



Research article

Assessment of the contribution of Precambrian deposits in forming the petroleum potential of the eastern part of the Volga-Urals basin using results of modeling

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Abstract. Consideration is given to results of geochemical analysis of organic matter and oils of the Proterozoic (the RF-V complex) and the Paleozoic (the pay intervals D₂, D₃, C₁₋₂) of the eastern part of the Volga-Urals petroleum basin. The obtained data is corroborated by results of 2D basin modeling along four regional profiles two of which are situated in the Kama and two in the Belaya parts of the Kama-Belaya aulacogen. An update is given to earlier data on degree of catagenetic alteration of oil/gas source rocks of the Riphean-Vendian play, maps of catagenesis are constructed. New evidence is provided concerning presence of Precambrian oils in the Paleozoic plays. The oils under investigation are mixed – those formed from generation products of the Precambrian (Riphean, Vendian) and Paleozoic (Devonian and Early Carboniferous) source rock intervals. The results of modeling have shown that the principal source rock intervals in the RF-V play of the Kama part of the Kama-Belaya aulacogen are deposits of the Kaltasy formation of the Lower Riphean and the Vereshchagino formation of the Upper Vendian, while in the Belaya part these are rocks of the Kaltasy, Kabakov, Olkhovo, Priyutovo, Shikhan and Leuza formations of the Riphean and the Staropetrovo formation of the Vendian. It is found that the interval of the main oil and gas window increases in the southeastward direction. In both depressions of the Kama-Belaya aulacogen, a single oil play is distinguished that functions within the stratigraphic interval from the Riphean to the Lower Carboniferous. As the principal petroleum source rock intervals within this play, Riphean-Vendian deposits are considered, reservoirs are confined to the Riphean carbonate complex, Upper Vendian and Middle Devonian clastic deposits, while the Upper Devonian – Tournaisian deposits serve as the upper seal.

Keywords: Volga-Urals basin; basin modeling; geochemistry; organic matter; Precambrian; oil play

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Introduction. Analysis of possible oil and gas sources in petroleum basins is one of the key objectives in search for hydrocarbon (HC) accumulations. Evaluation of possible HC sources is especially critical in such basins where presence of several source rock intervals is predicted. One of such objects is the Volga-Urals petroleum basin. The said region is situated in the east of the East European platform and is confined to the Volga-Urals antecline. The basin's sedimentary cover is presented by Riphean, Vendian, Devonian, Carboniferous, and Permian deposits. Structurally, it is divided into two major complexes – the aulacogen (RF) and plate (V-P) ones. Stratigraphic scope of the Riphean complex of the lows within the Kama-Belaya aulacogen is different [1, 2], therefore in this work these deposits are analyzed separately – for its Kama and Belaya parts.

Commercial oil and gas presence of the Volga-Urals petroleum basin is mainly associated with petroleum plays of the clastic Devonian (the Ardatov, Mullino and Pashiya horizons), Upper Devonian (terrigenous-carbonate deposits of Frasnian and Famennian age), Lower (Tula and Bobriki horizons) and Middle Carboniferous (Bashkirian-Moskavian deposits), it is not unusual that Lower Permian (Asselian, Sakmarian and Artinskian) deposits demonstrate oil and gas presence. The underlying Vendian deposits include several small-size (Sokolovo, Siva, Sharkan, Debes) oil fields [1, 3, 4].



The cause for a practically total absence of HC accumulations in the Riphean-Vendian (RF-V) play is not completely clear up-to-date. This is possibly associated with destruction of previously formed accumulations or with availability of a merely insignificant amount of organic matter for hydrocarbon generation. Unavailability of an impervious top seal in the RF-V play is considered as the cause for such situation (D.I.Ivanov, 2008), due to which hydrocarbons generated by Riphean-Vendian rocks migrated and concentrated in the overlying Paleozoic sediments (Pz) [3].

Based on data of a literature review and own analytical research, analysis of accumulation and alteration of Riphean, Vendian and Upper Devonian-Tournaisian organic matter was conducted. Based on a limited set of biomarker parameters (distribution of normal alkanes, cheilanthanes and steranes) a genetic link of Paleozoic and Proterozoic oils with Precambrian organic matter was established*.

Results of the performed 2D basin modeling corroborated the data obtained earlier and also made it possible to reveal spatial and temporal peculiarities of development of the oil plays of the part of the basin under investigation.

The goal of this research was to analyze the influence of RF-V source rocks upon formation of hydrocarbon potential of the sedimentary cover of the eastern part of the Volga-Urals petroleum basin based on biomarker analysis and 2D basin modeling.

Objectives:

- Collect and analyze data on geological framework and hydrocarbon potential of Riphean-Vendian deposits of the eastern part of the Volga-Urals petroleum basin.
- Consider the available publications concerning composition (biomarkers including) of organic matter in Proterozoic source rock intervals in Russia and worldwide.
- Perform geochemical analysis of organic matter of Precambrian deposits and oils of the V₂, D₂, D₃, C₁₋₂ plays using methods of isotopic geochemistry and chromato-mass-spectrometry.
- Based on the thus obtained material, construct 2D basin models along regional profiles within the Kama and Belaya depressions of the Kama-Belaya aulacogen.
- Analyze performance of oil plays of the region, assess the role of source rock intervals of various ages in the formation of petroleum potential of the region, and present a model of petroleum plays non-contradictory to the available information.

Materials and methods. *Geochemical analysis.* There have been analyzed 12 oil samples and 8 samples of bitumoids extracted from Precambrian source rocks (V₂kc – Kocheshor formation). Oil samples were selected based on spatial closeness to near-flank zones of the Kama-Belaya aulacogen (proceeding from the recommendations suggested in the previous work [3]). Utilized were oil samples from pay intervals of the following areas: Debes (V₂kr), Sokolovo (V₂kr), Siva (D₃tm), Kudymkar (D₃tm), Krasnokamsk (D₃tm), Kuyeda (D₂ps), Kasib (D₂ps), Mishkino (D₃dm), Kuligino (D), Savino (C₁t) and Gozhan (C₁bb). Bitumoids were extracted from carbonaceous deposits of the Kocheshor formation (V₂kc) of the Efimovo area (Fig.1).

Separation of extracts and oils into groups was conducted on glass columns filled with ACKT grade silver-impregnated silica gel with grain size of 0.1-0.2 mm. After drenching of silica gel with hexane, a sample weight of maltenes was transferred into the column. Thereafter, elution of the paraffin-naphthene HC fraction with hexane was conducted. The aromatic HC fraction was desorbed and eluted with toluene. Upon completion of separation, flasks with fractions were put under exhaust hood until complete evaporation of the solvent. Subsequent geochemical analysis of analytical groups in organic matter and oils was made by the chromato-mass-spectrometry method on the Agilent 6890B chromatograph furnished with Agilent 5977A MSD mass-spectrometer.

Basin modeling. Performing 2D basin modeling made it possible to reveal and illustrate spatial-temporal peculiarities of the development of petroleum plays in the part of the basin under investigation. In this work, four regional profiles were utilized – one near-east-west and one near-north-south ones for each of the Kama and Belaya depressions of the Kama-Belaya aulacogen correspondingly (Fig.1).

*The idea concerning possible presence of oils generated by Precambrian source rock intervals in the Paleozoic plays was suggested at various times by V.I.Kozlov, K.R.Chepikova, I.A.Larochkina, G.N.Gordadze, et al. However, no comprehensive argumentation in favor of this idea has been presented up till present.

