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Jurassic and Cretaceous stratigraphy of the Anabar area (Arctic Siberia, Laptev Sea coast) and the Boreal zonal standard

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Abstract

Recent integrated studies of Mesozoic reference sections of the Anabar area (northern Middle Siberia, Laptev Sea coast) and the reinterpretation of all the previous data on a modern stratigraphic basis permit considerable improvement of the bio- and lithostratigraphic division and facies zoning of Jurassic and Cretaceous sediments in the region. Analysis of abundant paleontological data allows the development or considerable improvement of zonal scales for ammonites, belemnites, bivalves, foraminifers, ostracods, dinocysts, and terrestrial palynomorphs from several Jurassic and Cretaceous intervals. All the zonal scales have been calibrated against one another and against regional ammonite scale. Reference levels of different scales useful for interregional correlation have been defined and substantiated based on the analysis of lateral distribution of fossils in different regions of the Northern Hemisphere. It provides the possibilities to propose and consider parallel zonal scales within the Boreal zonal standard for the Jurassic and Cretaceous periods. A combination of these scales forms an integrated biostratigraphic basis for a detailed division of Boreal-type sediments regardless of the place of their formation and for the comparison with the international stratigraphic standard as far as a possible use of a set of reference levels for correlation.

Keywords: Jurassic; Cretaceous; stratigraphy; Boreal zonal standard; ammonites; belemnites; bivalves; foraminifers; ostracods; dinoflagellate cysts; spores and pollen; Siberia; Anabar area

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Introduction

Mesozoic terrigenous sediments contained Boreal-type macrofauna, microfauna, and palynomorphs are abundant in polar and circumpolar regions of the Northern hemisphere. Mesozoic marine sediments in many Arctic regions are a part of the sedimentary cover and often contain giant accumulations of hydrocarbons. Therefore, high-resolution stratification of Jurassic and Cretaceous sediments remains a topical problem. In the meantime, stratigraphic data on the Mesozoic of Arctic territories and the Russian Arctic shelf are fragmentary and incomplete. In recent years, wide integrated paleontological, stratigraphic, sedimentological, and geochemical studies of Mesozoic outcrops on the Laptev Sea coast have been conducted at the Trofimuk Institute of Petroleum Geology and Geophysics. All the previous data have been reinterpreted on a modern stratigraphic basis to develop and improve zonal scales on different fossil groups and the next generation of high-resolution stratigraphic charts.

High-latitude Arctic territories of Russia are characterized by peculiar Mesozoic biota. This sometimes precludes a direct correlation of Boreal-type sections with West European ones, included most of the stratotypes of Jurassic and Cretaceous stages and their zonal units. Therefore, the Boreal zonal standard was developed for Boreal (Arctic) regions, which contained a set of parallel zonal scales reflecting successions of biostratigraphic units of different ranks (Zakharov et al., 1997). The main purpose of the Boreal zonal standard is to provide the subdivision and correlation of biostratigraphic units in areas of Boreal-type sediments and their comparison with the units of West European (standard) scale.

The first version of the Boreal zonal standard for the Jurassic and Cretaceous was proposed by Zakharov et al. (1997). It comprised zonal scales on ammonites (Jurassic–

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Lower Cretaceous), belemnites (several Jurassic levels), bivalves (Jurassic–Cretaceous), foraminifers (Jurassic), ostracods (Lower and Middle Jurassic), dinocysts (several Jurassic and Cretaceous levels), and terrestrial palynomorphs (Lower and Middle Jurassic). It should be noted that the stratotypes of zones from the scales based on different groups of fauna and flora were located in different areas of the Boreal Realm. Further studies were aimed at the improvement and validation of the components of the Boreal zonal standard for the Jurassic and Cretaceous (Baraboshkin, 2004; Dzyuba, 2004, 2012; Knyazev et al., 2003; Mickey et al., 1998; Nikitenko, 2009; Nikitenko and Mickey, 2004; Shurygin, 2005; Shurygin et al., 2000, 2011; Zakharov et al., 2005; Zhamoida and Petrov, 2008). In addition, some zones established in the sections of the East European Platform (ecotone region) with a mixed Boreal–Peri-Tethyan fauna of ammonites were also proposed as the Boreal zonal standard (Zakharov et al., 2005; Zhamoida and Petrov, 2008).

Subsequently, it was shown that Boreal zonal standard should be based on the material from Boreal regions only. Thus, the Arctic should be considered as the stratotype region, because the Jurassic–Cretaceous Arctic biochorema, characterized by a typical Boreal (Arctic) rather than mixed (ecotone) fauna, was located in this region. Therefore, Siberia located in the center of the Panboreal Superrealm and characterized by the most complete set of calibrated scales on different fossil groups can be regarded as a stratotype region for Boreal scales of the Jurassic and most parts of the Lower and Upper Cretaceous (Meledina et al., 2011; Shurygin et al., 2011).

The Anabar area (Anabar River basin, coast of Anabar Bay, coasts of Anabar and Nordvik Bays of the Laptev Sea) (Fig. 1) is one of the largest regions in Arctic Siberia where many stratotypes of lithostratigraphic units and biostratigraphic subdivisions based on different fossil groups have been defined (Basov et al., 1970; Knyazev, 1975; Knyazev et al., 1991, 2003; Meledina, 1994; Nikitenko, 2009; Saks, 1976; Saks et al., 1963; Shurygin, 1978, 2005; Shurygin et al., 2000; Zakharov, 1981; Zakharov et al., 1983, 1997; and many others). Almost continuous succession of Jurassic and Cretaceous marine sediments of different facies are exposed in coastal cliffs and boreholes: from shallow-water marine (Anabar River and its tributaries) to deep-water (Anabar Bay, Laptev Sea coast, Bol'shoi Begichev Island) sediments as well as subcontinental and continental sediments of the upper part of the Lower Cretaceous and the lower part of the Upper Cretaceous. Rich assemblages of macro- and microfossils contained in these sections yielded detailed zonal scales on ammonites, belemnites, bivalves, foraminifers, ostracods, dinocysts, and terrestrial palynomorphs. Jurassic and Cretaceous outcrops in the Anabar area are an inexhaustible source of stratigraphic data. Recent studies of Jurassic and Cretaceous sections in this and adjacent regions permitted considerable modification and improvement of regional zonal scales (and, therefore, the Boreal standard) and the lithostratigraphic model for the Jurassic and Cretaceous.

Jurassic–Cretaceous rocks in the northern Anabar and Laptev Sea areas are of considerable interest as a potential source of hydrocarbons. Several levels of highly carbonaceous clays and sandy reservoirs with clay caps are known here. Besides that, oil shows are defined on the Yuryung-Tumus Peninsula in the sands of the Eren Formation (Lower Jurassic) and Upper Arangastakh Subformation (Middle Jurassic) (Kashirtsev et al., 2010; Meledina et al., 1987). Several gas yields with heavy hydrocarbons and an increased He content in the Tigyan Formation (middle Lower Cretaceous), lower reaches of the Anabar River (Ronkina, 1976).

Lithostratigraphy

The evolution of the Jurassic and Cretaceous basin in northern Middle Siberia can be divided into several major stages. Marine sections of the Hettangian and lower part of the Upper Bathonian are characterized by wide distribution of uniform sediments with little lateral variations. The rocks in large areas show regular quasi-synchronous variations according to the transgressive–regressive (T–R) events. Therefore, the same lithostratigraphic succession is observed in sections of the Nordvik and East Taimyr facies regions (Fig. 2).

Marine sedimentation in the Callovian, Late Jurassic, Berriasian, and Valanginian was characterized by considerable differentiation in facies environments. This determins the differentiation and diversity of lithostratigraphic units in adjacent facies regions (Paksa, Taz–Kheta, Taimyr, Lower Lena) (Fig. 2).

A global regressive stage in the development of Siberian sedimentary basins is observed in the late Valanginian–early Hauterivian. It resulted in the alternation of shallow-water marine, littoral-marine, and subcontinental environments. In the Aptian–Cenomanian, a stable continental regime was established and the environments were leveled. The sections are characterized by a similar quasi-synchronous vertical succession of lithostratigraphic units and their wide areal distribution. The Taimyr–Anabar facies region (Fig. 2) shows one lithostratigraphic succession and similar rock formation in many areas (Saks, 1981).

The lowermost Jurassic sediments in Arctic Siberia is characterized by wide distribution of **the Zimnyaya Formation** (Hettangian–lower Upper Pliensbachian), with type sections in the Ust'-Yenisei area (Baiborodskikh et al., 1968). The section of the Semenovskaya 1 borehole was proposed as the stratotype (Lebedev, 1972). The Zimnyaya Formation, overlaid Triassic sediments or basement rocks with an angular unconformity, is overlapped by the Airkat Formation in the East Taimyr and Nordvik facies regions and by the Levinskii Formation in the sections of the Khatanga facies region. The Zimnyaya Formation (Figs. 2, 3) is most complete in the northern Nordvik facies region (sections of Anabar Bay, Laptev Sea coast). Here, it consists of greenish gray littoral-marine sandstones interbedded with gravelstones and conglomerates. Its upper part is composed of brownish marine siltstones and mudstones with sandstone laminae and disseminated pebbles and gravel. The lower beds of the Zimnyaya Formation wedge out southward (Fig. 2), and the clays and

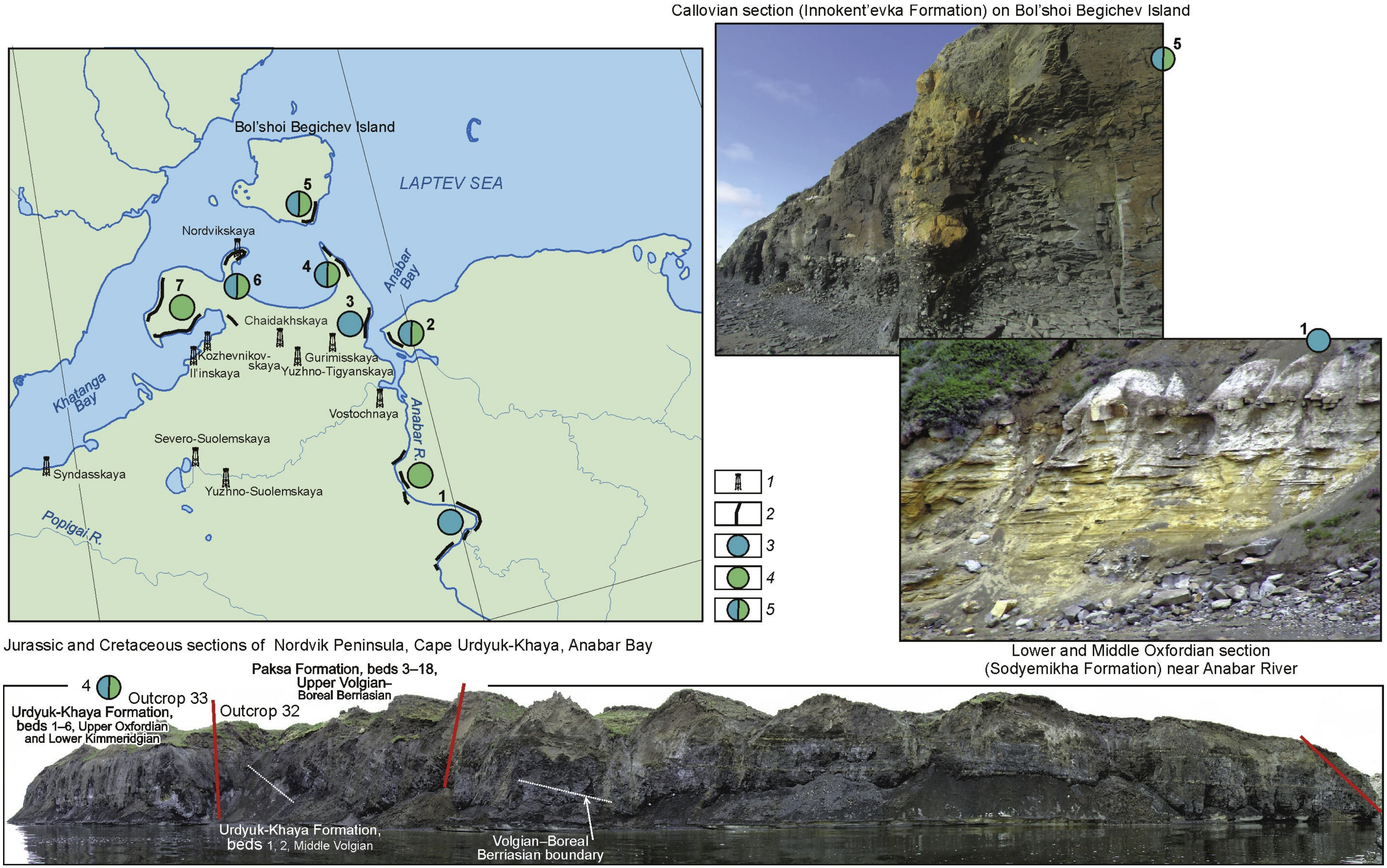

Fig. 1. Positions of the studied Jurassic and Cretaceous reference sections of the Anabar and adjacent areas. *1*, drilling site; *2*, outcrops; *3*, Jurassic; *4*, Cretaceous; *5*, Jurassic, Cretaceous. Positions of sections: 1, Anabar River; 2, 3, eastern and western shores of Anabar Bay, respectively; 4, Nordvik Peninsula; 5, Bol'shoi Begichev Island; 6, Yuryung-Tumus Peninsula; 7, Khara-Tumus Peninsula, Tigyan River.

siltstones of the overlying Airkat Formation unconformably overlie Triassic and Permian sediments in sections of the Suolama area and outcrops near the Anabar and Kharabyl Rivers. The thickness of the Zimnyaya Formation varies from 30 to 155 m. The foraminiferal assemblages in the terminal part of the Zimnyaya Formation evidence slight variation in the stratigraphic position of its upper boundary of the formation within the upper part of the Ammodiscus siliceus JF3 f-Zone and the lower part of the Trochammina lapidosa, Frondiculinita dubiella JF4 f-Zone (Fig. 2).

In the western part of northern Middle Siberia, the essentially sandy deposits of the Zimnyaya Formation are overlain by the clays and silts of **the Airkat Formation** (upper Upper Pliensbachian), with the stratotype section near Anabar Bay (Saks, 1981; Saks et al., 1978; Shurygin, 1978) (Fig. 3). The Airkat Formation shows a much wider areal distribution than the Zimnyaya Formation: it is observed far in the south, in the outcrops near the Anabar River (Fig. 2). Its thickness is fairly constant over the entire area and equals 90–130 m (Figs. 2, 3).

The Kiterbyut clays were first described as a marker horizon by T.M. Emel'yantsev (1939). The clays of **the Kiterbyut Formation** overlying silty sands of the Airkat Formation occur widely in northern Middle Siberia, serve as an interregional reference (Fig. 2). The Kiterbyut Formation is a continuous unit of dark gray to brownish black clays, sometimes, argillite-like, finely washed, with thin horizontal lamination, often highly carbonaceous, especially in the lower part of the section. Studies of carbon isotope variations in the Kiterbyut Formation (Anabar area) and the Kurung Subformation of the Kelimyar Formation (Olenek area) revealed a clear negative excursion on the $\delta^{13}C_{org}$ curve (6‰) from the boundary between the antiquum and falciferum Zones, which reaches its minimum (–32‰) in the lower part of the falciferum Zone (Nikitenko et al., 2011; Suan et al., 2011). The dramatic decrease of $\delta^{13}C_{org}$ is accompanied by an increase in C_{org}. High-resolution biostratigraphic control of geochemical data from the sections in northern Middle Siberia permits direct correlations with the previous data on the Toarcian oceanic anoxic event (T-OAE) in West European sections (Nikitenko et al., 2011; Suan et al., 2011). The thickness of the Kiterbyut Formation varies from 21 to 28 m (Fig. 2).

The upper Toarcian in the Anabar area (Nordvik facies region) consists of the Eren and Khorgo Formations. **The Eren Formation** (Shurygin et al., 2000) in the stratotype sections near Cape Eren, on the right shore of Anabar Bay (Fig. 2), is a light-colored cyclic unit of marine and littoral-marine sands and silts with laminae and lenses of greenish gray leptochloritic rocks. The latter contain rare lenticles saturated with pebbles and gravel as well as brownish and dark gray clays. The most complete section of the Eren Formation is located on the western shore of Anabar Bay. The upper beds of the Eren Formation quickly wedge out southward (Figs. 2, 3), so that only Lower Toarcian beds are known in sections of the Suolama area and Anabar River. Oil accumulations in the Eren Formation are found in the northern part of the area. Devonian saliferous layers are considered a potential oil source rocks (Kashirtsev et al., 2010, 2013).

The Khorgo Formation in the stratotype (western shore of Anabar Bay, 7.3 km downstream of Cape Airkat) (Shurygin et al., 2000) consists of several cyclic beds 2.0–3.5 m thick, which are often calcareous, with alternation of littoral-marine clayey and sandy silts are very often interbedded with dark gray clays at the base. The rocks contain poorly rounded boulders, wood fragments, accumulations and separate grains of pebbles (Figs. 2, 3). The Khorgo Formation shows a limited distribution and occurs in outcrops on the western and eastern shores of Anabar Bay and in the sections of boreholes in the Eastern area (Figs. 2, 3). The thickness of Khorgo Formation in the stratotype area is 15–26 m.

The overlying **Arangastakh Formation** (Aalenian–Lower Bajocian) consists of two lithostratigraphic bodies: the lower one consists of clays and silts, whereas the upper one is dominated by sands. The stratotype of the Arangastakh Formation (Saks, 1957, 1959) is established in the boreholes of the Yuryung-Tumus area. The Arangastakh Formation is represented by an alternation of gray and greenish marine sandy siltstones with dark gray siltstones and clayey siltstones in its lower part. It contains abundant pyrite nodules as well as periodically occurring gravel lenticles and the layers of shellrocks. At the Formation base, there is a layer of calcareous sandstone with pebble accumulations, rounded sandstone and mudstone boulders, wood fragments, washed bivalve shells, and redeposited globular concretions (Figs. 2, 3).

