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New Methodological Approaches to Assessment of Oil Resources in the Bazhenov Formation Sediments

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Today there is no verified methodology to calculate oil reserves in the Bazhenov Formation, which makes it impossible to identify any references for the initial oil reserves. Therefore, the analog approach that is usually applied for quantitative assessment of petroleum potential becomes inapplicable.

The paper considers different approaches to assessment of the petroleum potential of the Bazhenov Formation in West Siberia. Since oil distribution in the formation is determined by the initial content and catagenetic maturity of organic matter in the rock and controls the formation of an effective reservoir, it becomes apparent that estimating the oil resources and reserves requires geochemical studies.

The proposed methodological approaches consider separation of net oil pays using the Rock-Eval data, well log data, and results of oil-promising objects survey and the principles of differentiated assessment of oil resources and territory ranking by the compositions of saturating hydrocarbons.

Keywords: Bazhenov Formation, oil forecast, net oil pay, assessment of resources

INTRODUCTION

The methodological approaches presented in this paper can be applied for assessment of hydrocarbon resources in the Bazhenov Horizon being a part the Bazhenov Formation and Lower Tutleim Subformation. These are Late Jurassic–Early Cretaceous (Upper Tithonian–Valanginian) oil-source carbonate-argillaceous–siliceous sediments abnormally saturated with organic matter (OM). The Bazhenov Formation section is an alternation of these rocks and dense silicite, limestone and dolomite interlayers with relatively low content of OM (Panchenko et al., 2016).

Such alterations are widespread within the boundaries of West Siberia and their productivity is related to the sediments whose OM content is more than 5% and clay volume—no more than 30%.

The suggested approaches do not touch on the anomalous sections of the Bazhenov Formation, containing sandy-aleuritic interlayers.

REVIEW OF THE TERMS APPLIED FOR UNCONVENTIONAL HYDROCARBON SYSTEMS

The volumetric method is widely applied to estimate oil resources and, after certain changes and corrections, can be applied for their assessment in the Bazhenov Formation. What makes an unconventional hydrocarbon system different from a conventional one is that in the first case one considers being of commercial value those hydrocarbons that are generated by the oil-source formation and preserved within this formation. This approach calls for clarification of some of the general terms applicable to traditional hydrocarbon systems (Prishchepa and Aver'yanov, 2014).

An oil deposit of the Bazhenov Formation is a deposit of the movable parautochthonous hydrocarbons generated and preserved in the permeable rocks of an oil-source formation, surrounded by impermeable rock on all sides. Usually, lateral seals are formed due to secondary (postsedimentary) rock transformation. In their section they can form due to reduced rock permeability in diagenesis. But more often than not, it occurs due to the lithological transformations related to sedimentation, so in the vertical direction, the permeable rock is replaced by impermeable, loamy and carbonaceous one.

Free hydrocarbons are the hydrocarbons generated by the oil-source formations and preserved in its rock mass.

Movable hydrocarbons are the free hydrocarbons that are not linked to rock and kerogen by sorption processes.

Geological oil resources of the Bazhenov Formation are the total amount of movable fluid hydrocarbons in rock's porous volume composed of fractures, caverns and pores.

The Bazhenov Formation's porosity has been determined by two processes. The first of them is postsedimentary rock formation such as silification and carbonization that do not

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depend on OM catagenesis. The second is solid OM (kerogen) cracking due to increased catagenesis, leading to formation of oil and gaseous fluids. This process, due to increasing OM volume, is accompanied by formation of the so-called 'organic' porosity. The cross-linked pores appear in kerogen at the stage of OM catagenesis above Mesocatagenesis when the porosity strictly depends on OM content. It means OM cracking should not only result in horizontal fracturing, but also in significant pore volume in all Bazhenov rocks.

Whether it comes to catagenesis below Mesocatagenesis, these reservoirs only form due to intercrystalline, intergranular and interskeletal pores and fractures.

At the above Mesocatagenesis stage almost all the section of the formation becomes a reservoir due to the large amount of cross-linked kerogenic pores. For that reason, instead of 'porosity' we suggest the term 'capacity' to denote pore space takes by either fluid or gas or their mixture.

Effective oil-saturated thickness in Bazhenov Formation sediments is the total thickness of the reservoir interlayers containing movable hydrocarbons. Due to stratal water absence, this thickness is similar to a reservoir's total section thickness.

FLUID DYNAMIC MODEL

Before considering the volumetric parameters, one must consider the issue of the fluid's phase composition that we may expect. The bitumoids sampled from the boreholes penetrating the formation's oil-bearing level have much higher (78–85%) hydrocarbon content with saturated hydrocarbon prevalence, which allows us to conclude that the porous space of the Bazhenov rock is filled by relatively light low-resin oil. The wells with insignificant or 'dry' inflow produce bitumoids with less rich hydrocarbon but higher resin and asphaltene content (Fig. 1), which means these wells have penetrated into the residual reservoirs whose oil has migrated either to underlying or overlapping reservoirs.

Studying the bitumoids extracted from core samples of different sizes (Fig. 2) has demonstrated that both regular-shape and coarse-crushed (down to 0.25 mm) samples contain mostly hydrocarbons. At the same time, fine-crushed (less than 0.25 mm) bitumoids have turned out to be residual ones with 80% of their content composed of resins and asphaltenes. The studied regular-shape and coarse-crushed samples referred to open pores, and the fine-crushed ones—to mainly closed pores. The fine-crushed group bitumoids did not exceed 15% of the volume of all the extracts, which means the porosity of this group does not exceed 1% and they can be neglected when considering the total pore volume. So, the fluid dynamic model of the Bazhenov Formation is either light low-resin oil or heavy high-resin oil (Fig. 3) and that has been confirmed by the results of a surface-sample analysis.

