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The Jurassic/Cretaceous boundary in northern Siberia and Boreal–Tethyan correlation of the boundary beds

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Abstract

There is no international consensus regarding the GSSP for the Berriasian, the basal stage of the Cretaceous System. Any of the events discussed by the international expert community can be regarded as a marker of the Jurassic/Cretaceous boundary: a phylogenetic change of taxa, paleomagnetic reversal, or isotopic excursion. However, the problem of identification of this level in Boreal sections can be solved only using a combination of data obtained by paleontological and nonpaleontological methods of stratigraphy (bio-, chemo-, magnetostratigraphy, etc.). With any of the accepted markers, the Jurassic/Cretaceous boundary in Siberian sections will be within the upper part of the regional Bazhenovo Horizon. The least interval of the uncertainty of the position of this boundary in Siberian sections will be ensured by the selection of one of two markers: biostratigraphic (base of the Pseudosubplanites grandis Subzone) or magnetostratigraphic (base of the M18r magnetozone).

Keywords: Jurassic; Cretaceous; lithostratigraphy; biostratigraphy; magnetostratigraphy; chemostratigraphy; Siberia

Introduction

The Jurassic and Lower Cretaceous sediments in the Arctic stretch as a band all along the northern margin of Eurasia; also, they are known in northern Alaska and the adjacent water area, in Arctic Canada and eastern and northern Greenland. In northern Russia they make up the world's largest field. These sediments stretch here for >5000 km from west to east with almost no interruption (Saks et al., 1980). The Jurassic and Lower Cretaceous rocks in this huge territory are almost exclusively terrigenous.

The Jurassic and Cretaceous Systems, which are very rich in fossils, occur widely in Eurasia, North America, and South America; also, they can be found in Africa, Australia, and Antarctica. It is for Jurassic sediments that a biostratigraphic method was first applied for the subdivision and correlation of sedimentary rocks by W. Smith (1799–1819). The first large-scale geological map in the world, which he compiled in 1815, covered areas of Jurassic and, partly, Cretaceous rocks in England, Wales, and part of Scotland. The Jurassic and Cretaceous Systems have been known since the 1820s. The division into series (Buch, 1839) and stages (d'Orbigny, 1842–1851), as well as the first Phanerozoic zonation (Oppel, 1856–1858), were carried out for Jurassic sections of Western Europe. Thus, the Jurassic and Cretaceous Systems can be used as model systems to develop the principles of biostratigraphy.

With regard to the foregoing, the situation with the boundary between these two model systems is paradoxical. The switch of the international community of stratigraphers to the application of GSSP (Cowie, 1986; Remane et al., 1996) has intensified work on this issue worldwide. Stratotypes have been determined for boundaries in all the Phanerozoic systems (Cohen et al., 2013), but the lower boundary of the Berriasian Stage, which is also the boundary between Jurassic and Cretaceous Systems, remains problematic. This is explained, to a large extent, by the complicated interregional biostratigraphic correlation of Jurassic and Cretaceous boundary sediments, which is due to the high biogeographic differentiation of biota in Boreal and Tethyan paleobasins in the latest Jurassic and earliest Cretaceous. The requirements to the quality of candidate sections for the GSSP and the selection of their location (Cowie, 1986) considerably limit the possi-

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bility of the use of Arctic sections of Jurassic and Cretaceous boundary sediments, which are well described by different fossil groups but are not easily accessible. Now the International Working Group on the Berriasian Stage have focused their attention on the search for candidate sections for the GSSP of the Berriasian Stage (and the Cretaceous System) using easily accessible Mediterranean sections.

Also, the determination of the Berriasian GSSP is hindered by the ongoing discussion concerning the level and character of the marker of the boundary: according to some researchers, these are biostratigraphic reference levels based on calpionellids or ammonites; according to others, magnetostratigraphic reference levels. For example, the main (primary) markers of the Jurassic/Cretaceous boundary are considered to be the base of the Calpionella Zone (C. alpina Subzone), which coincides with a "boom" of small globular *C. alpina*, the first appearance of nanofossils *Nannoconus steinmannii minor* and *N. kamptneri minor*, and the base of the M18r magnetozone. Supporting (secondary) markers, which are useful in the identification of the Jurassic/Cretaceous boundary interval, include not only some paleomagnetic reference levels (bases of the M19n.1n and M19n.1r subzones) and reference levels based on calcareous nanofossils and palynomorphs but also the bases of ammonite zones and subzones (Berriasella jacobi, Subcraspedites lamplughi, and Pseudosubplanites grandis) (Wimbledon et al., 2011). Criticizing the above-mentioned priority of markers, V.A. Zakharov (consistent adherent of the view that ammonites play the leading role in the zonation and correlation of Jurassic and Cretaceous strata) points out that ammonites have no alternative in efficiency—accuracy and quickness—in the detailed biochronology of the Mesozoic, particularly the Jurassic and Lower Cretaceous (Zakharov, 2011, p. 74). According to Zakharov, ammonoids remain the most reliable fossil group for the chronostratigraphy of Mesozoic sediments, as they were during the previous two centuries; the high efficiency of work with this group was checked and proven by tens of generations on all the continents (Zakharov, 2011, p. 73). The most widely discussed ammonite markers are the bases of the Berriasella jacobi and Pseudosubplanites grandis Subzones, which mark off the so-called traditional basal Berriasian interval (Wimbledon et al., 2011), and the base of the Subthurmannia occitanica Zone (Hoedemaeker et al., 2003; Remane, 1991; Zakharov et al., 1996). Recently, we have provided some arguments for the selection of the base of the Pseudosubplanites grandis Subzone (Dzyuba et al., 2013). However, A.Yu. Guzhikov (2013) prefers the paleomagnetic markers of the Jurassic/Cretaceous boundary at the bases of the M18r or M17r magnetozones.

"Boundary" is one of the most important concepts in stratigraphy. According to B.S. Sokolov, the most informative model for a stratigraphic boundary was being developed for Phanerozoic systems; however, the boundless opportunities of the paleontological method are an illusion even for the Phanerozoic, because it has a great deal of limitations (Sokolov, 1987, p. 18). Discussing the problems related to the determination of the boundary, Sokolov (1987, p. 24) pointed out that the model for the biostratigraphic boundary of a regional stratigraphic unit (which might also become the world standard) can be based neither on the first appearance of the "zonal species" nor on the extinction of the preexisting species of the same rank. In fact, there is almost always an interval between such species. Most often, under particular local conditions, they are simply migrants, even if they exist in a single large basin.