The Upper Arangastakh Subformation is composed of light gray littoral-marine sandy siltstones and fine sands with thin lenticles of brownish clays containing disseminated pebbles, gravel, and boulders, beds and lenses of calcareous siltstone, wood fragments, and, sometimes, glendonite intergrowths and lenticular accumulations of large foraminifers. The distribution of macro- and microfauna in Anabar Bay sections indicates the presence of an unconformity between the Khorgo and Arangastakh Formations and the absence of sediments corresponding to the Mclearnia kelimyarensis and Retroceramus elegans b-Zones or the Verneuilinoides syndascoensis JF14 f-Zone and the lower Astacolus zwetkovi JF16 f-Zone (Figs. 2, 3). In the Anabar River sections, there is a larger stratigraphic gap, which spans the upper JF12 f-Zone as well as the JF14, JF16, and JF17 f-Zones (Figs. 2, 4).

The lower beds of the Arangastakh Formation pinch out quickly in southern direction. The sands and silts of the Eren Formation (Lower Toarcian) in the Anabar River sections are overlain by the sandy siltstones of the Upper Arangastakh Subformation (Lower Bajocian). The Lower Arangastakh Subformation is 60–70 m thick in the north and becomes thinner in the south decreasing to 7–20 m (Figs. 2–4).

The Upper Subformation of the Arangastakh Formation shows a wider areal distribution than the lower one. The thickness of the Upper Subformation varies from 30 to 50 m in the north and from 15 to 27 m in the south. Ingresses of oil, which are similar to their genesis to those found in the Eren Formation, are observed in the north of the area, in

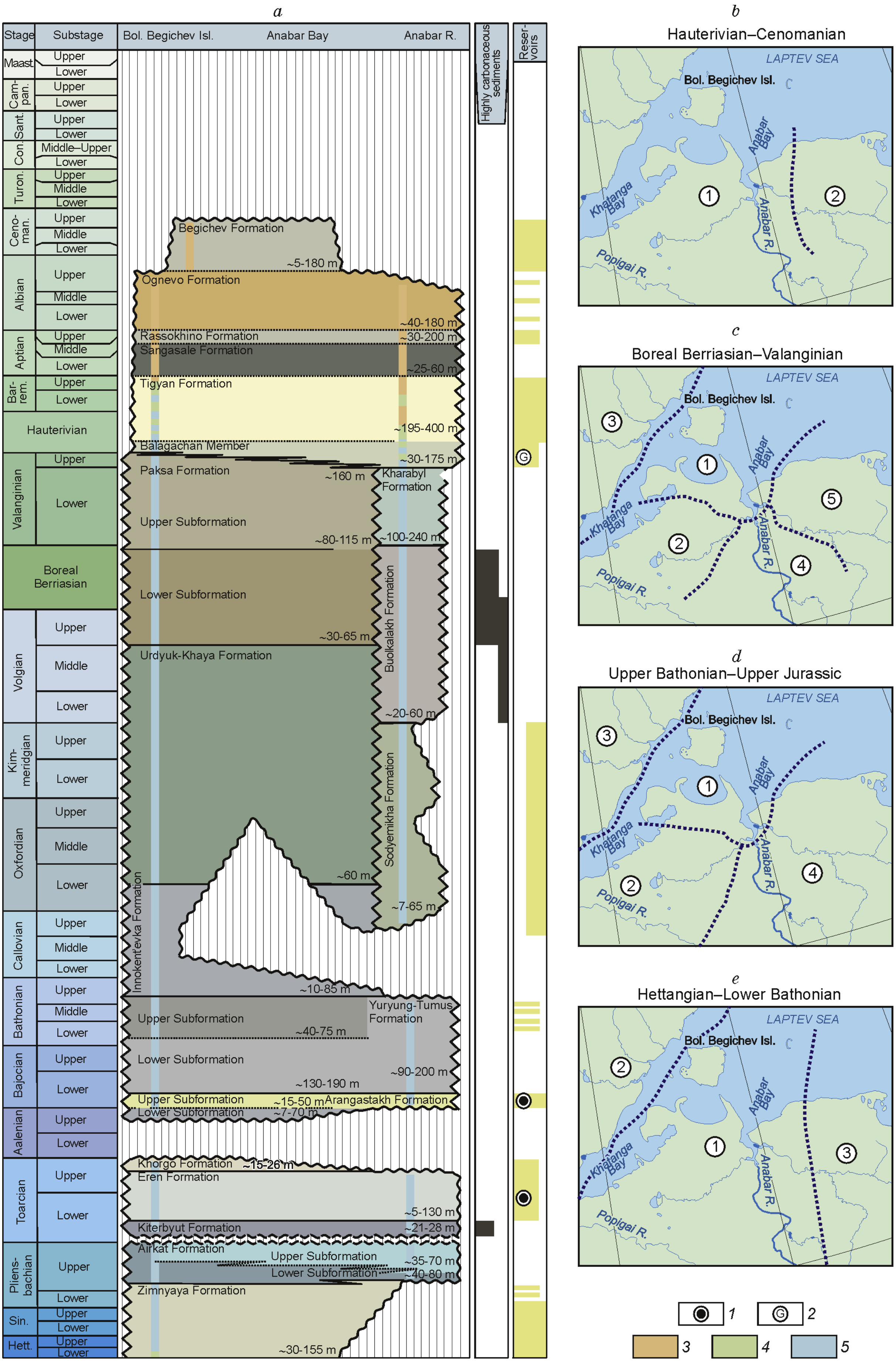
a
Stage
Substage
Bol. Begichev Isl.
Anabar Bay
Anabar R.
Highly carbonaceous sediments
Reser-voirs
Maast.
Upper
Lower
Cam-pan.
Upper
Lower
Sant.
Upper
Lower
Con.
Middle–Upper
Lower
Turon.
Upper
Middle
Lower
Ceno-man.
Upper
Middle
Lower
Albian
Upper
Middle
Lower
Aptian
Upper
Middle
Lower
Bar-rem.
Upper
Lower
Hauterivian
Valanginian
Upper
Lower
Boreal Berriasian
Volgian
Upper
Middle
Lower
Kim-meridgian
Upper
Lower
Oxfordian
Upper
Middle
Lower
Callovian
Upper
Middle
Lower
Bathonian
Upper
Middle
Lower
Bajocian
Upper
Lower
Aalenian
Upper
Lower
Toarcian
Upper
Lower
Pliens-bachian
Upper
Lower
Sin.
Upper
Lower
Hett.
Upper
Lower
Begichev Formation
~5-180 m
Ognevo Formation
~40-180 m
Rassokhino Formation
~30-200 m
Sangasale Formation
~25-60 m
Tigyan Formation
~195-400 m
Balagachan Member
~30-175 m
Paksa Formation
~160 m
Kharabyl Formation
Upper Subformation
~80-115 m
~100-240 m
Lower Subformation
~30-65 m
Buolkalakh Formation
Urdyuk-Khaya Formation
~20-60 m
Sodyemikha Formation
~60 m
~7-65 m
Innokent'evka Formation
~10-85 m
Yuryung-Tumus Formation
Upper Subformation
~40-75 m
Lower Subformation
~90-200 m
~130-190 m
Upper Subformation
~15-50 m
Arangastakh Formation
Lower Subformation
~7-70 m
Khorgo Formation
~15-26 m
Eren Formation
~5-130 m
Kiterbyut Formation
~21-28 m
Airkat Formation
Upper Subformation
~35-70 m
Lower Subformation
~40-80 m
Zimnyaya Formation
~30-155 m
b
Hauterivian–Cenomanian
LAPTEV SEA
Bol. Begichev Isl.
Anabar Bay
Khatanga Bay
Anabar R.
Popigai R.
①
②
c
Boreal Berriasian–Valanginian
LAPTEV SEA
Bol. Begichev Isl.
Anabar Bay
Khatanga Bay
Anabar R.
Popigai R.
①
②
③
④
⑤
d
Upper Bathonian–Upper Jurassic
LAPTEV SEA
Bol. Begichev Isl.
Anabar Bay
Khatanga Bay
Anabar R.
Popigai R.
①
②
③
④
e
Hettangian–Lower Bathonian
LAPTEV SEA
Bol. Begichev Isl.
Anabar Bay
Khatanga Bay
Anabar R.
Popigai R.
①
②
③
1
2
3
4
5

Fig. 2. Stratigraphic chart (*a*) and facies zonation of Jurassic and Cretaceous sediments of the Anabar and adjacent areas (*b–e*). (*a*) *1*, oil; *2*, gas; *3*, continental sediments; *4*, littoral, lagoonal, and subcontinental sediments; *5*, marine sediments; (*b*) 1, Taimyr–Anabar facies region; 2, Anabar–Olenek facies region; (*c*), (*d*) Ob'–Lena facies region: (*c*) 1, Paksa facies region; 2, Boyarka facies region; 3, Taimyr facies region; 4, Anabar facies region; 5, Anabar–Olenek facies region; (*d*) 1, Paksa facies region; 2, Taz–Kheta facies region; 3, Taimyr facies region; 4, Lower Lena facies region; (*e*) Yana–Anabar facies province: 1, Nordvik facies region; 2, East Taimyr facies region; 3, Lena–Anabar facies region.

sections of the Upper Arangastakh Subformation (Kashirtsev et al., 2010, 2013).

The Yuryung-Tumus Formation (upper Lower Bajocian–lower Upper Bathonian) (Saks, 1957, 1959) was first estabished in the Yuryung-Tumus brachyanticline and is well defined in northern Middle Siberia. Based on lithostratigraphic characteristics, this Formation is divided into two Subformations in the northern Nordvik facies region (Fig. 2). The Lower Subformation is composed of dark gray marine clays and argillite-like clays with silty interbeds. Its lower part contains pyrite nodules and numerous glendonite inclusions. Disseminated small pebbles, gravel, and wood fragments are sometimes observed at the base. The Upper Yuryung-Tumus Subformation consists of coarse-grained light gray sandy siltstones, gray siltstones, and dark gray clayey siltstones with bipyramidal and stellar glendonite intergrowths, numerous subglobular calcareous concretions, pyrite nodules, and wood fragments. Macrofaunal studies in the upper part of the subformation reveal numerous eroded levels within the formation as well as rounded bivalve and belemnite shells (Meledina, 1994).

A study of Middle Jurassic sections in the eastern part of the Yuryung-Tumus Peninsula (2009) shows almost complete exposure of the Yuryung-Tumus Formation in that area (Fig. 5). It was previously presumed that the Formation was crowned by the Arcticoceras harlandi a-Zone in this locality, as inferred from the presence of ammonites *A.* cf. *excentricum* on the beach near the formation outcrops (Meledina, 1994; Shurygin et al., 2000). Nowadays, the position of the Retroceramus vagt b-Zone is specified. In the set of parallel zonal scales of the Boreal standard, it corresponds to the Arcticoceras ishmae and A. cranocephaloide a-Zones, which directly overlie the A. harlandi a-Zone. The lowermost finds of the index species of the Retroceramus vagt b-Zone are from the base of a 22-m-thick silt–clay member (Fig. 5). This is also a dramatic change of belemnite assemblages at this stage: the assemblage of bl-beds with *Cylindroteuthis confessa* corresponding to the Articoceras harlandi a-Zone, are replaced by a new assemblage with *Cylindroteuthis* aff. *spathi*. Belemnite *Pachyteuthis* cf. *tschernyschewi*, found here in the talus by Meledina et al. (1987), is considered as the index species of the upper part of the Middle Bathonian in Siberia (Shurygin et al., 2000, 2011). Thus, the presence of the top of the Yuryung-Tumus Formation corresponding to the basal beds of the Upper Bathonian, are not proved in this section.

In the southern Nordvik facies region (Figs. 2, 4), there is no continuous vertical differentiation of the rocks and only the Yuryung-Tumus Formation is defined. A more or less uniform alternation of predominantly sandy and clayey beds 6–15 m thick is typical. They often contain small rounded boulders and pebble accumulations. In the north of the area, the thickness of the Lower Subformation varies from 130 to 190 m, whereas that of the Upper Subformation varies from 40 to 75 m. In the southern part of the area, the thickness of the Yuryung-Tumus Formation varies from 90 to 200 m.

The unit overlying the Yuryung-Tumus Formation is usually associated with a new sedimentation stage (uppermost Bathonian–Valanginian) in northern Siberia (Bogolepov, 1983). The facies differentiation of sedimentation in the uppermost Bathonian–Valanginian determined the diversity of lithostratigraphic units not only in the Anabar area (Fig. 2), but also over all Siberian regions. **The Innokent'evka Formation** (uppermost Upper Bathonian–lowermost Lower Oxfordian), named after the Innokent'evka River, is defined in the north of the area, with the stratotype in the outcrops situated on the eastern coast of Bol'shoi Begichev Island (Figs. 1, 2, 6). The Innokente'vka Formation is exposed in boreholes and outcrops on the northern coast of Khatanga, Nordvik, and Anabar Bays, Bol'shoi Begichev Island, and the western part of the Pronchishchev Ridge. The West Siberian Tochino Formation was previously defined in this area (Shurygin et al., 2000), but the differences in the lithostratigraphy, structure, and stratigraphic volume of the sediments resulted in definition of new formation. The most complete section of Innokent'evka Formation is situated on Bol'shoi Begichev Island. The Innokent'evka Formation here consists of argillite-like marine silty clays and siltstones, which are greenish gray and brownish gray, with numerous lenses, spots, and interbeds of jarositized clays. The Formation contains numerous calcareous concretions of different shapes (subglobular, ellipsoidal, irregular, *Dentalina*-like, etc.). Small globular brown phosphate–siderite nodules are observed at several levels. There are also several thick (up to 1.7 m) marker interbeds of concretions of yellowish gray sideritized limestones. Different levels of the Innokent'evka Formation contain accumulations of star- and saber-shaped glendonite and abundant pyrite nodules forming several interlayers. The upper part of the Formation is dominated by gray and brownish gray sandy siltstones and siltstones (Fig. 6).

In the Bol'shoi Begichev sections, the Innokente'vka Formation contains numerous ammonites of the family Cardioceratidae, which permit the definition of the most complete succession of Callovian ammonite biostratigraphic units for northern Siberia. The following biostratigraphic units are proposed for the Lower Callovian: Cadoceras elatmae Zone (with the C. frearsi and C. elatmae Subzones), C. tschernyschewi Zone, C. tolype Zone, beds with *Cadoceras sublaeve* (Knyazev et al., 2010, 2011a–c) as well as the Cadoceras durum Zone established for the first time. The Middle Callovian here contains the following biostratigraphic units here: beds with *Cadoceras wosnessenskii* and *C. postelatmae* in the lower part, and the Rondiceras (?) stenolobum Zone in

