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Facies-Stratigraphic Zonation of the Callovian–Kimmeridgian Deposits of the West Siberian Sedimentary Basin

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Abstract—We propose a facies-stratigraphic zoning of the Vasyugan and Georgievka horizons in the sedimentary cover of the West Siberian Basin, including the southern part of the Kara Sea. Based on the typification of well sections and taking into account the paleogeography of the Callovian–Kimmeridgian deposits, we have recognized 12 regions with different structures of the Vasyugan and Georgievka horizons. The Purpei–Vasyugan area is divided into three subareas according to the structure of the Vasyugan Formation including the petroliferous horizon Yu_1. Transition zones have been recognized between the Vasyugan Formation and the bordering Abalak, Tatar, and Naunak formations along the western, southern, and eastern boundaries of the area, respectively. The results of zoning of the Callovian–Kimmeridgian deposits, including the petroliferous horizon Yu_1, can be used on planning of exploration work, for selecting standard facies models, and for predicting the petrophysical properties of a reservoir.

Keywords: Callovian–Kimmeridgian deposits, petroliferous horizon Yu_1, facies-stratigraphic zonation, West Siberia

INTRODUCTION

Several stratigraphic horizons (e.g., Vasyugan, Georgievka, and Bazhenov) were distinguished (Kontorovich et al., 1975) with regard to the complexity of the stratigraphic schemes of the Jurassic of West Siberia. Clearly, further revisions regarding their stratigraphic volume, lithology, structure of the sections, and petroleum potential may be necessary, as new geological and geophysical data become available.

The problem of zonation of the Callovian and Upper Jurassic, as independent exploration targets in the West Siberian sedimentary cover, subdivided into Vasyugan, Georgievka and Bazhenov stratigraphic horizons, was investigated by different research and industrial institutions, such as Production Geological Association Glavtyumengeologiya, Production Geological Association Novosibirskgeologiya, Production Geological Association Tomskneftegazgeologiya, West Siberian Research Oil Exploration Institute (ZapSibNIGNI), Siberian Research Institute of geology, geophysics, and Mineral Resources (SNIIGGiMS), Institute of Geology and Geophysics (presently Trofimuk Institute of Petroleum Geology and Geophysics), All-Russia Petroleum Research Exploration Institute (VNIGRI), V.I. Shpilman Research and Analytical center for the rational use of the subsoil, Siberian Research Analytical Centre, and many others.

Several versions of facies, lithofacies and structural-facies zoning schemes have been proposed for these exploration targets. The proposed zoning schemes were named considering the main principles of zonation, i.e., paleogeographic, lithological and tectonic.

Recent studies on the Bazhenov Horizon as an independent geological object were conducted at Trofimuk Institute of Petroleum Geology and Geophysics (IPGG) to provide justification and unification of methods for horizon identification and well-to-well correlation in different facies zones of the West Siberian Basin (Ryzhkova et al., 2018). Similar studies were performed for the underlying deposits of the Vasyugan and Georgievka horizons, hosting the majority of Upper Jurassic hydrocarbon accumulations. This required the revision of zoning schemes based on the types of the sections of these horizons in the area of the West Siberian Basin, including the southern part of the Kara Sea. The proposed "facies-stratigraphic zonation" is understood as the identification of coeval formations that were deposited in different facies settings.

In this study, we discuss the results of a detailed analysis of Callovian–Kimmeridgian deposits of the West Siberian

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Basin and their facies-stratigraphic zonation, which are based on the integrated geological, geophysical, and paleontological data that have been accumulated since the early 1950s until the present. Particular attention is paid to the area that hosts oil and gas pools confined to the regional Yu_1 reservoir of the Vasyugan Formation.

MATERIALS AND METHODS

The facies-stratigraphic zonation was based on the analysis of types of Callovian–Kimmeridgian sections using geophysical, lithological, paleontological data from more than 6,500 wells collected by IPGG, and recent understanding of the paleogeography of the West Siberian basin (Kontorovich et al., 2013). The correlation of the Vasyugan and Georgievka horizons was performed using an interregional correlation method accepted by IPGG and based on the results of a comprehensive analysis of seismostratigraphic, geophysical (well logs), lithological and biostratigraphic data. This method is based on detailed correlation of the Vasyugan and Georgievka horizons between wells, in which the type sections of the formations constituting these horizons were identified. The type wells were selected to characterize the areas these two horizons have different structures. A factor taken into consideration when selecting wells was the availability of a complete well-log Formation, including electrical (resistivity, induction, lateral, and spontaneous potential logs), acoustic, radioactive, and caliper logs. Another factor taken into account was the proximity of the well to the stratotype section of formation or the confinement to the tectonic element, where the Vasyugan and (or) Georgievka horizons were characterized by core and macro- and microfaunal data. These studies were also based on a modern structural map for the top of the Jurassic constructed at IPGG. The well-to-well correlation of the Vasyugan and Georgievka horizons was verified using thickness maps generated for each horizon within individual prospects and facies regions.

Major specifics of the adopted methodology was a careful recording of all the data obtained by previous generations of geologists. Due to the greater density of observations and availability of modern paleogeographic reconstructions, the main goal of this study was the revision of formation boundaries rather than the identification of new formations.

FACIES-STRATIGRAPHIC ZONATION OF CALLOVIAN–KIMMERIDGIAN SECTIONS

In West Siberia, the Vasyugan and Georgievka regional stratigraphic horizons are represented by 17 formations or their parts (Fig. 1). The results of these studies were used to distinguish 12 regions, differing by the formations identified

