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Hydrocarbon systems of the Crimean-Caucasian segment of the Alpine folded system

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Abstract. The article is devoted to the generation and accumulation systems in the territory of the Crimean-Caucasian segment of the Alpine folded system. An area of prolonged and stable sagging in the Mesozoic and Cenozoic – the Azov-Kuban Trough, which is a typical foreland basin – is distinguished within this segment. According to the results of geological and geochemical studies and modelling, depocentres are identified in this area, consolisated in four generative and accumulative hydrocarbon systems: Triassic-Jurassic, Cretaceous, Eocene and Maikop. Chemical-bitumenological, pyrolytic and coal petrology analysis of rock samples were carried out to assess geochemical conditions of oil and gas content in Meso-Cenozoic sediments. The modelling results made it possible to study and model the elements and processes of hydrocarbon systems in the Meso-Cenozoic in the Western Crimean-Caucasian region. It has been established that the extended catagenetic zoning is typical for these areas, which is caused by high rates of sedimentation and sagging, and large thicknesses of oil-bearing sediments in the source of oil formation, accordingly. The degree of organic matter depletion characterized the residual potential of the oil and gas source strata, was investigated. It is important for predicting and assessing the possibility of hydrocarbon generation.

Keywords: hydrocarbon systems, generation, accumulation, migration, oil-bearing strata, Crimean-Caucasian segment, modelling

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Introduction

The object of this study is hydrocarbon systems and petroleum potential of Mesozoic-Cenozoic deposits in the western part of the Crimean-Caucasian region. Computer modeling provided an opportunity to study the architecture of hydrocarbon systems and the processes occurring within them, to assess the hydrocarbon (HC) generation potential, and to evaluate the degree of organic matter (OM) depletion, which characterizes the further potential of petroleum source rocks (PSR).

Modern ideas about geological and geodynamic systems in the study area are based on the works of Yu.A. Kosygin, S.I. Gorlov, M.V. Muratov, B.V. Senin, S.T. Korotkov, V.E. Khain, A.N. Shardanov, I.P. Zhabrev, M.R. Pustylnikov, V.P. Peklo, S.F. Sidorenko, A.N. Dyakonov, V.L. Kripinevich, N.E. Mitin, V.Yu. Kerimov, N.Sh. Yandarbiev and others.

The Crimean-Caucasian fold system consists of two elements: two meganticlinoria of the Crimean and Greater Caucasus Mountains connected by the Kerch-Taman Bridge. The traditional view is that most of the Crimean-Caucasian section of the Alpine fold system has been an area of long-term and stable downwarping in the Mesozoic and Cenozoic. The Azov-Kuban Basin, which is a typical foreland basin, is situated in this area. The major part of the Azov-Kuban Basin is located on the Scythian Plate, where several sub-latitudinal structures can be observed (Fig. 1). The East Kuban Depression and the Indolo-Kuban Foredeep are the largest among them.

The Crimean-Caucasian region is one of the oldest oil production regions (Fig. 2). Within the Western Pre-Caucasian petroleum region (PR), 39 petroleum fields were discovered, including 17 gas fields, 21 gas-condensate fields and 1 oil field. 32 petroleum fields were discovered within the East Kuban PR, including 5 gas fields, 25 gas/oil-condensate fields and 2 oil fields. Within the West Kuban PR, 128 petroleum fields were discovered, including 90 oil/gas fields, 23 gas fields, and 15 gas-condensate fields. Hydrocarbon deposits were found in rocks of the Late Paleozoic, Triassic, Early and Middle Jurassic, Late Jurassic, Early Cretaceous, Paleocene-Eocene, Maikop, Miocene and Pliocene. A number of fields and numerous shows of petroleum were also discovered in the Azov Sea. Commercial gas

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content was verified for the Oktyabrskaya, Strelkovaya, Severo-Kerchinskaya and other areas. Non-commercial gas reserves were found in the Seismorazvedochnaya, Morskaya, Obruchevskaya, Nebolshya and other promising structures.

Materials and methodology

Geochemical conditions in petroleum saturated Mesozoic-Cenozoic sediments of the Pre-Caucasian were studied in the geochemical laboratories of Gubkin Oil and Gas University and Moscow State University through chemical, bituminological, pyrolytic and coal petrographic analyses of core and rock samples. Nonextracted powders were used in pyrolysis experiments. 215 samples taken from the Khadumskaya Formation in 57 petroleum fields of the Pre-Caucasian region were studied using different methods (Kerimov et al., 2017b; Guliev et al., 2018, 2021).

Generation, migration and accumulation of hydrocarbons within hydrocarbon systems were modeled in Temis Suite (basin modeling software). 2D models were created along a number of profiles in both submeridional and sublatitudinal directions. In this paper, the results of 2D modeling are presented for a regional seismic profile crossing the Western Pre-Caucasian region in the submeridional direction (Fig. 1). The seismic profile crosses all the main tectonic features of the region (from south to north): West Kuban Foretrough (WKF), Timashevskaya Step, Kanevsko-Berezansky Arch, Irklievskaya Depression, Azovsky Wedge. The profile is about 250 km long. All the identified stratigraphic units were characterized

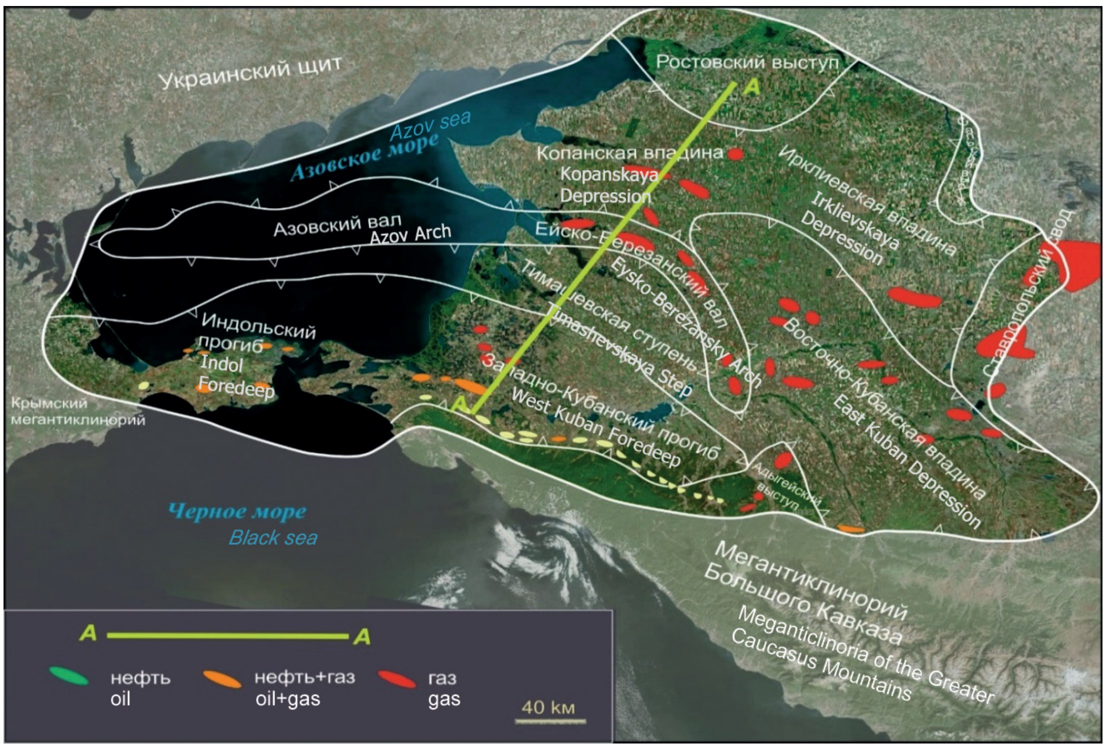

Fig. 1. Overview tectonic map of the Azov-Kuban Basin: A-A line depicts the regional seismic profile

