



GEOLOGICAL AND GEOCHEMICAL ASSESSMENT OF THE DOMANIC FORMATION IN THE VYCHEGDA TROUGH: SOURCE ROCK CHARACTERISTICS AND HYDROCARBON GENERATION POTENTIAL

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ABSTRACT

The Vycheгда Trough is one of the least studied structures in the northern part of the Volga-Ural Basin. In the meantime, the presence of Domanic Formation deposits with possessing geological and geochemical characteristics of source rocks in the Vycheгда Trough area makes this territory promising. In this paper we have collected and summarized the results of studies of sediments of the Domanic Formation in the Vycheгда Trough, and conducted lithological and geochemical studies of core material of the Domanic Formation in a well close to the territory under consideration. Kinetic spectra of kerogen degradation were obtained, basin analysis was performed, which allowed to study the spatial and temporal regularities of development of the hydrocarbon source kitchen, realization of the hydrocarbon potential, as well as to reveal modern catagenetic zonality of the Domanic Formation of the Vycheгда Trough. It was established that the hydrocarbon potential of the Domanic Formation of the Vycheгда Trough was formed in the time interval from the Early to the Late Triassic inclusive, and the main the hydrocarbon source kitchen developed within the boundaries of submerged areas, confined mainly to the northeastern and southeastern parts of the object under study. The paper also evaluates the prospects of hydrocarbon potential of the Domanic Formation in terms of generation possibilities.

Keywords: Vycheгда Trough; Domanic Formation; hydrocarbon potential; basin modeling; source rock; generation potential.

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1. Introduction

The Volga-Urals Basin is the largest and oldest oil and gas producing region of the Russian Federation. Resources of this basin started to be developed in the 1920s and 1930s [1, 2]. To date, the degree of depletion of fields in the Volga-Ural Basin is about 60–70 % on average [3], and a significant part of the large fields is in the stage of declining production. However, the potential of the Volga-Ural Basin is not exhausted yet. Increase in reserves and resources of the basin can be ensured through exploration of new prospecting sites in areas that are very insufficiently studied by geological and geophysical methods; however, there are signs, including the presence of a thick sedimentary cover with potential source rocks and numerous hydrocarbon manifestations, that make them promising in terms of search for new hydrocarbon fields. Such areas include the Vycheгда Trough, located in the northern part of the Volga-Ural Basin (fig. 1).

The Vycheгда Trough is a tectonic structure of the first order of the Pre-Timan Foreland Trough extending over 400

km to the northwest along the South Timan with a width of 50–70 to 120 km [4]. Administratively, the object of study occupies a part of the south of the Komi Republic and the north of Perm Krai.

The interest to this territory is due to the fact that its Upper Paleozoic sedimentary infilling is pervaded with bituminous-clayey sediments of the Domanic Formation, which is one of the most representative in terms of area and section of source rocks in the east of the Russian Plate [5]. The Domanic Formation has been the subject of extensive research, with particular attention given to lithofacies structure [6–9] and source rock characteristics [10–12]. Overall, in spite of a rather extensive study of the Domanic Formation of the Volga-Ural Basin, there is only scant factual material on these sediments in the Vycheгда Trough, that appeared to be insufficient for a comprehensive and systematic characterization. In particular, there are no published results on the geological and geochemical conditions of the development of hydrocarbon potential in the Domanic Formation of the Vycheгда Trough. Thus, it is necessary to study the spatial and temporal regularities of formation of hydrocarbon source kitchen and realization of hydrocarbon potential