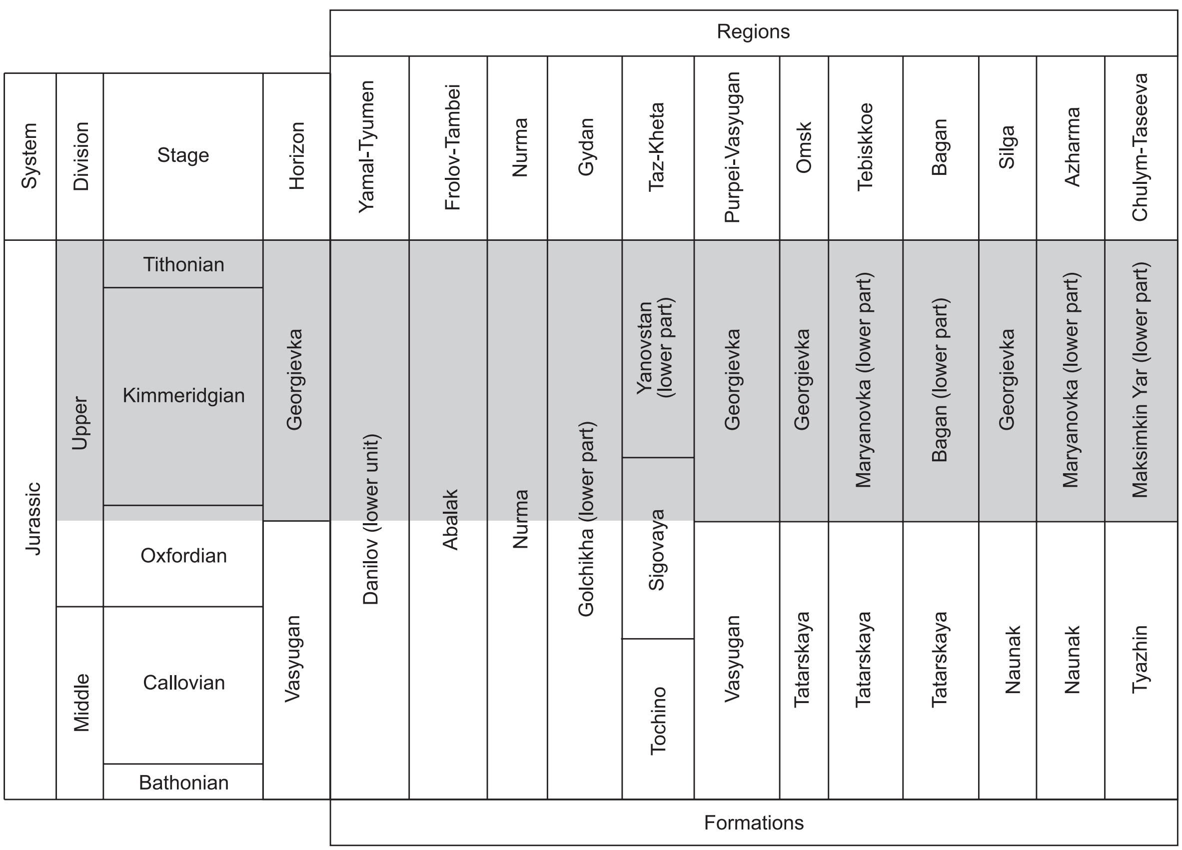

Fig. 1. Formations comprising the Vasyugan and Georgievka horizons within the identified regions of the West Siberian Sedimentary Basin, including the southern Kara Sea.

