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Jurassic paleogeography of the West Siberian sedimentary basin

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Abstract

Paleogeographic reconstruction of the West Siberian basin during the Jurassic is based on a variety of criteria used to evaluate the depositional environments (paleontological, sedimentological, geochemical, etc.). Extensive geochemical data on the hydrocarbon biomarkers in bitumen from organic matter are first used to constrain the depositional setting of this large region over a span of about 45 Myr. The study provides a detailed description of paleogeographic maps compiled for the main epochs of the Jurassic period with the reconstruction of paleorelief and differentiation of potential external and internal sources of terrigenous material. The paleogeographic reconstructions of the basin are considered with implications for the formation of regional seals and reservoir units. A special emphasis is given to interpretation of organic matter type and depositional setting of the major oil and gas source rocks. The study infers a paleogeographic control on the stratigraphic and areal distribution of hydrocarbon accumulations in the basin.

Keywords: paleogeography; Jurassic; aquatic organic matter; terrigenous organic matter; West Siberian sedimentary basin

Introduction

Paleogeographic maps are an essential part of the assessment of hydrocarbon potential of large sedimentary basins. They provide important constraints on the areal distribution of regional reservoir, seal and source facies and their hydrocarbon-generative potential. The maps describing our understanding at a given time should be regularly updated as new regional data and interpretations are gained. High quality paleogeographic mapping requires thorough integration of data and interpretations from several disciplines such as geology, paleontology, biostratigraphy, sedimentology, petrography, mineralogy, and geochemistry.

This is of special importance for the West Siberian basin, a mature sedimentary basin, because effective paleogeographic interpretations form the basis for defining the hydrocarbon potential of the arctic portions of this basin, including the Yamal, Gydan, and South Kara petroleum areas, predicting their oil and/or gas resource potential and opportunities for stratigraphic and facies change trap exploration, and thus provide a foundation for subsequent revision and updating the previous quantitative resource assessments of the West Siberian province and its petroleum areas, as new data and more detailed analyses emerge.

Historical background

Paleogeographic studies of the Mesozoic in West Siberia initiated in the late 1950s and were led by V.P. Kazarinov and V.N. Saks in the northeastern parts of the region (Kazarinov, 1958; Saks and Ronkina, 1958), which resulted in the publication of a monograph by T.I. Gurova and V.P. Kazarinov (1962) "Lithology and Paleogeography of the West Siberian Lowland in Connection with Hydrocarbon Potential". This was followed by the publication of an outline of the paleogeographic evolution of West Siberia during the Mesozoic and Cenozoic, in 1963, containing a series of paleogeographic maps that were built under the leadership of V.P. Kazarinov (Gurari et al., 1963). These publications provided the basis for paleogeographic reconstructions of West Siberia in Jurassic and Cretaceous times, which formed part of the Atlas of Lithological-Paleogeographic Maps of the

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USSR (1968) edited by A.P. Vinogradov. The maps of West Siberia were compiled by T.I. Osyko (editor), K.M. Abbakumova, Z.T. Aleskerova, N.I. Baiborodskikh, N.Kh. Belous, A.A. Bulynnikova, Yu.V. Braduchan, G.K. Boyarskikh, S.G. Galerkina, F.G. Gurari, V.P. Kazarinov, A.E. Kontorovich, P.F. Li, I.I. Nesterov, N.N. Rostovtsev, A.N. Rezapov, Z.Ya. Serdyuk, L.Ya. Trushkova, V.Ya. Sherikhora, K.V. Yaskina, G.S. Yasovich. A thorough monograph by A.V. Golbert, L.G. Markova, I.D. Polyakova, Yu.V. Teslenko, and V.N. Saks (editor) “West Siberian Paleolandscapes in the Jurassic, Cretaceous, and Paleogene” was released in 1968 and contained a series of full-color paleogeographic maps. Several research papers that summarized the Jurassic paleogeography of Siberia were published in the early 1970s by V.N. Saks and his fellow thinkers (Saks, 1972, 1976; Saks et al., 1971). In addition, the results from studies on the Jurassic and Cretaceous paleogeography of West Siberia were summarized in a series of maps created by a group of specialists at the Siberian Research Institute of Geology, Geophysics, and Minerals Resources (SNIIGGiMS) under the leadership of A.E. Kontorovich to interpret the depositional environments of organic-rich sediments (Kontorovich et al., 1967, 1971, 1974) and at the Institute of Geology and Exploitation of Combustible Resources (IGIRGI) (Korzh, 1978; Korzh and Filina, 1980; Zonn, 1980). A review of the paleogeography of West Siberia was also included in the monograph “Petroleum Geology of West Siberia” (Kontorovich et al., 1975).

In 1976, a large research team which included a number of dedicated geological and paleontological staff at ZapSibNIGNI, SNIIGGiMS, IGIRGI, VNIGRI, NIIGA, NGTU has come up, under the editorship of I.I. Nesterov, with the atlas of lithological-paleogeographic maps of the West Siberian plain (23 maps) compiled for numerous stages of the Jurassic and Cretaceous (Nesterov, 1976a). All these efforts were supplemented by a brief summary on the Jurassic paleogeography of the northern USSR published in 1983 (Zakharov et al., 1983).

The Late Jurassic paleogeography of West Siberia was a focus of two other monographs (Braduchan et al., 1986; Bulynnikova et al., 1978). Some problems of paleogeography of the same time period were discussed in a number of papers by Gurari (1981, 1983).

Several reviews of the available paleogeographic information were published in the late 20th–early 21st centuries (Devyatov et al., 2011; Gurari et al., 2005; Mukher and Tugareva, 1999; Myasnikova et al., 2009).

Methods

This review of the Jurassic paleogeography of West Siberia relies largely on a multiyear on-going research by IPGG staff, which is focused on paleonotological, stratigraphic, lithological, and geochemical studies of outcrops and drill cores, subdivision and correlation of stratigraphic units, coupled with a detailed seismic stratigraphic analysis and calibrated to historical data available on the region.

Recent information that became available over the past few decades has drastically reshaped our understanding of the Mesozoic landscapes of Siberia. Most of these results have been already published (Beizel, 2006, 2009; Devyatov et al., 2011; Kazanenkov et al., 2010; Kontorovich, 2002; Kontorovich et al., 1995a,b, 1998, 2000, 2010; Shurygin et al., 2000, 2011; Vakulenko et al., 2010; Zanin et al., 1999; and others)

The paleogeographic maps are available at a stage level and illustrate major evolutionary trends in the sedimentary environments of the West Siberian basin during Jurassic time (Gurari, 2004). The proportions of each lithology type (shale and mudstone, siltstone and sandstone) present in the section were estimated for the basin depocenters, with the fill dominated by terrigenous sediments. Zoning of both onshore and offshore regions using the morphology and genetic models provided the basis for paleogeographic reconstructions. Large relief features delineated at a basin-wide scale can be regarded as geomorphic features and their bathymetry/hypsometry for much of the area was calculated by analogy with the present-day depth and elevation values of the respective geomorphological levels. Paleontological, sedimentological and geochemical data were used to reconstruct the sea-floor topography, water depths and salinity of the Jurassic basins (Akopian, 1969; Guidelines..., 1967; Kontorovich et al., 1967, 1971, 1974; Legend..., 1962; Lithofacies..., 1963; Mikhailova, 1973; Rukhin, 1962; Strakhov, 1962; Strakhov and Zalmanzon, 1955). These data were supplemented by more recent studies (Dolotov, 1989; Gradzinskii et al., 1980; Lisitzin, 1991; Nichols, 2009; Reading, 1986; Seilacher, 2007; Verzilin, 1979). Marine benthic communities were used as useful indicators in bathymetric reconstructions and assessment of abiotic variables (temperature, salinity, hydrodynamic energy, oxygen supply, etc.) (Shurygin, 2005; Zakharov and Shurygin, 1985).

Biotic and abiotic variables were used to identify three main bionomic zones in northern Siberia, which roughly correspond to the lower (to 200 m), middle (to 100 m) and upper (to 50 m) sublittoral.

The nature and sources of sedimentary organic matter are widely used to reconstruct paleoenvironmental conditions by assessing the composition of kerogen and autochthonous bitumens. We identified marine (phytoplankton, bacteria), terrigenous (higher land plants) and mixed (marine plus terrigenous components) organic matter using a wide range of geochemical indicators (kerogen petrography, pyrolysis parameters of sedimentary organic matter, kerogen composition—C, H, S, δ^{13}C, sterane and tricyclane distribution) (Kontorovich et al., 1971, 1974, 1975, 1995a,b, 1998, 2000; Surkov et al., 1999).

Jurassic paleogeography

Hettangian, Sinemurian, Pliensbachian

During the Early Jurassic West Siberia was an upland area with subtle topographic relief and the peneplanized parts as high as 200–500 m (Kazarinov, 1958; Kontorovich et al., 1971; Nesterov, 1976b; Zakharov et al., 1983). Most outcrops within the region consist of late Paleozoic granites, schists of different ages, Paleozoic (mostly Devonian) carbonates, and Late Permian–Early Triassic volcano-sedimentary rocks, which are topped by the weathering profiles best developed in a humid climate (Gurari et al., 1963; Gurova and Kazarinov, 1962; Kazarinov, 1958). Volcano-sedimentary rocks mostly of Lower Triassic age are exposed in outcrops in the river valleys and lowland regions separated by high, open plateaus. Such topography has had a major influence on the distribution of sediment sources and depocenters in the West Siberian land mass.

This elevated, poorly dissected area with a number of granite massifs (Mezhovka, Yagylyakh, and others) was intensively eroded, and the eroded material was transported into the deep basin. The most active depocenters were located within subsiding parts of the basin such as depressions, troughs, and trenches.

During Early Jurassic time, the West Siberian basin was situated in the temperate zone and had a relatively warm and uniformly humid climate with little seasonality in temperature. This allowed the establishment of a Boreal paleobiogeographic province in seas and a Siberian paleofloristic province on land (Ilyina, 1969; Saks, 1976; Saks et al., 1971; Yasamanov, 1976). The mean annual temperature varied from +10 to +12 °C (Golbert, 1987). Bivalve oxygen isotope records yield the mean annual temperatures of +14.4 and +19.8 °C for the Late Pliensbachian.

The oldest Jurassic stages, the Hettangian and Sinemurian, can be identified with rather more confidence only for the northeast of Siberia, in the Anabar–Khatanga region. The presence of Lower Pliensbachian rocks in West Siberia is inferred from spore and pollen assemblages, as well as leaf macrofloras. Lithological variations in the respective formations reflect a change in the composition of sediments accumulated during the Hettangian, Sinemurian, and Pliensbachian.

This paper presents a generalized paleogeographic map, which depicts the following depositional environments in the Late Pliensbachian for the West Siberian basin (Fig. 1, Table 1):

– shallow sea, up to 25 m in depth;
– lowland coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– lowland erosional-depositional plain;
– elevated erosional plain;
– low mountains.

They are discussed in more detail below.

A shallow sea with a water depth of up to 25 m was established over much of the northern West Siberian basin that encompassed an area of the present-day Antipayuta–Tadebeyakha megamonoclise where it opened out towards the Kara megasyneclise in the west and Agapa–Yenisei trench in the east. During Hettangian, Sinemurian, and Early Pliensbachian times the southern margin of the marine basin was located to the north of the Messoyakha Ridge. It should be noted that the latter feature which did not exist until the early Jurassic, as it has no evident expression in thickness and lithology. During Late Pliensbachian times the sea transgressed onto the southern flank of the Bol'shaya Kheta megasyneclise and occupied an area of 100,000 km^2. The sediments that were deposited in the sea in early Jurassic time formed the Zimnyaya Formation, comprising dark gray mudstones, siltstones, greenish-gray sandstones with gravel and conglomerate, which contain plant debris and macrofloral remains. Partial isolation of the West Siberian Epicontinental Sea from normal marine environments and high fluxes of freshwater from rivers resulted in continued freshening of basin waters, as indicated by less diverse faunas. In the east, the offshore marine sequences contain a scarce marine macro- and microfauna. In the north, fossils are present only in the upper part of the Zimnyaya Formation and include bivalves and foraminifera, indicating the deeper marine setting in the northeast. The formation becomes shalier in this area.

The Late Pliensbachian transgression in a shallow-marine paleoenvironment led to a drastic change in sedimentation regime and brought deposition of the Levinskiy Formation. The formation comprises dark gray and brownish mudstones and fine-grained siltstones with few sandstone turbidite intercalations. Pebbles and gravel are present at the margins of the paleobasin. The Levinskiy Formation contains abundant foraminifera (*Ammodiscus*, etc.) and marine bivalve shells (Shurygin et al., 2000, 2011).

Shallowing environments in latest Pliensbachian time mark an increase in the proportion of coarser-grained facies, which is associated with deposition of the Sharapovo Formation. This comprises dark gray to gray mudstones, siltstones, and sandstones with gravel and conglomerate intercalations. The successions contain marine bivalves and foraminifera, but the faunas of cephalopods and echinoderms are totally absent, probably reflecting the existence of salinity anomalies in this marine basin.

A lowland coastal plain occasionally inundated by the sea bordered the sea to the south and southeast. It was initially located within the area of the present-day Bol'shaya Kheta megasyneclise. With progressive transgression, the coastal plain gradually migrated southwards along major structures such as the Pyakupur–Amputin and Middle Pur inclined megatroughs and along the northwestern termination of the Yenisei megamonoclise.

The Beregovaya Formation, defined close to the base of the Lower Jurassic in this area, consists of coarse-grained sandstones, gritstones, conglomerates with subordinate mudstone units, coalified plant remains and coal seams. The presence of shale breaks with a marine fauna indicates episodic marine incursions across the coastal plain. A transition from marine to continental deposition, which apparently started later in this paleogeographic area, is represented by the marginal-marine and lacustrine-lagoonal successions (Yagel Formation) of gray to dark gray clayey mudstones, containing scattered pebbles, intercalations of inequigranular siltstones and sandstones with plant remains. A wide variety of depositional environments produced considerable lithological

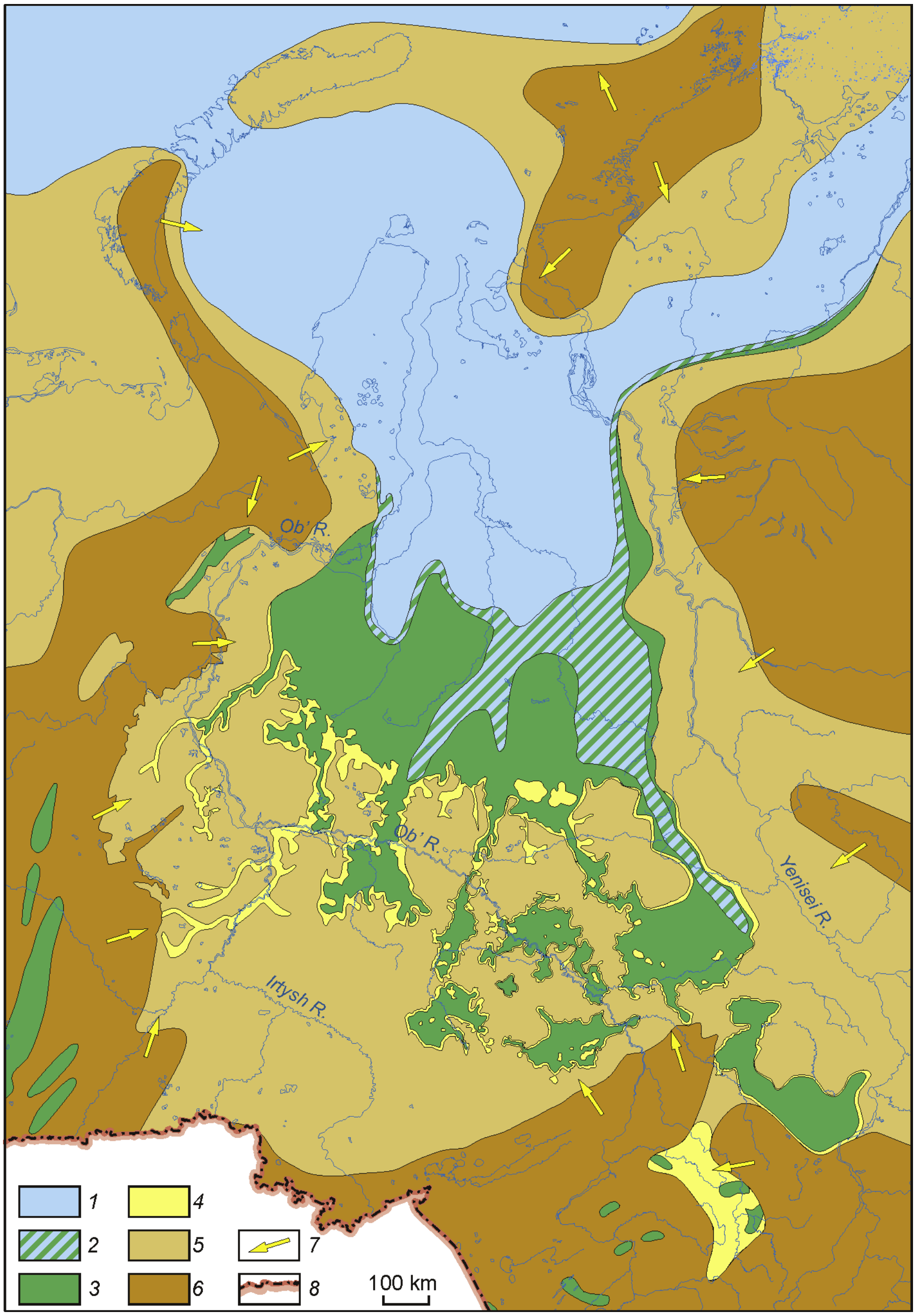

Fig. 1. Paleogeography of West Siberia in the Late Pliensbachian. *1–6*, Paleogeographic areas: areas of marine deposition: *1*, shallow sea, up to 25 m in depth; Transitional areas: *2*, coastal plain, periodically inundated by the sea (floodplain, swampy-lacustrine, channel, deltaic, barrier bar, beach facies); areas of continental deposition: *3*, low-lying depositional plain (channel, floodplain, lacustrine facies); *4*, erosional-depositional plain: *5*, elevated plain (erosional land), *6*, low mountains; *7*, direction of clastic sediment supply, *8*, state border.

changes in sediments, which were dominated by clay- and silt-rich oozes. A marine fauna present in places in some isolated shale breaks indicates the periodic intrusion of the sea into the basin through major troughs. The coastal floodplain occupied an area of 140,000 km^2.

A lowland depositional plain extended over the area of the present-day northern limit of the Krasnoleninsk megamonoclise, across the Nadym hemisyneclise and South Nadym megamonoclise, the southern part of the Middle Pur inclined megatrough and southern part of the Krasnoselkup monoclise. This setting was dominated by alluvial plain and lacustrine facies associations such as fluvial channel, swamp, and lake deposits. The southeastern part of West Siberia was dominated by lowland areas and the southwestern part by river valleys. Coarse-grained sediment supply was higher in the western than in the eastern part of the plain.