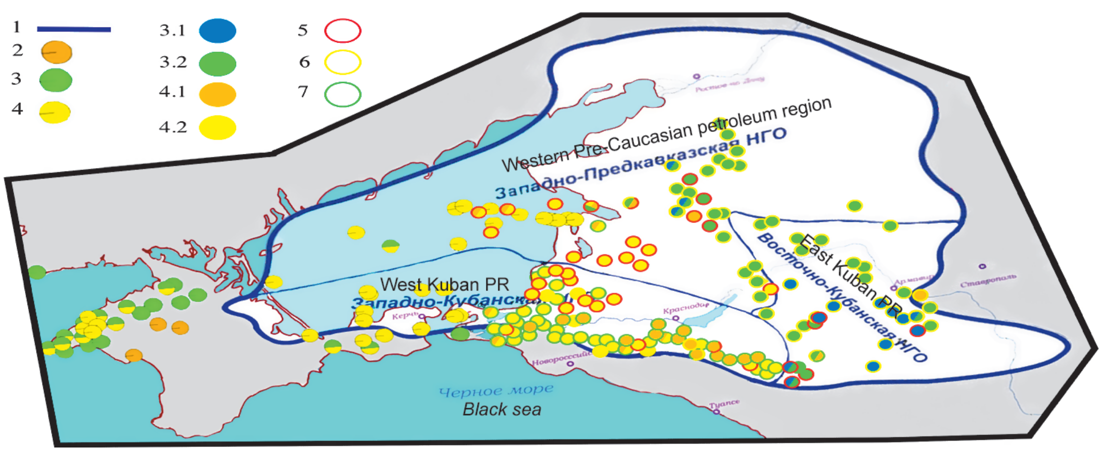

Fig. 2. Map of oil and gas fields in the Western Pre-Caucasian: 1 – boundaries of petroleum regions; 2–8 – deposits: 2 – Paleozoic; 3 – Mesozoic: 3.1 – Jurassic; 3.2 – Cretaceous; 4 – Cenozoic: 4.1 – Paleogene; 4.2 – Neogene; 5 – gas field; 6 – gas-condensate field; 7 – oil field

based on the following lithotypes: terrigenous deposits of the Lower and Middle Jurassic; sulfate-carbonate Upper Jurassic deposits; carbonate-terrigenous rocks of the Lower and Upper Cretaceous; terrigenous deposits of the Paleocene-Eocene; clays of the Maikop Series; terrigenous deposits of the Chokrak and Eopleistocene (Kerimov et al., 2016, 2017). The sedimentary cover reaches its maximum thickness (about 9 km) in the axial part of the West Kuban Trough.

To simulate the thermal history, a special calculation method was used which is based on deep heat flow and mean annual temperature recorded on the sediment's surface (Yandarbiev et al., 2014). The minimum values of heat flow are confined to the Precambrian basement highs, such as the Rostov High in the East European Platform, as well as to areas with a high sedimentation rate, where the deep heat flow is screened by "cold" overlaying sediments (the Indolo-Kuban Trough). In these areas, the heat flow values vary from 36 to 60 mW/m^2 (Khutorskoy et al., 2013). Mean annual temperature on the sediment's surface is 7 ^{o}C.

When modeling oil source beds, the following geochemical parameters were used: C_{org} – the percentage of organic carbon in sedimentary rocks; HI (hydrogen index) – the ratio of generated hydrocarbons (at S_2 peak of Rock-Eval pyrolysis) to C_{org}; type of organic matter – the type of kerogen (determined mainly on the basis of chemical and coal petrographic characteristics of kerogen).

Results

The studies and modeling uncovered four generation-accumulation hydrocarbon systems (GAHS) in the Mesozoic-Cenozoic complex of the Crimean-Caucasian section: Triassic-Jurassic, Cretaceous, Eocene and Maikop.

In the **Triassic-Jurassic** GAHS, Triassic-Jurassic deposits are the main source of petroleum. Chemical, bituminological and pyrolytic analyses showed that Triassic-Jurassic rocks contain large amount of organic carbon (2.3–4.6 %). Generation potential (S_1+S_2) is 0.7–0.8 mg of HC/g of rock; HI is 72 mg HC/g; CBA is 0.002–0.006 %; β=0.6–4.8 %. Kerogen is of II and III types. Triassic-Jurassic source rocks transformed through several catagenetic phases – up to MC_3-MC_4 (Fig. 3). In the southeastern part of the East Kuban Depression, the residual concentration of organic matter in Jurassic deposits reaches 2.48 %. Elemental analysis showed high maturity of organic matter in Jurassic sediments. The initial organic content was naturally high in these sediments, thus allowing rocks to produce hydrocarbons. In the southeastern part of the West Kuban Trough (the Khadyzhensky region), the organic content increased to 0.4–0.9 % (the Middle Jurassic). However, the rocks show low content of bitumen (CB=0.002–0.004 %) and OM (β^{CB}=2–5 %) and extremely low pyrolytic parameters – (S_1+S_2)=0.2 kg of HC/ton of rock, HI=44–110 mg of HC/g of C_{org} – along with high vitrinite reflectance R_o=1.22–1.37 % (the MC_4 phase) which altogether indicate the residual nature of petroleum generation potential, i.e. the rocks have already passed the main zone of oil generation ("oil window").

Coal petrographic studies showed that Lower Jurassic deposits in the southern regions of the Western Pre-Caucasian have the maximum values of R_o (1.8 %) which corresponds to the MC_4-MC_5 catagenetic phases (Suzdalskaya and Abkhazskaya areas). In the southeastern part of the West Kuban Trough (the Khadyzhensky region), the R_o values for Middle Jurassic rocks are 1.22–1.37 % (the MC_4 phase). Vitrinite reflectance in Jurassic deposits of the East Kuban Depression corresponds to the MC_3-MC_4 phases. The maximum value of T_{max} (485 ^{o}C) was recorded in Jurassic

