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Forecast of the Geothermal and Geochemical Conditions of the Mrakovskaya Depression and the Adjacent Territories of the Shikhano-Ishimbayskaya Saddle

Svetlana E. Bashkova[1,2], Yury A. Yakovlev[1,2], Anastasia S. Kapitanova[3], Andrey N. Bashkov[4]

[1]Perm State National Research University (15 Bukireva st., Perm, 614068, Russian Federation)
[2]Kama Research Institute for Comprehensive Studies of Deep and Ultra-Deep Wells (15 Krasnoflotskaya st., Perm, 614016, Russian Federation)
[3]PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)
[4]Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

Прогноз геотермических и геохимических условий Мраковской депрессии и прилегающих территорий Шихано-Ишимбайской седловины

С.Е. Башкова[1,2], Ю.А. Яковлев[1,2], А.С. Капитанова[3], А.Н. Башков[4]

[1]Пермский государственный национальный исследовательский университет (Россия, 614068, г. Пермь, Букирева, 15)
[2]Камский научно-исследовательский институт комплексных исследований глубоких и сверхглубоких скважин (Россия, 614016, г. Пермь, ул. Краснофлотская улица, 15)
[3]Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми, (Россия, 614015, г. Пермь, Пермская, 3а).
[4]Пермский национальный исследовательский политехнический университет (Россия, 614990, г. Пермь, Комсомольский пр., 29)

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The actual problem of analyzing the conditions of oil and gas formation in poorly studied areas, such as the Mrakovskaya depression and the adjacent territory of the Shikhano-Ishimbai saddle (the southern part of the Pre-Ural trough and the West Ural outer folding zone) is considered. These territories, which have a complex heterogeneous geological structure and low exploration, are of undoubted interest from the point of view of potential oil and gas potential. The paper considers the main geological factors that determine the geothermal regime of the subsoil of the southern part of the Pre-Ural trough and the West Ural outer folding zone. An extremely low and uneven density of geothermal observation points was noted in the wells of the Mrakovskaya depression and the Shikhano-Ishimbai saddle. Maps of predicted modern temperatures on deep sections of the study area, as well as geothermal gradients of various parts of the Ural region, were constructed and analyzed. Materials on paleotemperature-catagenetic studies of the sedimentary cover were presented. Predictive maps of changes in the catagenesis of sedimentary substances in Paleozoic deposits within the stratigraphic units of the territory under consideration were constructed. To restore the geotemperature regime of the subsoil and predict the catagenetic zoning of the section, one-dimensional basin modeling of three wells located in the southern and northern promising areas was performed.
Prediction of geothermal and geochemical conditions with a complex heterogeneous structure is a difficult task associated with insufficient information on the structure and composition of deposits, lack of information about the geothermal conditions of sections, inconsistency of geophysical data, etc. The conducted studies showed the effectiveness of combining actual data with calculation methods in predicting geothermal and geochemical conditions. The results obtained by the authors made it possible to conclude that there were rather high prospects for the discovery of petroleum hydrocarbons in a wide range of the Paleozoic part of the section.

Ключевые слова:
Предуральский прогиб, Западно-Уральская зона складчатости, Мраковская впадина и Шихано-Ишимбайской седловина, бассейновое моделирование, нефтегазоматеринские породы, палеотемпературные условия, отражательная способность витринита, главная зона нефтеобразования, главная зона газообразования, формирование и перспективы нефтегазоносности.

Рассматривается актуальная проблема анализа условий нефтегазообразования малоизученных районов, таких как Мраковская депрессия и прилегающая территория Шихано-Ишимбайской седловины (южная часть Предуральского прогиба и Западно-Уральская внешняя зона складчатости). Указанные территории, имеющие сложное гетерогенное геологическое строение и низкую изученность, представляют несомненный интерес с точки зрения потенциальной нефтегазоносности. В работе рассматриваются основные геологические факторы, определяющие геотермический режим недр южной части Предуральского прогиба и Западно-Уральской внешней зоны складчатости. Отмечена крайне низкая и неравномерная плотность пунктов геотермических наблюдений в скважинах Мраковской депрессии и Шихано-Ишимбайской седловины. Построены и проанализированы карты прогнозных современных температур на глубинных срезах изучаемой территории, а также геотермические градиенты различных частей Уральского региона. Представлены материалы по палеотемпературно-катагенетическим исследованиям осадочного чехла. Построены прогнозные карты изменения катагенеза органических веществ палеозойских отложений в пределах стратиграфических подразделений рассматриваемой территории. Для восстановления геотемпературного режима недр и прогноза катагенетической зональности разреза выполнено одномерное бассейновое моделирование трех скважин, расположенных на южном и северном перспективных участках.
Прогноз геотермических и геохимических условий, имеющих сложное гетерогенное строение, представляет собой непростую задачу, связанную с недостаточным объемом информации по строению и составу отложений, недостатке сведений о геотермических условиях разрезов, противоречивостью геофизических данных и т.д. Проведенные исследования показали эффективность комплексирования фактических данных с расчетными методами при прогнозе геотермических и геохимических условий. Результаты, полученные авторами, позволили сделать вывод о достаточно высоких перспективах обнаружения нефтяных углеводородов в широком диапазоне палеозойской части разреза.

