Timan–Pechora and Bazhenovo petroleum regions were the subject of study of Kozlova (1983, 1994; Braduchan et al., 1986), who suggested the characteristic stratigraphically significant Middle Volgian, Middle–Upper Volgian, and Upper Volgian–Berriasian assemblages. These assemblages in a rank of the fauna-bearing beds were accepted in a regional stratigraphic scheme of the Upper Jurassic of Western Siberia (*Reshenie*..., 2004). A slightly different succession of the West Siberian assemblages was later suggested by Amon (2011). At the same time, the main disadvantage of the above-indicated biostratigraphic schemes was related to the fact that all their index species were invalid (O'Dogherty et al., 2009), because they were described from occasional thin sections. The Volgian radiolarian assemblages were also described from the basin of the Volga River (Gorodishchi section; Vishnevskaya and Baraboshkin, 2001) and Mezen River (a section along the Pesha River; Vishnevskaya and Kozlova, 2012) and the Volgian–Ryazanian assemblages were described in the Nordvik section of the Arctic coast (Bragin, 2011), whereas the Ryazanian assemblages were described in the delta of the Lena River (Vishnevskaya et al., 2014) (Fig. 5). In the Jurassic–Cretaceous boundary interval of the Nordvik section (Arctic Siberia), Bragin (2011) established two significantly different radiolarian assemblages with *Arctocapsula magna* (the middle substage of the Volgian Stage, Epivirgatites variabilis Zone) and

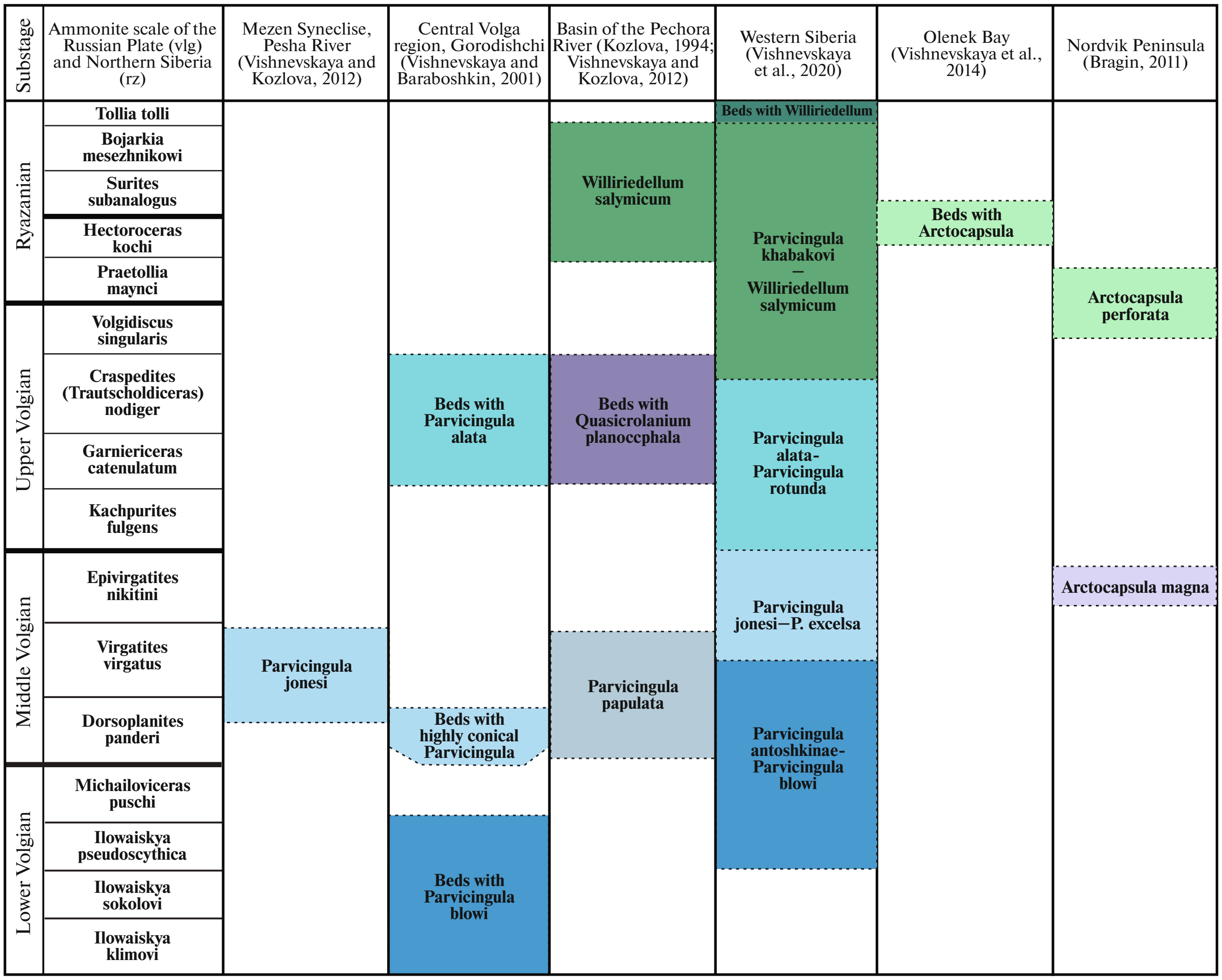


Fig. 5. Subdivision of the Volgian and Ryazanian by radiolarians.

Arctocapsula perforata (the upper parts of the upper substage of the Volgian–the lower parts of the Ryazanian, Chetaites chetae and Chetaites sibiricus zones), which contain only one common species (*Acaeniotylopsis nordvikensis* Bragin), whereas the genus composition strongly differs.

Interest in radiolarians of the West Siberian Bazhenovo Formation has grown in the last years. Because of rare findings of macrofauna in a drill core, the age of six members of the Bazhenovo Formation and its analogs cannot always be identified, and the area is characterized by sliding datings (Dzyuba et al., 2022; Panchenko et al., 2022). The lack of recognizable macrofossils in drill core from the formation (Figs. 9, 10 in Panchenko et al., 2022) or even their complete absence in highly carbonaceous siliceous intervals (Panchenko et al., 2015) required the necessary attraction of nonpaleontological and micropaleontological methods for the subdivision and correlation of these deposits. Because the Jurassic–Cretaceous boundary deposits (Bazhenovo Formation and its analogs) in Western Siberia are not exposed on the surface and are studied only in a drill core, the findings of rock-forming radiolarians in this interval are especially significant, because the probability of their finding in a drill core is much higher than that of the leading macrofauna.

The aforementioned thus required more thorough study of radiolarians from a drill core using new modern analytical methods (Vishnevskaya et al., 2020; Isaeva and Gatovsky, 2023; Isaeva et al., 2023).

The application of X-ray microtomography and chemical extraction of volumetric radiolarian forms from carbonate–siliceous rocks allowed the identification of five stratigraphic subdivisions in a rank of zones and beds and characterization of index species of zonal radiolarian assemblages (Vishnevskaya et al., 2020) (Fig. 5). In recent years, a new scenario of the scheme began to be used for the biostratigraphic subdivision and the correlation of sections of the Bazhenovo Horizon (Panchenko et al., 2015, 2021; Vishnevskaya, 2017; Amon et al., 2022).

In the Arctic area of Russia, the present-day radiolarian scheme of the subdivision of the Volgian deposits was suggested only for the Bazhenovo Formation of the West Siberian petroleum province (Vishnevskaya et al., 2020). The basement of the formation hosts the Parvicingula antoshkinae–P. blowi Zone (the lower substage of the Volgian–the lower parts of the middle substage of the Volgian), the index species of which include the highly conical cyrtoid Nassellaria with a large amount of chambers. The zonal assemblage contains all morphological radiolarian groups (Amon et al., 2022). The beds with *P. blowi* can be established in the Gorodishchi section within the Lower Volgian ammonite zones from *Klimovi* to *Pseudoscythica* by mass findings of index species (Vishenvskaya and Baraboshkin, 2001). The overlying Parvicingula jonesi–P. excelsa Zone in the Bazhenovo Formation is of significant interest because of the maximum petroleum occurrences in this interval of the sections, which is composed of kerogene–siliceous rocks (Kalmykov and Balushkina, 2017). The index species belong to the taxa with the greatest number of chambers and are well identified under both a scanning electron microscope (SEM) and an optical light microscope (Vishnevskaya et al., 2020). The age of the zone is confirmed by the findings of *Epivirgatites* cf. *laevigatus* Rogov in the stratotype, as well as single ammonites of the Groenlandicus, Vogulicus, and Exoticus zones in the upper parts of the zone of other sections (Braduchan et al., 1984; Panchenko et al., 2015). It is possible that the interval of this zone partly corresponds to the Middle Volgian beds with *Parvicingula papulata* in the Barents Sea–Pechora area, beds with *Parvicingula jonesi* from the Panderi–Virgatus ammonite zones of the Mezen River basin (Vishnevskaya and Kozlova, 2012), and beds with highly conical *Parvicingula* composing >50% of the composition of the assemblage from the shale-bearing sequence of the Panderi ammonite Zone of the Gorodishchi section (Vishenvskaya and Baraboshkin, 2001). The recognition of the Upper Volgian Parvicingula rotunda–P. alata Zone is based on the first onset of the zonal species *Parvicingula alata* Kozlova et Vishnevskaya, 2012 and acme *P. rotunda* (Hull, 1977); the last index species is well recognized under SEM and from X-ray tomography (Vishnevskaya et al., 2020). The Late Volgian time is characterized by a decreasing height of cyrtoid shells and the full disappearance of highly conical radiolarian forms. The Parvicingula rotunda–P. alata Zone is confirmed by the findings of ammonites of the Chetae Zone in the sections of the Latitudinal Ob region (Panchenko et al., 2015) and can be traced in the Volga region, whereas a similar assemblage was identified in the Catenulatum–Nodiger ammonite zones (Fig. 5). The Parvicingula rotunda–P. alata Zone in Western Siberia is often divided from the P. jonesi–P. excelsa Zone by a thin microinterlayer with redeposited carbonate material, *Buchia* detritus, and broken shells of prismatic inocerams layers. The lower parts of the zone contain several tuffaceous interlayers (Panchenko et al., 2021, 2022).