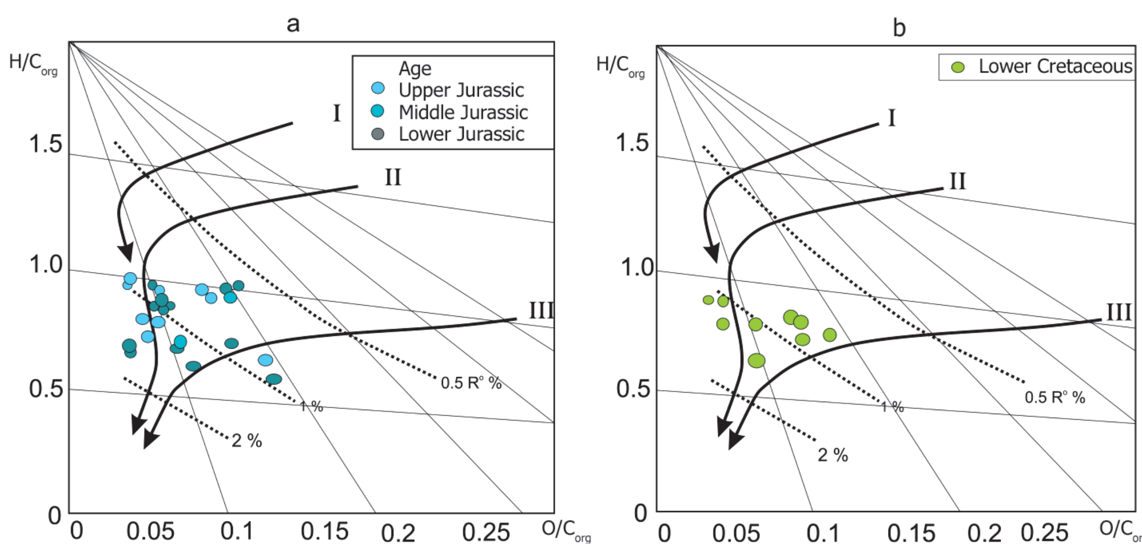

Fig. 3. Van Krevelen diagram: a – for the Jurassic deposits of the East Kuban Depression; b – for the Lower Cretaceous deposits of the Western Pre-Caucasian; I – type 1 kerogen; II – type 2 kerogen; III – type 3 kerogen

rocks of the West Neftegorskaya Foretrough Area. One of the main modeling parameters was geochemical characteristics of oil source beds.

The conditions for organic matter accumulation in the East Kuban Depression were favorable in the Early Jurassic (in the eastern part of the depression), in the Middle Jurassic (in the southeastern part), and in the Late Jurassic (in the central part) (Bolotov, 1977). The organic matter is of mixed nature. The organic matter in undifferentiated sediments of the Lower and Middle Jurassic is characterized by the following distribution of steranes C_{27}:C_{28}:C_{29} – 41:27:32; the predominance of cholestan (C_{27}) indicates a significant role of the algogenic component in the formation of the initial OM. In Middle Jurassic deposits, a more uniform distribution of steranes is observed: C_{27}:C_{28}:C_{29} – 31:37:32. Occasional predominance of ethylcholestan (C_{29}) is typical for deposits of a normal sea basin. Marine phytoplankton was the main bioproducer, but the contribution of terrigenous OM is also noticeable: this is evidenced by the sterane ratio C_{28}/C_{29} (0.5–1.0) which is a genetic indicator of OM types. In both complexes of Jurassic deposits on the southern slope of the Caucasus, the presence of a rare hopane, G_{28}-trisnorgopane, was noted. The mixed composition of OM in Jurassic deposits of the Caucasian region (formed in the sea basin) is also indicated by alkane hydrocarbons. In almost all samples, phytane (Ph) predominates over pristane (Pr), and the maximum amount of n-alkanes can be seen in the C_{16}–C_{18} range which is indicative of a normal sea accumulation basin (Lapidus et al., 2018). The ratios of different bioproducers at different times and in different parts of the basin were not the same, but marine organic matter predominated in almost all the studied samples.

Alkane and sterane indices show that OM has mostly passed the "oil window" (Gordadze et al., 2018). Sterane maturity indices are: $K^1 = S/(S+R) = 0.4–0.56$ (lim 0.55); $K^2 = \beta\beta/(\alpha R+\beta\beta) = 0.6–0.8$ (lim 0.86); $K^3 = \beta\beta/[\alpha(S+R)+\beta\beta] = 0.6–0.7$ (lim 0.71); C_{29} (dia/reg) = 0.2–0.9. All these coefficients are typical for OM of sediments situated in the lower part of the main zone of oil generation. The most transformed are rocks of the Lower and Middle Jurassic undifferentiated complex.

A high degree of catagenesis and coastal-marine depositional environment of the initial Jurassic OM are also reflected in the Connan-Cassou diagram obtained with gas chromatography (Fig. 4a). Petroleum generation potential increases in this direction which is confirmed by the composition of condensates: an increased content of methane homotypes ($C_2H_{6+higher}$) is confined to the southern part of the Western Pre-Caucasian (Chakhmakhchev, 1983).

Jurassic rocks were transformed to a maximum degree (the MC_4-MC_5 phases) in the center of the depression. Towards the sides of the trough, especially in the southern direction (the Adygei Wedge), the degree of catagenesis decreases to the MC_1-MC_3 phases (R_o=0.57–0.94 %). The elemental composition of kerogen, the amount and composition of bitumoids change in accordance with the catagenetic characteristics of OM. The highest bitumen content (β^{CB}=6–12 %) and increased amount of the oil fraction in the bitumen (45–50 %) are also confined to the southern part of the East Kuban Trough, which is consistent with the increased amount of sapropel in the composition of OM and its less transformed state.

In the **Cretaceous** GAHS, the Mesozoic Aptian-Albian terrigenous complex is the main petroleum source. In Aptian-Albian pelitic rocks of the Azov-Kuban petroleum basin (PB), the C_{org} values vary from

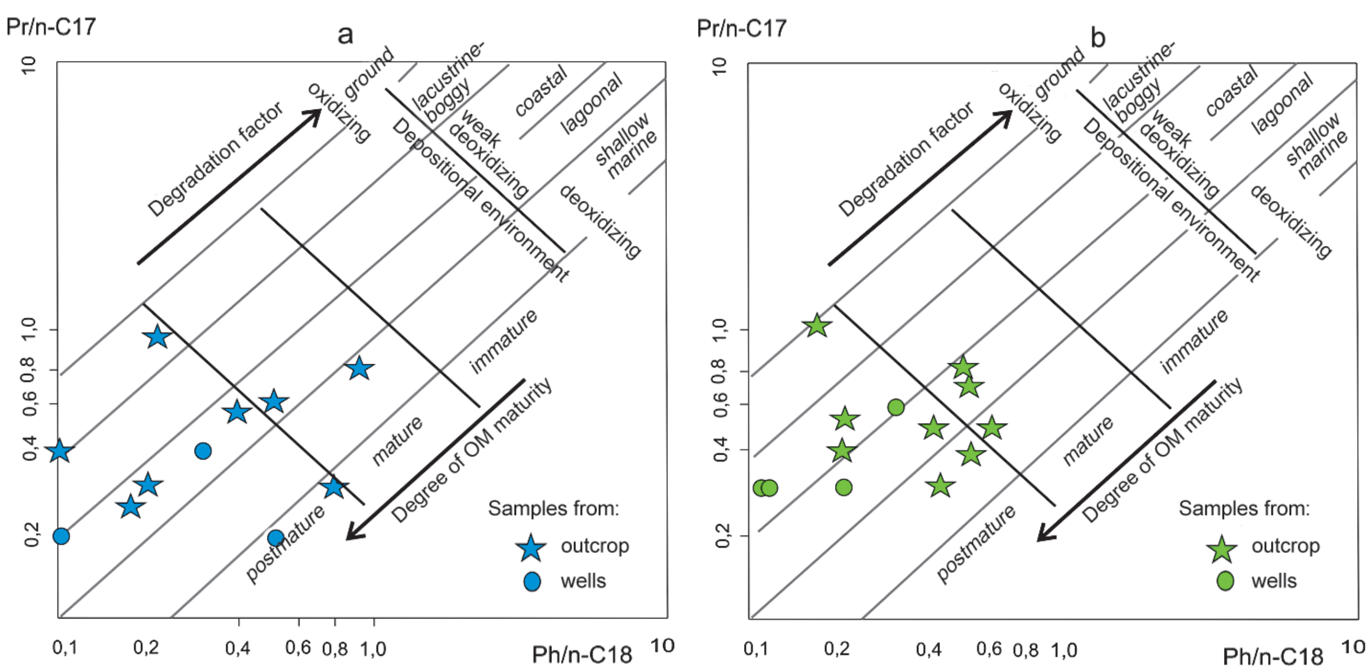

Fig. 4. Connan-Cassou diagram: a – for the Jurassic deposits; b – for the Lower Cretaceous deposits