Svetlana E. Bashkova (Author ID in Scopus: 37561140000) – PhD in Geology and Mineralogy, Associate Professor of the Department of Regional and Petroleum Geology, Scientific Secretary; Deputy Head of the Department of Scientific Support for Parametric and Ultra-Deep Drilling (tel.: +007 951 936 74 60, e-mail: sbashkova@mail.ru). The contact person for correspondence.
Yury A. Yakovlev (Author ID in Scopus: 57216374073) – PhD in Geology and Mineralogy, Associate Professor, Associate Professor of the Department of Hydrogeology, Advisor to the Department of Geology and Petroleum Potential (tel.: + 007 (912) 882 17 67, e-mail: yyakovlev@yandex.ru).
Anastasia S. Kapitanova – 2nd category Engineer (tel.: +007 902 830 15 12, e-mail: kapitan19.95@mail.ru).
Andrey N. Bashkov – PhD in Geology and Mineralogy, Associate Professor of the Department of Geology of Oil and Gas (тел.:+007 912 882 94 91, e-mail: bashkov41@yandex.ru).

Башкова Светлана Евгеньевна – кандидат геолого-минералогических наук, доцент кафедры региональной и нефтегазовой геологии, ученый секретарь; заместитель начальника отдела научного сопровождения параметрического и сверхглубокого бурения (тел.: +007 951 936 74 60, e-mail: sbashkova@mail.ru). Контактное лицо для переписки.
Яковлев Юрий Александрович – кандидат геолого-минералогических наук, доцент, доцент кафедры гидрогеологии, советник Департамента геологии и нефтегазоносности (тел.: + 007 (912) 882 17 67, e-mail: yyakovlev@yandex.ru).
Капитанова Анастасия Сергеевна – инженер второй категории (тел.: +007 902 830 15 12, e-mail: kapitan19.95@mail.ru).
Башков Андрей Николаевич – кандидат геолого-минералогических наук, доцент кафедры геологии нефти и газа (тел.:+007 912 882 94 91, e-mail: bashkov41@yandex.ru).

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Introduction

The territory of the Pre-Urals depression and the West-Urals folding zone are of certain interest for the assessment of potential oil-and-gas-bearing capacity. In the Southern Urals Mrakovsk depression and Shikhano-Ishimbay saddle can be considered as the most perspective regions.

The study of the catagenetic features of the section includes a sequential assessment of the current geothermal field and the main factors of its formation, paleogeothermal characteristics and calculation of the degree of catagenesis based on analytical dependencies. A logical continuation of these studies is the implementation of basin modeling, which integrally takes into account the history of the section formation, its transformation, paleotemperature and dynamic conditions.

Major geological factors of the Geothermal Field Formation

By now, significant factual material has been accumulated on the regional geothermia of the section, predictive estimation of the value of the thermal field, and the construction of digital geothermal models of the lithosphere of the Urals and the Pre-Urals has been carried out. The research was reflected in the works of Y.A. Yezhov, V.E. Salnikov, Y.I. Galushkin, V.D. Khutorsky, I.V. Golovanova [1–18].

The following factors should be considered as the main ones in the formation of the geothermal regime of the territory:

– particular features of tectonic development and sedimentation [19–22];

– paleoclimatic conditions as a consequence of global tectonic and planetary processes [1, 11, 15, 16, 24–29].

– geological-structural and paleogeographic conditions for the formation of macroheterogeneity of the heat-conducting properties of the section, geothermal anomalies of local structures and salt diapirs [7, 16, 30].

– the probability of formation of frictional heat sources during the formation of thrust structures [18, 31–34].

The estimation of the magnitude of heat fluxes and the evolution of the thermal regime of the Southern Urals and the adjacent part of the Pre-Ural depression have been repeatedly considered by I.V. Golovanova, Y.A. Galushkin, and M.D. Khutorsky [1–4, 7, 18, 33].

Depending on the quality of the initial data, the research methodology and the authors' ideas, the quantitative estimates of the heat flux may vary. Thus, according to V.E. Salnikov (1984), the value of the heat flux for the region under study is estimated to be from 23 to 33 mW/m^2. The eastern margin of the Russian platform adjacent to the Urals is characterized by V.A. Shchapov (2006) as a zone with heat flux values of 35–40 mW/m^2. According to M.D. Khutorsky, heat flux values in the range of 19–34 mW/m^2 are typical for the studied area [18]. Higher heat flux values for the Pre-Ural depression and the West Ural outer folding zone are presented in the works of I.V. Golovanova [7, 8, 11]. For the Mrakovsk depression, the heat flux is estimated in the range of 23–58 mW/m^2 (average 40 mW/m^2) according to 11 measurements, and 40–50 mW/m^2 taking into account paleoclimatic corrections. For the Shikhano-Ishimbay saddle (three measurements), similar indicators correspond to the range of 33–37 mW/m2 (average 35 mW/m^2) and 40–50 mW/m^2, taking into account paleoclimatic corrections. The West Ural folding zone and the Pre-Ural trough, together with the eastern part of the Volga-Ural anticlines, belong to the vast Ural Region with general reduced heat flux values and local zones (sections) of its sharp differentiation (from 23 to 58 mW/m^2), but are not included in the Ural zone of abnormally low heat flux values. In the eastern part of the Mrakovskaya depression there is a local Isimovsk anomalous zone with a heat flux value of up to 48–58 mWt/m^2 [7, 8, 11].