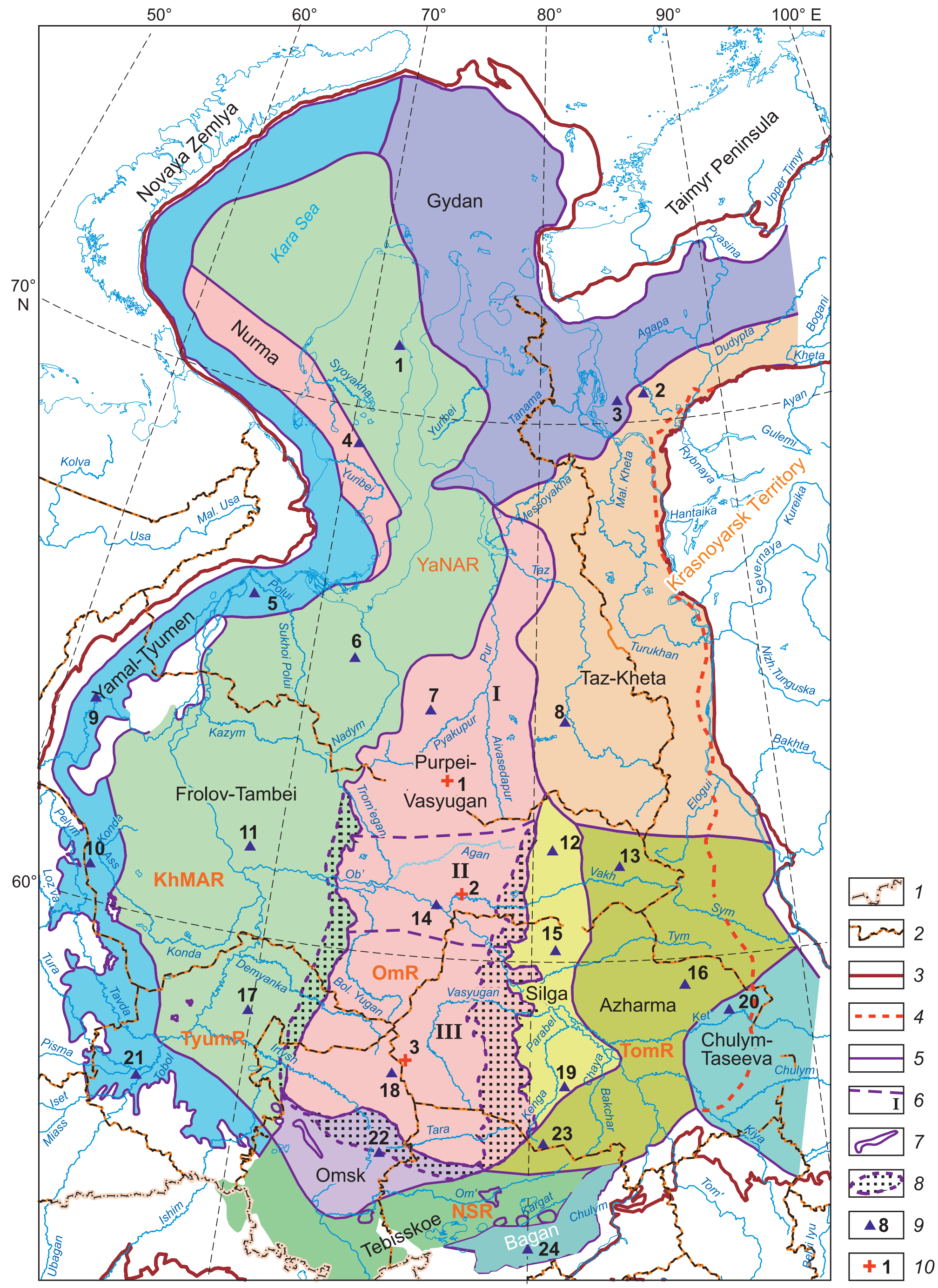

Fig. 2. Map of the facies-stratigraphic zonation of the Vasyugan and Georgievka horizons of the West Siberian sedimentary basin, including the southern part of the Kara Sea. Borders of 1, Russian Federation; 2, administrative (abbreviations on the map: TyumR, south of the Tyumen Region, OmR, Omsk Region, NSR, Novosibirsk Region, TomR, Tomsk Region); 3, Mesozoic sediments; 4, Georgievka Horizon; 5, regions; 6, sub-regions of Purpei-Vasyugan region (I , Verkhnepur, II, Ob-Agan, III, Ob-Tara); 7, zones of partial or complete absence of Callovian–Kimmeridgian sediments; 8, facies substitution zones of the Vasyugan Formation; wells, which are mentioned in the text and their numbers in the map, type sections within: 9, regions, 10, sub-regions of Purpei-Vasyugan region (1, West Novogodnaya 210, 2, West Sorominskaya 16, 3, Krapivinskaya 201).

within each horizon (Figs. 1 and 2). The names of the regions, in compliance with the Stratigraphic Code (The Stratigraphic ..., 2006), reflect their geographic location.

Special attention was paid to the analysis of trends in a sand content of the J_1 reservoir within the zones where the Vasyugan Formation is replaced by the Abalak, Naunak and Tatarka formations in the west, east and south, respectively. A gradual facies change allowed us to identify several “transition zones”, which are characterized by different types of sections. The styles of facies change in different zones have been discussed in previous studies (Ryzhkova, 2001; Vakulenko et al., 2011; Kontorovich et al., 2006; Khabarov et al., 2009; Chernova and Zhilina, 2011).

The characteristics of the identified facies regions are summarized below.

The Yamal-Tyumen region is located along the western margin of the West Siberian sedimentary basin (Fig. 2). It stretches from north to south, along the Novaya Zemlya part of the Kara Sea and further along the Urals to the Tobol-Ishim interfluve.

In this region, the Vasyugan and Georgievka horizons are represented by the Lower Danilov Subformation (Fig. 1). The Danilov Formation was first distinguished as a member based on the results of deep drilling at the Danilovskaya prospect in the southwestern part of the region (Eliseev and Nesterov, 1971). The member was later formally ranked as a formation (Braduchan and Yasovich, 1984). The stratotype of the formation was established in the Danilovskaya 62 well (Atlas ..., 1990). The silty-clayey lower unit of the Danilov Formation, with glauconite and carbonate nodules was deposited under quiet conditions (Braduchan and Yasovich, 1984). The Callovian–Kimmeridgian age of the Lower Danilov Subformation was assigned based on macro- and microfaunal remains recovered from wells drilled at the West Yarrotinskaya, Danilovskaya, Vladimirovskaya, Chelnokovskaya, and other prospects.

For the areal characterization of the region, the type sections of the Lower Danilov Subformation were identified in wells located in the northern (East-Salekhard 1, 652–721 m), central (Lyapinskaya 31, 1410–1541 m), western (South Iusskaya) 8007, 1325–1347 m) and southern (Borkovskaya 5, 1604–1636 m) parts of the region (Fig. 2, well Nos. 5, 9, 10, and 21, respectively).

The Nurma region is distinguished in the northwestern part of the West Siberian Sedimentary Basin (Fig. 2). It extends from NW to SE, along the southwestern part of the Kara Sea and the southern part of the Yamal Peninsula.

This region is dominated by the Nurma Formation (Fig. 1). This formation, named after the Nurma Yakha River, was first recognized by Kulakhmetov et al. (1994). The stratotype of the formation was taken to be the section of the Vasyugan and Georgievka horizons in the South Nurminskaya 8 well drilled in the southern part of the Yamal Peninsula. This formation, predominantly consisting of clays and sandy-silty deposits in its middle part, was deposited in a shallow-marine setting with depths of about 100 m (Kontorovich et al., 2013). The thickness of the formation varies from 10 to 60 m and increases westward. The Callovian–Kimmeridgian age was assigned based on ammonites and microfauna recovered from wells drilled at the Novoportovskaya, Maloyamalskaya and South Nurminskaya prospects.

For the areal characterization of the region, the type section of the Vasyugan and Georgievka horizons was taken to be in the West Arkticheskaya 41 well, in the interval 3048–3081 m (Fig. 2, No. 4).

The Gydan region covers the eastern part of the southern Kara Sea, part of the Gydan Peninsula and the northwestern part of the Yenisei-Khatanga regional trough (Fig. 2).

In this region, the Vasyugan and Georgievka horizons are represented by the lower part of the Golchikha Formation (Fig. 1), which was first recognized in the Deryabinskaya 5 well by Kislukhin (1986). This formation was named after the settlement of Golchikha at the mouth of the Yenisei River. It is predominantly composed of clays in its lower part and was deposited in a marginal marine to a deep-water setting with <200 m depths in the southwestern part of the region (Kontorovich et al., 2013). In the north and northeast, the region is bounded by the denuded land surfaces of paleo-Taimyr and north Siberian threshold. Within contrasting local uplifts, the thickness of the lower part of the Golchikha Formation varies from 57 to 140 m (Khabeiskaya, Shtormovaya, Tota-Yakhinskaya prospects) and increases to 200 m, reaching 395 m in some wells in the axial part of the Yenisei-Khatanga regional trough. The Callovian–Kimmeridgian age of the lower part of the Golchikha Formation was assigned based on macro- and microfaunal remains recovered from well drilled at the South Noskovskaya, Sredneyarovskaya, Payakhskaya, Khabeiskaya, and other prospects.

For the areal characterization of the region, the type section of the Vasyugan and Georgievka horizons was taken to be in the Payakhskaya 1 well, in the interval 3770–4165 m (Fig. 2, No. 3).

The Taz-Kheta region is traced on the left bank of the Yenisei River, from the Messoyakha River in the north to the middle reaches of the Elogui River in the south, and also comprises the southwestern part of the Yenisei-Khatanga regional trough (Fig. 2).