METHODOLOGICAL APPROACHES TO VOLUMETRIC PARAMETS DETERMINATION

The highest uncertainty in application of the volumetric method for assessment of the Bazhenov Formation's oil resources lies with determination of the oil productive area and effective oil-saturated thickness. This is due to current production well logging measurements that do not allow one to unambiguously identify oil-saturated intervals and deter-

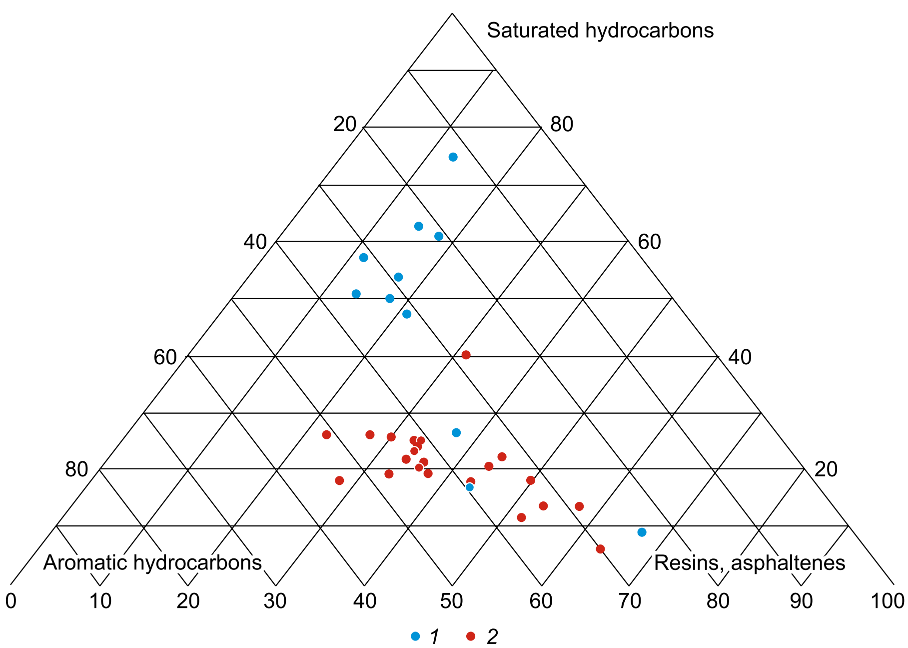

Fig. 1. The triangular diagram of bitumoid group composition from the Bazhenov productive, low-rate and dry wells.

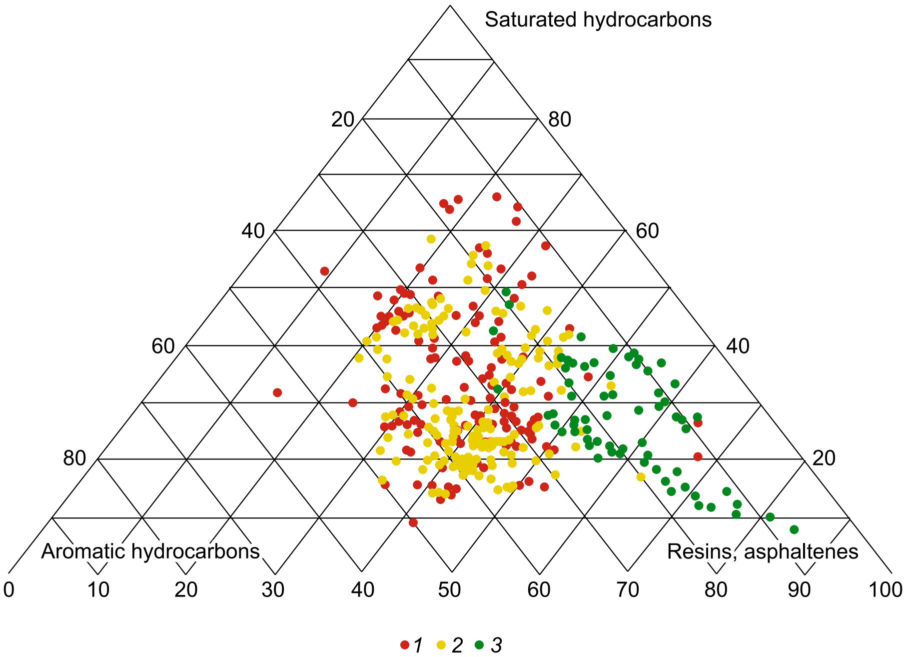

Fig. 2. The triangular diagram of bitumoid group composition from the Bazhenov rock (open and closed pores).

mine their thickness. The traditional methods to determine petrophysical parameters that are commonly used to calculate oil resources cannot be used here because of a number of lithological differences that occurs core extraction. Since oil distribution in the considered sediments remains understudied, to estimate hydrocarbon resources in these rock masses one commonly applies the time—domain method in combination conditional computation parameters (Petersilie et al., 2003; Petersilie and Komar, 2016; Temporal methodological guidelines, 2017a,b).

Effective oil-saturated thickness. To calculate this parameter for the Bazhenov Formation we suggest using the Rock-Eval results (Fig. 4).

These results allow one to:

– separate oil-saturated intervals,

– and estimate their oil content.

The oil-saturated intervals are identified by high free hydrocarbon content values ($S_1 + S_2a$) relative to OM content and S_2 (residual potential for generating oil/gas). In other words, high free hydrocarbon content is a sign of reservoir presence.

Oil distribution in the Bazhenov Formation is determined by initial OM content in the rock and its catagenetic maturity, i.e., formation of effective reservoirs is directly related to catagenetic OM transformation, which makes it essential to introduce geochemical data when estimating the formation's reserves. The Rock-Eval sections allow one to trace changes in OM content as well as its composition such as of relatively low-molecular free hydrocarbons (S1, mg HC/g of rock mass); relatively high-molecular free hydrocarbons (S_2a); and of residual kerogen generation potential (S_2b, mg HC/g of rock mass):

$$S_2a = S_{2\ (\text{before extraction})} - S_2b_{\ (\text{after extraction})}.$$

The relation between the S_1, S_2 parameters and well-logging measurements is strongly affected by the degree of OM catagenesis, and rock polimict composition. For the territories with high degree of OM maturity such as the Bol'shoi Salym oil fields, almost total section oil saturation has been proved (for high-productive wells), while for the Krasnoleninsk field with much lower degree of catagenesis only certain lithotypes have proved to be productive.