Thus, there is still no international consensus on the GSSP of the Berriasian—the basal stage of the Cretaceous System. Therefore, there is still no accurate determination of the position of the Jurassic/Cretaceous boundary in particular sections in the huge area of occurrence of Jurassic and Cretaceous rocks in Siberia. To find the optimum solution concerning the Berriasian GSSP, it is necessary to focus on the search for the most preferable level or, at least, interval for determination of the GSSP in each region. The present paper is fully concerned with Siberia. It is clear that, ideally, such an interval has to be characterized by a sufficient number of markers, so that interregional (including Boreal–Tethyan) correlations can be carried out. We can agree with Sokolov (1987, p. 18) in the idea that the ideal model for the boundary can be approached only using a combination of two methods: physical and paleobiological (in the broad meaning, it can be called geobiological).

Lithostratigraphy of the Siberian Jurassic/Cretaceous boundary interval

The Siberian Jurassic and Cretaceous boundary beds are observed in a huge territory (Fig. 1); they are dominated by terrigenous rocks of marine and continental geneses, which are of very different lithologic compositions and belong to the upper part of the regional Bazhenovo Horizon (Resolution, 2004).

The Bazhenovo Formation, which is typical of the regional horizon, is widespread in central and northern West Siberia; it is a well-known reference unit in the Mesozoic rocks of West Siberia (Braduchan et al., 1986; Bulynnikova et al., 1978; Gurari, 1988; Shurygin et al., 2000). The Bazhenovo Formation consists of highly carbonaceous brownish black mudstones, which are massive, tabular, and lamellar, interbedded with radiolarites and clayey limestones and containing remnants of marine fossils. The rocks sometimes contain ≥20% organic matter. Based on finds of numerous remnants of macro- and microfauna, the stratigraphic extent of the formation is everywhere determined as upper Lower Volgian–lower "Boreal Berriasian" (Atlas, 1990; Resolution, 2004). In southern and southeastern West Siberia, the Bazhenovo Formation is replaced by the upper part of the Mariyanovka Formation, which is dominated by mudstone-like clays with abundant macro- and microfauna, indicating that this part of the section belongs to the regional Bazhenovo Horizon (Shurygin et al., 2000). In the south the areas of distribution of the Mariyanovka Formation are bounded by the zone of occurrence of the upper part of the predominantly sandy Bagan Formation; in the southeast, mainly by the continental sandstones of the upper Maksimkin Yar Formation. The mudstones

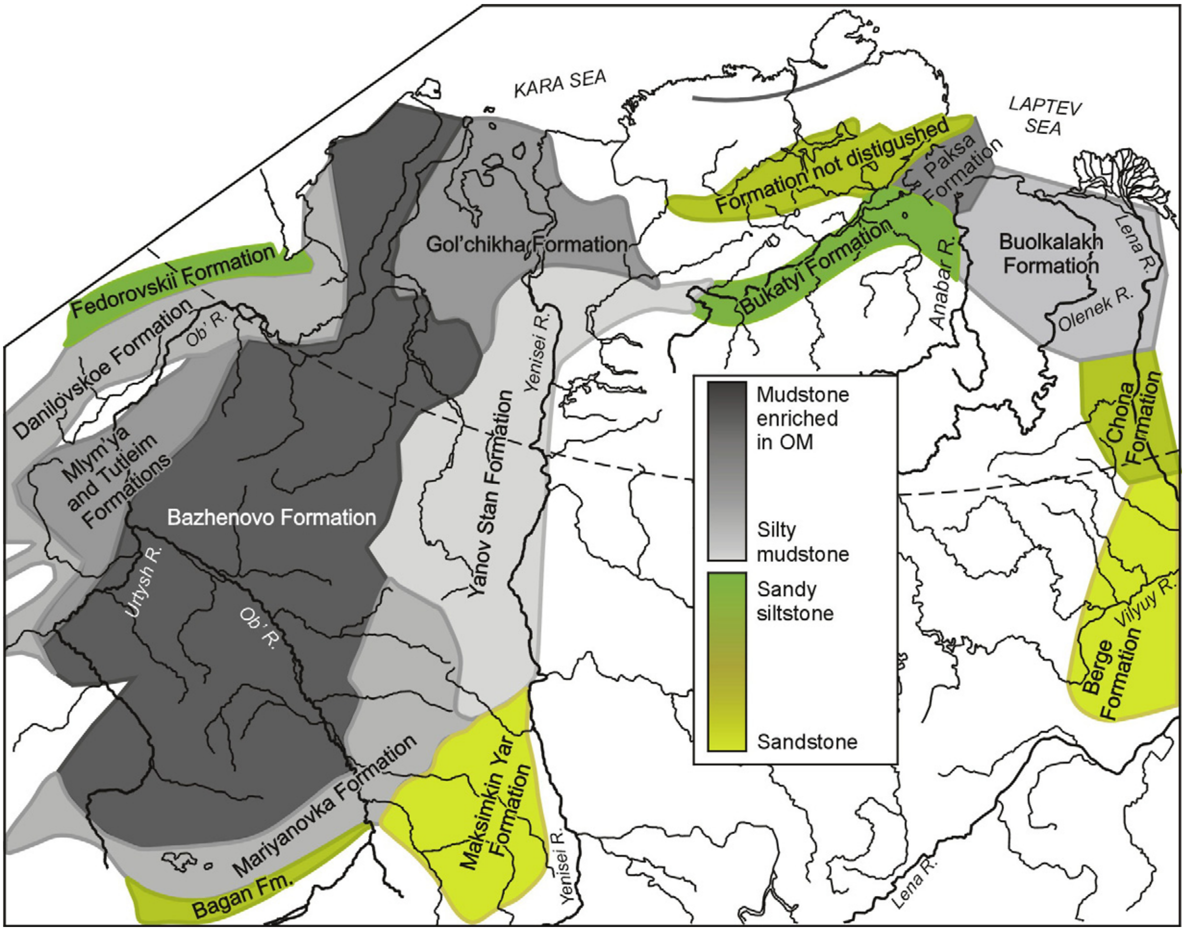

Fig. 1. Distribution of the formations of the upper part of the Bazhenovo Horizon (Jurassic/Cretaceous boundary sediments) in Siberia.