In the Taz-Kheta region, the Vasyugan Horizon is represented by the Tochino Formation and the Lower Sigovaya Subformation. The Georgievka horizon is represented by the Upper Sigovaya Subformation and the lower part of the Yanovstan Formation (Fig. 1). The Yanovstan Formation was first identified in the Turukhanskaya 1 well in 1965 by N.I. Baibarodskikh, A.A. Bulynnikova and A.N. Rezapov (Belkina et al., 1965). It was named after the village of Yanov Stan, located in the middle reaches of the Turukhan River, Krasnoyarsk Territory.

The Tochino Formation, named after the settlement of Tochino, Krasnoyarsk Territory, was first recognized in 1967 in the Malokhetskaya 10 well by A.A. Bulynnikova, N.I. Baibarodskikh, G.N. Kartseva, and Z.Z. Ronkina (Argentovskii et al., 1968).

The Sigovaya Formation, named after the Sigovaya River, was first recognized in 1968 in the Turukhanskaya 1 well by N.I. Baibarodskikh, A.A. Bulynnikova and N.Kh. Kulakhmetov (Argentovskii et al., 1968). In the early 1970s, the sections of the above wells were taken as the stratotypes of the Yanovstan, Sigovaya, and Tochino formations.

In the Callovian–Kimmeridgian, the deposition within the Taz-Kheta region took place mainly in a marginal marine setting, with depths of <25 m (Kontorovich et al., 2013). The section has a clinoform structure. Its thickness increases northeastward from 200 to 500 m. The Callovian-Kimmeridgian age of the Tochino and Sigovaya formations, and the lower unit of the Yanovstan Formation was assigned based on the analysis of macro- and microfaunal remains and spore and pollen assemblages (Verkhnechaselskaya prospect, Khalmerpayutinskaya 2099, Tukolando-Vadinskaya 320 wells, etc.).

For the areal characterization of the region, the type section of the Vasyugan and Georgievka horizons was defined in the Ozernaya 8 well (3200–3741 m) in the north and in the North Tolkinskaya 304 well (2442–2844 m) in the south (Fig. 2, Nos. 2 and 8).

The Frolov-Tambei region occupies the western half of the central part of the West Siberian Sedimentary Basin (Fig. 2). It extends from north to south, from the southern part of the Kara Sea through the Ob Gulf to the Ob–Irtysh interfluve.

In this region, the Abalak Formation (Fig. 1) was first distinguished in 1959 in wells drilled at the Abalakskaya prospect, located in the southern part of the area (Li et al., 1960). The formation yielded rich macro- and microfaunal remains, but the depths to its top and base were not documented. To meet the requirements of the Stratigraphic Code, the stratotype was equated with the hypostratotypes of the Abalak Formation in the South Talinskaya 324 (2547–2583 m) and Salymskaya 90 wells (2862–2885 m) for shale beds, and Lazarevskaya 10126 well (2104–2158 m) for sandy-silty beds (Glinskikh et al., 1999). These sections characterize the southwestern and central parts of the Frolov-Tambei region.

The Abalak Formation, predominantly consisting of clays was deposited in a marine setting ~100–200 m deep (Kontorovich et al., 2013). Further west, near the Severnaya Sos'va River, Callovian-Kimmeridgian deposits are entirely or partially absent (Fig. 2). This area is characterized by shallowing into marginal marine conditions. Silts and sands of the Vogulka sequence (Shaimsky petroleum region) were deposited in the southwestern part of the region within the archipelago. The thickness of the Abalak Formation varies from 25 to 45 m and increases to 65 m locally in the north.

The Callovian–Kimmeridgian age of the Abalak Formation was assigned based on a rich macro- and microfaunas recovered from a well-core from the central part of the region (Shurygin et al., 2000). In the north, the formation yielded mainly ammonites at the Shuginskaya, Nydinskaya, Urengoiskaya, North Malyginskaya, Kharasaveiskaya and other prospects.

A transition zone where the Abalak Formation is replaced by the Vasyugan and Georgievka Formations is distinguished in the southeastern part of the region. It extends from north to south, from the western slope of the Surgut arch to Starosoldatsky megaswell. Deposition in this region occurred in a shallow marine setting, with depths of about 25 m.

For the areal characterization of the region, the type sections of the Abalak Formation were established in wells located in its arctic (South Tambeiskaya 70, 3328–3434 m), northern (Kheiginskaya 2, 3091–3168 m), central (North Arkanovskaya 30, 2752–2744 m) and southern (South Ligiyarskaya 41, 2682–22732 m) parts (Fig. 2, Nos. 1, 6, 11, and 17, respectively).

The Purpei-Vasyugan region occupies the eastern half of the central part of the West Siberian Sedimentary Basin (Fig. 2). It extends in a submeridional direction from the mouth of the Taz River in the north to the Irtysh and Tara Rivers in the south.

The Vasyugan and the overlying Georgievka formations were identified in this region (Fig. 1). The Vasyugan Formation, named after the Vasyugan River, was first recognized by V.Ya. Sherikhora (1961). The stratotype of the formation was defined in the Novovasyuganskaya 1 well. The Georgievka Formation, first distinguished as a member and named after the settlement of Georgievka, Omsk Region, was later formally ranked as a formation in 1967 (Bulynnikova and Yasovich, 1972). The stratotype of the formation was defined in the Bolsherechenskaya 1 well. In the early 2000s, the boundaries of the Vasugan and Georgievka formations in the stratotypes were refined based on the revision of paleontological data and in accordance with recent biostratigraphic scales (Shurygin et al., 2000; Nikitenko, 2009).

During the Callovian–Kimmeridgian, deposition within the Purpei-Vasyugan region occurred in a marginal marine (<25 m deep) and shallow marine environment (25–100 m deep) (Kontorovich et al., 2013). Two groups of local uplifts where Jurassic strata are entirely or partially absent are identified in the south (Urna-Usanov in SW and Mezhovka in SE, respectively). The Vasyugan Formation ranges from 50 to 85 m in thickness in the southern and central parts of the region and thickens northeastward to 167 m (e.g., South Pyreinaya prospect). The Georgievka Formation appears to be only <5 m thick but it thickens up to 15 m at the Kuzyrskaya, Novoyutymskaya, South Ostrovnaya, Verkhnepurpeiskaya, and other prospects. The formation thickens again to 35–40 m southeastward and southward (Buynovskaya and Pribelinskaya prospects) and to 80 m northeastward (Ety-Purovskaya, Khancheiskaya, and other prospects). The age of both formations was assigned based on numerous macro- and microfaunal remains, spore-pollen assemblages and dinocysts. This region can be subdivided into three sub-regions on lithological grounds, which are discussed below.