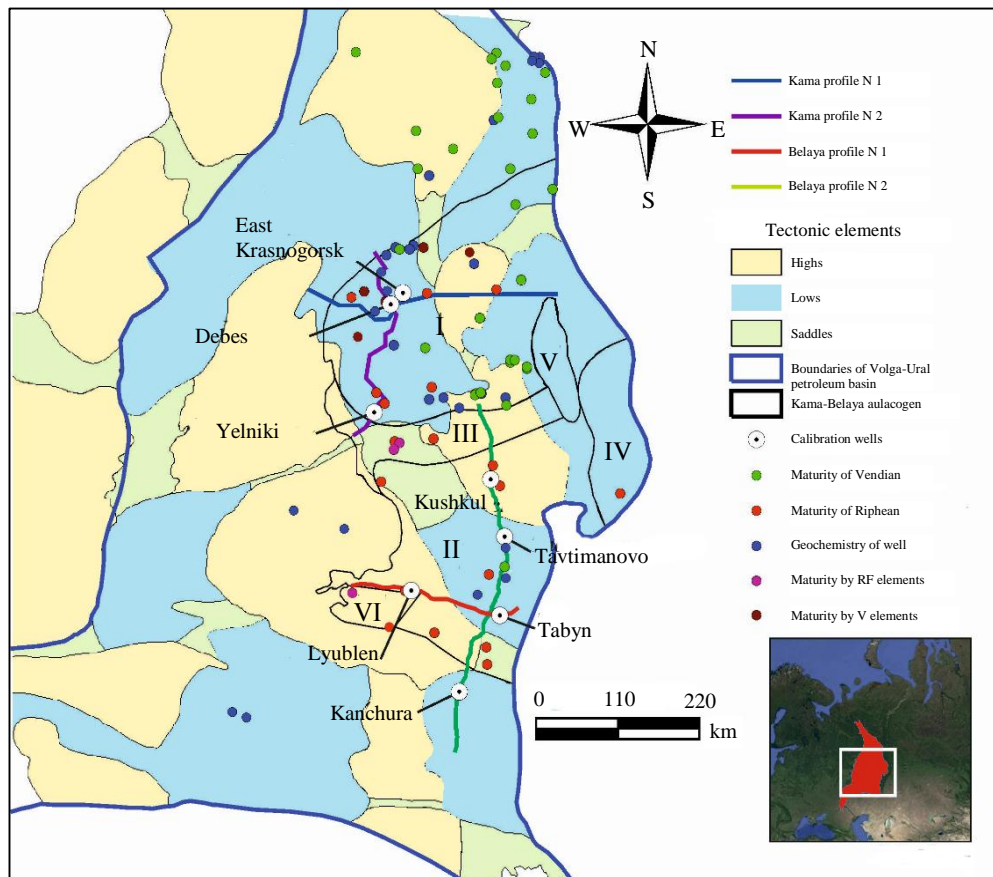


Fig.1. Factual basis map on tectonic base
Structures of the Kama-Belaya aulacogen:
I – Kama depression; II – Belaya depression;
III – Oriebash-Tatyshly-Chernushino uplifted zone; IV – Druzhinino bulge;
V – Osintsevo-Krasnoufimsk bulge; VI – Novotroitsk terrace

Source data were borrowed from field level reports of various years (2005-2009). Length of the profiles totals to more than 1450 km. Sections in the models were populated with stratigraphy and lithology in accordance with regional schemes, paleogeography reconstructions and well data [1]. Modeling was performed using several scenarios – with and without availability of source rock intervals in the RF-V play. The lithology characteristic was downloaded with due regard for various paleofacies maps and reconstructions (Fig.2).

The model takes in due account the *erosion events* that took place in the territory of the Volga-Urals petroleum basin. At the Riphean-Vendian boundary, thickness of deposits being eroded did not exceed 1500 m, at that a maximum thickness of eroded sediments is characteristic just of the northern regions [5, 6]. The beginning of the Early Paleozoic was also marked with a significant erosion event for the eastern margin of the East European platform. Up to 1000 m of Riphean-Vendian deposits were supposedly denudated at that time. At the end of Late Permian and beginning of Triassic, the territory again experienced upward movements, that having resulted in “cutting-off” of up to 250-300 m of rocks.

Fault tectonics. During the time of its formation, the territory of the basin under consideration has experienced rather a lot of alterations caused by the geology evolution of the region and to a greater extent by its geodynamic rearrangements. Manifestations of fault tectonics are traced at all structural stages. Within the eastern part of the Volga-Urals basin, principal zones of fault tectonics manifestation are confined to boundaries of various basement blocks (the Tatar, Bashkir and Perm arches), that having been caused by Archean-Early Proterozoic processes of formation of consolidation zones of protoplatforms. Northwestern (almost meridional) strike is typical of these faults. It is supposed that “opening” of the available faults took place in the time period of tectonic activation (at the end of Vendian and in the Late Permian-Triassic).

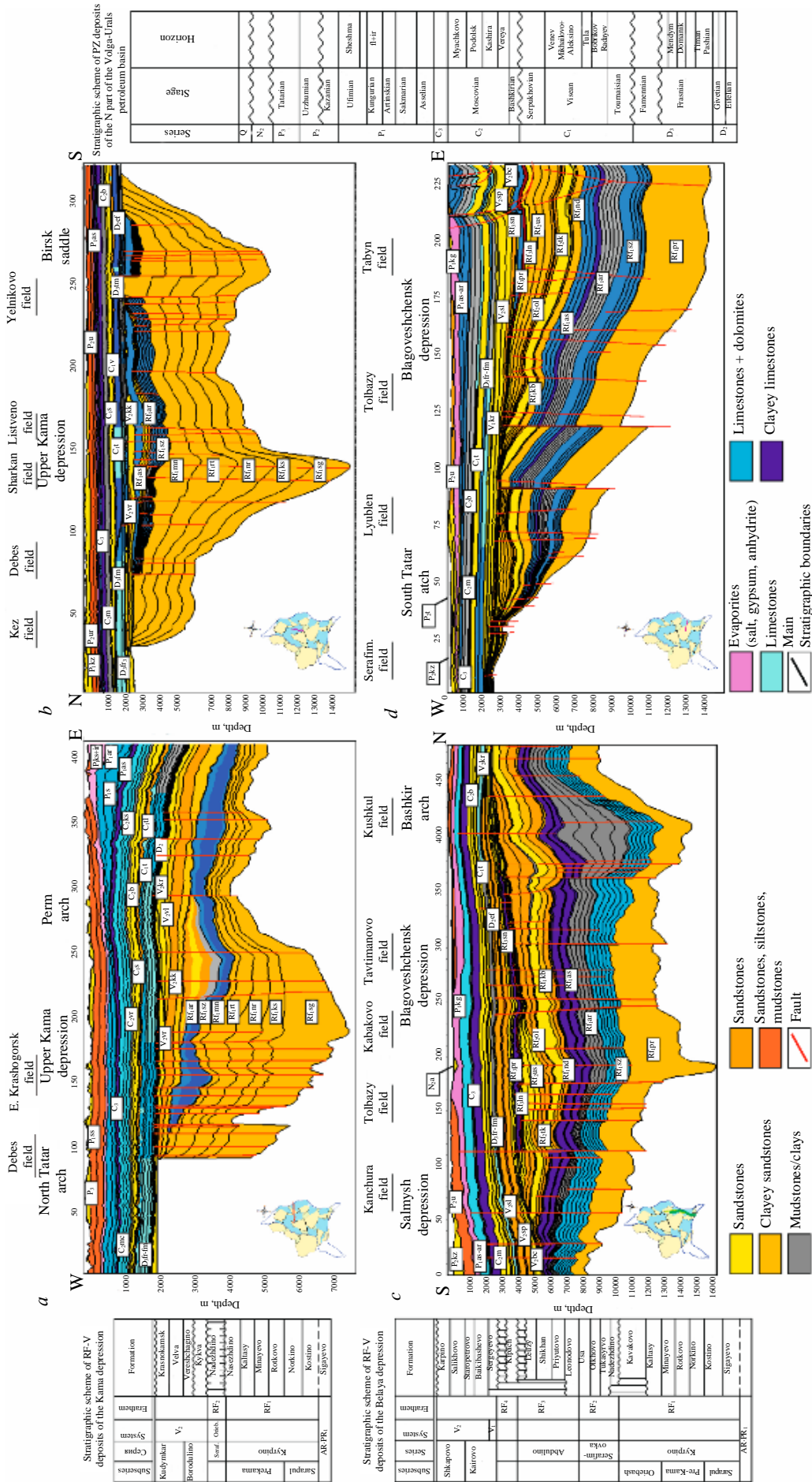


Fig.2. Lithology-stratigraphy profiles with position of the section line on structure map of the Volga-Ural petroleum basin and stratigraphic columns



Boundary conditions. Heat flux values versus time were matched in accordance with the geotectonic regime of the basin's evolution [7]. At the Riphean (aulacogen) stage in the zones of active rifting (the eastern part of the area) heat flux values reached 50-60 mW/m². The time of closure of the rift basin in RF₃-V₁ was characterized by a moderate heat flux of up to 50 mW/m². At the Vendian-Cambrian boundary heat flux could increase to values of 55 mW/m². Further on, up to the Permian-Triassic boundary heat flux was stable (at a level of 40-50 mW/m²). Thereafter at the Meso-Cenozoic stage, heat flow values reduced, especially in the western parts of the study area (down to the level of 19 mW/m²). Heat flux values were ranked area-wise and section-wise. Maximum values of the said parameter are observed in depression parts of the section. Data on values of present-time formation temperatures were taken from reference books and depository reports. The parameters introduced into the model are presented in Table 1.