of the Bazhenovo Formation, which are uniquely rich in planktonogenic and bacteriogenic organic matter, are replaced by the lower part of the clayey series of the Tutleim and Mulym'ya Formations in western West Siberia and by the upper subformation of the Danilovskoe Formation of clayey composition in the northwest. The latter in the Urals region is replaced by the siltstones and sandstones of the Fedorovskii Formation, whose stratigraphic extent also approximately corresponds to that of the Bazhenovo Horizon, judging by assemblages of macro- and microfauna (Resolution, 2004). In northeastern and eastern West Siberia, the Bazhenovo Formation is replaced by the upper horizons of the thick clayey series of the Gol'chikha and Yanov Stan Formations, which contain assemblages of marine macro- and microfossils typical of the Bazhenovo Horizon. The latter formation also partly occurs to the east of West Siberia, in the northwestern framing of the Siberian Platform.

In northern East Siberia, in the framing of the Siberian Platform, the upper Bazhenovo Horizon consists of the greenish gray and greenish dark gray silts and sandy silts of the Bukatyi Formation with vast assemblages of macro- and microfauna. To the northeast the Bukatyi Formation is replaced by dark gray deep-water marine mudstone-like clays with thin interbeds of highly carbonaceous brownish clays and massive bluish clays (lower part of the Lower Paksa Subformation) (Nikitenko et al., 2013). Biostratigraphic units based on ammonites, belemnites, bivalves, foraminifers, dinocysts, and spores and pollen were recognized in the thoroughly studied type section of this subformation, which contains abundant fossils (Basov et al., 1970; Dzyuba, 2012; Nikitenko et al., 2013; Saks, 1976; Zakharov and Rogov, 2008; Zakharov et al., 1983, 2014). The paleomagnetic (Bragin et al., 2013; Houša et al., 2007) and isotope–geochemical (Dzyuba et al., 2013; Zák et al., 2011) studies of these sections with regard to the whole combination of biostratigraphic scales showed that the interval in which the Berriasian Working Group is searching for markers of the Jurassic/Cretaceous boundary (Wimbledon et al., 2011) corresponds to the lower part of the Lower Paksa Subformation.

To the south and southeast, the Lower Paksa Subformation is replaced by marine clayey siltstones, siltstones, and clays with thin interbeds of silty sands belonging to the upper part of the Buolkalakh Formation, which contains assemblages of ammonites, bivalves, foraminifers, and microphytofossils (Nikitenko et al., 2013; Resolutions, 1981; Shurygin et al., 2000). To the south, in the eastern framing of the Siberian Platform, the Buolkalakh Formation is replaced by the sandstones and siltstones of the Chona Formation, whose interbeds often contain remnants of sea mollusks, predominantly ammonites and buchias (Shurygin et al., 2000; Zinchenko et al., 1978).

The stratigraphic analog of the Lower Paksa Subformation in southern East Siberia is part of the Berge Formation, which is a gray-colored carbonaceous, predominantly sandy series of continental genesis (Kirina et al., 1978).

Thus, the traditional basal Berriasian interval, like the boundary between Volgian and Ryazanian (= Boreal Berriasian) Stages, is localized within homogeneous rock series in all the regions of Siberia.

Biostratigraphy of the Jurassic/Cretaceous boundary interval in Siberia

The boundary between Jurassic and Cretaceous Systems in northern Russia and adjacent Arctic territories has long been viewed as the boundary between Volgian Stage and "Boreal Berriasian." In Siberia it was assigned to the base of the Chetaites sibiricus or Praetollia maynci ammonite Zones. In both Russian and non-Russian publications, the lower stage of the Cretaceous System in Boreal sections is often considered to be Ryazanian (e.g., Birkelund et al., 1982; Bragin et al., 2013; Casey, 1973; Dzyuba, 2012, 2013; Dzyuba et al., 2013; Gradstein et al., 2012; Houša et al., 2007; Nagy and Basov, 1998; Rawson et al., 1978; Smelror and Dypvik, 2006; Surlyk and Ineson, 2003; Surlyk et al., 1973; Zakharov et al., 2014), which, in contrast to the Volgian, has never been included in the General Stratigraphic Scale (GSS) of Russia, accepted by the Interdepartmental Stratigraphic Committee. Since 1996 both Boreal stages have been officially recognized in Russia as regional (Zhamoida and Prozorovskaya, 1997). The term "Boreal Berriasian" is a misnomer, if only because the stratigraphic extent of this unit does not correspond to the Berriasian Stage, as it is clear for many experts, and the adjective "Boreal" does not solve the problem. The relationship of the Volgian and Ryazanian Stages with the Tithonian and Berriasian Stages, which are standard for this interval, is widely discussed. No clear-cut solution of this problem was obtained by biostratigraphic means. In 1996, based on the results of I.I. Sey and E.D. Kalacheva (1993), the Interdepartmental Stratigraphic Committee of Russia accepted a correlation chart in which the zones (lonas) of the Upper Volgian Substage are considered in the extent of two lower zones of the Berriasian Stage, whereas the zones (lonas) of the Lower and Middle Volgian Substages correspond to the Tithonian Stage. Thus, the Volgian Stage was removed from the GSS of Russia (Zhamoida and Prozorovskaya, 1997). Many experts were not satisfied with this solution of the problem; they questioned both the conclusions concerning the correlation of the Tithonian, Volgian, Berriasian, and Ryazanian Stages (e.g., Bragin et al., 2013; Houša et al., 2007; Mitta, 2001; Zakharov, 2011) and the necessity of removing the Volgian Stage from the GSS of Russia (e.g., Mitta, 2001; Zakharov, 2003, 2011). Some members of the Cretaceous Commission of the Interdepartmental Stratigraphic Committee of Russia suggested restoring the Volgian Stage and, simultaneously, introducing the Ryazanian Stage (Baraboshkin et al., 2013). In our view, the most important objective is to correct the position of the Volgian and Ryazanian ammonite zones in the GSS of Russia with respect to the Tithonian and Berriasian zonal successions in accordance with the latest data of bio-, magneto-, and chemostratigraphic correlations (Bragin et al., 2013; Dzyuba et al., 2013; Houša et al., 2007). As regards the status of the Volgian and Ryazanian Stages, it does not matter much to us whether they will be recognized as stages of the GSS of Russia or as regional stages. As neither of them is a standard stage of the International Stratigraphic Chart, both stages are, in fact, regional (note that the whole Boreal domain can be meant by "region").

