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Interpretation of electrical logging data from the Hettangian-Aalenian terrigenous reservoirs in the Southeast of Western Siberia

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Abstract. In the southeast of Western Siberia, the most studied are the Upper Jurassic deposits, most of the oil and gas fields being confined to them. However, the probability of discovering new hydrocarbon deposits in the Upper Jurassic horizons is extremely small. Therefore, of great importance is finding new hydrocarbon deposits in less studied deep-lying complexes.

The article considers the development of a criterion for determining the saturation type of the terrigenous reservoirs in the Hettangian-Aalenian deposits in the southeast of the West Siberian sedimentary basin. We use the example of the Ust-Tym megadepression, a large depression located in the central part of the Tomsk region. The Lower and Middle Jurassic sections are represented by the Urman and Togur formations, Salat formation (Peshkov formation is its isochronous analogue) and Tyumen formation, and characterized by the alternation of predominantly sandy (potential reservoirs) and argillaceous-carbonaceous (seals) sequences. In the studied interval, tests were carried out in just a few wells, for which reason the identification of deposits and promising objects is complicated. Determining the type of reservoir saturation will significantly improve the assessment of oil and gas potential.

As a result of interpreting lateral logging sounding data, the geoelectric parameters of the invasion zone and undisturbed formation were reconstructed for the Lower Jurassic and Aalenian deposits. Based on the well logging data interpretation by means of numerical inversion, we obtained the criterion for the saturation type of the reservoirs (Ju_{11-17}) in the Hettangian-Aalenian complex. The boundary resistivity values for the oil-saturated reservoirs vary from 8 to 20 ohm·m, while for the water-saturated ones they do not exceed 5 ohm·m.

Keywords: Ust-Tym megadepression, Hettang-Aalenian deposits, fluid saturation, electrical resistivity, quantitative interpretation

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Introduction

For the socio-economic development of oil and gas producing regions in the southeast of Western Siberia, it is necessary to maintain oil production volumes and increase the resource potential. Most of the large and medium-sized hydrocarbon fields have been discovered in the Upper Jurassic and Lower Cretaceous sediments. The current state of the geological-geophysical exploration regarding the southeast of Western Siberia indicate that the high degree of knowledge of the traditional Upper Jurassic deposits (Ju_1 horizon) does not allow us to count on the discovery of new large and medium hydrocarbon (HC) deposits.

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A topical direction is the discovery of new HC deposits in poorly studied, in particular deep-lying, sediments. In the southeast of Western Siberia and in the Tomsk region in particular, great opportunities for the discovery of new hydrocarbon deposits are associated with the Lower-Middle Jurassic deposits.

The interest of petroleum geologists has recently been directed to the search for HC deposits within large depressions. Depression zones, in contrast to the positive structures adjacent to them, are characterized by an irregular network of seismic time profiles using the common depth point (CDP) method of low density and a small number of drilled wells. The Ust-Tym megadepression belongs to such areas, its Hettangian-Aalenian deposits being the subject of this study (Fig. 1).

Within the megadepression, 16 wells were drilled, exposing the Lower-Middle Jurassic complex, in which there are no HC deposits. During the tests at the Tolparov and South-Pyzhin areas, non-industrial oil