0.01 to 4.1 %. The maximum values (up to C_{org}=45.6 %, South-Ukrainian area) are confined to the Albian dark clays, which can be found in the southern part of the West Kuban Trough and Kanevsko-Berezansky Arch, as well as to the Aptian dark clays in the western part of the East Kuban Depression. Petroleum generation potential is slightly increased: (S_1+S_2) = 0.3–3.2 kg of HC/ton of rock, but fairly minor – like it was in the Neocomian. The type of kerogen formed in the Lower Cretaceous rocks determines their relatively low petroleum generation potential.

Bitumen content is 0.001–0.2 %, β^{CB}=0.8–4.3 % in the variety of rocks enriched with OM, which indicates the syngenetic nature of the bituminous components. In the Aptian and Albian mudstones and clays, the geochemical parameters are slightly higher (Afanasenkov et al., 2007): C_{org} = 0.7–2.8 %, (S_1+S_2) = 0.4–1.9 kg of HC/ton of rock; HI = 36–206 mg of HC/g of C_{org}; T_{max} = 427–452 °C. Gas-liquid chromatography detected n-alkanes of the C_{15}-C_{33} series among the hydrocarbons (the distribution maximum falls at C_{18} and C_{22}). Minor maxima were also observed at C_{26} and C_{29}. High ratio of normal alkanes (nC_{18}/nC_{28}=4.8–5.3) and low ratio of pristane to phytane (Pr/Ph – 0.6) indicated predominance of phytogenic OM.

The typical distribution of steranes in the Aptian and Albian sediments is C_{27}: C_{28}:C_{29}=40:23:37. C_{27} prevails (C_{27}/C_{28}=1.4–1.8) over the rest of steranes, which is typical for OM accumulated in the sea basin with the main bioproducer being marine phytoplankton (C_{28}/C_{29} – 0.6).

Almost throughout the entire area of the Azov-Kuban PB, the Lower Cretaceous deposits are characterized by a maturity corresponding to the "oil window" (the MC_1-MC_3 phases), and only in the central part of the East Kuban Depression did they reach the MC_4 phase. Low petroleum generation potential of the Lower Cretaceous rocks stems from type III kerogen, and this was the reason for insignificant amount of liquid hydrocarbons generated by these deposits: hydrocarbon content of OM does not exceed 1–2 %, and it remains practically constant at different catagenetic phases; the average HC content of the rock is 270 g/m^3. In the northern part of the Eastern Black Sea PB, the T_{max} values and alkane and sterane maturity indices support the idea about the Lower Cretaceous rocks residing in the "oil window", and in most cases they are either at the pinnacle of the main phase of oil generation or in its final stages: $K^1tm_{(thermal\ maturity)}$ = 0.45–0.5, K^3tm = 0,7; C_{29}(dia/reg) = 0.2–0.3. Hopane maturity indices (M_{30}/H_{30} = 0.1–0.8, Ts/Tm = 0.5–1.8) vary in a wider range and do not always correlate with the transformation level.

Thus, the Lower Cretaceous deposits have low petroleum generation potential, part of which has been realized. Deposits of the Neocomian should be considered mainly as a gas source. The Aptian-Albian deposits of the Greater Caucasus and its southern slope, obviously, can be considered an oil source, but their potential is not very high.

In the Lower Cretaceous rocks of the continental part of the Eastern Black Sea Basin, OM is predominantly of sapropel type, but is oxidized (oxysorbosapropelite) to a large extent. The chemical composition often corresponds to type III kerogen, and the level of transformation points to the beginning of the "oil window" (Fig. 3b).

The degree of catagenetic transformation of OM in the Lower Cretaceous deposits varies over a wide range. Within the West Kuban and Kerch-Taman Troughs, on the southern slope of the Caucasus (Khadyzhensky region, Severo-Tamansky Arch, Kukolovskaya area), and within most of the Scythian Plate, the deposits are situated in the "oil window" (Suslova, 2006), T_{max} – 423–448 °C, Ra = 7.5–8.6 %). In the axial part of the Indolo-Kuban Trough, the transformation reaches its maximum (up to the MC_5-AC catagenetic phases at a depth of about 7 km). The continental type of OM and a high degree of catagenesis are also confirmed by the Connan-Cassou diagram (Fig. 4b).

In the **Eocene** GAHS, the Khadyzhenskaya and Kumskaya formations of the Upper Eocene, both with high petroleum generation potential, are the main petroleum source. Within the West Kuban Trough, the current C_{org} content is 0.63–11.32 % (with the average of 3.32 %). It is lower (C_{org}=1.2–1.6 %) in the clays of the East Kuban Depression and the Yeisk-Berezanskaya Zone. Deposits of the Kumskaya Formation contain type II kerogen which has a high petroleum generation potential (Fig. 5a). The HI values in pure kerogen reach 500–800 mg HC/g TOC; in the rock, the values are lower and average about 300 mg HC/g TOC. The difference in the values of HI is due to the adsorption of hydrocarbons on the mineral matrix (very active clay minerals). This effect often leads to lower hydrocarbon yield at the S_2 peak and, consequently, underestimated HI of the rock. Debituminized kerogen contains large amount of H (7.1–8.6 %) and H/C (1.1–1.4). Both rocks and organic matter are enriched with bitumoids: chloroform bitumen (CB) reaches 0.05–0.49 %, sometimes 0.7–1.2 %, β^{CB} 4–16 %, at different phases of catagenesis.

Gas-liquid chromatography showed that alkanes C_{17}-C_{31} and heavy arenes (T_{BP}=400–460 °C) make up the bulk of hydrocarbons at a depth of 3.8 km. Light C_{11}-C_{17} n-alkanes dominate at a depth of 4.5–5.0 km (MC_2, possibly MC_3 phase). Among the arenes, low-molecular hydrocarbons (T_{BP}=200–300 °C) appear in high concentrations. Pristane and phytane predominate among isoprenoids. Isoalkanes and cyclanes contain significant amount of steranes and triterpanes (C_{28}-C_{30}) which increases with the catagenesis phase.