A transition zone where the Vasyugan Formation is replaced by the Naunak Formation is distinguished in the east, along the boundary with the Silga region, from the Aleksandrov arch in the north to the eastern part of the Mezhov structural meganose in the south. In this zone, deposition occurred in a coastal plain environment that was periodically inundated by the sea. In the Late Oxfordian and Kimmeridgian, deposition transitioned to marginal marine settings, with depths of up to 25 m (Kontorovich et al., 2013).

For the areal characterization of the region, the type sections of the Vasyugan and Georgievka horizons were defined in the northern (West Purpeiskaya 703, 3022–3082 m), central (Megionskaya 2, 2476–2552 m) and southern (Yagyl-Yakhskaya 5, 2444–2504 m) parts of the region (Fig. 2, nos. 7, 14, and 18, respectively).

The Silga region was distinguished east of the Purpei-Vasyugan region. It extends in a near NS direction from the middle course of the Vakh River in the north to the Kyonga River in the south (Fig. 2).

Within this region, the Vasyugan and Georgievka horizons are represented by the Naunak and Georgievka formations, respectively (Fig. 1). The Naunak Formation, named after the settlement of Naunak, Tomsk Region, was first recognized by Bulynnikova et al. (1969) in the Ust-Silginskaya 2 well, which was taken as the formation stratotype. Clays, silts and sands of the Naunak Formation intercalated with coal seams were deposited mainly in a coastal plain environment that was periodically inundated by the sea (Kontorovich et al., 2013), whereas silts and clays of the Georgievka Formation were deposited in a marginal marine setting <25 m deep. The thickness of the Naunak Formation varies from 65 to 80 m. The thickness of the Georgievka Formation in the central part of the region appears to be only <5 m thick but it thickens up to 25 m to the north and south. The Callovian age of the Naunak Formation was assigned based on ammonites and bivalves recovered from the Laryakskaya 1 well.

For the areal characterization of the region, the type sections were defined in its northern (West Sabunskaya 1, 2517–2581 m), central (Kiev-Yoganskaya 355, 2520–2603 m), and southern (West Krylovskaya 1, 2523–2637 m) parts (Fig. 2, Nos. 12, 15, and 19, respectively).

The Azharma region embraces the areas from the head of the Eloguy River in the north to the head of the Om' River in the south (Fig. 2).

In this region, the Vasyugan and Georgievka horizons are represented by the Naunak Formation and the lower part of the Maryanovka Formation, respectively (Fig. 1). In the central part, the section of the Nyarginskaya 1 well was taken as the stratotype of the Kimmeridgian-Volgian deposits (Nikitenko, 2009). The Naunak Formation was deposited on a fluviolacustrine plain repeatedly flooded by the sea, over which a coastal plain was formed (Kontorovich et al., 2013). The thickness of the formation varies from 33 to 98 m. This formation, predominantly consisting of clays in its lower part, was deposited in a marginal marine environment <25 m deep. The thickness of this part of the section varies from 14 to 44 m. The Callovian–Kimmeridgian age was assigned based on bivalves recovered from the Beloyarskaya 1 well, and Oxfordian–Kimmeridgian age was assigned based on ammonites (Vostok 1 and 3, Nyarginskaya 1 wells).

For the areal characterization of the region, the type sections of the Callovian–Kimmeridgian were defined in its northern (Kys-Yoganskaya 91, 2029–2109 m), central (Vostok 3, 2484–2602 m), and southern (Verkhne-Kengskaya 91, 1957–2050 m) parts (Fig. 2, Nos. 13, 16, and 23, respectively).

The Chulym-Taseeva region is distinguished in the southeast of the West Siberian Sedimentary Basin (Fig. 2). In this region, the Vasyugan and Georgievka horizons are represented by the Tyazhin Formation and lower part of the Maksimkin Yar Formation, respectively (Fig. 1).

The Tyazhin Formation, named after the settlement of Tyazhin, Kemerovo Region, was first distinguished by N.I. Lebedev in the Mariinskaya stratigraphic test well (Transactions..., 1957). The Maksimkin Yar Formation, named after the settlement of Maksimkin Yar, Tomsk Region, was first distinguished by M.A. Tolstikhina in 1957. The section of the Maksimoyarskaya 1 well was taken as the stratotype. The Tyazhin Formation, predominantly consisting of clays was deposited on a continental depositional plain, while silts and clays in the lower part of the Maksimkin Yar Formation were deposited on a coastal plain periodically flooded by the sea (Kontorovich et al., 2013). This part of the Maksimkin Yar Formation varies in thickness from 22 to 46 m, and the Tyazhin Formation appears to be 108 m thick. Callovian–Kimmeridgian deposits yielded spore and pollen assemblages from some wells.

For the areal characterization of the region, the type section was defined in the Yarskaya 1 well, at 1818–1910 m (Fig. 2, No. 20).

The Omsk region lies in the middle course of the Irtysh River, immediately to the north of the city of Omsk (Fig. 2).

The Tatarskaya and Georgievka formations are widespread in this region (Fig. 1). The Tatarskaya Formation was first distinguished based on drilling results at the Tatarskaya prospect (Rostovtsev, 1955). Later, the interval of the Tatarskaya 2 well was taken as stratotype of the formation (Geological ..., 1958). In the 2000s, the section of the Tatarskaya 1 well was taken as the hypostratotype of the formation (Shurygin et al., 2000). Throughout the distribution area of the retinue, the age of the formation was assigned based on macro- and microfossils only at the Tatarskaya prospect, in the remaining part of the region, its age was defined by palynological assemblages of the Callovian and Oxfordian age. The formation was named after Tatarskaya railway station, Novosibirsk Region. The stratotype of the Georgievka Formation was taken to be in the Bolsherechenskaya 1 well located in the central part of the region.

In the southern part of the region, silts and clays of the Tatarskaya Formation were deposited on a coastal plain, periodically flooded by the sea (Kontorovich et al., 2013). Clays of the Georgievka Formation were deposited in a marginal marine setting, with depths of up to 25 m. The thickness of the Tatarskaya Formation ranges from 47 to 84 m and increases southward. The Georgievka Formation appears to be 15 m thick and locally thickens to 34 m (Bolsherechenskaya prospect).

A transition zone was recognized in the northern part of the region. In this zone, the section of the Tatarskaya Formation contains sand layers, ranging in thickness from 2 to 5 m. Sediments were deposited in a marginal marine setting, with depths of <25 m (Kontorovich et al., 2013).