It is justified to use the Volgian and Ryazanian Stages in the vast territory of Boreal paleobasins, because they reflect two different stages of geologic history—primarily that of paleobasins in the East European Platform. To some extent this is also a tribute to the traditions according to which most geological documents for Boreal regions were compiled in the 20th–early 21st centuries. Unlike the boundary between the standard Tithonian and Berriasian Stages, only the Volgian/Ryazanian boundary in Boreal sections has reliable bioevent markers. However, it is hardly correct now to regard the boundary between Jurassic and Cretaceous Systems (= boundary between Tithonian and Berriasian Stages) as parallel to the boundary between Volgian and Ryazanian Stages.

In the Jurassic System, the lower boundaries of all the stages have traditionally been based on ammonites. Now mostly ammonite genera and species are selected to substantiate the GSSP of Jurassic stages (or discussed as markers of the boundaries of stages) (Gradstein et al., 2012). In Siberia the lower stages of the Cretaceous System have a close lithostratigraphic relationship with the Jurassic System and are well described by ammonites. That is why the determination of the Jurassic/Cretaceous boundary in Siberian sections was initially based on the determination of the boundaries of local ammonite zones and hypothetical correlations of the latter with the standard Mediterranean ammonite succession, based on Tethyan taxa.

However, the application of exclusively ammonite scales to distant correlations has its limitations. As a rule, it is postulated that ammonite zonation is based on phylogenetic events, and the lower boundary of zones in individual sections is defined by the first appearance of the index taxon. The principle of the basic link, used to differentiate between species, presupposes the determination of the divergence node. On ammonite-based phylogenetic trees, a dashed line going below the boundary of the indexed ammonite zone usually joins the index species of the zone to the ancestral species (Fig. 2). This stresses the fact that new significant diagnostic differences from the ancestral phene do not appear instantly. Therefore, even without regard to the time required for the geographic distribution of the new phenotype or the time of migration, there will always be an uncertainty interval for the boundary of phylo- or phenozones near the divergence node (Fig. 2). In some publications on ammonites, to eliminate this contradiction to the postulated isochronous character of the boundaries of ammonite zones, phylogenetic trees are presented in which the phylum line of the ancestral species horizontally joins the beginning of the descendant phylum line.

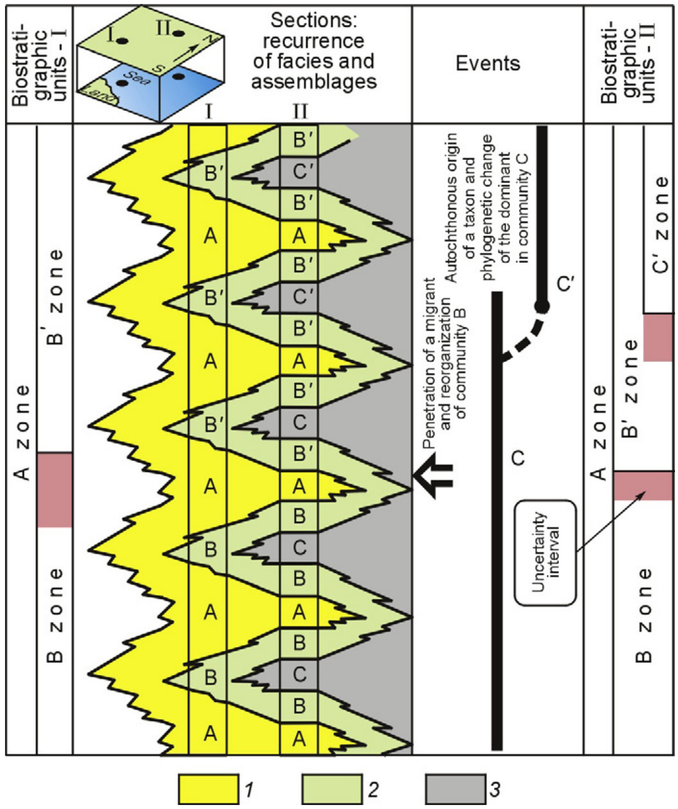

Fig. 2. Biostratigraphic units in sections of different facies: I, close to the paleoshore; II, remote from the paleoshore. A–C, Typical assemblages of taxa. *1*, predominantly sandy sediments; *2*, predominantly silty sediments; *3*, predominantly clayey sediments.

The logic of such phylogenetic trees is not quite clear, because they presuppose the origin of the descendant from an already extinct ancestor, if the final and initial points of the phylum lines are connected, or instantaneous mass (in all the populations) transformation of the ancestral phenotype into a distinct descendant phenotype. Even if the lower boundary of the zone in the section is based on the first appearance of the index taxon owing to migration, the migrant does not simultaneously penetrate the communities of all the bionomic zones (Fig. 2). Therefore, the first appearance of a migrant taxon in sections of different facies will hardly indicate an isochronous level, and the uncertainty interval for the boundary of the biostratigraphic zone can be rather wide.

The new practice of determination of GSSP makes the problem more difficult when it is postulated that the boundary should be based on the first appearance of a taxon. The achievement of this goal is very much complicated by (1) the extreme subjectivity of experts on ammonites in the taxonomic assignment of the same specimens, which is due to the lack of large-scale monographic studies of ammonites, and (2) the desire, under these circumstances, to carry out a too detailed subdivision with the use of biohorizons.