The deposits of the Beregovaya Formation were initially very widespread over much of the plain area. The Nadym depression and eastern Mansi synecliseare dominated by channel sandstones interbedded with grits and conglomerates, representing the lowermost part of the Sherkaly Formation,

Table 1. Areas of Jurassic paleolandscapes in West Siberia (thousand km^2)

Time	Low mountains	Plain: Elevated	Plain: Erosional-depositional	Plain: Lowland depositional	Plain: Coastal	Inland freshwater lakes and ponds	Sea: Near-shore, 0–25 m	Sea: Shallow sea, 25–100 m	Sea: Shallow sea, 100–200 m	Sea: Deep sea, 200–400 m	Sea: Deep sea, > 400 m	Total area of the sea	Total area of the basin
Volgian	670	1390	320	260	220	0	1080	750	780	630	50	3290	3770
Oxfordian	970	1370	300	220	490	0	1040	1070	0	0	0	2110	2820
Callovian	980	1330	390	450	310	0	570	820	540	140	0	2070	2830
Bathonian	1050	1030	490	1040	340	0	1290	470	0	0	0	1760	3140
Bajocian	1140	1480	440	840	630	0	1260	370	0	0	0	1630	3100
Aalenian	1330	1980	180	710	550	0	1110	290	0	0	0	1400	2660
Late Toarcian–Early Aalenian	1380	860	130	720	620	0	960	240	0	0	0	1200	2540
Early Toarcian	1800	1410	80	400	470	4	950	330	0	0	0	1280	2154
Late Pliensbachian	2170	2160	190	470	140	0	100	0	0	0	0	100	710

which contains J_{12} sand bed. Further west and southwest, the mudstones of the Yagel Formation, overlying the Beregovaya Formation, pass into sandier facies of the Middle Sherkaly Subformation. This subformation in general displays a lower proportion of finer argillaceous material, reflecting proximity to sediment source areas.

In the first half of the Early Jurassic (Hettangian, Sinemurian, Early Pliensbachian), the southeastern part of West Siberia represented an erosional-depositional plain where deposition took place within the axial parts of the super-order and first-order negative structures (Koltogory mesotrough, Nyurolka and Ust'-Tym megadepressions, Bakchar mesodepression). The Azharmin region, which encompasses the East Paidugina megadepression, Vladimirov mesomonocline, and Ket' megaincision, is characterized by very similar depositional settings.

Erosion of local source areas accompanied by a widening of the depositional basin resulted in the transformation of the landscape into a low-lying depositional plain. A subsequent phase of the basin evolution was marked by widespread deposition of lacustrine, floodplain and swamp sediments.

The complex environmental setting in this part of the paleobasins resulted in the considerable diversification of lithologies and pronounced lateral facies variations. The fluvial channel facies passed over a short distance into lake, floodplain and swamp sediments, which are grouped into the Lower Urman Subformation. This formation comprises inequigranular sandstones, gravel, siltstones, with coalified plant mesofossils and rare coal seams, which contain J_{17} sand bed (its age equivalent, J_{12} bed, was delineated in the southwest of the province). During the Late Pliensbachian, deposition in this area is represented by the Middle Urman Subformation. In the Bakchar and Central Nyurolka mesodepressions and Koltogory mesotrough, this subformation comprises gray to black mudstones, containing plant debris as well as coal bands and lenses. In the Ust'-Tym megadepression and the adjacent eastern areas of the plain, the sediments grade into sandier mudstones with siltstone and sandstone intercalations and thick sand layers. In the Azharmin region, the Middle Urna Subformation displays a change in lithology to greenish gray and dark gray mudstones intercalated with siltstones and sandstones. The presence of green algae in the pollen spectra from the Middle Urman Subformation indicates a freshwater lake (Shurygin et al., 2000). The low depositional plain occupied an area of 470,000 km^2.

The organic matter in sediments accumulated in the Pliensbachian landscapes of the northern West Siberian is derived from higher plants (terrigenous) and phytoplankton (marine) or it may have a mixed source. Most of the present-day organic carbon concentrations average about 1.26% in Pliensbachian mudstones (Zimnyaya, Levinskiy, Sharapovo horizons) from northern West Siberia. The proportion of samples with organic carbon content less than 1% is approximately equal to that with 1–3% C_{org}. The highest average C_{org} concentrations were found only in a few samples from the Levinskiy and Zimnyaya horizons (>3%) and from the Sharapovo horizon (5%). The average organic carbon content of mudstones ranges from 1.1% (Levinskiy horizon) to 1.34% and 1.31% (Zimnyaya and Sharapovo horizons), respectively.

A few carbon isotope analyses of kerogen showed that most Pliensbachian rocks contain organic matter of both terrigenous and mixed origins. Analysis of a wider range of bitumens (sterane and tricyclane distributions) suggests significant contributions of aquatic organic matter in rocks of the Zimnyaya horizon, whereas organic matter originating from marine, terrigenous and mixed sources is present in almost equal proportions in rocks of the Levinskiy and Sharapovo horizons (Figs. 2, 3).

An erosional-depositional plain was dominated by erosional rather than depositional processes. In the northeastern West Siberian (Trans-Ural megamonoclise), sediments accumulated in a system of freshwater lakes connected by river valleys. In the southeast, the plain occupied the area of the

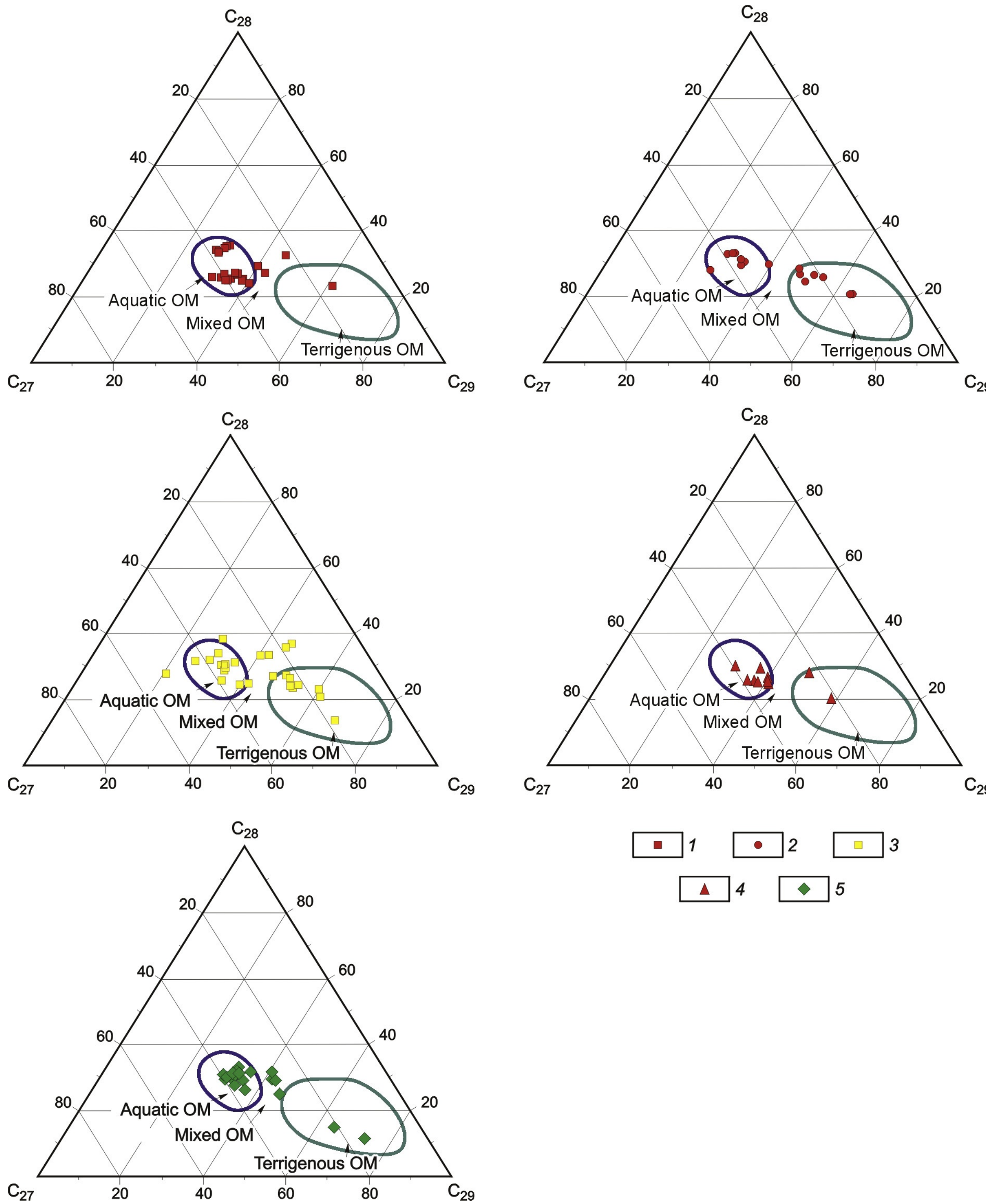

Fig. 2. Triangular diagram showing the distribution of C_{27}, C_{28}, C_{29} steranes in Lower Jurassic bitumens from northern West Siberia. *1–5*, horizons: *1*, Zimnyaya; *2*, Levinskiy; *3*, Sharapovo; *4*, Kiterbyut; *5*, Nadoyakha.

Teguldet megahemisyneclise where mostly sandstones of the Makarovo Formation were deposited. The formation comprises channel sandstones, intercalated gravel, fluvio-lacustrine siltstones, and shales with coal seams. This erosional-depositional plain was as much as 190,000 km^2 in area.

During the Hettangian, Sinemurian, and Pliensbachian, almost all positive structures within the central and southern parts of the West Siberian geosyneclise (Khantey hemianteclise, Upper Vasyugan anteclise, Ob'–Vasyugan and Kurzha ridges) were the *land areas of erosion*, and the structures of the Outer tectonic belt such as the Yenisei megamonoclise in the east and the Trans-Ural megamonoclise and part of the Krasnoleninsk megamonoclise in the west were represented by upland erosional plains or, rarely, low mountains. The

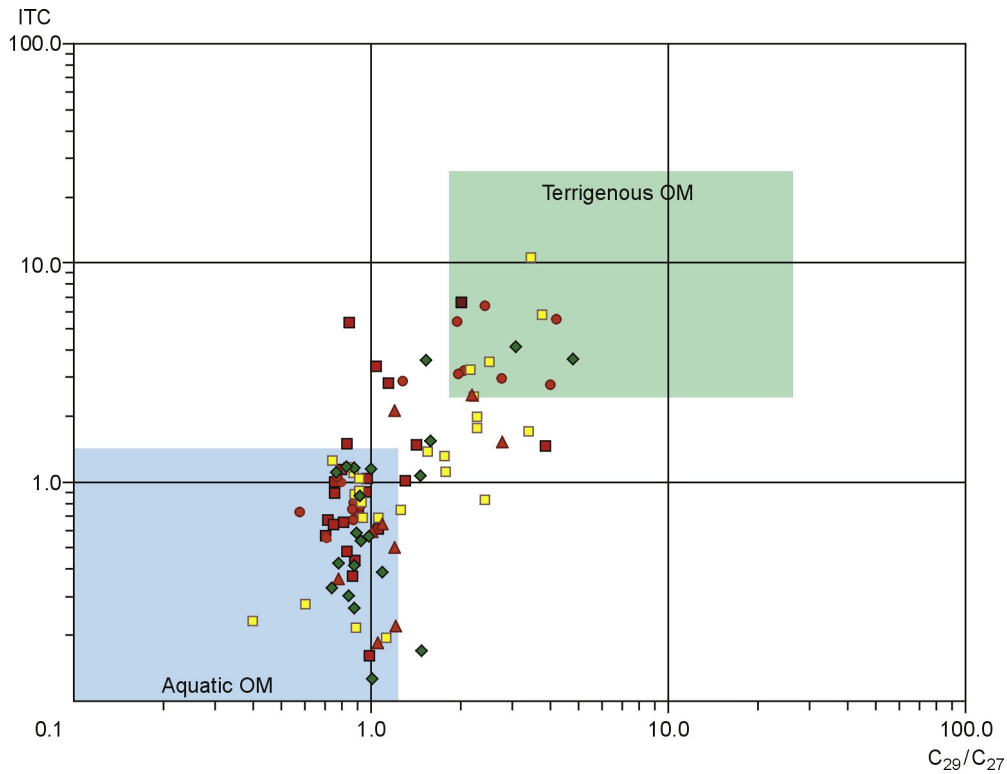

Fig. 3. Classification of genetic types of organic matter from Lower Jurassic deposits of northern West Siberia using an ITC (tricyclane index) vs. C_{29}/C_{27} sterane plot. For legend see Fig. 2.

Khantey hemianteclise became split into two blocks (Surgut and Nizhnevartovsk–Varyegan–Tagrin) and the Kurzha ridge was divided into the western and eastern parts. The latter was part of a large remnant erosional “island” within the Yenisei megamonoclise. The western part of the present-day Mansi syneclise also formed a land area at this time.

Local sediment sources were the areas of erosion within the basin, whereas structures of the Outer tectonic belt, bordering the West Siberian geosyneclise and extending into mountains beyond the basin limits, represented external sediment sources. These included the Altai–Sayan and Kazakhstan mountain systems in the south, the Urals in the west, and the Central Siberian landmass in the east. The area of erosion was about 2,160,000 km^2. In addition, sediment source areas were located in the north (paleoislands of the Novaya Zemlya Archipelago and Taimyr Peninsula). In the Early Jurassic, the southern Novaya Zemlya island was part of the Ural mountain system. The northern Novaya Zemlya island and Taimyr formed a single large erosional landmass, which encompassed an area of 360,000 km^2.

Early Toarcian

A modest Late Pliensbachian regression was followed by a rise in sea level and further major transgression in the Early and Middle Jurassic. However, southern upland area prevented this marine transgression, which advanced southward into the West Siberian basin.

Unlike the other ages of the Early and Middle Jurassic, the Early Toarcian, along with the climatic optimum traceable in global sea level curves, experienced a generally warm and more humid climate (Shurygin et al., 2000; Yasamanov, 1976). The flora of West Siberia at this time was strongly influenced by the Indo-European paleofloristic province (Ilyina, 1971). The presence of the xerophytic floras indicates that dry conditions prevailed locally (Golbert, 1987).

Oxygen isotope data from belemnite rostra showed that the mean annual sea-surface temperatures in the Early Toarcian varied between +16.9 °C and +24.5 °C (averaging +20.5 °C) (Saks and Nalnyaeva, 1975). Lower temperature estimates were recorded for deeper environments. Increasing seawater temperatures produced a massive bloom of the diverse marine species and the immigration of abundant West European faunas (Saks, 1976). This time was also marked by colonization of the Siberian seas by a belemnite fauna (Meledina et al., 2005; Saks anf Nalnyaeva, 1975).

The expansion of the marine depositional areain early Toarcian time coincided with a general deepening of the basin, as indicated by the accumulation of fine oozes. Overall, the location of the most active subsidence at the eastern and southeastern basin margins migrated westwards at this time.

Shale-dominated successions, which were deposited during this stage, form laterally persistent seals of the Togur and Kiterbyut Formations.

The following depositional environments were identified in the Early Toarcian (Fig. 4, Table 1):

– open sea, up to 25–100 m in depth;

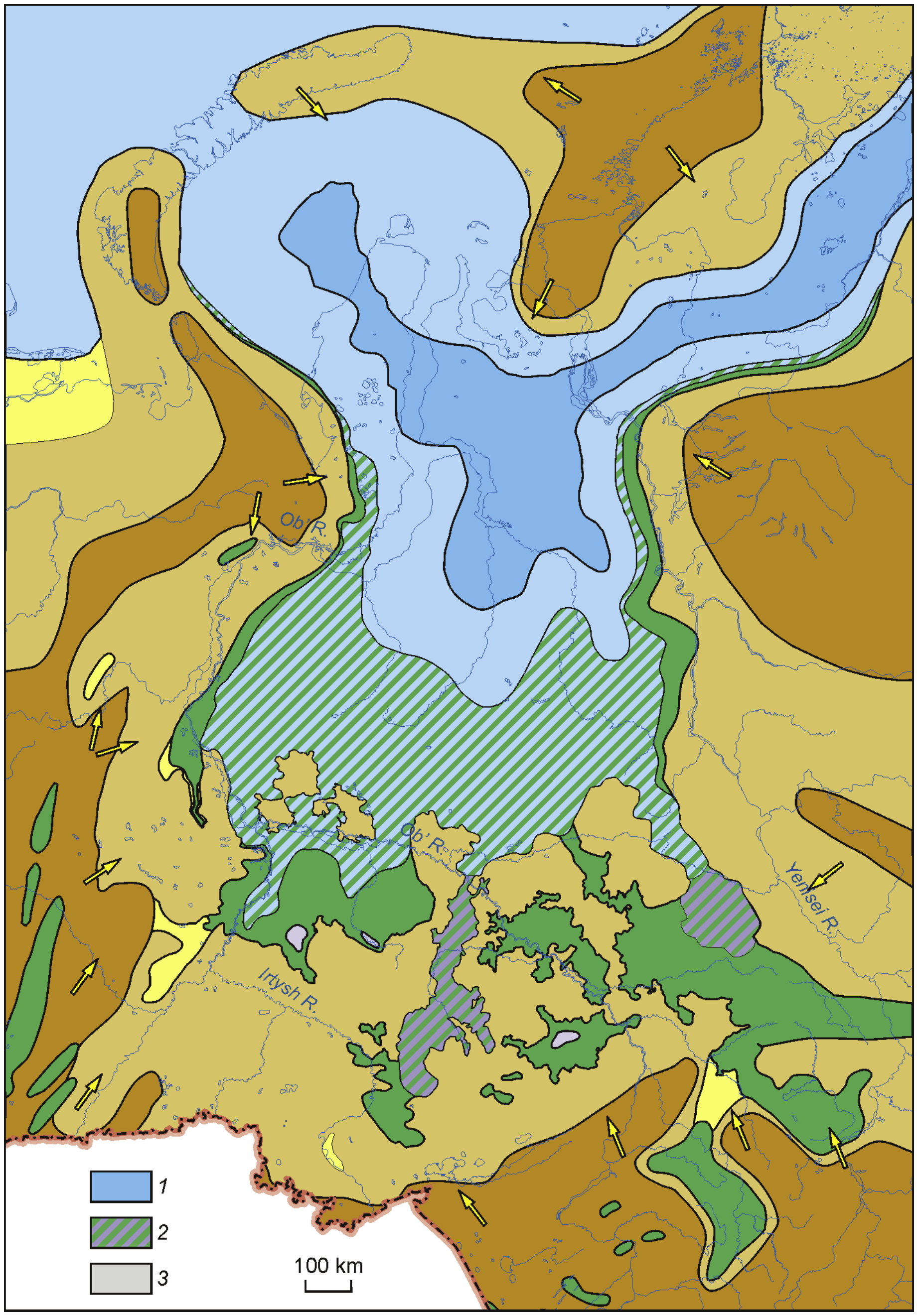

Fig. 4. Paleogeography of West Siberia in the Early Toarcian. *1–3*, Paleogeographic areas: areas of marined eposition: *1*, shallow sea, up to 25–100 m in depth; transitional areas: *2*, low-lying depositional plain with numerous lakes and a periodic connection to the sea, inland lakes and ponds: *3*, freshwater. The remaining symbols are the same as in Fig. 1.

– shallow sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain with numerous lakes;
– lowland depositional plain;
– elevated erosional-depositional plain;
– elevated erosional plain;
– low mountains.

They are discussed in more detail below.