Deposits of the Kumskaya Formation located at

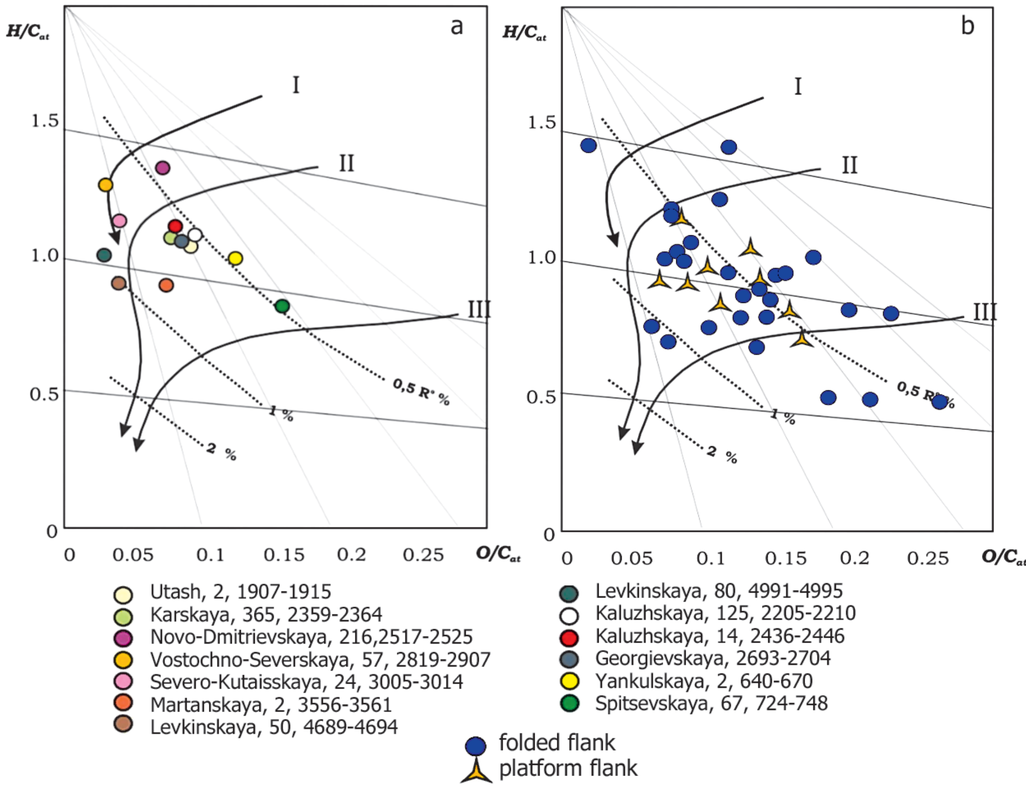

Fig. 5. Van Krevelen diagrams: a – for deposits of the Kumskaya Formation; b – for the Maikop deposits (data from the works of Pepper, Corvi, 1995; Khramovoy, 1986)

depths less that 2.5–3.5 km (in the platforms and folded areas of the Azov-Kuban PB) reflect the initial stage of catagenesis (protocatagenesis (PC)), and those located at 3–5 km represent the MC_1-MC_2 phases, i.e. the "oil window". Catagenesis triggers significant changes in the composition of OM: in debituminized kerogen, the number of heteroatoms sharply decreases (from 34 % to 23 %), and the carbon content increases (from 60 to 70 %). At the same time, the total C_{org} content in the rocks decreases, which is due to the increased generation of hydrocarbons during the main oil generation phase and partial loss of carbon escaping with gaseous and low-boiling hydrocarbons. When rocks subside to a greater depth, new bitumoids (and HC) form: in the OM, the share of CB and HC sharply increases (from 3.2 % and 1.4 % during the PC phase to 8–18 % and 7 % during the MC_1-MC_2 phases, respectively). Migratory bitumoids could be found even in the PC phase, and they are extremely widespread in the MC_2 phase (4.6–5.0 km, 140–165 °C).

Thus, the geochemical characteristics of OM in the rocks of the Kumskaya Formation showed that these rocks not only have a high petroleum generation potential, but constitute one of the main oil-producing formations in the Caucasus.

In the **Maikop** GAHS, the main petroleum producers are the Maikop clays which have high petroleum generation potential. In Maikop sediments of the West Kuban PB, the C_{org} content varies from 0.1 to 9.3 % with the average of 1.46 % and increasing eastward. Over the entire Taman Peninsula, the average C_{org} content is 0.87 %. In the central part of the trough it is 1.1 %, and in the eastern part it reaches 1.2 % (Nadezhkin, 2011). Pyrolysis results showed that organic matter of the Maikop deposits is immature; the majority of the samples are kerogens of the II-III and III types (Fig. 5b).

The Connan-Cassou diagram obtained with gas chromatography shows that the Maikop OM was formed in coastal-marine environment and now is at various stages of maturity – from immature to heavily transformed (Fig. 6).

In the West Kuban Trough, the C_{org} content is 0.1–9.3 % with the average of 1.46 % (pyrolysis data showed slightly lower value – 1.06 %); (S_1+S_2) 0.06–20 kg of HC/ton of rock (the average is 1.36 kg of HC/ton of rock). The C_{org} values are more than 2 times higher in the Lower Maikop than in the Upper (2.4 % and 1 %, respectively).

The C_{org} content (and petroleum generation potential S_1+S_2) increases eastward. Over the entire Taman Peninsula, the average C_{org} content is 0.87 %. In the central part of the trough it is 1.1 %, and in the eastern part it reaches 1.2 %; (S_1+S_2) – 0.77, 1.81, and 2.74 kg of HC/ton of rock, respectively, for each part of the trough. In the East Kuban Trough and within the Adygei Wedge the OM content is similar: 1.32 % and 0.9 %, respectively. The Lower Maikop (the Khadumskaya Formation) rocks have high petroleum generation potential: C_{org} > 2 %, (S_1+S_2) > 6 kg of HC/ton of rock.

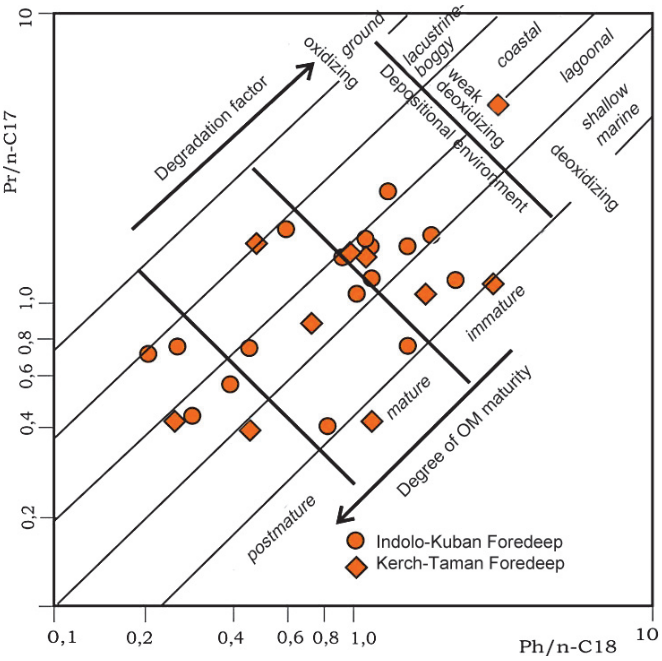

Fig. 6. Connan-Cassou diagram for the Maikop deposits

Thus, clays of the Maikop Series in the western part of the Caucasus show the properties of petroleum source rocks, however their potential is usually mediocre due to the mixed nature of organic matter (Kerimov et al., 2014, 2018). Petroleum generation properties are higher in the Lower Maikop part of the section (the Khadumskaya Formation), and these rocks are petroleum producers.