Not long ago, researchers started to use the Jurassic and Cretaceous Boreal standard for a more accurate correlation in the giant pan-Boreal territory. It is a system of parallel zonal scales based on different fossil groups (Nikitenko et al., 2013; Shurygin et al., 2011; Zakharov et al., 1997). Parallel zonal scales based on belemnites, bivalves, microfauna, and microphytofossils, calibrated with respect to the ammonite scale, are regarded as components of the Boreal standard rather than a supplement to the ammonite scale. The combination of biostratigraphic scales—the regional ammonite scale and scales based on other fossil groups—has not only expanded the area to which they can be applied but also increased the resolution of the general biostratigraphic base in the subdivision and the accuracy of the correlations (Shurygin et al., 2011).

If the Boreal standard is regarded as a set of scales, it is a "bioevent" combination in which the reference intervals are characterized by a unique succession of the results of combination of biologic events of independent origins (phylogenetic, chorologic, and ecosystem). It is a fixed succession of independent events that is the most likely to show an isochronous character during identification in different territories.

The boundaries of biostratigraphic units based on different fossil groups often do not coincide. When the whole set of parallel zonal scales is analyzed, this inconsistency makes it possible to identify and trace very narrow intrazonal intervals (analysis of cointervals of adjacent zones) (Shurygin, 2005; Shurygin et al., 2000).

The Jurassic/Cretaceous boundary interval in Siberian sections (if it is viewed as the interval from the Craspedites okensis Zone to the Hectoroceras kochi Zone) is now well described by a combination of mutually correlated parallel zonal scales based on different fossil groups (Fig. 3) (Nikitenko et al., 2013; Shurygin et al., 2011). Along with five ammonite zones, five biostratigraphic units based on belemnites, four based on buchias, five based on foraminifers, two based on dinocysts, and two based on spores and pollen are recognized in this interval (Fig. 3). However, there are no biostratigraphic markers here which permit a direct correlation between some of the above-mentioned biostratigraphic units and biostratigraphic units in Tethyan sections of Jurassic and Cretaceous boundary sediments.

Nonpaleontological methods of Boreal–Tethyan correlation

The magnetic polarity data from some intervals of Jurassic and Cretaceous boundary strata with typical Tethyan fossil assemblages are given in publications on many European sections (e.g., Channell et al., 2010; Grabowski, 2011; Grabowski et al., 2010, 2013; Guzhikov et al., 2012; Houša et al., 1999; Lukeneder et al., 2010; Michalík et al., 2009; Pruner et al., 2010; Wimbledon et al., 2013). It became possible to solve the problem of Boreal–Tethyan correlation of Jurassic and Cretaceous boundary sediments with the appearance of data from magnetostratigraphic studies of these sediments in the Nordvik Peninsula key section, East Siberia (Bragin et al., 2013; Houša et al., 2007). A continuous succession of magnetozones from M20n to M16r, including the M20n.1r (Kysuca) and M19n.1r (Brodno) subzones, is detected in the

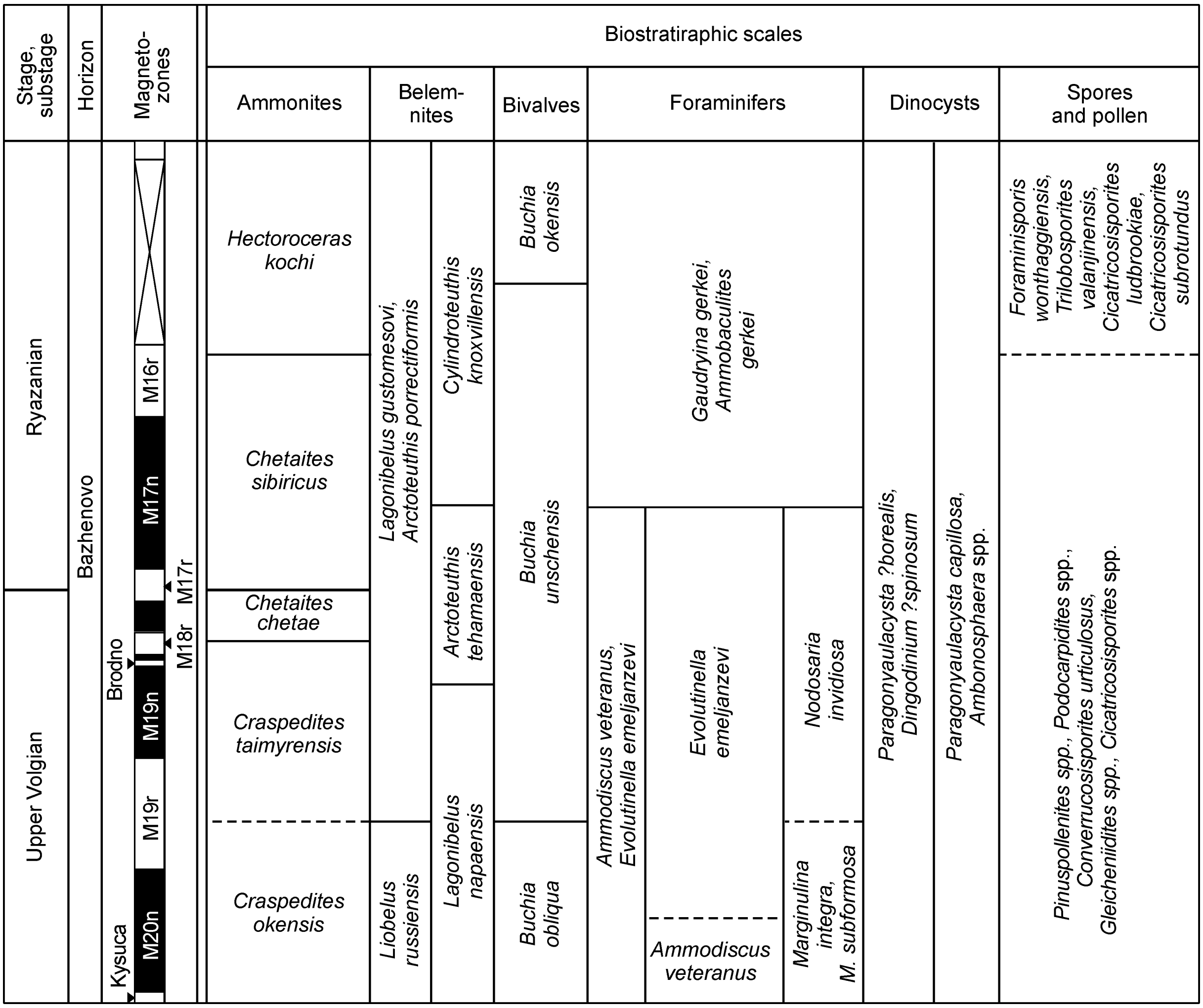

Fig. 3. Regional scales for the Jurassic/Cretaceous boundary sediments of Siberia (modified and supplemented after (Bragin et al., 2013; Nikitenko et al., 2013; Shurygin et al., 2011)).

