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# Biofacies of Upper Jurassic and Lower Cretaceous Sediments of Central West Siberia

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**Abstract**—Paleontological study of Upper Jurassic and Lower Cretaceous sediments recovered by boreholes in the Agan–Vakh and Nadym–Vengapur interfluves clarified environments of their deposition. As is shown, influx of siliciclastic material to central areas of the West Siberian sea basin varied through time. Taxonomic composition and ecological structure of nektonic and benthic fossil assemblages are analyzed and considered in terms of environmental factors such as hydrodynamics, aeration, temperature, and salinity of seawater.

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*Key words*: Biofacies analysis, Upper Jurassic, Lower Cretaceous, West Siberia.

## INTRODUCTION

The Upper Jurassic and Lower Cretaceous marine sediments of West Siberia attract attention of geologists primarily because of their hydrocarbon potential. After a long-term study, depositional setting of these unique facies are known better than for over- and underlying stratigraphic intervals of the Mesozoic–Cenozoic sedimentary cover. Many works are dedicated to various aspects of Jurassic and Early Cretaceous history of the region, e.g., to paleogeography (Gol'bert et al., 1968; *Atlas…*, 1976; Yasamanov, 1976; Bulynnikova et al., 1978; Zakharov et al., 1983; and others), sedimentation and sequence-stratigraphy modeling of the Jurassic–Lower Cretaceous structural stage of the West Siberian plate (Chernavskikh, 1994; Shurygin et al., 1999; Ershov et al., 2001; Polyakova et al., 2002; Yan, 2003; Grishkevich, 2005; and others), lithology (Gurova and Kazarinov, 1962; *Atlas…*, 1976; Zakharov et al., 1983; Yan et al., 2001; an others), and geochemistry (Kontorovich et al., 1975, 2000; Ushatinskii and Zaripov, 1978; and others), the isotope analysis included (Berlin et al., 1970, Kontorovich, 1985; Zakharov et al., 2005). In the other works, there were published geophysical characteristics (Nesterov and Vysotskii, 1985; Mkrtchan et al., 1987; and others) and data on paleogeomorphology, hydrogeology, and paleoecology of the paleobasin (Naumov, 1977; Bulynnikova et al., 1978; Braduchan et al., 1986; Bochkarev, 1999; and others). Nevertheless, interest to origin of Mesozoic hydrocarbon-bearing sediments remains vivid, as it is evident from growing quantity of recent publications devoted to problems of their genesis. Genesis and structure of Lower Cretaceous sediments are of particular interest. Some researchers believe that their structure reflects a lateral filling of paleobasin with siliciclastic material, and sediments form therefore a clinoform composed of cross-bedded layers (Naumov, 1977; Gurari, 2003; Karogodin et al., 2000, Grishkevich, 2005; and many others), while other scientists argue for a horizontally bedded structure of Neocomian sediments (Onishchenko, 1994; Dankov, 1996; and others). Accumulation environments of the unique Bazhenovo Formation of black shales, one of the main hydrocarbon sources in West Siberia, are also interpreted controversially. A most plausible explanation is that the elevated content of dispersed organic matter in these sediments reflects specific paleogeographic, hydrologic, and hydrodynamic conditions, primarily an extremely low sedimentation rate in a relatively deep basin with restricted water aeration, rather than a high biological productivity in the Bazhenovo sea (Zakharov and Saks, 1983; Braduchan et al., 1986; and others). Depth in particular areas of the Jurassic–Cretaceous West Siberian basin, their position relative to the shore, hydrodynamics, water mineralization, temperature, and aeration are variably assessed as well.

To evaluate variations in some environmental parameters of the West Siberian sea during the Jurassic and Cretaceous, we analyzed in relevant aspects main fossil groups. Gekker (1957, p. 5) justly noted: "fossil organisms are more adequate indicators of habitat and sedimentation environments than sediments." Many

† Deceased.

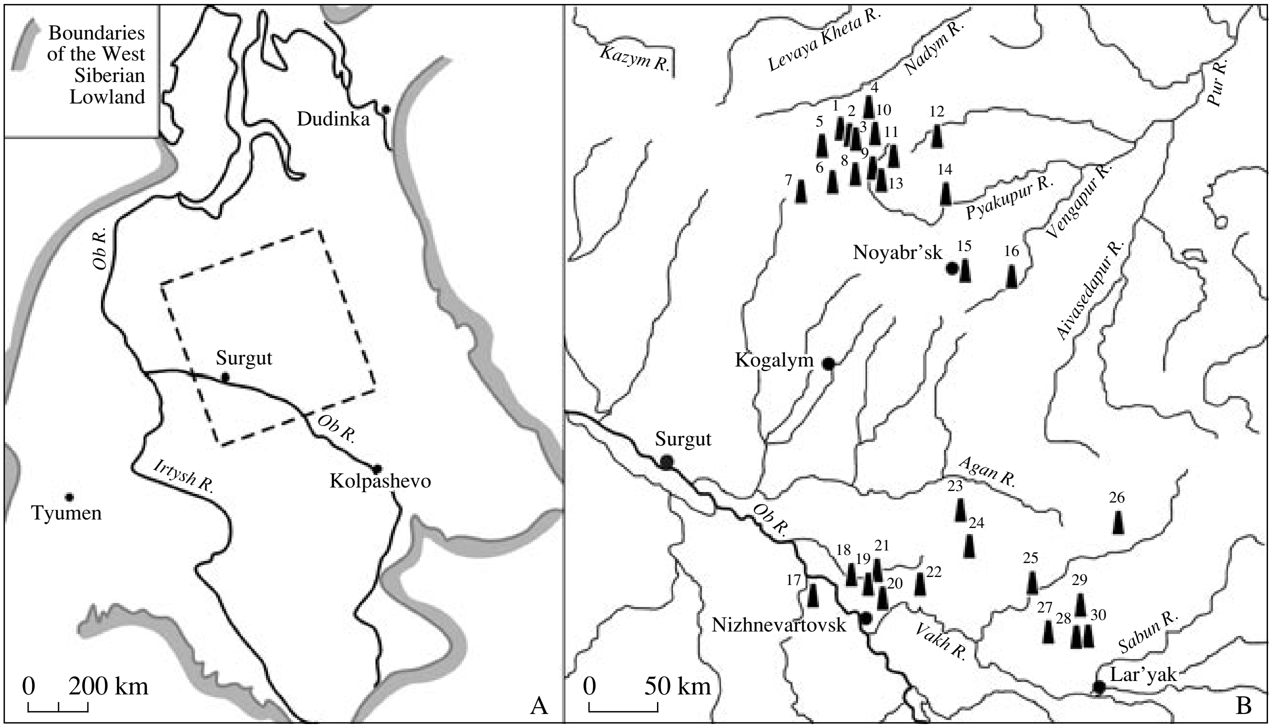



**Fig. 1.** Location of study region in West Siberia (A) and studied drilling areas (B): (1) Nasel'skaya; (2) Pyakuta; (3) Malaya Pyakuta; (4) Malaya Kheta; (5) Nyudeyakh; (6) Verkhnii Nadym; (7) Yuznyi Inuchin; (8) Velitoi; (9) Vostochnaya Pyakuta; (10) Sugmut; (11) Romanov; (12) Umei; (13) Yuzhnaya Pyakuta; (14) Sutormin; (15) Ort'yagun; (16) Zapadnyi Novogodnyaya; (17) Biryuzovaya; (18) Vatin; (19) Zapadnyi Samotlor; (20) Samotlor; (21) Rubinovaya; (22) Zapadnyi Soromin; (23) Vanegan; (24) Tyumen; (25) Enitor; (26) Srednii Kul'egan; (27) Kolik'egan; (28) Labaznaya; (29) Khokhryakov; (30) Permyakov.

researchers demonstrated efficiency of paleoecological approach to reconstruction of depositional environments for Jurassic and Lower Cretaceous sediments in the region under consideration (Bulynnikova et al., 1978; Komissarenko and Tylkina, 1981; Nezhdanov and Ostanina, 1981; Belousova et al., 1981; Zakharov and Saks, 1983; Braduchan et al., 1986; and others).