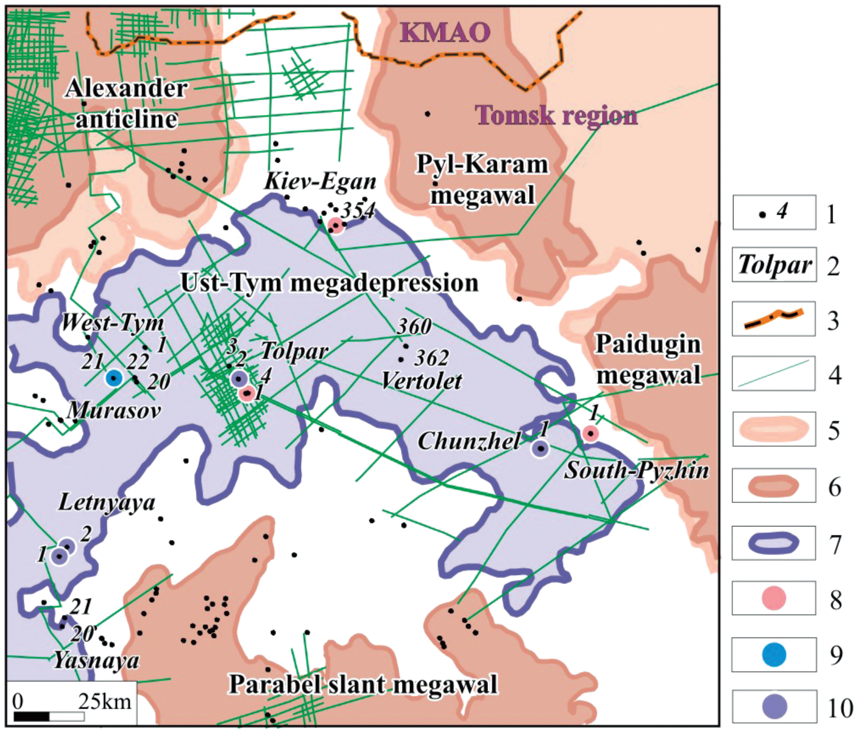

Fig. 1. Ust-Tym Jurassic sedimentary sub-basin: 1 – wells; 2 – areas; 3 – administrative boundaries; 4 – seismic profiles; 5–7 – outlines of structures according to the tectonic scheme of the top of the Jurassic structural stage (Kontorovich et al., 2001): 5 – zero-order positive structures, 6 – first-order positive structures, 7 – first-order negative structure; 8–10 – well test results: 8 – oil, 9 – water, 10 – no fluid

flows were obtained: in the lower subformation of the Urman formation and in the lower subformation of the Tyumen formation (Tolparov-1 well), as well as in the lower subformation of the Tyumen formation (South-Pyzhin-1 well).

The field geophysical studies carried out in the wells were mainly aimed at studying the Upper Jurassic, Cretaceous and Paleozoic deposits. Concerning the Lower and Middle Jurassic intervals, their fluid saturations were not determined from logging data. One of the methods for estimating the saturation type is the analysis of lateral logging sounding data. As a criterion for oil saturation at the terrigenous intervals of the Lower-Middle Jurassic deposits in the southeast of Western Siberia, the values of true resistivity (TR) can be used. Interpretation of resistivity logging data has previously been successfully applied to the terrigenous Upper Jurassic and Neocomian reservoirs (Epov at al., 2013).

There is no single approach for a correct assessment of the oil-and-gas potential and for specifying the geological structure of the Hettangian-Aalenian complex. It is necessary to apply an integrated approach and modern research methods, core materials, well logging, seismic exploration, petrophysical and geochemical data, seismic facies analysis and structural-tectonic analyzes, as well as basin modeling.

The aim of the presented study is to develop the criterion for determining the saturation type of terrigenous reservoirs of the Hettangian-Aalenian deposits in the southeast of Western Siberia (using the example of the Ust-Tym sedimentary sub-basin), based on the quantitative interpretation of lateral logging sounding (BKZ) data. This approach to evaluating the saturation of the untested intervals of the Hettangian-Aalenian section will increase the reliability of identifying the objects that are most promising for hydrocarbon deposits.

The territory of the Ust-Tym megadepression, according to the scheme of structural-facies zoning of the lower and middle (without Callovian) Jurassic of Western Siberia, belongs to the Ob-Taz and Ob-Irtysh structural-facies regions (SFR). The Ob-Taz SFR is characterized by a transitional sedimentation environment – from marine to continental, whereas in the Ob-Irtysh region continental sedimentation is evidenced (Decision…, 2004; Shurygin et al., 2000).