An unexpected explosion of the amount of radiolarians of the genus *Williriedellum* (Vishenvskaya, 2019), the representatives of which are easily recognized under both a SEM and an optical microscope, as well as from X-ray microtomography, allows us to distinguish the base of the Upper Volgian–Ryazanian Parvicingula khabakovi–Williriedellum salymicum Zone in a sequence of siliceous–carbonate rocks of Western Siberia. The index species *Williriedellum salymicum* is an endemic of the Arctic area. It was first described from the Kochi Zone of the Upper Salym borehole 17P (Braduchan et al., 1984) and occurs up to the Mesezhnikowi Zone (Panchenko et al., 2015) in the sections of the central part of Western Siberia (Latitudinal Ob region).

The zonal species of the Volgian (*Parvicingula blowi*, *P. jonesi*, and *P. rotunda*, which were first described in California) were previously used as the index species of the upper Kimmeridgian–Tithonian and Tithonian beds for the subdivision of siliceous sections of the Chukotka and Koryak–Kamchatka regions of Northeast Russia (Filatova et al., 2022). These species can potentially be used for interregional correlation. The North American zonal scheme by radiolarians shows a broad use of species of family Parvicingulidae (*Parvicingula blowi*, *P. excelsa*, and *P. jonesi*), which are the important biostratigraphic markers or index species. A single straton by radiolarians (beds with *Parvicingula khabakovi–Mirifusus baileyi*) is proposed for the upper part of the Tithonian and the lower part of the Berriasian of Northeast Russia. Owing to the presence of *Parvicingula khabakovi* in most sections of the Arctic area (Nordvik, Western Siberia, and Pechora) and Pacific area (Northeast Russia and California), it can also be used for stratigraphic correlation. The beds with *Sethocapsa trachyostraca–Mirifusus chenodes* correspond to the middle–upper Berriasian and the lower Valanginian. Their index species have not been found in the Boreal–Atlantic and Arctic realms to date. In single cases, the sections with known radiolarians are characterized by the findings of the Berriasian–Valanginian *Buchia* (Vishnevskaya, 2001). In the Tethyan radiolarian scheme, the Jurassic–Cretaceous boundary occurs inside zone 13, which includes the upper parts of the Tithonian and the lower parts of the Berriasian. The correlation of the radiolarian subdivisions of the North Pacific region of Russia, as well as the Arctic–Boreal area, including the Barents Sea and Upper Volga regions, north of Western Siberia, and Laptev Sea region, is possible with radiolarian zones of North America and is difficult with Tethyan ones because of the absence of Tethyan marking species. In the North American radiolarian scheme, as well as the radiolarian scheme proposed for Argentina, however, zones 4α and 5 correspond to the upper parts of the Tithonian and the lower parts of the Berriasian, respectively (Vishnevskaya, 2020).

In the absence of the leading fauna, the radiolarians are thus one of the significant tools for stratigraphic subdivision and correlation of clayey–siliceous and carbonate–siliceous sections of the Panboreal Superrealm.

Dinocysts

The systematic study of fossil cysts of dinoflagellates (dinocysts) in Russia was started by T.F. Vozzhenikova in the 1960s. In her studies, special attention was paid to the morphology and systematics of this microfossil group and problems of terminology, because these questions were poorly elaborated at that time. As a result, she published a series of monographs describing many genera, species, and families (Vozzhenikova, 1965, 1967, 1979). These monographs also included the materials on the Volgian and Ryazanian stages from various localities of European Russia and Siberia. The descriptions of taxa contained the data on their stratigraphic occurrence in a wider range up to the stage. No detailed biostratigraphic studies were conducted by T.F. Vozzhenikova.

Later, palynologists noted the presence of dinocysts in the Volgian Stage without the description of the composition of algological assemblages. The first published succession of the Volgian–Valanginian dinocysts was based on materials from the Kuzminskoe, Chevkino, and Chernaya rechka sections of the Oka River basin (Fedorova and Gryazeva, 1984). This work provided a biostratigraphic distribution of dinocysts relative to the ammonite zones with indication of semiquantitative characteristics of taxa. The dinocyst assemblage from the Upper Volgian Substage (Subditus (=Catenulatum here) Zone) contains numerous representatives of the genus *Tenua* (up to 28%) and diverse Gonyaulacysta, as well as the taxa which are currently considered stratigraphically important: the genus *Spiniferites* and the species *Gochteodinia villosa* (Vozzh.) Norris. The zonal subdivision of the Volgian Stage by dinocysts for the European part of Russia was suggested on the basis of study of the Gorodishchi and Kashpir type sections, as well as the Kuzminovskoe section (Riding et al., 1999). Four zones were established, the boundaries of which were defined by the appearance and disappearance of stratigraphically important taxa. Each zone was characterized by the description of typical dinocysts assemblages, the quantitative characteristics of genera and species, and their dynamics along the sections. Later, the biostratigraphic succession of the dinocyst biostratons and the composition of stratigraphically important taxa were refined and supplemented by the materials from the Gorodishchi section (Pestchevitskaya, 2021). Note that the dinocyst bioevents, which are the basis for the subdivision of the Volgian of the European part of Russia, have a significant correlation potential and are defined at close stratigraphic levels on both the territory of Siberia and the north of Western Europe, where the scale on dinocysts is the most detailed (Fig. 6). The foreign authors suggested an alternative subdivision of the Volgian by dinocysts on the basis of the materials from the Gorodishchi and Kashpir type sections (Harding et al., 2011). The reasons for the rejection of the previous model were not provided in the paper. This alternative subdivision can hardly be considered successful, because the determination of the boundaries of the dinocyst zones was mostly based on taxa of a broad stratigraphic range (Pestchevitskaya, 2021).

The comparative analysis of the dinocyst assemblages from the Volgian Stage and its stratigraphic analogs shows a significant similarity of the genus composition of the dinocysts in the European part of Russia, North Sea region, and Bulgaria, which is due to the links between these water basins through the Danian–Poland and Caspian straits (Pestchevitskaya et al., 2022). The highest interrelation is observed between the dinocyst assemblages of the Russian Sea and North European basins, which is expressed in biostratigraphic successions: several reference correlation bioevents are distinguished in the lower and middle parts of the Volgian Stage (Fig. 6). Note that these correlation boundaries are also defined on the northwestern coast of the Atlantic, because the detailed succession of the North European dinocyst zones is well applicable in this region. This is a natural consequence of close localities of the Western Europe and America at the end of Jurassic, because the opening of the Paleoatlantic Ocean had just begun. At the same time, the attempt to recognize the North American dinocyst zones in the Volgian of Poland was unsuccessful (Fig. 6). This is similar to the European part of Russia: their direct definition is impossible, but there are several boundaries where the key taxa appear/disappear at stratigraphically close levels. It is interesting to note that the level of the appearance of the genus *Muderongia* in Poland is closer to the Siberian one, whereas it is better compared with the North Sea level in the European part of Russia. Some bioevents are also defined in Tethyan regions, but in most cases in other stratigraphic levels (Fig. 6). Note that the uppermost Jurassic in the southern areas of Europe, which is represented here by the Tithonian, is often composed of calcareous deposits unfavorable for the preservation of organic-walled dinocysts. These regions are characterized by few data and poor dinocyst assemblages, which do not seem quite consistent with dinoflagellate communities inhabiting the Tethyan basins at the time. Perhaps, it also resulted in different dinocyst successions of various Tethyan regions (Fig. 6). A decrease in similarity between the dinocyst assemblages of the European part of Russia and other regions at the end of the Volgian was insignificant (Pestchevitskaya et al., 2022). It is suggested that this is related to the ability of dinoflagellates to form cysts and thus cross the ecological barriers which