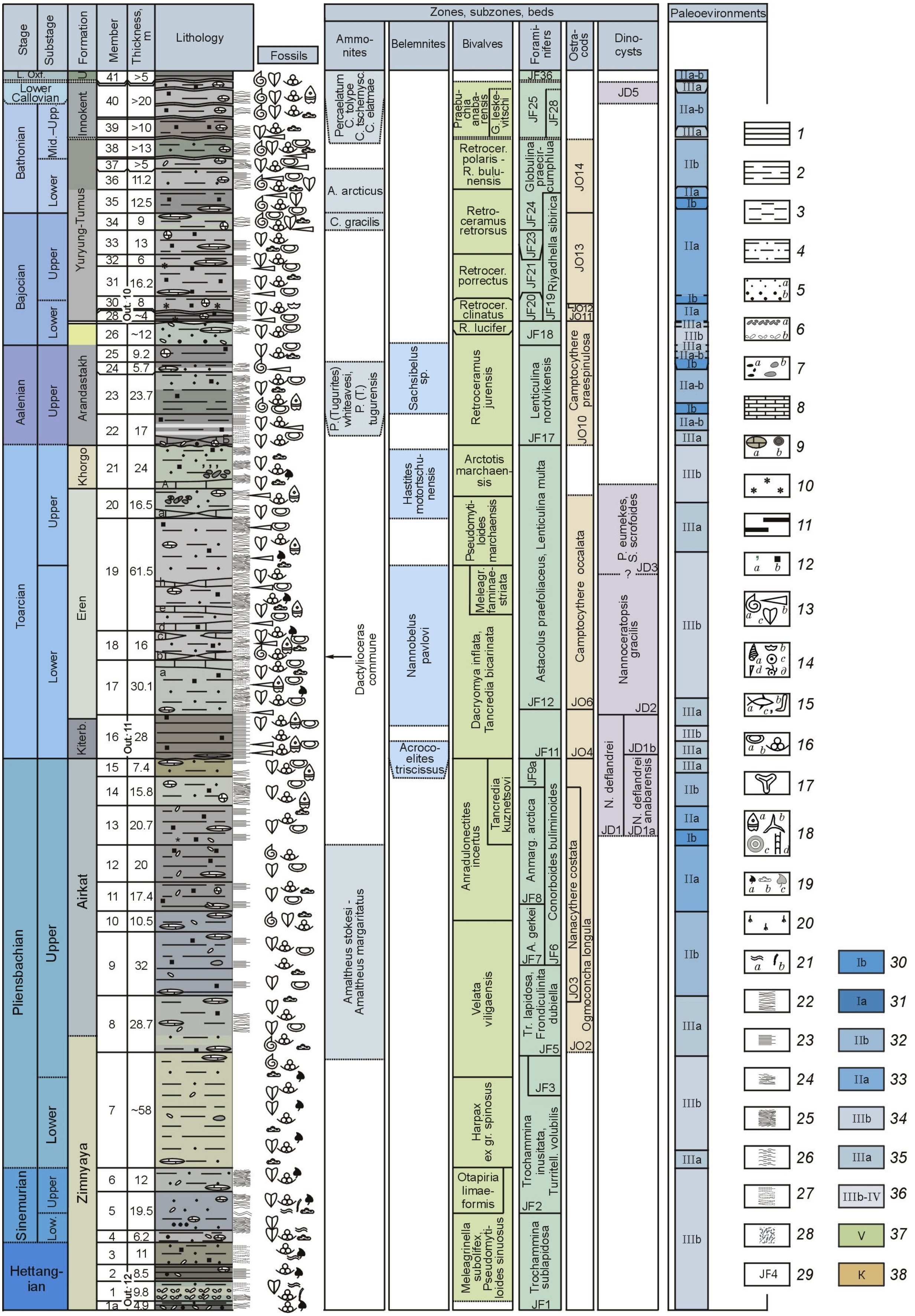
Stage
Substage
Formation
Member
Thickness, m
Lithology
Fossils
Zones, subzones, beds
Ammonites
Belemnites
Bivalves
Foraminifers
Ostracods
Dinocysts
Paleoenvironments
L. Oxf.
Lower Callovian
Bathonian
Mid.–Upp.
Lower
Bajocian
Upper
Lower
Aalenian
Upper
Toarcian
Upper
Lower
Pliensbachian
Upper
Lower
Sinemurian
Upper
Low.
Hettangian
Innokent
Yuryung-Tumus
Arandastakh
Khorgo
Eren
Kiterb.
Airkat
Zimnyaya
41 >5
40 >20
39 >10
38 >13
37 >5
36 11.2
35 12.5
34 9
33 13
32 6
31 16.2
30 8
28 ~4
Out. 10
26 ~12
25 9.2
24 5.7
23 23.7
22 17
21 24
20 16.5
19 61.5
18 16
17 30.1
16 28
Out. 11
15 7.4
14 15.8
13 20.7
12 20
11 17.4
10 10.5
9 32
8 28.7
7 ~58
6 12
5 19.5
4 6.2
3 11
2 8.5
1 9.8
1a 4.9
Out. 12
a
b
c
d
e
f
A
Б
Percaelatum C. tolype C. tschernysc. C. elatmae
A. arcticus
C. gracilis
P. (Tugurites) whiteavesi, P. (T.) tugurensis
Dactylioceras commune
Amaltheus stokesi - Amaltheus margaritatus
Sachsibelus sp.
Hastites motortschunensis
Nannobelus pavlovi
Acrocoelites triscissus
Praebuchia anabarensis
G. jeskevitschi
Retrocer. polaris - R. bulunensis
Retroceramus retrorsus
Retrocer. porrectus
Retrocer. clinatus
R. lucifer
Retroceramus jurensis
Arctotis marchaensis
Pseudomytiloides marchaensis
Meleagr. faminaestriata
Dacryomya inflata, Tancredia bicarinata
Anradulonectites incertus
Tancredia kuznetsovi
Velata viligaensis
Harpax ex gr. spinosus
Otapiria limaeformis
Meleagrinella subolifex, Pseudomytiloides sinuosus
JF36
JF25
JF28
Globulina praecircumphlua
JF24
Riyadhella sibirica
JF23
JF21
JF20
JF19
JF18
Lenticulina nordvikensis
JF17
Astacolus praefoliaceus, Lenticulina multa
JF12
JF11
JF9a
Anmarg. arctica
Conorboides buliminoides
JF8
A. gerkei
JF7
JF6
Tr. lapidosa, Frondiculinita dubiella
JF5
JF3
Trochammina inusitata, Turritell. volubilis
JF2
Trochammina sublapidosa
JF1
JO14
JO13
JO12
JO11
Camptocythere praespinulosa
JO10
Camptocythere occalata
JO6
JO4
Nanacythere costata
Ogmoconcha longula
JO3
JO2
JD5
P. eumekes, S. scrofoides
?
JD3
Nannoceratopsis gracilis
JD2
N. deflandrei
JD1b
N. deflandrei anabarensis
JD1
JD1a
IIa-b
IIIa
IIa-b
IIIa
IIb
IIa
Ib
IIa
Ib
IIa
IIIa
IIIb
IIIa
IIa-b
Ib
IIa-b
Ib
IIa-b
IIIa
IIIb
IIIa
IIIb
IIIa
IIIb
IIIa
IIIa
IIb
IIa
Ib
IIa
IIb
IIIa
IIIb
IIIa
IIIb
1
2
3
4
5 a b
6 a b
7 a b
8
9 a b
10
11
12 a b
13 a b c
14 a b c d ∂
15 a b c
16 a b
17
18 a b c d
19 a b c
20
21 a b
22
23
24
25
26
27
28
JF4 29
Ib 30
Ia 31
IIb 32
IIa 33
IIIb 34
IIIa 35
IIIb-IV 36
V 37
K 38

Fig. 3. Hettangian–Lower Oxfordian reference section on the western shore of Anabar Bay (subdivision based on belemnites after (Nal'nyaeva, 1986), with some improvements; on dinocysts after (Riding et al., 1999), with some improvements). *1*, clay, mudstone; *2*, clayey silt, clayey siltstone; *3*, silt, siltstone; *4*, sandy silt, sandy siltstone; *5*, sands, sandstones (*a*); gravelstones (*b*); *6*, breccias (*a*), conglomerates (*b*); *7*, pebbles (*a*), boulders (*b*); *8*, concretion interbeds; *9*, nodules, concretions: siderite (*a*), phosphate (*b*); *10*, glendonites; *11*, coals, coal interbeds; *12*, glauconite (*a*), pyrite (*b*); *13–15*, macrofossils: *13*, ammonites (*a*), belemnites (*b*), bivalves (*c*); *14*, gastropods (*a*), brachiopods (*b*), crinoids (*c*), *Dentalium* (*d*), shell detritus (*e*); *15*, fish fossils (*a*), *Serpula* worms (*b*), onychites (*c*); *16–18*, microfossils: *16*, ostracods (*a*), foraminifers (*b*); *17*, spore–pollen assemblages; *18*, microphytoplankton: dinocysts (*a*), acritarchs (*b*), prasinophytes (*c*), Zygnemataceae (*d*); *19*, *20*, plant fossils: *19*, coalified plant detritus (*a*), wood (*b*), leaves (*c*); *20*, root fossils; *21*, trace fossils: horizontal (*a*), vertical (*b*); *22–28*: lamination: *22*, lenticular; *23*, horizontal; *24*, inclined, subhorizontal; *25*, oblique; *26*, wavy; *27*, uncertain; *28*, disturbed by bioturbation; *29*, biostratigraphic zone index; *30–38*, paleoenvironments: lower sublittoral—*30*, inner part; *31*, outer part; middle sublittoral—*32*, inner part; *33*, outer part; upper sublittoral—*34*, inner part; *35*, outer part; *36*, inner part of the upper sublittoral–littoral; *37*, littoral to subcontinental; *38*, continental.

the upper part. It should be noteed the domination of large shells of *Rondiceras* spp. Zonal assemblage of the lower biostratigraphic unit is dominated by *Rondiceras milaschevici*, whereas *C. postelatmae* is rare. Upper Callovian sediments are here represented by two zones (Longaeviceras keyserlingi, Eboraciceras subordinarium) and are overlain by Lower Oxfordian sediments containing *Cardioceras* ex gr. *percaelatum* (Fig. 6). In addition, these sections give the most detailed foraminiferal zonation of the upper Bathonian–Callovian was proposed here (Lutova, 1981; Nikitenko, 2009; Shurygin et al., 2000). Thus, the type section of the Innokent'evka Formation can be regarded as stratotype for zones on many fossil groups included in the Boreal zonal standard. The formation thickness in the type section is more than 64 m (Figs. 2, 6).

Somewhat to the south, near Anabar Bay, the Innokent'evka Formation is also dominated by argillite-like marine siltstones and clayey siltstones, but occurs in fragments. Several outcrops are known on the western shore of Anabar Bay. They are only represented by the uppermost Bathonian with *Kepplerites* ex gr. *rosenkrantzi* and *Cadoceras perrarum* (Knyazev and Meledina, 2011), and the Lower Callovian (Cadoceras elatmae, C. tschernyschewi, and C. tolype Zones) (Knyazev et al., 2010) having total thickness of about 30 m (Figs. 2, 3, 6). Bivalve assemblages of the Praebuchia anabarensis and Grammatodon leskevitschi Zones, foraminiferal assemblages of the JF25 and JF28 Zones (Nikitenko, 2009), and dinocysts of the Evansia dalei, Paragonyaulacysta retiphragmata Zone are also defined here. The relations with the overlying lithostratigraphic units are uncertain. Besides that, the belemnites were found in the Innokent'evka Formation on the eastern shore of Anabar Bay (Saks, 1976; and others). The Formation in this section contains a stratigraphic gap corresponding to the Middle Callovian. The lower boundary of the Innokent'evka Formation is usually conformable. The boundary with the overlying Urdyuk-Khaya clays is unconformable and eroded, there is a stratigraphic gap in the uppermost Callovian–Middle Oxfordian. The thickness of the Innokent'evka Formation in this section is 83.4 m.

A conformable contact with the dark gray glauconitic clays of the overlying Urdyuk-Khaya Formation is observed in the complete sections of the northern Paksa facies region. Under certain conditions, it is established in the middle part of the Lower Oxfordian, in the upper part of the ammonite Zone Cardioceras percaelatum in several boreholes and outcrops. Southern regions are characterized by stratigraphic gaps in the middle part and in the top of the Formation (Fig. 2).

Until recently, the overlying dark gray glauconitic clays were assigned to the Sigovoe and lower part of the Paksa Formations (Shurygin et al., 2000). However, these sediments differ dramatically from the quasi-synchronous deposits of the West Siberian Sigovoe Formation in lithostratigraphic srtucture and lithologic composition being represented by dark gray to black, greenish, and bluish clays, which are often glauconite-leptochloritic and locally silty with rare thin interbeds and lenses of glauconitic and sandy silts) and lithostratigraphic structure (Basov et al., 1970; Gerke, 1953; Nikitenko, 2009; Nikitenko et al., 2008; Saks, 1976; Zakharov et al., 1983). Therefore, **the Urdyuk-Khaya Formation** (named after Cape Urdyuk-Khaya) was defined in the Paksa facies region. Its stratotype is established on the western shore of Anabar Bay and on the Nordvik Peninsula, Cape Urdyuk-Khaya (Nikitenko, 2009; Nikitenko et al., 2008) (Figs. 1–3, 7).

The Paksa Formation was previously defined within the Volgian–Valanginian Stages as brownish clays, which are sometimes argillite-like, with bluish clay interbeds (Gol'bert, 1981). However, the lowermost member of the Middle Volgian (unit 5 (Basov et al., 1970)) in the stratotype section are genetically closer to the underlying sediments consisting of dark gray glauconite-leptochloritic clays, with bluish and greenish tints, and containing glauconite grains (Fig. 7).

The overlying sediments are argillite-like dark gray clays alternating with thin-bedded brownish and massive bluish clays. Therefore, we propose to assign this member (member 5, Fig. 7) to the Urdyuk-Khaya Formation as well (Nikitenko, 2009; Nikitenko et al., 2008). The clays and silts of the Urdyuk-Khaya Formation contain numerous ammonites (*Cardioceras* spp., *Amoeboceras* spp., *Laugeites* sp., *Epivirgatites variabilis*) of the middle part of the Lower Oxfordian–Middle Volgian (Basov et al., 1970; Gerke, 1953; Nikitenko, 2009; Nikitenko et al., 2008, 2011; Saks, 1976; Zakharov et al., 1983) as well as foraminiferal assemblages of the JF36, JF37, JF40, JF41, JF45, and JF51 Zones and lower part of the JF52 Zone. Rich assemblages of dinoflagellates, spore and pollen are defined in the Upper Oxfordian and Lower–Middle Volgian parts of the section. Thus, the formation spans the middle Lower Oxfordian–Middle Volgian (Figs. 2, 7).

The most representative and well-studied outcrop, with a continuous section of the Urdyuk-Khaya Formation starting from the uppermost Oxfordian, is found on Cape Urdyuk-Khaya (Nordvik Peninsula) (Fig. 7). The formation has here detailed paleontological and biostratigraphic characteristics both on the above-mentioned ammonites and foraminifers as well as bivalves and belemnites. This interval contains bivalve

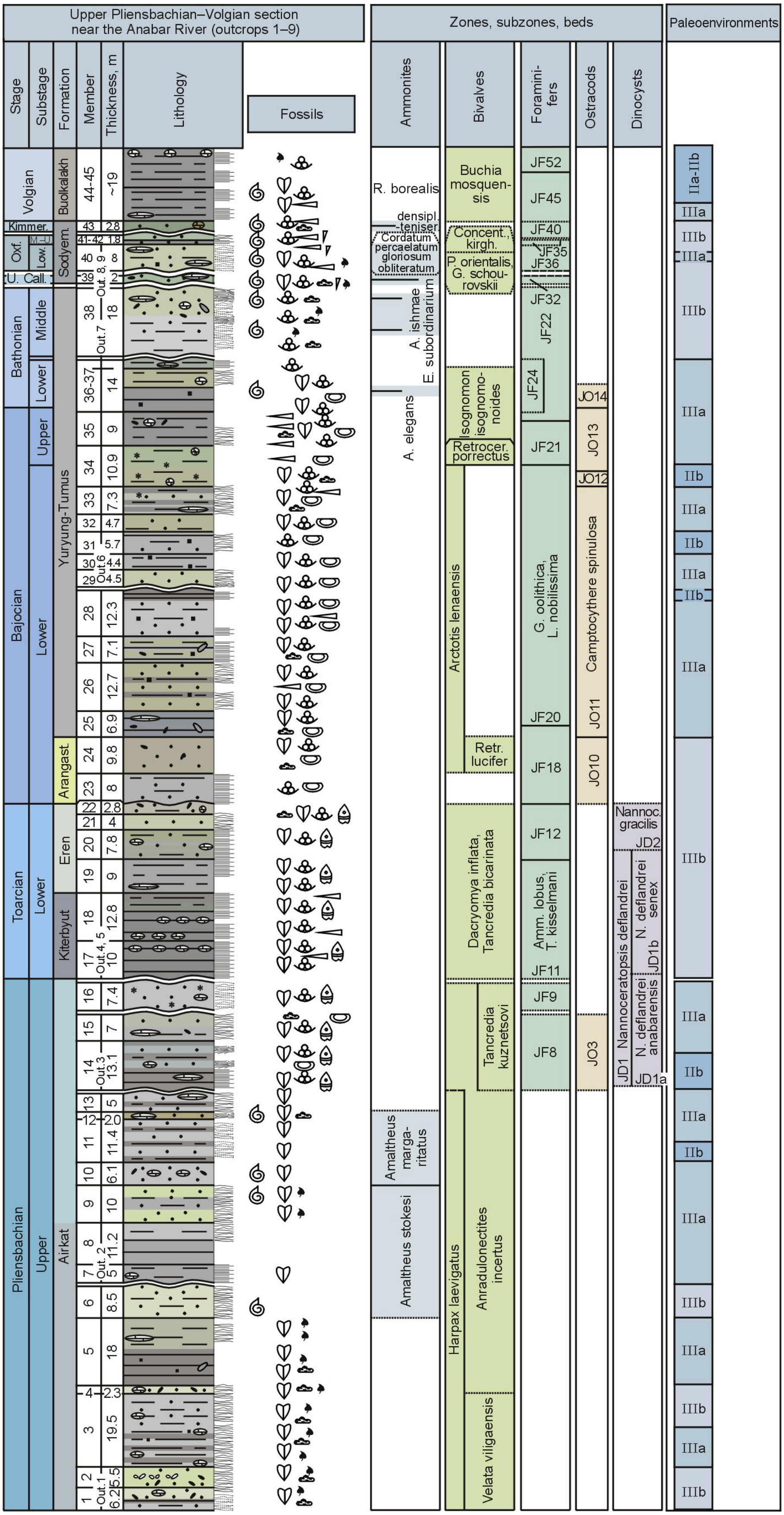

Fig. 4. Pliensbachian–Volgian reference section near the Anabar River. Subdivision on bivalves for the Oxfordian and Volgian, with data from (Saks, 1976; Zakharov, 1981). See legend in Fig. 3.