Table 1

Characteristics of source rock intervals

Rocks	Lithology	Thickness, m	Organic matter type	TOC, %	HI ₀ , mgHC/gTOC
RF ₁ sz	Argillite	Up to 300 (cumulatively)	II	1.5	900
RF ₁ ar	Dolomitic marl	Up to 100	II	1.5	600
RF ₂ ol	Argillite	Up to 50	II	0.47	400
RF ₃ shn	Argillite	Up to 50	II	0.53	650
V ₂ vr (sp)	Argillite	Up to 100	II	5	710
D ₂ af	Argillite	30	II/III	1.0	250
D ₃ fr-fm	Siliceous argillite	Up to 60	II	2.0-10.7	600-710
C ₂ vr	Carbonaceous argillite	30	II/III	0.54	300

Characteristics of source rock intervals. As the input parameters, there were used analytical values of total organic carbon content (TOC₀) and hydrogen index (HI₀) recalculated to initial values. The detailed description of organic matter of source rock intervals was presented in the previous work [3] and is also shown in Table 1. In light of the fact that organic matter of various (in age, type and areal extension) source rock intervals has various individual characteristics, the kinetic models selected for modeling only partly reflect the character of realization of generation potential of the deposits under investigation.

The degree of catagenetic alteration of organic matter in various source rock intervals was assessed based on literary data [2, 8, 9]. Calibration of the models was made by data of present-time formation temperatures from wells located in the areas: Kanchura, Tavtimanovo, Kushkul, Lyublen, Tabyn, Debes, East Krasnogorsk, Lozolyuk, Yeseney, Baklanovo, Yelniki, and others (Table 2); by values of *R_o* ((Vitrinit) Reflection in oil) taken from maps, and by zones of catagenesis identified previously by the authors [4, 8, 9]; and by location of hydrocarbon fields area-wise and section-wise.

Geological characteristic. Tectonics. Tectonic appearance of the study area is presented by three structural stages. The lower – aulacogen stage is located within boundaries of the Kama-Belaya aulacogen – it comprises ancient-laid structures. It is divided into the Kama and Belaya depressions separated by the Oriebash-Talyshly-Chernushino uplifted zone. In the east, there are identified uplifted blocks of the crystalline basement – the Osintsevo-Krasnoufimsk and Druzhinino bulges (see Fig.1).

In the middle (syncline) structural stage, two lows are identified – the northern (Upper Kama depression) and the southern (Shkapovo-Shikhany depression) separated by the Sarapul-Yanybayevo saddle. All structures are composed of Upper Vendian deposits. Stratigraphic fill of the depressions is similar to one another, though names of complexes are different. Brief description of the Riphean-Vendian stratigraphy is presented below separately for the northern and the southern depression parts of the study area.



Table 2

Main calibration parameters utilized in the model

HC field	Structure	Depth, m / T, °C	Depth, m / Ro, %	Catagenesis grade
Kanchura	Salmysh depression	25/4	25/0.5	–
Tavtimanovo	Blagoveshchensk depression	2067-2125/41	2067-2125/0.5	–
Kushkul	Bashkir arch	25/6	25/0.5	–
Lyublen	South Tatar arch	1413-1451/28	–	–
Tabyn	Blagoveshchensk depression	339/12 1585/31 1669/36	–	–
Debes	Upper Kama depression	1276/26 1760/36	–	1797/PC ₃ -MC ₁
East Krasnogorsk	Upper Kama depression	1306/26 1580/28 1611/28	–	1705/PC ₃
Lozolyuk	Upper Kama depression	1292/27 1383/28	–	1724/MC ₁
Yeseney	Upper Kama depression	– 1267/23	–	2011/PC ₃
Baklanovo	Perm arch	1276/24 1631/29	–	2446/MC ₁
Yelniki	Birsk saddle	786/18.5 895/23 1410/28 1470/29	–	–

The third (present-time) structural stage within the study area is presented in the composition of the Upper Kama, Bym-Kungur, Yuryuzan-Sylva, Blagoveshchensk and Salmysh depressions, Perm, Bashkir and Tatar arches, and also the Birsk saddle. Similarity in stratigraphic and facies appearance of various parts of the said structural stage afforded the opportunity to consider Paleozoic deposits in concordance with the regional stratigraphic schemes (Fig.2).

Stratigraphy. Stratigraphic fill of depressions of the Kama-Belaya aulacogen is different – the northern (Kama) depression is composed of Lower and piecewise Middle Riphean deposits, the southern (Belaya) depression is composed of rocks of all the three series of the Riphean – Kyrpy (Lower), Serafimovka (Middle) and Abdulino (Upper) series. The composition of the Lower Riphean complex of the sedimentary cover of the northern (Kama) depression include clastic deposits of the Sarapul and Pre-Kama series and also clayey-carbonate sequences of the Kaltasy formation of Kyrpy series. The Upper Vendian part of the overlying Upper Kama depression is presented in the composition of the Kykva, Vereshchagino, Velva and Krasnokamsk formations [1]. The section of the Riphean-Vendian part of the Belaya depression of the Kama-Belaya aulacogen has a significantly wider span. In addition to Lower Riphean deposits, present are also mainly terrigenous rocks of the Middle Riphean and terrigenous-carbonate sequences of the Upper Riphean. The Upper Vendian terrigenous complex of the said part of the Volga-Urals region is presented practically in the same volume, though names of stratigraphic subdivisions are different: Baykibashevo, Staropetrovskoye, Salikhovo and Karlino formations (Fig.2).

Oil and gas presence. In the section of the basin's sedimentary cover, several oil plays and promising oil/gas plays are identified, each of which is characterized by similar conditions of oil/gas accumulation and types of HC deposits. Boundaries of plays are drawn along regionally persistent impervious seals. As source rocks of the Riphean-Vendian play, the deposits of the Lower Riphean Kaltasy formation, as well as clayey deposits of the Vereshchagino and Staropetrovo formations of the Upper Vendian are considered. In the Paleozoic part, as source rock intervals there serve deposits



of the Afonino horizon of Middle Devonian, Domanik high-carbonaceous formation of the Upper Devonian-Tournaisian, and coal-bearing rocks of the Vereya horizon of the Middle Carboniferous. In the Belaya part, in addition to the above-mentioned ones, there are also source rocks of the Kabakovo, Olkhovo and Shikhan formations of Riphean. Reservoirs are mainly presented by Upper Vendian, Middle Devonian clastic deposits, and also carbonate sequences of the Middle-Upper Carboniferous and Lower Permian. As impervious seals, there serve Upper Vendian argillites, Upper Devonian-Tournaisian clayey-carbonate-siliceous sequences, and also carbonate-evaporite deposits of the Kungurian stage of the Lower Permian.

Availability of a considerable number of source rock intervals in combination with favorable thermobaric conditions for generation of liquid and gaseous hydrocarbons, presence of reservoirs and impervious seals in the section caused appearance of a considerable amount of oil and gas fields in the territory of the basin. Most of them are confined to structures draping major projections of the basement: the South Tatar, North Tatar, Perm and Bashkir arches, Birsik and Kosva-Chusovaya saddles. The biggest number of HC accumulations are revealed in Middle Devonian and Lower-Middle Carboniferous deposits. In the overlying sequences, there are less HC deposits – from the Upper Devonian-Tournaisian play to the Lower Permian play the number of revealed accumulations gradually decreases. Apparently, the Upper Devonian-Tournaisian clayey-carbonate deposits present a seal impeding free movement of hydrocarbons.

Within the Kama depression of the Kama-Belaya aulacogen, oil and gas presence in Precambrian deposits of the Volga-Urals petroleum basin is associated with Kykva and Krasnokamsk formations of Upper Vendian (the Siva, Sokolovo, Sharkan, Debes fields and others). In the Riphean play, but insignificant oil and gas shows were observed in deposits of the Kaltasy formation [2, 4].