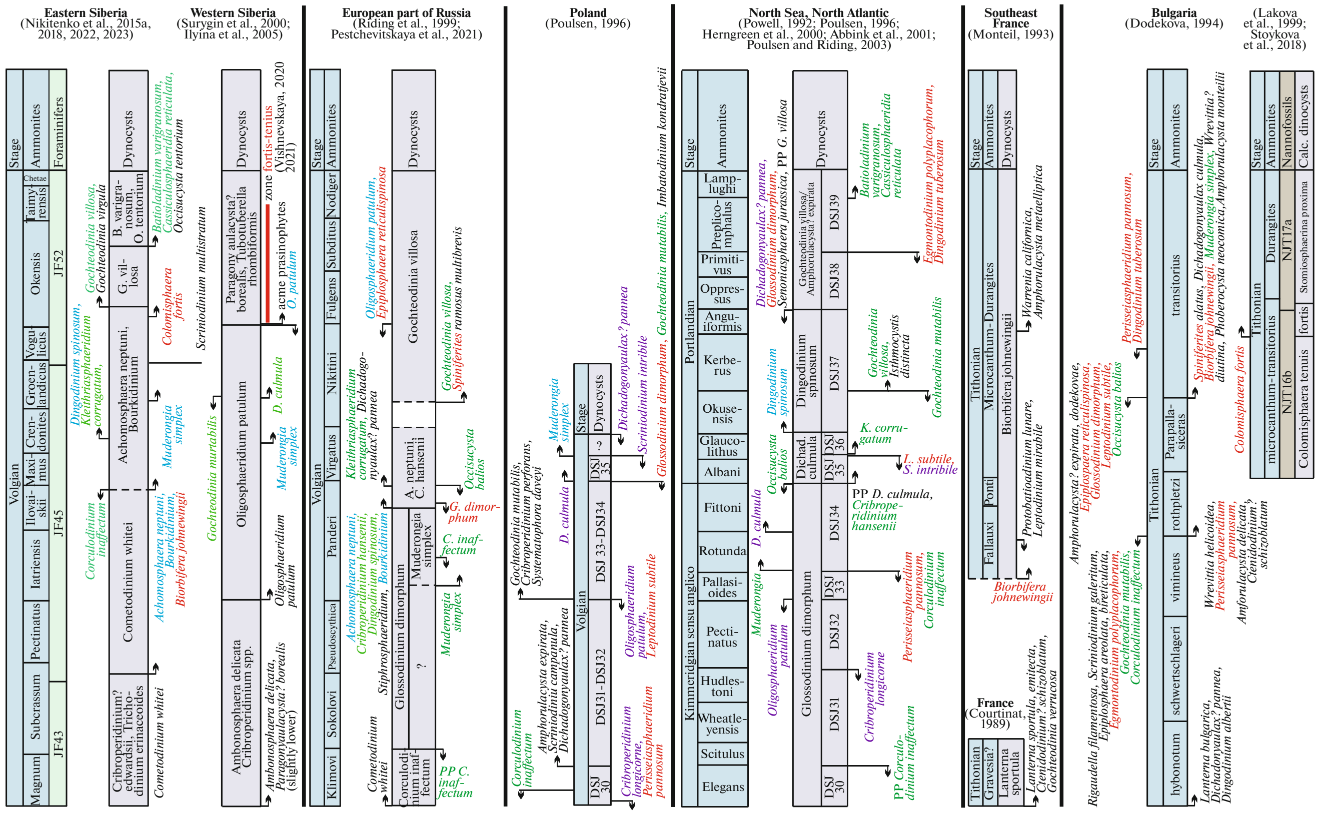


Fig. 6. Key biostratigraphic markers by dinocysts in the Volgian and its stratigraphic analogs on the territory of Siberia and Eastern and Western Europe. Color font: blue and green, Siberian and North Sea marking taxa of dinocysts, respectively; violet, common for the North Sea region and Poland; red, markers that are traced in the Boreal, Subboreal, and Tethyan realms; bold, markers that are traced in various regions at similar stratigraphic boundaries; PP, permanent presence. Here and in Figs. 7 and 8, the calibration of dinocyst biostratons and those distinguished by other groups is given in the authors' versions. The ammonite scale in the left part of the figure, the Boreal standard after (Nikitenko et al., 2015a). The Praechetaites exoticus Zone in this scale is considered a subzone of the Craspedites okensis Zone rather than the terminal zone of the Middle Volgian.

resulted from shallowing and periodic closure of the straits. Nonetheless, this reduction of the taxonomic similarity is reflected in biostratigraphic successions: no correlation references are observed between the European part of Russian and North Sea regions.

The Volgian dinocyst assemblages of the European part of Russian are characterized by diversity and, locally, a large number (up to 85%) of the representatives of the genus *Cribroperidinium*, especially in the middle and upper parts of the stage (Riding et al., 1999; Pestchevitskaya, 2021; Pestchevitskaya et al., 2022). Genus *Dingodinium*, which is an indicator of medium and deep parts of the neritic zone and good aeration of the water masses, is abundant (30–76%) in the lower half of the stage (to the middle part of the Panderi Zone) (Pestchevitskaya, 2021; Lidskaya et al., 2023a). The middle and upper parts of the stage exhibit quantitative peaks of indicators of unstable and anoxic conditions: dinocysts with simple morphology of Escharisphaeridia and Pilosidinium groups (up to 40%) and prasinophytes (up to 90%). An assemblage dominated by *Senoniasphaera*, *Circulodinium*, and *Meiourogonyaulax* that is typical of shallow areas is defined in the uppermost Volgian on the basis of materials from the sections of Yaroslavl region (Lidskaya et al., 2023b). In general, the composition of the microphytoplankton assemblages from the European part of Russia shows a regressive trend in the upper part of the Volgian.

In Western Siberia, the dinocysts are less numerous and diverse. Nonetheless, the Volgian biostratigraphic succession by this group is established here on the basis of materials of boreholes from the Urengoi, Shaim, Azharmin, and Vasyugan regions (Shurygin et al., 2000; Ilyina, 2003; Ilyina et al., 2005). The representative dinocyst assemblages were studied in a section from the Tyumen SG6 borehole (Ilyina et al., 2005). *Systematophora*, *Sentusidinium*, and *Cribroperidinium*, as well as *Ambonosphaera delicata* Leb., are abundant in the lower part of the Volgian. These features of the assemblage are of regional significance. The amount of dinocysts is reduced up the section, while the amount of prasinophytes increases. They are often dominant in the upper part of the stage, which is especially typical of the Bazhenovo Formation (Shurygin et al., 2000; Ilyina, 2003; Ilyina et al., 2005).

Some dinocyst bioevents in the middle part of the Volgian provide the correlation with Eastern Siberia and the European part of Russia (Fig. 6). A distinctive feature of microphytoplankton successions in the upper part of the stage is an alternation of the assemblages consisting of prasinophytes and dinocysts with characteristic *Paragonyaulacysta*? *borealis* (Brid. et Fish.) Stov. et Ev. and *Tubotuberella rhombiformis* Vozz. These features of the microphytoplankton assemblages are defined in Subpolar Urals in the Yatriya section in the range of Subditus–Chetae zones (Fedorova et al., 1993; Lebedeva and Nikitenko, 1998). *Dingodinium*, *Sentusidinium*, *Gonyaulacysta*, and *Stephanelytron membranoideum* (Vozz.) Cour. are the most numerous among the dinocysts. There are also *Sirmiodiniopsis orbis* Drugg, *Sirmiodinium grossii* Alb., *Gonyaulacysta jurassica* (Def.) Nor. et Sarj., *Stanfordella fastigiata* (Dux.) Hel. et Luc.-Cl., *Wrevittia helicoidea* (Eis. et Cook.) Hel. et Luc.-Cl., *Imbatodinium* aff. *kondratjevii* Vozz., *Tubotuberella apatela* (Cook. et Eis.) Ioan., and *Cassiculosphaeridia magna* Dav. In the Mauryn'ya section (North Urals), the microphytoplankton in the upper part of the Volgian is studied in coastal deposits (Dzyuba et al., 2018). The assemblage is also dominated by prasinophytes, but the species *Paragonyaulacysta*? *borealis* (Brid. et Fish.) Stov. et Ev. and *Tubotuberella rhombiformis* Vozz. were not found among the dinocysts. There are rare *Dingodinium jurassicum* Cook. et Eis., *Cribroperidinium granuligerum* (Klem.) Stov. et Ev., and *Apteodinium granulatum* Eis. and the representatives of the Escharisphaeridia and Pilosidinium groups.