A complete section of the Hettangian-Aalenian deposits is distinguished in the most submerged part of the Ust-Tym megadepression. It is represented by the Urman and Togur formations, Salat formation with its isochronous analogue (Peshkov formation), and the lower subformation of the Tyumen formation. The thickness of the complex reaches 440 m. The deposits were formed in the conditions of a low-lying accumulative plain and large lakes periodically connected to the sea. The authors distinguish three oil and gas bearing subcomplexes in the Hettangian-Aalenian sediments: Hettangian – Lower Toarcian, Toarcian – Lower Aalenian and Upper Aalenian (Fig. 2).

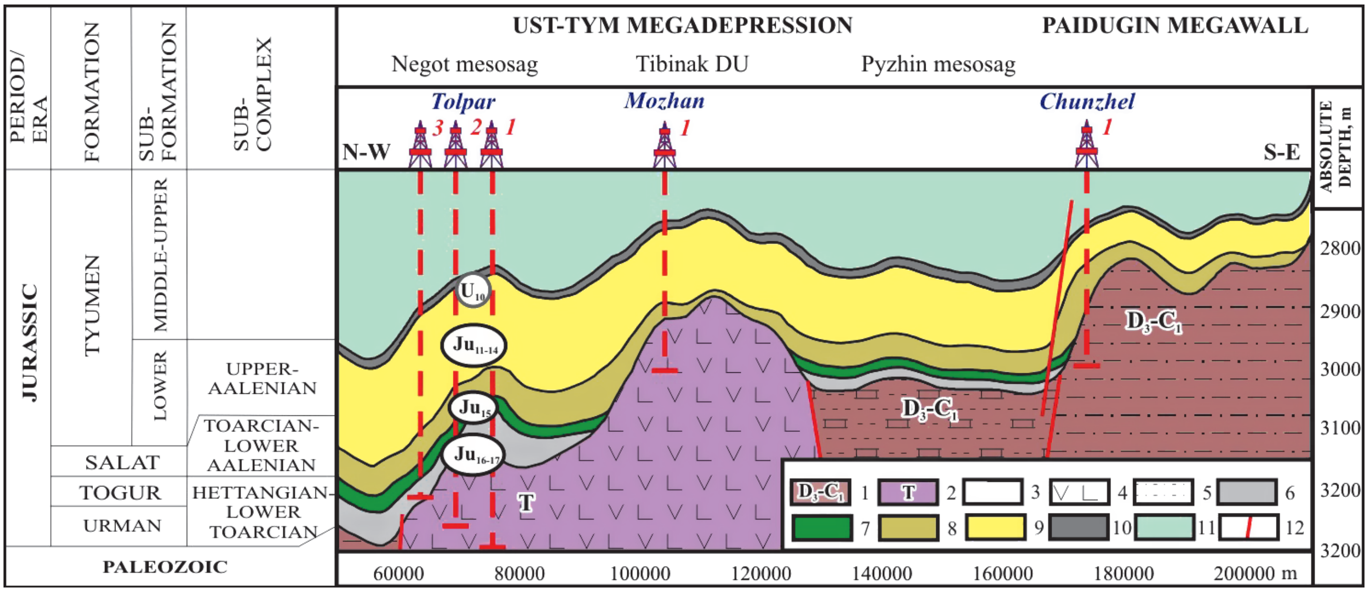

Fig. 2. Geological section of the Hettangian-Aalenian deposits: 1 – Devonian period (upper section) – Carboniferous period (lower section); 2 – Triassic period; 3 – argillaceous shale with limestone; 4 – andesites, andesite-basalts and their tuffs, mafic volcanics; 5 – interlayering of rocks of different composition (volcanic-sedimentary stratum); 6 – Urman formation; 7 – Togur formation; 8 – Salat formation; 9 – lower subformation of the Tyumen formation; 10 – U_{10} coal layer; 11 – middle and upper subformation of the Tyumen formation; 12 – faults

The ***Hettangian – Lower Toarcian subcomplex*** is represented by the Urman and Togur formations, dated as the Hettangian-Pliensbachian and Early Toarcian, respectively.