Jurassic/Cretaceous boundary interval of this section. Boreal–Tethyan correlation with the use of magnetozones showed that the boundary between Jurassic and Cretaceous Systems, if it is determined in Tethyan sections within the M19n magnetozone, is localized in the Upper Volgian Craspedites taimyrensis Zone in the Nordvik section. Note that the beds assigned in the Nordvik section to the Craspedites taimyrensis Zone, are poorly described by ammonites and no specimens of the index species were found there (Zakharov and Rogov, 2008; Zakharov et al., 1983). Most of the M19n magnetozone in this section belongs to an ammonite-free interval. The lower boundary of the above-lying Chetaites chetae Zone in the Nordvik section is localized within the M18r magnetozone (Bragin et al., 2013; Houša et al., 2007). The latter in Tethyan sections contains the lower boundary of the Pseudosubplanites grandis Subzone (Guzhikov et al., 2012), one of the historic markers of the Jurassic/Cretaceous boundary (in accordance with the resolution of the Colloquium on the Jurassic/Cretaceous Boundary (Lyons, 1963), published in 1965).

After additional magnetostratigraphic studies on the Nordvik Peninsula, the position of the magnetozones M18n, M17r, and M17n in the section was determined considerably more precisely and the magnetozone M16r was identified (Bragin et al., 2013). It became evident that the traditional boundary between Volgian and Ryazanian Stages in Siberia (base of the Chetaites sibiricus Zone) is localized within the M17r magnetozone, whose lower part in Tethyan sections contains the lower boundary of the obviously Berriasian Subthurmannia occitanica Zone (Fig. 4). As it turned out, the lower boundary of the Hectoroceras kochi Zone, which goes next in Boreal sections, is localized in the reverse-polarity paleomagnetic zone indexed by us as M16r, which contains the boundary between the standard Subthurmannia occitanica and S. boissieri Zones in Tethyan sections (Bragin et al., 2013). Analysis of interregionally correlated macrofaunal horizons detected in the Middle/Upper Berriasian boundary interval confirmed the reliability of the obtained magnetostratigraphic base (Bragin et al., 2013). The position of the upper boundary of the H. kochi Zone, detected by A.Yu. Guzhikov and E.Yu. Baraboshkin (2008), with respect to the interval of predominant reverse polarity on the Boyarka River (northern East Siberia) remains disputable. Two versions are considered, both of