As has been said before, the formation's reservoirs capacity can be of different nature such as:

– 'mineral' when pores and fractures are located between the mineral components of the rock – this is a very a common composition of the Bazhenov productive layers;

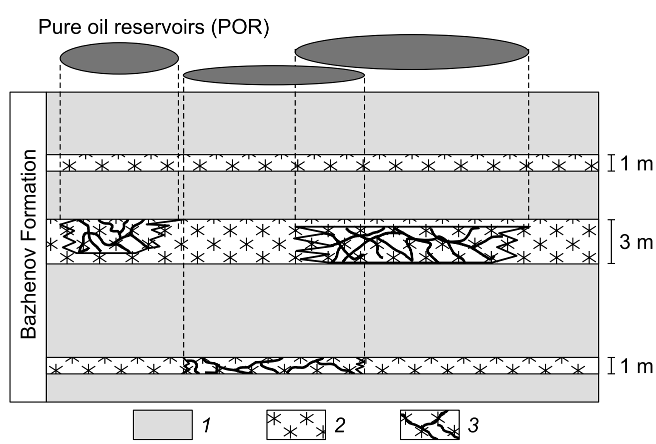

Fig. 3. Model of the Bazhenov oil reservoir.

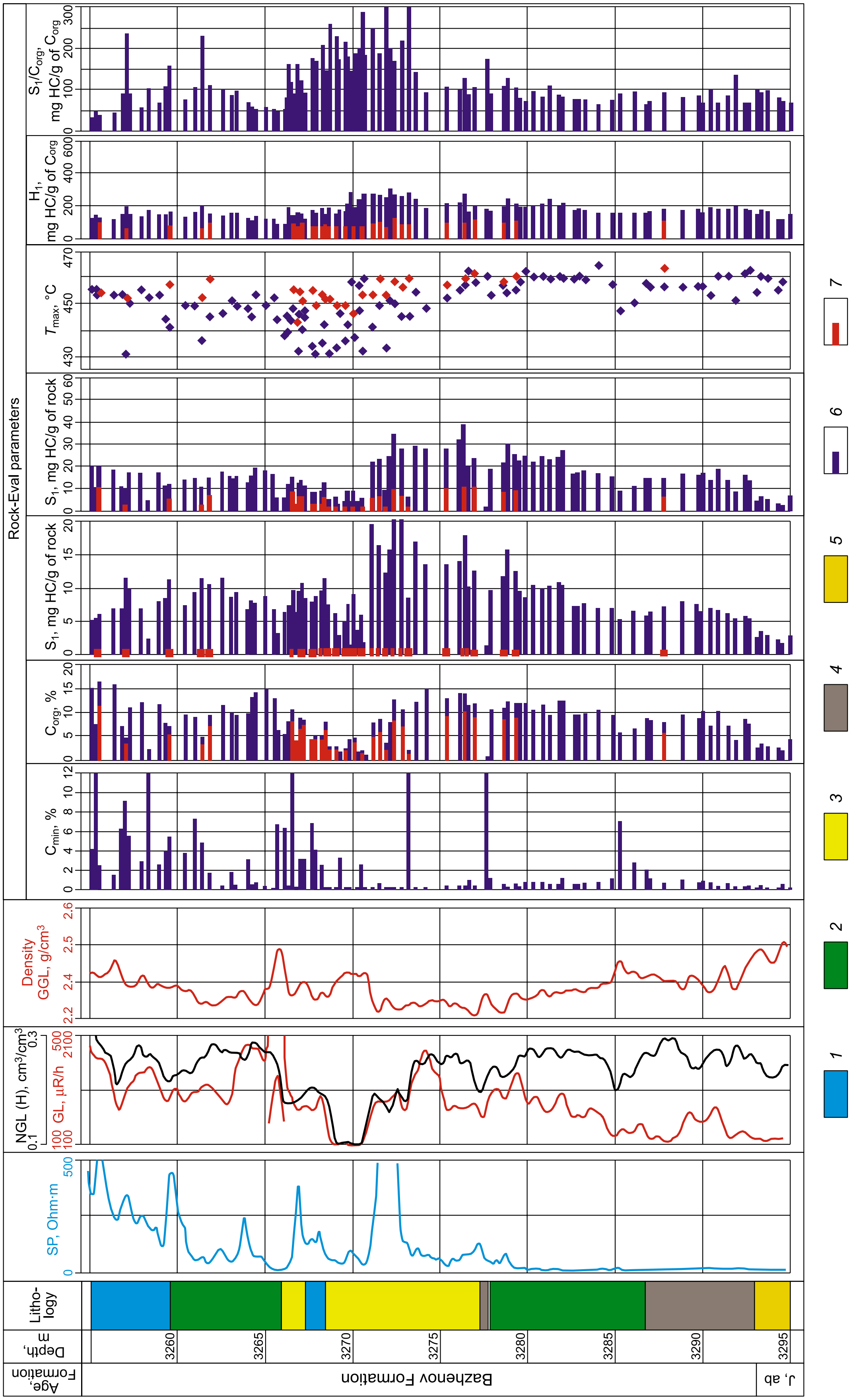

Fig. 4. Geological and geochemical section of a Salym field well.

– and ‘organic’ that are formed in kerogen during hydrocarbon generation. In this case, nature’s effect on rock capacity characteristics increases together with OM cracking increase. Considering this observation, all the diversity of the Bazhenov lithotypes can be reduced to two groups, whose physical characteristics and capability to accumulate and extract movable hydrocarbons differ dramatically. The first group includes thin-layer, high-carbon and loamy rocks, while the second—denser, brittle, layered and massive rocks with lower clay and OM content.