In the territory of the Belaya depression of the Kama-Belaya aulacogen, no Riphean-Vendian oil and gas fields have been found. However oil and gas shows are presented rather widely in deposits of the Kaltasy, Tukayevo, Olkhovo and Usa formations of the Riphean, as well as in the Baykibashevo, Salikhovo and Karlino formations of the Upper Vendian [2, 4].

Geochemical peculiarities of Precambrian organic matter and oils. It is known from the history of geologic evolution that biotic communities of the Archean-Proterozoic are presented mainly by bacteria and also primitive algae and protozoans (phyto- and zooplankton). This have reflected in all-round dominance of hopanes over steranes [10]. Organic matter accumulation was taking place exclusively in marine environments in conditions of arid and moderate climate (except the time of Laplandian glaciation) [11, 12]. This is also distinctly indicated by ratio of tricyclic terpanes t19/t23, whose values are usually less than 0.5 [13].

The initial kerogen type is determined as II – aquagenic (sapropelic) organic matter. At that, geochemical appearance of initial OM often might be distorted by alteration processes in source rock sequences that took place in the past [14]. That is why at present the appearance of type III and IV kerogens can be observed, that however contradicting the composition of the biosphere of that time [10, 15, 16]. Inconsistency in determining OM accumulation environments in the Precambrian also resulted in distribution of steranes C27:C28:C29. In particular, a peculiarity of Precambrian oils is dominance of ethylcholestane over cholestane proper and methylcholestane [17-19]. Usually such distribution is characteristic of humic OM. As one more detected geochemical peculiarity of ancient oils is presence of high concentrations of monomethylalkanes (12-, 13-monomethylalkanes, 2-, 3-monomethylalkanes [11, 20]) and dimethylalkanes (2.7-dimethylalkanes) [21]. The nature of this phenomenon is at present not clear until the end. Nonetheless, it is obvious that presence of such HC compounds is characteristic of just a narrow stratigraphic interval (Vendian) and a small number of petroleum basins worldwide (East Siberia and Oman) [10]. A specific marker of Precambrian OM is lightened isotopic composition of carbon. After the conducted analysis of numerous publications it was revealed that most oils have values of indicator $\delta^{13}\text{C}$ from -30 to -31 ‰. Such peculiarity is also explained by the nature of initial OM (aquagenic, bacteriogenic). Note that the ratio $\delta^{15}\text{N}$ used for most Precambrian oils varies within the range of 0 to $+8$ ‰ [22].

Apparently, the revealed geochemical peculiarities are indicative of high aggressiveness of the environment of that time [22-24], high water salinity [22], low diversity of living organisms [11, 22, 25], low-oxygen composition of the atmosphere [26] and lengthy epochs of earth glaciations (Greenlandian, Laplandian, etc.) [11, 27].



Discussion of results. *Geochemical analysis of PR₂ and Pz oils of the study area.* The authors conducted geochemical studies of organic matter and oils from Precambrian and Paleozoic deposits of the eastern part of the Volga-Urals petroleum basin (Table 3). The degrees of catagenetic alteration of source of oils of V₂-Pz plays were revealed, paleogeographic environments of initial OM accumulation were determined.

Table 3

Estimated coefficients obtained by results of cromato-mass-spectrometry of oils and extracts

Well, area	Fluid type	Stratigraphic interval	Environment								Maturity			
			Pr/Ph	Pr/n-C ₁₇	Ph/n-C ₁₈	t ₁₉ /t ₂₃	C ₂₇ /C ₂₉	C ₂₈ β/C ₂₉ ββ	ETR (4)	DBT/P	T _s /T _m	MPR (1)	MPI 1 (2)	MDR (3)
Debes, 600	E	V ₂ kr	0.3	0.66	0.48	0.06	0.1	0.14	0.6	0.04	0.4	1.0	0.4	0.3
Sokolovo, 52	O	V ₂ kr	1.13	0.86	0.85	0.1	0.1	0.15	0.7	0.08	0.4	0.8	0.7	2.8
Siva, 1	O	D ₃ tm	1.12	0.75	0.85	0.12	0.1	0.15	0.7	0.07	0.6	1.2	0.7	8
Kudymkar, 1	O	D ₃ tm	0.89	0.76	0.85	0.06	0.5	0.3	0.8	1.1	0.23	0.7	0.5	1.8
Krasnokamsk, 207	O	D ₃ tm	1.13	0.73	0.65	0.11	0.5	0.4	0.7	0.64	0.65	0.6	0.5	2.5
Kuyeda, 2	O	D ₂ ps	0.63	0.81	1.19	0.04	0.4	0.4	0.9	0.71	0.13	1.3	0.8	2.4
Kasib, 3	O	D ₂ ps	1.29	0.67	0.53	0.17	0.6	0.3	0.7	0.65	0.6	0.6	0.5	3.2
Mishkino, 185	O	D ₃ dm	0.55	1.02	1.76	0.02	0.7	0.4	0.9	1.3	0.09	1.6	0.9	1.4
Kuligino, 61	O	D	0.68	0.79	1.13	0.05	0.5	0.3	0.9	–	0.19	–	–	–
Savino, 140	O	C ₁ t	0.62	1.09	1.78	0.02	0.7	0.3	0.9	0.68	0.14	1.2	0.8	1.8
Gozhan, 3	O	C ₁ bb	0.63	0.93	1.38	0.02	0.6	0.3	0.9	1.1	0.2	1.0	0.9	1.7
Krasnovishersk, 2.4 (1 extr)	E	V ₂ kc	1.0	0.78	0.8	0.26	1.2	1.12	0.7	0.09	0.5	1.0	0.7	3.9
Krasnovishersk, 2.4 (hot)	E	V ₂ kc	0.24	0.95	1.0	0.1	1.2	1.1	0.6	0.06	0.5	1.1	0.9	2.2
Krasnovishersk, 2.4 (cold)	E	V ₂ kc	0.07	0.77	0.76	0.05	1.1	1.1	0.6	0.12	0.5	1.0	1.0	1.4
Krasnovishersk, 301-2	E	V ₂ kc	0.23	0.56	0.54	0.07	0.9	0.85	0.7	0.03	0.5	2.6	0.9	5.0
Krasnovishersk, 301-2 (extr)	E	V ₂ kc	1.04	0.79	0.79	0.3	1.1	1.12	0.7	0.1	0.5	1.1	0.7	3.4
Krasnovishersk, 301-2 (hot)	E	V ₂ kc	0.13	0.72	0.85	0.11	1.1	1.2	0.6	0.07	0.5	1.3	1.0	1.6
Krasnovishersk, 301-2 (cold)	E	V ₂ kc	0.04	0.72	0.67	0.04	1.0	1.0	0.6	0.07	0.5	0.8	0.9	1.3
Krasnovishersk, 301-26	E	V ₂ kc	0.18	0.53	0.48	0.07	0.9	0.8	0.7	0.04	0.5	2.0	0.9	4.6

Note: O – oil; E – extracts; DBT – dibenzothiophenes; P – phenanthrene; Pr – pristene; Ph – phytane; n-C₁₇₋₁₈ – normal alkanes; C₂₇:C₂₈:C₂₉ – steranes; t₁₉/t₂₃ – cheilanthanes; T_s/T_m – trisnorhopanes.

Genetic peculiarities. Let us characterize genetic peculiarities of organic matter and oils (Fig.3, a). The ratios DBT/P and Pr/Ph (Fig.3, b) demonstrate that the Vendian OM belongs to lithofacies zone 2 (sulfur-poor lacustrine deposits). Values obtained by results of studying V-Pz oils are also located over there. Part of samples gravitate to zone 3 (marine clays and other lacustrine deposits). Samples of Domanik deposits of the Volga-Urals petroleum basin [28] are practically completely located in the zone 1B (marine carbonates and marine marls).