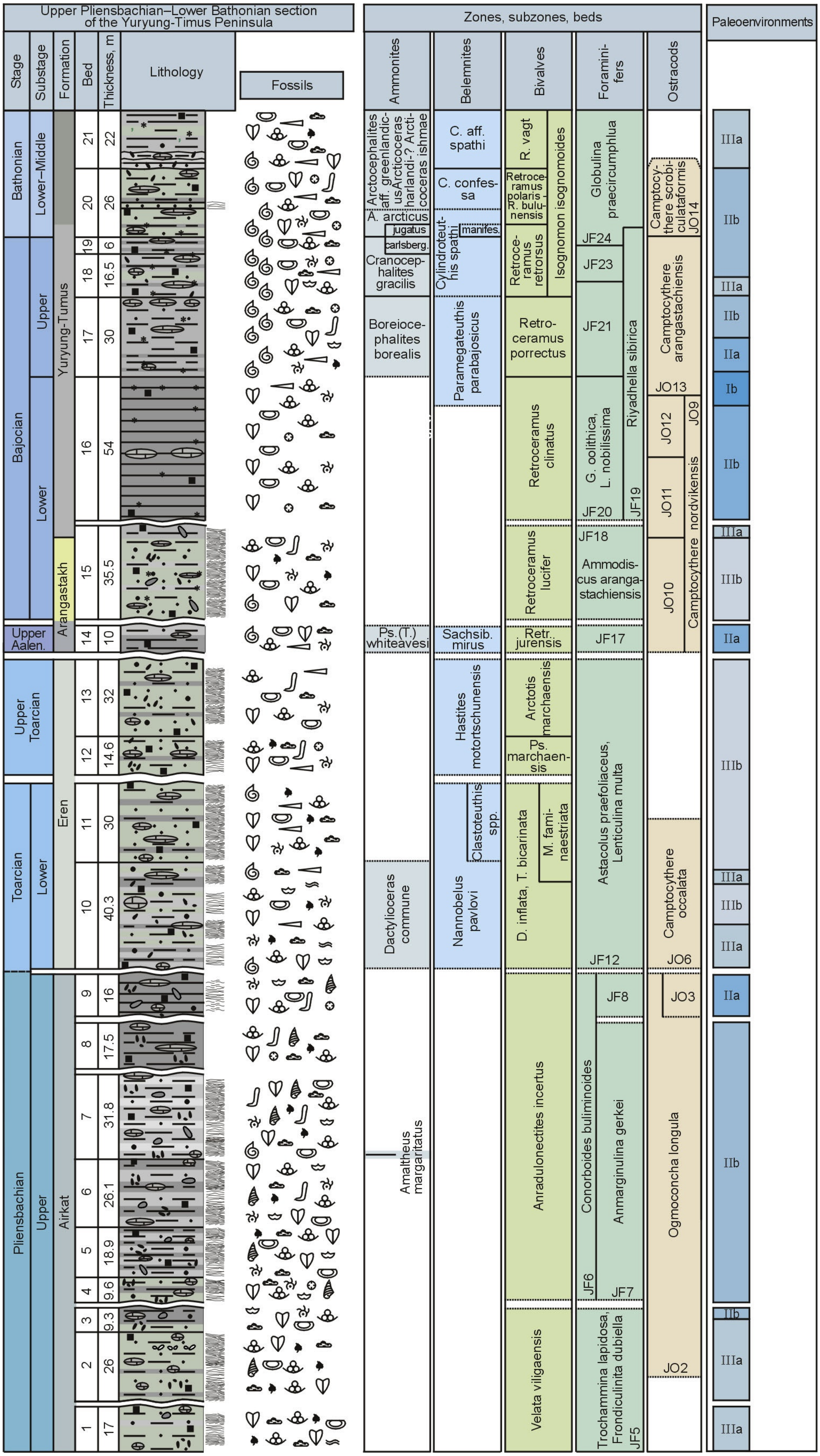

Fig. 5. Pliensbachian–Bathonian reference section of the Yuryung-Tumus Peninsula. Subdivision on belemnites after (Meledina et al., 1987), with some improvements. See legend in Fig. 3.

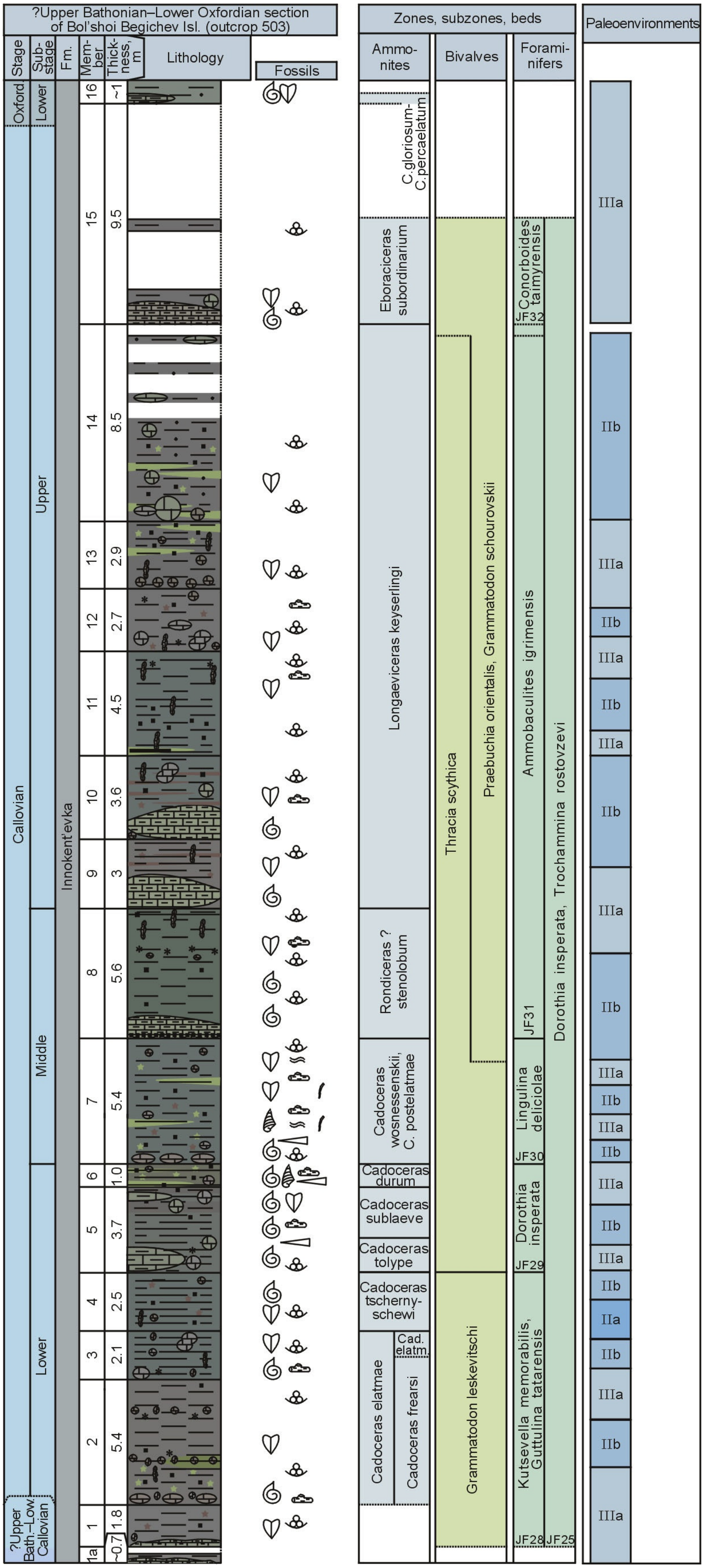

Fig. 6. Callovian reference section for Bol'shoi Begichev Island. Subdivision on foraminifers after (Lutova, 1981). See legend in Fig. 3.

assemblages of the Buchia concentrica, B. tenuistriata, and B. mosquensis Zones (Zakharov, 1981; Zakharov et al., 1983). The biostratigraphic division of the Nordvik section on belemnites previously proposed by O.V. Shenfil' (1995) has been revised in the last decade according to new obtained data. The following units are now defined in the uppermost Oxfordian–Middle Volgian: beds with *Cylindroteuthis cuspidata*, the Lagonibelus ingens Zone, beds with *Boreioteuthis explanata*, and the Liobelus russiensis and Lagonibelus napaensis Zones (Dzyuba, 2004, 2012; Dzyuba et al., 2007).

The Urdyuk-Khaya glauconitic clays overlie the Innokent'evka silts conformably or with erosion (Saks, 1976). It should be noted that different layers of the Oxfordian and Kimmeridgian of the Urdyuk-Khaya Formation overlie the eroded Innokent'evka Formation with the erosion even in a small area (Fig. 2).

In the Paksa facies region, the brownish clays of **the Paksa Formation** conformably overlie the glauconite-leptochloritic clays of the Urdyuk-Khaya Formation (Figs. 2, 7). The stratotype is localized in outcrops near Anabar Bay, on Cape Urdyuk-Khaya (Gol'bert, 1981; Nikitenko, 2009; Nikitenko et al., 2008). The Paksa Formation is defined in boreholes and outcrops on the northern coast of Khatanga, Nordvik, and Anabar Bays, Bol'shoi Begichev Island, and western part of the Pronchishchev Ridge. The formation is composed of dark gray to black argillite-like and sometimes silty clays of marine and deep-water marine genesis. In the lower part of the Formation, they are carbonaceous in different extent, with a bluish or brownish tint. The Paksa Formation is divided into Lower and Upper Subformations (Nikitenko, 2009; Nikitenko et al., 2008) (Figs. 2, 7). The Lower Subformation (30–65 m thick) consists of argillite-like deep-water marine clays, dark gray or sometimes black, alternating with thin-bedded, highly carbonaceous brownish and massive bluish clays with abundant debris of bivalves, ammonites, belemnites, fishes, crustaceans, and foraminifers.

Judging by the macro- and microfossil assemblages, the Lower Paksa Subformation corresponds to the Upper Volgian–lower (greater) part of the Boreal Berriasian (to the middle part of the Tollia tolli a-Zone) (Basov et al., 1970; Meledina et al., 2010; Saks, 1976; Zakharov et al., 1983). The hypothetical position of the Jurassic–Cretaceous boundary within the Lower Paksa Subformation was determined by the paleomagnetic method. According to the obtained data, two most widely used Tethyan markers of the Jurassic–Cretaceous boundary (bases of the ammonite Zone Berriasella jacobi and calpionella Zone B) might span the Craspedites taimyrensis Zone on ammonites (upper part of the Upper Volgian) (Bragin et al., 2013; Housa et al., 2007). The base of magnetozone M18r corresponding to the Jurassic–Cretaceous boundary on the Geologic Time Scale-2012 (Ogg and Hinnov, 2012), is also within this interval. Recently, an analysis of new magnetostratigraphic data from the stratotype section of the Paksa Formation with regard to interregionally correlated biostratigraphic horizons showed that the Boreal Chetaites sibiricus Zone corresponds at least to the most part of the Tethyan Tirnovella occitanica Zone and the Boreal Hectoroceras kochi Zone corresponds to the lower part of the Malbosiceras paramimounum Subzone of the Fauriella boisseri Zone (Bragin et al., 2013). This result is important for the solution of the problems of Boreal–Tethyan correlation, which is quite complicated near the Jurassic–Cretaceous boundary. In the Upper Jurassic and adjacent Cretaceous beds of Siberia, a study of carbon and oxygen isotope variations in the rostra of the Nordvik belemnites has revealed several isotope-geochemical excursions also identified in several sections of Western and Eastern Europe (Dzyuba et al., 2011; Izokh et al., 2011; Zák et al., 2011).

The Upper Paksa Subformation (up to 115 m thick) is composed of marine predominantly silty clays, dark gray to gray, sometimes, with a bluish tint. Its upper part contains interlayers and alternation of thin-bedded gray silts, sandy silts, and argillite-like clays with rich assemblages of ammonites, belemnites, bivalves, and foraminifers of the uppermost Boreal Berriasian (upper part of the Tollia tolli Zone)–lower Hauterivian (Homolsomites bojarkensis Zone) (Basov et al., 1970; Gol'bert, 1981; Nikitenko, 2009; Nikitenko et al., 2008; Shenfil', 1992; Zakharov et al., 1983; and others). The Upper Paksa Subformation is well exposed on the Nordvik Peninsula and Bol'shoi Begichev Island (Figs. 2, 7, 8). A standard ammonite succession established here was later identified in many sections of Siberia, Barents Sea shelf, and Arctic Alaska, was found here (Bogomolov, 1989). The succession of biostratigraphical beds with dinocysts and beds with spores and pollen, established on the Nordvik Peninsula and the western coast of Anabar Bay, is well-defined in West Siberia, and some changes in the taxonomic composition of assemblages at the boundaries of the spore–pollen stratigraphic units can be also observed in larger areas (East European Platform, Western Europe, Canada) (Peshchevitskaya, 2010; Pestchevitskaya, 2007a,b,). Judging by ammonite finds, the stratigraphic position of the upper boundary of the Paksa Formation varies from the upper part of the Upper Valanginian to the lowermost Lower Hauterivian (Gol'bert, 1981; Nikitenko et al., 2008) (Figs. 2, 8, 9).

In the southern Anabar area (Lower Lena and Anabar facies regions), the sediments stratigraphically corresponding to the upper part of the Innokent'evka, Urdyuk-Khaya, and Paksa Formations are represented by the Sodyemikha, Buolkalakh, and Kharabyl Formations.

The Sodyemikha Formation with the stratotype sections on the right bank of the Anabar River, near the Sodyemikha River proposed for the first time (Fig. 1). These sediments were previously regarded as the West Siberian Sigovoe Formation (Nikitenko, 2009; Saks, 1981; Shurygin et al., 2000). Considerable differences in lithologic structure and the construction of sections allow the definition of new lithostratigraphic unit here (Figs. 2, 4). The Formation is defined in borehole sections and several outcrops in the western part of Lower Lena facies region (Fig. 2).

In the stratotype sections, the Sodyemikha Formation consists of yellowish and greenish shallow-water marine and littoral-marine sands and sandstones, predominantly fine-grained, with lenses of glauconite-leptochloritic sands,

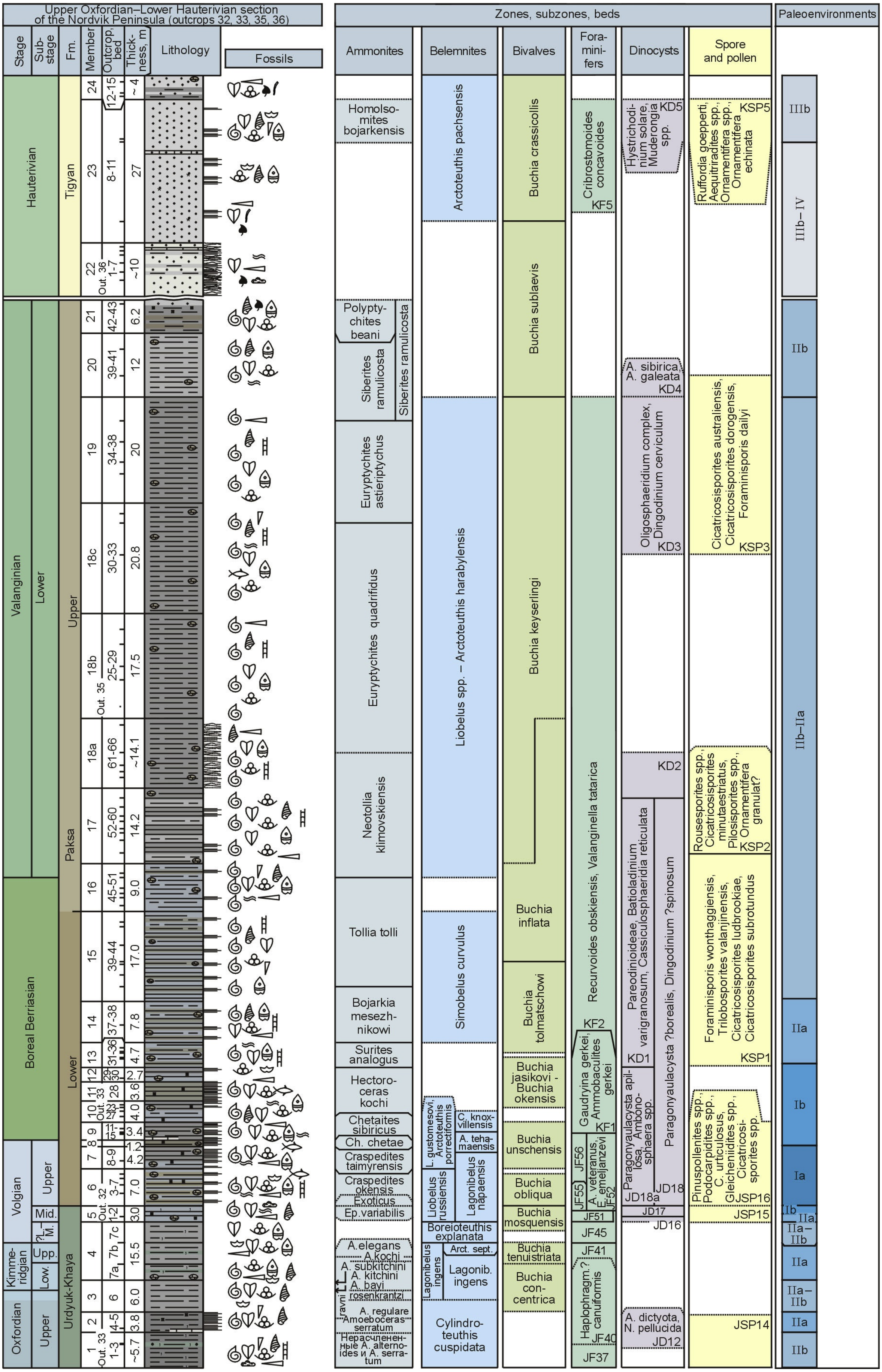
Upper Oxfordian–Lower Hauterivian section of the Nordvik Peninsula (outcrops 32, 33, 35, 36)
Stage
Sub-stage
Fm.
Member
Outcrop, bed
Thick-ness, m
Lithology
Fossils
Zones, subzones, beds
Ammonites
Belemnites
Bivalves
Fora-mini-fers
Dinocysts
Spore and pollen
Paleoenvironments
Hauterivian
Valanginian
Lower
Boreal Berriasian
Volgian
Upper
Mid.
?L.–M.
Kimme-ridgian
Upp.
Low.
Oxfordian
Upper
Tigyan
Paksa
Upper
Lower
Urdyuk-Khaya
24
12-15
~ 4
23
8-11
27
22
Out. 36
1-7
~10
21
42-43
6.2
20
39-41
12
19
34-38
20
18c
30-33
20.8
18b
Out. 35
25-29
17.5
18a
61-66
~14.1
17
52-60
14.2
16
45-51
9.0
15
39-44
17.0
14
37-38
7.8
13
31-36
4.7
12
29-30
2.7
11
Out. 33
28
3.6
10
23-27
4.0
9
11-15
3.4
8
1.2
7
8-9
4.2
6
Out. 32
3-7
7.0
5
1-2
3.0
4
7c
7b
7a
15.5
3
6
6.0
2
4-5
3.8
1
Out. 33
1-3
~5.7
Homolso-mites bojarkensis
Polypty-chites beani
Siberites ramulicosta
Siberites ramulicosta
Euryptychites astieriptychus
Euryptychites quadrifidus
Neotollia klimovskiensis
Tollia tolli
Bojarkia mesezh-nikowi
Surites analogus
Hectoro-ceras kochi
Chetaites sibiricus
Ch. chetae
Craspedites taimyrensis
Craspedites okensis
Exoticus
Ep.variabilis
A.elegans
A.kochi
A. subkitchini
A. kitchini
A. bayi
rosenkrantzi
ravni
A. regulare
Amoeboceras serratum
Нерасчлененные A. alternoides и A. serratum
Arctoteuthis pachsensis
Liobelus spp. – Arctoteuthis harabylensis
Simobelus curvulus
L. gustomesovi, Arctoteuthis porrectiformis
C. knox-villensis
A. teha-maensis
Liobelus russiensis
Lagonibelus napaensis
Boreioteuthis explanata
Lagonibelus ingens
Arct. sept.
Lagonib. ingens
Cylindro-teuthis cuspidata
Buchia crassicollis
Buchia sublaevis
Buchia keyserlingi
Buchia inflata
Buchia tolmatschowi
Buchia jasikovi - Buchia okensis
Buchia unschensis
Buchia obliqua
Buchia mosquensis
Buchia tenuistriata
Buchia con-centrica
Cribrostomoides concavoides
KF5
Recurvoides obskiensis, Valanginella tatarica
KF2
Gaudryina gerkei, Ammobaculites gerkei
KF1
JF56
JF55
A. veteranus, E. emeljanzevi
JF52
JF51
JF45
JF41
Haplophragm.? canuiformis
JF40
JF37
Hystrichodi-nium solare, Muderongia spp.
KD5
A. sibirica, A. galeata
KD4
Oligosphaeridium complex, Dingodinium cerviculum
KD3
KD2
Pareodinioideae, Batioladinium varigranosum, Cassiculosphaeridia reticulata
KD1
Paragonyaulacysta apil-losa, Ambono-sphaera spp.
Paragonyaulacysta ?borealis, Dingodinium ?spinosum
JD18a
JD18
JD17
JD16
A. dictyota, N. pellucida
JD12
Ruffordia goepperti, Aequitriradites spp., Ornamentifera spp., Ornamentifera echinata
KSP5
Cicatricosisporites australiensis, Cicatricosisporites dorogensis, Foraminisporis dailyi
KSP3
Rousesporites spp., Cicatricosisporites minutaestriatus, Pilosisporites spp., Ornamentifera granulat?
KSP2
Foraminisporis wonthaggiensis, Trilobosporites valanjinensis, Cicatricosisporites ludbrookiae, Cicatricosisporites subrotundus
KSP1
Pinuspollenites spp., Podocarpidites spp., C. urticulosus, Gleicheniidites spp., Cicatricosi-sporites spp.
JSP16
JSP15
JSP14
IIIb
IIIb–IV
IIb
IIb–IIa
IIa
Ib
Ia
Ib
IIa
IIa–IIb
IIa
IIa–IIb
IIa
IIb