The Urman formation lies at the base of the subcomplex; it contains 3 subformations represented mainly by sandstones, gravelstones, siltstones and mudstones, with rare interlayers of coals and charred remains (Shurygin et al., 1995; Shurygin et al., 2000; Decision…, 2004). The thickness of the formation varies from 8 to 92 m, Ju_{16} and Ju_{17} sandy beds being potential reservoirs.

The Togur formation limits the subcomplex at the top. It is represented by black thin-layered mudstones enriched in organic matter; there are interlayers of siltstones and small sandstones, the thickness varies from 10 to 40 m. The formation was first identified by F. Gurari in 1960 in the section of the well Kolpashev-2 as the Togur member (Decision …, 1961). A. Kontorovich, O. Stasova and A. Fomichev (Kontorovich et al., 1964) found that the Togur mudstones have a sufficiently high generation potential and serve as a potential HC source for deposits in the basal horizons of the sedimentary cover.

The ***Toar-Aalenian subcomplex*** is represented by the Salat/Peshkov formations, dated as the second half of the Early Toarcian – Early Aalenian. The formation is composed of sandstones and siltstones, argillaceous and carbonaceous interlayers occur, the thickness varies from 0 to 44 m. The Ju_{15} sandy layer is a reservoir. The carbonaceous-argillaceous U_{14} (Radom) member is distinguished in the top of the subcomplex; it serves as a seal.

The ***Upper Aalenian subcomplex*** is represented by the Lower Tyumen subformation of the Tyumen formation, dated to the Upper Aalenian. The subformation is composed of sandstones and siltstones, contains coal seams, the thickness reaches 202 m. The reservoir is a group of hydrodynamically connected sandy layers Ju_{11-14}, which alternate in the section with U_{11-13} carbonaceous-argillaceous units. The subcomplex is bounded at the top by the thick U_{10} carbonaceous-argillaceous member, which acts as an impermeable seal.

The alternation of sandy strata (potential reservoirs) and overlying argillaceous and carbonaceous-argillaceous strata (seals) makes it possible to consider the Hettangian-Aalenian complex as promising for oil and gas deposits. The sand beds have not been sufficiently tested and no tests have been carried out in the Ju_{15} reservoir. Saturation evaluation at the untested intervals through the interpretation of electrical logging data is a relevant task for the poorly studied deep-seated Lower-Middle Jurassic deposits.

Research methods and study methods

In this study, the determination of reservoir saturation was carried out according to the electrical logging data, based on the analysis of the radial resistivity profile in each selected formation. Thus, the formation fluid displacement by the drilling mud filtrate and changes in salinity in the near well-bore zone have a direct impact on the radial resistivity distribution. The latter was determined by numerical inversion within the framework of a one-dimensional cylindrically-layered interpretation model (Epov, Nikitenko, 1993; Epov et al., 2010, 2013; Glinskikh et al., 2017). The one-dimensional inversion approach makes it possible to quickly and efficiently perform the numerical interpretation of electric logging data, and can be used for terrigenous deposits with a relatively low resistivity contrast and layer thicknesses exceeding the lengths of the probes (Glinskikh et al., 2013; Mikhaylov et al., 2017).

The logging data analysis was carried out using the EMF Pro integrated log data interpretation system (IPGG SB RAS) (Epov et al., 2010). Log data of four BKZ lateral devices were imported from LAS files into the system: A0.4M0.1N, A1.0M0.1N, A2.0M0.5N and A4.0M0.5N. The BKZ logs are of good quality, which is also noted in the well reports. After uploading the BKZ data, the reservoir boundaries were placed using the automatic algorithm and manually, with refinement using a set of well logs (self-polarization potential, gamma-ray logging, neutron gamma-ray logging, acoustic logging and induction logging). At the next stage, we performed the layer-by-layer numerical inversion of the BKZ data (Fig. 3). This is valid in relation to the objects under study, since the sections under consideration are relatively low-contrast in terms of electrical resistivity, and the layers are, generally, of sufficient thickness. However, in cases where the formation thickness was less than or comparable to the probe system, the signals of the longer probes were either given less weight during the inversion or not taken into account.