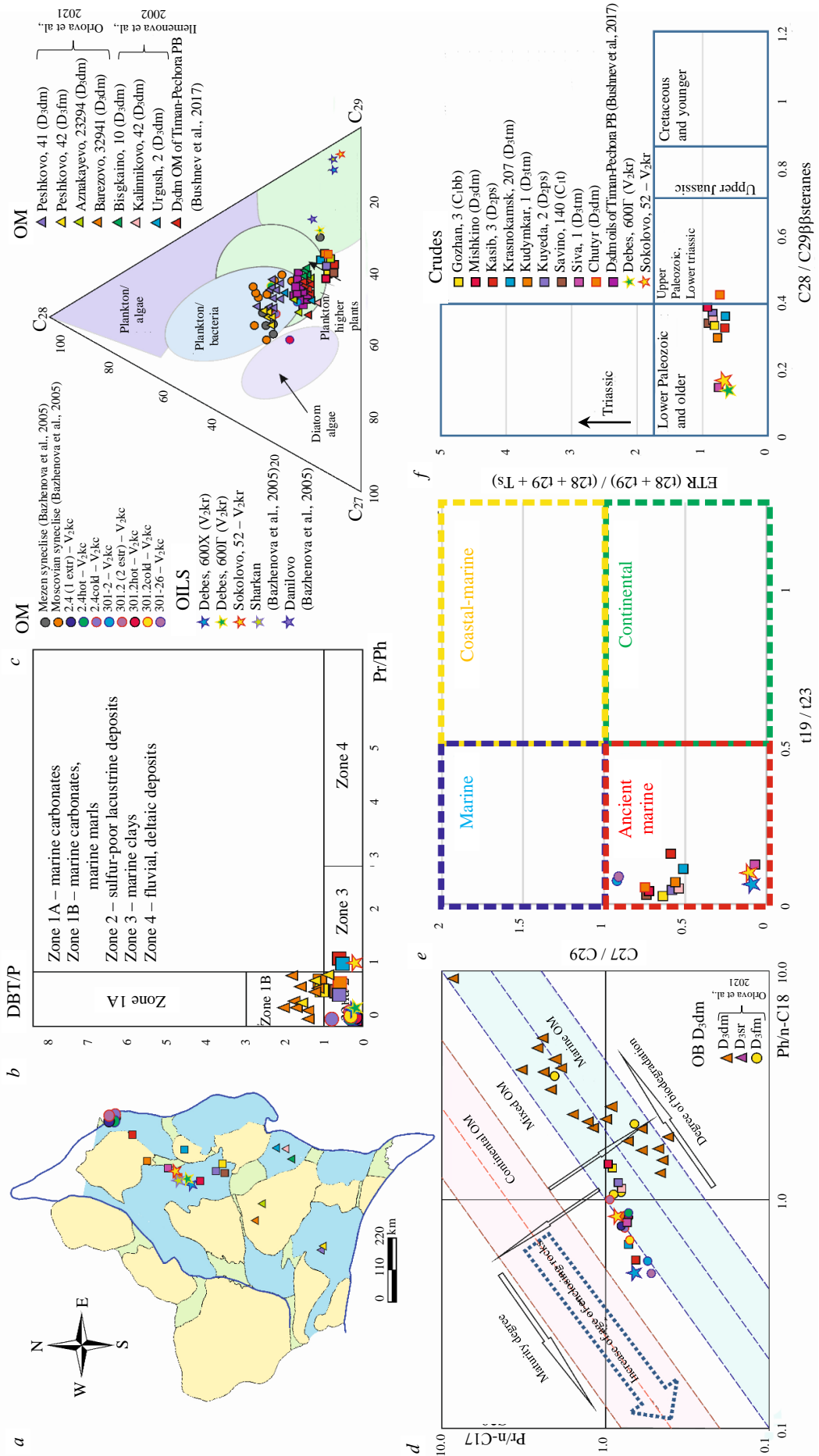


Fig.3. Results of the performed chemical analysis of OM and oil: *a* – position of oil sampling points; *b* – diagram of ratios of indices DBT/P and Pr/Ph; *c* – trigonogram of distribution of content of steranes C27:C28:C29; *d* – Comman – Cassou diagram; *e* – diagram of ETR versus t19/t23 [29, 30]; *f* – diagram of ETR versus C28/C29



For genetic tie of the oils under study and for OM-oil correlation, trigonogram of ratio of steranes C27:C28:C29 was used (Fig.3, c). All the studied OM and oil samples are divided into four geochemical groups. The first group includes oils sampled from Precambrian pay intervals, as well as oil from the Siva field (D_{3tm}). These samples are characterized by a sharp dominance of sterane C29. The second group is presented by organic matter of pay rock intervals of Upper Vendian and Upper Devonian age. It is characteristic of dominance of sterane C27, that being associated with sapropelic type of initial OM [28]. The third group includes OM and oil samples from Domanik deposits of the Volga-Urals and Timan-Pechora petroleum basins in which content of sterane C29 increases. This peculiarity is explained by a mixed (II/III) type of initial organic matter.

The oils under study form the fourth group situated between the OM of Domanic deposits and the Proterozoic oils. It is established that all oils under study are characterized by significant contents of ethylcholestane C29. Its share in the total volume of steranes varies from 51 to 88 % (Fig.3, c). This peculiarity is indicative of mainly ancient bacteriogenic origin of OM. For complex genetic characterization of oils and OM under study, we also constructed a Connan – Cassou diagram (Fig.3, d). It was found out that these samples are located in zones of mixed and marine OM, while Domanik ones have solely marine genesis. It is interesting that maturity of oils and OM (determined using this diagram) regularly increases with age of host rocks.

Catagenetic characteristic. In addition to genetic peculiarities, we also made an attempt to determine degree of maturity of oils based on biomarker characteristics. For this purposes the authors conducted molecular analysis by the technique described by Matthias Radke [31]. The following coefficients were calculated (Table 3):

$$\text{MPR} = [2 - \text{MP}]/[1 - \text{MP}]; \quad (1)$$

$$\text{MPI 1} = 1.5 ([2 - \text{MP}] + [3 - \text{MP}])/([P] + [1\text{MP}] + [9 - \text{MP}]); \quad (2)$$

$$\text{MDR} = [4 - \text{MDBT}]/[1 - \text{MDBT}], \quad (3)$$

where MP – methylphenanthrenes; P – phenanthrene; MDBT – methyldibenzothiophenes.

Subsequent computation of the parameter *Rm* (Mean Vitrinite Reflectance) was made using the diagrams presented in [32]. Grades of catagenesis were determined by data of V.T.Frolov (1992). All oils under study were generated by source rocks at MC₁-MC₂ catagenesis grades. The Ts/Tm ratio demonstrates rather high maturity – values of this parameter vary from 0.13 to 0.65 (Table 3). The revealed values generally coincide with position of catagenetic zones determined previously for RF-V [2, 4]. Nonetheless, one cannot exclude influence of Upper Devonian-Tournaisian source rock intervals, because in adjacent structures (the Solikamsk depression, the eastern part of the Upper Kama depression, the Belaya depression and others) mature rocks of this age are present. In connection with this, it is necessary to conduct combined age characterization of HC sources in the part of the basin under study.

The following diagram implying age of source rocks is constructed based of ratios of steranes C27/C29 and cheilanthanes t19/t23 (Fig.3, e). The said parameters were determined by the authors for a good reason because in this case they make it possible to divide OM into purely marine and purely continental. A kind of ‘contradiction zone’ is also identified where ratio of tricyclic hydrocarbons would be indicative of aquagenic origin of OM, while steranes would indicate ancientness. As a result, plotting the obtained valued showed that the oils and bitumoids under study again got into the area of ancient marine organic matter.

For higher reliability of the obtained results, the authors constructed one more diagram that is also based upon ratio of steranes C28 and C29 and cheilanthane index (Fig.3, f),

$$\text{ETR} = (\text{t28} + \text{t29})/(\text{t28} + \text{t29} + \text{Ts}). \quad (4)$$

By data of T.B.Abay [32], analysis of distribution of the said coefficients makes it possible to determine age tying of source rocks, which have generated the fluid under consideration. It is interesting that on this diagram practically all samples under study (except oil from the Chutyr field)



also appeared in the zone corresponding to the age interval of the Lower Paleozoic and older (Fig.3, f). Since Lower Paleozoic rocks are not revealed in the section of the part under study of the Volga-Urals basin, there is no doubt that these oils were generated from the Precambrian organic matter. Ancient OM and HC compounds generated by it are characterized by presence of isotopically light carbon. In the eastern part of the Volga-Urals petroleum basin, such oils are encountered on the Sokolovo, Siva, Debes fields ($\delta^{13}\text{C}$ from -31 to -30 ‰). Carbon of the Paleozoic OM is isotopically heavier ($\delta^{13}\text{C}$ from -27 to -28 ‰) [33]. This peculiarity allows making correlation of oil to OM of a source rock interval. Based on retrospective data [33], such analysis was also made. It was found out that in Middle-Upper Devonian and Lower Carboniferous oils, the $\delta^{13}\text{C}$ indicator varies within the range of -27.3 to -30.5 ‰, not exceeding value of -29 ‰ on the average. Isotopically light carbon in oils of the Paleozoic part of the section is indicative of presence of hydrocarbons generated by ancient (Precambrian) source rock intervals. These peculiarities (OM type, TOC_0 , HI_0) were used in modeling for revealing sources of HC accumulations in the part of the section under study. Analysis of modeling results was conducted with consideration of the revealed connection between oils of the Proterozoic and Paleozoic.