The territories with high degree of OM catagenetic maturity, the effective oil-saturated thicknesses include rocks with proven free HC-saturation, i.e., rock whose $(S_1 + S_2a)/TOC > 100$ mg HC/g TOC or S_1/S_2 C > 0.2, etc.). Effective capacity can present in any lithotypes, while effective organic capacity—only in the lithotypes of the second group.

In the zones with lower catagenetic OM maturity, distribution of effective oil-saturated thicknesses can be reduced to separation of the lithotypes prone to brittle deformations and detections among them oil-saturated ones (Fig. 5).

A layer’s electric resistivity depends on the section’s lithology, fluid-filled pore volume, and saturation. Absence of other fluids but S_1 and S_{2a} in the Bazhenov Formation allows us to forecast the $S_1 + S_{2a}$ value for every lithotypes using focused methods of resistivity logging:

$$S_1 + S_2a – \text{function} – V_{\text{formation}} \cdot (F_{\text{din porosity}} + F_{\text{recovery}}).$$

This parameter is proportional to total porosity, which means it characterizes both the movable hydrocarbons ($F_{\text{din porosity}}$) and unmovable ones (F_{recovery}) and is expressed the best way through resistivity (Fig. 6).

The relation between kerogen content and radioactivity can be forecasted through the spectral (and in some areas through integral—depending on clay matter content) gamma-logging characteristic. For the purposes of this study, we used the integral function of gamma-logging being a part of a standard suite and measured for almost every well (Fig. 7).

Not all kerogen generated oil is movable because a part of it is retained due to sorption processes inside kerogen rock. For that reason, it is not enough to obtain the S_1 parameter higher than 0, one also must account for residual saturation, i.e., to obtain S_1 grain. To do so, we used the S_1/S_2 to OM content ratio of more than 0.2 (Fig. 8). Figures 9 and 10 exemplify separation of effective oil-saturated thicknesses using well logging data.

Oil productive area. To map perspective oil deposits, we used complex spectral-velocity prediction (CSVP) developed on the basis of spectral-time analysis, and pseudoacoustic seismic record transformation to predict geological section types and reservoir properties (permeability and porosity coefficients, effective thickness, specific volume and flow capacity) through building of attribute maps and cubes. The physical basis of the CSVP approach has been in correlation with the classical theory elastic vibrations saying that changes in the elastic properties of a medium determined by constantly changing section lithofascial and granulometric characteristics, reservoir properties and presence of fluid result in changing waveforms and wave–propagation velocity (Surova et al., 2016).

The most complete imaging of waveform change can be obtained after its 2D spectral decomposition (time-frequency signal analysis, TFSA). The TFSA energy spectra are characterized by quantitative spectral-time attributes being a ratio of high-frequency energy and large times to low-frequency energy and lower times, and the product of specific spectral density, and weighted-mean and maximum frequencies and times. These parametrizations in time sections and cubes allow one to obtain 7 corresponding attributes, 6 of them are spectral-time (3 on the frequency scale and 3 on the time scale) and 1 pseudoacoustic (velocity). Using the cross-correlation coefficient, these 7 seismic attributes are certified to match different geological section types and reservoir parameters in reference wells. The certified attributes are determined for all the seismic traces with building attri-

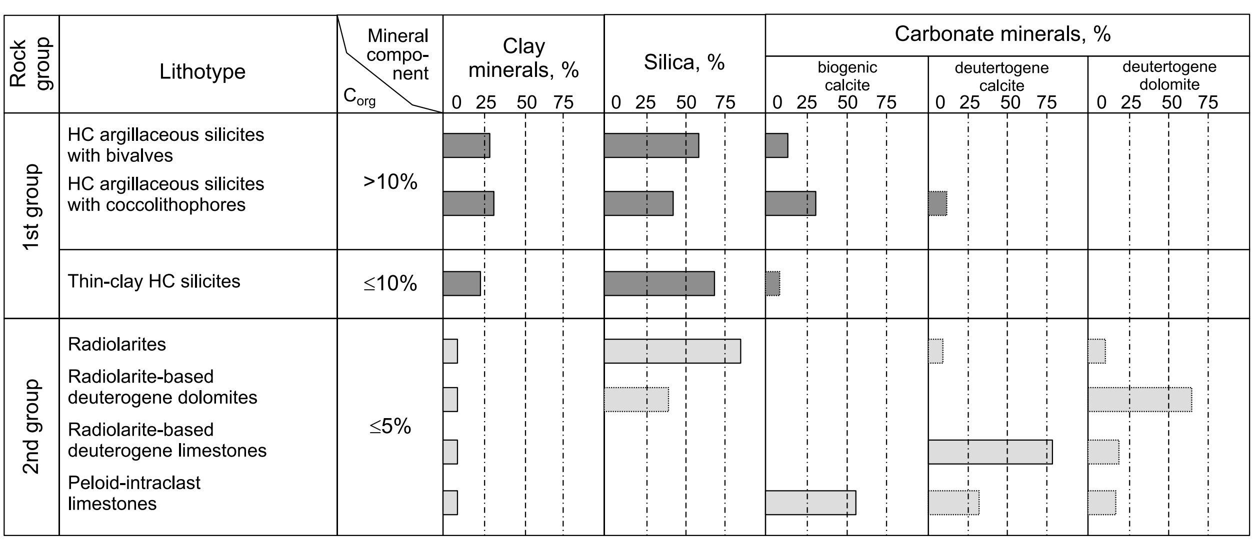

Fig. 5. Lithological typology of Bazhenov Formation sediments (high-hydrocarbon concentrations).