A depleted dinocyst assemblage with *Paragonyaulacysta*? *borealis* (Brid. et Fish.) Stov. et Ev. and *Tubotuberella rhombiformis* Vozz. and abundant prasinophytes were revealed in the upper part of the Volgian in the north of Eastern Siberia in the Nordvik section (Shurygin et al., 2000). This part of the section was further studied again and subdivided in more detail on the basis of the features of local significance (Nikitenko et al., 2008). Further study of this section, as well as the Anabar and Olenek sections, resulted in definition of a succession of local dinocyst zones from the upper Bathonian to Hauterivian (Nikitenko et al., 2015a, 2015b, 2018, 2022, 2023). The subdivision of the Volgian was revised. The boundaries of the biostratons were based on the species identified in coeval deposits of Northern Siberia and correlative taxa appearing/disappearing at close stratigraphic levels in Eastern and Western Europe (Fig. 6). It is interesting to note the presence of rare *Biorbifera johnewingii* Hab., which is a typical taxon of the upper part of the Tithonian in Tethyan regions, in the middle part of the Volgian (Nordvik section). The upper part of the stage hosts a level with calcispheres/calcareous dinocysts *Colomisphaera fortis* Reh., which is close in stratigraphic position to an eponymous Tethyan zone. The occurrences of calcareous dinocysts *Colomisphaera fortis*, *C. tenuis*, and *Stomiosphaerina proxima*, which are the indexes of Tethyan zones, are also known in Western Siberia (Vishnevskaya, 2017, 2019, 2020).

In general, the East Siberian assemblages of the Volgian dinocysts are more diverse than the West Siberian ones, but less diverse than in the European part of Russia. Poorly preserved proximate dinocysts (without long radial spines) (up to 47%) and dinocysts with simple morphology of Escharisphaeridia and Pilosidinium groups (up to 32%) and sometimes *Paragonyaulacysta* spp. and *Sirmiodinium grossii* Al. reach a significant amount (up to 10%), and *Tubotuberella*, *Scriniodinium*, and *Apteodinium* are diverse (Nikitenko et al., 2015a, 2015b, 2018, 2022, 2023). As in Western Siberia, there are quantitative peaks of prasinophytes (up to 88%) in the upper part of the stage.

On the Norwegian Barents Sea shelf, the Volgian dinocysts are rare and mostly include the taxa of a wide stratigraphic extent (Smelror et al., 1998). The key species for the upper part of the Portlandian are, however, determined in the upper part of the stage: *Gochteodinia villosa* (Vozz.) Nor., *Dingodinium tuberosum* (Git.) Fish. et Ril., and *Egmontodinium polyplacophorum* Git. et Sar., giving a possibility in fragmentary application of the North Sea scale (Smelror and Dypvik, 2005). Quantitative peaks of prasinophytes confined here to the boundary interval are suggested as the indicator of the Jurassic–Cretaceous boundary. The key dinocyst taxa of the North Sea scale are also present at several Volgian levels in microphytoplankton assemblages of the Norwegian shelf (Van der Zwan, 1990; Smelror et al., 2020).

In Spitsbergen, the Volgian dinocyst assemblages include the taxa of wide stratigraphic extent, and no North Sea key species have been found here (Dalseg et al., 2016; Koevoets et al., 2018a). Two zones are defined in the middle part of the Volgian, which are evidently of local significance, because their boundaries are determined on the basis of quantitative changes of dominant taxa typically related to facies peculiarities in the sections (Dalseg et al., 2016). The Paragonyaulacysta sp., Sirmiodinium grossii Zone is the lower one and characterized by a significant amount of *Valensiella* cf. *ovulum* (Def.) Eis. and index taxa. The amount of the latter increased in the next zone and the dominant taxa also include *Tubotuberella apatela* (Cook. et Eis.) Ioan. and *Kallosphaeridium* spp. In general, the taxonomic composition of the assemblages is similar to the Siberian ones.

The biostratigrahic studies of the Ryazanian microphytoplankton in Russia were started by V.A. Fedorova (Shakhmudes). She studied the sections in the Oka River region, Pechora Syneclise (Izhma River), Subpolar Urals (Yatriya River), and north of Siberia (Boyarka River) (Fedorova and Gryazeva, 1984; Fedorova et al., 1993). The works show the systematic composition of microphytoplankton assemblages and analyze the stratigraphic distribution of many dinocyst genera. The dinocyst assemblages mainly include taxa

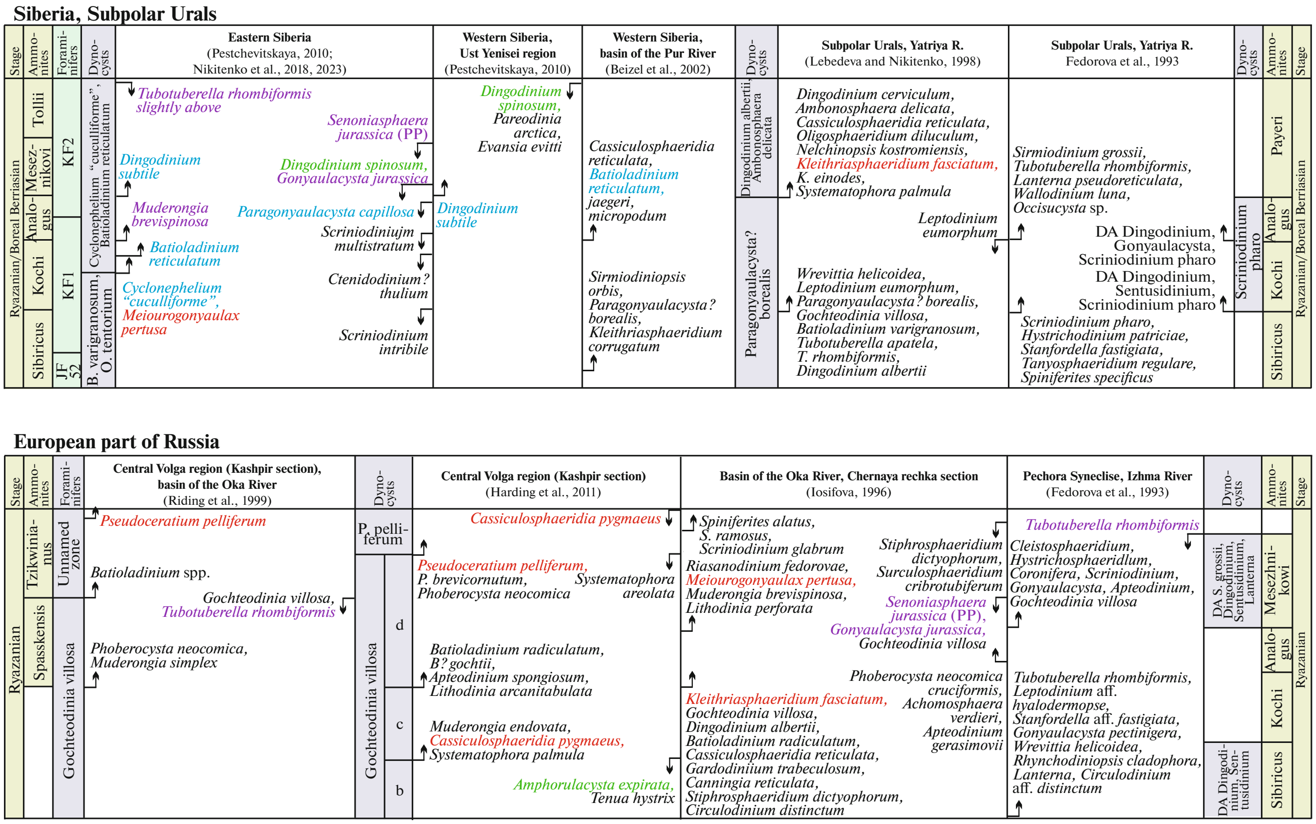


Fig. 7. Key biostratigraphic markers by dinocysts in the Ryazanian on the territory of the European part of Russian and Siberia. Here and in Fig. 3, color font: blue, green, and violet, Siberian, North Sea, and European Russia marking taxa of dinocysts, respectively; red, markers that are traced in the Boreal, Subboreal, and Tethyan realms; PP, permanent presence.

of wide stratigraphic extent (Fig. 7). V.A. Fedorova noted the continuity of the Ryazanian dinocyst assemblages, which contained many taxa originating from the Volgian. The study of the Early Cretaceous microphytoplankton in the Oka River region was continued by Iosifova (1996). She analyzed the distribution of dinocysts in the section of the Ryazanian, Valanginian, and Hauterivian deposits at the Chernaya River and described several new species. The materials of V.A. Fedorova and V.I. Ilyina on the dinocysts of the Ryazanian of the Oka River and Central Volga regions became a part of a summarizing work on the biostratigraphic subdivision of the Jurassic and lowermost Cretaceous on this fossil group in Russia (Riding et al., 1999). A succession of dinocysts was studied in the upper part of the Gochteodinia villosa Zone of rather wide stratigraphic extent (the Upper Volgian–Ryazanian without the uppermost part). It was shown that the Ryazanian dinocyst assemblages of the Central Volga region are characterized by the dominant genus *Cribroperidium* (48%), and *Circulodinium* (up to 20%) and *Chlamydophorella* (up to 18%) are abundant in the Oka River region. On the basis of materials from the Kashpir section, the West European researchers later suggested four subzones within this zone, where the two upper subzones and a part of the underlying zone correspond to the Ryazanian (Harding et al., 2011). The subzones are distinguished by the appearance of *Cassiculosphaeridia pygmaeus* Stev., *Muderongia endovata* Rid. et al., and *Batioladinium*? *gochtii* (Al.) Lent. et Will. (Fig. 7). The first of them allows the correlation with Southwest France (Fig. 8). The latter two have wider stratigraphic extents, appearing in the Portlandian (Abbink et al., 2001; Riding et al., 2001). The Pseudoceratium pelliferum Zone, the lower boundary of which corresponds to the appearance of the index species, is distinguished in the upper parts of the Ryazanian (Fig. 7). This bioevent is well recognized in various regions of Western Europe, as well as Crimea (Fig. 8).