The density of geothermal observation points in the wells of the Mrakovsk depression and the Shikhano-Ishimbay saddle is estimated as low and extremely uneven, since almost all temperature measurements were made in wells in oil fields. In the eastern regions of these structures, as well as in the adjacent zone of the folded Urals, there are no points of geothermal observations in the wells.

The analysis of the modern temperature field of the studied area was based on the data presented in the works of Y.A. Ezhov and I.V. Golovanova in the form of regional schemes of isotherms on the roof of sediments, isotherms on sections, geothermal profiles, single and generalized thermograms.

An example of isotherm schemes is a map of temperatures reduced to the roof of Domanic deposits [35]. It illustrates a clear trend of a sharp increase in temperatures in the Shikhano-Ishimbay saddle and, especially, in the Mrakovsk depression with an increase in the depth of sediments. Regional maps of isotherms on cross-sections are also informative [13]. For the area of the Mrakovsk depression, a geothermal profile drawn through the study area with a temperature forecast in the adjacent eastern structures is indicative. The works of I.V. Golovanova et al. [9, 11] present small-scale schemes of predictive isotherms of the southern part of the Republic of Bashkortostan on sections of minus 2000, minus 5000 and minus 1000 m, calculated with the consideration of the heat flux values corrected for the influence of paleo climate. With a high general differentiation of the thermal field elevated temperatures are characteristic of the area of the Mrakovskaya depression. Mapping of forecast temperatures at minus 500 m, minus 1000 m, minus 2000 m, minus 3000 m, minus 5000 m and minus 10000 m according to the geothermal data of the IG USC RAS showed the following: a general increase in the differentiation of the temperature field with depth, the probability of the presence of a geothermal anomaly in the area of the Saratov structure near the western border of the southern prospective area under conditions of presumably high thermal conductivity insulation of the section, as well as a relatively low temperature background in the areas of the southwestern border of the northern prospective area, which may be caused by the increased thermal conductivity of the Permian salt diapirs of the Voskresensky Val in the upper part of the section.

Indicative parameters are geothermal gradients of various parts of the Ural region. According to Yu.A.Yezhov (1968), the lowest average geothermal gradient is characteristic of the “cooled” structures of the central Urals (1,73 °C/100 m). In conditions of high geothermal isolation of the Trans-Urals section the gradient reaches a value of 4,77 °C/100 m. For the Pre-Urals the average gradient is estimated at 1,86 °C/100 m, which actually corresponds to platform conditions. The predicted values of interval geothermal gradients of the studied area are 1,0–3,2 °C/100 m. In the Western and Central zones the average geothermal gradient of the upper part of the section (up to minus 1000 m) corresponds to a relatively low average value of 1,6 °C/100 m, which can be determined by high thermal conductivity of Permian halogen deposits. In the interval of minus 1000 - minus 5000 m the average gradient increases to 1.7-1.8 ‰ C/100 m. The minimum predicted value of the average gradient is assumed in the interval below minus 5000 m (1.3 ‰ C/100 m) and can only be associated with increased thermal conductivity of the section at great depths. The southeastern zone is characterized by higher average geothermal gradients which may be predetermined by increased geothermal isolation of the section. Differences between the southeastern zone and the western and central zones can be seen in the generalized thermogram of the actual final temperatures in the wells of the region (Fig. 1).

According to the equations obtained the geothermal gradient in the southeastern zone can be estimated at 2.7 °C/100 m, and in the western and central zones – 1.4 °C/100 m.

Paleogeothermal zonation of deposits

The peculiarities of the paleotemperature zoning of the southern part of the Pre-Ural trough were considered in the works of Gorshkov [12]. Based on the materials of paleotemperature-catagenetic in the Lower Permian and Lower Carboniferous deposits of the southern part of the Pre-Ural trough, zones of medium and high catagenesis are distinguished. Most of the northern section and the entire southern part are located in the zone of high catagenetic transformations and paleotemperature. This zone is characterized by a flake-thrust structure of the sedimentary cover, which is confirmed by the study of well sections of the Taushskaya and Berkutovskaya areas. The Famennian-Tournaisian deposits in the zone of the Zilair synclinorium (Zilair series), thrust over the younger complexes of Devonian and Carboniferous deposits, are most likely transformed to the stage of apocatagenesis, and paleotemperature may be 220–250 °C. The catagenesis of sub thrust (autochthonous) deposits of the Middle and Lower Carboniferous corresponds to gradations of MK_2–MK_4 and paleotemperature equal to 140–210 °C.

At determination of the vitrinite reflectance (VR) on the core of wells drilled in the West Ural folding-thrust zone and the subsequent interpretation of the results obtained catagenetic unconformities and the inversion nature of catagenesis are quite often noted. This is most often associated with the intersection of the suture zones of thrust dislocations by the borehole. For example, well 7409 of the Berkutovsk area in the interval of 3848–3870 m revealed deposits of the Upper Carboniferous with MK2 catagenesis. It is possible that such a low catagenesis at a considerable depth may indicate that there is a thrust displacement above the specified interval, and the deposits of the Lower Carboniferous are thrust by formations catagenetically more transformed.

In complex conditions of fold-thrust structure and the presence of inversion movements together with the application of the SALT method, it is advisable to use computational methods and basin modeling programs in the prediction of catagenetic zoning.