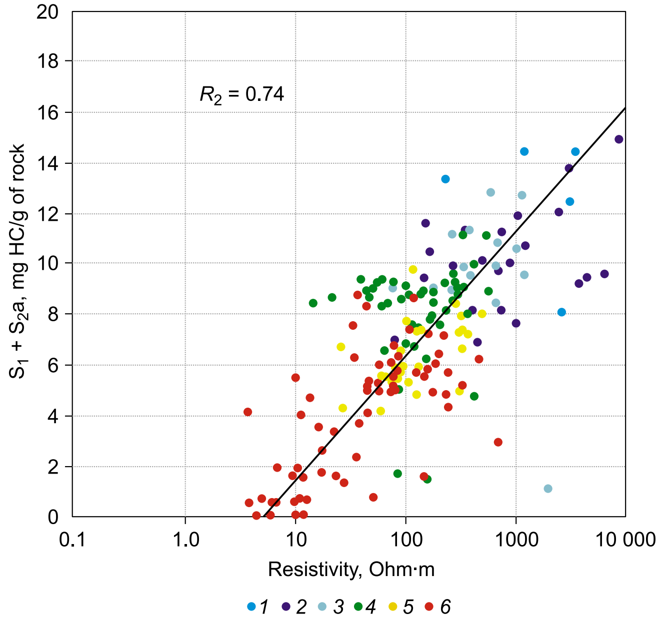

Fig. 6. An example of the relation between the $S_1 + S_2a$ geochemical parameter and electric resistivity from the well-logging data of the Bol'shoi Salym wells (high-degree of OM catagenetic maturity) for the Bazhenov Formation interval.

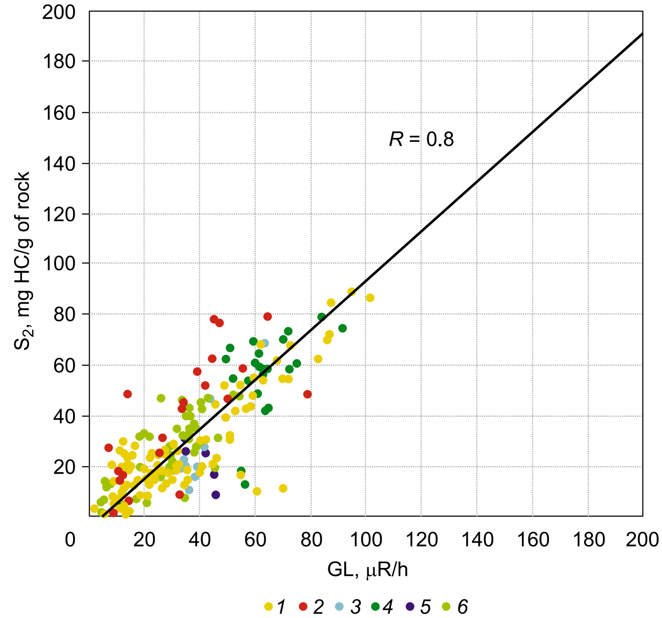

Fig. 7. An example of the relation between the S_2 geochemical parameter and natural radioactivity from the well-logging data of the Bol'shoi Salym wells (high-degree of OM catagenetic maturity) for the Bazhenov Formation interval.

bute maps and cubes, which are interpreted using up-to-date mathematical tools such as neural networks and statistical spectral-correlation algorithms.

In our study, we used well production rates as references. In total, 50 thousand meters of regional seismic profiles were analyzed, and the distance to wells selected for certification (selection of the most optimal seismic attributes) did not exceed 10 km.

As the representative sample, we selected wells of four section types. The wells referred to section type I were those whose production rate exceeded 100 m^3/day; section type II—the wells whose production rate was from 15 to 100 m^3/day; type III—wells whose rate did not exceed 15 m^3/day; and type IV were 'dry' wells. As it has been mentioned above the bitumoid HC composition is different in the different parts of the province, so for same OM contents, the concentration of free hydrocarbons may differ several times. However, in the areas with high S_1 values, saturated hydrocarbons prevail, while in those with low S_1 values prevail naphthene-aromatic hydrocarbons. Based on this fact, an assumption can be made that a bitumoid composition is one of the criteria of the potential productivity of the Bazhenov Formation (Fig. 10). Based on this assumption, the sections with potential rates from 15 to 100 t/day and more can be regarded as perspective ones that contain light low-resin oil, while the section whose rate does not exceed 15 t/day—as the areas containing low-movable high-resin oil.

Since the considered difference is firstly related to the degree of catagenesis, we performed analysis of the thermobaric conditions to detect perspective zones. For that purpose, for each of the seismic traces a whole set of CSVP attributes was calculated with enumeration of the adjustable parameters such as applied-filter width (F) to obtain the TFSA column, and spectrum cut-off level (L). So, for each of the attributes we calculated a set of values with the filter width varying from 30 to 80 Hz, and the cut-off level—from 0.1 to 0.3. For each well type all kinds of attributes were calculated and certified. The criterion to select an attribute for further complex interpretation was the maximum difference of average values (Δ) within a type in relation to the mean–square difference within the same type (σ), i.e., Δ/σ. The certification results for spectral –time attributes (STA) are presented in Fig. 8. To distinguish geological sections I and II we selected attribute STA3 (F = 30; L = 0.3) in the frequency domain and STA4 (F = 50; L = 0.3)—in the time

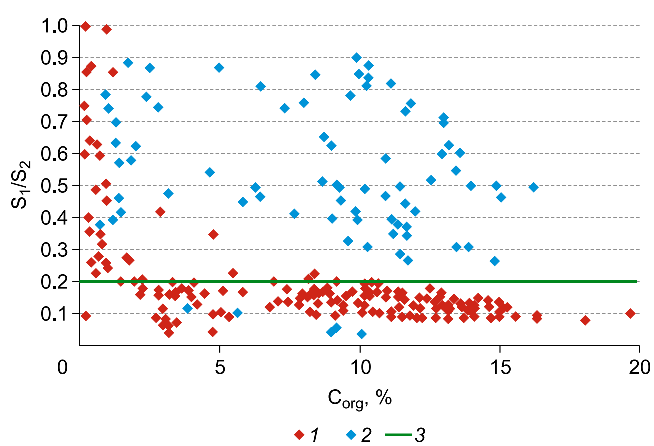

Fig. 8. The graphic definitions of the S_1 boundary value from core tests and the Rock-Eval data.