For the areal characterization of the region, the typical section of the Vasyugan and Georgievka horizons was taken in the Nikolskaya 1 well, at 2780–2877 m (Fig. 2, No. 22). A transition zone was recognized along the northern margin of the region, where the Vasyugan Formation is replaced by the Tatarskaya Formation from north to south.

The Tebisskoe region is located in the extreme south of the West Siberian Sedimentary Basin (Fig. 2). The southwestern and southern boundaries of the region are traced along the pinch-out of the Jurassic beds.

The Tatarskaya Formation and the overlying lower part of the Maryanovka Formation (Fig. 1) are distinguished in the region. As shown earlier, the stratotype and hypostratotype of the Tatarskaya Formation were defined at the Tatarskaya prospect. The Maryanovka Formation, named after the settlement of Maryanovka, Omsk Region, was first described in 1957 by Z.T. Aleskerova and T.I. Osyko. In the 2000s, the stratotype of the Maryanovka Formation was defined in the Tatarskaya 1 well. In the south, this formation predominantly consisting of clays was deposited on a low-lying depositional plain, which is replaced in a northward direction by a coastal plain periodically flooded by the sea (Kontorovich et al., 2013). The lower part of the Maryanovka Formation was deposited in a shallow marine setting, with depths of up to 25 m. Its Late Oxfordian-Kimmeridgian age was assigned based on a fauna of bivalves and ammonites recovered from wells at the of Omskaya and Tatarskaya prospects. The lower part of the Maryanovka Formation varies in thickness from 15 to 34 m.

The type section was not defined in this region because of the difference in the structure of the section and thickness of the Tatarskaya Formation between the western, Irtysh part of the region (Omskaya 1 well, etc.) and eastern part confined to the Om-Kargat interfluve (Tatarskaya, Chanovskaya prospect, etc.), as indicated by core and log data.

The Bagan region is located southeast of Tebisskoe region (Fig. 2). The southern boundary of the region is defined by the pinch-out of the Jurassic deposits.

The Tatarskaya Formation and the lower part of the Bagan Formation are distinguished in the region (Fig. 1). The Bagan Formation, named after the Bagan River, Novosibirsk Region, was first described by V.A. Martynov in 1991 in the South Chulymskay 1 well (Resolution..., 1991). Silts and clays of the Tatarskaya Formation were deposited on a low-lying depositional plain, which, during the deposition of the lower part of the Bagan Formation, was supposedly replaced by a coastal plain, repeatedly flooded by the sea (Kontorovich et al., 2013). The Tatarskaya Formation appears to be 93 m thick in the central part of the region, whereas the lower part of the Bagan Formation is about 44 m thick. The Kimmeridgian age of the Bagan Formation was assigned based on bivalves and microfaunal remains, as well as by spore and pollen data from its stratotype.

For the areal characterization of the region, the typical section of the Vasyugan and Georgievka horizons was taken to be in the South Chulymskaya 1 well (1164–1300 m) (Fig. 2, No. 24).

LITHOLOGICAL CRITERIA FOR DISTINGUISHING SUB-REGIONS OF THE PURPEI-VASYUGAN REGION

In the West Siberian Petroleum Basin, most hydrocarbon accumulations of the Upper Jurassic reservoir were found in the Yu_1 horizon as part of the Vasyugan Formation in the Purpei-Vasyugan region. Based on the core analysis, interpreted lithology and facies of the Vasyugan Formation, the Purpei-Vasyugan region was subdivided into three facies sub-regions (from south to north): Ob-Tara, Ob-Agan and Verkhnepur (Yan et al., 2001). The most recent geological data have confirmed the proposed division of the region.

In the Ob-Tara sub-region, the lower unit of the Vasyugan Formation, some 10–50 m thick, is composed mostly of clay and silt. At its base, the Pakhomov member, with varying thickness (0.5 to 6 m) is composed of brownish sandstones and argillaceous siltstones, poorly sorted, often calcitized, containing siderite nodules, carbonate ooliths, pyrite, glauconite, and some marine fauna (J_2^0 sandy-silt bed) (Krapivinskaya, West Moiseevskaya, South Karasevskaya and other propsects (Fig. 3*a*). The stratotype of the Pakhomov member is defined in the Pakhomovskaya 1 well, at 2685–2678 m (Atlas..., 1990; Decisions ..., 1991). The J_2^0 bed rests unconformably on the erosion surface of the Tyumenskaya Formation or on the pre-Jurassic basement (Shurygin et al., 2000).

The middle part of the lower unit of the formation (predominantly clays) is interpreted as representing a major transgression event. It is characterized by the presence of trace fossils *Chondrites*, typical of the Cruziana ichnofacies (Yan and Vakulenko, 2011) and contains abundant pyrite, occurring as isometric micronodules or as larger bladed and radial concretions. Foraminifers and interbeds with a very rich marine microfauna (ammonites, bivalves, less often belemnites) are common throughout the section.

The upper part of the lower unit of the formation often contains silt and sand layers, the proportion of which increases to the east, reflecting the progressive progradation of the coastline (J_1^4 bed occurring in most sections of this sub-region, and locally persistent J_1^5 and J_1^6 beds indicating the transition to the Naunak Formation).

The upper unit of the Vasyugan Formation, comprising the most part of the Yu_1 horizon, also contains sub-, inter-, and supra-coal members (PU, MU, and NU, respectively) (Danenberg et al., 1979). The sub-coal member ($J_1^{3\text{-}4}$ beds, often undivided) in most wells is dominantly a regressive section consisting of silt and clay grading upward. The detrital material has a feldspar-lithoclastic-quartz, less feldspar-quartz-lithoclastic composition, with smaller amounts (2–3 to 15%) of carbonate-clay cement, containing organic matter and authigenic pyrite. No macrofauna and traces of bio-