Results of basin modeling. The models along four regional profiles located in the Belaya and Kama parts of the Kama-Belaya aulacogen (see Fig.1, 2) are constructed with consideration of history of tectonic evolution, paleogeographic peculiarities of formation and further alteration (erosion events) of sequences in the sedimentary cover of the basin. The model was calibrated against values of present-time formation temperatures and vitrinite reflectance (see Table 2, Fig.4). Thus, these models are well posed and can be considered in studying processes of generation, migration and accumulation of hydrocarbons in the part of the basin under study.

By results of the conducted modeling, temperature gradient values were obtained for various parts of the basin. Crestal parts are characterized by highest temperature gradient values, especially in their uppermost parts where gradual decrease down the section of this parameter takes place (the Bashkir – 2.4 - 3.3 and South Tatar arches – 2.0 - 3.1 °C/100 m). High values are characteristic of major depressions: Blagoveshchensk and Upper Kama – 2.7 to 2.93 and 2.6 to 3.4 °C/100 m, respectively. In the Bym-Kungur and Yuryzan-Sylva depressions this parameter values are a bit lower. The lowest values are predicted for the Salmysh depression and the Birsk saddle – within the range of 1.0 to 2.5 °C/100 m. Assessment of catagenetic alteration degree for deposits over sections was made. The main oil windows and gas windows are situated in the depth interval of 1.36 to 4.1 km in the northern part and 1.6 to 5.8 km in the southern one. Maximum catagenesis grades are achieved at >5 km depths near the Kama depression and >6.6 km near the Belaya depression of the Kama-Belaya aulacogen. The difference in thermal regime is associated first with sedimentary cover thickness; considerable intervals of main gas window and main oil window within the Belaya depression are caused by proximity of the Pre-Urals foredeep. OM maturity degree in source rock intervals over the area was assessed by results of basin modeling with consideration of pyrolysis data from depository and retrospective sources [8, 34, 35]. Adjustment of the revealed catagenetic zones was made using structure maps. As a result there were constructed schematic maps of catagenesis for top of Lower Riphean deposits ($\text{RF}_{1\text{kl}}$) (Fig.5, a) and of Upper Vendian deposits ($\text{V}_{2\text{vr}}$, $\text{V}_{2\text{sp}}$) (Fig.5, b).

Catagenetic alteration degree of organic matter of Riphean deposits depends on depth of maximum submergence thereof. OM metamorphism degree increases in the southeastward direction and reaches its maximum within the Belaya depression (main gas window). At the same time, most studied deposits are situated within the main oil window.

Vendian deposits are characterized by a lesser alteration degree – OM metamorphism increases in the eastward and southeastward directions. The least altered deposits are located in the northwestern part of the study area – catagenesis grades over there do not exceed PC_3 values. Further eastward, a zone of MC_1 is developed, which gradually changes into MC_2 . In the east, within the Yuryzan-Sylva depression and the Solikamsk depression, OM alteration degree values reach MC_3 grade and higher. A significant part of development of the Vendian complex of deposits, the same as with the Riphean, is situated within the main oil window.

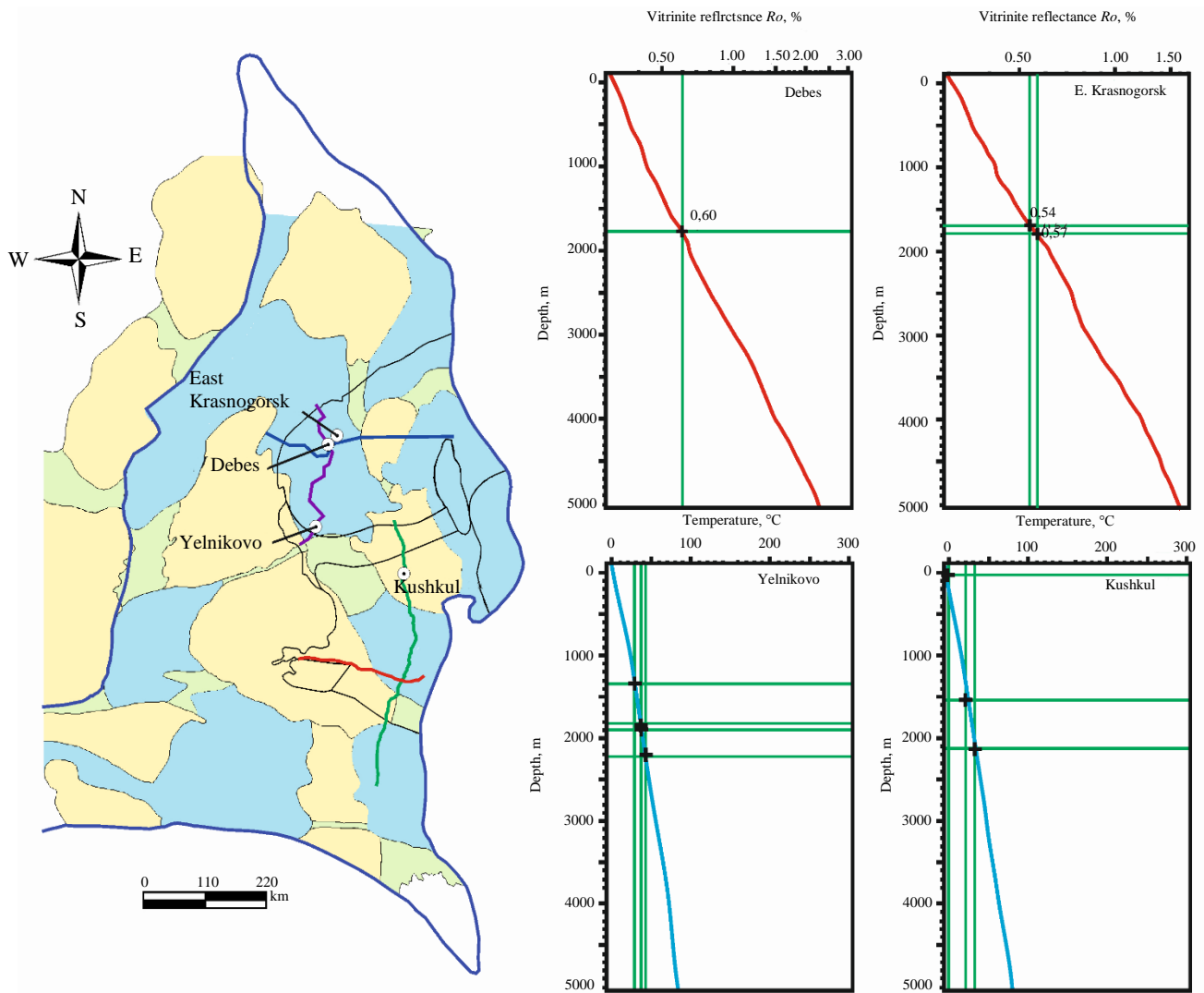


Fig.4. Examples of calibration diagrams using vitrinite reflectance and formation temperature values

The overlying Middle Devonian – Permian deposits within the study area are much less altered. Most part of the Upper Devonian-Tournaisian complex that is considered as a source rock interval is situated within MC₁ zone, maturity increases in structural lows (the Upper Kama and Blagoveshchensk depressions) and in eastward and southeastward directions where formations under consideration are altered up to MC₂-MC₃. By results of the performed modeling, oil-gas source rocks of Middle Carboniferous have not entered the main oil and gas windows in most part of the area, however within the Blagoveshchensk and Upper Kama depressions alteration degree of these deposits reaches MC₁ stage (Fig.5). Thus, most intensive generation processes progressed in the Riphean-Vendian source rock intervals.

While examining the processes taking place in petroleum systems, special attention should be paid to time of generation, migration and accumulation, as well as time of formation of traps. Manifestation of such or another process depends on history of geologic evolution of the region, specifically on deposition rate, time and intensity of erosion processes, local and regional temperature field variations.