As a result of the application of computational methods it has been constructed prognostic maps of changes in the catagenesis of organic substances (OS) of Paleozoic deposits within the stratigraphic subdivisions of the territory under consideration (Fig. 2). There is a general tendency to increase the catagenetic transformation of rock agents in the area in the submeridianal direction from north to south, and in the section from the Permian to the Devonian deposits, reaching late mesocatagenesis (MK4). For the Permian deposits, the chemical agent in a large part of the territory is at the stage of protocatagenesis. The Bashkir and Tula deposits are characterized by a wide range of changes in the catagenetic transformation of the chemical agent from protocatagenesis (PC_2) to mesocatagenesis (MC_3). Chemical agent is the least catagenetically transformed in the north of the territory in the Kurgashlinsk, Uruzbayevsk, Khlebodarovsk, and Ishtuganovsk areas. In the Taushsk and Saratovsk areas the OS reaches 1,0 % (MC_3). For the Tournaisian deposits OS in most of the area has been transformed to the sub stage MC_4.

Domanic deposits throughout the study area are in mesocatagenesis (MC1–MC4). For the Kynov-Pasha deposits, the OS in the southern regions is at the late stage of mesocatagenesis (MC4), the OSV is more than 1.5 %. Less catagenetically transformed OS is characteristic of the northern and central regions, the catagenesis of OS does not

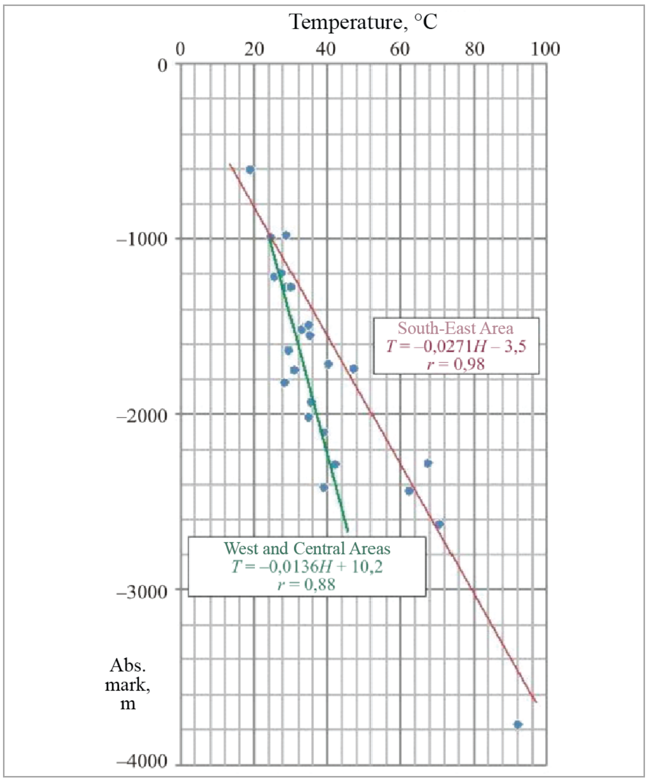

Fig. 1. Thermogram based on actual final temperature measurements in the wells of the Shikhansk-Belebeyevsk saddle and Mrakovsk depression (based on the materials of the IG UC RAS)

exceed the MC1 substage (Uruzbayevsk, Khlebodarovsk, Kurgashlinsk and other areas) For the western and partly central regions, the OS was transformed to the MK2–MK3 substages Kinzebulatovsk, Teyruksk, Salikhovsk, Voskresenska, etc.).

Basin modeling

Modeling of the processes of oil and gas formation and restoration of the geotemperature regime of the subsoil was carried out in the PetroMod program, which allows reconstructing paleotemperature, the degree of catagenesis, the potential for hydrocarbon generation of parent formations, etc., in complex thrust structures with the combination of several sections [1]. For the zone of maximum paleotemperature, 1D basin modeling was carried out in the section of the Taushsk 2 exploratory well located in the Mrakovsk depression, for the zone of medium degree of catagenetic transformation - in the sections of the Teyruksk 2 (Shikhano-Ishimbay saddle) and Urazbayevsk 11 (Mrakovsk depression) wells. Verification of models based on actual borehole temperature measurements, predicted current temperatures, vitrinite reflectance (Ro) and reservoir pressure showed satisfactory results (Fig. 3, *a*). At a depth of 1686 m in the borehole section Taushsk 2 between the autochthonous (R–P1) and the allochthon (C_1v–P_1) catagenetic unconformity is recorded a consequence of the Taushsko-Urginsk upthrust (Fig. 3, *b*).

The study of the formation of the sedimentary cover showed that the main sedimentation took place in three stages: Riphean, Late Vendian, and Silurian-Late Paleozoic. At the Permian-Triassic boundary in the area of the Taushskaya 2 and Urazbayevsk 11 wells, the Taushsko-Urginsk and Urazbayevsk thrusts appeared. After the intensive submergence of the basal terrigenous deposits of the Lower Riphean, an increase in reservoir temperatures to 180–185 °C in the bottom of the sedimentary cover is observed in the evolution of the geotemperature regime. By the end of the