By the Early Toarcian, *marine conditions* with water depths not exceeding 100 m developed in the northern West Siberian basin. Deeper water sedimentation was established in areas of the Kara, Antipayuta–Tadebeyakha, Bol'shaya Kheta megasyneclises and the Agapa–Yenisei trench and occupied an area of 330,000 km^2. The West Siberian sea was connected to the East European and East Siberian seas through the relatively narrow channels. The southern limit of the Early Toarcian marine basin is inferred to lie within the northern flanks (from west to east) of the Nerutin megadepression, Middle Pur inclined trench, and Taz structural mesobay.

The deeper part of the Early Toarcian basin was characterized by accumulation of dark gray to black fine oozes with variable amounts of carbonaceous material and phosphate nodules (Kiterbyut Formation). The faunas of bivalves, foraminifera and belemnite rostra in the Lower Toarcian successions indicate a fully marine environment. This is also supported by the rare occurrence of the Dactylioceras ammonites in the Lower Jurassic successions of northeastern West Siberia (Medvezh'ya 316 borehole) (Devyatov et al., 2006).

A shallow sea with water depths of up to 25 m (950,000 km^2 in area) surrounded the normal marine areas and had a width of 200 km within the paleo-Urals and 100 km within the Central Siberian landmass.

In the north of the West Siberian basin, marine argillaceous sediments of the Kiterbyut horizon contain as much as 3% organic carbon with an overall average of 0.83% organic carbon. Much of the organic matter in these sediments apparently is of marine origin (Figs. 2, 3).

A broad coastal plain occasionally inundated by the sea was located further southwards at this time and had an area of 470,000 km^2. The western part of the coastal plain periodically invaded by seawater had a relatively simple geometry because it occupied areas of the Nadym hemisyneclise, South Nadym megamonoclise, the northern plunge of the Krasnoleninsk megamonoclise and a part of the Khantey hemianteclise. These areas were dominated by argillaceous sediments of the Togur Formation, reflecting a quiet environment of freshwater and oxbow lakes, and swamps. These pass southwards into alluvial sedimentation with higher proportions of sand.

In the east the northern margin of the basin was bounded by the western flank of the Yenisei megamonoclise, which was characterized by a widespread development of lagoonal, lacustrine and, more rarely, transgressive marine facies of dark gray to black oozes (presently mudstones, containing lenses and bands of siltstones and fine-grained sandstones). These beds yielded abundant conchostracans together with rare foraminifera, marine bivalves, and fish scales.

In southeast, the coastal plain had a complex geometry that was controlled primarily by a pre-existing system of lakes and river valleys. These were characterized by the development of lagoonal, overbank, pond andfluvial channel facies. The adjacent paleohighs represented the remnant erosional islands in central parts of the basin. Lacustrine and locally marine transgressive deposition at this time was dominated by dark gray to black mudstones of the Togur Formation (Kontorovich et al., 1995b) with common interbeds of siltstones and fine-grained sandstones, containing plant remains. Sediments having a continental provenance contain layers of very fine-grained mudstones with marine foraminifera and bivalves.

These sediments are considered to be of marine origin. However, as indicated by data from core studies, only a few thin layers within the Togur Formation representing several lacustrine systems can be interpreted as transgressive marine deposits (Kontorovich et al., 1995a). Some of these sedimentary systems were characterized by deposition of sapropels. This fact was first described by Kontorovich (1964) in his Candidate's dissertation in the section of the Togur Formation penetrated by Kolapshevskaya-2 well. More recent studies showed that the rocks of the Togur Formation, enriched inaquatic organic matter, have been encountered only in a few wells and that the generative potential of this stratigraphic level in the southeast of the basin was overestimated (Kontorovich et al., 1995a). In the southeast of the basin, concentrations of organic carbon in individual mudstone range from 0.5–0.7% to 3–5%. A more detailed analysis revealed that these rocks are dominated by terrigenous organic matter (Figs. 2, 3).

A lowland depositional plain occupied a small area and extended as a narrow strip along the western, southwestern, and eastern flanks of the basin. Sediments were deposited in fluvio-lacustrine and swamp environments. The southeastern part of the basin was occupied by a number of plains in which black argillaceous deposits of the Togur Formation were deposited. These plains, spatially associated with the Bakchar mesodepression, Ust'-Tym and East Paidugina megadepressions, Teguldet megasyneclise, were separated by vast erosional areas. In the East Paidugina megadepression and Teguldet megasyneclise, these marine argillaceous sequences pass southwards into the continental units of the Ilan Formation. The formation comprises greenish-gray or dark gray mudstones, siltstones with interbeds of light gray sandstones. The lowland depositional plain occupies an area of 400,000 km^2, whereas the southeastern plains range from 20,000 to 70,000 km^2 in area.

During the Early Toarcian, *the erosional-depositional plain* was considerably reduced to 80,000 km^2, but remained extensive in the southeast of the basin.

An elevated erosional plain, some 1,410,000 km^2 in area, developed along the paleobasin margins. In the west and southwest, it was bounded by extensive upland areas along the Kazakhstan mountain ranges and the paleo-Urals. Two structural highs, such as the eastern flank of the Krasnoleninsk megamonoclise and the Surgut arch, occupied the central part of the basin within the coastal plain, occasionally invaded by the sea. A number of other paleohighs, including the Ob'–Vasyugan ridge, Pyl-Karamin and Paidugina megaswells, Parabel' inclined megaswell, Pudin and Gorely Yar dome-shaped uplifts and part of the Yenisei monoclise were delineated in southeast. Some of them appear to have acted as local sediment sources. In the north of the basin, the southern Novaya Zemlya paleoisland and the Urals still formed part of a single system. The area of the landmass that comprised the northern Novaya Zemlya island and Taimyr was reduced to 336,000 km^2.

Beyond the basin margins, the erosional plain passes gradually into plateaus and uplands.

Late Toarcian–Early Aalenian

A renewed marine regression in the late Early Toarcian caused a relative shallowing and freshening of the marine environments leading to a reduction in the area of lacustrine sedimentation, especially in southern West Siberia (Fig. 5). This was also accompanied by a decrease in the mean annual sweater temperature (Berlin et al., 1970). The fall in sea level and local changes in base level during the late Toarcian–early

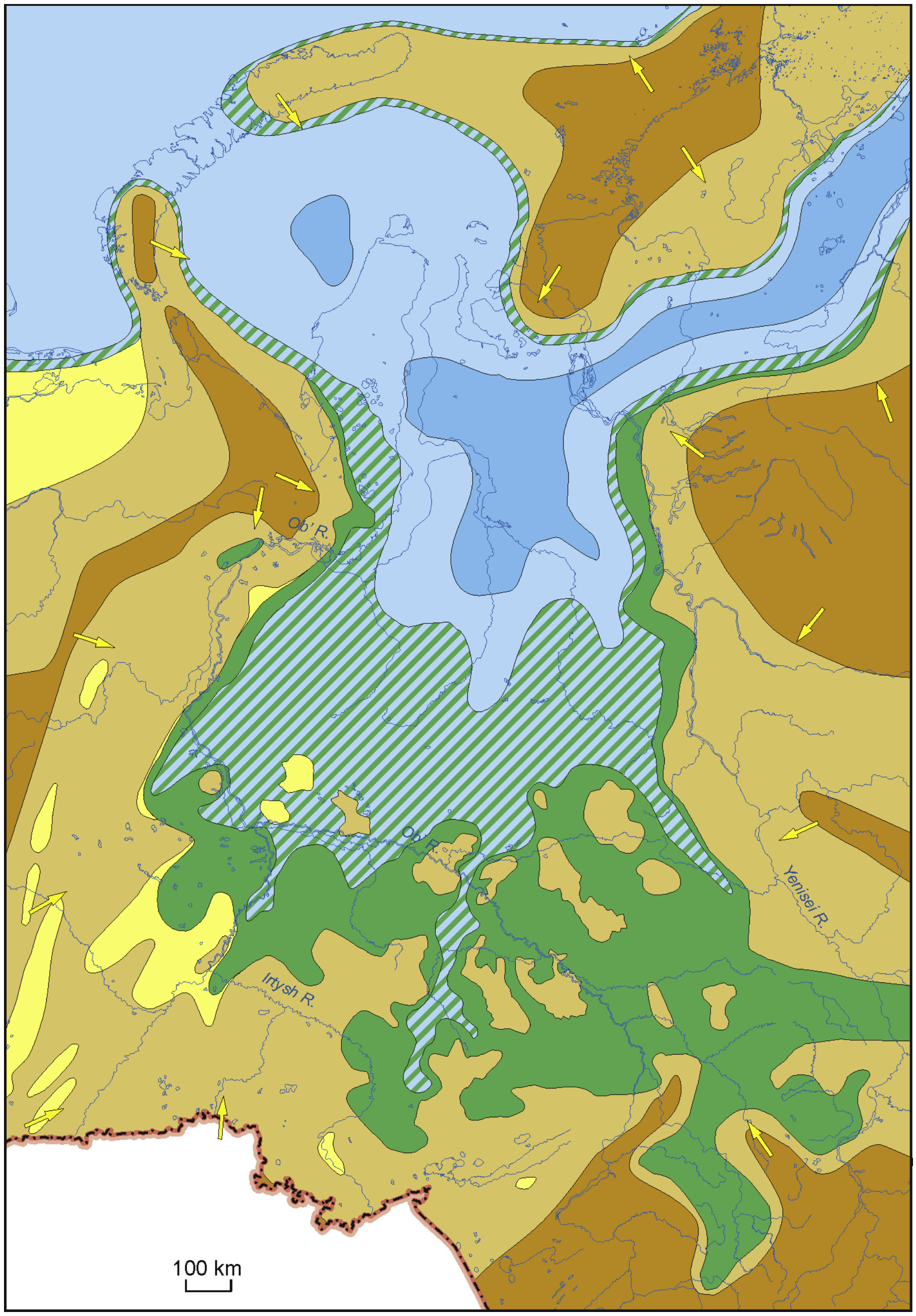

Fig. 5. Paleogeography of West Siberia in the Late Toarcian, Early Aalenian. For legend see Figs. 1, 4.

Aalenian, combined with the elevated topography of adjacent land areas and the presence of basement uplifts, were responsible for increased clastic sediment input to the basin. This time saw the deposition of JK_{10} bed, a major reservoir of the giant Talinka oilfield (Kontorovich et al., 1995a).

The following depositional environments were identified in the Late Toarcian–Early Aalenian (Fig. 5, Table 1):

– open sea, up to 25–100 m in depth;
– shallow sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– elevated erosional-depositional plain;
– elevated erosional plain;
– low mountains.

They are discussed in more detail below.

The area of *an open sea (25–100 m) and shallow sea (up to 25 m) environment* remained nearly the same in the central and eastern parts of the basin or was reduced slightly to 240,000 km^2. During this time, the West Siberian basin was also connected to the East European and East Siberian seas through the Kara megasyneclise and Agapa–Yenisei trench. The marine basin, together with the coastal area, has an area of 1,200,000 km^2. The establishment of shallowing environments and a tectonic reactivation in major catchment areas led to thick clastic accumulations in the emergent Nadoyakha Formation, represented by shallow-marine, marginal-marine and deltaic gray to greenish-gray sandstones and siltstones, with intercalated mudstones. These sediments contain plant debris, marine bivalves and foraminifera, and bioturbation is common. Significant shale-dominated sections occur in the central part of the basin, while the proportion of clastic material increases and sand is present in the succession towards adjacent paleohighs.

The organic matter content of the Nadoyakha marine succession is highest in the Lower Jurassic sediments of northern West Siberia (1.75%), ranging from 0.5–0.8% to 3–5%. The biomarker data revealed that the Nadoyakha horizon contains organic matter of predominantly marine origin (Figs. 2, 3).

In coastal areas of the Late Toarcian–Early Aalenian basin, the depositional environments vary greatly and include deltas, tidal flats, beaches, as well as other settings representing a transition from marine to continental deposition. This time was marked by deposition of the lower part of the Upper Kotukhta Subformation consisting of gray to greenish-gray sandstones, siltstones, mudstones, with occasional gravel intercalations. These beds contain dispersed plant debris, pyrite, siderite, marine bivalves, and foraminifera.

To the east, facies change progressively to fluvio-lacustrine and alluvial sediments representing the lower part of the Upper Khudosey Subformation, which is dominated by sandstones intercalated with gritstones, conglomerates, siltstones and mudstones, containing macrofloral remains and plant debris.

The configuration of *a coastal plain occasionally inundated by the sea* remained much as before, except for the southeastern flank of the basin. The area of this plain, being about 620,000 km^2, increased at the expense of a littoral area formed in a narrow fringe around the western coast of the Kara Sea and southeastern coast of the Barents Sea. A similar costal fringe formed around the northern Novaya Zemlya island and Taimyr has an area of 60,000 km^2. Marine incursions reached as far south as a major river network confined to the Koltogory–Nyurolka trench. Lithologies represented here include fluvial channel deposits of the Lower Salat Subformation, which comprises the J_{15} group of sand beds (equivalent to J_{10} bed using the Tyumen-based indices). These beds area composed of alternating siltstones and inequigranular sandstones with frequent gravel and conglomerate intercalations. Coal lenses and bands and floral remains are also common.

Much of the coastal plain occasionally inundated by the sea occupied the same areas as those established during the Early Toarcian. It covered the Nadym hemisyneclise, South Nadym megamonoclise and northern part of the Krasnoleninsk megamonoclise and comprised a variety of facies represented by marginal-marine, deltaic, lagoonal, and fluvio-lacustrine deposits in the lowermost parts of the upper subformations of the Kotukhta, Sherkaly, and Gorelaya Formations. These are mostly gray inequigranular sandstones, often kaolinitized, with intercalations of gravel, conglomerates, siltstones, and mudstones. Plant debris, coal seams, and foraminiferal remains are locally present.

In the Late Toarcian–Early Aalenian, *a lowland depositional plain* was much larger in area than in the Early Toarcian. It formed a narrow continuous strip along the western and eastern basin margins and occupied the entire southeastern portion of the sedimentary basin. It was bounded to the south by the northern flank of the Barabinsk–Pikhtovaya megamonoclise and to the west by the eastern flank of the Koltogory–Nyurolka trench. These extensive areas were dominated by a fluvio-lacustrine environment in which the Peshkov Formation was deposited. The formation consists of silty-sand deposits, forming J_{15} reservoir, with subordinate mudstone and coal layers of variable thickness. The number and thickness of coal seams decrease southwards with an abrupt increase in the proportion of coarse sandstones within the Vladimirov mesomonocline. Significant variations in lithology within the Teguldet megahemisyneclise are reflected by the dominance of coarse-grained sandstones, gravel and volcanic pebbles, coals lenses and fragments, intercalated siltstones and mudstones, which are grouped into the lower subformations of the Itat Formation. The formation contains occasional coal seams.

In the west, the depositional plain occupied the area of the Krasnoleninsk megamonoclise. Numerous river valleys developed in the Early Toarcian were filled with alluvial and lacustrine sediments represented by siltstones, mudstones, sandstones, and coals of the Tugrov Formation, as well as quartz sandstones, gritstones with intercalations of dark gray mudstones of the Peshkov Formation. The sandstones, siltstones, gritstones, conglomerates and lignite seams of the Yany-Manyin Formation were deposited in a narrow strip along the western flank of the Krasnoleninsk megamonoclise.

The area of the depositional plain at this time was about 720,000 km^2.

In the west of the basin, e*rosional-depositional plains* must have been relatively insignificant features in the Late Toarcian–Early Aalenian landscape. They developed only locally within the upper reaches of large river valleys and intermountain lows along the paleo-Urals. They have an area of about 130,000 km^2.

During the Late Toarcian, the areas of erosion within the intrabasinal paleohighs were considerably reduced. A series of paleohighs remained on some of the large positive structures in the central and southeastern parts of the geosyneclise, such as the Central Surgut arch, Nizhnevartovsk and Aleksandrovsk arches, Middle Vasyugan and Pyl-Karamin megaswells, Parabel' inclined megaswell, etc. These paleohighs formed a chain of small, flattened erosional upland remnants, which were acted as local sources of fine argillaceous material. A land area extending from Northern Kazakhstan to the Kaimysov arch forms part of a single erosional upland remnant.

In the Late Toarcian–Early Aalenian, the erosional upland occupied an area of 860,000 km^2.

Aalenian

During the Aalenian, the West Siberian geosyneclise continued to subside. The Depositional environments altered insignificantly compared to those of the Late Toarcian and the

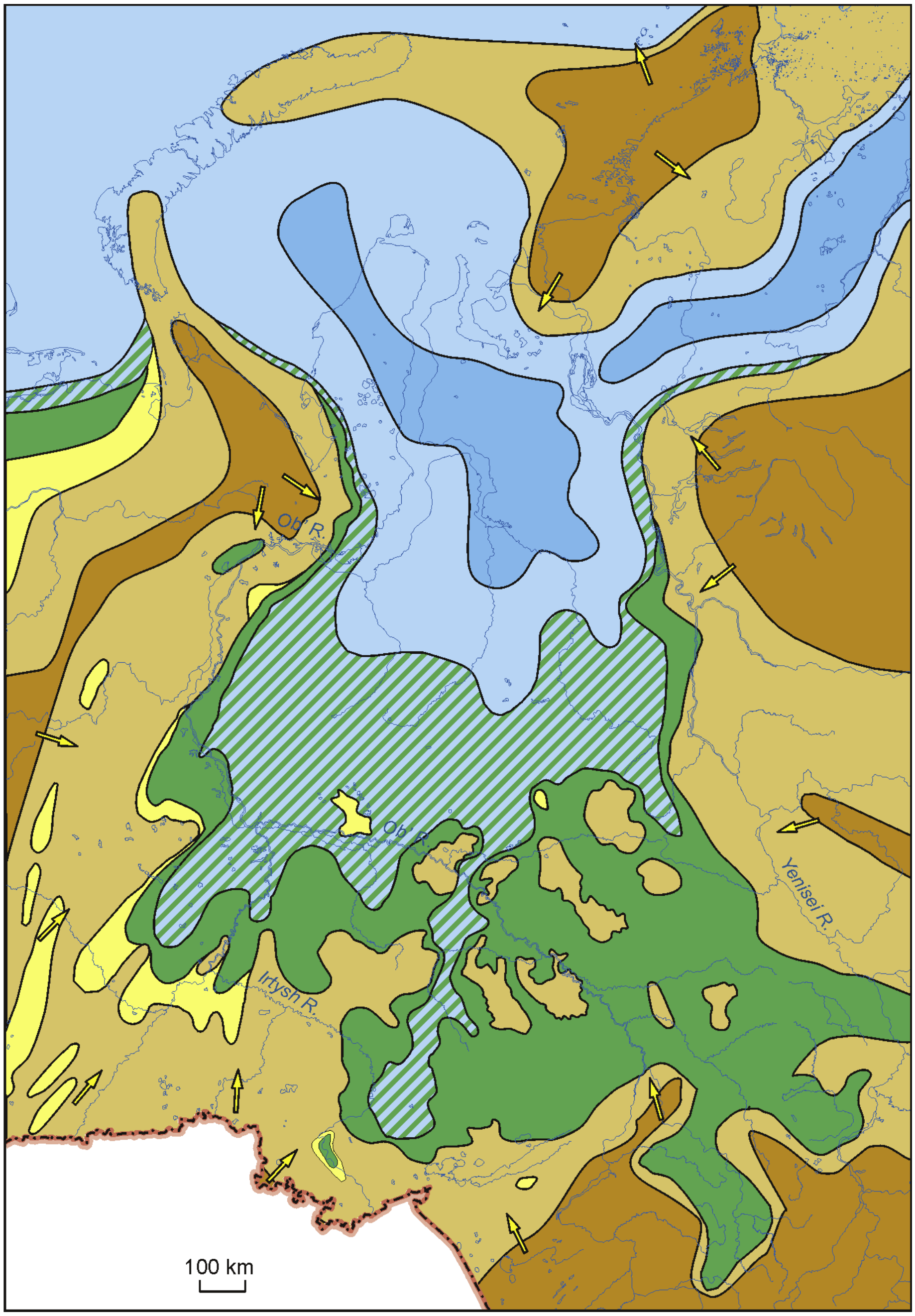

Fig. 6. Paleogeography of West Siberia in the Aalenian. For legend see Figs. 1, 4.

relatively stable conditions persisted in the northern part of the basin over much of the Aalenian. At this time, the minimum annual sweater temperatures in northern Siberia sharply decreased to +15–+20 °C (Berlin et al., 1970). The composition and character of land vegetation indicate a more humid and warm climate during the Aalenian with seasonal temperature fluctuations (Glushko, 1984). Deposition occurred in a marine basin and on a fluvio-lacustrine and coastal plain. The configuration of the marine basin at this time changed only insignificantly as compared to the Toarcian. Despite the continuing subsidence, the overall depositional area did not expand considerably, but there was a marked shift in the spatial distribution of depositional environments (Fig. 6, Table 1). Open marine conditions with water depths of 25–100 m were represented at this time by two depressions located in the west and east of the northern half of this sedimentary basin. These comprise the South Kara megadepression and Bol'shaya Kheta megasyneclise in the west and the Agapa trough in the east. Shallow-marine environments with water depths up to 25 expanded considerably towards the coastal plain surrounding the northern Novaya Zemlya–Taimyr paleoisland and the southern peninsular in the former area of Novaya Zemlya islands.