Modeling results

2D basin modeling conducted over a number of regional profiles crossing the Western Pre-Caucasian region was used to reconstruct the processes of generation, migration and accumulation of hydrocarbons within hydrocarbon systems. The modeling results showed that the upper boundary of the main zone of oil generation runs at a depth of about 2000 m, which in the central part of the West Kuban Trough corresponds to the top of the Upper Miocene or the base of the Pliocene. The lower boundary of the "oil window" is located at a depth of about 5000 m, which in the lower part of the trough corresponds to the base of the Maikop Series (Yandarbiev, 2014). Within the platform, the upper boundary of the main zone of oil generation in located at depths of about 1800–2300 m. The main zone of oil generation transfers into the gas generation zone at a depth of 5500–6000 m within the Timashevskaya Step and at a depth of 4000–4500 m in the Irklievskaya and Kopanskaya Depressions. Table 1 shows the averaged geochemical parameters of the main petroleum source beds used in modeling.

The lithological and facies model (Fig. 7) reflects

Petroleum source rocks	C_{org}, %	HI, mg HC/g C_{org}	Type of OM
P_3 - N_1^1	1.5	350	II-III
Paleocene- Eocene	4.7	500	II
K_1	1.7	300	II-III
T-J	2.1	400	II

Table 1. Input geochemical parameters used for modeling

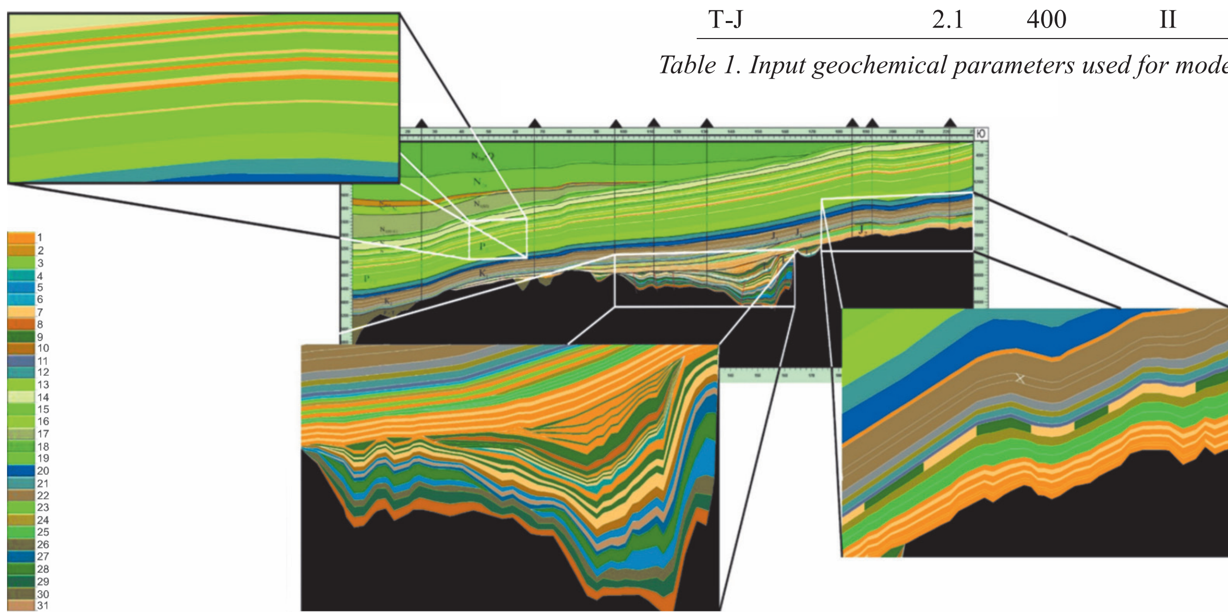

Fig. 7. The distribution of lithotypes: 1 – sandstone; 2 – 50 % sandstone, 50 % clay; 3 – clay; 4 – marl; 5 – limestone; 6 – dolomite; 7 – siltstone; 8 – conglomerate; 9 – argillite; 10 – 50 % siltstone, 50 % argillite; 11 – 30 % limestone, 30 % argillite, 30 % siltstone, 10 % conglomerate; 12 – 60 % marl, 15 % siltstone, 15 % argillite, 10 % clay; 13 – 95 % clay, 5 % sandstone; 14 – 60 % clay, 15 % siltstone, 15 % sandstone, 10 % marl; 15 – 80 % clay, 10 % limestone, 10 % marl; 16 – 80 % clay, 20 % sandstone; 17 – 40 % sandstone, 50 % clay, 10 % limestone; 18 – 70 % clay, 50 % sandstone, 15 % conglomerate; 19 – 80 % clay, 20 % sandstone; 20 – 70 % limestone, 30 % marl; 21 – 90 % limestone, 10 % sandstone; 22 – 55 % sandstone, 25 % argillite, 15 % siltstone, 5 % limestone; 23 – 80 % clay, 20 % limestone; 24 – 60 % sandstone, 20 % siltstone, 10 % limestone, 10 % marl; 25 – 75 % clay, 25 % siltstone; 26 – 70 % argillite, 15 % sandstone, 15 % argillite; 27 – 60 % limestone, 20 % dolomite, 10 % marl, 10 % siltstone; 28 – 80 % argillite, 5 % limestone, 5 % marl, 10 % siltstone; 29 – 50 % argillite, 50 % limestone; 30 – 50 % argillite, 50 % limestone, 30 – 60 % argillite, 40 % sandstone

the distribution of lithological types along the section. Lithotypes were classified based on reference data available for the study area and the standard parameters used in Temis Suite. Each lithotype is characterized by a set of petrophysical parameters that are used in calculations.

Figure 8 shows hydrocarbon saturation of the sedimentary cover and modern catagenetic zoning of petroleum producers along the modeled profile.

The "gas window" is located at a depth of 5000–8000 m. Cretaceous-Jurassic deposits fall within the main gas generation zone in the West Kuban Trough, while in the platforms they are replaced by Triassic-Jurassic rocks. Deposits of the Lower and Middle Jurassic in the most lowered regions of the West Kuban Trough are presumably hypermature and may still be generating "dry" gas.