As a result, the resistivity and radius of the invaded zone were reconstructed, along with the resistivity of the undisturbed formation at a specified depth interval. Oil-saturated reservoirs are identified by significantly higher true resistivity values than in water-saturated ones. Note that the induction logs at the disposal of the authors were not involved in the joint inversion of the borehole electrical exploration data, since they are not available for all the wells and were not always recorded at a small time interval relative to the BKZ measurements.

Results

To develop the criterion for estimating reservoir saturation type (Ju_{11-17}) in the Hettangian-Aalenian complex, the BKZ data were interpreted by utilizing the one-dimensional numerical inversion method in the EMF Pro software package. We considered sandy formations in the wells where cased-hole tests were carried out, and which are located in the most probable area of HC migration from the Togur formation: Tolparov-1 and Murasov-21 (Loktionova et al., 2019).

Oil inflows were obtained when testing the Tolparov-1 well in the Ju_{16-17} and Ju_{11-14} sandy layers; we created geoelectric models for the tested terrigenous oil and gas reservoirs. The permeable intervals, according to the high-frequency logging data, include the invasion zone, as well as the resistivity annulus in the oil-water-saturated reservoirs with mobile oil and water (Antonov, Zhmaev, 1979; Antonov et al., 2012). We analyzed the signals from four BKZ probes: A0.4M0.1N, A1.0M0.1N, A2.0M0.5N, A4.0M0.5N. Due to the vertical heterogeneity of the interval, most of it was divided into layers with a thickness of about 0.5 m, and the data inversion was carried out layer-by-layer.

Fig. 4 shows the numerical inversion results for the Tolparov-1 well. It was drilled in the interval of the Hettangian-Aalenian deposits with clay drilling mud

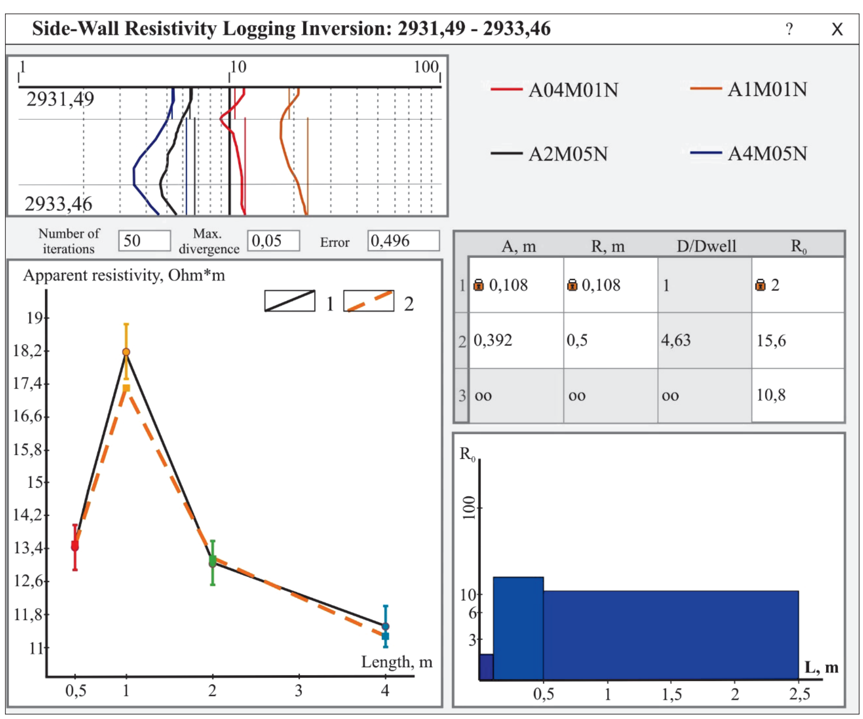

Fig. 3. Numerical inversion of the BKZ data in the interval 2931.49–2933.46 m in the Tolparov-1 well: 1 – field sounding curve; 2 – calculated sounding curve

having a resistivity of 2.0 Ohm·m. When inverting the BKZ field data, we obtained a realistic geoelectric model of the terrigenous section.