Concentrations of organic carbon in mudstones of the Aalenian marine basin (Laida horizon) are higher than those of the Nadoyakha horizon. The ranges of C_{org} concentrations

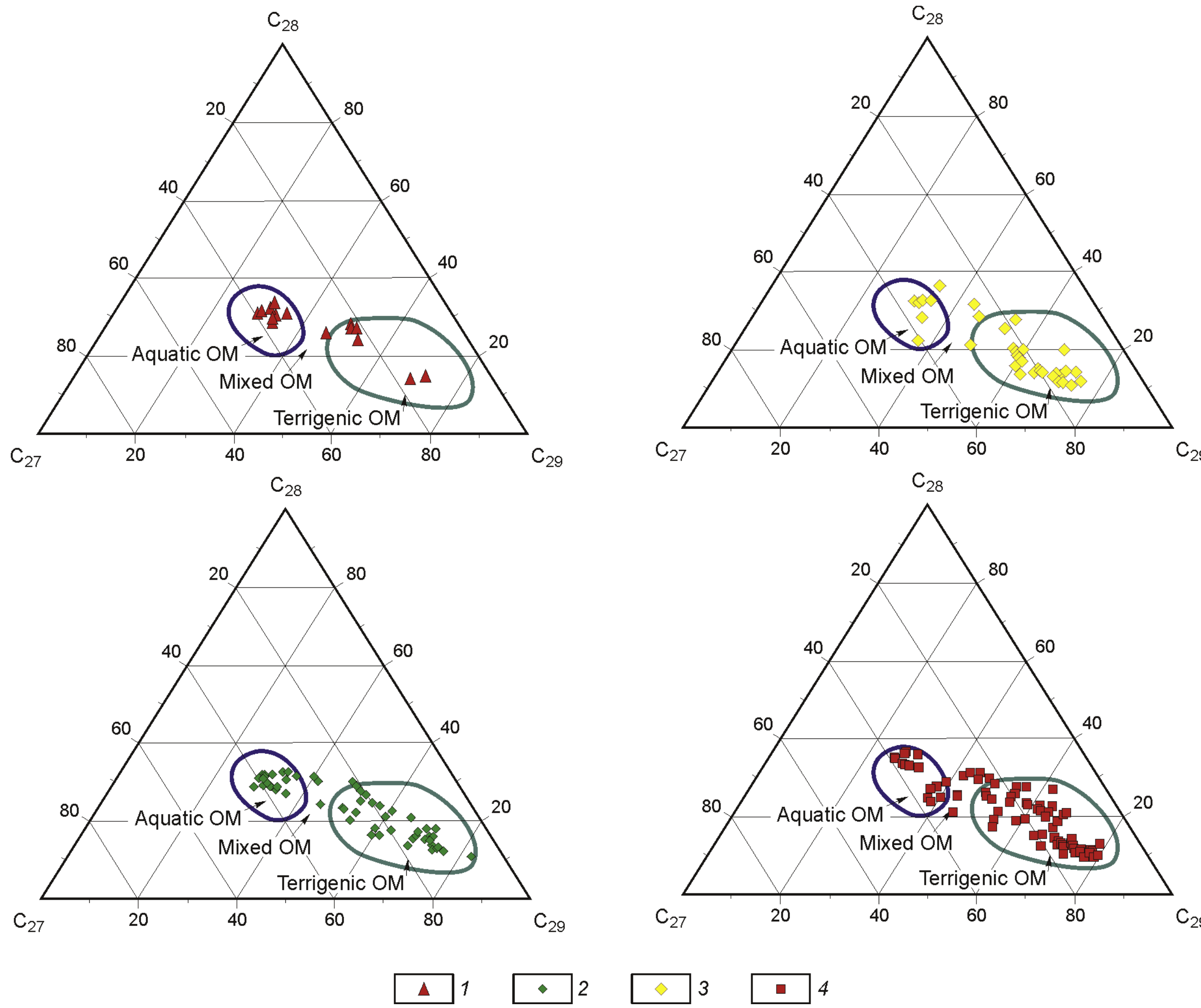

Fig. 7. Triangular diagram showing the distribution of C_{27}, C_{28}, C_{29} steranes in Middle Jurassic bitumens from northern West Siberia. *1–4*, horizons: *1*, Laida; *2*, Vym; *3*, Leontyev; *4*, Malyshev.

are the same as in the above horizon, with an overall average of 1.87%. The organic matter in these sediments was derived from higher land plants (terrigenous) and phytoplankton, as suggested by the distribution of sterane and tricyclane biomarkers in bitumens (Figs. 7, 8).

In the southwest of the basin, the coastal plain periodically invaded by the sea extended southwards, whereas a broad fluvio-lacustrine plain with numerous swamps and thick peat accumulations developed in the southeast of the basin.

Bajocian

During the Bajocian, the sedimentary basin widened and the area of erosion was reduced due to degradation and subsidence of earlier erosional topography. Short-term sea-level fluctuations and associated marine regression and transgression in the Early and Late Bajocian had little visible effect on paleogeography as compared to the Aalenian.

In the Bajocian, the location of the greatest subsidence migrated from the eastern and southeastern parts of the basin to the west.

The decreased base-level caused the formation of large lakes and broad alluvial plains. This resulted in increased proportions of clay to silt material and widespread peat deposition. These processes are recorded in the southeast of the basin by a series of regionally persistent coal beds (U_6, U_7, U_8, U_9, and U_{10}) in the lower and middle subformations of the Tyumen Formation.

The climate through the Bajocian was relatively cool and humid, with lower mean annual temperatures (+14 °C to +16 °C) (Berlin et al., 1970). The disappearance of a thermophilic flora suggests significantly cooler mean annual temperatures in terrestrial settings (Ilyina, 1971; Vakhrameev et al., 1970).

The following depositional environments were identified in the Bajocian (Fig. 9, Table 1):

– open sea, up to 25–100 m in depth;
– open sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– elevated erosional-depositional plain;
– erosional land passing into low mountains.

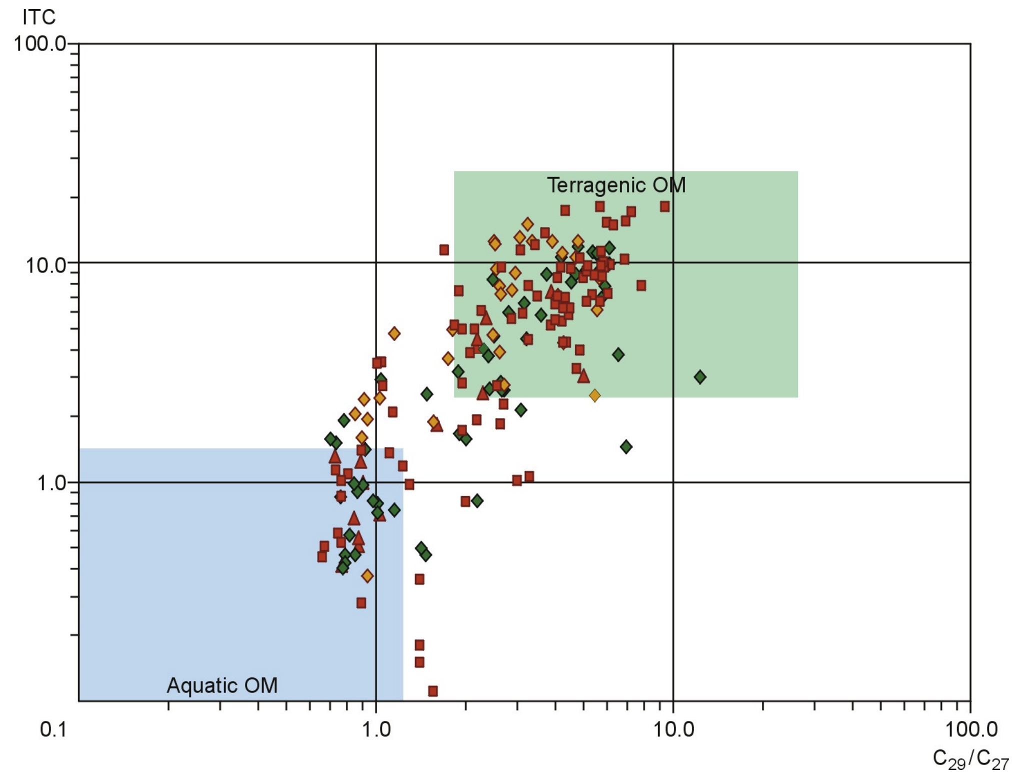

Fig. 8. Classification of genetic types of organic matter from Middle Jurassic deposits of northern West Siberia using an ITC (tricyclane index) vs. C_{29}/C_{27} sterane plot.

They are discussed in more detail below.

The open marine basin with depths of 25–100 m widened considerably, forming a continuous strip, which encompassed areas of the present-day Kara and Antipayuta–Tadebeyakha megasyneclises and Agapa–Yenisei trench. These areas of the marine basin were dominated by deposition of shallow-marine and marginal-marine facies of the Vym Formation comprising inequigranular sandstones alternating with siltstones and mudstones. The formation contains abundant marine (or rare freshwater) bivalves and foraminifera. These sediments grade into sandier facies towards the paleoshoreline. Renewed marine transgression in the Late Bajocian produced a transition to deep water marine conditions with accumulation of fine oozes, which were subsequently lithified to form mudstones of the Leontyev Formation. It yielded a diverse fauna of bivalves, foraminifera, and ostracods. No ammonoids, however, are known from these lithologies in West Siberia, although various Bajocian ammonites were previously found on Novaya Zemlya islands (Dibner, 1962). At this time, this marine basin has an area of about 370,000 km^2.

Sediments accumulated in the Bajocian marine basin contain higher concentrations of organic matter than the Aalenian sequences. In the mudstones of the Vym Formation, organic carbon concentrations average about 2.63%. Only in a few samples contain less than 1% organic carbon, while in 20% of samples organic carbon contents range from 3–4 to 7–9%. In contrast to the Laida horizon and Lower Jurassic sequences, the Vym horizon is dominated by terrigenous organic matter, with the exception of a few isolated beds, which contain organic matter derived from marine sources. The Bajocian interval of the Leontyev horizon has the lower organic content, averaging 1.77% and higher contribution of terrigenous organic matter than the rocks of the Vym horizon (Fig. 7, 8).

A shallow marine zone with water depths less than 25 m developed around the deeper part of the basin. The main clastic depocenters were located in the north, in the present-day East Pay-Khoy and North Kara monoclises and North Kara megadepression. A broad area of shallow sea was to the south and encompassed the present-day Nadym hemisyneclise and Middle Pur inclined megatrench. The coastal region of this shallow sea was characterized by a variety of depositional settings, from deltaic to tidal and fluvio-lacustrine where deposition was dominated by inequigranular sandstones, siltstones, and mudstones intercalated with carbonaceous mudstones and coal, which comprised the lower subformation (Tolkina) of the Tyumen Formation. The shallow sea extended in the east to the western flank of the Yenisei megamonoclise and in the west to the eastern flank of the Trans-Ural megamonoclise. A further transgression in the Late Bajocian brought renewed deposition of shale-dominated sequences of the middle Tyumen (Sandibin) Subformation with abundant bivalve shells. The shallow sea was 1,260,000 km^2 in area. During the Bajocian, the West Siberian basin was connected to the Arctic basin through a channel passage separating the southern and northern islands of the Novaya Zemlya Archipelago, and via a channel separating Novaya Zemlya's northern island and Taimyr paleoisland.

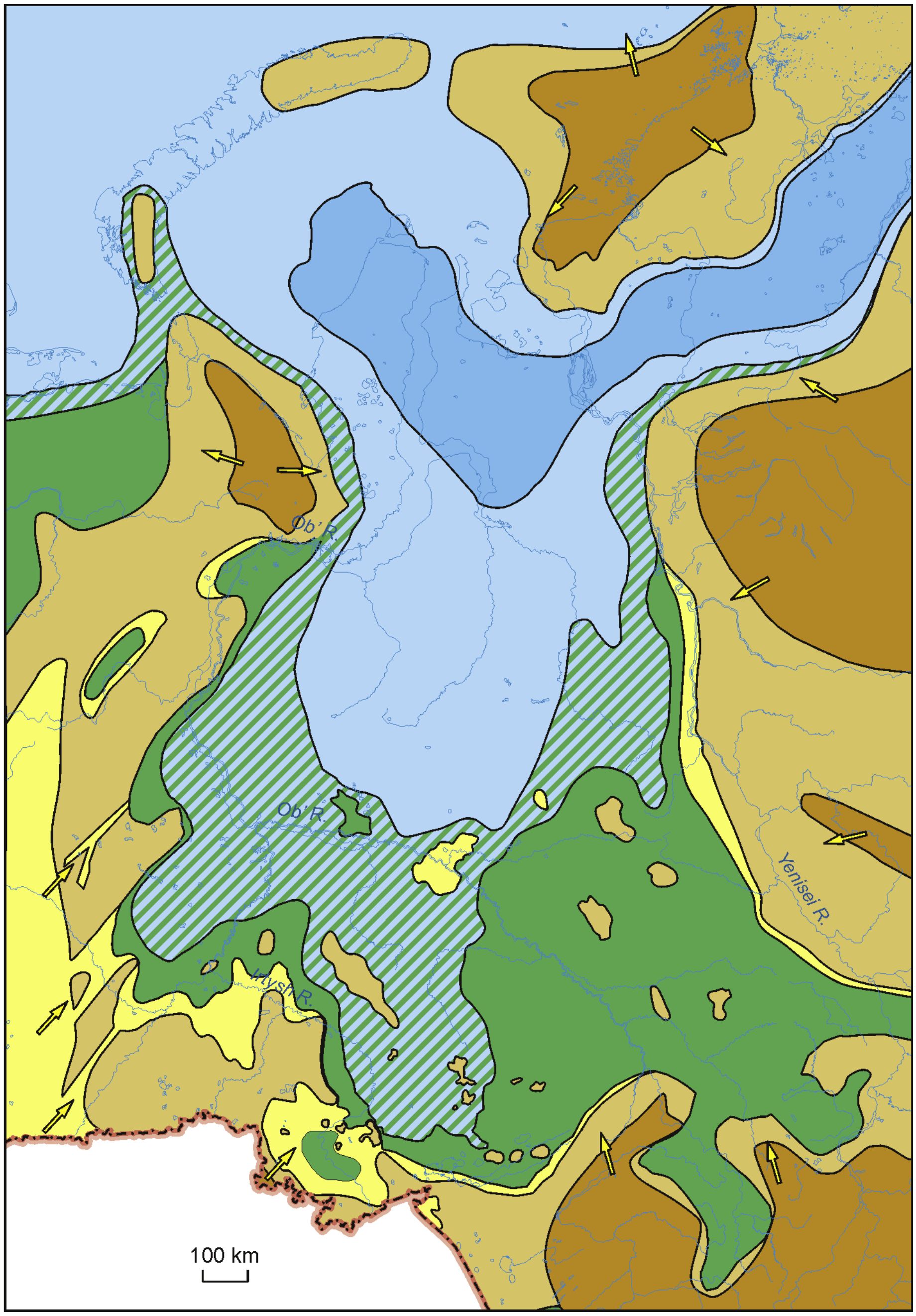

Fig. 9. Paleogeography of West Siberia in the Bajocian. For legend see Figs. 1, 4.

A lowland coastal plain occasionally inundated by the sea occupied the coastal region around the western, southern and eastern margins of the basin. It expanded considerably with respect to the Aalenian in the central and southern parts of the basin towards the Outer belt of the platform (Barabinsk–Pikhtovaya megamonoclise). With the progressive spread of the plain further northwest, Novaya Zemlya's southern island became separated by a channel from the paleo-Urals.

The Late Bajocian sea-level rise brought considerable changes in paleogeography of the region. Sedimentation took place in the lagoonal (with short-term marine incursions), lacustrine, swampy, fluvial, and deltaic settings and was dominated by argillaceous siltstones and mudstones, containing abundant terrestrial plant remains and thick coal seams of the Middle Tyumen Subformation. The widespread processes of paralic peat accumulation were interrupted by marine incursions. The fauna is dominated by freshwater bivalve shells, but there are beds containing marine bivalves and foraminifera. The fauna and lithology indicate a shallow freshwater environment during marine incursions.

This lowland coastal plain periodically invaded by the sea had an area of about 630,000 km^2.

A lowland depositional plain was smaller in area during the Bajocian than during the Aalenian. This period was marked by a transition from mostly continental to coastal plain environments that were periodically flooded by the sea.

The lowland depositional plain was located mostly in the southeast of the basin and extended from the present-day eastern flank of the Koltogory–Nyurolka trench to the Yenisei megamonoclise. This large area comprised the continental sandy-argillaceous and coal-bearing Lower Tyumen Subformation, which passed into sandier sediments to the east or was replaced towards the south, within the Tegulda megahemisyneclise, by shale-dominated successions with thin coal beds of the Upper Itat Subformation. Coal beds became much less widespread in Leontyev times (Upper Itat Subformation) but sediments of this age contain abundant freshwater bivalves and land plant impressions.

Bajocian continental deposition was along the western part of the basin, within the Trans-Ural, Tyumen and much of the Krasnoleninsk megamonoclises and was dominated by the Tolkina Formation of interbedded sandstones and siltstones and the overlying Sandibin Formation, consisting of argillaceous-silty sediments with coal beds.

The area of the lowland depositional plain in the Bajocian was about 840,000 km^2.

The expansions of *the erosional-depositional plain* took place in Bajocian times with the amalgamation of isolated areas in the west and southwest of the basin and formation of a broad plain located at latitude of Omsk. A broad zone, up to 50 km wide, showing alternations of erosional and depositional landscapes, was established in the east along the East Siberian upland. The plain had an area of about 440,000 km^2.