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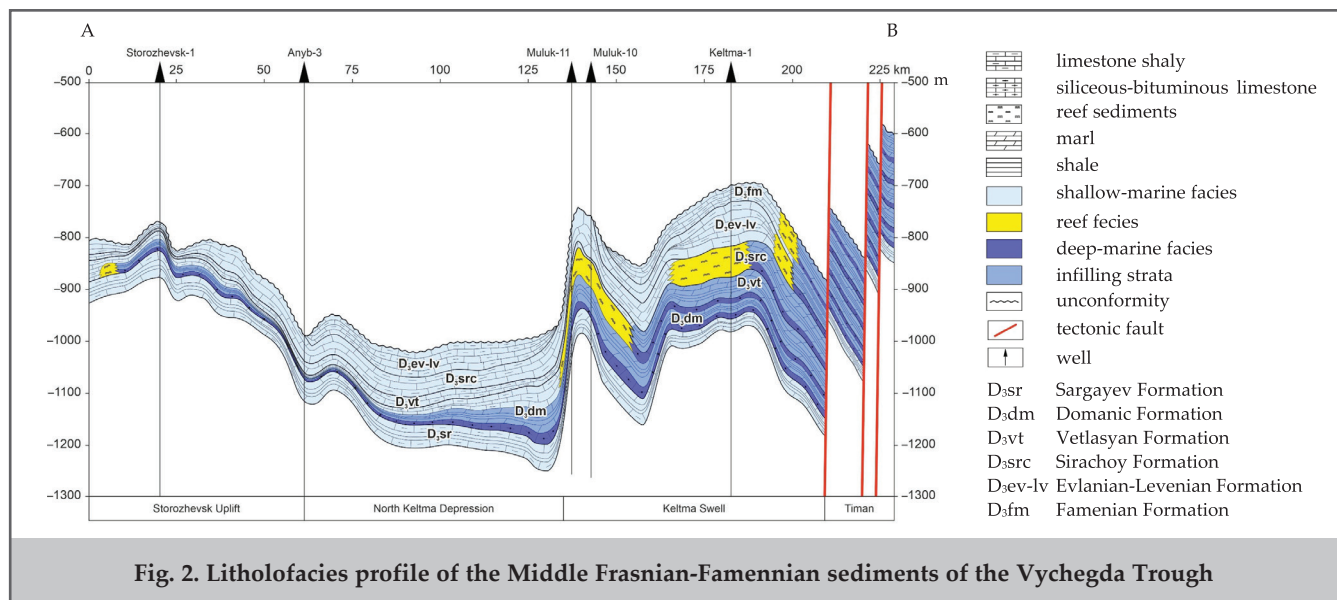
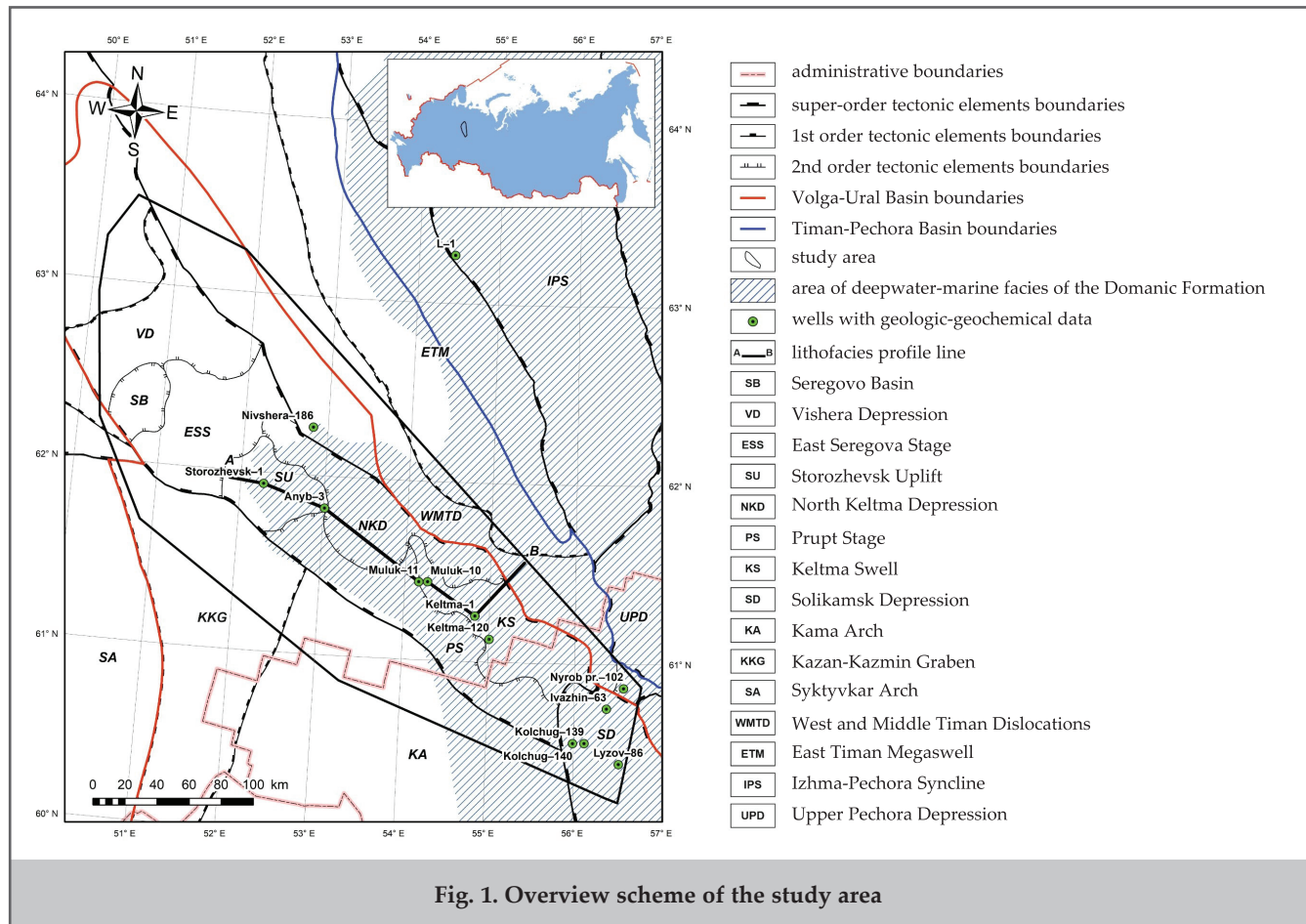
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of the Domanik Formation using such a modern research method as basin modeling.

The Domanik Formation section in the Vycheгда Trough and associated structures is characterized by a polyfacies structure. Overall, the Domanik Formation has a structure similar to that of the Upper Devonian-Tournaisian carbonate platforms, which are widely known and are oil-producing both in the Perm Region (within the Kama-Kinel Trough system) and the Komi Republic [13–17]. Laterally, this Domanik Formation is composed of a number of zones: the coastal, internal platform (shallow-marine shelf), plat-

form edge (barrier reefs), platform slope, and deep-water basin (moderate-deep-water shelf).

Of particular interest are the depressional facies acting as key source rocks. This type of section is rather extensive (fig. 1) and lies at absolute elevations varying from –600 to –1600 m, whereas in the area of Dzhezhim-Parma, Nem and Ksenofontovo Uplifts the sediments are wedged out and completely fall out of the section. The base of the Domanik Formation submerges from the central parts of the Vycheгда Trough toward the Timan Ridge and the Solikamsk Depression. The section of moderate-deepwa-



ter genesis was penetrated by wells at Storozhevsk (wells Storozhevsk-1, 80), Anyb (well Anyb-3), Nivshera (well Nivshera-186), Muluk (well Muluk-10) and Yelmach-Parma (wells Keltma 1, 120 and Yelmach-Parma-20) areas (fig. 2), where it consists of dark-colored (gray, black) pelitomorphic irregularly dolomitized limestones, clayey and clayey-bituminous, lenticularly silicified with marls and shales interbeds. Organic remains in the well cores include tentaculites, brachiopods, pelecypods, goniatites, and ostracods, which are typical of deepwater sedimentation conditions. The total thickness of the sediments varies from 12 to 68 m.

2. Materials and methods

Due to the lack of conditioned core material from deep wells of the Vycheгда Trough, the authors were unable to conduct their own analytical studies to determine the generation potential, type and maturity of organic matter (OM) of rocks of the Domanic Formation. As a consequence, the work focuses on generalization of historical geochemical data (pyrolytic, chemical-bituminological, and elemental composition of OM). In addition, the authors conducted experiments to obtain kinetic spectra of the Domanic Formation of the East Timan Megaswell, which was chosen as an analog for the Vycheгда Trough because these structures in the Middle Frasnian time belonged to a single area of uncompensated sedimentation [18, 19] with the formation of siliceous-bituminous-clayey sediments.