During the last 15 years, geologists from the Institute of Petroleum Geology of the Siberian Division RAS sampled a unique collection of macrofossils from the Upper Jurassic and Lower Cretaceous sections of central West Siberia (Agan–Vakh and Nadym–Vengapur interfluves), which are represented by many hundreds specimens. In addition, microfossils have been studied in nearly 500 samples from more than 50 boreholes drilled in 30 areas (Fig. 1). Data on taxonomic composition of studied fossils, their distribution in sedimentary sections, and stratigraphic inferences are discussed in several works (Zakharov et al., 1999; Shurygin et al., 2000, Marinov et al., 2003, 2005; Dzyuba, 2004; and others). Paleontologic and lithologic characteristics of separate intervals penetrated by boreholes have been discussed as well (Marinov et al., 2005). The main result of mentioned works is a composite biostratigraphic scheme that includes the parallel ammonite, bivalve, and foraminiferal zonations, which are correlated between each other. The scheme is a reliable tool for a high-resolution biostratigraphic subdivision of drilled sections, chronostratigraphic positioning of formations and subformations, and for their spatial correlation. Biostratigraphic zonations of a high resolution represent a strict framework that can be used to establish relationships between separate lithostratigraphic units of sedimentary succession, to define peculiarities of sedimentation, and to reconstruct geological history of the region. In this work, that framework is used in biofacies analysis aimed at reconstruction of fauna habitats and deposition environments in the Upper Jurassic and Lower Cretaceous basins of the study region.

## INVESTIGATION METHODS

Prior to biofacies analysis, we assessed secular changes in siliciclastic material influx to central areas of the West Siberian basin. Correlating local bio- and lithostratigraphic units with regional biostratigraphic zones of West Siberia, Boreal standard, and General stratigraphic scale (*Resolution…*, 2004, 2005), we assessed ranges and accumulation rates of individual formations, subformations, and sequences. Chronological intervals of zonal units are calibrated relative to the International geochronological time scale (Gradstein et al. 2004) as in the work by Haq et al. (1988). Sedimentation rates are calculated by dividing the lithostratigraphic unit thickness to its formation time. A possible effect of diagenetic sediment compacting has been discarded, since our purpose was to establish general trends of sedimentation rate variations but not the absolute values. The established variations of sediment influx through time are so significant that the compacting effect could hardly influence the relevant general trend of changes in sedimentation rates. As the entire sedimentary succession composed of siliciclastic largely pelitic and silty rocks is of a uniform lithological structure, it is possible to suggest that ratio of a unit thickness to its deposition time approximates the sediment influx to the deposition basin in the relevant period of time.

We paid particular attention to analysis of fossils, since they record sedimentation environments of a rock unit (Logvinenko, 1967). For example, presence of ammonites and belemnite rostra in sediments is indicative of their deposition in a sea basin. Ammonites and belemnites are remains of stenohaline organisms, and their occurrence in sections outlines existence period of a sea basin with normal salinity. Morphological characteristics of ammonite shells and belemnite rostra are also informative. Hydrodynamic and hydrostatic properties of particular cephalopod groups, which dwelt at certain depth in different hydrological zones of the basin, depended on the shell shapes, their ornamentation, and structure of septae (Reyment, 1958; Saks and Nal'nyaeva, 1970; Gustomesov, 1976; Westerman, 1990, 1993; Dzyuba, 2000).

Changes in taxonomic compositions of families and genera through succession of stratigraphic units are determined by both evolutionary and migratory processes, i.e., by invasion of taxa untypical of the basin. Par example, genera *Rasenia, Zonovia, Aulacostephanus* (Aulacostephanidae), *Ringsteadia*, and *Aspidoceras* migrated from the west and became widespread in the West Siberian basin in the terminal Oxfordian and Kimmeridgian. Invasion of immigrants was determined by paleogeographic reorganization accompanied by changes in current directions and by temperature increase in the basin. Leveling or differentiation of taxonomic composition in assemblages occupying different parts of the basin and widening or, in contrast, contraction of arctic taxa distribution areas, which reflect migration of hydrological fronts, provide valuable information as well.

Benthic organisms are important for reconstructing physicochemical conditions in the bottom zone of the basin. Of particular significance are bivalves, the main components of macrofossil assemblages found in drill cores. They are reliable indicators of various environmental parameters, e.g., of salinity, temperature, substrate, hydrodynamics, bottom waters aeration and, to some extent, of the basin bathymetry. The available paleoecological classifications (Zakharov and Yudovnyi, 1974; Zakharov and Shurygin, 1978; Zakharov et al., 1979) depict relationships between taxonomic composition and abiotic environmental factors. Because of core material specifics, it is difficult to perform biofacies analysis with details inferable from natural outcrops. Examining core samples, we cannot accomplish full taphonomic and paleoecologic observations in the layer proper and define the whole composition of the relevant bivalve assemblage in the section. The biofacies analysis is performed therefore for stratigraphic intervals wider than a layer, and results are naturally generalized to some extent.

Based on available data on ecological specialization of molluscan genera established in drill cores, we defined the following groups of taxa adaptable to certain environmental parameters:

(1) Rheophobic infauna includes genera dwelling on muddy–clayey substrate and prosperous under oxygen deficiency (*Malletia, Nuculana*);

(2) Euryoxybiont infauna living on soft substrate under conditions of low-energy hydrodynamics (*Astarte, Nuculoma, Thracia, Paleoneilo, Dacryomya*);

(3) Euryoxybiont infauna preferring low-energy hydrodynamics (*Buchia, Praebuchia, Inoceramus, Oxytoma, Aequipecten, Limea, Limatula, Camptonectes*);

(4) Oxyphilic infauna and epifauna of habitats with medium-energy near-bottom hydrodynamics (*Meleagrinella, Grammatodon, Chlamys, Protocardia, Pleuromya, Pinna*);

(5) Oxyphilic and rheophilic infauna and epifauna populating zones with high-energy hydrodynamics (*Liostrea (Praeexogyra), Entolium, Isocyprina, Tancredia, Mclearnia, Pronoella, Arctica, Rolierella, Proveniella, Lima, Striatomodiolus*);

(6) Nektonic fauna of free-floating stenohaline dwellers of pelagic zone: ammonites, belemnites, teuthids (represented in sediments by onychites only).

Categories "rare," "common," and "abundant" are used for quantitative assessment of particular ecological groupings in the core.

The biofacies analysis has been applied to benthic foraminifers as well. Ecological specialization of individual foraminiferal taxa is considered in many works (Kipriyanova et al., 1975; Basov et al., 1975; Bulynnikova and Gol'bert, 1980; Kipriyanova, 1981; Basov, 1991; Marinov and Zakharov, 2001; and others). Presence and diversity of foraminiferal ecological groupings are informative with respect to abiotic factors. Of particular significance among these groupings are oxyphilic taxa (nodosariids, polymorphinids, and ceratobuliminids), euryhaline genera *Globulina* and *Guttulina*, thermophilic immigrants from the Boreal–Atlantic biogeographic region (genera *Epistomina, Valanginella, Ceratolamarckina, Pseudolamarckina*), and representatives of rheophilic taxa (genus *Ammodiscus*, species with spheroid tests of the genus *Cribrostomoides*) dwelling at the bottom regularly affected by wave activity, i.e., at the depth of 10 m (Zakharov et al., 2005). Analysis of variations in abundance of indicative foraminiferal taxa in the Upper Jurassic and Lower Cretaceous sediments is useful for defining periods of the warm water influence, strengthened/weakened hydrodynamics, changes in concentration of dissolved oxygen, unstable salinity, and bathimetric changes in particular areas of the basin. We performed such an analysis for the Kimmeridgian–Hauterivian interval based on sections with most representative foraminiferal assemblages, which are recovered in the Pyakuta (Nadym–Vengapur interfluve), Kolik'egan and Khokhryakovo areas (Agan–Vakh interfluve).

Taxonomic diversity of foraminiferal assemblages is determined based on the Simpson's index:

$D = 1/\Sigma p_i^2$ ,where $p_i$ is the occurrence frequency of the i-species.