Remnants of *the inner upland (erosional) plain* are present only locally, in the southern basin, and comprise areas of the present-day Upper Demyanka megaswell, West Mezhovsk, Paidugina–Beregovoi, and Stepanov domal uplifts, etc.

Bathonian

Further subsidence of the West Siberian geosyneclise continued to control deposition over much of the basin area. The area of marine deposition did not change, but marine incursions became increasingly prolonged. The areas of erosion and the number of highs were reduced. The continued leveling of the topography and increased influx of argillaceous material to the basin led to the widespread deposition of shales and siltstones of the Upper Tyumen Subformation. The reduced topography resulted in the deposition of floodplain deposits of meandering river systems. Peat accumulation continued but was not as extensive as before. The climate did not change significantly compared to the Bajocian. A gradual, but uneven marine transgression deposited the Bathonian successions, as reflected in the uppermost part of the Upper Tyumen Subformation over the present-day Middle Ob' region (Kontorovich et al., 2010; Mkrtchyan and Filina, 1985).

Within the Bathonian a range of depositional environments remained the same as that established for the Bajocian:

– shallow sea, up to 25–100 m in depth;
– shallow sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– elevated erosional-depositional plain;
– erosional land.

The spatial distribution of these depositional environments and lithological heterogeneities reflects the time of maximum transgression in the Late Bathonian (pre-Vasyugan) (Fig. 10, Table 1).

A marine depositional area (25–100 m in depth) covered the Kara, Antipayuta–Tadebeyakha megasyneclises and Agapa–Yenisei trench. This area extended towards the west, approaching the southwestern margin of the Taimyr paleoisland in the northeast. The sandstones and siltstones of the Malyshev Formation with sparse shale breaks were deposited in the north of the basin, within the Yenisei zone. In the Ural zone, the Malyshev Formation consists of sandstones, siltstones, and mudstones alternating with thinly laminated units of fine silt and shale. These sediments yielded bivalve assemblages, foraminifers and ostracods. This depositional area covered approximately 470,000 km^2.

A shallow sea, up to 25 m in depth extended west in the northern part of the basin and spread over a low-lying plain along the paleo-Urals and Novaya Zemlya's southern island. During the Late Bathonian transgression, the sea reached as far as the present-day Yugansk megadepression and resulted in the deposition of marginal-marine, deltaic, lagoonal and, rarely, alluvial inequigranular sands, silts, clay oozes, and peats (Nadym Formation, Upper Tyumen Subformation). Sediments contain abundant macrofloral remains and plant debris, sporadic marine bivalves and foraminifers; bioturbation, pyrite and siderite inclusions are common. The number and thickness of coal beds and carbonaceous mudstones increase eastward, approaching the paleobasin margins. By the late Bathonian, this area covered about 1,290,000 km^2.

The most organic-rich sediments are those deposited in the Lower and Middle Jurassic sequences of the Bathonian marine basin. The organic carbon content of the mudstones averages 3.53%. The organic carbon content increases from a low of 1% in a few samples to a high of 3–4 and 7–9% in 25% of samples. Much of the organic matter in the Malyshev horizon originated from land plants (terrigenous organic matter). At the same time, these sediments have somewhat larger proportions of organic matter originated from phytoplankton (aquatic organic matter) and mixed sources than are found in the underlying Bajocian deposits (Figs. 7, 8).

A lowland coastal plain occasionally inundated by the sea had a much larger area than in the Bajocian and reached locally the Outer tectonic belt. A short period of regression in the Early Bathonian in the southern and southeastern regions greatly reduced the area of the plain (Fig. 10) and led to a widespread development of the alluvial plain facies, which were deposited in fluvial, lacustrine, waterlogged floodplain, and swamp settings. Such depositional environments are best represented by a monotonous sandy-argillaceous-silty stratum of the Upper Tyumen Subformation. There are indications in the rock record of a changing tectonic regime in the source areas, as suggested by a significant increase in the proportion

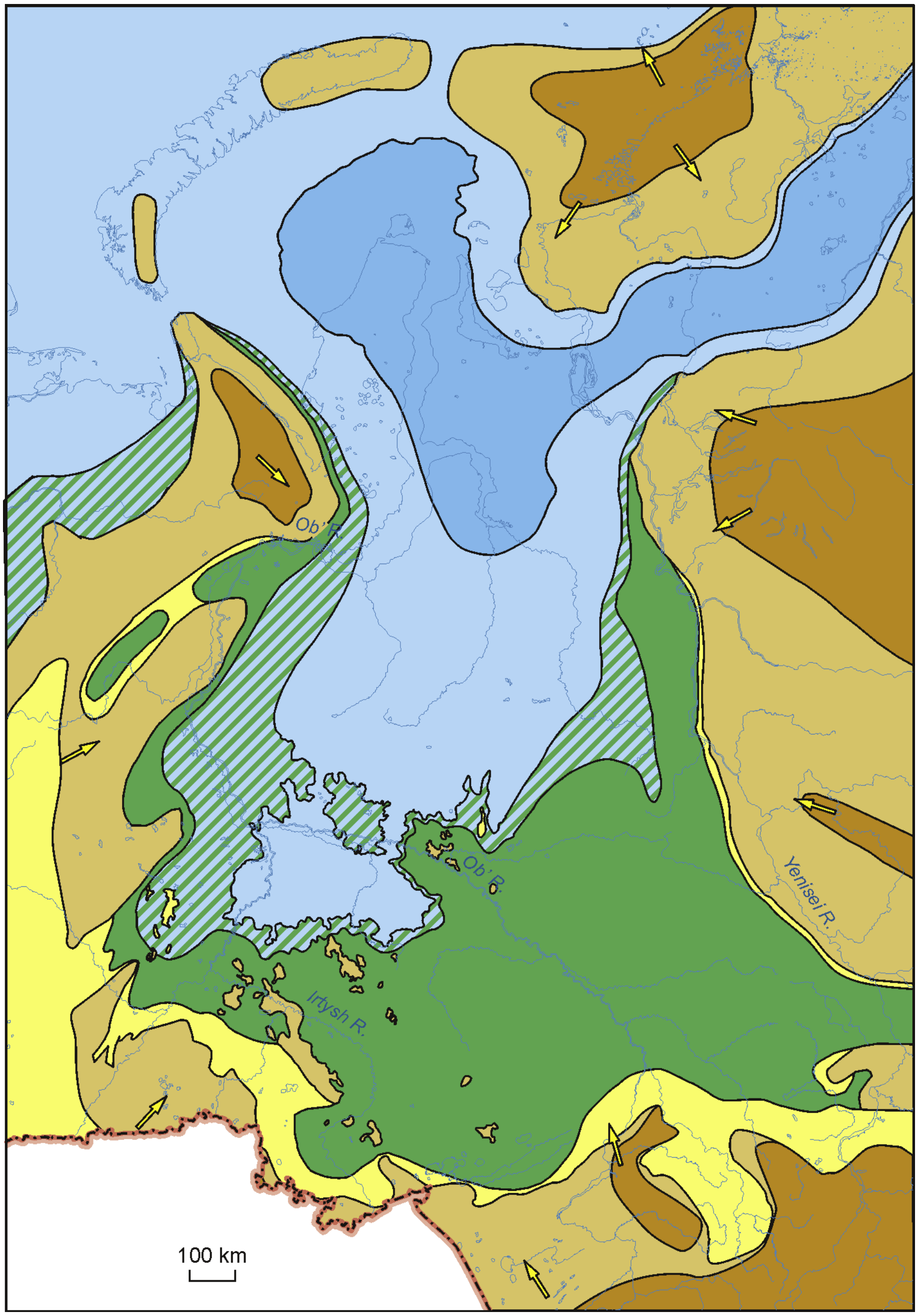

Fig. 10. Paleogeography of West Siberia in the Bathonian. For legend see Figs. 1, 4.

of sand material and thickness of sand beds (J_2 reservoirs), but the role of coal beds is reduced.

Detailed sedimentological core descriptions integrated with well log interpretation, paleontology and ichnology showed that the topmost layers of the Upper Tyumen Subformation in central West Siberian has a polyfacies nature (Fig. 11) (Kontorovich et al., 2010). Six genetically-related facies associations are distinguished in the Bathonian sequences (J_2 bed) of central West Siberia: fluvial, lacustrine (continental), deltaic, coastal continental (transitional), marginal-marine, and shallow-marine (marine) (Vakulenko and Yan, 2010). The J_2 bed represents a major marine transgression started during the late Middle–early Late Bathonian, which may have been influenced by a strongly irregular topography and local source areas. The lower part of the bed comprises persistently developed continental braided fluvial deposits. As the sea transgressed southwards, sediments deposited on a fluvio-lacustrine plain passed into deltaic and coastal-continental deposits, which passed upwards again into marginal-marine successions in the north. During the late Bathonian, continental deposition persisted over the most elevated parts of the basin.

Each facies association has a typical range of the external sandstone body geometries. Fluvial facies tend to be elongate to variably sinuous sand bodies, with the largest ones trending

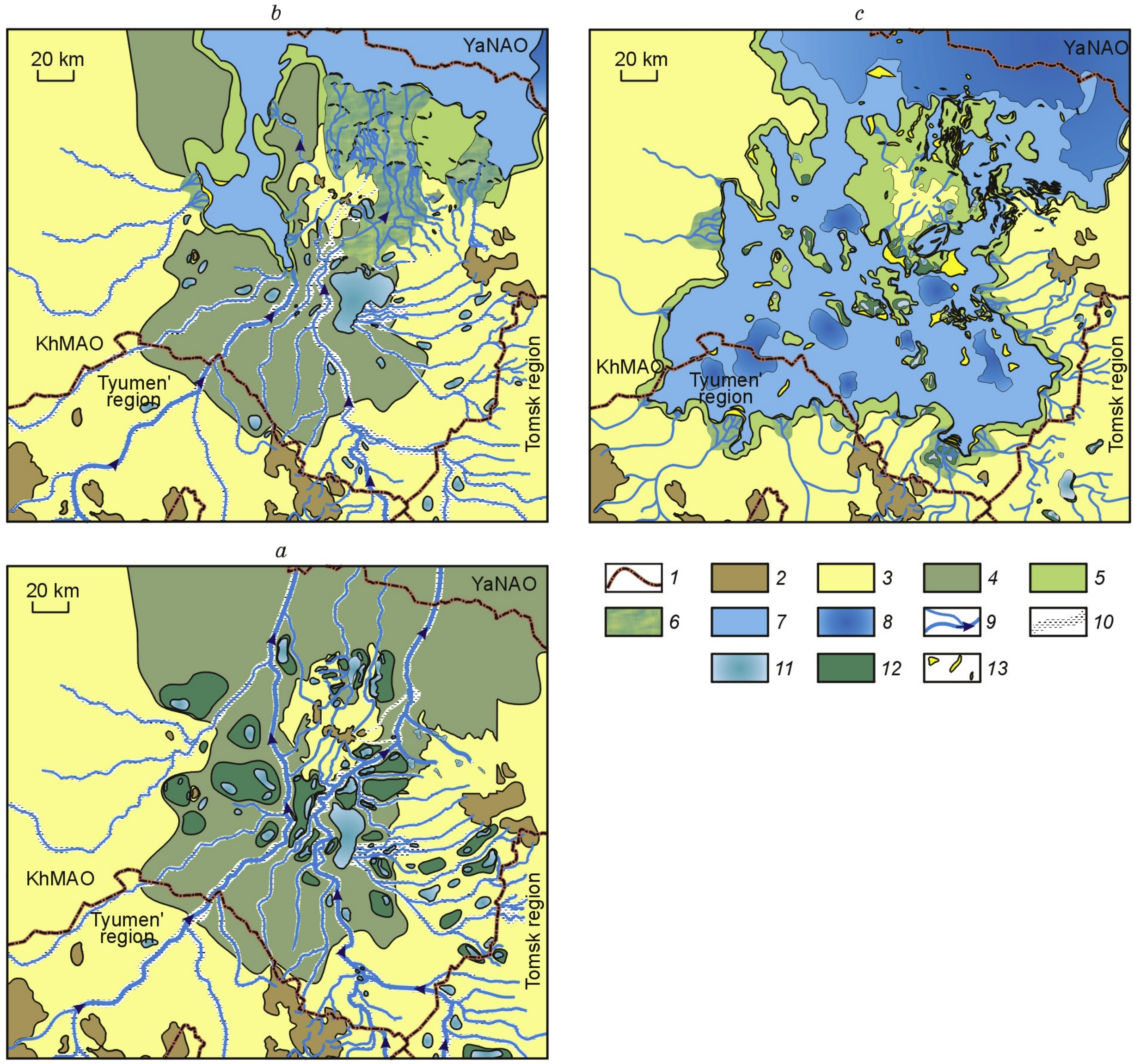

Fig. 11. Paleogeographic reconstruction of the central and southern parts of the West Siberian basin at the time of deposition of: *a*, lower part, *b*, middle part, *c*, upper part of J_2 horizon (Bathonian), modified after Kontorovich et al. (2005)]. *1*, administrative boundaries; *2–8*, Paleogeographic areas: areas of erosion: *2*, erosional land; areas of continental deposition: *3*, fluvio-lacustrine depositional plain; *4*, fluvio-lacustrine-swampy depositional plain; transitional areas: *5*, coastal area, *6*, delta; areas of marine deposition: *7*, *8*, shallow sea: *7*, water depths up to 10 m; *8*, water depths up to 10–20 m; *9–13*, paleolandscape elements: *9*, channels, distributary channels; *10*, flood plains; *11*, lakes; *12*, swamps; *13*, sand bodies.

SSE to NNW. Constructional deltaic systems developed during the short-term slowdown in sea-level rise and prograded southwards with renewed transgressions. The sandstone contained in these lithofacies units form lenticular bodies of complex geometries, while coastal continental and marginal-marine sandstone facies have a sheet-like geometry, which features marked variations in the paleorelief and the amount and principal direction of clastic sediment input from land.

The J_3 bed and the lowermost part of J_2 bed are represented by the alluvial and floodplain facies associations with sporadic traces of the *Skolithos* and *Fugichnia* escape structures (Kazanenkov et al., 2010). A transition from continental to marginal-marine facies in the middle and upper parts of J_2 bed is marked by an increase in diversity and abundance of ichnofossils including the *Skolithos* and *Cruziana* ichnofacies types, as well as marine bivalves and foraminifera.

By Late Bathonian time, the plain periodically inundated by the sea covered an area of about 340,000 km^2.

Lowland depositional plains were widespread in the south and southeast of the basin (Zolotova, 2009, 2011) where sediments were deposited on a large fluvio-lacustrine plain. This area exhibits an increase in the proportion of fluvial facies from west to east. In contrast to the southern part of the basin, the rugged topography of the southeastern sections resulted in major lithological heterogeneity and the presence of thick and extensive fluvial sand bodies. These lowland depositional plains covered an area of about 1,040,000 km^2.

The area of *erosional-depositional plains* was considerably reduced in the southeast and east of the basin, compared to that established in the Bajocian. They developed in small areas (490,000 km^2) along the mountainous belt fringing the West Siberian basin to the west, south, and east.

Callovian

A major marine transgression started at the end of the Late Bathonian but reached its maximum extent during the Callovian. Marine conditions were well established over much of the West Siberian sedimentary basin connected through the Kara megasyneclise to the East European and North seas. As transgression continued, the maximum depth of the West Siberian basin may have reached 200–400 m and several plains with a continental depositional regime were preserved only at the southern and southeastern margins of the basin.

The Callovian climate was as warm and humid as that of the Bajocian–Bathonian (Sarkisyan et al., 1967). The paleotemperature estimates indicate a 2–3 °C warming of seawater temperatures in the Arctic basin (Saks and Nalnyaeva, 1975). In the south of the basin, the boundaries of the Indo-European and Siberian paleofloristic provinces were shifted to the north (Golbert et al., 1968).

This period saw the deposition of marine shales in the lowermost sections of the Golchikha, Yanov Stan, and Abalak Formations; shallow marine silts and clays in the lower sections of the Maurynya, Danilovo, and Nurmin Formations, the lower subformation of the Vasyugan Formation and Tochin Formation; lagoonal sediments in the lowermost part of the Tatarka Formation; marginal-marine and continental sediments in the lowermost sections of the Naunak and Tyazhin Formations. Shale-dominated successions of the Golchikha, Abalak, Danilovo, and Tochin Formations, as well as the Lower Vasyugan Subformation developed to form a regional cap rock (Kontorovich et al., 1975). On the western and southwestern flanks of the basin, the basal layers of the Abalak and Danilovo Formations contain conglomerates, gritstones, sandstones, and calcareous mudstones of the Vogulka member in places. A distinctive feature of this period is that the axis of subsidence drifted eventually to the west, producing the asymmetrical depositional profile of the basin.

The following depositional environments were identified in the Callovian (Fig. 12, Table 1):

– deep sea, up to 200–400 m in depth;
– shallow sea, up to 100–200 m in depth;
– shallow sea, up to 25–100 m in depth;
– shallow sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– erosional-depositional plain;
– erosional land.

They are discussed in more detail below.

A deep sea (200–400 m in depth) occupied the area of the present-day Kara and Antipayuta–Tadebeyakha megasyneclises. The sea transgressed over West Siberia had normal salinity, as indicated by the composition of authigenic minerals from deposited sediments and a diverse marine fauna of bivalves, foraminifera, cephalopod, and gastropod mollusks. Very fine muds (mudstones of the Abalak Formation) were deposited in the deep part of the basin, which had an area of about 140,000 km^2.

The deep marine zone was bordered by *a shallow-marine zone (typical depth 100 to 200 m)*, which occupied a 250–300 km wide band running north–south along the paleo-Urals. Shale-dominated sequences with glauconite and marl intercalations were deposited in the northern part of this band, forming part of the Bol'shaya Kheta megasyneclise.

To the east, this shallow-marine zone extended over a much wider area, varying in width between 100 and 600–700 km. It occupied the area of the Agapa–Yenisei trench, stretching southwards along the Middle Pur inclined megatrench. A series of small islands were located in the south of the basin, within the present-day Upper Demyanka megaswell and Starosoldatsky swell.

The shallow sea with depths of 100–200 m had an area of about 540,000 km^2.

Shallow-marine environments with water depths of 25–100 m persisted over much of the Callovian basin. This part of the basin covered an area of about 820,000 km^2.

This vast shallow marine environment was dominated by the deposition of the Lower Vasyugan Subformation, consisting of black marine mudstones with occasional siltstone intercalations and marine faunas. The laterally persistent J_2^0 bed that occurs at the base of the Lower Vasyugan Subformation rests on an eroded surface of the underlying mudstones and comprises poorly sorted argillaceous sandstones and brownish- to greenish-gray siltstones, sometimes glauconitic, strongly bioturbated, calcitized, sideritized, pyritized, containing carbonate oolites, belemnite rostra, marine bivalve shells, and abundant foraminifera.

A Late Callovian marine regression in the southeastern part of the basin is manifested by shallower sand facies of the J_1^4 bed.

Within the Ust'-Portovsk megasalient and South Krasnoselkup mesosalient, the mudstones of the Lower Vasyugan Subformation pass laterally southeastwards into the Tochin Formation, consisting predominantly of mudstones with sandstone and siltstone intercalations, and grade northwards and northeastwards into its lateral equivalent, the lowermost section of the Golchikha Formation composed of very fine, sometimes carbonaceous, deeper marine mudstones. These sediments yielded abundant faunal remains, including ammonites, bivalves, and foraminifera.