An oil-saturated reservoir is identified in the Ju_{17} sandy reservoir at a depth of 3224–3240 m (relative depths), which is overlain by the argillaceous deposits of the Middle Urman subformation, the average porosity coefficient (Cp) of the Ju_{17} reservoir is 7 %. Oil-saturated formations are distinguished in the upper part of the reservoir (3200–3230 m); below, at depths of 3237–3240 m, water-saturated sections of the reservoir are observed. A high-resistivity layer corresponding to coal deposits is identified at a depth of 3225 m.

There is an oil-saturated reservoir (3028–3032 m)

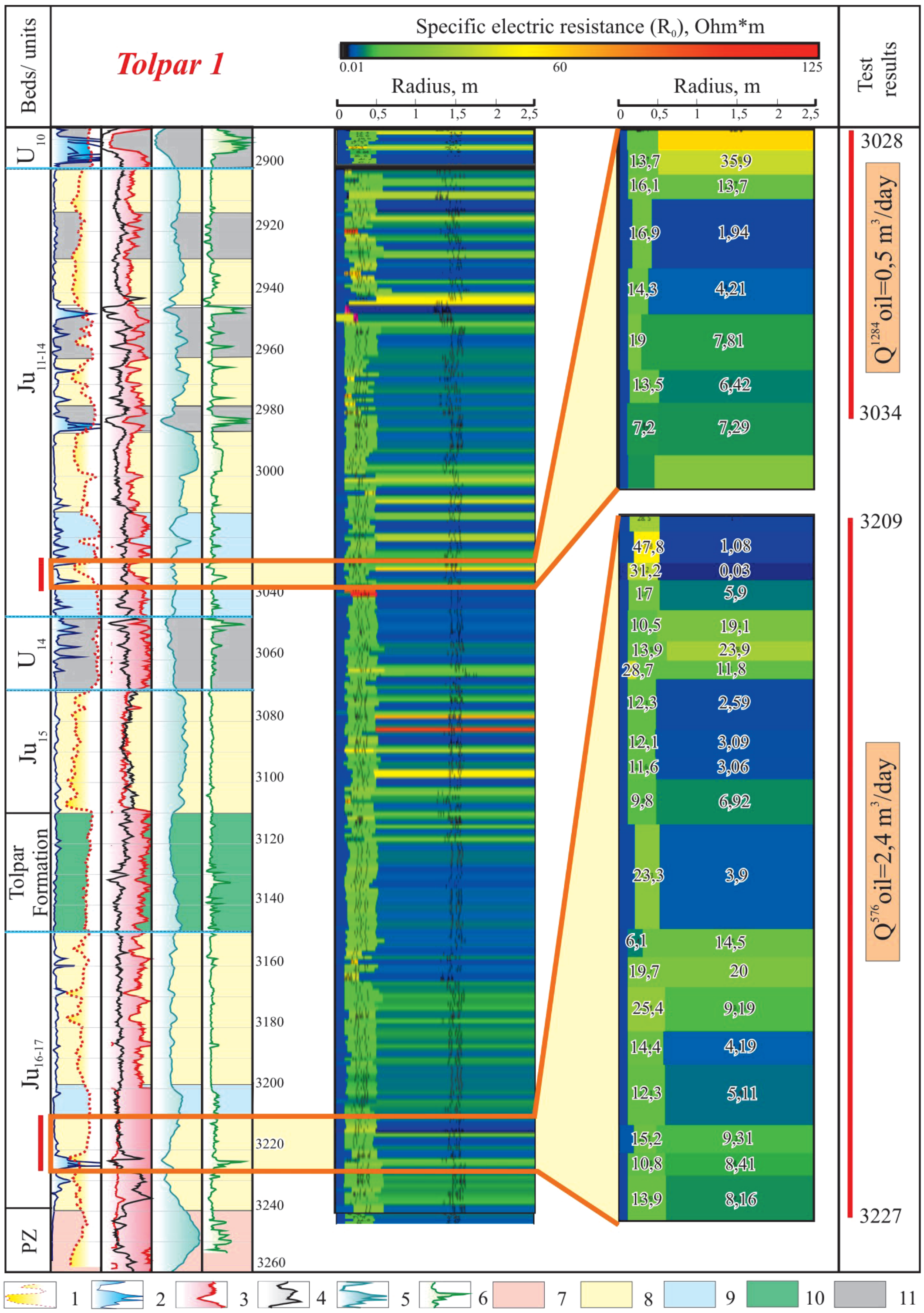

*Fig. 4. BKZ data numerical inversion result in the terrigenous section of the Hettangian-Aalenian complex: 1–6 – well logs: 1 – self-polarization potential (SP: 0–100 c.u.), 