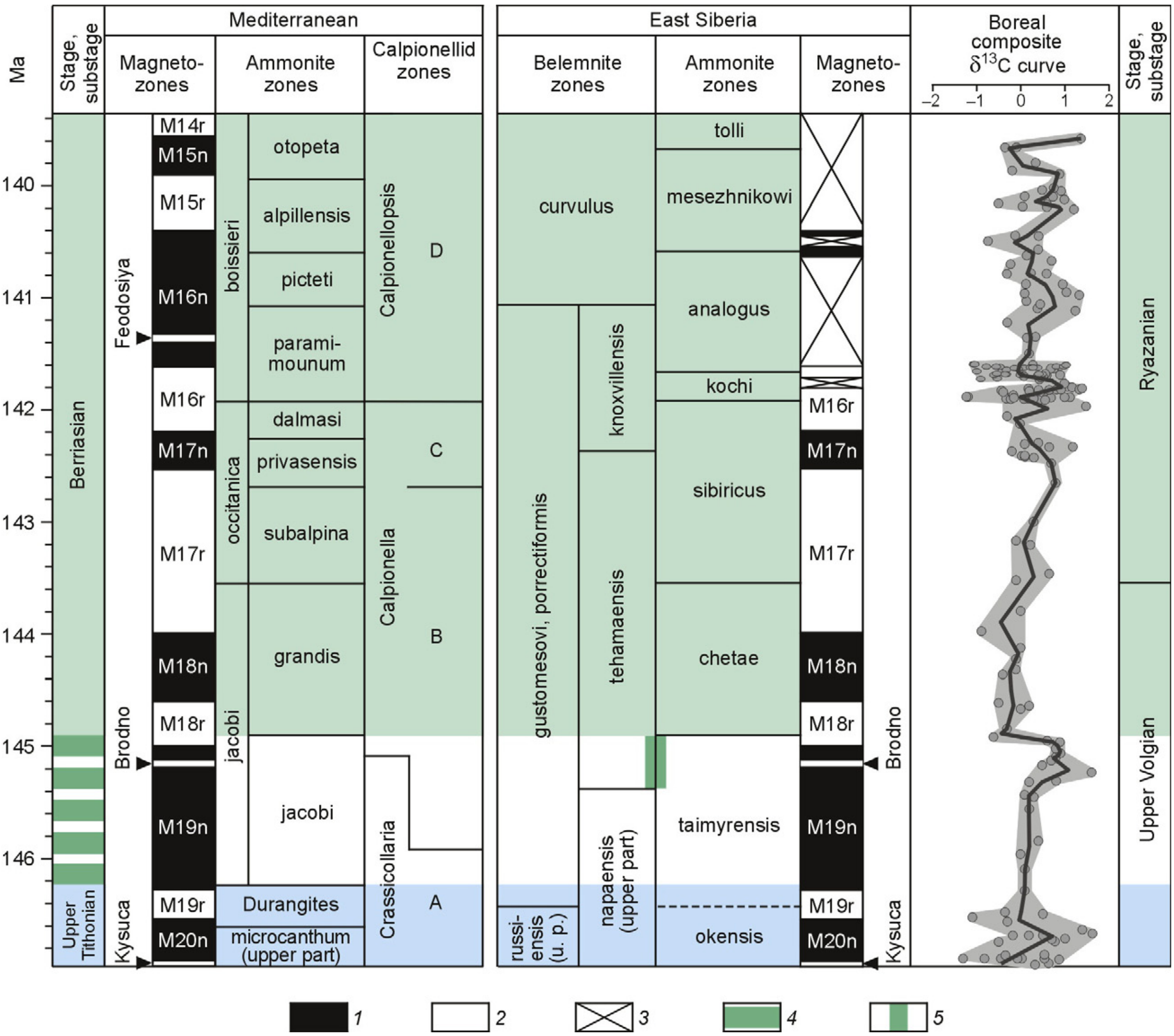

Fig. 4. Boreal composite carbon isotope curve; Upper Volgian and Ryazanian ammonite, belemnite, and magnetostratigraphic scales for East Siberia, compared with the Tethyan (Mediterranean) standard (refined after (Bragin et al., 2013; Dzyuba et al., 2013; Guzhikov, 2013). The scale of absolute age is given after (Gradstein et al., 2012). *1*, normal polarity; *2*, reverse polarity; *3*, no data available; *4*, basal Berriasian interval, in which the search for markers of the Jurassic/Cretaceous boundary is being carried out; *5*, cointerval of the Arctoteuthis tehamaensis and Craspedites taimyrensis Zones.

which meet biostratigraphic criteria for correlation: correspondence to the upper part of the M16r magnetozone (Bragin et al., 2013) or to the M16n.1r subzone (Feodosiya) of the M16n magnetozone (Guzhikov, 2013). In general, the results obtained for northern Siberia are good evidence that paleomagnetic scales should be used to substantiate the position of the Jurassic/Cretaceous boundary interval in different regions. However, paleomagnetic criteria for determination of the boundary can be used only together with biostratigraphic indicators because of the nonspecific character of magnetozones (Guzhikov et al., 2012). Correct identification of magnetic chrons is hardly possible without biostratigraphic markers.

Isotope–geochemical data are other nonpaleontological data which help Boreal–Tethyan correlation of the Jurassic/Cretaceous boundary interval. Carbon isotope variations near the Jurassic/Cretaceous boundary in carbonate sections of Tethyan regions are widely studied (Emmanuel and Renard, 1993; Grabowski et al., 2010; Katz et al., 2005; Michalík et al., 2009; Savary et al., 2003; Tremolada et al., 2006; Weissert and Channell, 1989; Weissert and Lini, 1991; Weissert and Mohr, 1996; Zák et al., 2011). Until recently, Jurassic/Cretaceous transition beds were not considered in detail, if at all, in publications on carbon and oxygen isotope variations in Boreal sections of the Volgian and/or Ryazanian Stages (Ditchfield, 1997; Gröcke et al., 2003; Hammer et al., 2012; Nunn and Price, 2010; Nunn et al., 2010; Podlaha et al., 1998; Price and Mutterlose, 2004; Price and Rogov, 2009; Price et al., 2000; Ruffel et al., 2002). The section on the Nordvik Peninsula was the first Boreal section for which carbon and oxygen isotope curves describing variations of $\delta^{13}C$ and $\delta^{18}O$ in the Jurassic/Cretaceous boundary interval were obtained

(Zák et al., 2011). However, the Jurassic/Cretaceous boundary interval showed no significant deviations in the carbon and oxygen isotope records which might be used for Boreal–Tethyan correlations.

Another Boreal section of Jurassic/Cretaceous boundary sediments characterized by unique completeness, with a detailed paleontological and stratigraphic description, is located in the foothills of the North Urals, on the Mauryn'ya River, West Siberia (Alifirov et al., 2008; Dzyuba, 2009, 2013; Urman, 2010). The Jurassic/Cretaceous boundary interval on the Mauryn'ya River is rich in fossils, including belemnite rostra. A collection of well-preserved belemnite rostra was recovered from this interval, and their isotope–geochemical studies permitted plotting detailed curves for carbon and oxygen isotope variations (Dzyuba et al., 2013). Simultaneously, the previous data on carbon and oxygen isotope variations in the Jurassic/Cretaceous boundary sediments of the Nordvik Peninsula were supplemented. Comparison of the $\delta^{13}C$ and $\delta^{18}O$ curves characterizing the Mauryn'ya River and Nordvik Peninsula sections showed the isochronous character of the main excursions and the same general trends of variation in both carbon and oxygen isotope compositions. With regard to the published data on other Boreal sections, the Volgian and Ryazanian Stages are completely described by carbon isotope data, but only the data on the Upper Volgian–Ryazanian interval are verified for several sections. The positive excursion marking the upper part of the Craspedites taimyrensis Zone in the Mauryn'ya section (Dzyuba et al., 2013), which is observed in the Mar'evka (East European Platform) (Price and Rogov, 2009), Nordvik Peninsula (northern East Siberia) (Dzyuba et al., 2013), and Guppen–Heuberge (Switzerland) (Weissert and Mohr, 1996) sections, is the most important for Boreal–Tethyan correlation. Comparison of isolated data on carbon isotope variations in different Boreal sections based on detailed biostratigraphic studies permitted plotting a composite (for Boreal regions, reference) carbon isotope curve, which provides a good description of the Upper Volgian Substage and the Ryazanian Stage (Fig. 4) (Dzyuba et al., 2013). This curve was based on the data obtained from the Mauryn'ya and Nordvik sections for the interval including the Craspedites okensis–Chetaites sibiricus ammonite Zones. For the above-lying sediments, the curve based on data for Yatriya (West Siberia) (Price and Mutterlose, 2004) and Boyarka (East Siberia) (Nunn et al., 2010) was used.

Comparison of the composite Boreal carbon isotope curve with the curve for this interval, plotted for the Tethyan Guppen–Heuberge section of Switzerland (Weissert and Mohr, 1996), suggests interesting conclusions about Boreal–Tethyan correlation. In the Jurassic/Cretaceous boundary interval of the Swiss section, calpionellid zones A and B are recognized (Weissert and Mohr, 1996), whose boundary, detected from the bloom of small globular *Calpionella alpina*, is discussed as a marker of the Jurassic/Cretaceous boundary (Michalík and Reháková, 2011; Wimbledon et al., 2011). The conspicuous positive shift of $\delta^{13}C$ recorded in many Boreal sections (see above) was observed in this section immediately above the Jurassic/Cretaceous boundary, which is here correlated with the boundary of calpionellid zones A and B. This positive excursion and the subsequent return to background values of $\delta^{13}C$, observed within the calpionellid zone B (Guppen–Heuberge section), at the base of beds with *Subcraspedites maurynijensis* (Mauryn'ya section), and at the base of the Chetaites chetae Zone (Nordvik section), might be useful for Boreal–Tethyan correlation of Jurassic/Cretaceous boundary sediments.