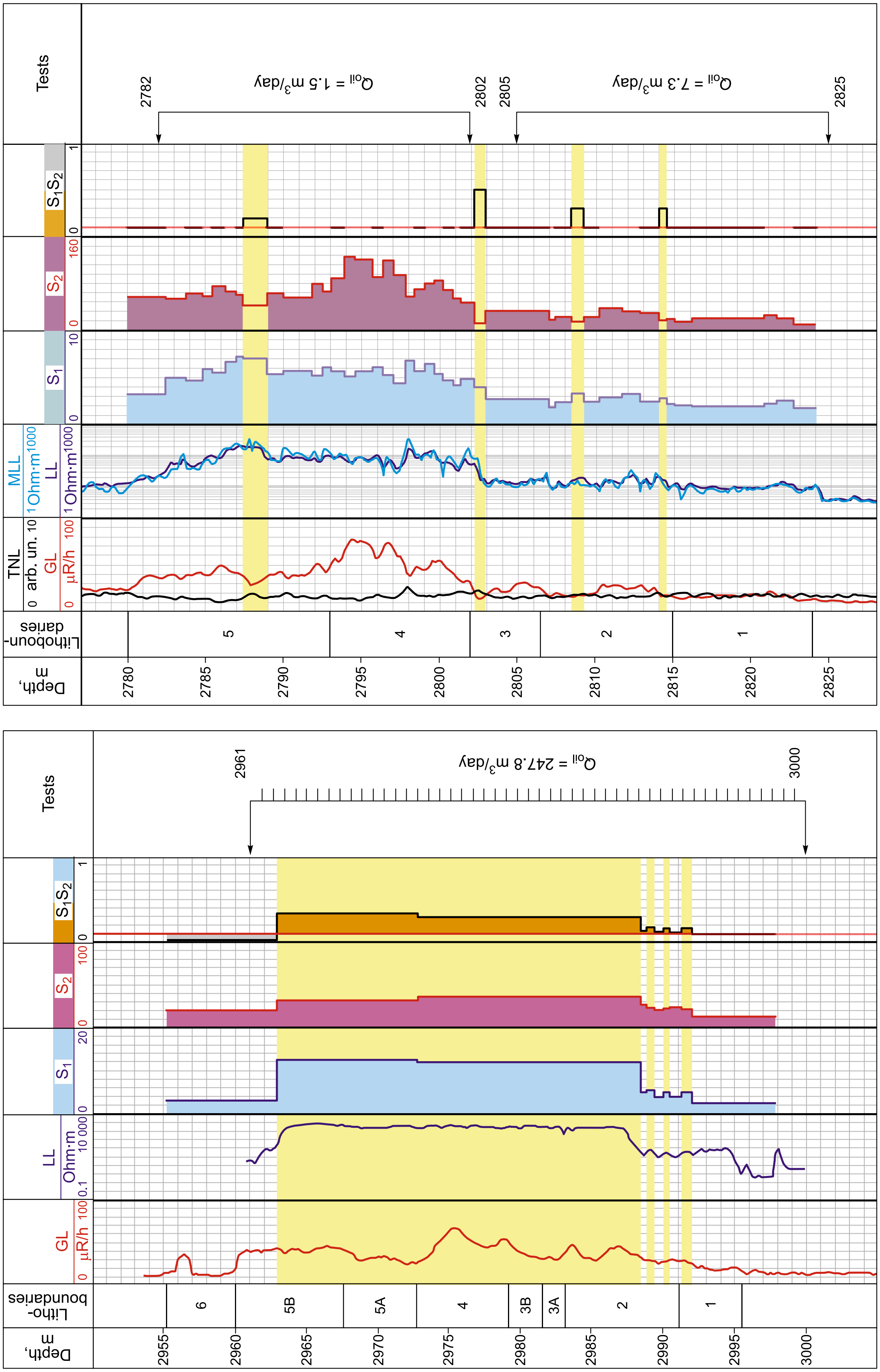

Fig. 9. Detection of effective oil-saturated thicknesses from the well-logging data obtained in a well with high production rate.