Core material from well L-1 in the East Timan Megaswell area was studied (see fig. 1). Two samples were taken from the interval of 925–948 m, photographed and briefly described lithologically in micro- and macro terms. The samples were extracted in Soxhlet apparatuses, chloroform bitumen extracts (B_{chl}) were isolated, pyrolytic parameters of the rocks were determined, and kinetic spectra were obtained on a HAWK pyrolyzer (Wildcat Technologies). A series of weighed quantities of the studied samples were heated at different rates (3, 5, 10, 30, 50 °C/min), after which pyrograms were processed in the specialized Kinetics2015 software to obtain kinetic spectra with non-fixed frequency factor (A) and fixed frequency factor ($A=1 \times 10^{14} \text{ sec}^{-1}$).

Basin modeling was used as the main tool for studying

the conditions of oil and gas potential formation. A regional model of the Vycheгда Trough (with an area of about 56000 km² and a cell size of 1000×1000 m) consisting of 40 layers (main stratigraphic subdivisions of the section and 54 tectonic faults) was created. The model takes into account the lithology and age of the layers, the initial generational parameters of source rocks, the periods of fault activation, erosion events and their thickness, and the boundary conditions: including heat flow, paleowater depth, and sediment water interface temperature.

3. Results and their discussion

Sediments of the Domanic Formation in the Vycheгда Trough have a generative potential varying from poor to excellent ($S_1+S_2=0.4-94.5$, average 16.2 mg HC/g rock) according to the classification [20] (fig. 3). The total organic carbon (TOC) content ranges widely from 0.2 to 11.7%. The OM is represented by kerogen of mixed (type II/III) and marine (type II) origin (HI=170–787 mg HC/g TOC). The catagenetic transformation of OM varies from immature ($T_{max}<430^\circ\text{C}$) to the main zone of oil formation ($T_{max}=438-448^\circ\text{C}$). According to the classification by N. B. Vassoevich and G. T. Filippi [21], the sediments are often characterized by increased and high bituminosity – the content of chloroform bitumen extracts (B_{chl}) ranges from 0.06 to 5% (average 0.5%).

The section of L-1 well is composed of interbedded brownish-gray clayey-bituminous, silicified, bioclastic fine-micrograined, thinly layered, dense, strong limestones with detritus and dark gray and black calcareous, bituminous, pyritized, thinly layered, brittle shales. Detritus is represented by tentaculites, brachiopod spheres and shells, and shell detritus. Overall, the sediments of the Domanic Formation of the East Timan Megaswell and the Vycheгда Trough have quite similar lithofacies characteristics, indicating the existence of a large-scale uncompensated sedimentation basin in the Late Devonian.

The authors selected samples of bituminous calcareous shales for the study. According to the description of thin sections, the rocks consist of clayey matter (60–65%), bituminous OM (15%), calcite (10–15%), plant detritus

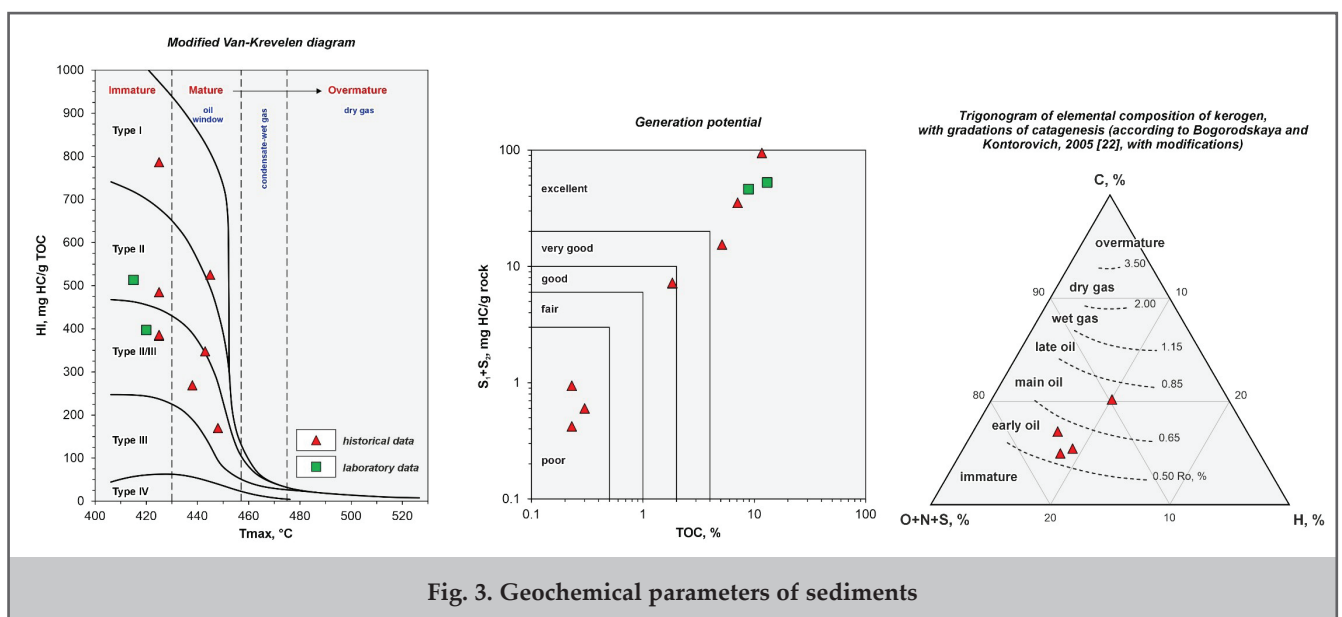


Fig. 3. Geochemical parameters of sediments

(8–10 %), rare grains of pyrite and quartz, as well as bioclasts (15%). The group composition of the isolated chloroform bitumen extracts is dominated by asphalt-resin fraction (more than 57%), which is typical of immature OM, while the content of saturated and aromatic hydrocarbons is 25–30 % and 12–14 %, respectively. The bitumoid coefficient ($\beta = (B_{chl}/TOC) \times 100\%$) is less than 25%. The results of pyrolytic studies (after removal of chloroform bitumen extract) also indicate low catagenetic transformation of kerogen ($T_{max} = 415\text{--}420\text{ }^\circ\text{C}$) (see fig. 3). The hydrogen index value $HI = 397\text{--}513\text{ mg HC/g TOC}$. The TOC content (8.9–13.1 %) and generative potential values (46.1–52.6 mg HC/g rock) suggest that the sediments is an excellent source rock (see fig. 3).