Fig. 7. Upper Oxfordian–Hauterivian reference section of the Nordvik Peninsula. Subdivision on bivalves after (Zakharov, 1981; Zakharov et al., 1983); on ammonites for the Volgian–Hauterivian after (Basov et al., 1970; Bogomolov, 1989; Saks, 1972; Zakharov et al., 1983); on belemnites for the Upper Berriasian–Hauterivian after (Shenfil', 1992); on dinocysts for the Oxfordian and on spores and pollen for the Oxfordian and Volgian after (Shurygin et al., 2000). See legend in Fig. 3.

brownish silts, many suboval calcareous concretions and concretion marker beds. The Formation often contains disseminated pebbles, gravel, wood fragments, *Dentalium* tubes, and numerous eroded levels. The traces of weathering crusts are observed in the lower part (Saks, 1976), and exactly this level is associated with the Callovian–Oxfordian boundary. Sometimes ammonites from different zones are observed. A bed of coarse-grained greenish oolitic glauconitic sandstone with fossil tree stems, pebble accumulations and lenses occured in the base. The entire Formation is about 15 m thick.

The stratotype section of the Sodyemikha Formation served as a standard for the most complete zonal scale of the Lower Oxfordian in northern Siberia (Figs. 2, 4) (Knyazev, 1975). It is in this section that the position of the Callovian–Oxfordian boundary in northern Siberia was paleontologically substantiated for the first time (Knyazev et al., 1973). Upward the section of the Sodyemikha Formation, *Cardioceras* (*Vertebriceras*) *densiplicatum*, *C.* (*Plasmatoceras*) spp., *C.* (*Cawtoniceras*) sp., and *Amoeboceras* spp., were found in several outcrops, and *Rasenia* spp. were found on the towpath, that suggest the presence of Middle–Upper Oxfordian and Lower Kimmeridgian sediments (Knyazev, 1983; Saks, 1976) (Figs. 2, 4).

The Formation thickness increases northward reaching 65 m. The section consists here of brownish silts and clayey silts interbedded with yellowish and brownish sands and silty sands. Different levels of the Formation contain accumulations and lenses of pebbles, and they are also characterized by numerous stratigraphic gaps. Interlayers of calcareous concretions, wood debris, and many *Dentalium* tubes are observed. Bivalves typical of Callovian–Oxfordian zonal assemblages are found in the Sodyemikha Formation. Foraminiferal assemblages are quite abundant: The Conorboides taimyrensis JF32, Trochammina oxfordiana JF36, Ammodiscus thomsi, Tolypammina svetlanae JF35, and Haplophragmoides? canuiformis JF40 Zones (Figs. 2, 4) are defined.

The glauconitic sands at the base of the Sodyemikha Formation transgressively overlie the eroded siltstones of the upper part of the Yuryung-Tumus Formation. The fossil finds in these sediments allow the estimation of the extent of the stratigraphic gap, which correspond to uppermost Bathonian–lower Upper Callovian). The upper boundary of the Sodyemikha Formation is often eroded, and the Volgian clays of the Buolkalakh Formation overlie different stratigraphic levels of the Sodyemikha Formation.

The stratigraphic analog of the uppermost part of the Urdyuk-Khaya Formation and Lower Paksa Subformation in the Lower Lena facies region is **the Buolkalakh Formation** (Figs. 2, 4) (Volgian–Boreal Berriasian) (Saks, 1981). This formation is composed of argillite-like gray, dark gray, and brownish marine clays, and more rarely of siltstones and clayey siltstones (Figs. 4, 9), sometimes with thin interlayers of fine silty sands, light gray and gray with a greenish tint. A thin interlayer of small-pebble conglomerate with calcareous cement is sometimes present at the base of the Buolkalakh Formation. In the Anabar area, the Buolkalakh clays transgressively overlie the eroded Oxfordian and Kimmeridgian beds of different ages. The clays in the lower part of the Formation (Volgian–lower Boreal Berriasian) often contain highly carbonaceous interbeds. The type section of the Formation is proposed along the Buolkalakh River (Saks, 1981). The formation thickness varies from 20 to 60 m (Figs. 2, 4, 9).

The Kharabyl Formation with the type section near the Anabar River (Lower and base of Upper Valanginian) conformably overlies the Buolkalakh clays (Gol'bert, 1981). The Kharabyl Formation (Fig. 2) consists of greenish gray shallow-water marine clayey silts with large concretions, and layers of dark gray clays in the lower part. Gray silts and sandy silts with a yellowish greenish tint, sometimes containing glauconite–chamosite interbeds, are predominant in the upper part. Sands, gravelstones, and oolitic chamosites sometimes occur in the marginal areas of the Kharabyl Formation distribution. Analysis of the fossil distribution shows that the upper boundary of the Formation can shift from the base of the Upper Valanginian to the top of the Lower Valanginian. The thickness of the Kharabyl Formation varies from 100 to 240 m (Figs. 2, 9).

The Paksa and Kharabyl sediments in the Paksa and Anabar areas (Fig. 2) are overlain by **the Tigyan Formation** (upper Valanginian–?Barremian) established in 1947 by T.M. Emel'yantsev and T.P. Kochetkov in Nordvik sections (Saks et al., 1958, 1963). It is present in the eastern Khatanga trough, on the eastern Taimyr Peninsula, on the islands in the western Laptev Sea, and in the Pronchishchev Ridge. In the west, in the lower reaches of the Yenisei River, it is replaced by the sands of the Malaya Kheta Formation (Gol'bert, 1981; Saks, 1981).

The Formation is dominated by fine-grained shallow-watersands of marine, littoral, lagoonal, and subcontinental genesis. They are light gray with a greenish or yellowish tint and horizontal, lenticular, and oblique bedding. They contain rarer silt interbeds and layers as well as brown-coal seams and, rarely, clay. The rocks are rich in coalified plant detritus, they also contain laminae with abundant brown-coal crumbs. Large bun- and pancake-shaped carbonate concretions often form steadily spread beds. The Formation contains rare ammonites, belemnites, bivalves, foraminifer assemblages, dinocysts, plant spores and pollen of terrestrial plants, and trace fossils (Basov and Sokolov, 1983; Gol'bert, 1981; Saks, 1981; Saks et al., 1959, 1963; Zakharov et al., 1983).

The so-called Balagachan Formation was previously defined between the Kharabyl, Paksa, and Tigyan Formations in several sections of the Anabar River basin, Anabar Bay, Bol'shoi Begichev Island, and eastern Taimyr Peninsula (Chirva and Shul'gina, 1978; Saks, 1981). Like the Tigyan Formation (in the former meaning), this Formation is com-

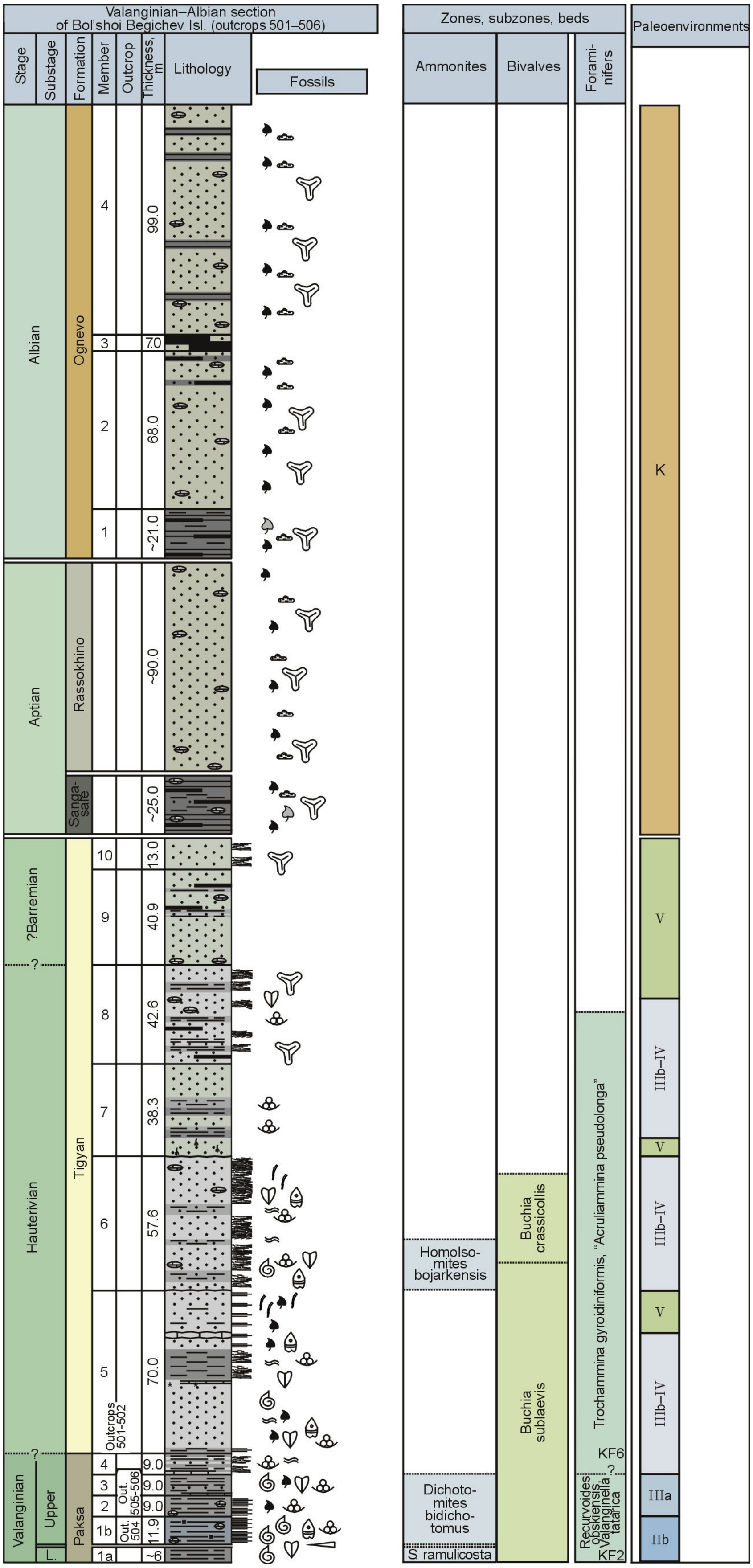

Fig. 8. Valanginian–Albian reference section of Bol'shoi Begichev Island. Subdivision on ammonites, bivalves, and foraminifers after (Basov and Sokolov, 1983; Burdykina, 1981, 1982; Saks et al., 1963). See legend in Fig. 3.

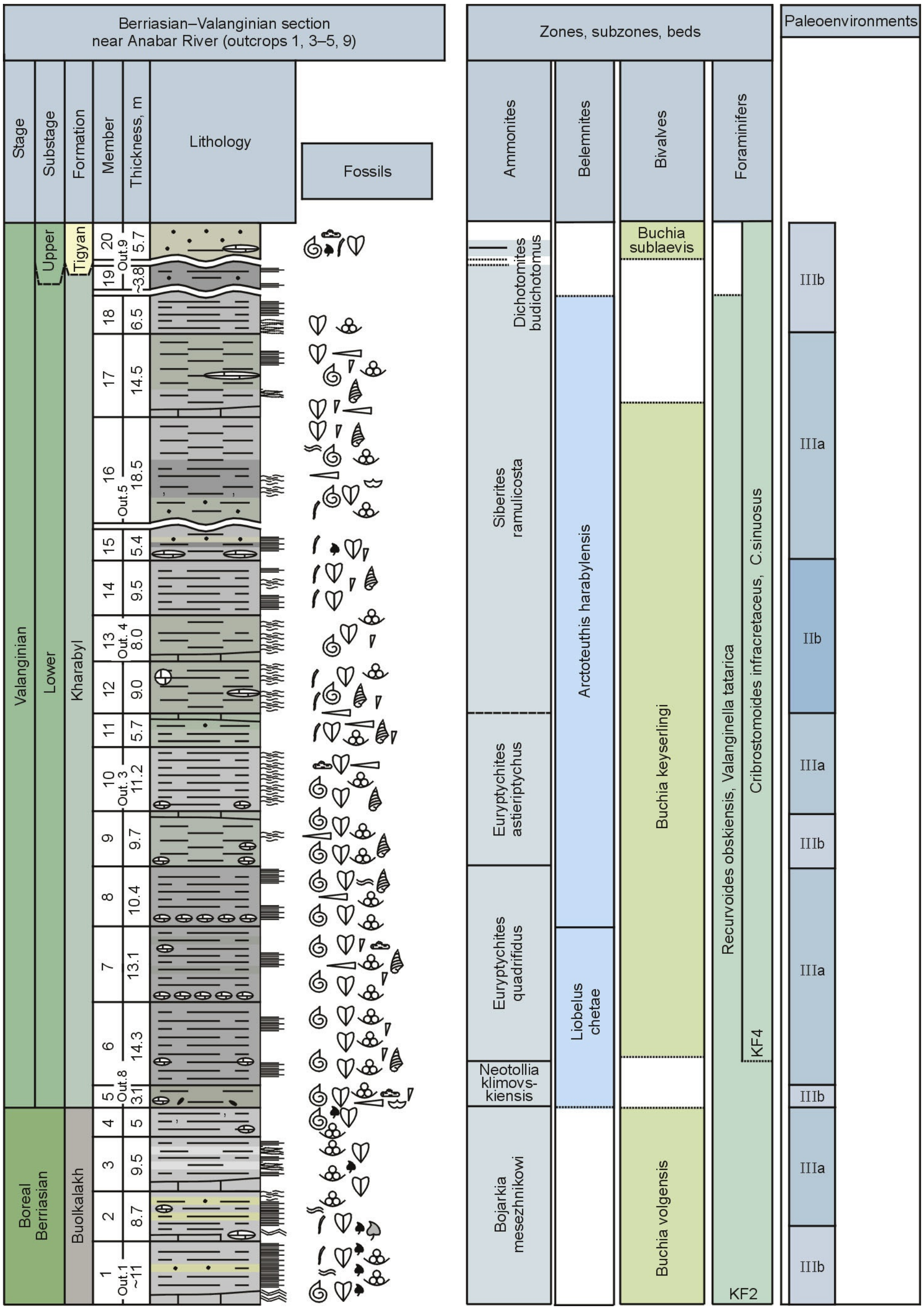

Fig. 9. Boreal Berriasian–Valanginian reference section near the Anabar River. Subdivision on ammonites and bivalves after (Bogomolov, 1989; Gol'bert, 1981; Sanin, 1976; Zakharov, 1981), with some improvements; on belemnites after (Shenfil', 1992). See legend in Fig. 3.

posed of shallow-water marine and littoral-marine sands with interbeds of siltstones and clays. The difference is that the Balagachan Formation contains ammonites, whereas the Tigyan Formation contains interbeds of coal and carbonaceous rocks. However, marine fossils (foraminifers, ostracods, bivalves) are periodically found up to the top of the Tigyan Formation (Gol'bert, 1981; Saks et al., 1963), and carbonaceous lenses also occur in the lower part of the these strata. Considering the lithologic composition identical to that of the Tigyan Formation, the Balagachan Formation will be almost unidentifiable in log data analysis. There are also some problems concerning the definition of the Balagachan–Tigyan boundary within sandy layers on the base of macrofauna last appearances. Thus, we propose to consider the Balagachan Formation as a member in the base of the Tigyan Formation (Fig. 2).