Almost continuous succession of the local dinocyst zones from the Upper Volgian to the lower Hauterivian is established in Subpolar Urals in the section from the Yatriya River region (Lebedeva and Nikitenko, 1998). The biostratons are compared with the dinocyst scales of the Boreal regions of Europe and Canada, and the main regularities of the microphytoplankton distribution depending on facies are revealed. A Ryazanian dinocyst assemblage contains the taxa typical of the uppermost part of the Jurassic and the lowermost part of the Cretaceous. The comparison of the taxonomic composition of the dinocysts shows that a correlative

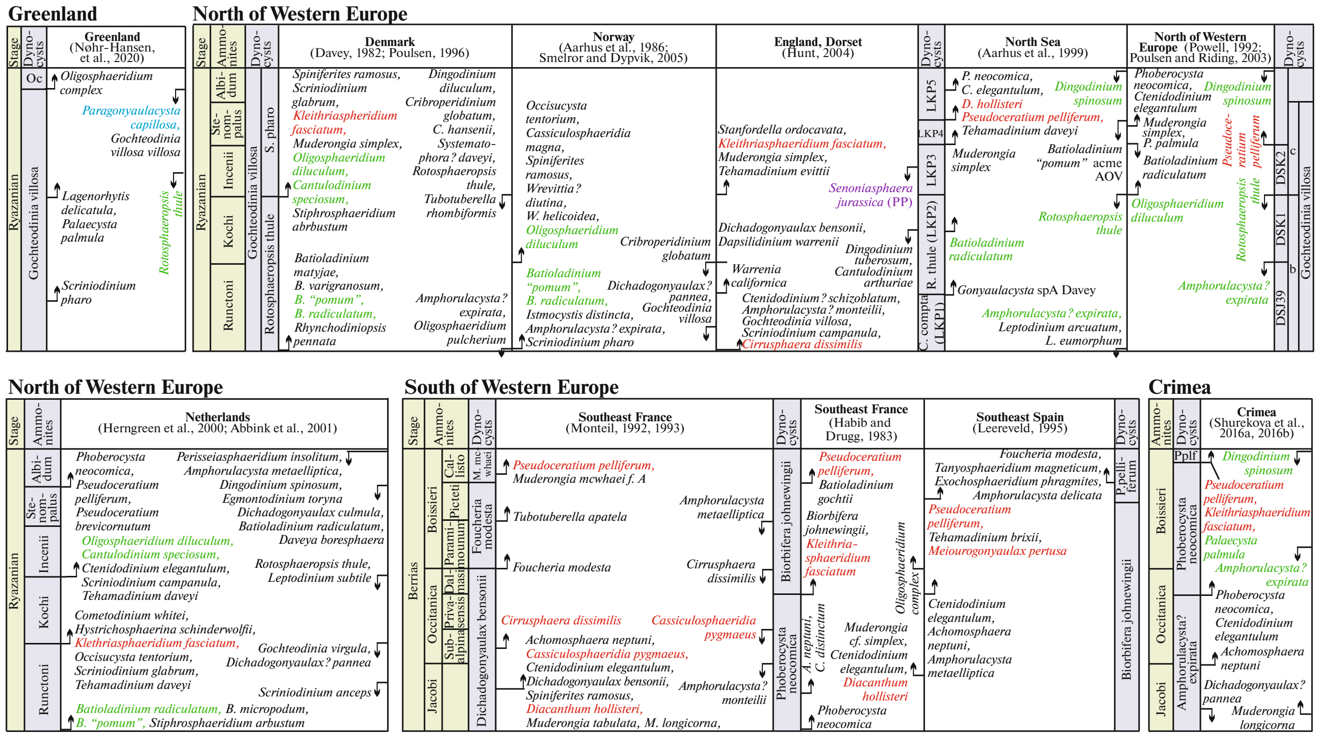


Fig. 8. Key biostratigraphic markers by dinocysts in the Ryazanian on the territory of Greenland and Boreal areas of Western Europe and in the Berriasain of some Tethyan regions. For explanations, see Fig. 7.

species (*Kleithriasphaeridium fasciatum* (Dav. et Will.) Dav.) appears in the middle part of the Ryazanian providing the correlation with sections of European Russia as well as northern and southern regions of Western Europe (Figs. 7, 8).

In Siberia, the microphytoplankton of the Jurassic–Cretaceous boundary deposits of Nordvik Peninsula was studied by Ilyina (1988). The systematic composition of the dinocysts from the overlying Lower Cretaceous beds was described by N. Aarhus (Schulgina et al., 1994). Further study of the microphytoplankton in the sections of the Khatanga River region and the boreholes in the north of Western Siberia gave a succession of dinocyst biostratons from the base of the Lower Cretaceous to the Barremian (Pestchevitskaya, 2010, 2020; Nikitenko et al., 2018, 2023). Several key taxa important for the biostratigraphic subdivision of the North Siberian sections and their comparison with coeval sections of the European part of Russia and Western Europe are revealed in the Ryazanian (Figs. 7, 8). The appearance of *Cyclonephelium "cuculliforme"* (Dav.) Aarh. and disappearance of *Paragonyaulacysta capillosa* (Brid. et Fish.) Stov. et Ev. are also defined in the middle part of the Ryazanian in Arctic Canada, and the appearance the *Batioladinium reticulatum* Stov. et Hel. is traced in Australia (Nikitenko et al., 2023). The most abundant and diverse dinocyst assemblages are identified from deep and middle shelf facies (Nordvik section) with dominant poorly preserved proximate dinocysts (up to 45%) and abundant (in some levels) *Dingodinium* (up to 53%), *Sirmiodinium grossii* Alb. (up to 28%), *Escharisphaeridia* (up to 30%), *Sentusidinium* (up to 15%), and *Cassiculosphaeridia* (up to 25%). In general, there is a regressive trend up the section, which is most typical of shallow facies (Olenek and Anabar sections), where the amount of microphytoplankton is significantly reduced up the section, and the dinocyst assemblages are established only in the lower part of the stage (Nikitenko et al., 2018, 2023).

Outside Russia, the Ryazanian dinocyst assemblages are studied in detail in northern areas of Western Europe, especially, in the North Sea region (Duxbury, 1977; Davey, 1982; Aarhus et al., 1986; Duxbury et al., 1999; Abbink et al., 2001). Some works provide a review of dinocyst biostratigraphy for the entire West European region in general and propose the regional stratigraphic scales (Davey, 1979; Fisher and Riley, 1980; Powell, 1992; Poulsen and Riding, 2003). At the present time, two alternative successions of the detailed dinocyst zones are suggested for the North Sea region and the north of Western Europe in general (Fig. 8). Some key bioevents are well defined not only within this territory but also in the southern areas of Western Europe and various regions of Russia (Figs. 7, 8). Note that much attention is also paid to the study of the Early Cretaceous microphytoplankton of the Barents Sea shelf, which is related to the oil exploration works in this region (Aarhus et al., 1990; Smelror et al., 1998; Smelror and Dypvik, 2005; Bruhn et al., 2023). To subdivide the Ryazanian on the basis of borehole materials, the researchers try to use here the dinocyst zones of the North Sea region, but sometimes their direct application is impossible.

The Ryazanian of Spitsbergen is characterized by poor dinocyst assemblages represented by taxa of wide stratigraphic extents (Dalseg et al., 2016; Rakocinski et al., 2018; Koevoets et al., 2018a). The taxonomic composition displays many features similar to the Volgian dinocyst assemblages. The domination of *Sirmiodinium grossii* Alb., *Tubotuberella apatela* (Cook. et Eis.) Ioan., *Escharisphaeridia rudis* Dav., and *Valensiella* cf. *ovulum* (Def.) Eis. is a characteristic feature. A decreased composition of the dinocyst assemblages is also typical of the Ryazanian in Greenland (Hakansson et al., 1981; Nøhr-Hansen et al., 2020). Some key bioevents are, however, defined in the north of Western Europe and Siberia (Figs. 7, 8).

We can thus conclude that, in spite of the presence of correlative taxa in the dinocyst assemblages of the Volgian and Ryazanian providing the comparison with the dinocyst successions from stratigraphic analogs of these stages in Western Europe, the scale of the North Sea region is impossible to apply in full even at the nearest territories in the Norwegian and Barents seas. The Volgian and Ryazanian dinocyst assemblages have certain specific features and vary in different regions of their occurrences. The Boreal and Tethyan dinocyst assemblages are significantly different and their correlation here is highly difficult.