The diversity is classed as low, medium, and high, when D is 1–3, 4–6, and >6, respectively. Lagoonal foraminiferal communities are of low diversity. Maximal diversity is peculiar of assemblages from shallow and modestly deep settings. Deepwater assemblages are again of the low taxonomic diversity.

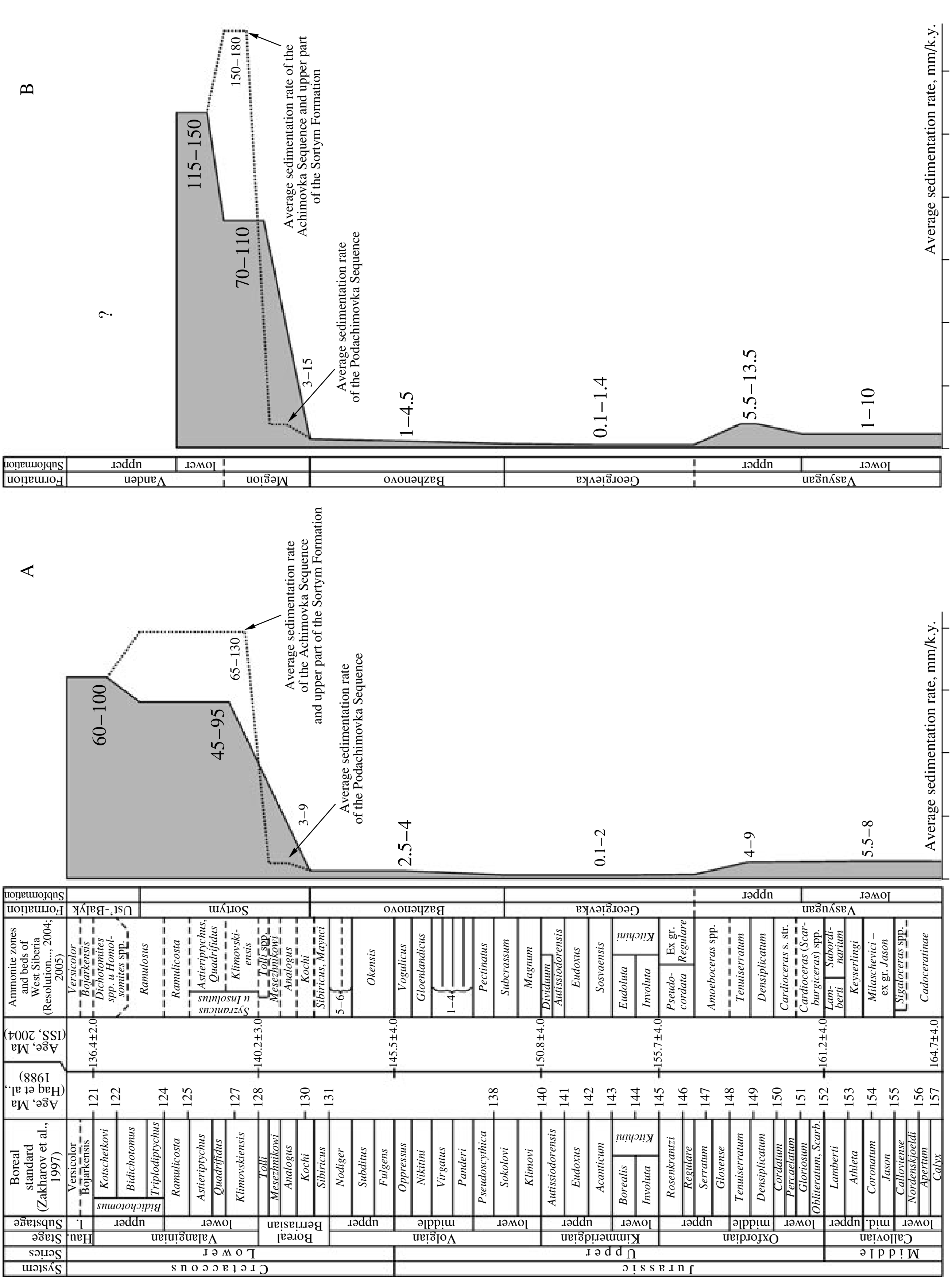
## RESULTS

Data on thickness of lithostratigraphic units (formations, subformations, and individual sequences) and time spans of their deposition, which are coordinated with the high-resolution biostratigraphic scale, substantiate the qualitative assessment of sedimentation rate dynamics in the study region. Earlier estimates of this kind (Ushatinskii and Zaripov, 1978; Nesterov and Vysotskii, 1985; Chernavskikh, 1994) were based on substantially less detailed biostratigraphic scale (stage level only), being obtained mostly for the formation-rank units. The average deposition rate of the Jurassic–Neocomian succession in the study region was highly variable through time (Fig. 2). In the Vasyugan period (Callovian–Oxfordian), sedimentation rates were low, with minimal values corresponding to the Georgievka (terminal Ozfordian–Kimmeridgian) and Bazhenovo (Volgian–early Boreal Berriasian) times. In the second half of the Boreal Berriasian, sedimentation rate slightly increased to reach maximal values in the terminal Berriasian–initial Valanginian. This maximum is best expressed in the Agan–Vakh interfluve, being slightly lower in the Nadym–Vengapur area. The onset of avalanche sedimentation corresponds to formation of the Achimovka siltstone–sandstone sequence. In the terminal Valanginian–initial Hauterivian, influx of siliciclastic material decreased, though remained several times higher than in the Late Jurassic. Since the upper Vanden Subformation (upper Valanginian–Barremian) is lacking marine fossils, we failed to establish its formation time and to calculate sedimentation rates for separate members.

Distribution of ecological groupings of mollusks and foraminifers in different stratigraphic intervals of the Upper Jurassic–Lower Cretaceous section in the Nadym–Vengapur and Agan–Vakh areas is illustrated in Figs. 3 and 4. The lower Vasyugan Subformation composed largely of clays and argillites with subordinate interbeds of silty–sandy sediments encloses rare remains of nektonic and benthic mollusks. The Callovian and early Oxfordian ammonites and belemnites belong to Boreal families Cardioceratidae and Cylindroteuthidae. Taxonomic composition of ammonite genera *Longaeviceras, Quenstedtoceras (Soaniceras)*, and *Cardioceras (Scaburgiceras)*, and belemnites of the genus *Longibelus (Holcobeloides)* suggest that the West Siberian sea, the Nadym–Vengapur and Agan–Vakh areas included, was closely connected in the Callovian and early Oxfordian with Arctic seas washing the Siberian platform and with the East European basin. Widespread remains of nektonic cephalopods imply a normal-salinity of open sea basin. Bivalve mollusks in silty–sandy sediments are represented by species of genera *Meleagrinella, Protocardia, Pleuromya, Entolium, Mclearnia, Arctica, Proveniella, Lima*, and of the family Buchiidae. The prevailing oxyphilic and rheophilic forms of bivalves are indicative of shallow-water sedimentation settings, good water aeration, and high-energy hydrodynamics near the bottom, i.e., of conditions favorable for many bivalve genera. These bivalves are particularly abundant in the Agan–Vakh interfluve, where they are accompanied by thermophilic *Mclearnia* species. Other taxa could exist in a wide temperature range.

The upper Vasyugan Subformation composed largely of sandstones and siltstones with argillite interbeds hosts remains of nektonic and benthic organisms (epifauna and infauna). The ammonite assemblage is still dominated here by representatives of Arctic genera *Cardioceras* and *Amoebeoceras.* Sandstones and siltstones yield diverse bivalve genera *Malletia, Nuculana, Astarte, Nuculoma, Thracia, Paleoneilo, Oxytoma, Aequipecten, Camptonectes, Meleagrinella, Entolium, Tancredia, Pronoella, Rolierella*, and *Striatomodiolus.* Thus, benthic macrofossils correspond in this case to both the rheophobic and rheophilic forms (Fig. 3) that can be explained by unstable aeration and hydrodynamic in bottom waters. It is likely that zones with high-energy hydrodynamics and sufficient aeration of bottom waters alternated in the basin with areas of a low-energy hydrodynamics. In the Nadym–Vengapur area, siltstones yield eurybiont and rheophlic bivalve genera *Thracia, Praebuchia, Inoceramus, Limatula, Entolium*, and *Pseudolimea*, but rheophobic forms have not been encountered.