The fossil distribution in the Tigyan Formation is quite nonuniform. The lower part (Balagachan Member) contains diverse and abundant assemblages of ammonites, belemnites, bivalves, and foraminifers, whereas the middle part contains only rare bivalves and foraminifers (Figs. 2, 8). The upper part of the Formation yields only rare foraminifers.

Fossil wood and plant impressions as well as rich spore–pollen assemblages and diverse microphytoplankton were found in different levels of the section (Gol'bert, 1981; Kara-Murza, 1960; Peshchevitskaya, 2000, 2005, 2007; Pestchevitskaya, 2006, 2007c). According to the paleontological data, the formation belongs to the uppermost Valanginian–?Barremian. The stratigraphic position of the lower boundary of the Tigyan Formation varies from the Upper Valanginian to the lowermost Lower Hauterivian (Figs. 2, 7–9). The formation thickness varies greatly: from 9 m near the marginal areas to 400 m in the central areas.

The overlying sediments of the Aptian, Albian, and lower part of the Cenomanian, which overlie the Tigyan Formation in the eastern Khatanga trough, on the eastern Taimyr Peninsula, and on the islands in the western Laptev Sea are represented only by the continental deposits of the Sangasale, Rassokhino, Ognevo, and Begichev Formations. **The Sangasale Formation** (lower part of the Aptian) consists of gray and dark gray silts with clay interbeds and coal layers up to 1.3 m thick. The middle part of the Formation is composed of gray and light gray sands with plant debris. Gray silts with clay interbeds and coal layers up to 2.2 m thick occur in the upper part of the section. The total thickness of the Formation varies from 25 to 60 m. The Formation contains only Aptian macroflora and spore–pollen assemblages (Saks, 1981; Saks et al., 1963) (Figs. 2, 8).

The overlying **Rassokhino Formation** (upper part of the Aptian) is predominantly sandy composition, being represented by inequigranular light gray and gray sands with interbeds of silts, clays, and coal with concretions of sandstone and siderite. The Formation also contains interbeds of coalified plant remnants. The Formation thickness varies from 30 to 220 m. Only Aptian spore–pollen assemblages are found in the Rassokhino Formation (Saks, 1981; Saks et al., 1963) (Fig. 2).

The Rassokhino Formation is conformably overlain by the Albian Ognevo Formation, which consists of sands (Saks, 1981; Saks et al., 1963). **The Ognevo Formation** (40–180 m thick) is composed of light gray and gray sands containing interbeds of dark gray silts and clays as well as coal, with calcareous sandstone concretions. Albian spore–pollen assemblages are defined in the Formation (Figs. 2, 8). The overlying Begichev Formation is observed only in the basins of the Kheta and Khatanga Rivers and in the Khatanga–Anabar interfluve. **The Begichev Formation** (uppermost Albian–lower half of the Cenomanian) is made up of fine- and medium-grained light gray and yellow-gray sands and sandstones containing gravel, pebbles, and coal lenses and fragments. Intense ferruginization is observed. Conglomerate interbeds often occur at the base of the Formation. Albian and Cenomanian spore–pollen assemblages are observed (Saks, 1981; Saks et al., 1963). The Formation thickness varies from 5 to 180 m (Fig. 2).

In the eastern part of the region, in the Anabar–Olenek area, the Tigyan, Sangasale, Rassokhino, Ognevo, and lower part of Begichev Formations are replaced by the continental sands and clays of the Salga, Lukumai, Ukin, Meng-Yuryakh, and Charchyk Formations.

Jurassic and Cretaceous parellel zonal scales of the Boreal standard

By the late 1990s, a set of parallel zonal scales was developed in application to some Jurassic and Cretaceous intervals on ammonites, belemnites, bivalves, foraminifers, ostracods, dinocysts, and terrestrial palynomorphs and proposed as the Boreal zonal standard (Zakharov et al., 1997). The ammonite scale of the Boreal standard is a combined regional scale reflecting the taxonomic peculiarities of Boreal Jurassic biota. This scale should be regarded as the most important as it includes geochronological information (Zhamoida, 2007).

The parallel zonal scales on different groups of macrofauna, microfauna, and palynomorphs, calibrated against the ammonite scale, are regarded as constituents of the Boreal standard. In its turn, the ammonite scale is calibrated against other parallel zonal scales. The combination of the ammonite (priority) scale and scales on other fossil groups not only provides their application on the wider territories, but also increased the resolution of the total biostratigraphic basis and the correlation accuracy. Recent studies of stratotype sections in the Anabar and adjacent areas have permitted the improvement of zonal scales on different faunal groups for some stratigraphic intervals and the inclusion of new zonal scales on new fossil groups, which was previously unused or poorly known, in the Boreal standard.

Ammonite zonal scale

Detailed review of the ammonite zonal scale, used for the division and correlation of Jurassic sediments in Russian boreal and subboreal regions, are given in several recent publications (Meledina et al., 2011; Sei et al., 2006; Shurygin et al., 2011; Zakharov et al., 2010; Zhamoida and Petrov, 2008). We will focus on the latest modifications proposed for this scale.

Since the Upper Toarcian, only the genus *Pseudolioceras* existed in the Arctic seas, that brings some uncertainties to the understanding of the stratigraphic extent of the Upper Toarcian and the possibility of its subdivision. In the Middle Jurassic, there was a significant change in the ammonite composition in the Arctic seas caused by the isolation of the Arctic from the West European seas (Meledina et al., 2005). European genera or species are almost absent. The Lower Aalenian is equal to a one zone, Pseudolioceras (Tugurites) maclintocki, which lower part contains the beds with *Pseudolioceras* (*P.*) *beyrichi*. The latter are sometime interpreted as a separate zone (lona) (Repin, 1997; Zakharov et al., 2010; Zhamoida and Petrov, 2008). There is an evidence that *Pseudolioceras beyrichi* appeared in the Upper Toarcian; so we propose to start the Lower Aalenian with the appearance of *P.* (*T.*) *maclintocki* (Knyazev et al., 2007) (Fig. 10). Like previously Yu.S. Repin and I.V. Polubotko (2011) are regarded the Pseudolioceras beyrichi Zone as the lower Zone of the Aalenian. In their scheme, it comes after Toarcian terminal zone—the Pseudolioceras replicatum Zone. Like many researchers, we question the independence of the species *Pseudolioceras replicatum*. It is included in *P. beyrichi*.

The beginning of the Late Bajocian was marked by the appearance of the highly specialized subfamily Arctocephalitinae arisen from the family Cardioceratidae. The arctocephalitins gave the phylogenetic succession of the genera *Boreiocephalites – Cranocephalites – Arctocephalites – Arcticoceras*, which give way to the genus Cadoceras (subfamily Cadoceratinae) in the Late Bathonian. Direct correlation of Siberian regional zones with the standard ones is impossible for lack of common species (Meledina et al., 2011). The Arctocephalites zones were very tentatively assigned to the Lower Bathonian, whereas the Arcticoceras harlandi and A. ishmae Zones were considered as Middle Bathonian ones (Fig. 10). The researchers of the Jurassic of European Russia previously proposed a different interpretation of the stratigraphic position of these zones (Mitta and Sel'tser, 2002; Mitta et al., 2004). They provided the evidences for the shift of the Arcticoceras ishmae (and A. harlandi) Zone to the Lower Bathonian. S.V. Meledina et al. (2009) recommended to make no hurried changes in Jurassic stratigraphic chart of Siberia.

A group of scientists from Moscow, Novosibirsk, and Saratov revised Middle Jurassic sections in European Russia (Volga region) in summer 2012. The new data suggest that the Arctocephalites arcticus Zone corresponds to the Upper Bajocian, and the overlying zones correspond to the Lower Bathonian (Mitta et al., 2012). These new paleontological data on the more ancient ages of the genera *Arctocephalites* and *Arcticoceras* and, consequently, the age of Siberian zones based on them led Meledina to revise the previous stratigraphic conclusions. One of the possible versions of interregional correlations for the Bajocian–Bathonian interval is given below. Oxycerites jugatus, the Lower Subzone of the Arctocephalites arcticus Zone, can be a good interregional reference. This biostratigraphic unit is constrained by several species of the genus *Arctocephalites*, including *arcticus* and *pilaeformis*, which are very similar to the North pacific species *Megasphaeroceras rotundum*. The latter is the index species of the Megasphaeroceras rotundum Zone, which is defined in southern Alaska and widely distributed in North America and the Far East (Imlay, 1962; Westermann, 1992). In its turn, the Megasphaeroceras rotundum Zone is an analog of the Strenoceras niortense Zone in the International Standard. The Oxycerites jugatus Subzone is rich in *Oxycerites*, which bears a general similarity to the subgenus *Liroxytes*. Throughout the Middle Jurassic, the Arctic seas were connected to the North Pacific seas. It is evidenced by many genera and species, although they are not abundant and not always characterized by an accurate stratigraphic correlation (Meledina, 1991). Abundant collection of Siberian *Oxycerites*, which has increased considerably in recent years, includes forms very close to *O.* (*Liroxytes*) *kellumi*. This species is typical of the assemblage of the M. rotundum Zone. Common or very close ammonite genera and species in Siberian and North American sections can be interpreted as stratigraphically identical. In this case, the Arctocephalites arcticus Zone should be placed in the Upper Bajocian; the O. jugatus Subzone should be placed opposite the Strenoceras niortense ("subfurcatum") Zone; and the A. arcticus Subzone should be correlated with its two upper zones (Garantiana garantiana, Parkinsonia parkinsoni). The position of the Arcticoceras ishmae (and A. harlandi) Zone is determined from East European data as the upper part of the Lower Bathonian Zigzagiceras zigzag Zone (Mitta et al., 2012), and therefore, the Arctocephalites aff. greenlandicus Zone of Siberia corresponds to the lower part of the standard Z. zigzag Zone. This suggests that the Middle Bathonian of Siberia, including the Anabar area, contains no ammonites but is constrained by belemnites and bivalves. After this stratigraphic version is presented in publications and conference reports by Meledina, the appropriate changes to the Boreal zonal standard will be proposed.

Considerable changes have been made in the Callovian zonal scheme of northern Siberia. A unified scale for northern Siberia has been proposed (Figs. 6, 10, 11). The improvements included into the former schemes are based on the analysis of abundant new ammonite collections and revision of the previous ones derived from the key sections exposed in the coastal cliffs of Anabar Bay and Bol'shoi Begichev Island (Figs. 10, 11). Recent data on the stratigraphic range of some Cardioceratidae species indicate that some sediments, which used to be considered as the Middle Callovian, should be included in the Lower Callovian (Knyazev et al., 2010). The stratigraphic volume and boundaries of some biostratigraphic units in the uppermost Lower and Middle Callovian have been refined, so that they can be regarded at the zonal level (Fig. 11).

The zonal scale for the Middle and Upper Oxfordian was developed in Scotland (Isle of Skye) and East Greenland (Sykes and Callomon, 1979; Sykes and Surlyk, 1976). The standard Amoeboceras glosense Zone is defined at the base of the Upper Oxfordian in Siberian sections (Sykes and Callomon, 1979; Sykes and Surlyk, 1976). However, the Amoeboceras alternoides regional Zone (or beds) (Sykes and Callomon, 1979; Sykes and Surlyk, 1976) is identified in some sections (Mesezhnikov et al., 1989; Nikitenko et al., 2011; Saks, 1976; and others). One of the standard sections of the uppermost Oxfordian and Kimmeridgian is the section of the Nordvik Peninsula on Cape Urdyuk-Khaya. A continuous sucession of Upper Oxfordian zones is defined here based on the finds of index species: undivided Amoeboceras alternoides and A. serratum Zones as well as the A. serratum, A. regulare, and A. rosenkrantzi Zones (Nikitenko et al., 2011; Rogov and Wierzbowski, 2009) (Fig. 11). Despite the similarity in the biostratigraphic division of this part of the section, we should note the different interpretations of the ammonite finds (Nikitenko et al., 2011), and this leads to different estimates of the zone volumes in this section. In northern Siberia, it was previously proposed to define the Amoeboceras ravni Zone, which is an equivalent of the Amoeboceras regulare and A. rosenkrantzi Zones. This appears quite reasonable, because

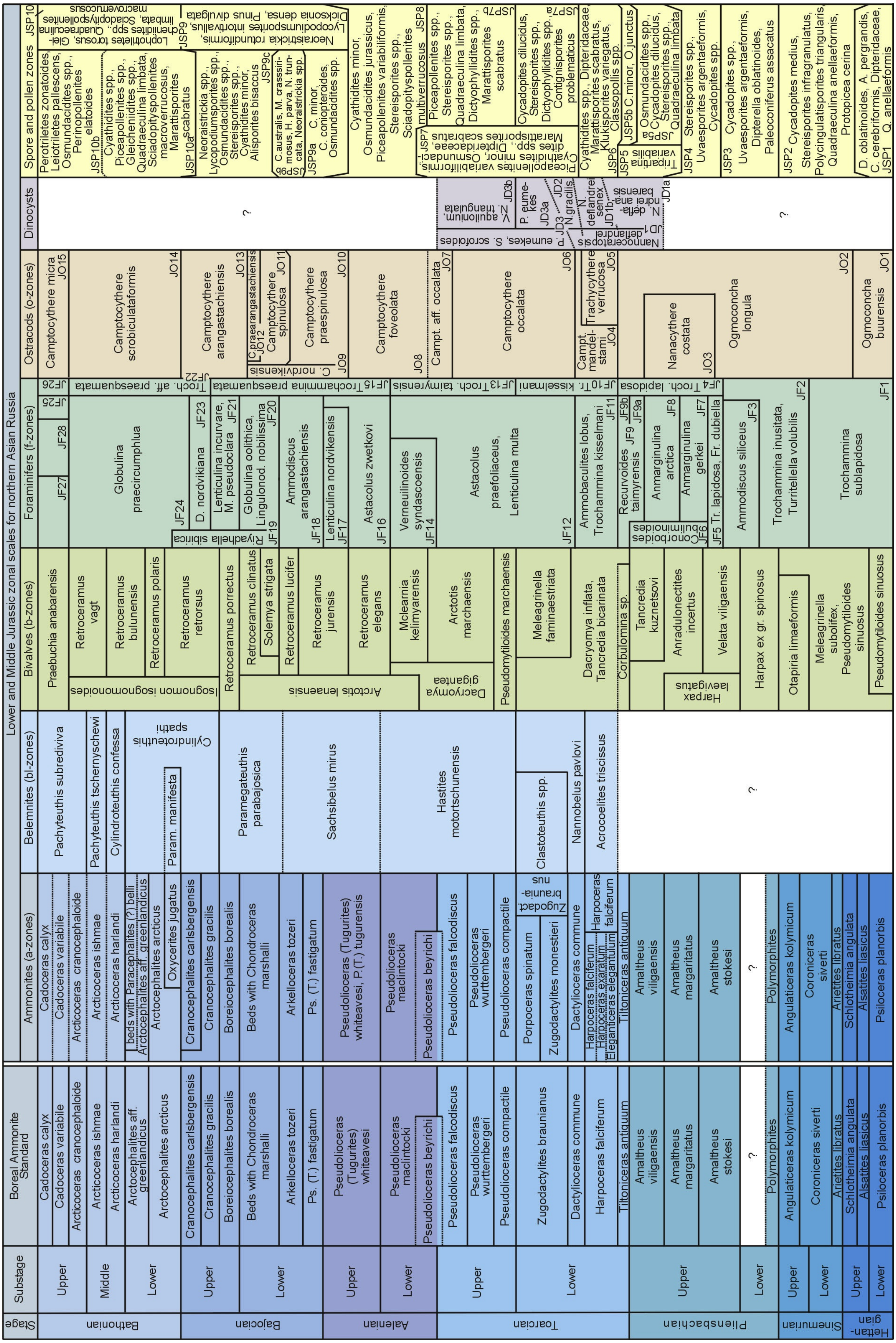

Fig. 10. Hettangian–Bathonian zonal scales of northern Asian Russia in the Boreal standard.

it is impossible to separate the Amoeboceras regulare and Amoeboceras rosenkrantzi Zones in many Siberian regions (Mesezhnikov, 1967; Mesezhnikov et al., 1989).

The Kimmeridgian zonal scale for Siberia was developed in the Subpolar Urals (Mesezhnikov, 1984) and included as a standard in all Siberian biostratigraphic charts (Shurygin et al., 2000; Zakharov et al., 1997). The Lower Kimmeridgian is separated as the Amoeboceras kitchini Zone, which corresponds to the Pictonia involuta and Rasenia borealis Zones (Fig. 11). The Oxfordian–Kimmeridgian boundary was marked by the appearance of *A.* (*Amoebites*) spp. descended from the *kitchini* group, which replaced Oxfordian species of the subgenera *Amoeboceras*, *Paramoeboceras*, and *Prionodoceras*. An independent Kimmeridgian zonal scale, based on the change srecies composition of the genus *Amoeboceras*, was developed for the western Panboreal Realm (East Greenland, Svalbard, southwestern shelf of the Barents Sea) (Wierzbowski, 1989; Wierzbowski and Smelror, 1993). At the base of the Lower Kimmeridgian, *Amoeboceras* (*Plasmatites*) *bauhini* was defined as a separate zone beneath the Amoeboceras (Amoebites) kitchini Zone, whereas the Amoeboceras (Amoebites) kitchini Zone was divided into several faunal horizons (Wierzbowski and Smelror, 1993).