2 – apparent resistivity (GZ: 0–100*3 Ohm·m), 3 – gamma-ray log (GR: 0–16 μR/h), 4 – neutron gamma-ray log (NGR: 0–4 c.u.), 5 – induction log (IL: 0–300*2 mS/m), 6 – sonic log (SL: 150–500*2 μs); 7 – Paleozoic deposits, 8 – predominantly sandy formations, 9 – argillaceous-carbonaceous stratum, 10 – Togur formation, 11 – carbonaceous-argillaceous member*

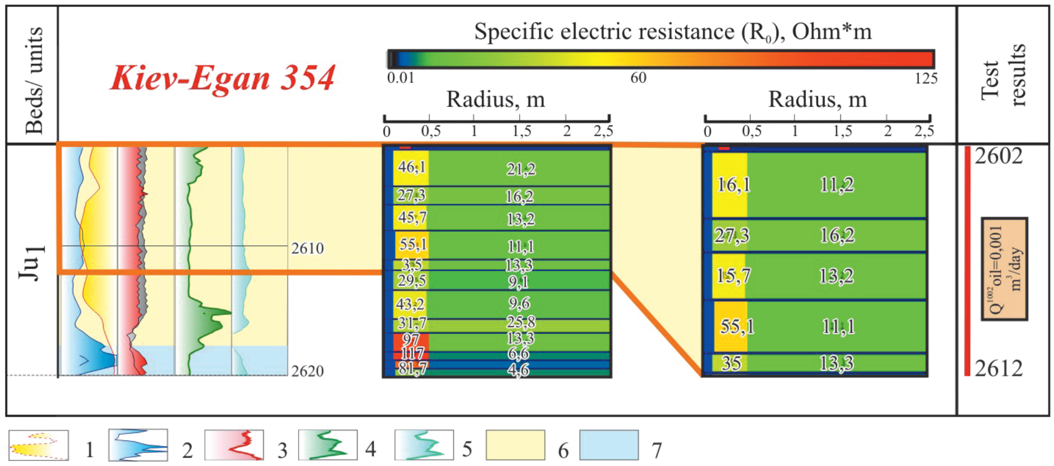

*Fig. 5. BKZ data interpretation results in the interval of the Upper Jurassic oil-saturated terrigenous reservoir: 1–5 – well logs: 1 – self-polarization potential (SP: 0–100 c.u.), 2 – apparent resistivity (GZ: 0–100*3 Ohm·m), 3 – gamma-ray log (GR: 0–16 μR/h), 4 – sonic log (SL: 150–500*2 μs), 5 – induction log (IL: 0–300*2 mS/m); 6 – predominantly sandy formations, 7 – carbonaceous-argillaceous member*