In the Agan–Vakh area, the molluscan assemblage from the Georgievka Formation of substantially clayey sediments includes representatives of all ecological bivalve groupings (*Malletia, Paleoneilo, Buchia, Meleagrinella, Chlamys, Isocyprina*), which indicate variable hydrodynamic and aeration environments and diverse substrate types in their biotopes. Presence of stenohaline ammonites, teuthids, and abundant belemnites implies that salinity in the basin was normal.


A
B
Average sedimentation rate, mm/k.y.
60–100
45–95
65–130
3–9
2.5–4
0.1–2
4–9
5.5–8
115–150
70–110
150–180
3–15
1–4.5
0.1–1.4
5.5–13.5
1–10
?
Average sedimentation rate of the Achimovka Sequence and upper part of the Sortym Formation
Average sedimentation rate of the Podachimovka Sequence
Formation
Subformation
Vanden
Megion
Bazhenovo
Georgievka
Vasyugan
Sortym
Ust'-Balyk
upper
lower
System
Series
Stage
Substage
Boreal standard (Zakharov et al., 1997)
Age, Ma (Hag et al., 1988)
Age, Ma (ISS, 2004)
Ammonite zones and beds of West Siberia (Resolution…, 2004; 2005)
Cretaceous
Jurassic
Lower
Upper
Middle
Valanginian
Boreal Berriasian
Volgian
Kimmeridgian
Oxfordian
Callovian
136.4±2.0
140.2±3.0
145.5±4.0
150.8±4.0
155.7±4.0
161.2±4.0
164.7±4.0

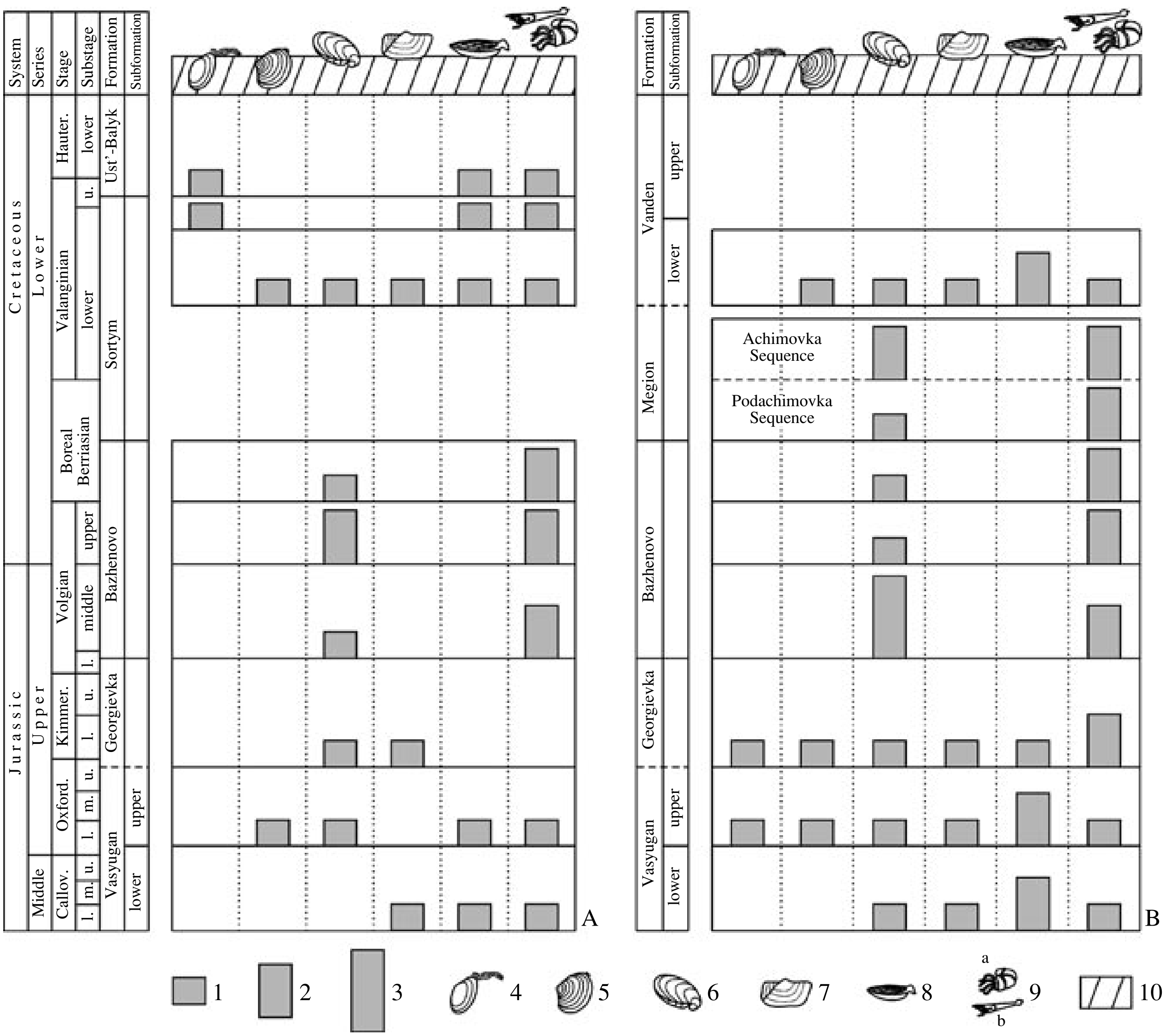



**Fig. 3.** Stratigraphic distribution of ecological molluscan groupings in the Callovian–lower Hauterivian section of the Nadym–Vengapur (A) and Agan–Vakh (B) interfluve areas; (1–3) occurrence frequency (1) rare, (2) common, and (3) abundant; (4–9) ecologic groupings of bivalves and cephalopods: (4) rheophobic infauna, (5) euryoxybiont infauna preferring low-energy hydrodynamics, (6) euryoxybiont epifauna preferring low-energy hydrodynamics, (7) oxyphilic infauna and epifauna preferring moderate-energy hydrodynamics, (8) oxyphilic and rheophilic infauna and epifauna; (9) nektonic (a) ammonites, (b) belemnites and teithids; (10) sediments; (Callov.) Callovian; (Oxford.) Oxfordian; (Kimmer.) Kimmeridgian; (Hauter.) Hauterivian; (l.) lower; (m.) middle; (u.) upper.

Belemnites are represented by species of subgenera *Pachyteuthis (Pachyteuthis, P. (Boreioteuthis), Simobelus (Simobelus)*, and *Lagonibelus (Lagonibelus)* of the family Cylindroteuthide, which suggest shallow or relatively deep sedimentation settings. Foraminiferal assemblages are very diverse (Marinov et al., 2005), typical of the same environments. Bivalve mollusks in the Nadym–Vengapur area are represented by rare remains of euryoxybiont and oxyphilic genera *Oxytoma, Meleagrinella*, and *Protocardia*.

Abundant bivalves found in the lower argillaceous part of the Bazhenovo Formation (the uppermost lower Volgian–middle Volgian) of the Agan–Vakh area represent byssiferous euryoxybiont epifauna of biotopes

**Fig. 2.** Variations of sedimentation rate in the Callovian–early Hauterivian, the Nadym–Vengapur (A) and Agan–Vakh (B) interfluve areas, (1–6) ammonite zones and beds: (1) *Lariensis*, (2) *Ilovaiskii*, (3) *Maximus*, (4) *Crendonites* spp., (5) *Taimyrensis*, (6) *Maurynijensis, Pulcher*; (Scarb.) *Scarburgense*; (Hau) Hauterivian; (l.) lower; (m.) middle; (u.) upper.