Analysis of the obtained kinetic spectra of the studied samples shows that the spectra are characterized by similar parameters of kerogen degradation. The distributions of activation energies (Ea) are characteristic of type II kerogen [23]. The spectra have an asymmetric shape with a shift to the region of lower Ea. In kinetic spectra with a non-fixed pre-exponential multiplier, the range of variation of Ea varies from 46 to 56 kcal/mol with a pronounced peak in the region $E_a = 48\text{--}49\text{ kcal/mol}$ (fig. 4). In kinetic spectra with a constant pre-exponential multiplier, the range of variation Ea is within 50 to 61 kcal/mol, with a peak corresponding to 54 kcal/mol (fig. 4). However, the spectra with a non-fixed frequency factor are somewhat different from each other; in particu-

lar, sample L-3 is characterized by the destruction of basic chemical bonds at a lower Ea, which is most likely due to the lower catagenetic transformation of OM [24], as well as its lithological composition.

In the absence of original kinetic spectra of immature source rocks of the studied object, library (standard) spectra or spectra of other geological objects that are similar in age, facies composition and kerogen type are used as analogs in basin modeling. In comparison with the known spectra [25–31], which are used for modeling the OM transformation processes of the Domanic Formation, the obtained kinetic spectra are characterized by a later onset of the kerogen to hydrocarbon transformation process and a narrower temperature range of the transformation ratio (TR) change (fig. 5). This peculiarity, apparently, is associated with variability of the Domanic Formation sediments in different territories and kerogen structural features. Notably, the spectra with non-fixed frequency factor reach the critical moment (TR is > 50% [32]) at temperatures of 132–136 °C, and with fixed frequency factor – at 151–153 °C.

Next, in order to restore the geological and geochemical conditions for the formation of the HC potential of the Domanic Formation, the kinetic spectra obtained during the experiments were incorporated into the regional model of the Vycheгда Trough. It is worth noting that spectra with a non-fixed frequency factor were used during the basin modeling stage. Spectra with a fixed pre-exponential factor were used