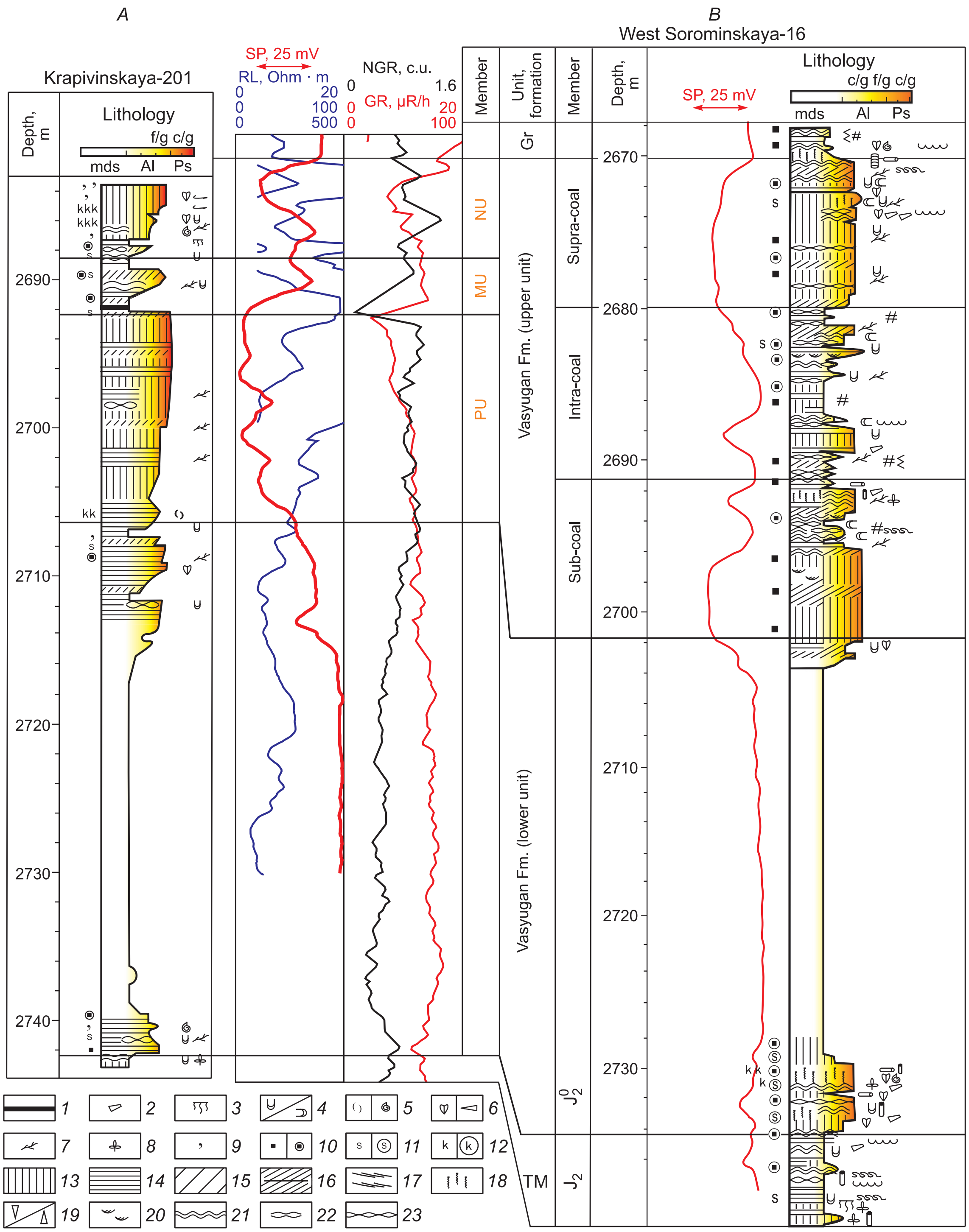

Fig. 3. Lithology and geophysical characteristics of the Vasyugan Formation: A, Ob-Tara sub-region in the Krapivinskaya 201 well, B, Ob-Agan sub-region in the West Sorominskaya 16 well (for well locations see Fig. 2). Legend to Figs. 3,4: Gr, Georgievka Formation, TM, Tyumen Formation. Lithology column: f/g, fine-grained, c/g, coarse-grained, mds, mudstone, slt, siltstone, snd, sandstone.
Rocks: 1, coals, 2, clayey intraclasts. Inclusions: 3, rhizoids, 4, trace fossils, 5, detritus/marine fauna, 6, bivalve/belemnite, 7, carbonized detritus, 8, floral impressions, 9, glauconite, 10, pyrite/pyrite concretions, 11, siderite/siderite concretions, 12, calcite/calcite concretions. Textures: 13, massive, 14, horizontal bedding, 15, thick tabular oblique bedding, 16, thin tabular oblique bedding, 17, gentle oblique bedding, 18, bioturbation structures, 19, gradational bedding (reverse/forward), 20, thin shallow oblique bedding, 21, wavy bedding, 22, wavy-lenticular bedding, 23, lenticular bedding.

turbation are recorded. These sediments were deposited in marginal marine environments influenced by tidal currents and wave. The presence of deltaic deposits in some sections is confirmed by geochemical indicators of brackish-water conditions (the boron content does not exceed 60–70 ppm). Sub-coal sandstones often have a laterally persistent sheet-like geometry. The maximum thickness of the sub-coal member (up to 50–55 m thick) is confined to depressions and decreases to 10–25 m toward areas of higher relief.

An inter-coal member consisting of silt- and mudstones with interlayers of sandstone, secondary limestone and a basal layer of coal or carbonaceous mudstone is characterized by an increase in thickness (from 1 to 40 m) and the number of coal interlayers to the east. Another distinctive feature is the thickening of the inter-coal member from depressions toward the upper parts of first-order structures. The carbonized plant remains, root fragments, pyrite and siderite are common. The member was deposited on a periodically flooded coastal plain and on a fluviolacustrine, periodically swamped plain.

The thickness of the supra-coal member is 3–10 m and increases to a maximum of 30 m in the southeast of the Nyurolka depression. Several J_1^{1-2} beds, separated by a silty-clayey member or an erosion surface were identified in the most complete sections of the member. However, the section of the supra-coal member often appears, with one or both beds being absent due to earliest or latest Oxfordian erosion (Lontyn-Yakhskaya 60, Pervomaiskaya 263, Shakhmatnaya 1 wells, etc.). In the upper part of the member contains rare glauconite grains, interlayers of bioclastic limestone, and a rich marine fauna (bivalves, scaphopods, belemnites). The detrital material has a lithoclastic-feldspar-quartz composition, with variable amounts of clay-carbonate- cement (from 5 to 50%) and high pyrite content (1–15%). The member also contains several intervals displaying deformation spotted structures caused by intensive bioturbation (Skolithos, Cruziana ichnofacies) (Yan and Vakulenko, 2011). The sediments were deposited in shallow-marine or marginal marine conditions, with normal marine salinities, as indicated by the elevated boron content (up to 110 ppm). The top of the Vasyugan Formation is recognized on logs as a transition from a high resistivity, low gamma-ray response of J_1 sands of the Vasyugan Formation to a low resistivity, high gamma-ray response of clays of the Georgievka Formation or a high resistivity, high gamma-ray response of the Bazhenov Formation.