In our view, there is no sufficient data for the definition of the Amoeboceras (Plasmatites) bauhini Zone. The status of the subgenus *Plasmatites* remains uncertain: the species of this taxonomic unit are included in the subgenera *Amoeboceras* (e.g., Mesezhnikov et al., 1989), *Amoebites* (Birkelund and Callomon, 1985), or *Plasmatites* itself (Matyja et al., 2006; Rogov and Wierzbowski, 2009; and others). This subgenus has also a problematic species composition, being represented by the species *prebauchini*, *bauhini*, and *lineatum* with small shells and the type species *Plasmatites crenulatus* (Buckman, 1925) having uncertain stratigraphic extent. The species *prebauchini* is the oldest synonym for *Plasmatites crenulatus*, and its stratigraphic position is also uncertain (Birkelund and Callomon, 1985). The identification of the species *bauhini* is complicated, because the species now includes dramatically different forms, previously assigned to different species (Schweigert and Callomon, 1997). It is not impossible that many former determinations of *Plasmatites bauhini* actually belong to *Amoebites bayi* (Schweigert, 1995; Zeiss, 2003), a completely different subgenus. Also, *Plasmatites lineatum* might be a synonym for *Amoebites bayi* (Zeiss, 2003). Thus, the identification and stratigraphic extent of the subgenus remain uncertain according to some researchers (Birkelund and Callomon, 1985; Zeiss, 2003). Therefore, we cannot agree that the Amoeboceras bauhini Zone should be placed at the base of the Kimmeridgian on the “Boreal” scale, as proposed in Matyja et al. (2006) and Wright (2003). In our view, the ammonites determined by M. Rogov and A. Wierzbowski (2009) from the Kimmeridgian sediments on the Nordvik Peninsula as *Amoeboceras* (*Plasmatites*) *bauhini* or *Amoeboceras* (*Amoebites*) *bayi* cannot serve as a basis for the definition of the Amoeboceras bauhini Zone in the standard section of the Nordvik Peninsula, on Cape Urdyuk-Khaya.

The most complete successions of Boreal Berriasian–lower Hauterivian ammonite zones are known in the Anabar area (on the Nordvik Peninsula and Bol’shoi Begichev Island) (Bogomolov, 1989; Zakharov et al., 1983) (Figs. 7, 8). The Volgian–Boreal Berriasian boundary is marked by a change of the species of the genus *Chetaites* (Fig. 12). It is proposed to divide the Boreal Berriasian into five zones (Alekseev, 1984; Zakharov et al., 1997) (Fig. 12). A more detailed (subzonal) division of this interval should be improved, as the boundaries of some biostratigraphic units are defined only by the disappearance of species (Alekseev, 1984). It is hardly reasonable to introduce such a subzonal division into the Boreal standard. Moreover, some subzones cannot be identified even in neighboring regions. The Boreal Berriasian zones (Chetaites sibiricus, Hectoroceras kochi, Surites analogus, Bojarkia mesezhnikovi, Tollia tolli) occur widely throughout the Boreal Realm.

The zonal scale for the Valanginian and lowermost Hauterivian has not undergone any significant changes in recent years (Bogomolov, 1989; Zakharov et al., 1997) (Fig. 12). It should be noted, that the zonal index species *Homolsomites bojarkensis*, abundant in the lower Hauterivian, first appears in the uppermost Upper Valanginian Dichotomites bidichotomus Zone (Neocraspedites kotschetkovi Subzone). The Valanginian–Hauterivian boundary is defined only on the base of the disappearance of *Polyptychites* spp. and *Neocraspedites kotschetkovi*. Therefore, the stratigraphic extent of the Homolsomites bojarkensis Zone should be expanded (Fig. 12). The Valanginian Boreal standard is well correlated with the Tethyan standard through the intermediate ecotone sections of Germany (Bogomolov, 1989; Zakharov et al., 1997).

The end of the Hauterivian, Aptian, and Albian of Siberia are characterized by predomonantly continental regime, and ammonite finds in the remaining sea basins are extremely rare. Therefore, the scale developed by E.Yu. Baraboshkin (2004) is accepted for boreal regions as the standard zonal succession for this interval, with minor modifications (Fig. 12). The type sections of the zones included in this scale are localized mainly within the East European Platform, but many biostratigraphic units are well-defined in the Arctic regions of Canada, Alaska, Svalbard, Greenland, and northern Europe.

Belemnite zonal scale

Jurassic and Cretaceous marine sediments contain abundant representatives of one more group of fossil cephalopods-belemnites. They might occur in abundance in Boreal sections where biostratigraphically important macrofossils such as ammonites, buchias, etc., are absent or rare. Therefore, belemnite zonal scales for the Jurassic and Lower Cretaceous of Siberia within the Toarcian-Hauterivian have been developed actively during the last few decades (Dzyuba, 2000, 2004, 2012; Meledina et al., 1987, 1991; Nal’nyaeva, 1986; Shenfil’, 1992, 1995). Lateral distribution of belemnites was rigidly controlled by the depth of sediment formation, and it confines the application of belemnite scales to shallow-water marine and deep-water facies (but no deeper than 200–250 m).

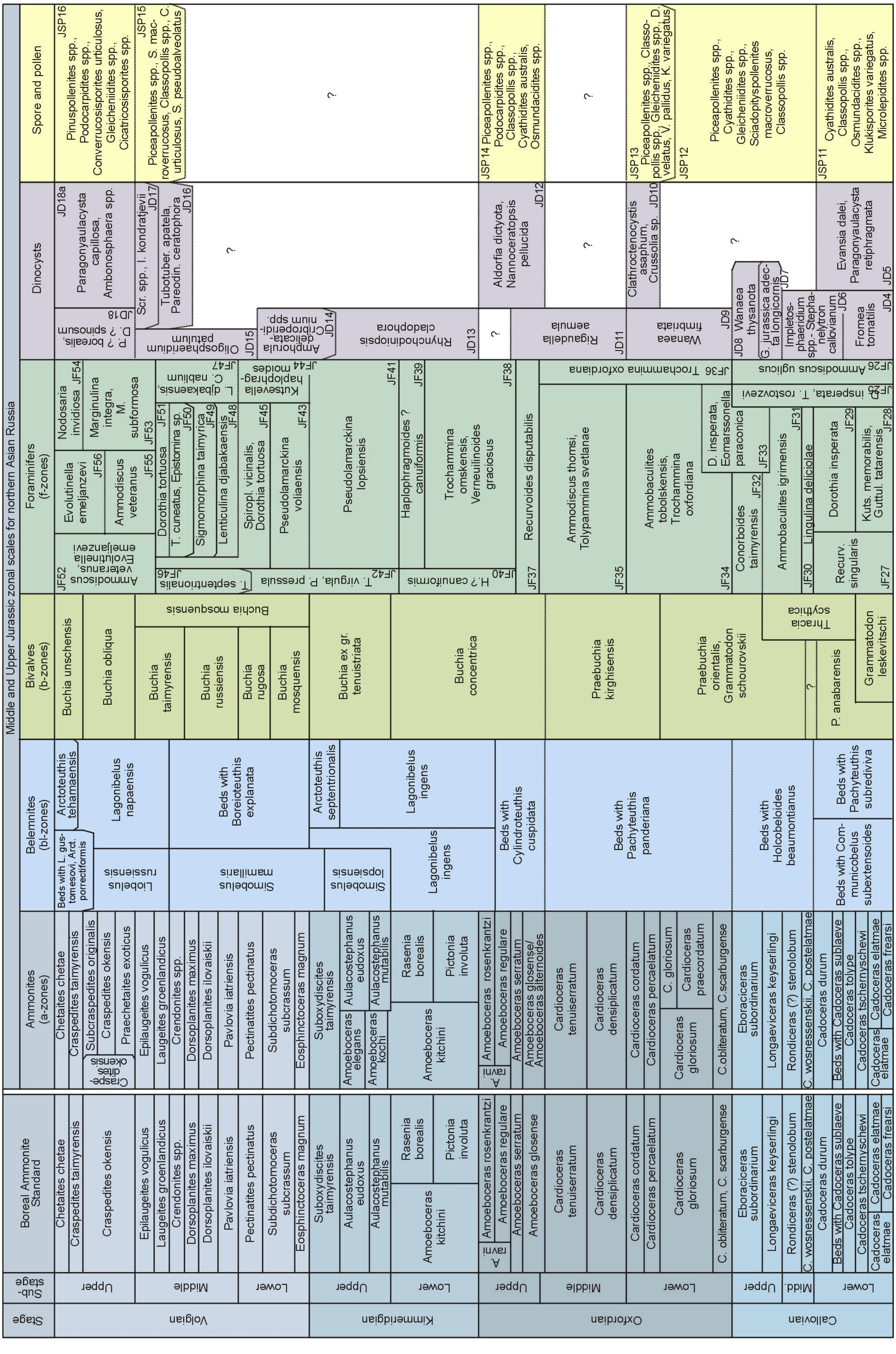

Fig. 11. Callovian–Volgian zonal scales of northern Asian Russia in the Boreal standard.

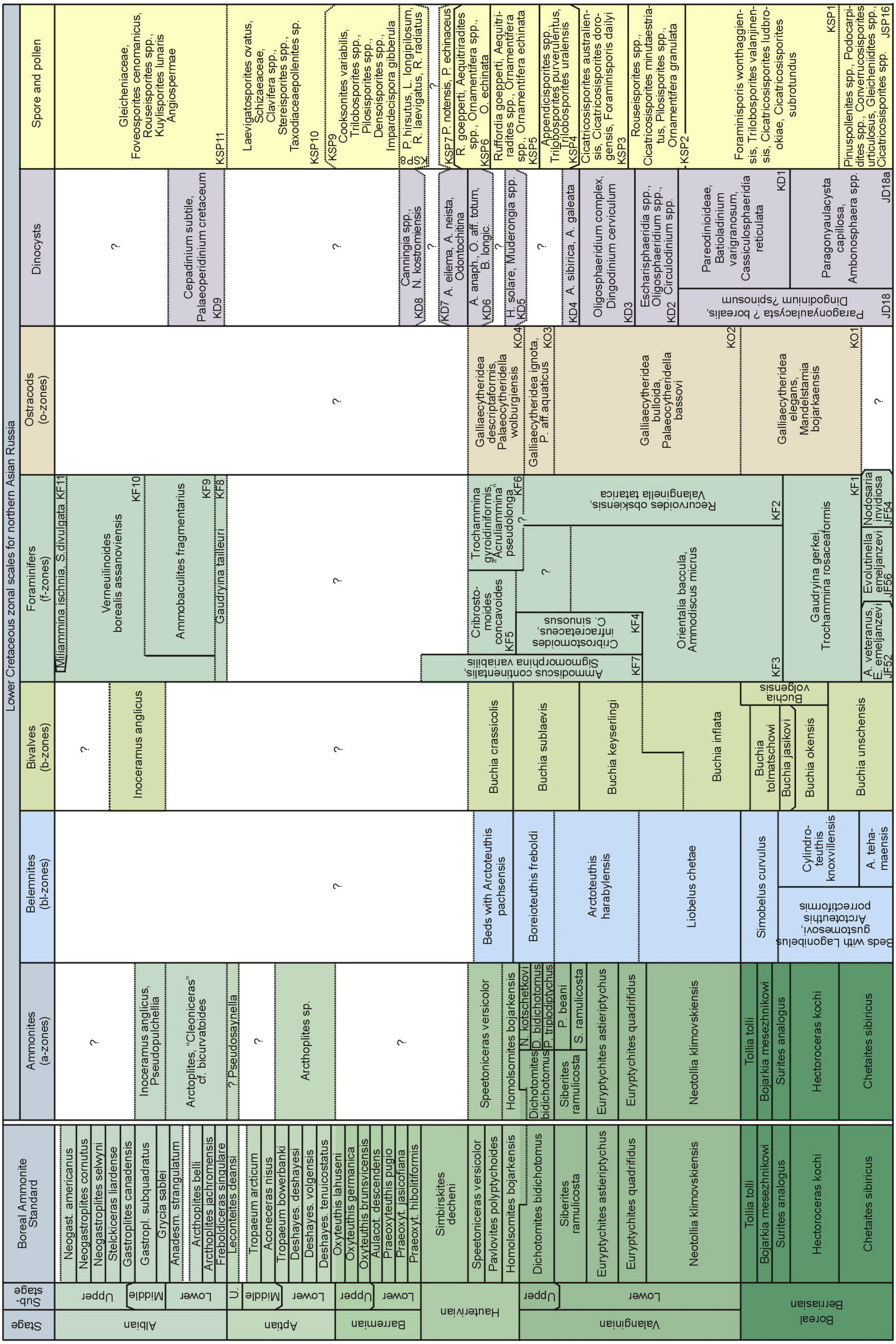

Fig. 12. Lower Cretaceous zonal scales of northern Asian Russia in the Boreal standard.

The belemnite distribution over the section is also nonuniform. They occur massively near the Lower–Middle Jurassic boundary, and they are also abundant in the Upper Jurassic and lower half of the Lower Cretaceous (Dzyuba, 2013; Meledina et al., 2005; Saks and Nal'nyaeva, 1979). In the Bajocian-Oxfordian and Hauterivian, the number and taxonomic diversity of belemnites in Siberian sections are low. They are not found in the Anabar area in the sediments overlying the Lower Hauterivian.

Detailed monographic studies of belemnites from Toarcian and Middle Jurassic outcrops on the northern and eastern peripheries of the Siberian Platform (Yuryung-Tumus Peninsula, Anabar area, lower reaches of the Lena River, basins of the Vilyui and Olenek Rivers) (Saks and Nal'nyaeva, 1970, 1975; and others) served as a basis for the development of belemnite zonal scales for this Jurassic interval (Meledina et al., 1987, 1991; Nal'nyaeva, 1986; Shurygin et al., 1996; and others). The succession of zones and beds defined here were later included in the Boreal zonal standard (Zakharov et al., 1997) and has not changed so far (Shurygin et al., 2011) (Fig. 10). Note that, according to new studies of the Middle Jurassic on the Yuryung-Tumus Peninsula, the zonal species *Paramegateuthis manifesta* occurs massively not only in the Oxycerites jugatus Subzone on ammonites, as was presumed before (Meledina et al., 1987), but also in the overlying beds of the Lower and, maybe, Middle Bathonian (Fig. 5). Apparently, the stratigraphic range of the Paramegateuthis manifesta Zone, defined on the index species epibole, should be expanded.

The Callovian–Upper Jurassic belemnite zonal scale for Arctic Siberia (Dzyuba, 2004), and then the zonal scale for the Jurassic–Cretaceous boundary sediments (Dzyuba, 2012), have been considerably changed. New ammonite finds in Oxfordian and Kimmeridgian transitional beds on the Nordvik Peninsula and redating of their host sediments permitted a more precise determination of the position of the boundary between *Cylindroteuthis cuspidata* beds and the Lagonibelus ingens Zone with respect to the ammonite scale (Fig. 7). The ammonites evidence more ancient age of this boundary in the Boreal standard, which now corresponds to the bottom of the Upper Oxfordian Amoeboceras rosenkrantzi Zone of ammonites (Figs. 7, 11). As compared with the previous version included in the set of parallel zonal scales of the Boreal zonal standard (Zakharov et al., 1997), the updated belemnite scale has a higher correlation potential. Several biostratigraphic units defined in the sections of the Anabar and Khatanga areas have been defined in West Siberia (Dzyuba, 2004, 2013). Some levels are identified in the sections of Eastern and Northwestern Europe, Svalbard, East Greenland, Northern California, and the Upper Amur region (Dzyuba, 2004, 2010, 2011, 2013; Nal'nyaeva et al., 2011).

The Valanginian-Lower Hauterivian zonal scale of Siberia, developed on belemnites and based on the material from Anabar (Figs. 7, 9) and Khatanga areas, has remained unchanged since the publication by O.V. Shenfil' (1992). It is first included in the Boreal zonal standard in the present paper (Fig. 12). In general, the belemnite zonal scale for the Jurassic and Lower Cretaceous of Siberia now consists of 30 biostratigraphic units in the rank of zones, subzones, and biostratigraphical beds with belemnites (Figs. 10–12).

Zonal scales for benthic groups (bivalves, foraminifers, ostracods)

As a rule, modern Siberian Jurassic scales for benthic groups (bivalves, foraminifers, ostracods), as well as marine and terrestrial palynomorphs are the most efficient tool for direct subdivision and correlation of sections revealed by boreholes. The entire variety of parallel biostratigraphic zones is regarded as an operational combination of biologic-event scales. Note, that the variety of independent methods for subdivision and correlation is also used for mutual control (feedback). A combination of all zonal scales yields detailed section correlation, considerably reduces the risk of errors, and provides mutual control of the stratigraphic position of biostratigraphic units.

Bivalves. By the late 1970s-first half of the 1980s, the first parallel zonal scale on buchias for the Upper Jurassic and Lower Cretaceous was first created (Zakharov, 1981), after that, a parallel zonal scale on bivalves for the Lower and Middle Jurassic was created (Shurygin, 1986, 1987a,b). The bivalve zonal scale for the Upper Jurassic and Lower Cretaceous of Siberia was originally based on principles different from those for the Lower and Middle Jurassic scale. The Lower–Middle Jurassic scale is considered predominantly as a biologic-event scale, which consists of polytaxon zones, whereas the Upper Jurassic–Lower Cretaceous buchia scale is constructed as a typical phylozonal scale. Twenty-seven bivalve zones are defined in Lower and Middle (without the Callovian) Jurassic sections of Siberia (Fig. 10). As practice shows, the bivalve scale developed for this interval permits interregional correlations and accurate calibration of Arctic sections of Russia and other countries (Shurygin, 2005; Shurygin et al., 2000, 2011).