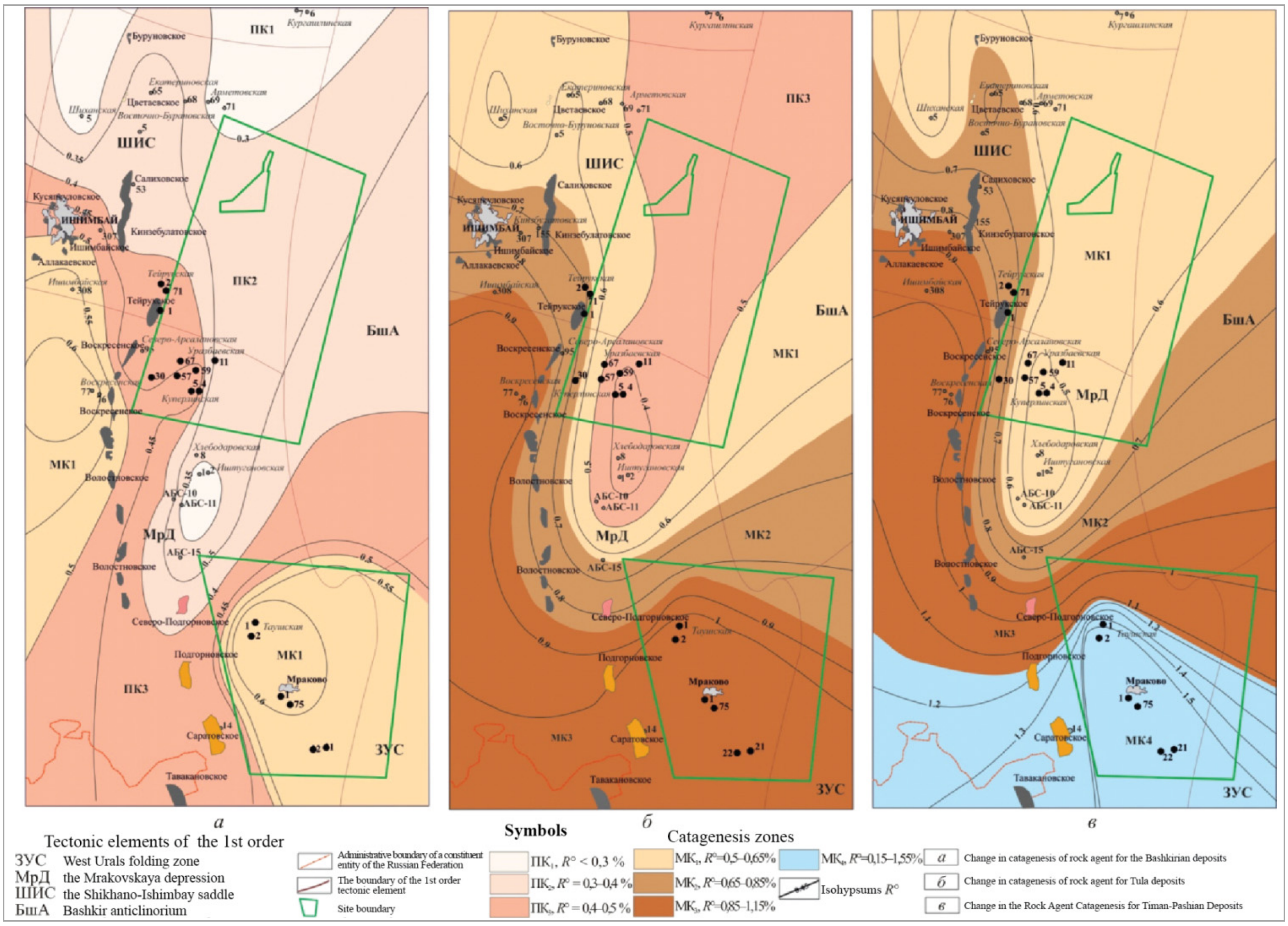

Fig. 2. Forecast maps of changes in the catagenesis of organic substances of the rocks of the Mrakovskaya depression and the Shikhano-Ishimbay saddle