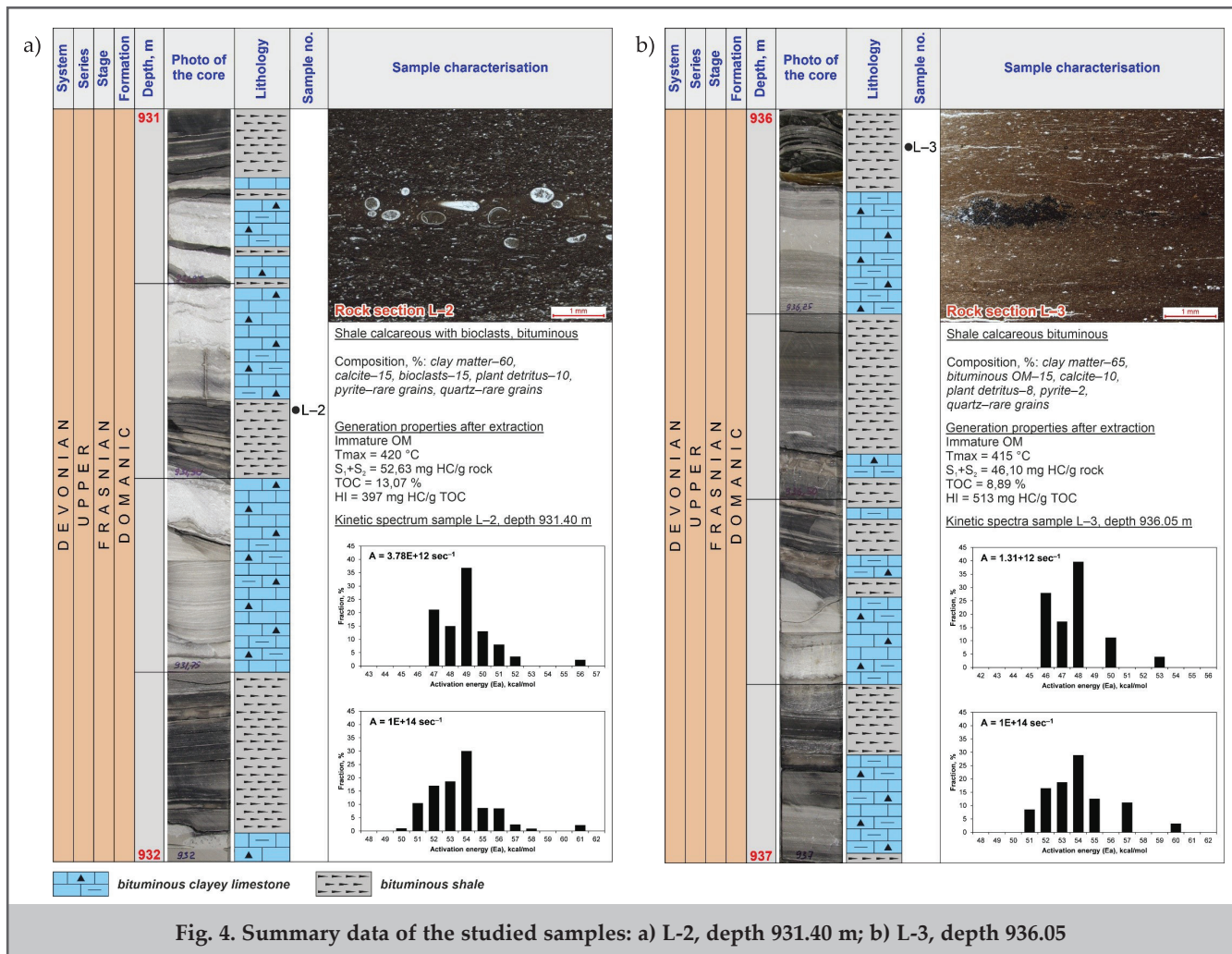


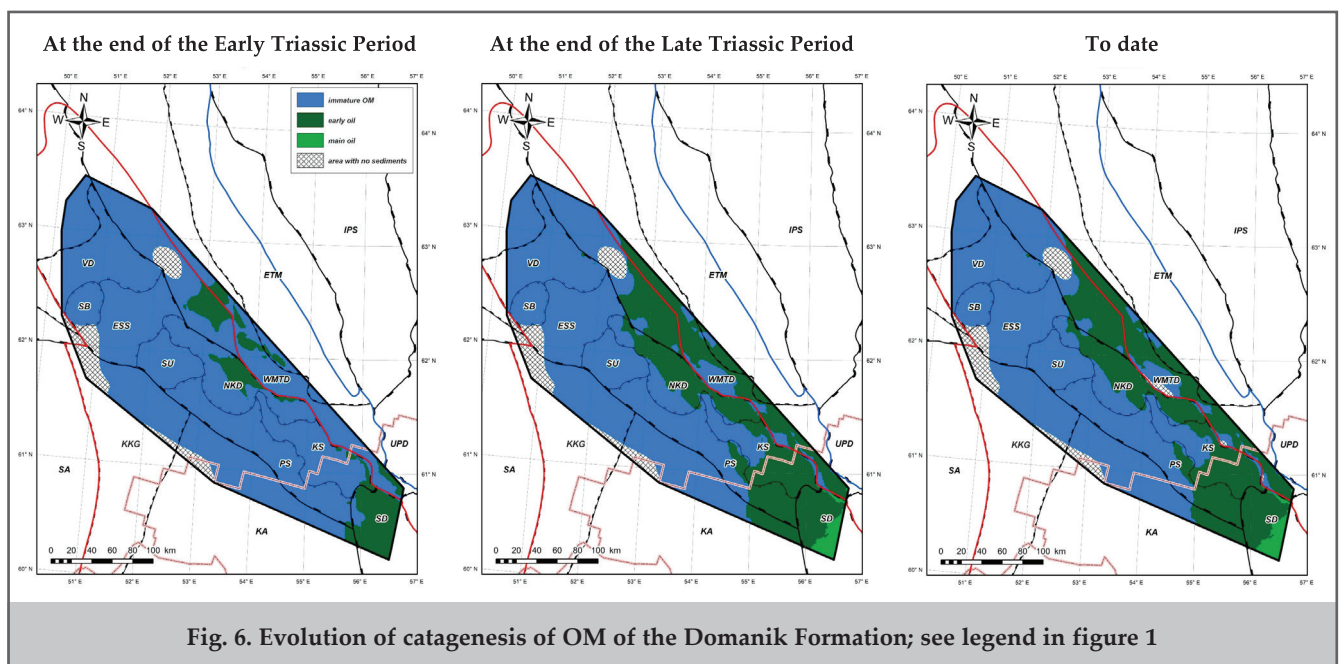
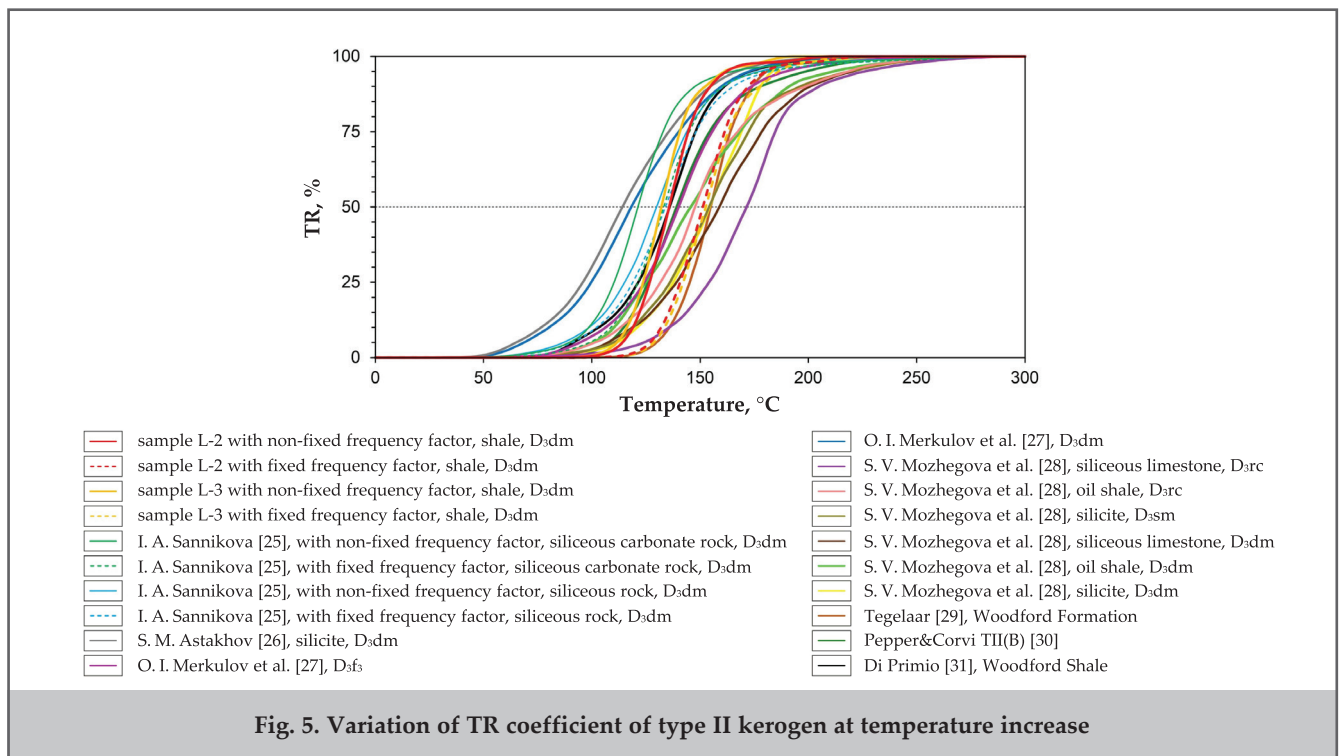
Fig. 4. Summary data of the studied samples: a) L-2, depth 931.40 m; b) L-3, depth 936.05

solely for comparison. Calculating generation processes using kinetic spectra with a non-fixed frequency factor allows for more reliable modeling results, as these spectra reflect the true characteristics of a specific sample under experimental conditions.