In the west, shallower marine conditions with a water depth of 25–100 m were established in a 50–80 km wide zone along the eastern flanks of the Trans-Ural and Tyumen megamonoclises.

A shallow-marine area with water depths of up to 25 m formed in a continuous fringe, some 50–80 km wide, around the deeper sea with a depth of up to 100 m. It extended as a relatively narrow zone along the eastern flank of the Koltogory–Nyurolka trench and western flank of the Tyumen megamonoclise and then broadening towards the northeast within the Yenisei megamonoclise. Facies variations across

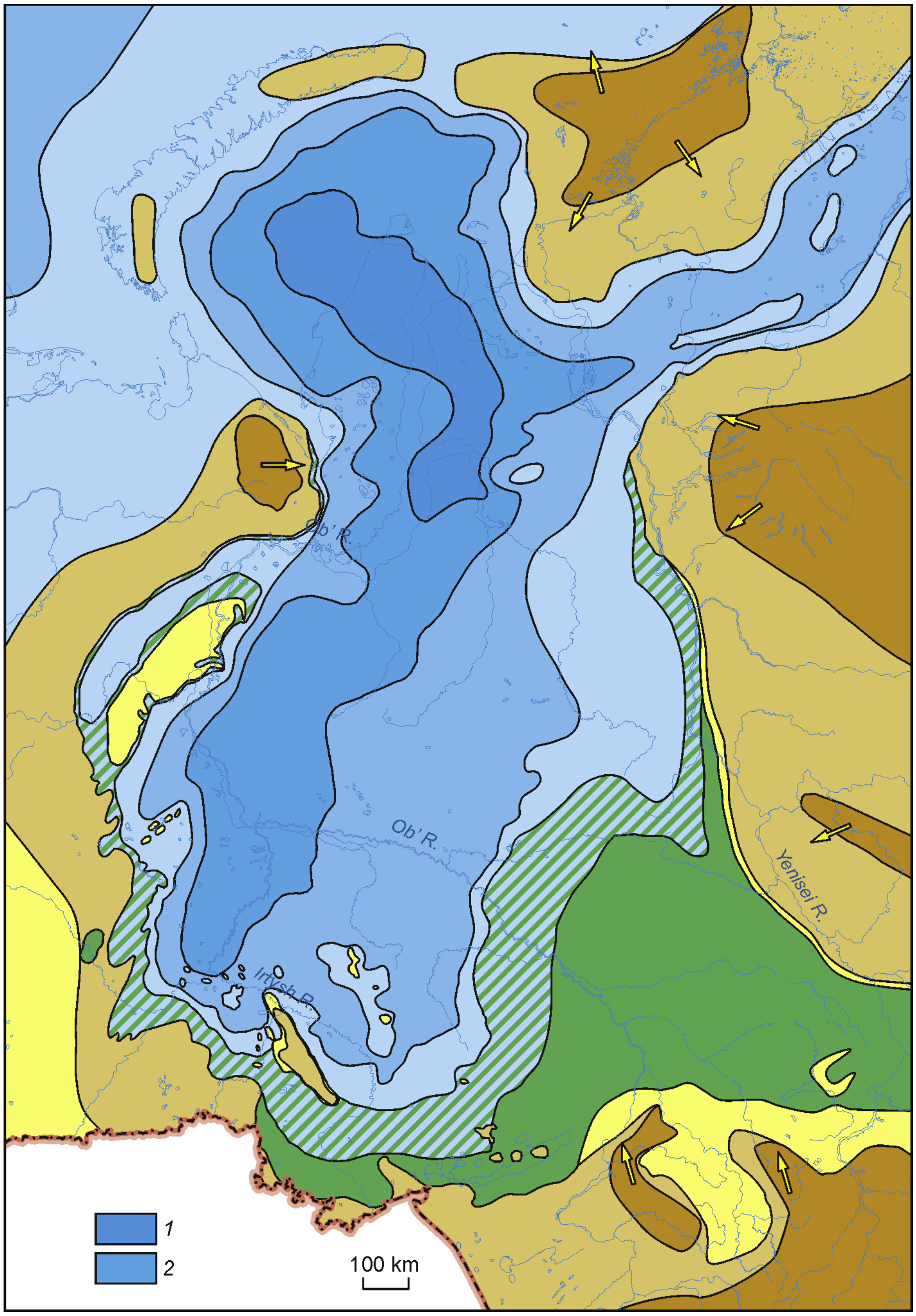

Fig. 12. Paleogeography of West Siberia in the Callovian. *1*, *2*, Paleogeographic areas: areas of marine deposition: *1*, deep sea, 200–400 m in depth; *2*, shallow sea, 100–200 m in depth. The remaining symbols are the same as in Figs. 1, 4.

this area were quite substantial, indicating the frequent alternation of marginal-marine and continental depositional environments. These are represented by marginal marine shales and silts of the Tochin Formation, which becomes sandier and attains a great thickness at the eastern basin margin.

The replacement of the silty-argillaceous Lower Vasyugan Subformation by argillaceous-silty-sandy Naunak Formation occurred to the southeast, in coastal environments of the Callovian marine basin. The Naunak Formation contains J_1^5 and J_1^6 beds.

Numerous islands emerged in the western part of the Early Callovian sea, such as the Shaimsk megasalient that once formed an archipelago with a deeply dissected topography. This was the area of erosion, which supplied terrigenous sediments to a shallow zone around the islands and accumulated coarse glauconitic clastic sediments with silt and clay intercalations (Volgulka member) and fine glauconitic mudstones of the Danilovo Formation.

The transgressive basal J_2^0 bed is widespread over the area. Sandstones and siltstones with glauconite and oolites contain abundant bivalves and foraminifera. Coalified plat debris and

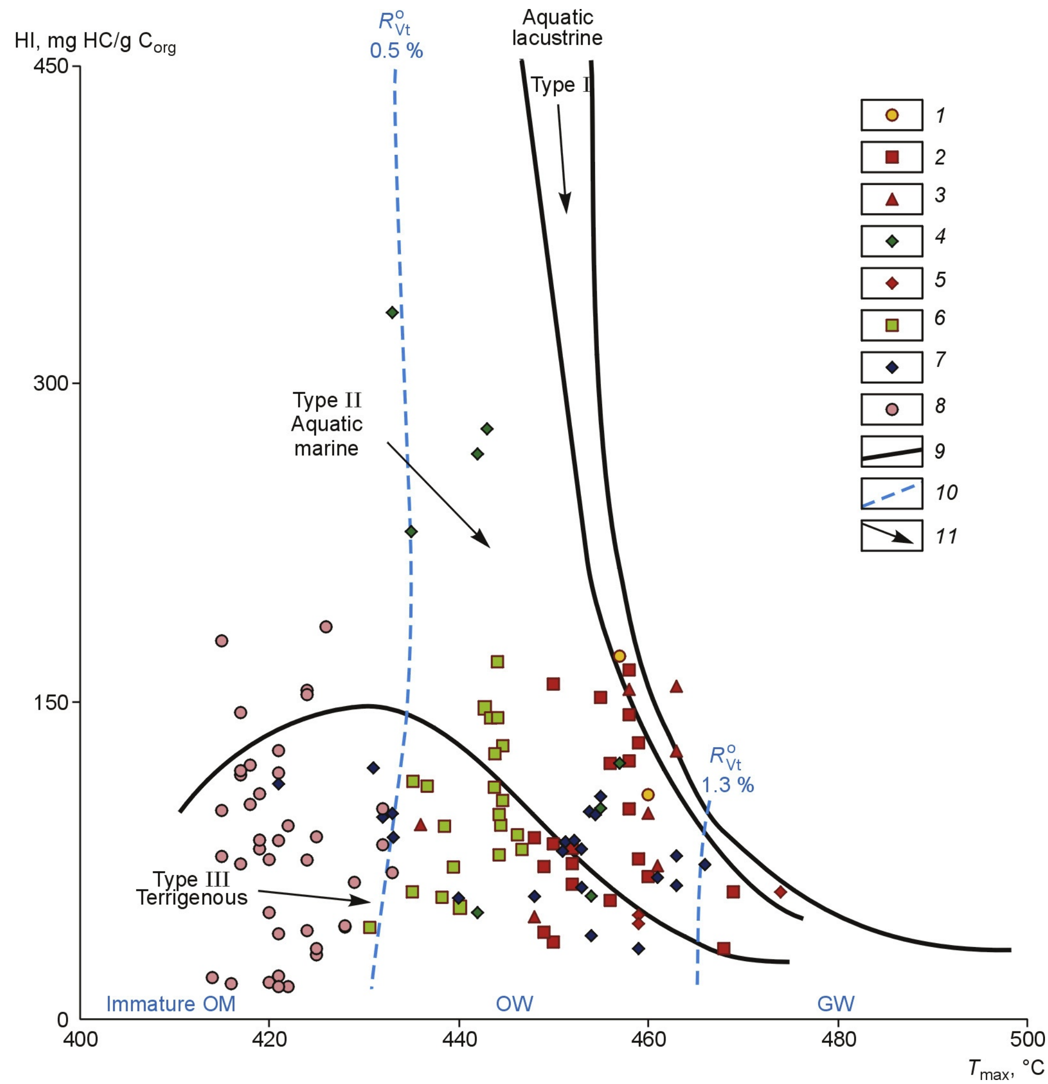

Fig. 13. Hydrogen index (HI) vs. T_{max} (temperature of maximum rate of hydrocarbon generation) diagram for Vasyugan and Georgiev horizons of West Siberia. *1–8*, Formations: *1*, Abalak; *2*, Vasyugan, Upper Subformation; *3*, Vasyugan, Lower Subformation; *4*, Georgiev; *5*, Nurmin; *6*, Sigov; *7*, Tochin; *8*, Abalak (*1–7*, samples from the north of West Siberia; *8*, samples from the west); *9*, lines showing the maximum limits of HI for three types of organic matter: I, aquatic OM of lacustrine origin; II, aquatic OM of marine origin; III, terrigenous OM derived from higher land plants; *10*, isolines of vitrinite reflectance (R^0_{Vt}); *11*, trends of HI and T_{max}values during maturation. OW, Oil window; GW, gas window.

fossil wood fragments may be locally present in individual layers. Fragments of scaphopods and brachiopods (*Lingula*) at different stratigraphic levels suggest that the basal J_2^0 may have been deposited in either marine or lagoonal subcontinental environment (Shurygin et al., 2000).

A large paleohigh, which separated a shallow embayment incised deeply into the Ural land, existed within the Trans-Ural megamonoclise. Isolation of the embayment by large continental landmasses was contributed greatly to the freshening of the surface waters in a littoral area. A shale-dominated sequence with abundant plant debris was deposited in this environment, while a coarser facies of conglomerates, sandstones with glauconite and shell debris fringed the coast, indicating the proximity of their source and a near-shore high-energy regime.

The shallow sea with depths up to 25 m occupied an area of 570,000 km^2.

In the Callovian marine sequences, organic carbon concentrations average 1.83%. Most sediment samples contain less than 1% organic carbon and 30% of samples contain 1–3% organic carbon. The maximum is 7% and some samples contain up to 3% C$_{org}$.

The pyrolysis data, combined with kerogen elemental composition analysis, isotope ratios of the kerogen and biomarker data from syngenetic hydrocarbons suggest that the organic matter from Callovian sediments is dominated by land plant debris (terrigenous OM), which was transported from land together with terrigenous sandy-argillaceous material (Figs. 13–15). The aquatic organic matter indicating major contributions from phytoplanktonic lipid polymers and bacte-

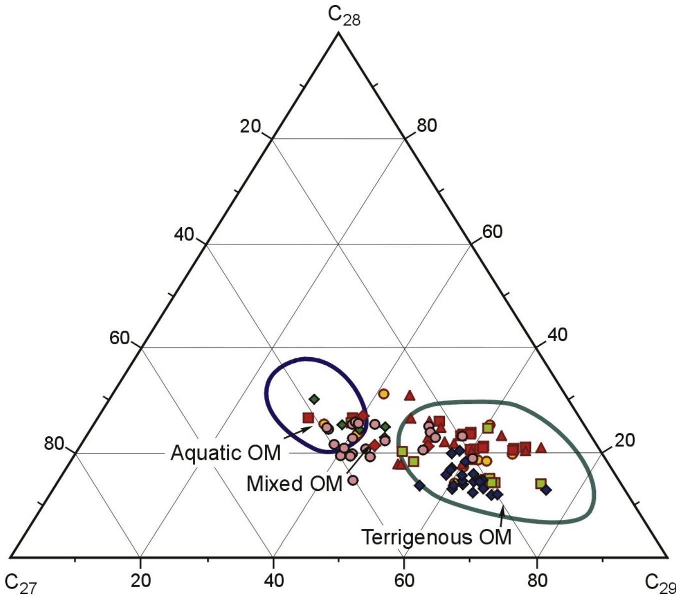

Fig. 14. Triangular diagram showing the distribution of C_{27}, C_{28}, C_{29} steranes in Middle–Upper Jurassic bitumens from the Vasyugan and Georgiev horizons of West Siberia. For legend see Fig. 13.

rial lipidsis largely associated with the Abalak Formation, which was deposited in the central part of the Callovian marine basin (Figs. 14, 15).

The Callovian organic matter has low hydrocarbon generative potential.

During the Callovian, *a coastal plain periodically inundated by the sea* covered a vast area of 310,000 km^2. Much of this plain occupied relatively high relief areas at the southern and southeastern basin margins, which encompassed a series of present-day positive and negative structures, such as the Krasnoleninsk megasyneclise, the North Mezhovsk and North Parabel' megamonoclines, and the Krasnoselkup monoclise. The plain was dominated by repeated changes in sedimentation regime as a result of alternating continental and marine conditions.

The sediments mainly comprise richly fossiliferous marine shales deposited in the southeast of this area, which grade into marginal-marine and continental (fluvio-lacustrine) facies (Naunak Formation).

The variegated shales and sandstones of the Tatarka Formation were deposited in the extreme south of the plain in a very shallow basin of freshwater-brackish salinity, which received a substantial amount of ferric hydroxides from the nearby continent (Korzh, 1978; Ryzhkova, 2012). The coastal plain, periodically inundated by the sea, extended as a very narrow strip along the western margin of the platform, which was marked by sedimentation of dark brown to gray, argillaceous and, rarely, silty and glauconitic muds (lowermost Danilovo and Maurynya Formations).

To the south and southeast, the coastal plain was bordered by *a lowland depositional plain*, which covered an area of about 450,000 km^2 formed by the deposition of the Tyazhin Formation, continental equivalent to the Naunak and Tatarka Formations.

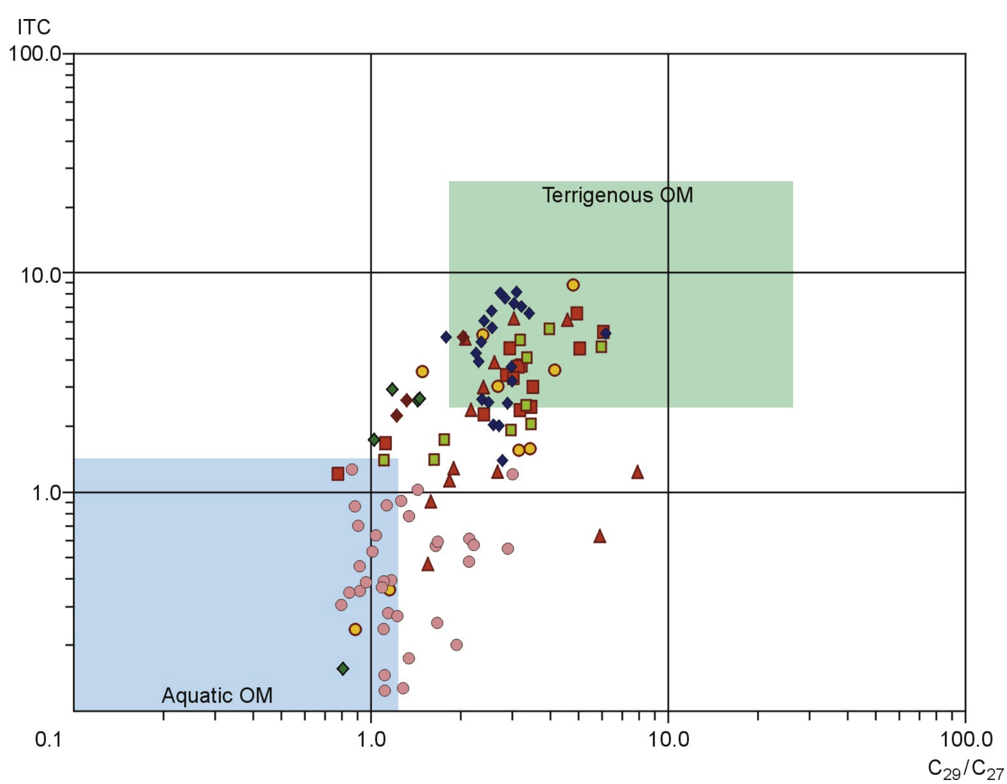

Fig. 15. Classification of genetic types of organic matter from the Vasyugan and Georgiev horizons of West Siberia using an ITC (tricyclane index) vs. C_{29}/C_{27} sterane plot. For legend see Fig. 13.

An erosional-deposition plain was separated into broad areas in the southwest and southeast of the basin and occupied an area of about 390,000 km^2.

To the west, east, and south, the West Siberian basin was fringed by *an erosional elevated plain* and had a marine connection to Boreal seas in the north.

Oxfordian

The Oxfordian was marked by the progressive expansion of the marine depositional area, despite a general shallowing of the basin. The climate was mainly semiarid in southern and central West Siberia and humid in the north of the region (Yasamanov, 1976). The annual paleotemperatures calculated from belemnite rostra decreased slightly to +11 to +13 °C in northern West Siberia (Berlin et al., 1970).

A marine transgression at the Callovian–Oxfordian boundary was followed by regression, which reached its maximum extent by the late Early Oxfordian time and exerted the strongest influence on the eastern part of the basin. In the southeast, this resulted in deposition of J_1^{3-4} sand beds and intercoal member, which form part of the Upper Vasyugan Subformation. The subsequent late Early–early Middle Oxfordian transgression deposited the sand-dominated succession (J_1^{1-2} beds) within the supracoal member.

The following depositional environments were identified to replace each other in chronological order from the deepest part of the basin to its margins (Fig. 16, Table 1):

– shallow sea, up to 25–100 m in depth;
– shallow sea, up to 25 m in depth;
– coastal plain extending to the southeast (dominated by a shallow-marine conditions during brief marine incursions);
– low-laying depositional plain;
– erosional-depositional plain;
– erosional land.

They are discussed in more detail below.

A shallow-marine (25–100 m in depth) zone occupied an area of about 1,070,000 km^2 and encompassed the present-day Kara, Antipayuta–Tadebeyakha, and Bol'shaya Kheta megasyneclises in the north of the basin. It stretched to the west into the Pay-Khoy–Novaya Zemlya megamonoclise and also eastwards into the Agapa–Yenisei trench. The sediments of the Golchikha Formation were deposited in the northeast of the basin. They comprise dark gray, very fine clays, silty in places, with carbonaceous intercalations that contain a rich fauna of ammonites, belemnites, bivalves, gastropods, brachiopods, and foraminifers.