Nonetheless, in spite of the local peculiarities of the dinocyst assemblages and certain differences in the dinocyst successions of various regions within the occurrence of the Volgian and Ryazanian, several correlation levels can be suggested, with some of them extended on the territory of distribution of their stratigraphic analogs. These levels are mostly defined in the Boreal and Subboreal regions. Only a few of them suggest the possibility of correlation with Tethyan regions.

Note that the current biostratigraphic studies of the Late Jurassic and Early Cretaceous dinocysts are mostly limited to the regional level, and interregional comparisons are in the process of formation. It is evident that the composition of the correlative taxa and the stratigraphic position of the correlation levels will be refined and supplemented. It is difficult to estimate the precision of the correlations by dinocysts. Many biostratigraphic successions of dinocysts are calibrated against the scales based on other biofossil groups: ammonites, bivalves, belemnites, foraminifers, calpionellids, and nannoplankton. At present, however, there is no unambiguous correlation of faunistic successions of the Tethyan and Boreal regions of Europe and Siberia. For some intervals of the Volgian and Ryazanian, there is no standard opinion on biostratigraphic subdivision even within one region. It is possible that further emendation of faunistic correlations will result in the revision of the correlation levels by dinocysts. Note that the dinocysts are generally a promising group for interregional correlations, because they are easily spread by currents and cross ecological barriers.

Marine Vertebrates

At present, the study of marine vertebrates of the end of the Late Jurassic—the beginning of the Cretaceous of Boreal regions is only gathering pace. The cartilaginous and bony fishes are studied in detail in the Tethyan sections of South Germany and Southeast France (Lambers, 1992; Arratia et al., 2015; Villalobos-Segura et al., 2023), whereas data on these fishes in Boreal regions are extremely scarce and limited to several findings or just mentions (Kozlov, 1928; Zonov and Khabakov, 1935; Zhuravlev, 1943; Popov and Shapovalov, 2007, 2021; Popov and Efimov, 2012; Koevoets et al., 2018b). Judging from the available data on chimaeroid fishes, a paleobiogeographic differentiation in their assemblages was suggested for the end of the Jurassic (Popov and Shapovalov, 2021). The remains of chimaeroid fishes of the genus *Stoilodon* were found in both the Volgian and Ryazanian (Popov and Efimov, 2012). The study of otoliths of the bony fishes is promising direction. Numerous findings of otoliths of the genus *Palealbula*, which was previously known only from the Lower Cretaceous, were recently described from the Middle Volgian of the Moscow region (Schwarzhans and Mironenko, 2020).

The findings of marine reptiles from the Volgian were described more often than fishes; however, their study was not systematic for a long time (Pervushov et al., 1999). Numerous publications that shed light on the taxonomic diversity of the Volgian ichthyosaurians of European Russia appeared only at the turn of the 21st century (Arkhangelsky, 1997, 1998, 1999, 2000, 2001; Efimov, 1998, 1999a, 1999b), followed by a series of papers on ichthyosaurians and plesiosaurians of Svalbard (Druckenmiller et al., 2012; Knutsen et al., 2012a, 2012b, 2012c, 2012d; Roberts et al., 2014, 2017, 2020; Delsett et al., 2017). Although the researchers initially suggested provincialism and endemism of fauna of marine reptiles at the end of the Jurassic—the beginning of the Cretaceous of various regions of the Northern Hemisphere (Hurum et al., 2012; Roberts et al., 2014, 2017), the revisions of recent years show a significant similarity at the genus and species level between the ichthyosaurians and plesiosaurians in Subboreal localities of Western Europe and Boreal localities of Spitsbergen, Arctic Canada, and Russia (Arkhangelsky et al., 2020; Zverkov and Efimov, 2019; Zverkov and Prilepskaya, 2019; Zverkov and Jacobs, 2021; Zverkov et al., 2022). In addition, new findings from the Ryazanian of the Arctic showed no dramatic events in the evolution of ichthyosaurians at the Jurassic—Cretaceous boundary, and the genera *Arthropte-*

rygius and *Nannopterygius*, which were previously considered typically Late Jurassic, were found in the Ryazanian of the Franz Josef Land and Svalbard (Zverkov and Prilepskaya, 2019; Zverkov and Jacobs, 2021). The comparison of the Boreal fauna of marine reptiles is difficult with fauna of other regions of the world. The Tithonian ichthyosaurians and plesiosaurians are understudied compared to the Volgian ones, whereas their findings in the Berriasian are extremely rare and fragmentary. Judging by thalattosuchians, which generally gravitate to the lower latitudes, common Tethyan fauna is observed in Germany, Mexico, and Argentina, where the representatives of the genus *Cricosaurus* were dominant in the Tithonian and Berriasian (Herrera et al., 2021), whereas, in contrast, the findings of thalattosuchians within the Panboreal Superrealm are extremely rare and fragmentary for any comparisons (Young et al., 2023). The application of marine reptiles for the aims of stratigraphy still seems illusory; however, the accumulation of new data can possibly help to recognize important evolutionary events, which may make it possible to develop a kind of stratigraphic scheme, even though not so detailed as by invertebrates. It is evident now, however, that the Boreal fauna of vertebrates in the Volgian and Ryazanian time was significantly homogenous along the entire Panboreal Superrealm.

BOREAL–TETHYAN CORRELATION OF THE VOLGIAN AND RYAZANIAN STAGES

The Boreal–Tethyan correlation of the Volgian (Fig. 9) and its Tethyan equivalents is based on paleontological data for the Lower Volgian and the lower part of the Middle Vogian, because the Tethyan ammonites often occur in this interval of the Boreal–Atlantic Realm. In total, ten levels used for the direct Boreal–Tethyan correlation are established from the base of the Volgian to the terminal part of the Panderi Zone of the Middle Vogian (Rogov, 2021). All these levels, except for the highest, are based on joint findings of ammonites of various biogeographic affinities. The uppermost level near the top of the Dorsoplanites panderi Zone of the Middle Volgian in Poland contains calpionellids typical of the lower–upper Tithonian boundary interval (Pszczółkowski, 2016). Up the section, the joint findings of the Boreal and Tethyan ammonites are unknown in the Volgian (they again appear only in the lower part of the Ryazanian; Mitta, 2005; Zakharov and Rogov, 2020). Recently, there was evidence on the presence of calcareous dinocysts in the upper part of the Volgian of Siberia, which can possibly be used for the comparison of the Boreal and Tethyan scales (Vishnevskaya, 2017; Nikitenko et al., 2023), but this group remains poorly studied.

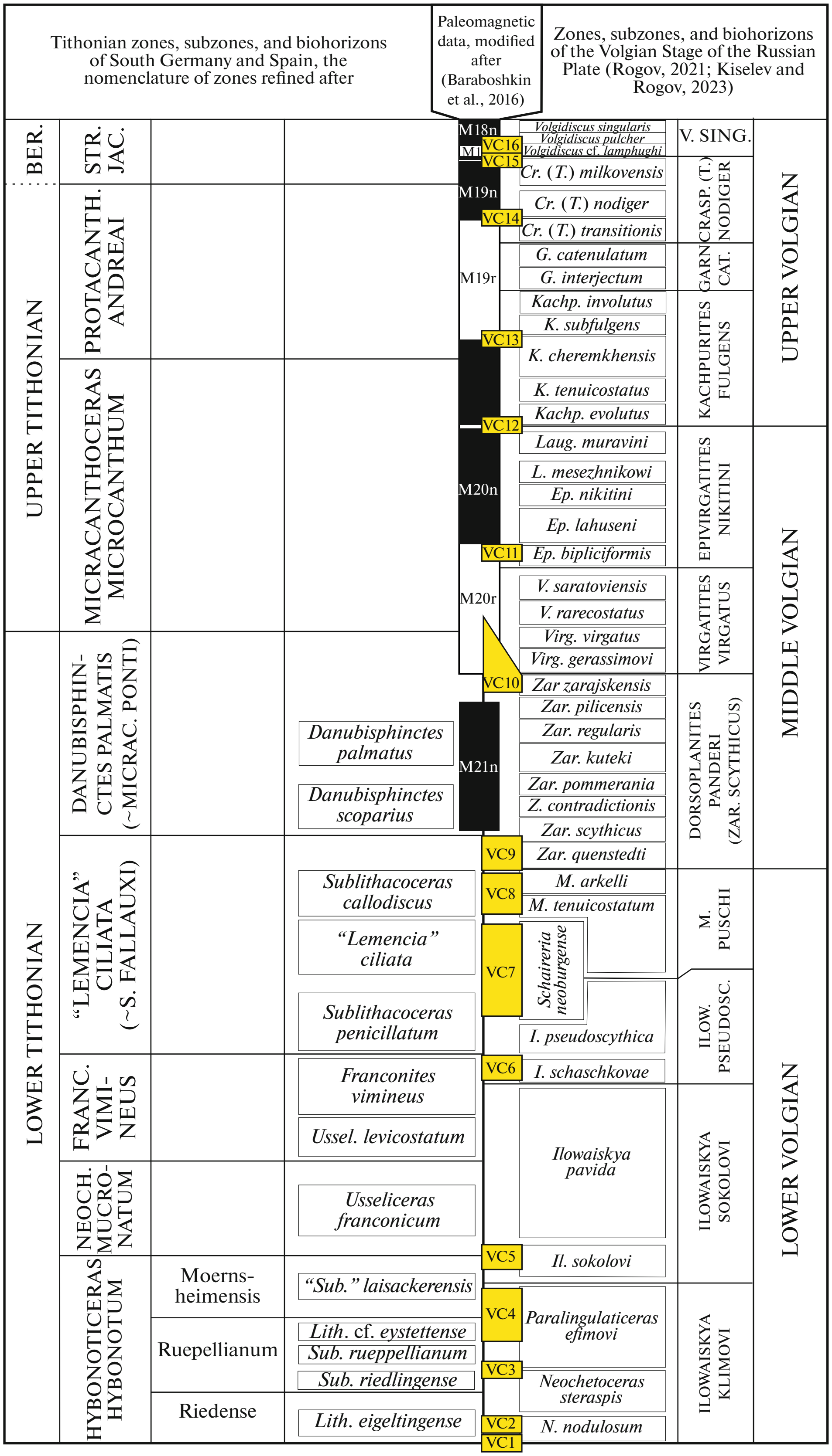
Because of the absence of possibilities of direct comparison of the greater part of the Volgian with its Tethyan equivalents by fossil findings, the Boreal–Tethyan correlation of the Middle and Upper Volgian is conducted by paleomagnetic data (Fig. 9). First of all, there are data on the section of Nordvik Peninsula (Houša et al., 2007; Bragin et al., 2013; Schnabl et al., 2015). Recent paleomagnetic results on the Volgian of the Volga and Moscow regions (Manikin et al., 2018, 2020) are in agreement with the results for Siberia and do not allow the refinement of already available correlation.