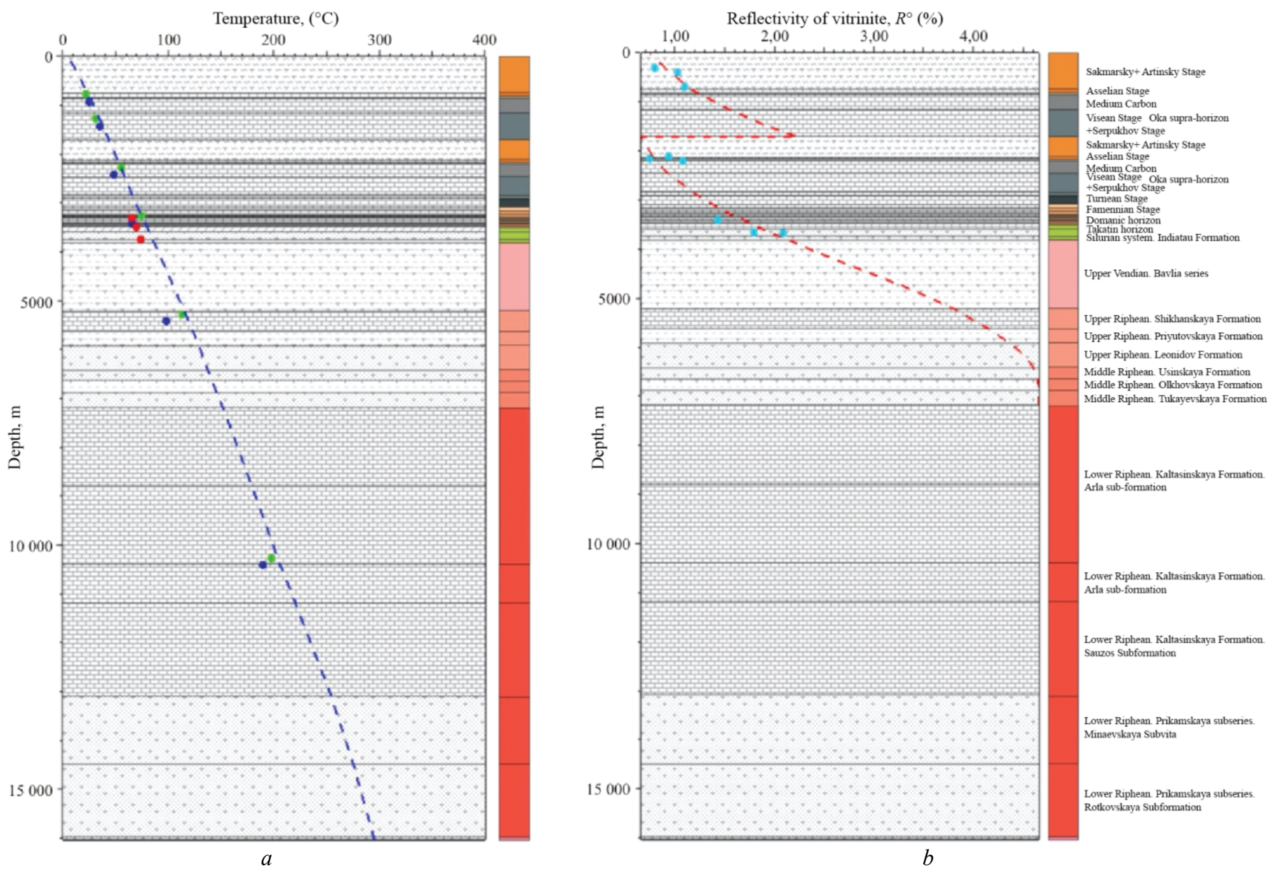

Fig. 3 Calibration of modeling results in the section of the Taushsk 2 well: *a* – by temperature; *b* – by the vitrinite reflectance (R^o)

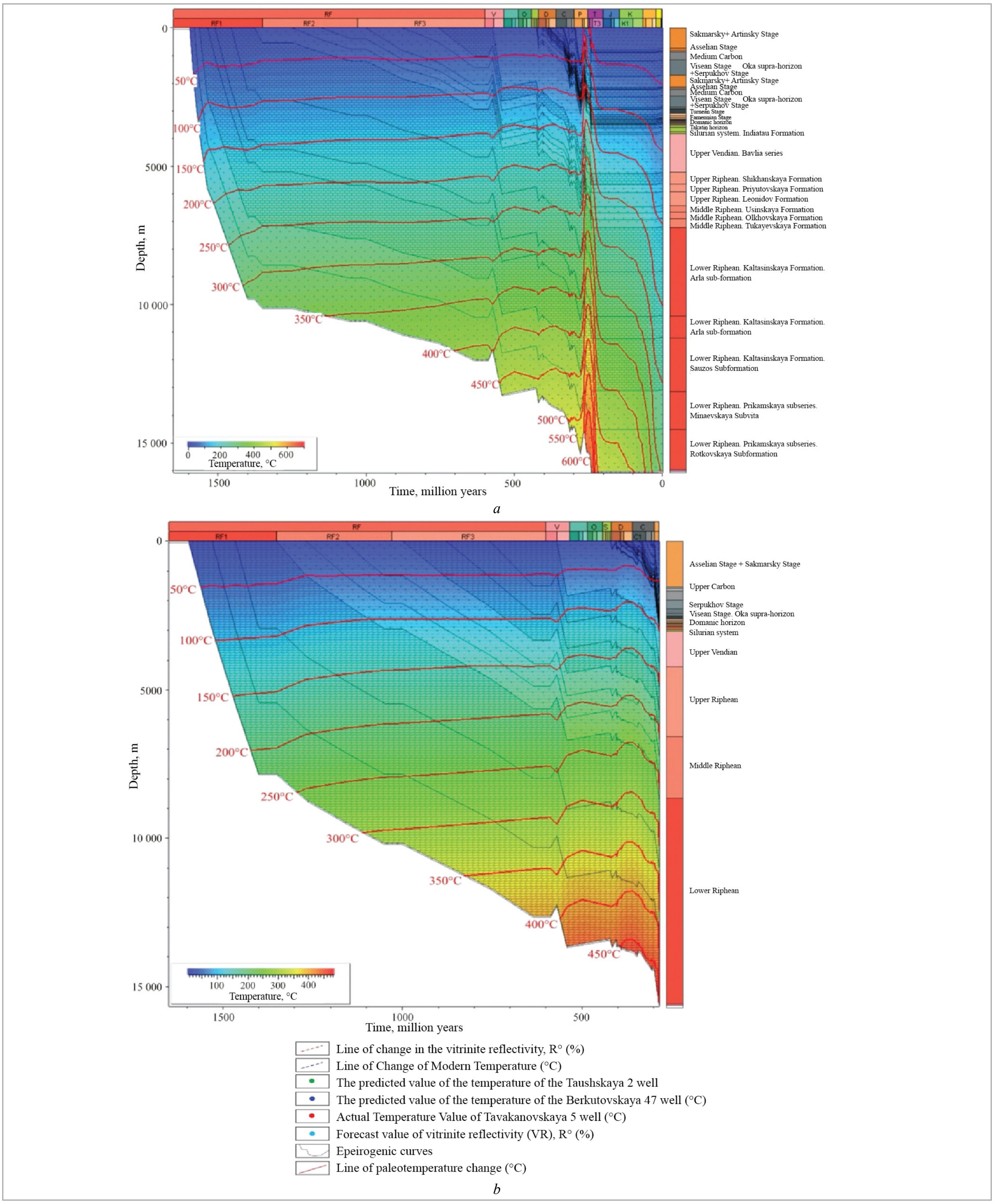

Fig. 4. Immersion and heating model: *a* – along the section of well Taushskaya 2; *b* – allochthon of well Urazbaevskaya 11 (before the period of thrust dislocations)