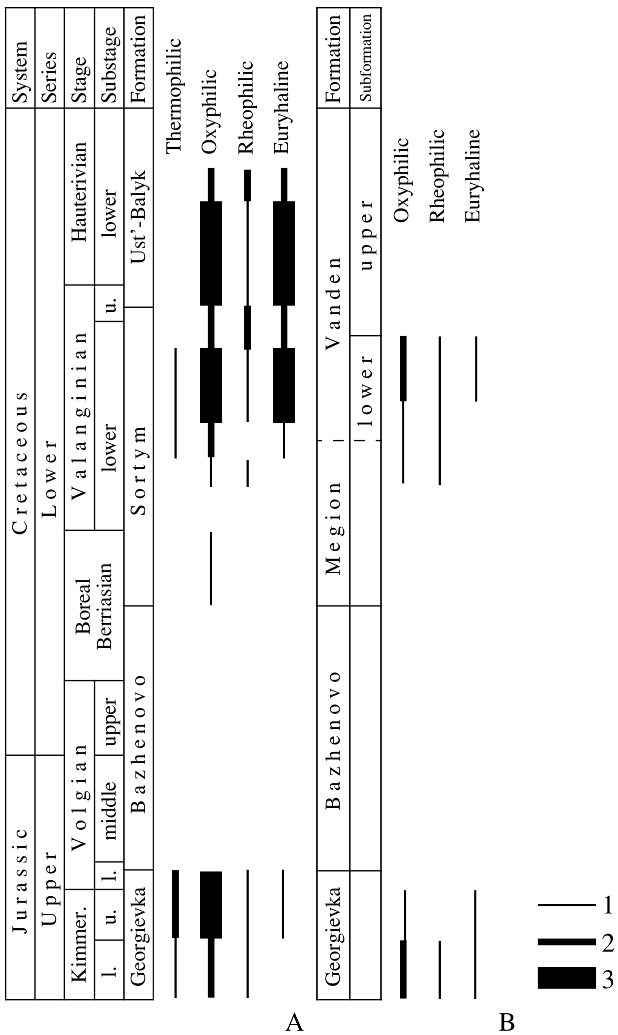



**Fig. 4.** Stratigraphic distribution of some ecological foraminiferal groupings (A) in the Kimmeridgian–lower Hauterivian of the Pyakuta area (Nadym–Vengapur interfluve); (B) in the Kimmeridgian–lower Valanginian of the Kolik'egan amd Khokhryakov areas (Agan–Vakh interfluve); occurrence frequency (1) single, (2) common, (3) dominant (other symbols as in Fig. 3).

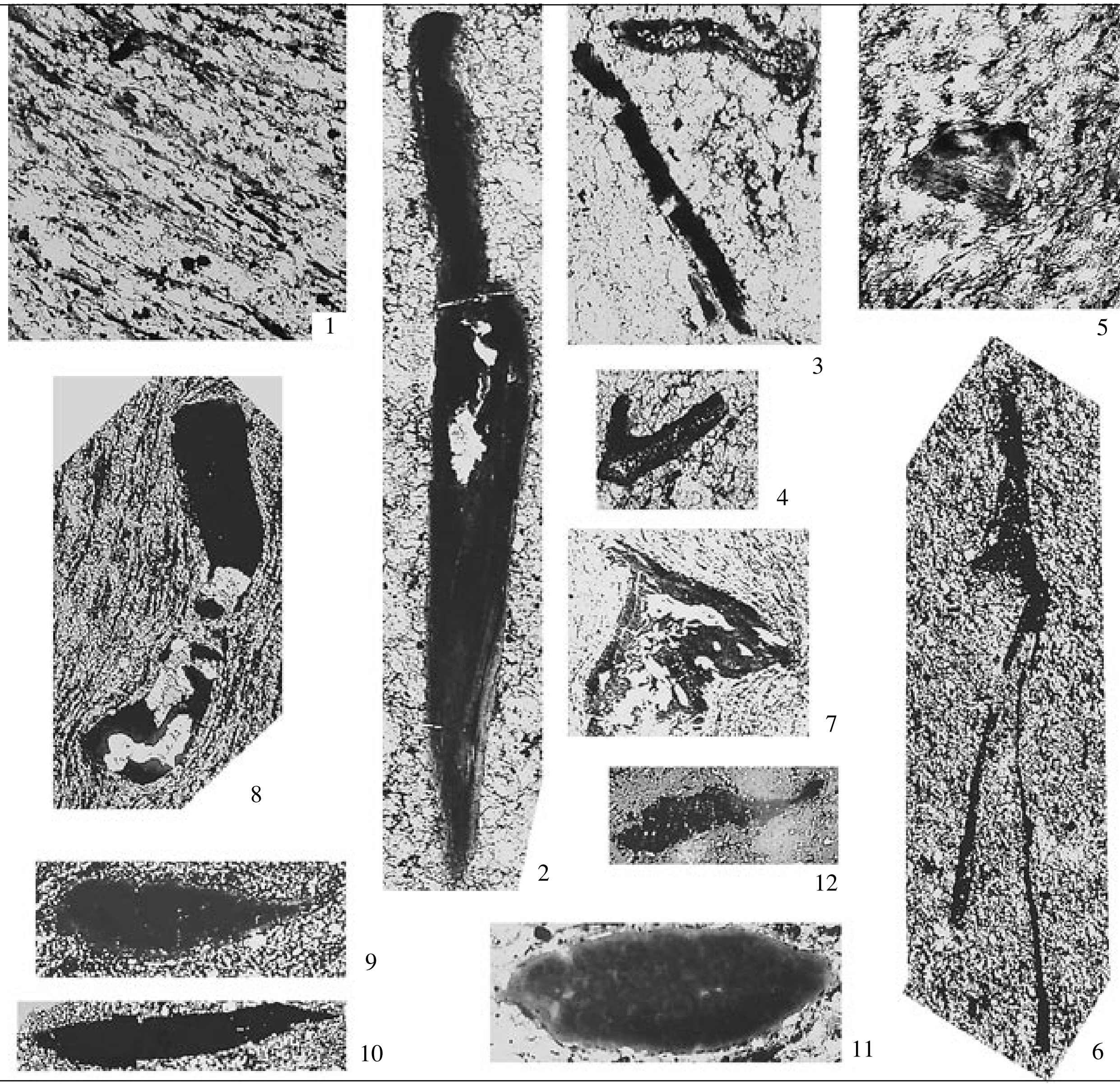
with low-energy hydrodynamics (*Buchia, Oxytoma, Inoceramus*). Rare foraminifers represent an impoverished assemblage with dominant *Trochammina septentrionalis.* Abundant remains of nektonic organisms belong to ammonites (*Dorsoplanites, Laugeites, Epilaugeites*), belemnites (*Pachyteuthis*), and teuthids (onychia). In addition, there were found scarce pseudoplanktonic *Ostrea* species *Liostrea plastica* (Trd.), the bivalves dwelling attached to shells of living ammonites and migrated together with them in the basin (Zakharov and Saks, 1983). As infaunal organisms are missing from bivalve assemblages, conditions below the sediment–water interface were likely unfavorable for them. Disappearance of infauna from benthic community at the beginning of the Bazhenovo time is explained by the onset of anoxic environments in bottom sediments. In the Nadym–Vengapur area, remains of benthic organisms in the lower part of Bazhenovo Formation are scarce, represented only by buchiids, while prevailing ammonites (*Pavlovia, Strajevskya, Dorsoplanites, Laugeites, Epilaugeites*) occur in association with belemnites (*Cylindroteuthis, Pachyteuthis*) and onychites. *Liostrea plastica* valves are present as well. In opinion of Zakharov, buchiids could survive a slight but not high oxygen deficiency (Zakharov and Saks, 1983). Prevalence of hemipelagic nekton over benthos suggests however that the oxygen-deficient zone in the Nadym–Vengapur area involved a part of bottom waters that is a common consequence of stagnation.

In the middle part of the Bazhenovo Formation (upper Volgian Substage) in the Agan–Vakh area, dominant onychites and ammonites *Craspedites (Craspedites), C. (Taimyroceras), Kachpurites* (family Craspeditidae), and *Virgatosphinctes* are accompanied by scarce bivalves (*Inoceramus*). A low proportion of mollusks in the upper Volgian sediments of the Agan–Vakh interfluve might be explained by a slight anoxia in bottom waters. In the Nadym–Vengapur area, coeval sediments contain, along with Craspeditidae, *Virgatosphinctes*, and onychia, abundant bivalves of genera *Buchia* and *Inoceramus*, and aeration of bottom waters in this part of the basin was therefore sufficient for epifauna existence.