In the Ob-Agan sub-region, the structure and lithology of the lower unit of the Vasyugan Formation are the same as in the Ob-Tara region. A distinctive feature of this sub-region is the persistent concretions leveling the J_2^0 bed (Fig. 3*b*). The bed has a markedly erosive base where it occurs on the silty-clayey member of the Tyumen Formation. However, the erosion is always intraformational, because of the absence of any disturbance of the distribution of spore

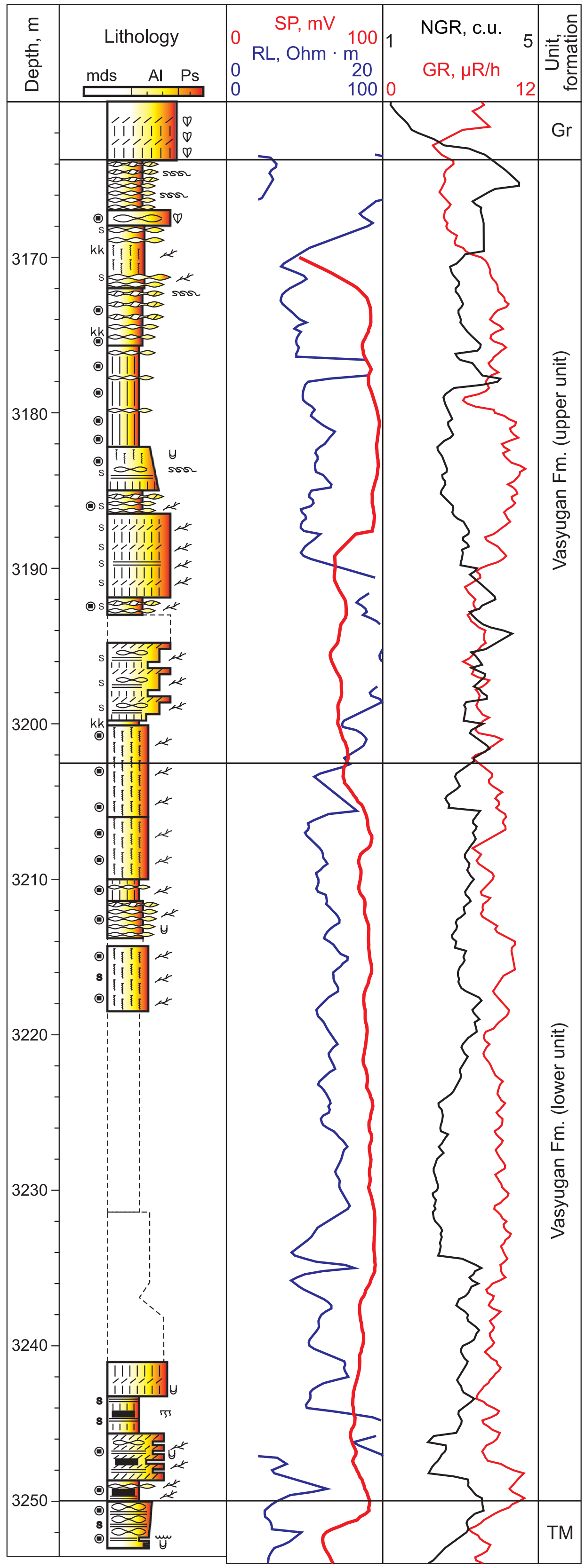

Fig. 4. Lithology and geophysical characteristics of the Vasyugan Formation, Verkhnepur sub-region in the West Novogodnyaya 210 well (for well location see Fig. 2).

and pollen assemblages in some well sections (Entelskaya 2, Lul-Yakhskaya 5P, Ust-Balykskaya 2002 wells, etc.) (Goryacheva, 2005). The following features of the Yu_1 horizon were identified: the presence of small amounts of carbonated rocks in a member separating the coal and supra-coal beds, which is referred to as the coaly-clay member; J_1^2 and J_1^1 beds often form a single reservoir; higher shale content of the J_1^4 bed. The detrital material has a feldspar-lithoclastic-quartz composition, with a predominance of quartz and almost identical feldspar and lithoclast contents.

In the Verkhnepur sub-region, the Vasyugan Formation appears to increase in thickness to 140 m (Tyumenskaya-SG 6 well). As opposed to the southern regions, the transition from the Tyumen Formation to the J_2^0 bed is gradual, with no evidence of erosion. Siderite nodules are not found in the bed (Tyumenskaya-SG 6, Sugmutskaya 423 wells). The upper unit of the Vasyugan Formation contains no coals, and the inter-coal member is totally missing (Fig. 4). The number of sandy-silt layers in the J_1 bed decreases from three to zero in the northern and western direction. As opposed to the southern regions, the rocks are finer-grained and contain pyrite nodules, marine macrofaunal remains, irregular trace fossils (specimens of Cruziana and Skolithos are predominant in the lower and upper parts, respectively) and intensely bioturbated levels (Yan and Vakulenko, 2011). The detrital material has feldspar-lithoclastic-quartz, rarely lithoclastic-eldspar-quartz composition, with a decrease in the proportion of lithoclasts upward the section and from east to west. The Vasyugan Formation in this sub-region was deposited in a marginal marine and shallow marine setting, as supported by geochemical data (high boron content of 77–150 ppm). The degree of marine influence in the section increases in the northern and western directions, which is indirectly confirmed by a decrease in the content of kaolinite and carbonized plant debris.

CONCLUSIONS

This study summarizes recent understanding of the relationship between formations, units, and members identified in the Vasyugan and Georgievka horizons of the West Siberian sedimentary basin, including the southern Kara Sea.

The proposed scheme of facies-stratigraphic zoning is based on section types and Callovian–Kimmeridgian paleogeography and reflects the regional structural model of the horizons. The results of the detailed zoning of Callovian-Kimmeridgian sediments, which comprise the Yu_1 reservoir, can be used in exploration planning, selecting standards of facies models, reservoir petrophysical modeling, etc.

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