According to the results of basin analysis, the source rocks of the Domanik Formation in the area of the Vychehga Trough and associated structures in the Permian-Triassic period reached favorable conditions for the transformation of OM and entry into the main oil formation zone (fig. 6). In the territory, including the southeastern part of the Vychehga Trough, the Southern Timan and the Solikamsk Depression, similar catagenetic conditions for the onset of oil formation were formed during this geological period. The reason for this was the intensification of the temperature field of the

subsurface due to an increased heat flow, which was caused by the tectonic activity of the Timan ridge [33], the orogeny of the Ural and thrust processes in the inner zone of the Cis-Ural marginal trough [34–38]. It is worth noting that the thermobaric conditions necessary for the onset of hydrocarbon generation were the same only in the Paleozoic paleo-depressions of the Vychehga Trough, the Timan Ridge and the Solikamsk Depression (fig. 7). As we move west, northwest and southwest from these structures, the catagenetic maturity of OM in the rocks significantly decreases, which is associated with a decrease in the depth of the source rocks and an increase in the distance from the main Permian-Triassic epicenters with an elevated temperature field.

The peak of oil generation in the Domanik Formation occurred in the time interval from the Early to the Late Triassic



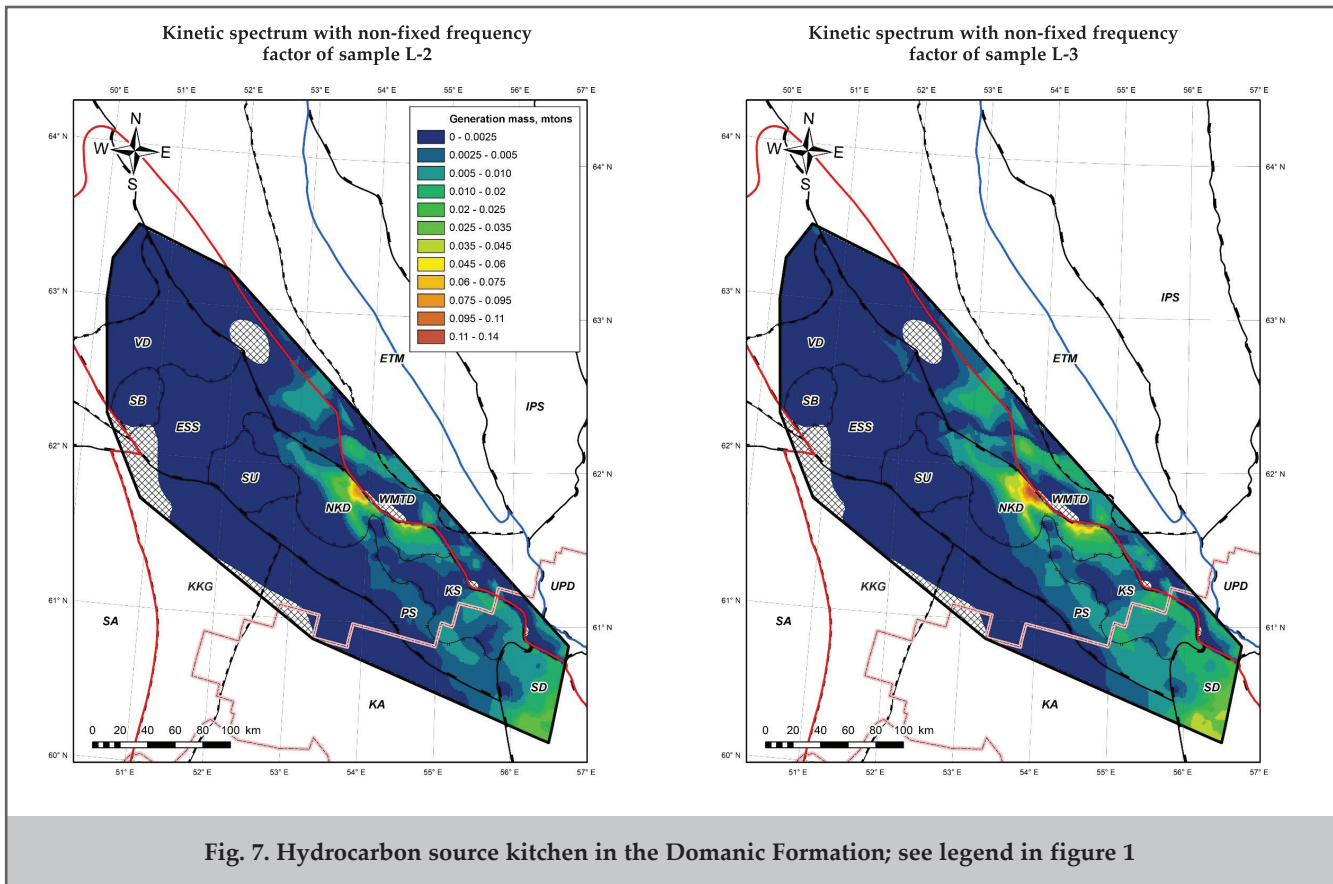


Fig. 7. Hydrocarbon source kitchen in the Domanic Formation; see legend in figure 1