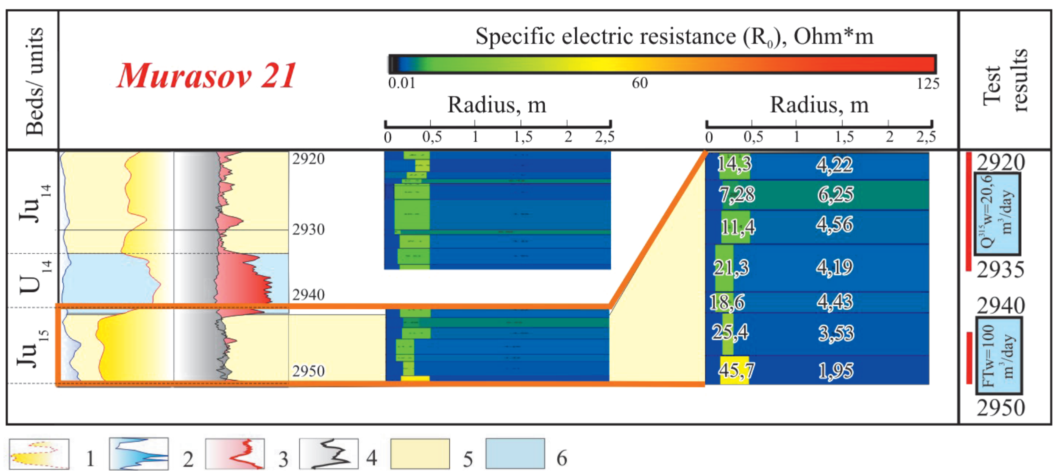

*Fig. 6. BKZ data interpretation results in the water-saturated terrigenous reservoir. 1–6 – well logs: 1 – self-polarization potential (SP: 0–100 c.u.), 2 – apparent resistivity (GZ: 0–100*3 Ohm·m), 3 – gamma-ray log (GR: 0–16 μR/h), 4 – neutron gamma-ray log (NGR: 0–4 c.u.), 5 – predominantly sandy formations, 6 – argillaceous-carbonaceous stratum*

distinguished in the Ju_{14} sandy bed (3028–3034 m), which is overlain by argillaceous sediments; below there is a section of the reservoir, interpreted as a water-saturated. The average Cp value of the Ju_{14} formation is 12 %.

Following the interpretation results of the considered BKZ data at the intervals with oil inflows, sandy reservoirs with a resistivity value from 8 to 20 Ohm·m are classified as oil-saturated.

To compare the characteristics of the oil-saturated reservoirs of the Hettangian-Aalenian complex and the Upper Jurassic ones, we built a geoelectric model for the terrigenous reservoir of the Ju_1 horizon in the Kiev-Yegan-354 well (Fig. 5). For the Upper Jurassic oil-saturated reservoir, the boundary resistivity values are from 11 to 25 Ohm·m. The average Cp value of the Ju_1 horizon equals 13 %.

As examples of water-saturated reservoirs, we present the intervals of the Ju_{14} and Ju_{15} sandy layers in the Murasov-21 well, from which water inflows were obtained during the testing (Fig. 6). Subsequent to the numerical inversion results, the water-saturated terrigenous reservoirs of the Hettangian-Aalenian complex are characterized by the resistivity values less than 5 Ohm·m.

Arising from the quantitative interpretation of the BKZ data at the tested sandy intervals of the Lower-Middle Jurassic deposits, it was found that the boundary resistivity value of the oil-saturated reservoirs makes 8–20 Ohm·m, while for the water-saturated ones it does not exceed 5 Ohm·m. The resulting criterion can be used to determine saturation types in untested intervals, as well as in wells with no fluid during inflow tests.

Conclusions

Well logging data interpretation combined with the numerical inversion of BKZ data made it possible to develop the criterion for distinguishing saturation types in the terrigenous reservoirs of the Lower-Middle Jurassic deposits. The reservoirs with a resistivity of up to 5 Ohm·m are regarded as water-saturated, whereas the oil-saturated ones have resistivity from 8 to 20 Ohm·m.

The criterion was tried out on the territory of the Ust-Tym megadepression when determining the saturation type of the Hettangian-Aalenian reservoirs. This approach allowed for increasing the reliability of identifying the intervals and objects that are most promising for the search for oil fields and can be recommended as priority ones for prospecting and exploration.

The use of the obtained criterion will enable determining the saturation type at untested intervals and refining the oil and gas potential of the Lower-Middle Jurassic deposits in the southeast of the West Siberian sedimentary basin.

Acknowledgements

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