In both the Nadym–Vengapur and Agan–Vakh areas, molluscan assemblages are of low diversity in the upper part of the Bazhenovo Formation (lower Boreal Berriasian, *Chetaites sibiricus* Zone and lower part of the *Hectoceras kochi* Zone). Like in underlying sediments of the formation, benthic organisms are represented only by euryoxybiont byssiferous epifauna (*Buchia, Inoceramus*). Ammonites *Praetollia, Shulginites, Subraspedites*, and *Hectocera*, fish skeletons, and onychites are more numerous. Paleontological data allow an assumption that in the terminal Bazhenovo time benthic organisms could dwell only on the bottom surface, since below there were anoxic environments. Density of benthic populations became substantially lower at that time, as it is evident from their decreased abundance in core samples.

Highly carbonaceous argillites of the Bazhenovo Formation penetrated by borehole Kolik'eganskaya-148 (Agan–Vakh interfluve) contain non-mineralized, partly coalified platy and band-like algae remains (Plate). In their appearance, macro- and microscopic phytoleims (remains of altered organic matter) are characterized by multicellular anatomic structure. Many fragments are pyritized. Abundance of algae and their good preservation imply environments favorable for accumulation of organic matter in the basin. It can be assumed that branching benthic algae comparable with present-day Phaeophyceae (*Laminaria* and Sargasso alga) formed large communities in coastal zones. During their development, algae could be torn off the

Plate




**P l a t e.** Algal remains from rocks of the Bazhenovo Formation recovered by borehole Kolik'eganskaya-148 (photos in transmitted light (thin section), magnification ×40, except for fig. 1, magnification ×10).

(1) general view of the rock in the thin section with alternating thin sediment laminae and fragmentary remains of filamentous algae, Sample 148-43, interval 2377.0–2382.0 m, depth 2380.5 m; (2, 3) fragments of organic-walled filamentous algae, Sample 148-22, interval 2377.0–2382.0 m, depth 2380.5 m; (4) fragment of a band-like thallus at the bifurcating area, Sample 148-20, interval 2388.5–2395.0 m, depth 2391.5 m; (5) a thallus fragment with signs of transverse cellular structure, Sample 148-20, interval 2388.5–2395.0 m, depth 2382.5 m; (6–12) fragments of organic-walled filamentous algae: (6) Sample 148-11, interval 2395.0–2402.0 m, depth 2396.0 m, (7) Sample 148-45, interval 2377.0–2382.0 m, depth 2380.5 m, (8) Sample 148-52, interval 2377.0–2382.0 m, depth 2377.2 m, (9) Sample 148-12, interval 2395.0–2402.0 m, depth 2396.5 m, (10) Sample 148-22, interval 2388.5–2395.0 m, depth 2391.5 m, (11) Sample 148-26, interval 2388.5–2395.0 m, depth 2380.5 m, (12) Sample 148-38, interval 2388.5–2395.0 m, depth 2388.5 m.

substrate to float freely at the surface through the basin. As is thought (Braduchan et al., 1986), algae and microphytoplankton were main sources of organic matter in the Bazhenovo Formation.

The fauna from higher layers of the Boreal Berriasian is found in the Podachimovka clayey sequence. In the Agan–Vakh area, benthic macrofossils are represented by rare buchiids. Assemblages of benthic foraminifers are dominated by species of the genus *Trochammina.* There are also rare shells of unidentifiable ammonites, abundant onychites, and fish remains. In the Nadym–Vengapur area, the assemblage of scarce

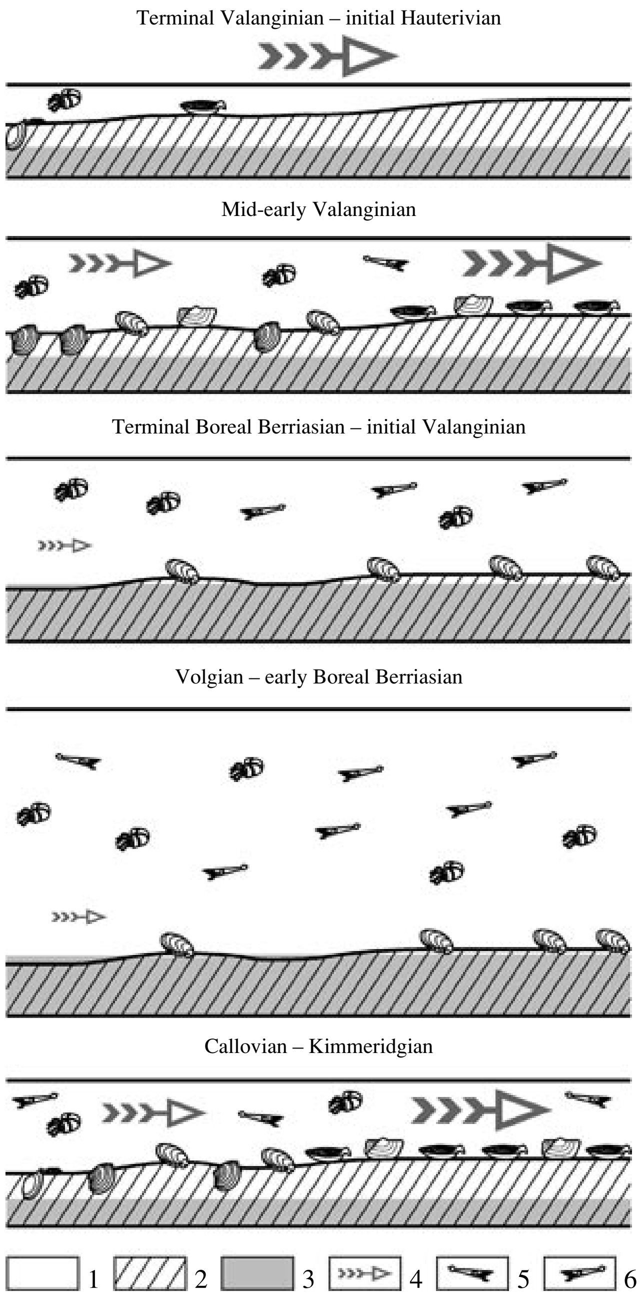



**Fig. 5.** Biotopes and habitat environments of the Callovian, Late Jurassic, and Neocomian marine fauna in the central part of the west Siberian basin: (1) water column; (2) sediments; (3) anoxic environments; (4) hydrodynamics in the bottom water layer (arrow size is proportional to hydrodynamic intensity); (5) belemnites; (6) teuthids (other symbols as in Fig. 3).

benthic foraminifers consists of specimens belonging to the genus *Recurvoides.* It is conceivable that this part of basin was characterized in the second half of the Boreal Berriasian by environment unfavorable for the benthic fauna because of oxygen deficiency in bottom waters.

In the Achimovka siltstone–sandstone sequence of the Megion Formation (uppermost Boreal Berriasian–lowermost Valanginian), the Agan–Vakh area, ammonites (*Tollia, Neotollia*) and buchiids are equally abundant. In examined boreholes of the Nadym–Vengapur area, the Achimovka Member of the Sortym Formation yielded only rare fragments of unidentifiable molluscan shells.

The interval of the *Euryptychites quadrifidus–Euryptychites astierptychus* ammonite zones in the lower Vanden Subformation is composed in the western part of the Agan–Vakh area of mudstone members alternating with sandstone–siltstone beds; the rocks contain only representatives of the ammonite genus *Neotollia* and bivalves genera *Buchia* and *Limatula*. The foraminiferal assemblage is of a modest taxonomic diversity, dominated by *Recurvoides* forms. The fauna composition indicates normal salinity of the basin in the mid-early Valanginian, aeration of bottom waters sufficient for the existence of epibenthic bivalves, and low-energy hydrodynamics. The eastern part of the basin (Kolik'egan area) was populated at that time by diverse benthic communities more tolerant to environmental factors; these communities included both the oxyphilic bivalve genera (*Protocardia, Tancredia, Mclearnia, Pronoella, Arctica*) preferring well-aerated mobile waters and euryoxybionts (genera *Buchia, Astarte, Nuculoma, Dacryomya*). Stenohaline genera and species were dominants. In addition to eurythermal taxa, bivalve communities included thermophilic forms (genus *Mclearnia*). Infauna was also diverse, represented by genera *Protocardia, Tancredia, Astarte, Nuculoma*, and *Dacryomya*.