Different-intensity stages of the geothermal regime determined sharp variations in the depths of catagenetic zones within the Kerch-Taman and West Kuban Troughs, the southern slope of the Caucasus (all three experienced active inversion), and tectonic elements of the Scythian Platform (which undergo almost zero inversion). In the Epipaleozoic platforms, the catagenetic zonal sequence

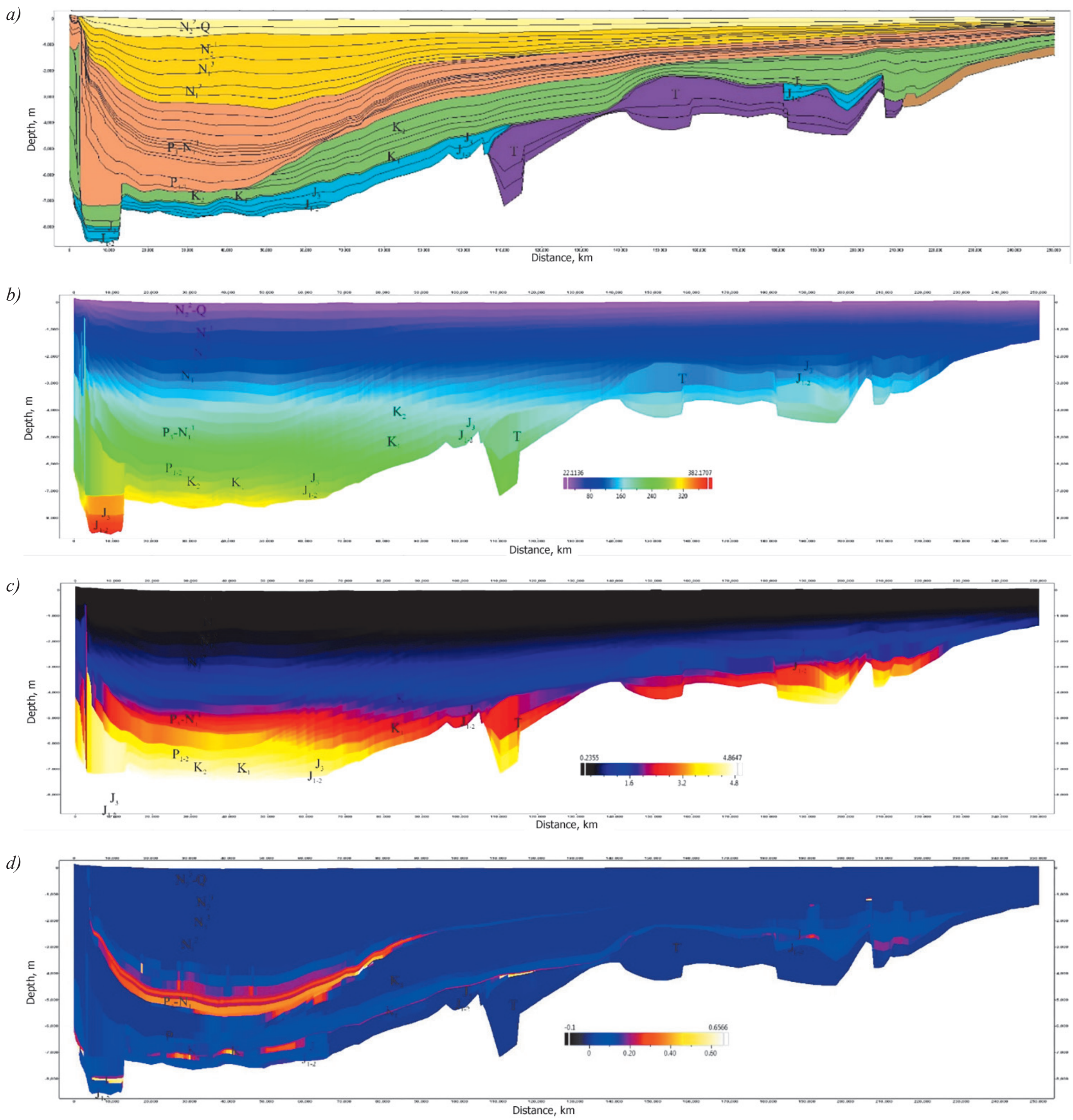

Fig. 8. Modeling results: a – simplified structural model; b – current temperature distribution along the sedimentary section; c – catagenetic zones in the sedimentary cover; d – hydrocarbon saturation of the sedimentary cover

is contracted: the upper boundary (the top) of the "oil window" is located at a depth of about 2.0–2.5 km, and the bottom is situated between 4 and 4.5 km. In the folded areas, the zonal sequence is extended, which leads to sharp differentiation and lowering of the "oil window" to a greater depth. Within the folded areas, the top of the "oil window" is located at the following depths: the North Taman Arch – 4.3–5 km, the West Kuban Trough – starting from 2.6–3.2 km (Khadyzhensky district) and up to 4–4.2 km (Dzhiginsko-Varenikovsky district) (Bazhenova et al., 2005; Guriev, 2010).

The "oil window" is located at a maximum depth within the most curved part of the Indolo-Kuban Trough, which is marked by mud volcanism and cryptodiapir folds, apparently due to heat coming from the deeper part of the section (Bazhenova et al., 2005).

There is another feature that is closely connected to the extended catagenetic zonal sequence: the large thickness of the petroleum source deposits. This can be clearly seen on the example of the Maikop source rocks in the Western Pre-Caucasian. They are more than 2 km thick. In the lowest parts, the bottom of the "oil window" has not been reached. At a depth of 5333 m, T_{max}=448 ^{o}C which corresponds to the center of the "oil window". This means that its bottom is located at an even greater depth (Bazhenova et al., 2004).

In order to understand the processes of petroleum formation in the study area, we should also consider the catagenetic evolution of the main petroleum sources in the central part of the WKT (Fig. 9).

The modeling results showed that in the West Kuban Trough hydrocarbons started to generate in the Late Jurassic–Early Cretaceous, when terrigenous Jurassic oil source beds entered the main zone of oil generation. The generation of petroleum fluids continued until the beginning of the Maikop. It was facilitated by the continuous subsidence of the area compensated

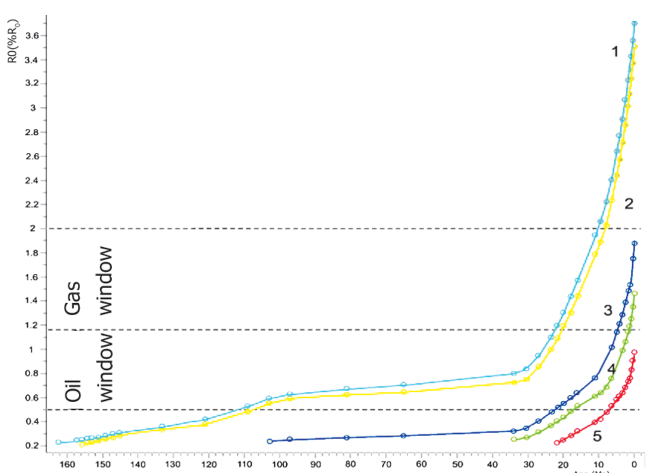

Fig. 9. Catagenetic evolution of the major petroleum source complexes: 1 – Middle Jurassic; 2 – Late Jurassic; 3 – Early Cretaceous; 4 – Early/Middle Paleogene; 5 – Late Paleogene/Early Neogene

by sedimentation (Yandarbiev et al., 2014). Within the Kanevsko-Berezansky Arch, Lower and Middle Jurassic oil source rocks entered the "oil window" at the beginning of the Paleocene by descending to a depth of about 2 km.

In the Oligocene, accumulation of the Maikop clays begins, which contributed to the transition of the Jurassic oil source rocks into the "gas window". Active sedimentation in the area and its continued subsidence at the beginning of the Oligocene led to a catagenetic transformation of Aptian-Albian oil source rocks – sufficient enough for the generation of hydrocarbons. Within the platforms (Kanevsko-Berezansky Arch), Lower Cretaceous deposits entered the "oil window" at the end of the Miocene. Within the Kerch-Taman Trough (the North Taman Arch), Aptian-Albian deposits entered the "oil window" in the middle of the Maikop by descending to a depth of 2.8–3.0 km.