In the northwest, the Novaya Zemlya islands appear to have been periodically invaded by the sea, as indicated by the presence early and late Oxfordian marine faunas in rock boulders (Dibner, 1962; Meledina, 1973).

To the south and southwest of the Bol'shaya Kheta megasyneclise, shallow marine environments were restricted to the areas of the present-day Krasnoleninsk megamonoclise and parts of the Nadym hemisyneclise, Mansi syneclise, Trans-Ural, Tyumen, and South Nadym megamonoclises, where the sediments of the Abalak Formation were deposited. The formation is a succession of dark gray to brownish very fine shales, silty and glauconitic in places, with sporadic pyrite nodules, which in the upper part becomes more carbonaceous and contains a diverse and rich marine fauna, including *Chondrites* and *Phycosiphon*, and other traces of the *Zoophycos–Cruziana* ichnofacies (Yan and Vakulenko, 2011).

A shallow marine zone (up to 25 m) coveredand area of 1,040,000 km^2 in the central and eastern parts of the sedimentary basin and also extended as a very narrow strip along the western basin margin.

The central part of the geosyneclise with a number of large structural highs (Surgut and Nizhnevartovsk arches, Ob'–Vasyugan ridge, Upper Vasyugan anteclise, etc.) separated by structural lows was characterized by a wide range of the near-shore sedimentary environments (deltas, delta-front, mouth bars, near-shore swamps, etc.), as indicated by argillaceous-silty-sand deposits of the Upper Vasyugan Subformation. The J_1^{3-4} and J_1^{1-2} sand recognized in the subformation are mostly gray inequigranular sandstones separated by shale breaks. These laterally variable sand and shale units show a great structural complexity.

The sands, silts, and shales of the Sigov Formation, containing a rich marine fauna of ammonites, belemnites, etc., were deposited in the northeast of this shallow-marine zone, which encompassed the Taz structural megabay, Krasnoselkup monoclise, and Yenisei megamonoclise. The sediments are poorly sorted and contain gravel, pebbles, sideritic and phosphoritic concretions, and coalified plant mesofossils.

Numerous remnant erosional islands remained in the western, shallower parts of the region, within the Trans-Ural and Tyumen megamonoclises, and Shaimsk megasalient. These paleohighs were subject to periodic uplift, causing reactivation of coastal processes, e.g., abrasion, and erosion over these paleohighs. The westernmost shallow-marine zone within the Trans-Ural megamonoclise was a broad embayment across which various depositional coastal landforms developed, including banks, barrier beaches, barrier spits, and bars. The embayment had a connection to an open marine area through a system of channels separated by islands. This was reflected in the lithology of the Volgulka suite as part of the Abalak and Danilovo Formations made up of alternations of mudstones, siltstones, and sandstones, sometimes glauconitic, containing Upper Oxfordian ammonites. The sand units in this part of the section (pay interval P) may have developed only locally.

Such paleohighs were also present in the southeastern near-shore area, within the present-day Mezhovsk meganose and Upper Demyanka megaswell.

A coastal plain, periodically inundated by the sea covered an area of about 490,000 km^2 in Oxfordian times. In the southeast of the basin, it was a landward extension of the near-shore zone and occupied the eastern flank of the Yenisei megamonoclise and the entire area between the present-day Koltogory–Nyurolka trench, Teguldet megahemisyneclise, and Barabinsk–Pikhtovaya megamonoclise. Variations in the sedimentary environments during the deposition of the Naunak

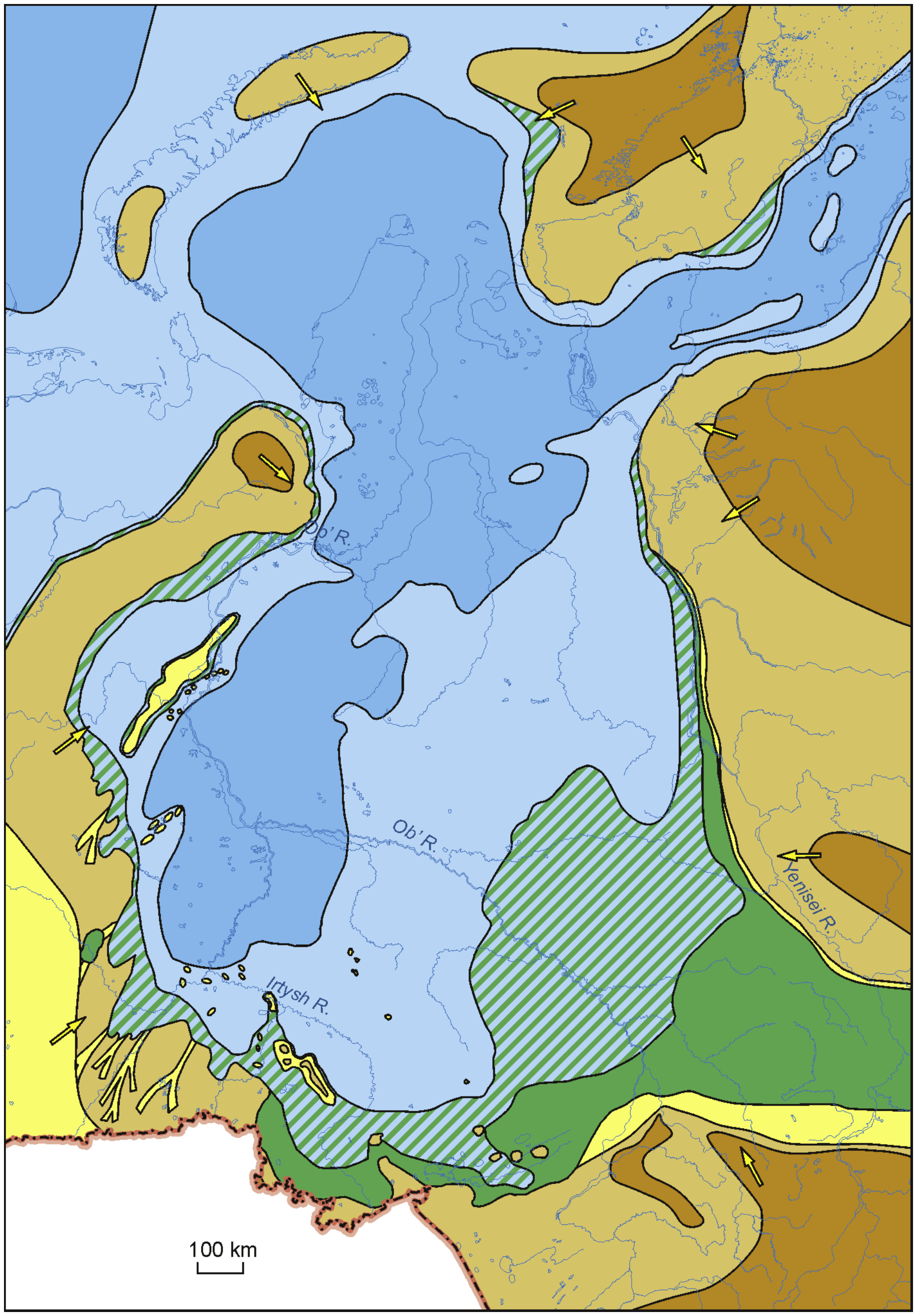

Fig. 16. Paleogeography of West Siberia in the Oxfordian. For legend see Figs. 1, 4.

Formation reflect distance from shoreline. The shoreline probably had significant topographic irregularities due to complex systems of river and delta channels.

The transitional coastal to alluvial plain facies comprise gray sandstones, siltstones, and mudstones with abundant plant fragments and coalified plant debris, pyrite inclusions and thin coal beds. Despite the overall heterogeneity, the lithology becomes siltier and sandier away from the shoreline.

Increased number of shale breaks with abundant belemnites, bivalves, ammonites, and foraminifera suggests that there were brief marine incursions over the alluvial plain. The sandy-silt bed that is laterally well traceable (equivalent to J_1^1) contains abundant marine faunas and exhibits extensive carbonatization. It is confined to the near top part of the Vasyugan horizon and represents the maximum of the transgression during the Late Oxfordian. It extends for a considerable distance to the south and east of the West Siberian basin, where it has been encountered in Vostok-1 and Vostok-3 wells in the southeast and at the Verkhtarskaya, Vostochnaya, and Dedovskaya prospects in the south (Khabarov et al., 2009; Vakulenko et al., 2010).

In the southern part of this area deposition continued within the framework established earlier in the Callovian and variegated successions of lagoonal shales and sands (Tatarka

Formation) accumulated within the southern flank of the Krasnoleninsk megamonoclise.

Continental sedimentation dominated by sandy-argillaceous-coaly accumulations was confined to *a lowland deposition plain,* which extended as a narrow strip along the eastern and southern margins of the West Siberian geosyneclise but widened to the southeast into a broad plain, covering an area of 220,000 km^2 within the Barabinsk–Pikhtovaya megamonoclise and Teguldet megahemisyneclise. The most widespread continental succession in this area is the Tyazhin Formation composed of bluish-gray mudstones and siltstones with subordinate sandstones becoming thicker northwards.

A series of erosional-depositional plains developed in the southeastern and southwestern parts of the basin. The area of these plains was considerably reduced (to 300,000 km^2) compared with that of the Callovian.

An elevated erosional plain was still within the limits established earlier in the Callovian around the margins of the West Siberian basin, except for the northern marine areas, and remained a major sediment source in Late Oxfordian times.

Kimmeridgian

A major marine transgression that was the most widespread and prolonged event during the Jurassic started in the late Late Oxfordian and resulted in the deposition of a thin but laterally continuous basal bed (J_1^0, Barabinsk Member). It is composed of glauconitic argillaceous-silty-sandy deposits, sometimes bioturbated, with abundant marine faunas.

Although this study does not actually include the reconstructed Kimmeridgian paleogeography, it should be noted that transgression caused drastic changes in paleogeography of the region, with the considerable expansion of marine conditions and a widespread development of the deeper water marine facies.

The area of marine deposition with depths up to 100–200 m extended into the former Oxfordian shallow marine environments with water depths of up to 25–100 m. Deep basinal environments spread further northwards into the present-day Kara and Antipayuta–Tadebeyakha megasyneclises, Agapa–Yenisei trench, and much of the Bol'shaya Kheta megasyneclise and Nadym hemisyneclise and also southwards into the Uvat–Tobolsk region. The deposition over this vast area was dominated by marine shales of the Abalak Formation with a diverse and abundant marine fauna. The formation passes to the northeast into the deep marine shales of the Golchikha Formation.

A shallow-marine area (25–100 m in depth) characterized by a widespread development of dark gray marine shales of the Georgiev Formation shifted southwards extending from the Middle Pur inclined trench and Koltogory–Nyurolka trench to the Kazakhstan highlands and covering the entire central part of the sedimentary basin.

The shallow marine area was surrounded by a near-shore setting with a water depth of up to 25 m. This area, up to 125 km wide, was characterized by the deposition of marine shales (Lopsin, Danilovo, and Nurmin Formations) in the west, shales (Yanov Stan Formation) and marginal-marine dark gray sandstones and shales (Upper Sigov Subformation) in the northeast. However, it widened up to 300 km in the southeast where silts and shales of the Maryanov Formation were deposited.

The transitional facies preserved only in the terminal southeastern part of the basin are mainly sandstones with siltstone and shale interbeds of the Maksimoyar and Bagan Formations.

Volgian

The Late Jurassic transgression in Siberia reached it maximum extent during Volgian times. The results of recent Tethyan–Boreal correlations indicate that the end of the Volgian corresponds to the Early Cretaceous (Bragin et al., 2013). During the Volgian, the area of marine deposition embraced much of the West Siberian geosyneclise. There were four factors that made the Volgian basin unique. The first factor is that asymmetric basinal subsidence was the dominant process and the most rapid subsidence, like that of the Callovian, continued to be in the west. The second factor is that peneplanation of the drainage areas surrounding the basin occurred by the beginning of Volgian times (Gurova and Kazarinov, 1962; Kazarinov, 1958; Kontorovich et al., 1971; Saks and Ronkina, 1960). Physical erosion was slowed but intense chemical weathering prevailed with a steady increase in the supply of chemical weathering products, a nutrient source for living organisms. This promoted increased primary productivity of the West Siberian basin during the Volgian (Kontorovich et al., 1971, 1974).

The black and brownish-black carbonaceous, argillaceous, and siliceous sediments of the Bazhenovo and Tutleyma Formations were deposited in the central, deeper basinal areas. Towards the basin margins, they pass into argillaceous and sandy-argillaceous successions of the Golchikha, Danilovo, Maryanov, and Yanov Stan Formations (equivalents to the Bazhenovo Formation).

The third control on Volgian depositional processes is considered to be due to the onset of biogenic sedimentation in the central deeper basinal areas. The sediments accumulated large amounts of biogenic material enriched in carbon, hydrogen, silica, and calcium, which was derived from phyto- and zooplankton. The concentrations of dissolved calcium and dissolved silica in seawater were highly variable in time and caused a significant variation in the organic productivity of phyto- and zooplankton and hence in the composition of sediments. The epicontinental character of the West Siberian sea and a limited connection to the world ocean suggest that the availability of dissolved calcium and dissolved silica in seawater was largely controlled by the influx of these elements from land.

The main mineral components of Bazhenovo rocks are authigenic silica, detrital clays, calcite, and pyrite. Radiolarians were the major sources of biogenic opal. The content of detrital quartz in the Bazhenovo rocks can rarely exceed 5%. Much of the carbonate material, although recrystallized and redeposited during diagenesis and catagenesis, is of biogenic origin (coccolithophorids, foraminifera, etc.). The pyrite which is very abundant in the Bazhenovo Formation (up to 15%) was formed through bacterial sulfate reduction during diagenesis. The concentration of organic carbon ranges from 3–5 to 10–15% in Volgian strata and may reach as high as 22%. Organic carbon increases from 3–4 to 22% in silicites and radiolarites and averages about 7% and, rarely up to 10%. The clay material that was supplied to the basin as suspended solids or colloids represents a single abiogenic component of the Bazhenovo rocks.

The more specific depositional environments, plus the biogenic nature of the sediments, played a critical role in the development of the most reducing conditions during early diagenesis. This indicates continued euxinic or, at least, oxygen-deficient bottom-water conditions in the central part of the basin (Bulynnikova et al., 1978). This appears to be the fourth important factor that controlled the Late Jurassic deposition in West Siberia.

Several specific depositional phases were distinguished for the central part of the Bazhenovo paleobasin.

The first phase is characterized by decreased fluxes of detrital clays (5–10%) and increased radiolarian productivity, which promoted accumulation of siliceous radiolarian oozes (about 80% authigenic silica).

The second phase is recognized by an increased input of detrital clays to the basin and enhanced productivity of phytoplankton containing high concentrations of carbon and hydrogen. This led to variations in the ratio of skeletal opal accumulation (50–60%) and the supply of detrital clays (up to 20%). The concentration of C- and H-rich organic matter in these sediments is 10–20% but the initial organic carbon content was higher by 25–40% (catagenetic loss). Individual thin intervals in the sediments were almost entirely composed of C and H-richorganic matter and upon lithification they became the fissile or laminated strata (Bulynnikova et al., 1978). In the central, deep sea part of the basin, Volgian sediments were deposited as an 18–20 m thick sequence in which the present-day concentration of organic matter is over 20% (bazhenovites, according to Vassoyevich).

The third phase is marked by widespread blooms of radiolarians and coccolithophorids, which result in the co-precipitation of authigenic silicain the amount of 20–30% (radiolarian skeletons) and calcite (20–30%). Concentrations of C and H-rich organic matter in these sediments are similar to those of the previous phase (10–20%). This phase is also marked by an increase flux of clay material to the sediments which appears in amounts up to 25–40%.

The central, deeper part of the Bazhenovo basin of West Siberia and areas along the paleo-Urals (Bazhenovo, Tutleyma, Danilovo Formations) are known to be dominated by aquatic organic matter, as indicated by kerogen analyses (elemental composition, carbon isotope data, petrographic examination), pyrolysis and biomarker data (Figs. 17–19). In the southeastern part of the basin (Maryanov Formation), the kerogens are of mixed origin. However, most of the terrigenous organic matter supplied to the basin was highly oxidized and relatively lipid-poor and may have played a minor role in the generation of bitumens. Consequently, the composition of biomarker hydrocarbons suggests their phytoplanktonic and bacterial sources. In the northeastern part of the basin, the sediments of the Yanov Stan and Golchikha Formations exhibit marked differences in sources of organic matter. They contain a terrigenous (predominant) and mixed type organic matter, as suggested by a kerogen composition, pyrolysis and biomarker data (Figs. 17–19). At the same time, the rocks of the Yanov Stan Formation contain the larger proportions of aquatic organic matter.

The final, fourth phase of the Bazhenovo rock evolution is marked by an abrupt increase in the influx of clay material to sediments and the widespread clay deposition. Changes in paleoenvironmental conditions that were less favorable for primary production led to a considerable decrease in the biogenic component in sediments.

The generally accepted interpretation is that mostly semiarid conditions and a major marine transgression in the southern part of the basin resulted in enhanced chemical weathering on land, leading to increased accumulation of clay- and organic-rich sediments over a broad flat shelf.

The absolute water depth of the Volgian sea is still a matter of debate, and proposed depths of the Bazhenovo basin range from 400–500 m (Kontorovich, 1976; Saks, 1972) or even 700 m (Bochkarev and Fedorov, 1985; Lopatin and Emets, 1999) to 250 m (Mazur, 1980; Rovnina et al., 1978; Ushatinskii, 1981; Ushatinskii and Zaripov, 1978; Zaripov et al., 1976) and 200–500 m (Braduchan et al., 1986; Bulynnikova et al., 1978; Filina et al., 1984; Gurari, 1981; Pluman, 1971; Yasovich and Poplavskaya, 1975; Zakharov and Saks, 1983; Zanin et al., 1999).

The following depositional environments were identified for the Volgian (Fig. 20, Table 1):

– deep sea with water depths over 400 m and, probably, up to 600–800 m;
– deep sea, up to 200–400 m in depth;
– shallow sea, up to 100–200 m in depth;
– shallow sea, up to 25–100 m in depth;
– shallow sea, up to 25 m in depth;
– coastal plain occasionally inundated by the sea;
– lowland depositional plain;
– erosional-depositional plain;
– erosional land.