In the Nadym–Vengapur area, the middle silty–clayey member of the Sortym Formation corresponding to the interval of the *Euryptychites quadrifidus–Euryptychites astierptychus* ammonite zones encloses the molluscan assemblage, which is close in terms of ecological groupings to assemblage from easterly sections of the Agan–Vakh area. The assemblage includes nektonic ammonite genera *Neotollia* and *Euryptychites (Propolyptychites)* associated with bivalve epifauna (genera *Buchia, Oxytoma, Limatula*, and *Entolium*) and infauna (genera *Astarte, Thracia, Striatomodiolus*, and *Pinna*). The foraminiferal assemblage is here of a high taxonomic diversity. Assemblages of macro- and microfossils suggest favorable habitat conditions in a shallow well-aerated basin (oxyphilic genera *Pinna, Entolium, Striatomodiolus* are diverse) with alternating zones of low- and high-energy hydrodynamics. Judging from presence of stenohaline groupings, salinity in the basin was normal. It should be noted that development of infauna and oxyphilic forms, which are absent in the Volgian and Berriasian stages, commenced in the Nadym–Vengapur area earlier than in Agan–Vakh area. Numerous representatives of *Astarte* (infauna), *(?)Pleuromya*, and *Entolium* (oxyphilic genera) are identified in the uppermost part of the *Neotollia klimovskiensis* Zone in the Sortym Formation. In general, the bivalve assemblage from sediments under consideration consists of genera *Astarte, Buchia, Inoceramus,*

*(?)Limea, (?)Pleuromya*, and *Entolium.* The foraminiferal assemblage is of a medium taxonomic diversity. Rostra of belemnite genus *Pachyteuthis (Acroteuthis)* are also present. The listed bivalve genera preferred mostly the low-energy hydrodynamic conditions and soft substrate, although some of them are rheophilic (*(?)Pleuromya, Entolium*).

In the Nadym–Vengapur area, the bivalve assemblage from the uppermost Sortym Formation and overlying Ust'-Balyk Formation of sandy, silty and clayey sediments (uppermost lower Valanginian, upper Valanginian, and lowermost Hauterivian) includes representatives of rheophobic infauna (*Malletia*) and associates with oxyphilic and rheophilic epifauna typical of biotopes with high-energy hydrodynamics: genera *Entolium* and *Liostrea (Praeexogyra).* The last genus is thermophilic, in addition. Such a combination of ecological groupings suggests contrasting environments. Diversity of foraminifers in the Ust'-Balyk Formation is lower than in the Sortym Formation; they are dominated by representatives of the genus *Cribrostomoides* whose spheroid tests are typical of sea shoals with high-energy hydrodynamics (Mariniov and Zakharov, 2001). Ammonites are scarce, belonging to genera *Siberites* (uppermost Sortym Formation) and *Simbirskites* (Ust'-Balyk Formation).

## DISCUSSION

During the early Callovian through mid-Kimmeridgian, the West Siberian basin developed against background of tectonic subsidence gradually progressing (Belozerov, 1989; Kontorovich et al., 2001). Characteristic of that time was gradual eustatic sea-level rise (Haq et al., 1988; Sahagian et al., 1996). The relevant period of Mesozoic history corresponded to a large transgression in the West Siberian sedimentation basin that terminated by the middle of the Boreal Berriasian. In the Callovian and Oxfordian, West Siberia was covered by a spacious epicontinental sallow sea with well-aerated water column (Zakharov et al., 1983; Kontorovich et al., 2000). Several transgressive–regressive cycles are recorded in accumulated sediments (Shurygin et al., 1999). Regression phases particularly notable in the Oxfordian were characterized by influx of coarser clastic material the from the south and east to the basin central part, where sandy–silty and sandy sequences accumulated (Yan et al., 2001; Yan, 2003). The greater part of the Callovian and some periods of the Oxfordian corresponded to accumulation period of silty–clayey sediments. In general, the Callovian–Oxfordian interval is represented in the basin areas by alternating lithofacies deposited in coastal–marine and shallow-marine settings, as it is evident from the mineralogical composition, structural features, boundary patterns, distribution of trace fossils, and their character (Vakulenko and Yan, 2001; Yan et al., 2001; Yan, 2003). Influx of siliciclastic material was insignificant (Fig. 2). In the Nadym–Vangepur and Agan–Vakh areas, benthic fossils are found mainly in silty–sandy rocks the Vasyugan Formation, which have been deposited in shallow-water settings (Fig. 5). In the terminal Bathonian, Callovian, and initial Oxfordian (the early Vasyugan time), benthic communities were dominated by oxyphilic and rheophilic bivalves (epifauna and infauna) indicative of well-aerated bottom environments with high-energy hydrodynamics. During the remaining interval of the Oxfordian (late Vasyugan time), benthic communities populated biotopes with different aeration and hydrodynamics in the bottom layer. It can be assumed that areas of high-energy hydrodynamics and good aeration alternated at that time in the basin with more stagnant zones of low-energy hydrodynamics. In the Agan–Vakh area, even rheophobic bivalve forms appeared in some periods.

A high diversity of biotopes was retained in the terminal Oxfordian, Kimmeridgian, and initial Volgian, although bottom water were slightly less aerated and calmer, as it is evident from decreased abundance of oxyphilic and rheophilic genera. A relatively deep zone of the West Siberian sea, the areas under consideration included, extended at that time (Zakharov et al., 1983), which is reflected in very slow accumulation of fine clays (Georgievka Formation) during a long period (8 m.y.). Abundance of belemnites, distant relatives of present-day squids, implies the water temperature close to that characteristic of the modern tropical zone (Gol'bert et al., 1968). The paleotemperature analysis supports this inference (Zakharov et al., 2005).

While in the Callovian–initial Oxfordian, the West Siberian basin was populated predominantly by Arctic families and genera, the ammonite, belemnite, bivalve, and foraminiferal communities of the terminal Oxfordian–Kimmeridgian developed under influence of a warm current, which promoted invasion of thermophilic ammonites (perisphinctids) and other invertebrate groups into the West Siberian basin.

During the Volgian–early Boreal Berriasian (Bazhenovo) time, sedimentation in the basin progressed under influence of significant regional subsidence, the onset of which corresponded with the general eustatic sea-level rise (Kontorovich et al., 1975; Belozerov, 1989; Shurygin et al., 1999). There is an opinion that this subsidence took place in a relatively short period (not more then 1 m.y.) in the early Volgian time as a consequence of eclogitization and compaction of mafic rocks at the crust base (Artyushkov, 1993). Whatever the reason, the Bazhenovo sea was undoubtedly deepest in the entire Mesozoic history of the West Siberian basin. Many researchers presume development of a pseudoabyssal depression in its interior part, where depth ranged from approximately 400 to 800–900 m in local areas (Gol'bert et al., 1968; Bulynnikova et al., 1978; Zakharov and Saks, 1983; Gurari et al., 1983; Braduchan et al., 1986; and others). In opinion of mentioned researchers, presence of that depression nearby the western shore of the basin is well consistent with distribution of biota and concentration of organic matter. According to calculations (Ushatinskii and Zaripov, 1978), this was a starved sedimentation basin: the average subsidence rate of 0.012–0.015 mm/year versus the average sedimentation rate of 0.002–0.003 mm/year. We estimated similar sedimentation rate for the Nadym–Vengapur and Agan–Vakh areas (Fig. 2).

Nektonic molluscan groups in the Bazhenovo sea were represented by ammonites, belemnites, and teuthids. Belemnites in the relevant core samples are rare, having small rostra, especially in the Bazhenovo Formation. They are interpreted as younger specimens from deepest zone of the basin, while adult specimens preferred shallow-water settings (Saks and Nal'nyaeva, 1979). According to other viewpoints, these belemnites represent separate small species. It is conceivable that young and, consequently, feeble specimens could be transported by currents or storms to open sea, where they died. Conditions were substantially more favorable for teuthids, which had no solid skeleton (carbonate or chitinous), being represented in the Bazhenovo Formation by abundant onychites (Braduchan et al., 1986).