The number, names, and succession of stratigraphic units in buchia scale for the Upper Jurassic and Lower Cretaceous used in recent years, have remained almost unchanged, as compared with the original ones (Zakharov, 1981), whereas the stratigraphic position of some buchia zones is permanently being corrected according to detalization and refinement of ammonite scales for this interval in Siberia. For example, the extents of the Buchia jasikovi, B. tolmatchowi, B. inflata, B. keyserlingi, and B. sublaevis Zones (Zakharov et al., 1997) were revised as early as the Boreal zonal standard was developed, takimg into consideration new studies of Berriasian and Valanginian ammonites (Alekseev, 1984; Bogomolov, 1989) (Fig. 12). However, the extents of the Buchia inflata and B. keyserlingi Zones are still uncertain because of the uncertain position of the boundary of these buchia zones with respect to the ammonite stratigraphic units. V.A. Zakharov (1981) established stratotype for the Buchia inflata Zone on the Nordvik Peninsula, in outcrop 33, beds 42–51 (Fig. 7). Beds 25–38 of the same section, outcrop 35, were defined as a stratotype for the Buchia keyserlingi Zone (Fig. 7). If we consider modern views on the stratigraphical extent of ammonite zones (Bogomolov, 1989), used in the Boreal standard, the upper boundary of the Buchia inflata Zone in the stratotype in outcrop 33 should be placed within the Neotollia klimovskiensis Zone, whereas the lower boundary of the Buchia keyserlingi Zone in outcrop 35 is localized in the lowermost part of the Euryptychites quadrifidus Zone (Fig. 7). Taking into consideration modern data on ammonites, the position of the this boundary of buchia zones in other sections is also ambiguous: near the Boyarka River, it is within the Neotollia klimovskiensis Zone (Bogomolov, 1989; Zakharov, 1981), whereas on the eastern shore of Anabar Bay, it is in the lower Euryptychites quadrifidus Zone (Bogomolov, 1989; Bogomolov et al., 1983). Thereafter, we show the uncertain position of the boundary between the Buchia inflata and B. keyserlingi Zones in the Boreal standard within the Neotollia klimovskiensis and Euryptychites quadrifidus Zone (Fig. 12).

It was presumed until recently that the lower boundary of the Buchia concentrica Zone coincides with the Oxfordian-Kimmeridgian boundary (Shurygin et al., 2000, 2011; Zakharov et al., 1997, 2005). It was stated that the extent of this buchia zone was changed in comparison to original one (Jeletzky, 1961) due to inclusion of its lower part into the new Praebuchia kirghisensis Zone (Zakharov, 1981). A complete extent of the Buchia concentrica Zone, established near the Boyarka River, where its relation with the underlying Praebuchia kirghisensis Zone is uncertain, was defined in the section on the Nordvik Peninsula (Zakharov, 1981). The lower part of the Nordvik section represented by Kimmeridgian–Oxfordian succession is now studied in detail (Fig. 7). Thereafter, the lower part of the Buchia concentrica Zone (Zakharov, 1981; Zakharov et al., 1983) is constrained by Upper Oxfordian ammonites. However, this section also does not contain bivalves from the underlying Praebuchia kirghisensis Zone. Considering all the above circumstances and the fact that the position of the lower boundary of the Buchia concentrica Zone in the East European Platform has been recently placed at the lower boundary of the Upper Oxfordian, we can also assign it to the Upper Oxfordian–Lower Kimmeridgian in Siberia (Fig. 11).

Owing to the wide geographic distribution of many Buchia taxa and their periodic penetration into peri-Tethyan zones, the zonal scale of the Upper Jurassic and Lower Cretaceous provides not only a reliable circum-Boreal correlation, but also a Boreal–Tethyan correlation at several stratigraphic levels (Rogov and Zakharov, 2009; Zakharov et al., 1997).

Foraminifers. An extensive micropaleontological studies in the Soviet Union were carried out due to oil and gas drilling and mapping works in northern Siberia. For example, as early as the 1970s, independent biostratigraphical units on foraminifers were defined (Bochkarev, 1981; Dain, 1972; Saks, 1976; etc.). Further, the unified foraminiferal scale for the Callovian and Upper Jurassic did not change much (Azbel' et al., 1991; Vyachkileva et al., 1990). The present foraminiferal zonal scale for the Lower and Middle Jurassic of Siberia (Fig. 10) (Nikitenko, 1992, 2009) is developed on reference sections of the Anabar area (Figs. 3–5). This scale has almost not changed with respect to the 1997 version (Zakharov et al., 1997). As an innovation, a more detailed subdivision of the interval near the Pliensbachian–Toarcian boundary has been proposed (Fig. 10). The stratigraphic extent and position of the boundaries of the foraminiferal zones have been revised according to the reinterpretation of the data on ammonites in the Callovian stratotype section of Bol'shoi Begichev Island and changes in the ammonite zonal scale (Figs. 6, 11). The Upper Jurassic zonal scale has been significantly modified and refined; several additional biostratigraphic units have been established as a standard; the stratigraphic position of the boundaries of some zones has been redetermined; and some intervals have been precisely defined (Fig. 9). The Jurassic foraminiferal scale consists of 56 zones (Figs. 10, 11).

It is the first time that the Cretaceous foraminiferal scales are proposed as a Boreal standard (Fig. 12). The Berriasian–Hauterivian zonal succession was based on the biostratigraphic units defined in northern areas of Central and West Siberia (Azbel' et al., 1991; Basov et al., 1970; Gol'bert, 1981; Nesterov, 1991; Vyachkileva et al., 1990; and others) (Figs. 7–9, 12). It should be noted, that the Volgian–Boreal Berriasian boundary is not marked by a change of foraminiferal assemblages. The first Cretaceous forms appear in the upper part of the Craspedites okensis Zone–lower part of the C. taimyrensis Zone. Jurassic taxa exist untill the middle of the Boreal Berriasian (KF1 Zone). The assemblages included only Cretaceous forms (KF2 and KF3 Zones) are defined only since the second half of the Boreal Berriasian (lower part of the Surites analogus Zone). This interval is also marked by some changes in belemnite, bivalve, and dinocyst assemblages (Fig. 12).

Recent studies in the Anabar area allows the revision of the stratigraphic volume and position of the boundaries of zones. Some biostratigraphic units (KF1, KF2, KF4, KF5) are defined in all Arctic regions: West Siberia, East Siberia, Arctic Alaska, Arctic Canada, and Barents Sea shelf (Basov et al., 2008; Fowler and Braun, 1993; Shurygin et al., 2000; Wall, 1983). Since the second half of the Hauterivian, a predominantly continental regime had set in East Siberia (Fig. 9). The uppermost Hauterivian and Aptian in West Siberia are dominated by continental, subcontinental, and littoral-marine facies, and only primitive foraminiferal taxa are observed. A succession of four biostratigraphic units (Fig. 10) also defined in all other Arctic regions (Azbel' et al., 1991; Basov et al., 1989, 2008) was identified in Albian sediments of northern and northwestern areas of West Siberia (Nesterov, 1991).

In Siberia, some Jurassic and Cretaceous intervals are characterized by the presence of migrant taxa having circumboreal distribution. There are also some events related to the migration of typically Arctic taxa to the Jurassic seas of Western Europe (Nikitenko, 2009). The succession of these events provides a basis for interregional correlations of the sections.

Ostracods. Data on the vertical distribution of ostracod species and the succession of Lower and Middle Jurassic assemblages in northern Siberia were summarized by O.M. Lev (Saks, 1976). This work resulted in taxonomic description of eight ostracod assemblages and their calibration against the general stratigraphic scale. Later, 16 Jurassic ostracod assemblages were described (Saks, 1981). It should be noted, that these assemblages contained similar species taxa and their taxonomic compositions often did not differ much. Biostratigraphic analysis showed that the successions of ostracod assemblages can be identified in wide territory. Fourteen biostratigraphic units on ostracods in the rank of zones and biostratigraphical beds have been established for Hettangian–Bathonian (Fig. 10), which are later defined in the studied deposits in East Siberia and northern areas of West Siberia. The stratotype sections of the succession of ostracod zones are located in the Anabar area (Nikitenko, 2009) (Figs. 3–5). Finds of ostracods abundant in the north of Western Europe and exotic for northern Siberia allow the estimation of the potential of this microfaunal group for interregional and circumboreal correlation and the definition of some interregional reference levels: in the middle of the Late Pliensbachian, in the end of the Pliensbachian, in the beginning of the Early Toarcian, and in the beginning of the Aalenian (Nikitenko, 1994, 2009). A single biostratigraphic unit, Camptocythere micra, was distinguished for the uppermost Bathonian and Callovian. Ostracods are extremely rare in the Upper Jurassic of Siberia. However, they become abundant and diverse in shallow-water marine and littoral-marine facies in the Berriasian–lower Hauterivian. The scale including four biostratigraphic units (Lev, 1983) was proposed for these sediments (Fig. 12) and further modified with regard to the data on West Siberia (Nikitenko et al., 2004, 2011). Some units of this scale are well defined on the Barents Sea shelf (Basov et al., 2008; Kupriyanova, 2000; Lev and Kravets, 1982; Nikolaeva and Neustrueva, 1999).

Dinocyst zonal scale

Palynological studies of the last few decades show that dinoflagellate cysts are widespread in the Jurassic and Cretaceous seas of Siberia. Dinocyst scales are characterized by high stratigraphical accuracy and give the detailed subdivision and dating of marine sediments, especially in borehole sections, where macrofaunal finds are rare.

The first dinocysts appeared in East Siberian Jurassic sediments in the Sinemurian. However, their abundant finds are known since the uppermost Pliensbachian. A continuous succession of two zones and five subzones from the upper Pliensbachian to the Toarcian was included in the Boreal standard for dinocysts (Il'ina et al., 1994; Zakharov et al., 1997) (Figs. 3, 4, 10). The dinocyst zonal scale was later improved (Gurari, 2004; Shurygin et al., 2000). The ages of some biostratigraphic units have been revised in the light of new data on the vertical distribution of some index species based on a more detailed study of sections in northern areas of East Siberia (Goryacheva, 2011; Nikitenko et al., 2011) (Fig. 10).

Upper Jurassic dinocyst scale of five biostratigraphic units proposed for the Boreal zonal standard in 1997 is not continuous (Zakharov et al., 1997). This succession was developed in the key sections of northern areas of East Siberia (Il'ina, 1988) (Figs. 3, 7). Later, new data were obtained on the dinocyst distribution in the Callovian–Volgian sediments of West Siberia (Ilyina et al., 2005). A succession of eleven biostratigraphic units was established in the key section of the Tyumenskaya superdeep borehole (SD-6). It is almost continuous succession well defined in West Siberian basin (Fig. 11).

The 1997 Boreal zonal standard for the Lower Cretaceous included a succession of biostratigraphical beds with dinocysts from the Berriasian to the Lower Hauterivian, defined near the Yatriya River in the Subpolar Urals (Zakharov et al., 1997). The subsequent studies yielded new data on the palynostratigraphic subdivision of Berriasian, Valanginian, and Hauterivian sections in the north of West Siberia (Nikitenko et al., 2006a, 2008; Peshchevitskaya, 2000, 2003, 2005, 2010; Pestchevitskaya, 1999, 2008; and others). These data permitted a reliable correlation of palynostratigraphic units with regional biostratigraphic units on macrofauna and foraminifers. These palynostratigraphic units were later defined in northern areas of West Siberia in the borehole sections (Nikitenko et al., 2006b; Peshchevitskaya, 2005, 2007, 2010; Pestchevitskaya, 2007a,b; Peshchevitskaya and Nikitenko, 2008a,b; and others). As a result, an almost continuous succession of biostratigraphical beds with dinocyst was developed.

The dinocyst assemblages in all the intervals contain stratigraphically important species, which are reliable markers for interregional correlations (Peshchevitskaya, 2010; Pestchevitskaya, 2006, 2007b, 2008) both in the Arctic and with Western Europe regions. Such marker levels are present in the middle part of the Boreal Berriasian (base of KD1) as well as in the lower part (top of KD1) and middle part (base of KD3) of the Lower Valanginian. Three marker levels established for West Siberia in the upper part of the Hauterivian and in the base of the Barremian are well defined in northern areas of Western Europe. Thus, the boundaries of Siberian biostratigraphical beds with dinocysts have a considerable correlation potential. The marker level of the middle part of the Berriasian is observed in Arctic Canada, the Moscow syneclise, and the Subpolar Urals, whereas the marker levels of the lower and middle parts of the Lower Valanginian can be defined in almost all the Boreal regions of Western Europe and Canada. The marker levels of the upper part of the Lower Valanginian and Lower Hauterivian are of regional importance, because they are present in different regions of Siberia and in the Subpolar Urals (Nikitenko et al., 2008; Peshchevitskaya, 2010; Pestchevitskaya, 2006, 2007b, 2008).

Spore-pollen zones

The 1997 Boreal stanard (Zakharov et al., 1997) included the Lower and Middle Jurassic palynostratigraphic scale for Siberia (without the Callovian) (Il'ina, 1985) (Fig. 10). A continuous succession of ten palynostratigraphical units in the rank of spore-pollen zones and biostratigraphical beds was defined for the Lower and Middle Jurassic. This scale has not changed so far. The Boreal standard did not contain any data on terrestrial palynomorphs for the Upper Jurassic sediments (Zakharov et al., 1997). The succession of palynostratigraphic units for the Callovian–Upper Jurassic of northern areas of East Siberia was based on the studies of key sections of Jurassic marine sediments on the coast of Anabar Bay, the Anabar River, Bol'shoi Begichev Island, the lower reaches of the Lena River, and the Nordvik Peninsula (Shurygin et al., 2000).

The succession of palynostratigraphic units is well defined in the Callovian–Oxfordian and Middle–Upper Volgian. The spore–pollen assemblages from the Kimmeridgian, Lower Volgian, and part of the Middle Volgian in northern areas of East Siberia have almost not been studied. The Callovian–Volgian biostratigraphical units in the rank of spore-pollen zones and biostratigraphical beds are calibrated against ammonite scale for the Callovian and Upper Jurassic of northern East Siberia. The proposed scale is almost continuous succession of six palynostratigraphic units (Il'ina, 1985, 1988; Shurygin et al., 2000) (Fig. 11).

The boundaries of the Lower Cretaceous biostratigraphical beds with spores and pollen were defined using the taxa which are stratigraphically important components of spore–pollen assemblages in northern Siberia as well as some species having first appearances well defined at certain boundary over large areas (Peshchevitskaya, 2005, 2010; Pestchevitskaya, 2007a). This fact determined the high correlation significance of these levels in Siberia. The standard succession of biostratigraphical beds with spores and pollen defined in northern Siberia is correlated with zones on ammonites, bivalves, and foraminifers in the Boreal zonal standard, according to stratigraphic data from several sections of northern areas of East Siberia (Peshchevitskaya, 2005, 2010; Pestchevitskaya, 2007a) (Fig. 12). Correlative levels on spores and pollen can be defined in the East European Platform, Subpolar Urals, and West Siberia on the base of core material and literature data (Peshchevitskaya, 2005, 2010; Peshchevitskaya and Smokotina, 2010; Peshchevitskaya et al., 2010; Pestchevitskaya, 2007a).

Conclusions

The evolution of the Jurassic–Cretaceous basin in northern Middle Siberia is divided into several major stages. The Hettangian–Late Bathonian stage is characterized by the formation uniform sediments showing little lateral changes in general as well as quasi-synchronous regular variations in large areas depending on T–R events. The Callovian–Valanginian is marked by a considerable facies differentiation. A global regressive stage is observed in the development of Siberian sedimentary basins in the late Valanginian–early Hauterivian. In the sections, this is represented by alternation of shallow-water marine, littoral-marine, and subcontinental environments. In the Aptian–Cenomanian, a stable continental regime was established and the environments were leveled. The sections are characterized by similar quasi-synchronous vertical succession of lithostratigraphic units and their wide areal distribution.

Recent integrated studies of Mesozoic standard sections of the Anabar area (northern Middle Siberia, Laptev Sea coast) and the reinterpretation of all the previous data on a modern stratigraphic basis permit considerable improvement of the bio- and lithostratigraphic division and facies zoning of the Jurassic and Cretaceous sediments in the region (Figs. 2–9). Analysis of abundant paleontological data allows the development or considerable improvement of zonal scales on ammonites, belemnites, bivalves, foraminifers, ostracods, dinocysts, and terrestrial palynomorphs for some intervals of the Jurassic and Cretaceous. All zonal scales are calibrated against one another and against the regional ammonite scale. Reference levels of different scales useful for interregional correlation have been defined and substantiated based on analysis of the lateral distribution of fossils in different regions of the Northern hemisphere. It provides the possibilities providing the suggestion and consideration of parallel zonal scales within the Boreal zonal standard for the Jurassic and Cretaceous (Figs. 10–12).

All the zonal scales of the proposed Boreal standard are based on the same Jurassic and Cretaceous sections of Siberia. Therefore, Siberia, a considerable part of which was occupied by the Arctic circumpolar sedimentary basin in the Jurassic and Cretaceous can be regarded as a stratotype locality for biostratigraphic units forming individual scales. A combination of these scales forms an integrated biostratigraphic basis for detailed division of Boreal-type sediments regardless of the place of their formation and their calibration against the international stratigraphic standard using a set of reference levels for correlation.

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