Riphean cycle, the temperature in the roof of the Kaltasin Formation was 120–190 °C. At the stage of freezing in the Early Vendian it is observed a slight decrease in temperatures (15–20 °C) and then a sharp increase in temperatures in the Late Vendian. By this time, the temperature in the roof of the Riphea was about 75–80 °C.

The Third stage of intense temperature rise in the area of wells Taushskaya 2 and Urazbayevskaya 11 can be traced in the Early Devonian-Famennian times. During this period, the temperature in the roof of the Riphean increased by about 25 °C, the temperature in the Silurian-Devonian part of the section by the end of the Famennian time did not exceed 35–40 °C. Modeling of the evolution of the geotemperature regime over the well section Teyruk 2 at this stage showed that a sharp increase in temperatures is observed only from the second half of the Carboniferous period. By the end of Permian Stage of Sedimentation Maximum Reservoir Temperatures in the roof of the Kaltasin formation were 225–275 °C, in the roof of

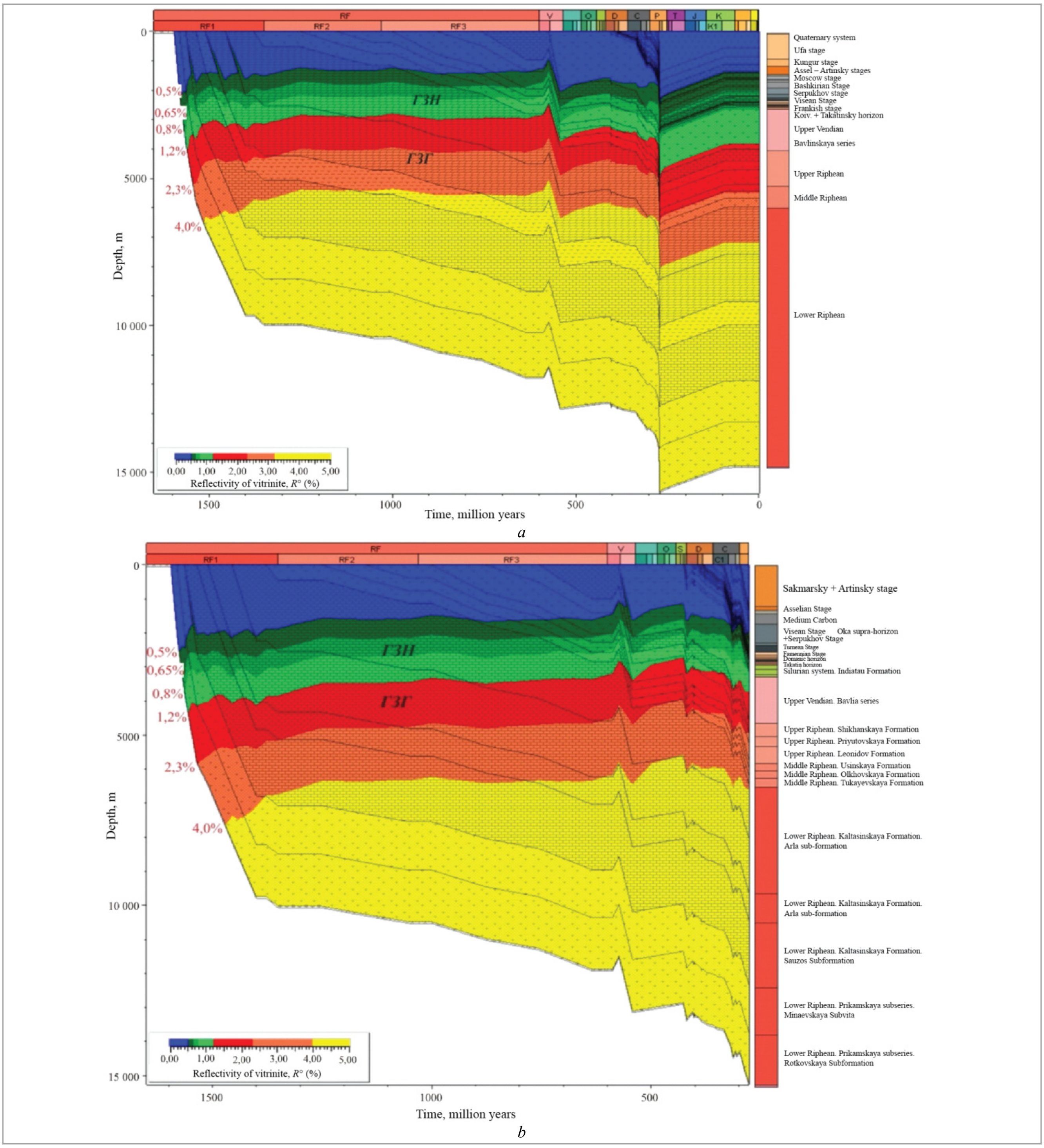

Fig. 5. Model of evolutionary-catagenetic zoning: a – based on the section of the Teyruksk 2 well;
b – allochthon of the Taushsk 2 well (before the period of thrust dislocations)

the Pashi-Kynov formation of the terrigenous Devonian – 88–100 °C, in the roof of the Domanic horizon – 86–118 °C. At the turn of the Mesozoic and Cenozoic, there was a stable stage of development characterized by the gradual cooling of deposits (Fig. 4, *a*).