Searching for the additional markers for the Boreal–Tethyan correlation of the Jurassic–Cretaceous boundary is ongoing (Shurygin and Dzyuba, 2015). There were some expectations from a VOICE isotopic excursion (Hammer et al., 2012), which is present in many Arctic regions (Nikitenko et al., 2018, 2020; Galloway et al., 2020; Vickers et al., 2023) and was recently established in Argentina (Weger et al., 2023). But the beginning and the end of this excursion are significantly diachronous, also inside the relatively small regions such as Spitsbergen, and this excursion at the current level of knowledge cannot be used even for the approximate comparison of remote regions.

Precise isotopic datings for the Volgian are almost absent. Only tuffaceous interlayers from the Middle–Upper Volgian boundary beds were recently dated from borehole sections in Western Siberia (Rogov et al., 2023a; Bulatov et al., 2024). The ages (slightly older than 141 Ma) are very similar to those from the upper parts of the Tithonian of Argentina. For the Volgian deposits of Spitsbergen, there is a Re–Os dating (Park et al., 2024), but its precision is low and it cannot be used for the refinement of the age of the Volgian.

Owing to frequent findings of Tethyan ammonites, the Boreal–Tethyan correlation of the Ryazanian of a type region with West European scales has first of all been based on biostratigraphy for more than 130 years (Nikitin, 1888). Although the taxonomic position of some Ryazanian ammonites is a matter of debate (Mitta, 2022), numerous findings of ammonites typical of the Occitanica and Boissieri zones, as well as rarer specimens close to ammonites from the Lower Berriasian Jacobi Zone, are known in the European part of Russia (Zakharov and Rogov, 2020). Reliable

Fig. 9. Boreal–Tethyan correlation of the Volgian and its analogs by ammonites, modified after (Baraboshkin et al., 2016; Rogov, 2021). Yellow rectangles with indices VC1–VC16 show the levels of direct Boreal–Tethyan correlation. Ber, Berriassian; Str.jac., *Strambergella jacobi*; Prothacanth., *Prothacanthodiscus*; Micrac., *Micracanthoceras*; S., *Semiformiceras*; Franc., *Franconites*; Neoch., N., *Neochetoceras*; Ussel., *Usseliceras*; Sub., *Subplanites*; Lith., *Lithacoceras*; I., Il., Ilow., *Ilowaiskya*; M., *Michaloviceras*; Z., Zar., *Zaraiskites*; V., Virg., *Virgatites*; Ep., *Epivirgatites*; L., Laug., *Laugeites*; K., Kachp., *Kachpurites*; G., *Garniericeras*; Garn. cat., *Garniericeras catenulatum*; Cr. (T.), Crasp. (T.), *Craspedites* (*Trautscholdiceras*); V. sing., *Volgidiscus singularus*.


Tithonian zones, subzones, and biohorizons of South Germany and Spain, the nomenclature of zones refined after
Paleomagnetic data, modified after (Baraboshkin et al., 2016)
Zones, subzones, and biohorizons of the Volgian Stage of the Russian Plate (Rogov, 2021; Kiselev and Rogov, 2023)
BER.
STR. JAC.
UPPER TITHONIAN
PROTACANTH. ANDREAI
MICRACANTHOCERAS MICROCANTHUM
LOWER TITHONIAN
DANUBISPHINCTES PALMATIS (~MICRAC. PONTI)
"LEMENCIA" CILIATA (~S. FALLAUXI)
FRANC. VIMINEUS
NEOCH. MUCRONATUM
HYBONOTICERAS HYBONOTUM
Moernsheimensis
Ruepellianum
Riedense
Danubisphinctes palmatus
Danubisphinctes scoparius
Sublithacoceras callodiscus
"Lemencia" ciliata
Sublithacoceras penicillatum
Franconites vimineus
Ussel. levicostatum
Usseliceras franconicum
"Sub." laisackerensis
Lith. cf. eystettense
Sub. rueppellianum
Sub. riedlingense
Lith. eigeltingense
M18n
M19n
M19r
M20n
M20r
M21n
VC1
VC2
VC3
VC4
VC5
VC6
VC7
VC8
VC9
VC10
VC11
VC12
VC13
VC14
VC15
VC16
Volgidiscus singularis
Volgidiscus pulcher
Volgidiscus cf. lamplughi
Cr. (T.) milkovensis
Cr. (T.) nodiger
Cr. (T.) transitionis
G. catenulatum
G. interjectum
Kachp. involutus
K. subfulgens
K. cheremkhensis
K. tenuicostatus
Kachp. evolutus
Laug. muravini
L. mesezhnikowi
Ep. nikitini
Ep. lahuseni
Ep. bipliciformis
V. saratoviensis
V. rarecostatus
Virg. virgatus
Virg. gerassimovi
Zar zarajskensis
Zar. pilicensis
Zar. regularis
Zar. kuteki
Zar. pommerania
Z. contradictionis
Zar. scythicus
Zar. quenstedti
M. arkelli
M. tenuicostatum
Schaireria neoburgense
I. pseudoscythica
I. schaschkovae
Ilowaiskya pavida
Il. sokolovi
Paralingulaticeras efimovi
Neochetoceras steraspis
N. nodulosum
V. SING.
CRASP. (T.) NODIGER
GARN. CAT.
KACHPURITES FULGENS
EPIVIRGATITES NIKITINI
VIRGATITES VIRGATUS
DORSOPLANITES PANDERI (ZAR. SCYTHICUS)
M. PUSCHI
ILOW. PSEUDOSC.
ILOWAISKYA SOKOLOVI
ILOWAISKYA KLIMOVI
UPPER VOLGIAN
MIDDLE VOLGIAN
LOWER VOLGIAN

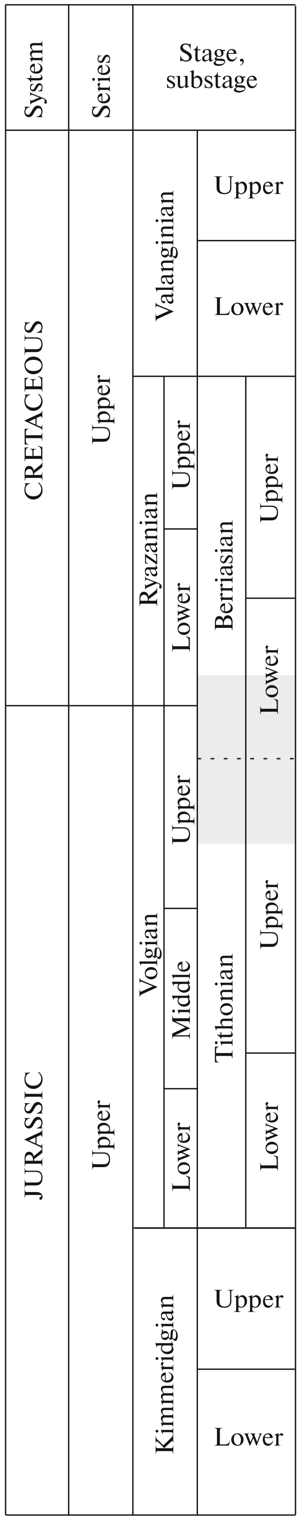


Fig. 10. Volgian, Ryazanian, Tithonian, and Berriasian stages in the General Stratigraphic Chart. Gray color shows an interval in which the Tithonian–Berriasian boundary can further be chosen.

paleomagnetic data which can be used for the Boreal–Tethyan correlation are available only for the lower part of the Ryazanian (Houša et al., 2007; Bragin et al., 2013). The coincidence of its upper boundary with the Berriasian–Valanginian boundary is established first of all by the presence of ammonites of the genus *Delphinites* in the basal part of the Valanginian of Central Russia and Western Europe (Mitta, 2018; Baraboshkin, 2024).