By results of basin modeling, source rocks of the Kaltasy formation started generating liquid and gaseous hydrocarbons as early as at the end of the Early Riphean. That said, in the Belaya part of the aulacogen, generation continued up until the Late Riphean. The pre Vendian unconformity resulted in temporary suspension of generation by the Riphean source rock intervals. The subsequent oil and gas generation took place as late as in the Late Carboniferous-Permian in the Kama depression and in the Early Carboniferous in the Belaya depression [36]. The source rocks of the Upper Vendian and partly of the Devonian also reached the level needed to start HC generation, at that formation of oil and gas continued (Fig.6, 7).

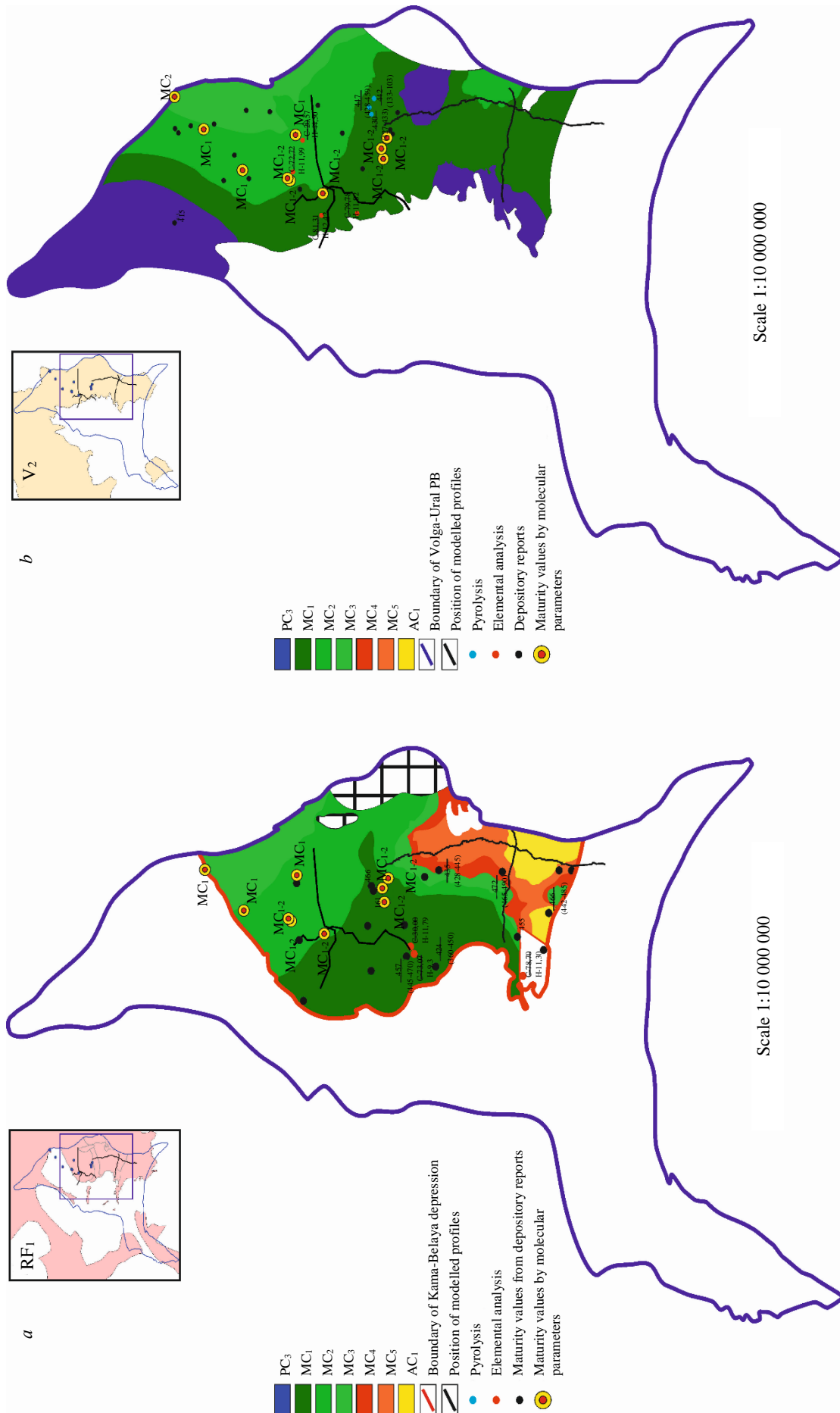


Fig.5. Schematic maps of catagenesis along top of RF₁ (a); top of V₂ (b)
 Fraction denotes variation of parameter T_{max} : in numerator – mean value, in denominator – minimum and maximum

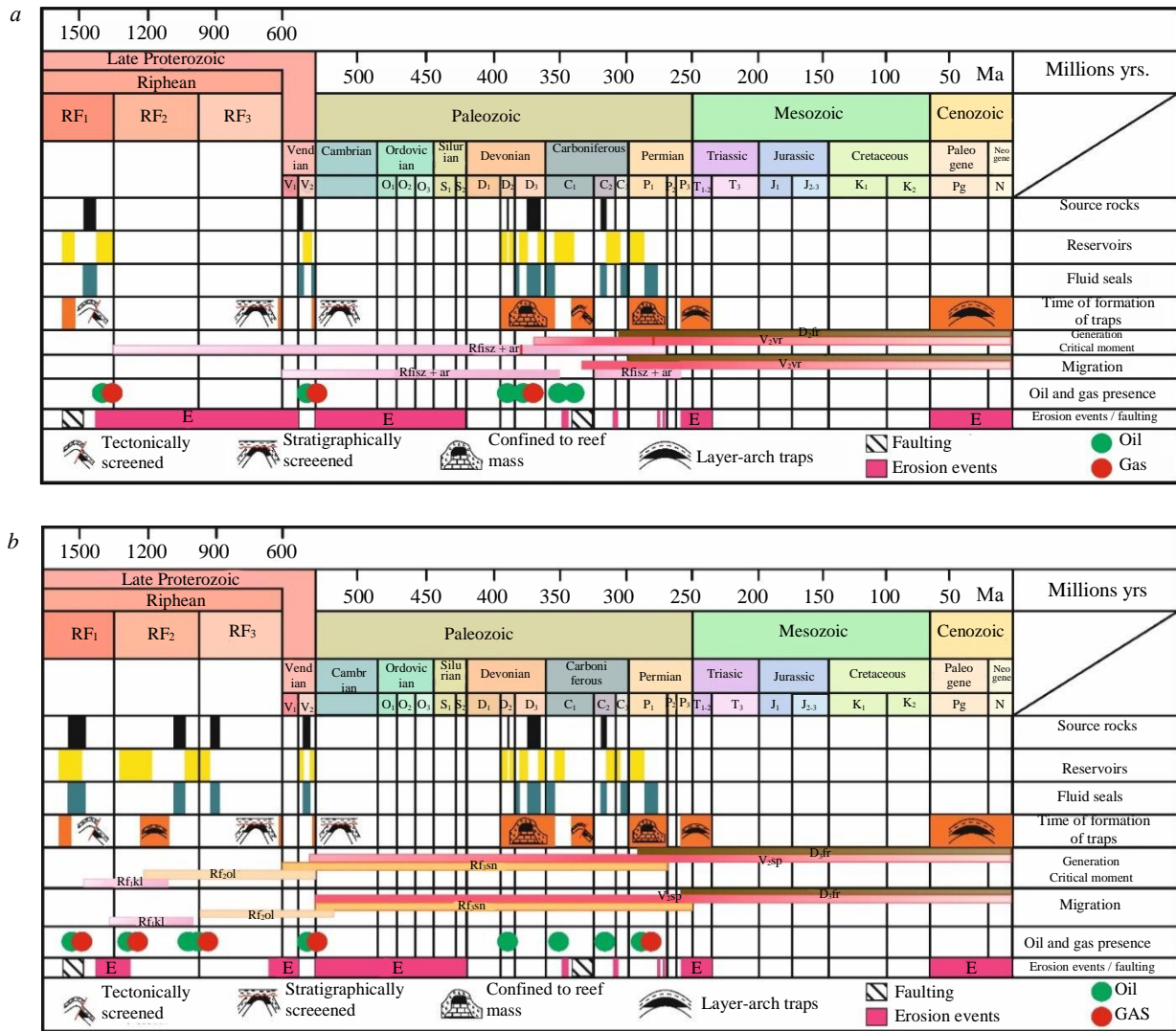


Fig.7. Scale of events constructed by results of 2D basin modeling for the Kama (a) and Belaya (b) parts of the Kama-Belaya aulacogen

The duration of oil and gas generation processes resulted in significant alteration degree of RF-V source rocks. In particular, the transformation degree of Riphean source rock intervals reaches 85-90 % in the Kama depression, while in the Belaya depression the Riphean has completely depleted its potential. Transformation index of Vendian source rock intervals in the northern (Kama) part of the Kama-Belaya aulacogen equals approximately 50-60 %, in the southern part its values vary within the range of 31 to 97 %. Upper Devonian-Tournaisian formations are least transformed, maximum transformation degree is 52 %, though in most part it does not exceed 30 %. Thus, the Riphean-Vendian source rock intervals have run out their oil generation potential practically completely. The Domanik formations, to the contrary, have a high potential to generation of liquid and gaseous hydrocarbons, though degree of their depletion is rather low within most part of the area [37], that raising doubt in the issue of prevalence of this source in forming HC deposits in the said part of the Volga-Urals basin.