According to the results of basin modeling of the allochthonous parts of the sections using palinspastic reconstructions (Fig. 4, *b*), no significant changes in the distribution of reservoir temperatures were observed until the Early Permian. The maximum warming of the Domanic horizon in the sections of the allochthons of the studied areas before the beginning of fold-thrust dislocations in the Artinian time was 87–117 °C, in the Pashia-Kynov deposits – 83–113 °C, the temperature in the roof of the Kaltasin formation increased to 252–265 °C. Maximum paleotemperatures were recorded during thrust manifestations, which is typical for many highly dislocated zones.

Reconstruction of the catagenetic zonality of the Teyrukskaya 2 well (Fig. 5) showed that the Lower Riphean passed the stage of mesocatagenesis and plunged into the main gas generation zone (MGGZ) in the Early Riphean time. For a long time, due to the lack of temperature increase at the beginning of the Paleozoic, the lower part of the Upper Vendian was in the MC1 zone, only during folding-thrust movements with an increased heat flux in the Permian time, the Vendian bottom at a depth of about 2300 m warmed up to the MC3 substage, the Vendian roof at that time only sank into the MK1 zone. The bottom of the terrigenous Devonian and the Domanic horizon entered the MGGZ at the Permian-Triassic boundary. According to the simulation results, the degree of catagenesis of the Paleozoic part of the section after thrust displacements did not exceed the MC1 substage. Accordingly, before the manifestation of thrust tectonics, namely, in the Early Permian time, the oil and gas source rocks of the Domanic horizon, the terrigenous Devonian of the autochthonous could produce oil hydrocarbons, while the more submerged deposits of the Lower Riphean could generate gases under favorable conditions. At the beginning of the Permian stage of sedimentation, a sharp increase in catagenetic maturity was observed in the area of the Teyrukskaya 2 well throughout the section, the Vendian bottom reached the gradation of MK2 catagenesis, and the Paleozoic part of the section remained in the zone of protocatagenesis. But after the accumulation of a thick terrigenous formation of rocks of the Ufa stage (270 million years), the lower Vendian enters in MGGZ (R^o – 1,20–1,23 %), the bottom of the Domanic horizon reaches the degree of catagenesis MK2 (R° – 0.66 %), the Famennian-Bashkir part of the section remains in the MC1 zone, while the overlying sediments remain in the zone of protocatagenesis (see Fig. 5, *a*).

The results of modeling on allochthonous sections showed that before the development of thrust formations only the upper Visean stage, Bashkirian, Upper Carboniferous, and Permian deposits remained in protocatagenesis. By the end of the Paleozoic cycle, favorable conditions for the generation of heavy and medium oil were created in the supposed oil and gas source rocks of the allochthons of the Domanic horizon and terrigenous Devonian (see Fig. 5, *b*).

Conclusion

Thus, despite the limited initial information, the results of the study of the geothermal and geochemical conditions of the southern part of the Pre-Ural trough and the West Ural folding zone made it possible to obtain a number of important conclusions for the forecast of oil and gas potential of the little-studied areas of the Volga-Ural oil and gas province [36–49]:

– geothermal studies have shown a general increase in the differentiation of the temperature field with depth, especially for the areas of the Mrakovskaya depression;

– the calculated constructions of paleo-temperature-catagenetic zoning showed a wide range of changes in the degree of catagenesis of rocks within stratigraphic units. There is a general tendency to increase the catagenetic transformation of rock agents over the area in the submeridional direction from north to south and along the section from the Permian to the Devonian deposits. The Middle to Upper Devonian deposits are in mesocatagenesis throughout the area. The Middle, Upper Carboniferous, and Permian complexes are characterized by a wide range of catagenetic transformation of rock OS, from substages PC1 to MC4;

– According to the results of basin modeling, the degree of catagenesis of the same-age deposits of both autochthonous and allochthonous in the southern part of the work area (Taushskaya 2) is slightly higher than in the northern part (Urazbayevskaya 11). The results of the restoration of catagenetic zoning in the thrust zone indicate that the presumed oil source deposits of the Paleozoic of the autochthonous and allochthonous could have realized their oil potential to a small extent, since they entered only the initial substage of the MGGZ ($R^o <$ 0,61 %, *TR* – 5–10 %). The early entry of the Paleozoic into the MFGZ in the pre-thrust epoch could have had a negative impact on the preservation of hydrocarbon deposits.

In the area of the Teyruksk 2 well, as well as in the eastern part of the studied area, the Riphean stage of sedimentary basin development occupied a leading position in the processes of gas formation, but by the end of the Late Vendian-Early Permian stage of submergence favorable catagenetic conditions were created for the generation of liquid hydrocarbons in the Devonian-Middle Carboniferous part of the section (MC1–MC2).

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