PARALLEL AND REGIONAL STAGES AND WORLD EXPERIENCE OF THEIR APPLICATION

The last several decades have shown a trend of unification of the Phanerozoic stage scales of various world regions, and the International Chronostratigraphic Chart (ICC) is used in most countries. Cope (1993, 1996) pointed to a negative side of this unification since it leads to the rejection of valid stages which are demanded by geological practice and important for those regions where these stages were proposed. He suggested using these stages equally with the ICC stages as chronostratigraphic subdivisions, the boundaries of which are determined using secondary standards in the same way as the boundaries of the ICC stages on the basis of the choice of the stratotype section and point (Cope, 1996). The parallel and regional stages continue to be effectively used by both geological surveys and researchers who study the regional geology. Even in Russia, in spite of an evident wish of the ISC authority to move the GSS closer to the ICC as much as possible (making the Volgian Stage a victim), the specific stage scales are used in the Cambrian and Middle–Upper Permian (State of knowledge..., 2008).

In the Jurassic system, the stages distinct from the ICC stages are applied more rarely, except for New Zealand, for which J. Marwick in the 1950s proposed a regional succession of the Mesozoic series, stages, and substages. The Jurassic of New Zealand contains six stages, none of which coincides with any ICC stage (Campbell, 2004), and these stages are constantly used in publications of New Zealand stratigraphers and paleontologists.

Such regional stages have been used at the Jurassic–Cretaceous boundary of the Northern Hemisphere for over 150 years (Fig. 10). Exactly on the basis of a situation with terminal Jurassic stages, Cope (1993) formulated a conception of parallel (secondary) stages. At present, the Volgian–Ryazanian and Tithonian–Berriasian couples are actively used in contrast to rarer use of the Portlandian and Bolonian. For the Volgian and its substages, Zakharov (2003) suggested the Secondary Stratotype Section and Points (SSSP). The lower boundary of the Volgian was chosen at the base of the Ilowaiskya klimovi ammonite zone of the lectostratotype of the Volgian near the settlement of Gorodishchi. This section contains both Boreal, Subboreal and Tethyan ammonites, which provides a reliable interregional correlation in the Kimmeridgian–Volgian boundary interval (Rogov, 2010, 2021). It was suggested that the SSSP of the lower boundary of the Middle Volgian should be positioned in the same section at the base of the Dorsoplanites panderi Zone, which occurs inside a clay bed (bed 1/5 in Rogov, 2013a) and corresponds to the appearance of *Zaraiskites*. The base of the Craspedites okensis Zone (Praechetaites exoticus Subzone) of the section in Nordvik Peninsula was suggested for the SSSP of the lower boundary of the Upper Volgian, but it was later shown that this subzone has the Middle Volgian age (Zakharov and Rogov, 2008). The SSSP of the lower boundary of the Upper Volgian could be chosen at the base of the Kachpurites fulgens Zone in one of the sections of the European part of Russia with a full succession of biohorizons at the boundary of the Nikitini–Fulgens zones. Such sections are mostly known in Moscow (Karamyshevskaya Embankment, Kuntsevo; Rogov, 2017).

For the Ryazanian, the SSSP choice is possible in the most complete sections of Northern Siberia rather than in a stratotype region, where the section is strongly condensed and contains numerous hiatuses, and the fauna succession requires further study. Zakharov (2011) noted that the section of Nordvik Peninsula characterized by detailed paleomagnetic, geochemical, and paleontological data (Zakharov et al., 2014; Nikitenko et al., 2023) meets GSSP (thus, SSSP) requirements among the Boreal sections of the Jurassic–Cretaceous boundary deposits. The disadvantages of this section are rare findings of ammonites in the uppermost part of the Volgian and its inaccessibility. Nonetheless, this section can be proposed for the choice of the lower boundary of the Ryazanian. The SSSP of the Upper Ryazanian can potentially be chosen in the section of the Boyarka River, but this section requires the restudy.

STATUS AND USAGE OF THE VOLGIAN AND RYAZANIAN STAGES

Although the Volgian has officially been moved by the ISC to regional stratigraphic units for almost 30 years, it continues to be actively used for the Boreal deposits by Russian specialists. This is related to the practical convenience of using this stratigraphic unit, which has well recognizable substages and specific fauna. Foreign biostratigraphers also constantly use the Volgian. The Decree of the ISC which forces use of the Tithonian and Berriasian stages on maps, unified schemes, and reports must be canceled. The Volgian must be returned to the GSS and used jointly with the Ryazanian parallel to the Tithonian–Berriasian pair (suitable for the Crimea–Caucasus region, Northeast Russia, and southern regions of the Far East).

We propose that the Bureau of the ISC reconsider the status of the Volgian, providing the following. It has convincingly been shown over the last 20 years that the Decree on the Refinement of the Jurassic–Cretaceous Boundary in the Boreal Realm and the Status of the Volgian, which was accepted at an extended session of the Bureau of the ISC on February 2, 1996, was based on erroneous Boreal–Tethyan correlation, and use of the Tithonian and Berriasian stages in practice of geological prospecting works in areas of the occurrence of Boreal deposits inevitably leads to confusion.

According to the proposal supported by the ISC Jurassic and Cretaceous commissions, we should return to the previous practice of using of parallel stages reflecting the specific fauna evolution in the Panboreal biogeographic Superrealm and beyond in the GSS of Russia in the Jurassic–Cretaceous boundary interval (Fig. 10). The Volgian–Ryazanian and Tithonian–Berriasian pairs should be shown in parallel between the Kimmeridgian and Valanginian stages. The Volgian and Ryazanian are recommended for use in geological survey and industrial works in areas of the occurrence of Boreal deposits in the Jurassic–Cretaceous boundary interval (this is the most part of Russia, excluding the Crimea–Caucasus region, partly Northeast Russia, and the Far East). The Volgian is subdivided into three substages, the boundaries of which have remained unchanged for almost 70 years from the moment of the accepted decision on the combination of the Lower Volgian and Upper Volgian stages into a single Volgian Stage. The Ryazanian is subdivided into two substages; the Lower–Upper Ryazanian boundary occurs in the top of the Hectoroceras kochi Zone, as was proposed by Casey (1973). This is one of the most recognizable interregionally correlated boundaries inside this stage.

Taking into account the current uncertainty in the position of the Tithonian–Berriasian boundary in the ICC, the boundary between these stages conditionally occurs at a traditional level for Russian researchers: at the base of the Jacobi ammonite zone. For convenience, the Volgian–Ryazanian boundary, which is not a matter of debate and is almost ubiquitously traced in Russia, can be used as a priority Jurassic–Cretaceous boundary in regional works. The Tithonian–Berriasian boundary, in the case of its official international acceptance in the nearest future, can potentially be identified in regions where these stages are traced (Crimea and North Caucasus), but its determination within the Boreal Russia will be very difficult.

CONCLUSIONS

The Volgian and Ryazanian are characterized by specific assemblages of fossil organisms, including marine invertebrates and vertebrates, as well as microphytoplankton. Because of almost full disappearance of an adequate biogeographic ecotone in the Middle–Late Volgian time, which contained both Boreal and Tethyan taxa (first of all, ammonites, which are the basis for the most detailed scales), the Boreal–

Tethyan correlation in this interval is feasible mainly with help of nonpaleontological methods.

The Volgian is a traditional and most convenient stratigraphic unit for the terminal Jurassic of the Panboreal Superrealm. In spite of significant biogeographic differentiation and different zonal scales of various regions, the substages are unambiguously distinguished in all cases. The reliable correlation of the Volgian with the Tithonian is possible only at several levels, and none of the substage boundaries inside the Tithonian corresponds even to the zonal boundaries of the Volgian. It is necessary to reinstate the Volgian in the GSS and to use it during geological prospecting works in areas of the occurrence of the Boreal Jurassic.

The Ryazanian has been used for over 60 years as the lower stage of the Cretaceous in study of the Boreal sections of the Northern Hemisphere. It is proposed to include it the GSS and use the Volgian–Ryazanian pair equally with the Tithonian–Berriasian pair, the application of which in Russia is mostly limited to the Crimea–Caucasus region.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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