The formation of anticipated accumulations of liquid and gaseous hydrocarbons in the northern and southern parts of the study area proceeded in a number of stages. In the southern (Belaya) part, migration of fluid generated by source rocks of the Kaltasy formation started as early as at the end of the Early Riphean. At that time formation of mainly oil deposits was taking place in deposits of the Sauzovo and Ashit subformations. In the Middle Riphean, gas content in them considerably increased, new accumulations were forming in the Tukayevo formation. By the end of Late Riphean,



total volume of accumulated fluid increased, new accumulations appeared in deposits of the Usa and Leonidovo formations. In the second half of the Late Vendian, hydrocarbons filled traps in deposits of the Baykibashevo, Salikhovo and Karlino formations. Closer to the end of Devonian, oil deposits did form in the clastic Devonian. In the Middle-Late carboniferous, filling of firstly Bobriki and thereafter of Bashkirian age reservoirs took place. HC accumulations in Lower Permian deposits were formed at the very end of the Paleozoic stage of evolution and their formation continues in the present time.

In the northern (Kama) part of the basin, processes of formation of HC accumulations proceeded somewhat differently. Because of the fact that sedimentary cover thickness over there is quite thinner than in the southern part, the processes of HC generation, migration and accumulation were more 'stretched' in time. Filling of traps in deposits of the Kaltasy formation was also detected at the end of the Early Riphean. In the Vendian, during the time of activation of the general subsidence of the basin, these processes continued, though they were running on primarily under their own inertia. Filling V₂ reservoirs took place at the end of the Vendian and thereafter in the Late Paleozoic.

In the Devonian-Permian, HC deposits were formed also in Middle-Upper Devonian and Lower-Middle Carboniferous deposits. As distinct from the southern part of the Volga-Urals petroleum basin, over there the dominant type of fluid for all HC deposits is oil. The important issue in analyzing the modeling results is determining types of traps and time of formation thereof. Tectonically screened traps were formed at the end of early Carboniferous and in the Late Permian. Formation of stratigraphically screened traps is associated with major erosion events that took place in the Middle Riphean-Early Vendian time, as well as in the Early Paleozoic. Detected are traps confined to reef buildups formed in the Late Devonian-Early Carboniferous (within the Kama-Kinel system of troughs) and in the Early Permian. Modeling was performed according to several scenarios – with and without availability of source rock intervals in the RF-V play. It was established that according to the second version, anticipated HC accumulations are practically not formed (even with so rich Domanik source rocks as having TOC = 10 %, HI = 710 mgHC/gTOC and thickness > 30 m). The critical factor in the process of HC generation is the factor of source rock transformation degree.

In the eastern part of the study area, there are detected zones of accumulation of hydrocarbons generated not only by the RF-V source rock intervals but also by D_{3fr2}-C_{1t} carbonaceous formations. Accumulation of liquid and gaseous hydrocarbons took place in deposits of the Moscovian stage of the Middle Carboniferous and in Asselian-Artinskian deposits of the Lower Permian. The anticipated oil and gas accumulations in the studied part of the section coincided with the position of real HC deposits and fields in Fig.6. In both depressions of the Kama-Belaya aulacogen, a single oil play is detected starting from Riphean deposits and ending with Lower Carboniferous deposits; within this play, RF-V formations are considered as main source rocks, reservoirs are confined to the terrigenous complex of the Middle Devonian, and Upper Devonian-Tournaisian deposits serve as the impervious top seal. Such oil play is characteristic mainly of the western and central areas of the Kama-Belaya aulacogen and for overlying complexes. In the eastern part of the basin, in immediate proximity to the Pre-Urals foredeep, the Upper Devonian-Tournaisian deposits act already not as top seals but as source rocks, that being associated with their wide areal extension and presence of zones falling within main oil and gas windows. At the same time they remain a reliable fluid seal for hydrocarbons generated by the RF-V source rock intervals.

The existence of a single oil play is also controlled by another factor – availability of a fluid seal between the Proterozoic and Paleozoic complexes. As the said element of the oil play, often considered are clayey Upper Vendian rocks – deposits of the Vereshchagino and Staropetrovo formations. However, the said deposits underwent various erosion events during geologic evolution history of the region, that having resulted in scarcity of their areal extent over the region, as well as practically complete absence thereof in the western parts of the basin. Absence of reliable fluid seals in the Vendian could contribute to cross-flow of hydrocarbons into overlying pay formations and also to formation of the single oil play from the Riphean-Vendian to the Upper Devonian-Tournaisian. That said, an interesting addendum to the suggested hypothesis is the fact of unity of the hydrodynamic system between the Riphean-Vendian clayey-carbonate complex and the Middle Devonian terrigenous complex [4, 38, 39].



By results of the performed modeling, two HC sources are revealed in the eastern part of the Volga-Urals petroleum basin – the Riphean-Vendian and Middle Frasnian-Tournaisian source rock intervals. These inferences corroborated by data of geochemical analysis conducted earlier allow us to note a considerable influence of the Precambrian source rock intervals upon formation of oil and gas presence in the eastern part of the Volga-Urals petroleum basin.

Conclusion. The following inferences have been made:

- In the section of Riphean deposits of the Kama depression and in the overlying Vendian-Paleozoic hydrocarbon plays, there are the following source rock intervals: RF_{1kl}, V_{2vr}, D_{3fr2}-C_{1t}; in the Belaya depression – RF_{1kb}, RF_{2ol}, RF_{3sn}, V_{2sp}. Pay intervals are associated with V_{2kr}, D_{2ps}, C_{1bb}, C_{2m} deposits (in the north) and RF_{2tk}, RF_{2ol}, RF_{2us}, V_{2bc}, V_{2sl}, V_{2kr}, D_{2ps}, C_{1bb}, C_{2m}, P_{1as,sm,ar} deposits (in the south).

- By ratios of steranes, cheilanthanes and normal alkanes, a genetic link is established between the Vendian and Paleozoic oils and the Precambrian organic matter.

- Basin modeling made it possible to infer that the RF-V source rock intervals exerted a considerable impact upon formation of oil and gas presence in the study region.

- The zones of accumulation of hydrocarbons generated by the RF-V source rock intervals are near-flank and uplifted zones of the Kama-Belaya aulacogen.

- Based on geological and geochemical data, a single oil play is detected in the eastern part of the Volga-Urals petroleum basin – from RF₁ to D₃-C₁.

It has been demonstrated that Riphean-Carboniferous deposits of the sedimentary cover within the eastern part of the Volga-Urals petroleum basin should be considered as parts of a single oil play. Oil and gas accumulated in the Devonian – Carboniferous deposits were generated by both Riphean-Vendian and Paleozoic formations. Moreover, the contribution of the Precambrian source rock intervals is so substantial that exclusion thereof from modeling resulted in absence of the observed oil and gas presence in the Paleozoic.

Geochemically (by ratios of steranes, cheilanthanes and normal alkanes), a genetic link is demonstrated between oils of the Paleozoic and Proterozoic reservoirs with organic matter of the Precambrian source rock intervals. A self-consistent model of formation of oil and gas presence in the part under study of the Volga-Urals Petroleum basin has been suggested.

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