Possibilities of correlation of the Siberian Jurassic/Cretaceous boundary interval with the Tethyan standard

If the Berriasian GSSP is determined in Tethyan sections, the identification of this level in Boreal sections is possible only based on a combination of data obtained by paleontological and nonpaleontological (independent) methods of stratigraphy (bio-, chemo-, magnetostratigraphy, etc.). The problem is not which event will be used to determine the GSSP. In our view, any event can be used as a marker of the Jurassic/Cretaceous boundary (phylogenetic change of taxa, paleomagnetic reversal, or isotopic excursion). The problem is the potential traceability of the boundary worldwide. It is evident that the absolutely precise position of the Jurassic/Cretaceous boundary, determined in the Tethyan section, will never be determined in Boreal sections. Even in continuous sections of boundary sediments, there will always be an uncertainty interval (including the case when the GSSP are determined using the base of the magnetozone or isotopic marker). It should always be taken into account that in geological studies of vast Siberian territories, the position of the boundary in individual sections will usually be determined on a biostratigraphic basis. The application of a set of parallel biostratigraphic scales with regard to isotopic and paleomagnetic events can ensure quite a narrow uncertainty interval for the position of this boundary in Boreal sections. After comprehensive studies of type sections of Jurassic/Cretaceous boundary sediments in Siberia, it became obvious that the primary markers, which are under consideration as candidates for the determination of the Berriasian GSSP (Wimbledon et al., 2011), are localized in the interval whose Boreal analog is within the Craspedites taimyrensis ammonite Zone (if it is determined within the boundaries tentatively accepted in the key section of the Nordvik Peninsula). The same applies to most of the so-called secondary markers, e.g., the base of the Berriasella jacobi ammonite Zone and the base and top of the Brodno subzone (Wimbledon et al., 2011).

Interestingly, if the levels corresponding to the bases of the Calpionella alpina Subzone (Calpionella Zone) or Berriasella jacobi Subzone (B. jacobi Zone) are determined in Siberian sections with no paleomagnetic studies, the uncertainty interval for the position of these levels here will be the whole Craspedites taimyrensis ammonite Zone (Fig. 4). Besides, the tentative stratigraphic extent of the latter zone on the Nordvik Peninsula does not yet preclude that these levels also belong to the upper part of the C. okensis Zone. With regard to the paleomagnetic data, the uncertainty interval for the position of the base of the B. jacobi ammonite Subzone in Boreal sections narrows down to the lower part of the M19n magnetozone, as in the Puerto Escaño (Spain) (Pruner et al., 2010) or Le Chouet (France) sections (Wimbledon et al., 2013). Note that the lower boundary of the B. jacobi Subzone in the Le Chouet section is correlated by the authors of the paper with the base of an interval with an uncertain or mixed polarity (beds 86–88) and it is shown below the boundary of the reliably detected interval with a normal polarity M19n (base of bed 89) (Wimbledon et al., 2013, Fig. 18), whereas the ammonites identifying the B. jacobi Subzone appear in the middle part of bed 89 (Wimbledon et al., 2013, Fig. 12).

The position of the base of calpionellid zone B and, therefore, the base of the Calpionella alpina Subzone of the Calpionella Zone has quite a wide uncertainty interval in Boreal sections even with regard to paleomagnetic data—the whole M19n magnetozone (both above and below the Brodno subzone), as it was shown by comparison of data on some Tethyan sections (Wimbledon et al., 2013).

If the base of the M18r magnetozone or the boundary between the Berriasella jacobi and Pseudosubplanites grandis ammonite Subzones are used as markers of the Jurassic/Cretaceous boundary, the uncertainty interval in Siberian sections, with the use of a combination of biostratigraphic scales, narrows down to the upper part of the Craspedites taimyrensis ammonite Zone—a cointerval of this zone with the Arctoteuthis tehamaensis belemnite Zone (Fig. 4). This cointerval is associated with a widely traceable positive carbon isotope excursion (Dzyuba et al., 2013) and the Brodno paleomagnetic subzone (M19n.r1) (Bragin et al., 2013).

Conclusions

Any of the events discussed by the international expert community can be regarded as a marker of the Jurassic/Cretaceous boundary: a phylogenetic change of taxa, paleomagnetic reversal, or isotopic excursion. However, the problem of identification of this level in Boreal sections can be solved only using a combination of data obtained by paleontological and nonpaleontological methods of stratigraphy (bio-, chemo-, magnetostratigraphy, etc.). The precise position of the Jurassic/Cretaceous boundary, whose marker will be defined in the Tethyan section, will never be determined in Boreal sections: There will always be an uncertainty interval, particularly for sections opened up by boreholes. In geological studies of vast Siberian territories, the position of the boundary in individual sections will usually be determined on a biostratigraphic basis. If a set of parallel biostratigraphic scales is applied with regard to isotopic and paleomagnetic events, this can ensure quite a narrow uncertainty interval for the position of this boundary in Boreal sections. With any of the accepted markers which are under the examination of the Berriasian Working Group, the Jurassic/Cretaceous boundary in Siberian sections will be within the upper part of the regional Bazhenovo Horizon. The least interval of the uncertainty of the position of this boundary in Siberian sections will be ensured by the selection of one of two markers: biostratigraphic (base of the Pseudosubplanites grandis Subzone) or magnetostratigraphic (base of the M18r magnetozone). Also, the boundaries of the M19n1r (Brodno) subzone are acceptable in this respect. When the position of the Jurassic/Cretaceous boundary is determined in individual Boreal sections, it is preferable to use cointervals of parallel zonal scales based on different fossil groups. If the Jurassic/Cretaceous boundary is placed at the boundary of calpionellid zones A and B or at the base of the Berriasella jacobi Subzone, its position will have a very large uncertainty interval in Siberian sections.

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