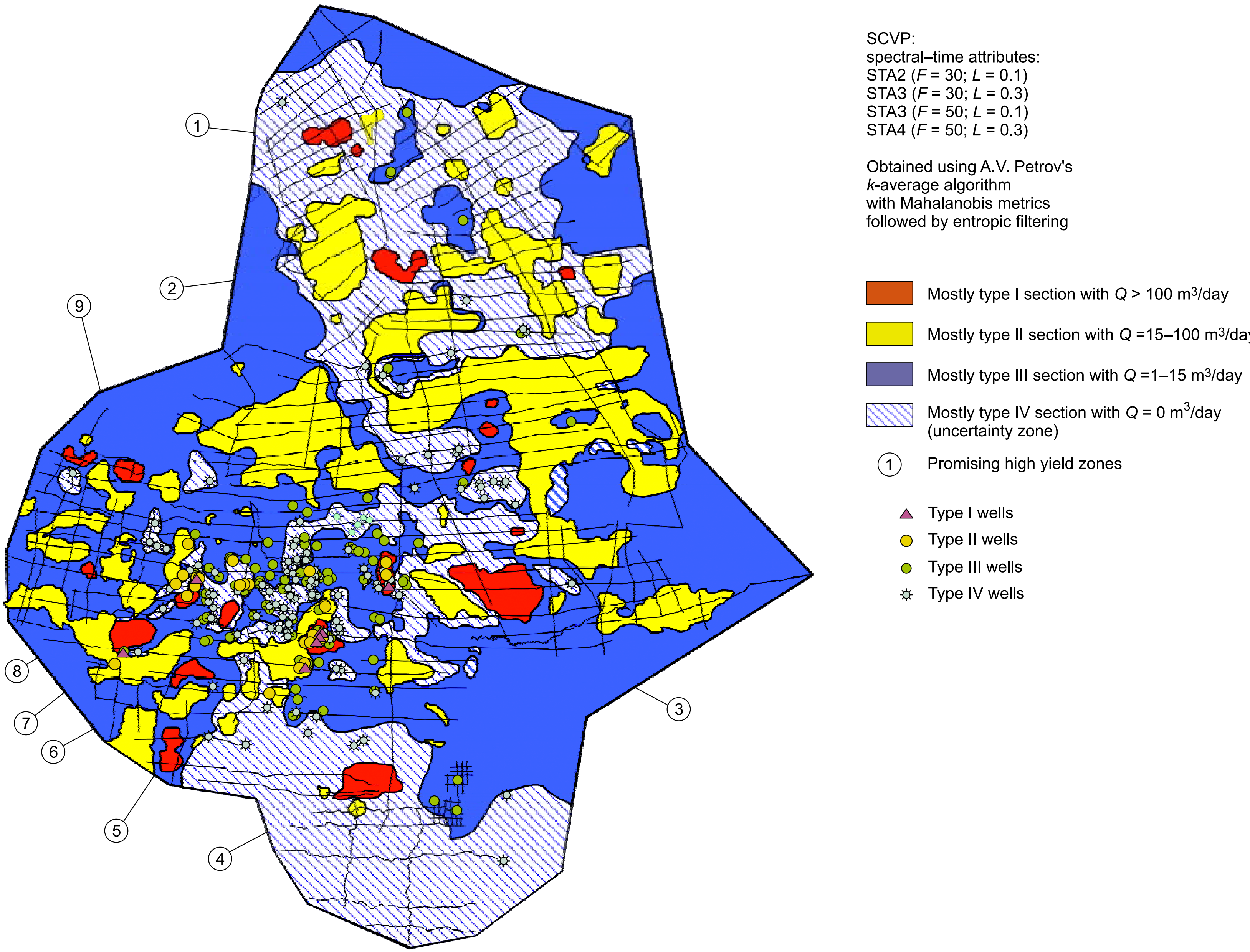

Fig. 10. Detection of effective oil-saturated thicknesses from the well-logging data obtained in a well with low production rate.

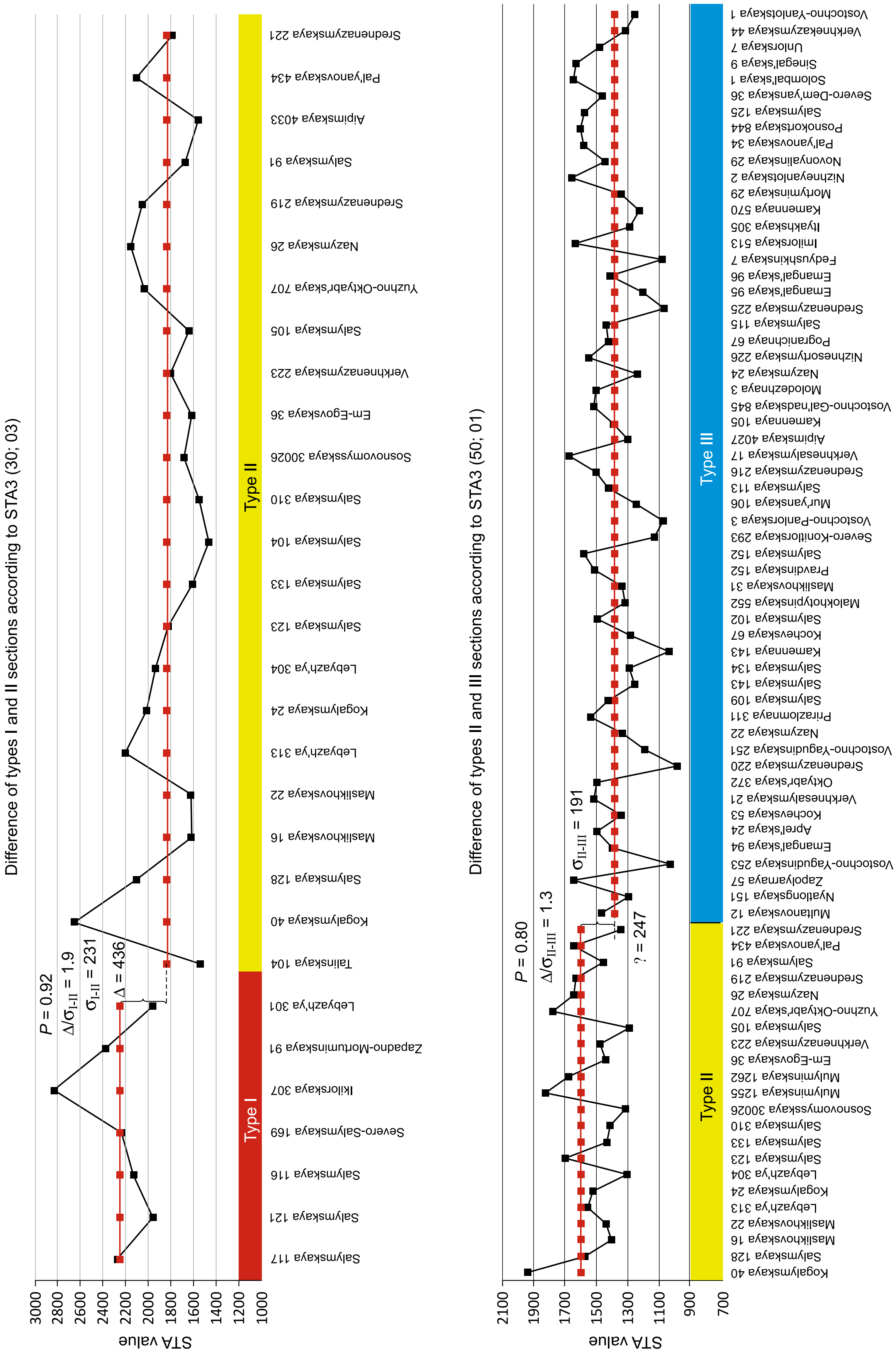

Fig. 10 (*to be continued*).