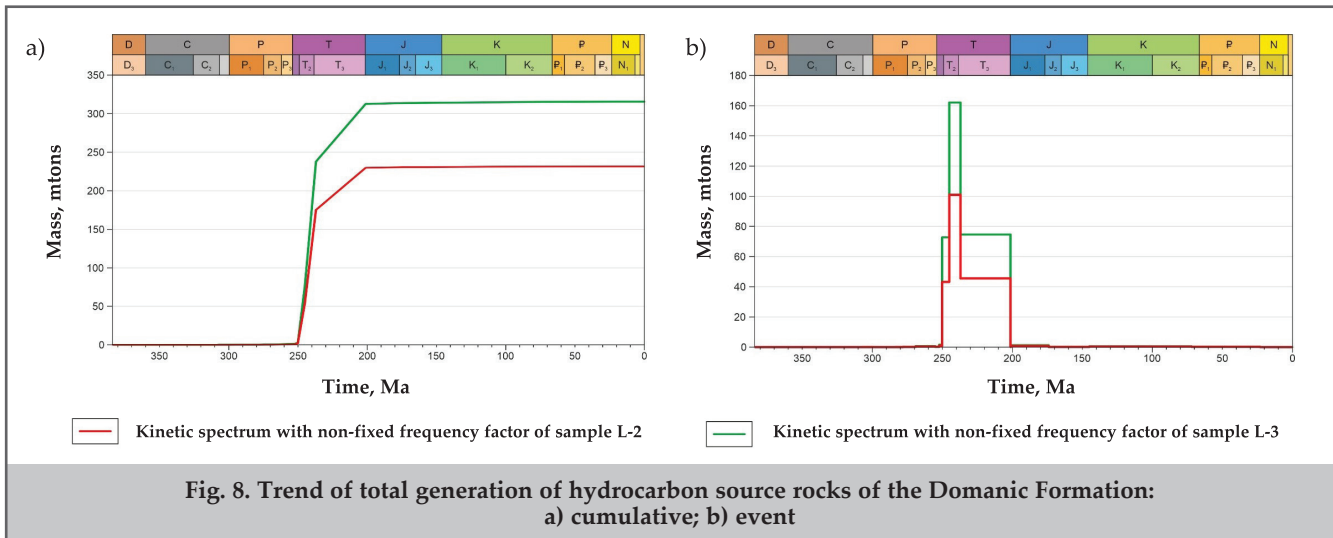


Fig. 8. Trend of total generation of hydrocarbon source rocks of the Domanic Formation: a) cumulative; b) event

inclusive (fig. 8). After that, insignificant hydrocarbon generation processes occurred until the Neogene, which is associated with the influence of regional inversion movements in the Early Jurassic and Late Cenozoic [39, 40].

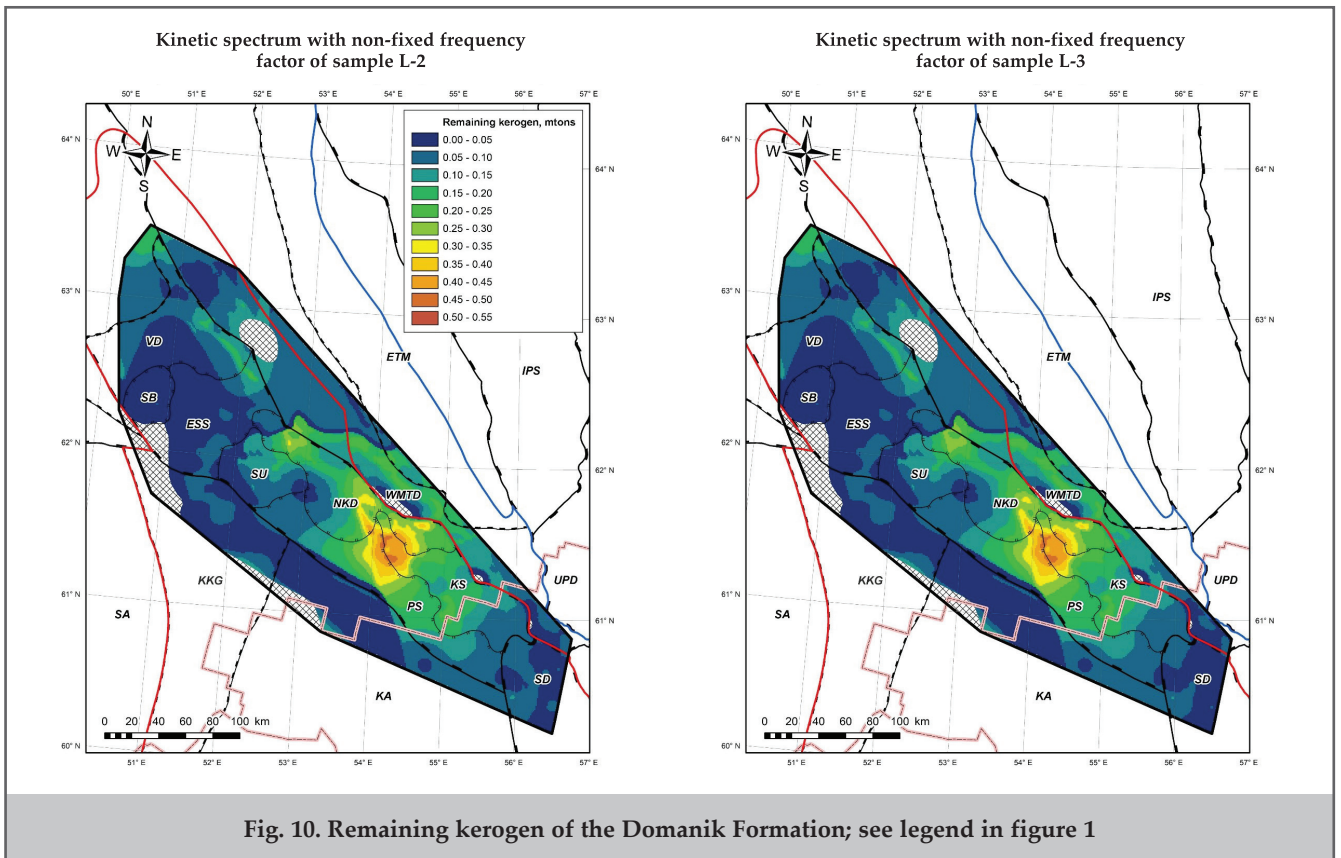
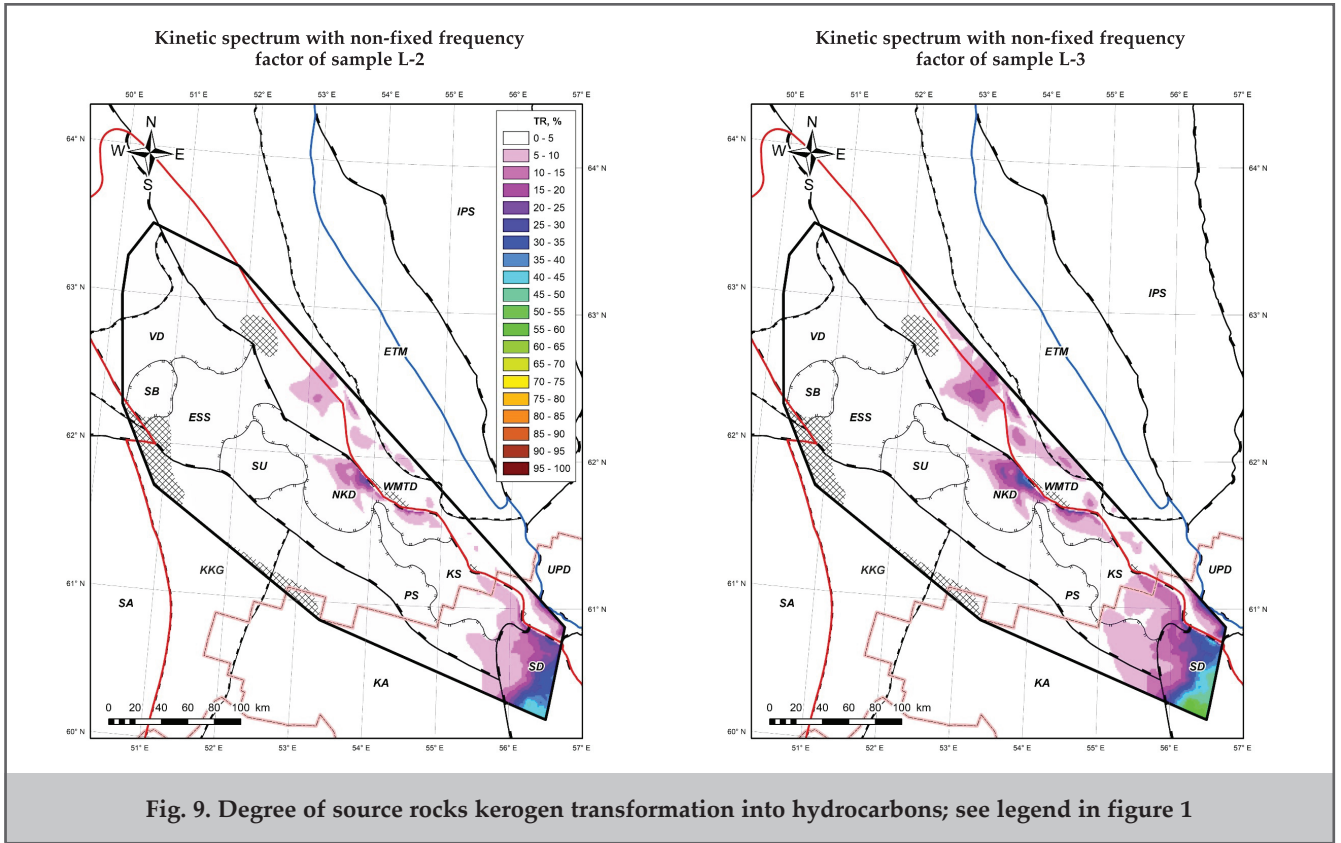
On the basis of the obtained models, one can assume the presence of catagenetic zonality in the Domanic Formation. In the northwestern and southwestern areas of the Vychevda Trough, the OM maturity corresponds to early catagenesis (immature). Along the South Timan structures and in the southeast of the Vychevda Trough, the OM transformability reaches the oil window (see fig. 6). First of all, it is characteristic of the Lopyu, Pomozdino, and North Keltma Depressions and the areas opening into the Pre-Ural Trough. These areas also correspond to higher TR OM ranging from 5 to 40%, increasing to 60% in the Solikamsk