Benthic communities in areas under consideration were practically lacking representatives of infauna forms that is well consistent with development of anoxic environments in bottom waters (Fig. 5). The relevant basin areas were populated by epibenthic buchiids and inoceramids, which are tolerant to a wide spectrum of environmental factors: hydrodynamics, bathymetry, and oxygen concentration in waters. At the same time, they preferred relatively deep (moderately cold) settings with low-energy hydrodynamic environments, but could not survive a considerable oxygen deficiency (Zakharov and Saks, 1983). In opinion of Zakharov, populations of buchiids and inoceramids were of a high density in the deepest part of the Bazhenovo sea, being concentrated here in the shallowest bottom areas. Inasmuch as these bivalves need well-aerated environments, the oxygen deficiency or even contamination of bottom waters by hydrogen sulfide, which was postulated by many researchers, is admissible only for deepest seafloor areas and/or for epochs between existence periods of bivalves (Zakharov and Saks, 1983; Braduchan et al., 1986). The content of dissolved oxygen in bottom water of the basin was controlled by intensity of water exchange with the Arctic basin, i.e., by shoaling or deepening of seaways for oxygen-saturated Arctic waters (Braduchan et al., 1986). Nevertheless, the idea of bottom waters contamination by hydrogen sulfide in the deep part of the Bazhenovo sea is still popular among some researchers (Kontorovich et al., 1994, 2000; and others).

We share the standpoint that anoxic conditions in bottom waters and at the sediment–water interface in the central deep part of the Bazhenovo sea were discontinuous and probably disappeared in some periods (Braduchan et al., 1986). The inference is consistent with occurrence of ichno-fossils in black shales of the Bazhenovo Formation (Zakharov et al., 1998; Eder et al., 2003), which needed some quantity of dissolved oxygen in interstitial waters for their life activity, undoubtedly for the *Chondrites* activity. The biota as a whole confirms this conclusion.

Temperature, illumination, and water circulation in coastal zone of the West Siberian sea were favorable for development of multicellular branching algae whose remains have been found in the study areas. Algae preserved in a form of isolated phytoleims have been likely transported from their original biotope and could represent an important source of organic matter buried in sediments of the Bazhenovo Formation.

The Neocomian stage in development of the West Siberian sedimentary basin differed substantially from the preceding one. It was a time of intensified tectonic activity in the basin and surrounding land areas; characteristic of the basin was regressive trend in general and increased sedimentation rate (Gurova and Kazarinov, 1962; Kontorovich et al., 1994; and others).

During the second half of the Boreal Berriasian (pre-Achimovka time), accumulation of clayey sediments was in progress in the study areas, although influx of siliciclastic material slightly increased (Fig. 2), and content of organic matter in sediments declined. Foraminifers appeared in benthic communities, which remained practically unchanged in structure of macrofauna assemblages. The pelagic zone was populated as before by teuthids, which dominated among nektonic mollusks. In the terminal Berriasian–initial Valanginian (Achimovka time), at the commencement of avalanche sedimentation, largely silty–sandy material was supplied into the basin, but benthic communities with increased abundance of bivalve mollusks experienced no transformation in structure. As is assumed by many researchers, the West Siberian basin was shoaling at that time, remaining relatively deep, however, comparable in depth with the lower subtidal zone: 100–150 m deep in the Nadym–Vengapur area (Bochkarev, 1999) and 70–100 (Bulynnikova et al., 1978) to 150–200 m deep (Nesterov and Vysotskii, 1985) in the Agan–Vakh area. Judging from the studied fossil assemblages, hydrodynamics and water aeration did not differ from conditions of the Bazhenovo time (Fig. 5); otherwise benthic communities just had no time for reorganization. The granulometric analysis of the Achimovka deposits in the Ob River middle reaches (Nesterov and Vysotskii, 1985) suggests the low-energy environments of sedimentation. Deposition of high-carbonaceous sediments probably ceased under influence of several factors: an increased influx of siliciclastic material, the basin shoaling, and aeration of bottom waters, although the last factor was less influential.

The mid-early Valanginian (*Euryptychites quadrifidus* and *E. astieriptychus* phases) was a time of more intense aeration in bottom sediment of the West Siberian sea. The intensified hydrodynamics in the study areas stimulated development of infauna represented by rheophilic and oxyphilic benthic organisms. Simultaneously, thermophilic *Mclearnia* and *Pinna* species appeared here in addition to eurythermal bivalve genera. The assumed changes in hydrodynamic environments are consistent with granulometric characteristics of the lower Valanginian sediments (Nesterov and Vysotskii, 1985). Based on biofacies analysis, Bulynnikova et al. (1978) suggested that the basin in the Agan-Vakh area was 60–100 m deep with reducing environments in the upper sedimentary layer. Corresponding paleontological data for the Nadym–Vengapur area were unavailable at that time. It seems that rheophilic, oxyphilic and thermophilic benthic forms point to a substantial shoaling of the basin in both areas, and the oxyphilic infauna found in many areas points to a good aeration and favorable geochemical conditions in both the bottom water and upper sedimentary layers.

In the Valanginian and early Hauterivian, regression in the West Siberian sea and northwestward displacement of its deep zone led to expansion of coastal and lagoonal settings with relevant sedimentation in southern, central, and eastern areas of the basin (Bulynnikova et al., 1978; and others). In the terminal Valanginian, this zone involved the Agan-Vakh area. At the same time, the basin shoaling resulted in a sharp differentiation of molluscan biotopes. In the Nadym–Vengapur area, there was a spectrum of biotopes, from stable calm stagnant habitatas of rheophobic genera, which flourished in anoxic environments, to high-energy well-aerated and warmer settings populated by rheophilic and thermophilic benthic communities. The contrasting environments remained unchanged until the early Hauterivian. In the late Valanginian–Hauterivian, stenohaline nektonic forms became scarce in the Nadym–Vengapur area, and benthos was represented here by marine taxa associated with species resistant to freshening and indicative, therefore, of intermittent salinity deviations from the standard marine values. In the Agan–Vakh area, typical marine fauna is missing at all.

## CONCLUSIONS

Data considered in this work elucidate time boundaries between stages of sedimentation in the central part of the West Siberian basin. An irregular trend of changes in sedimentation rate is established based on thickness of lithostratigraphic units and estimated periods of their accumulation. Using the biofacies analysis, we detected some abiotic factors responsible for environmental changes. The results obtained have been interpreted with due account for geological history of the study areas.

Development of transgression and deepening of the West Siberian basin in its central part were accompanied by deteriorated aeration and weakened hydrodynamics of bottom waters; these events are particularly notable in the Volgian Age and in the initial Boreal Berriasian. By the beginning of the Bazhenovo time, rheophilic, oxyphilic, and thermophilic taxa disappeared from benthic communities. In the Volgian and Berriasian ages, the basin bottom was colonized by bivalves and foraminifers characteristic of low-energy hydrodynamic environments and relatively cold waters. In the Neocomian, the West Siberian basin was in a regressive stage of its development and experienced shoaling. At the Berriasian–Valanginian transition, sedimentation rates sharply increased, although hydrodynamics and water aeration in the central part of the basin appeared to be inherited from the preceding stage. The distinct intensification of aeration and influence of high-energy hydrodynamics were characteristic of the mid-early Valanginian time only, when the basin experienced a substantial shoaling. Rheophilic, oxyphilic, and thermophilic taxa appeared again in benthic communities. Almost throughout the Late Jurassic and Neocomian, normal marine environments existed in the study areas. The decrease of water salinity, intermittent in the Nadym–Vengapur area and continuous in Agan–Vakh area, is established for the terminal Valanginian and initial Hauterivian. The salinity decrease was responsible for quantitative and qualitative impoverishment of typical marine fauna in the former area and for disappearance of marine taxa in the latter. During the time span under consideration, the central part of the basin was largely populated by high-Boreal (Arctic) families and genera. On the other hand, the local fauna experienced also the influence of low-Boreal waters. In the terminal Oxfordian–Kimmeridgian, for example, thermophilic ammonites and other groups of invertebrates immigrated together with a warm current into the West Siberian sea.

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