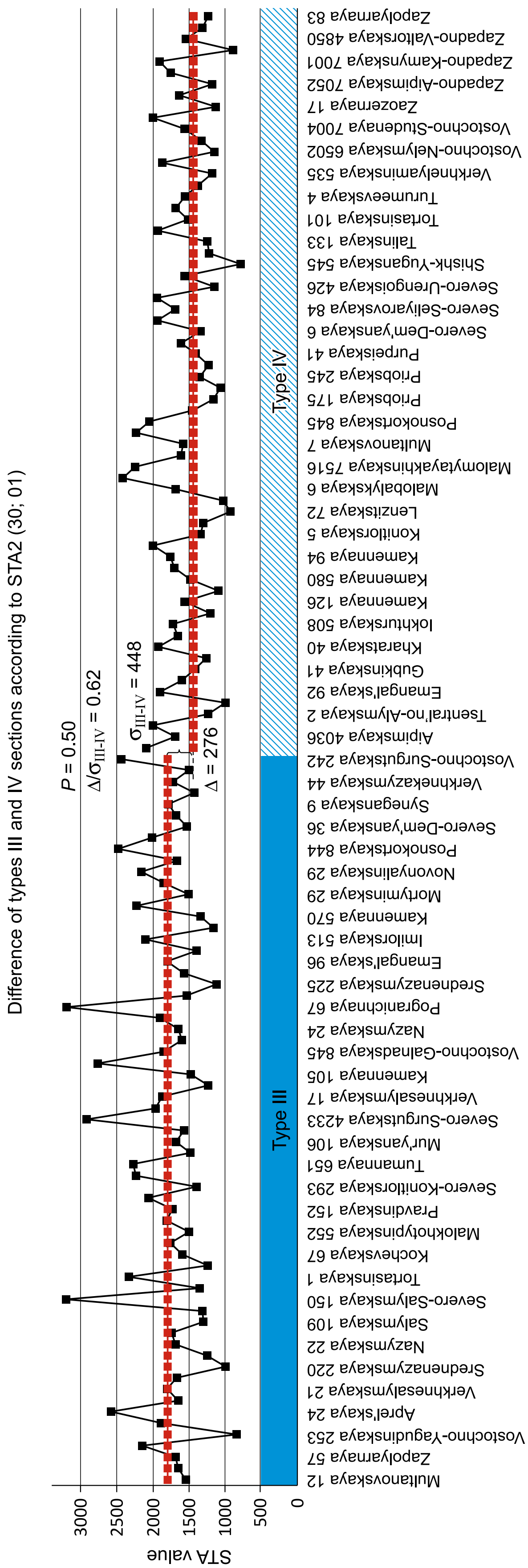

Fig. 10 (*continued*).

domain. In average (with confidence probability P = 0.86) these attributes allow one to distinguish the section type I from section type II (intermediate production rate) in the spectral-time attribute space and guarantee the high level of confidence for the following results after complex interpretation using spectral-correlation analysis (software package COSCAD 3Dt). In the same way, to distinguish section types II and III, attribute STA3 (F = 50; L = 0.1) was selected with the average attribute value difference Δ = 247 and the mean square difference σ = 191. For this case, the confidence probability was equal to 0.80. And finally, to distinguish section III and IV attribute STA2 (F = 30; L = 0.1) was selected. Unfortunately, its confidence probability did not exceed P = 0.5, so it was classified as an uncertainty area where sediments both dry sediments and sediments whose rate did not exceed 15 m^3/day could be found.

Thus, we selected four CSVP spectral –time attributes that allowed for confident distinction of different section types with average confidence probability P = 0.84. The next stage was spectral-correlation analysis followed by interpretation and building a map of section types, based on well rates that was performed in COSCAD 3Dt. The resulting map was obtained using A.V. Petrov's *k*-average algorithm with Mahalanobis metrics followed by entropic filtering. This map (Fig. 10) clearly defines such known fields as Salymskoe and Prirazlomnoe that are mainly within the zones of types I and II. Apart from them, 9 new perspective high-rate zone in the north, south, west and center of the region have been detected and will soon be subjected to survey seismic survey D and borehole surveying.

Later on, the prognostication map was limited to the distribution of the OM content of more than 5%, the zones with no reservoirs were corrected with account for newly interpreted wells, and an effective-thickness map was built for each fluid-content distribution zone.

Porosity. Since today there is no reliable method to determine porosity, in our computations its value was considered equal to the porosity distribution in the core samples with OM content of more than 5%. For the movable oil the average porosity value was considered to be equal 8.8% and for low-movable oil—4%.

Oil saturation. Wide distribution of hydrophobization in the Bazhenov Formation makes the volume taken by water (physically and chemically coupled) very small and it has never been properly studied. For that reason the water coefficient for the mineral reservoirs was considered equal to 5%, while the oil coefficient was considered to be 0.95.

Oil density and reciprocal formation volume factor were considered equal to 0.81 and 0.8 for the areas with light movable oil, as for the areas with residual oil they were 0.88 and 0.89, respectively.

Oil recovery value for the areas containing movable low-molecular hydrocarbons was considered equal to 0.15, and for areas with low-movable hydrocarbons to 0.1.

CONCLUSIONS

The performed calculations have revealed geological localized movable resources of 35.8 bln tons, including recoverable resources of 5.4 bln tons. In the areas with low-movable oil, the geological resources have been 43.2 bln tons, including recoverable resources of 4.2 bln tons. In total, the resources comprise 78.1 bln tons, including recoverable resources of 9.6 bln tons.

The performed study has demonstrated a correlation between free hydrocarbon content (S_1) and formation resistivity; residual kerogen oil generation potential (S_2) and gamma-logging, which makes it possible to detect effective oil-saturated fractures using well-logging data. The study has also demonstrated the advantages prospect mapping using seismic data.

The suggested methodological approaches to determine volumetric parameters can become a basis of a new method to calculate the resources of the Bazhenov Formation and estimate the resources of Domanic sediments.

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