Depression. In the remaining area of the Vychevda Trough, TR does not exceed 5% (fig. 9).

When assessing the prospects of the Domanic Formation in terms of its generative capabilities, it is evident that the highest remaining kerogen – source rocks are predicted in the central regions of the Vychevda Trough (fig. 10), in particular, in the Keltma Swell, the Storozhevsk Uplift, the Prupt Stage, and the North Keltma Depression. This pattern is related to the widespread occurrence of bituminous-clayey sediments in this area, which have a lower thermal maturity of kerogen. Previously, many authors [41–44] assessed this area as one of the most promising in terms of prospecting and exploration works, considering that abundant bitumen and oil manifestations in Carboniferous and Permian sediments were detected there.

To summarize, the use of the original kinetic spectra makes it possible to obtain more correct results of basin analysis relative to the results obtained when using standard kinetic spectra. The use of the studied spectra in basin modeling of the Vycheгда Trough territory showed similar features of the formation of hydrocarbon potential of the Domanik Formation.

However, when modeling the processes of oil and gas formation using the kinetic spectrum of a less catagenetically transformed sample, the source rocks have an earlier onset of hydrocarbon potential realization, a relatively larger scale of hydrocarbon source kitchen and, consequently, are characterized by lower residual generation characteristics.



Conclusions

- The research included laboratory experiments for obtaining original kinetic spectra of kerogen degradation in the Domanic Formation, which were further applied to restore the geological and geochemical conditions of the Domanic Formation hydrocarbon potential formation in the territory of the Vycheгда Trough by means of basin modeling.
- Based on the results of basin analysis, the active phase of oil generation in the Domanic Formation was determined, corresponding to the time interval from the Early to the Late Triassic inclusive. Relatively large hydrocarbon source kitchen located in the Lopyu, Pomozdino, North Keltma Depressions and areas opening into the Pre-Ural Trough were identified.
- The transformation of source rocks kerogen into hydrocarbons was estimated, which in general is not more than 5% and increases up to 40–60 % in hydrocarbon source kitchen. The modern catagenetic zonality of the section has been established, indicating that in most parts of the Vycheгда Trough the source rocks contain low catagenetic maturity OM. Towards the northeast and southeast, the sediment transformability increases up to oil window.
- The obtained models and conclusions supplement the results of research by other authors, and also introduce new concepts regarding the conditions of formation of hydrocarbon potential of the Domanic Formation, which can serve as auxiliary criteria for further regional studies of hydrocarbon potential in the Vycheгда Trough.

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