A deep-sea zone with water depths of 200–400 m was established over the northern and central part of the geosyneclise with a shift towards the paleo-Urals, a situation which is likely to be common to the Callovian, Oxfordian and Kimmeridgian seas. To the north, this zone occupied the areas of the present-day Kara, Antipayuta–Tadebeyakha megasyneclises and western flank of the Bol'shaya Kheta megasyneclise and to the south it extended into the Nadym hemisyneclise, Mansi syneclise, the adjacent Krasnoleninsk and South Nadym megamonoclises and part of the Khantey hemianteclise. The northeastern part of the basin was dominated by dark gray, tabulated, with carbon-rich laminae in places, argillaceous sediments of the Golchikha Formation. Black to brownish-

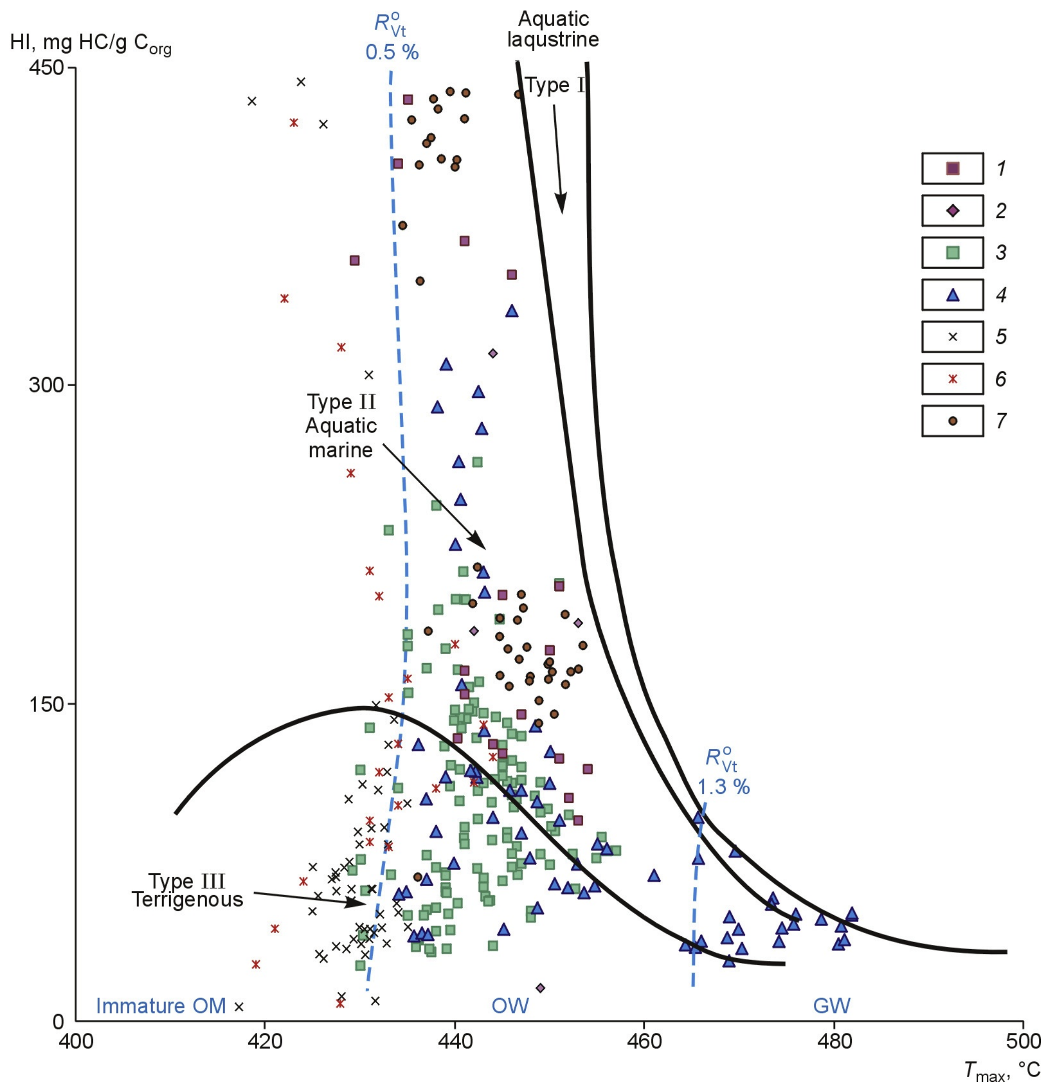

Fig. 17. Hydrogen index (HI) vs. T_{max} (temperature of maximum rate of hydrocarbon generation) diagram for Upper Jurassic deposits of West Siberia. *1*, *2*, rocks: *1*, bazhenovites; *2*, mudstones of the Bazhenovo Formation; *3–7*, formations: *3*, Yanov Stan; *4*, Golchikha; *5*, Maryanov; *6*, Danilovo; *7*, Bazhenovo (*1–4*, samples from the north of West Siberia; *7*, samples from the Middle Ob' region). The remaining symbols are the same as in Fig. 13.

black, tabulated, with carbon-rich laminae in places, siliceous-argillaceous-carbonate sediments of the Bazhenovo Formation were restricted to deeper parts of the basin. Concentrations of organic matter in C_{org}-rich lithologies of the Bazhenovo Formation range from 8 to 15%.

A deeper-sea zone (over 400 m in depth) formed two depressions in the northern part of the basin, which covered the areas of the Kara and Bol'shaya Kheta megasyneclises. The deeper sea zone had an area of over 50,000 km^2.

The deep-sea facies of the Bazhenovo Formation are characterized by the following physical parameters: high organic matter and silica contents, anomalous apparent resistivity responses, high gamma ray/neutron logging values due to high uranium content, and low sonic logging values. These values decrease away from the Bazhenovo zone.

The Bazhenovo Formation constitutes the major hydrocarbon source rock in the basin and a regional cap rock for hydrocarbon accumulations (Kontorovich et al., 1975). A number of oil accumulations were discovered in Bazhenovo fractured and laminated mudstones, which contain sandier intervals in places with dominating turbidity currents. These so-called 'Bazhenovo anomalous sections' display a limited lateral extent and are confined to a series of elongate interstructural topographic lows in the Khantey hemianteclise. Such sections comprise intercalations of organic carbon-rich siliceous shales, sands and silts with mudstone nodules. They also show increasing thickness and are characterized by numerous slickenslides and sediment flow structures. The exact genesis of these sections is still controversial (Gurari, 1981; Yasovich, 1981; Yasovich and Myasnikova, 1979).

The brownish-black mudstones of the Bazhenovo Formation may often contain siliceous and calcareous shales grading into marls.

The Volgian sea had abundant and diverse planktonic faunas, including coccolithophorids, peridineans, dinoflagellates, radiolarians, as well as numerous cephalopod mollusks, such as ammonites, teuthides lacking a calcified skeleton, and rare belemnites. The macrobenthos was represented by *Buchia*

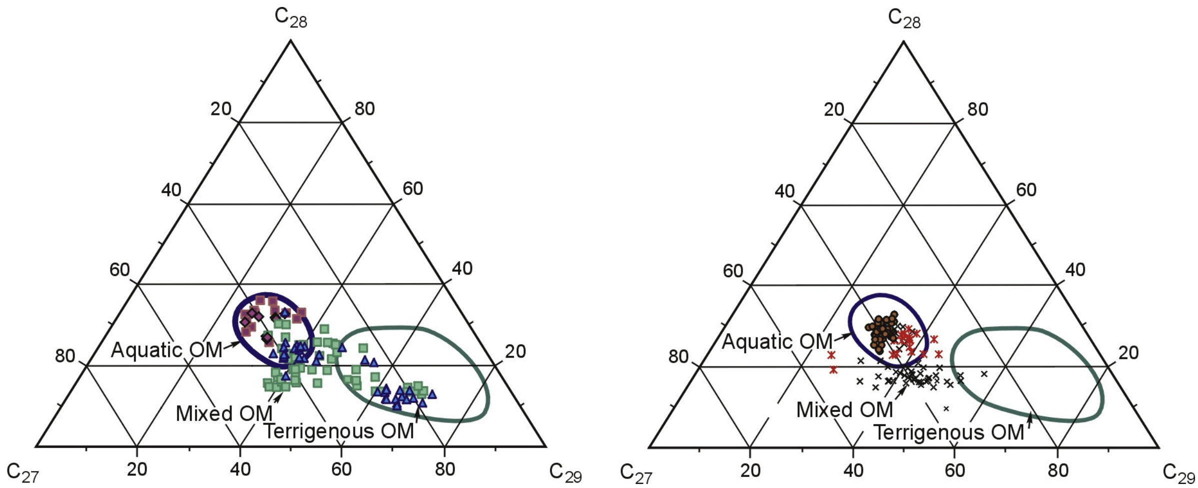

Fig. 18. Triangular diagram showing the distribution of C_{27}, C_{28}, C_{29} steranes in Upper Jurassic bitumens from West Siberia. For legend see Fig. 17.

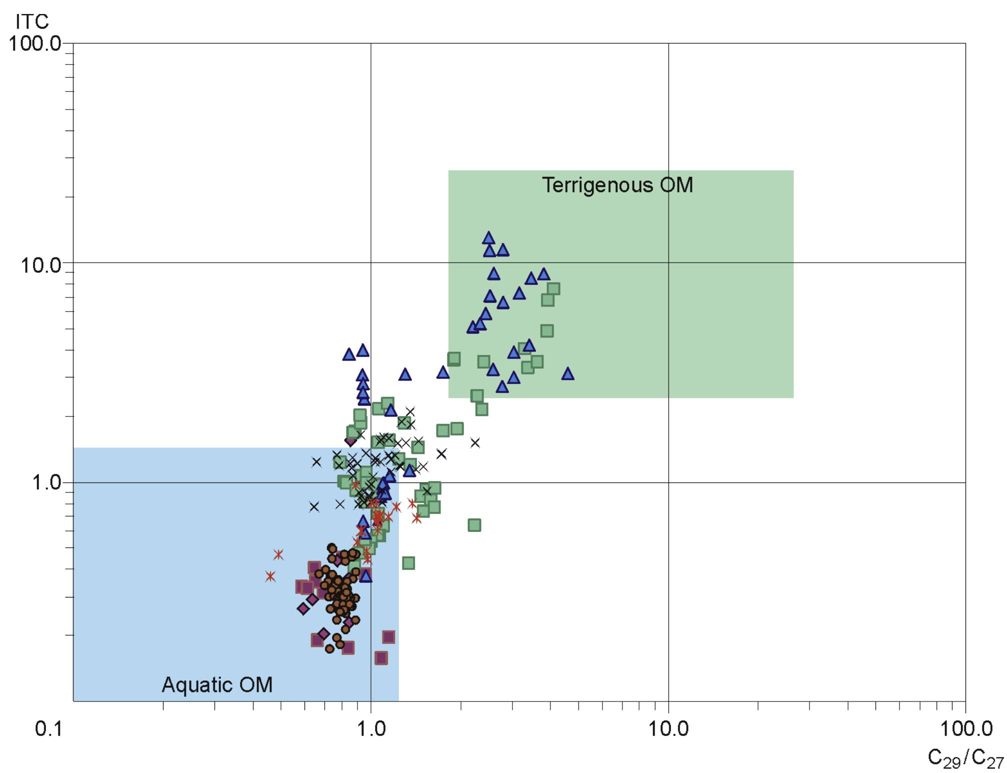

Fig. 19. Classification of genetic types of organic matter from Upper Jurassic deposits of West Siberia using an ITC (tricyclane index) vs. C_{29}/C_{27} sterane plot. For legend see Fig. 17.

and *Inoceramus* (Braduchan et al., 1986; Marinov et al., 2006). The faunal composition, high pyrite and sulfur content and the organic matter composition indicate the presence of hydrogen sulfide in the bottom water.

The deep-sea zone of the basin had an area of 630,000 km^2.

A shallow-marine zone with water depths of 100–200 m developed continuously around the deeper zone and covered an area of about 780,000 km^2. This zone was represented by widespread deposition of black to brownish very fine, organic carbon-rich sediments of the Bazhenovo Formation. These sediments are recognizable by increasing thickness, lower organic matter content (5–3%), low resistivity, gamma ray and neutron log values. The resistivity and gamma ray log values decrease towards the shoreline, where the Bazhenovo Formation gradually passes into the Maryanov and Yanov Stan Formations to the east and into Tutleyma and Danilovo Formations to the west. This part of the basin is characterized by the more diverse marine faunas, including ammonites, belemnites and fishes, as well as microplankton (radiolarians

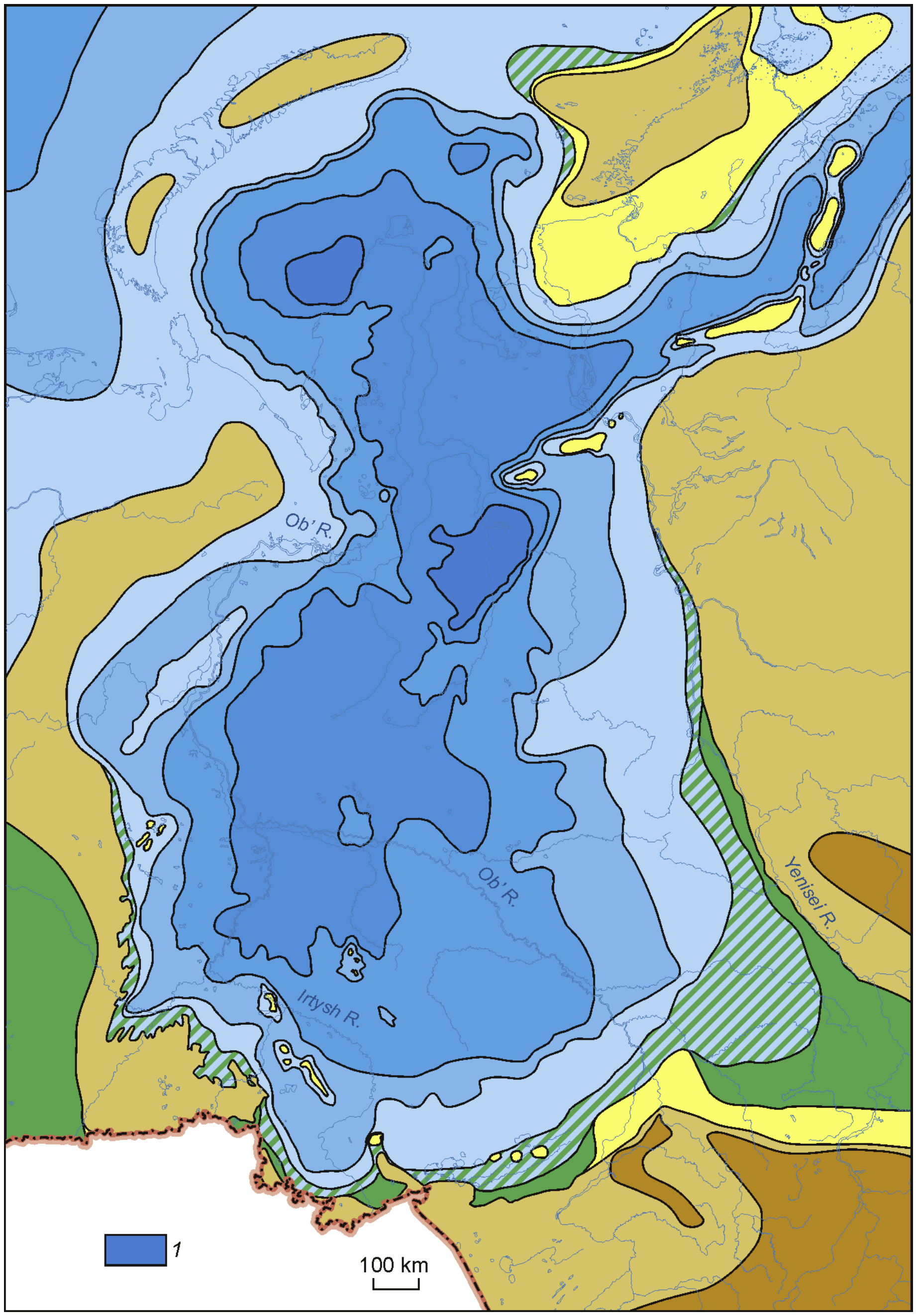

Fig. 20. Paleogeography of West Siberia in the Volgian. Paleogeographic areas: areas of marine deposition: *1*, deep sea with depths exceeding 400 m. The remaining symbols are the same as in Figs. 1, 4, 12.

and coccolithophorids) and benthos (bivalves, brachiopods, gastropods, and foraminifera).

The above zone was surrounded by *a shallow-marine zone with water depths of 25–100 m*. The deposition was dominated to the northeast by fine silty, locally carbon-rich clays (Yanov Stan Formation) grading eastwards into sandier facies. The Yanov Stan Formation contains marine bivalves, foraminifera, gastropods, and algae.

The Maryanov Formation developed in the southeast and south. It comprises compacted shales and a variable proportion of thinly interbedded sandstone and siltstone, which increases towards the east and south. The Maryanov shales contain up to 1–3% organic carbon and have low gamma ray and resistivity log values. The presence of a marine fauna suggests that these lithologies are of marine origin.

The sediments of the Tutleyma Formation, less rich in organic carbon, were deposited in conditions similar to those of the Maryanov Formation, and embraced the area along the western basin margin. These lithologies contain sporadic shell layers, grading into glauconitic shales over local highs. The presence of abundant bivalve and brachiopod shells indicates a shallow-marine, near-shore environment. The deposition over the Shaimsk megasalient was dominated by shales, locally organic carbon-rich, with conglomeratic layers, while calcareous shales with silt intercalations were the dominant lithologies within the Tyumen megamonoclise. The more northerly parts, such as the northern flank of the Trans-Ural megamonoclise, were dominated by the deposition of silts and shales with intercalations of glauconitic and quartz sandstones. These variations in lithology are indicative of the complex facies environments that were established in this part of the basin, which had an area of 750,000 km^2.

A shallow-marine zone with a water depth of up to 25 m developed as a strip along the shoreline. It varied in width from 10–100 m in the west and south to 100–300 m in the east. This zone marks a transition from marine to continental deposition and comprises a verity of sandstone and shale facies of the equivalent Fedorov, Danilovo, Mulymya, Maryanov, Yanov Stan, and Golchikha Formations. This zone covered an area of 1,080,000 km^2.

A coastal plain occasionally inundated by the sea occupied a narrow strip adjacent to the near-shore area in the west and south, extending over a vast area within the Teguldet megahemisyneclise. This zone was dominated by sandstones interbedded with siltstone and shale of the Maksimoyar and Bagan Formations and had an area of 220,000 km^2.

Conclusions

This review, integrated with more recent constraints on the Jurassic paleogeography of the West Siberian sedimentary basin and adjacent areas, provides new and more detailed information on the problem.

The Jurassic history of the West Siberian basin is critical to understanding a complex interplay of factors that account for the transformation of the basin during the Late Cretaceous and Cenozoic into a major oil and gas producing area.

Despite the widespread deposition of organic-rich marine shale strata with high generative potential from the Proterozoic through the Mesozoic (Upper Proterozoic strata around the margins of the Siberian craton, Cambrian Kuonamka complex of the Siberian Platform, Domanik sequences of the East European Platform, Eocene Kuma shales of the Northern Caucasus, etc.), only a few analogs to the Bazhenovo Formation have been reported so far. In this study, we propose a partial explanation for this phenomenon.

West Siberia is well known for its unique oil and gas resources. The results show that Jurassic continental and Middle Jurassic shallow-marine strata rich in terrigenous (land plants) organic matter were the major gas source rocks in the region.

Using paleogeographic interpretations, we attempted to explain this enrichment of coaliferous and subcoaliferous facies in the terrigenous organic matter (higher land plants) in West Siberia.

In addition, paleogeography provides critical evidence for predicting the geological distribution of oils with high or low sulfur contents within the West Siberian basin, understanding the patterns of vanadium enrichment in some of these oils, and determining the hydrocarbon composition of West Siberian oils (Kontorovich et al., 1967).

A paleogeographic reconstruction naturally results in a robust subdivision of the West Siberian basin into a series of regional permeable complexes and overlying impermeable seals (Gurari et al., 1968; Karogodin, 1971; Kazarinov, 1963; Kontorovich et al., 1975).

Finally, paleogeographic reconstructions provide the majority of basic geoscience data that can be used for numerical modeling of the processes and history of hydrocarbon generation, migration, and entrapment in the basin.

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