By the end of the Early Miocene, deposits of the Kumskaya Formation were also involved in the oil generation process within the West Kuban Trough. At the turn of the Middle and Late Miocene (about 10–15 Ma ago), Jurassic oil source rocks left the "gas window". At about the same time Aptian-Albian oil source rocks reached the "gas window" and are still in there. At the end of the Late Miocene, the sediments of the Kumskaya Formation entered the gas generation zone; at the same time the processes of oil formation began in the oil source beds of the Maikop Series (Yandarbiev et al., 2014).

The modeling showed that in the Albian (about 130 Ma ago) hydrocarbons began to migrate from the oil source beds of the Early and Middle Jurassic. The migration was of zonal nature, mostly vertical, and took place only within the depocenter of the West Kuban Trough. By the Late Cretaceous, migration processes took over almost all Jurassic strata, and the direction of migration changed from vertical to lateral, controlled by the bedding angle. The gradual subsidence of the sediments during the Paleogene did not affect the nature and direction of migration processes. In the WKT, migration was the most active in the Miocene. In the Middle Miocene, hydrocarbons began to migrate from the Aptian-Albian and Kumskaya oil source formations. Towards the end of the Neogene they started to leave the Maikop sediments. The direction of migration was controlled by the bedding angle again (Yandarbiev et al., 2014).

In general, the 2D modeling results confirm the current ideas about petroleum distribution over the sedimentary cover in the study area. For example, the model maps out proven hydrocarbon deposits which were found in the Paleogene-Neogene sediments of the southern flank and the central part of the trough, as well as gas and gas-condensate deposits in the Lower Cretaceous reservoirs of the Scythian Plate. The

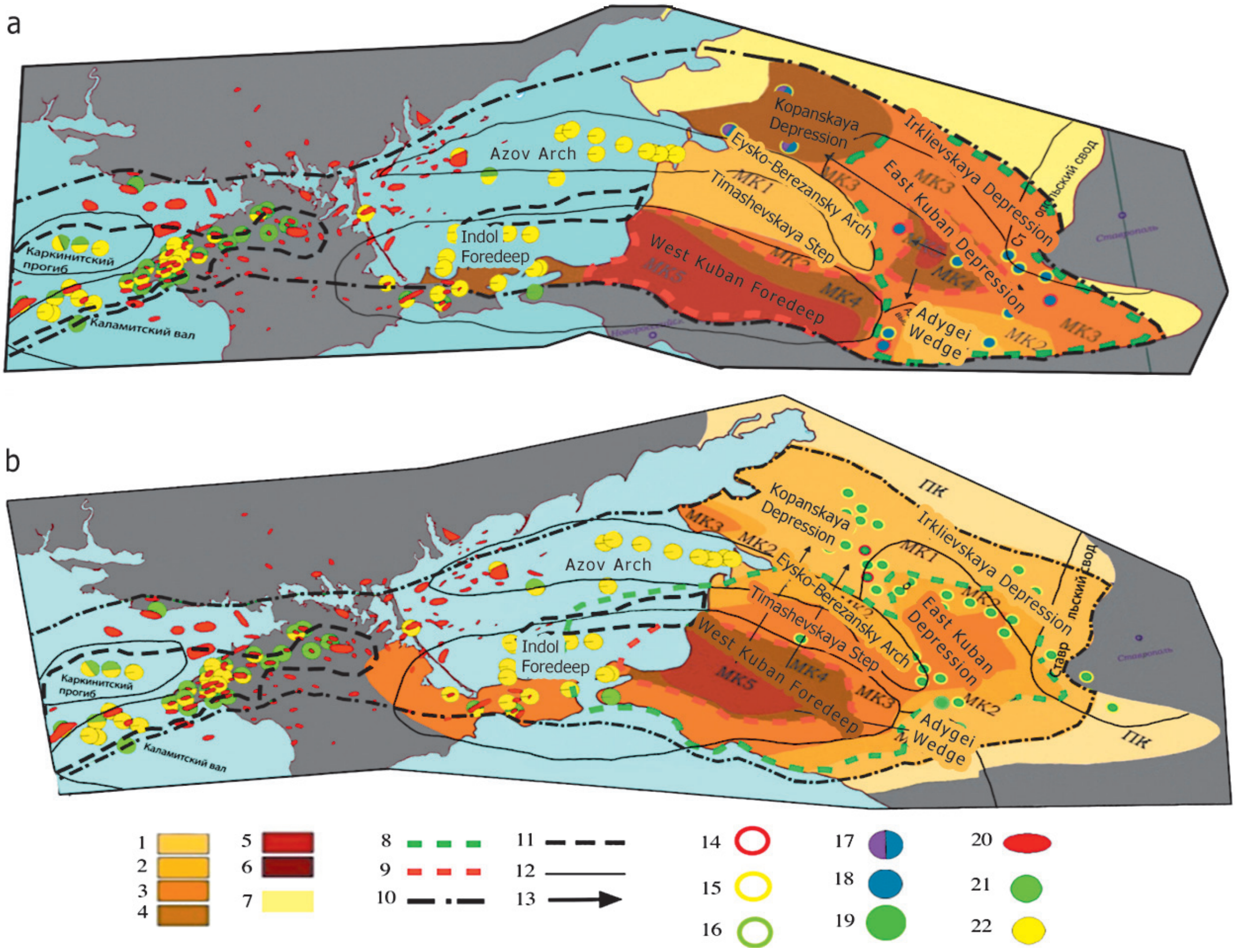

Fig. 10. Map of the Crimean-Caucasian Mesozoic GAHS: a – Triassic-Jurassic, b – Cretaceous. 1–6 – phases of catagenesis: 1 – MC_1; 2 – MC_2; 3 – MC_3; 4 – MC_4; 5 – MC_5; 6 – AC; 7 – location of the reservoir; 8 – boundary of the «oil window»; 9 – boundary of the «gas window»; 10 – boundaries of the hydrocarbon system; 11 – boundaries of the HC source; 12 – boundaries of structural and tectonic elements; 13 – direction of migration; 14 – gas deposit; 15 – gas-condensate deposit; 16 – oil deposit; 17 – field confined to the Triassic-Jurassic deposits; 18 – field confined to the Jurassic deposits; 19 – field confined to the Cretaceous deposits; 20 – perspective elevated areas; 21 – oil and gas showings in the Mesozoic sediments; 22 – oil and gas showings in the Cenozoic sediments

maximum saturation of the reservoirs reaches 80–90 % (Fig. 8d).

3D modeling made it possible to create maps of each hydrocarbon system in the Crimean-Caucasian section: Triassic-Jurassic, Cretaceous, Eocene and Maikop (Figs. 10, 11).

Discussion

The research results indicate that most of the Crimean-Caucasian section of the Alpine fold system has been an area of long-term and stable subsidence in the Mesozoic and Cenozoic. The Azov-Kuban Basin, which is a typical foreland basin, is situated in this area. 3D modeling made it possible to identify four GAHS in the Mesosoic-Ceinozoic complex of the Western Crimean-Caucasian region – Triassic-Jurassic, Cretaceous, Eocene and Maikop – and to study the elements of HS and processes occurring within them.

Within the study area, oil source beds were found in the following sedimentary complexes: the Triassic-Jurassic (terrigenous), the Aptian-Albian (terrigenous), the Paleocene-Eocene (terrigenous-carbonate), the Oligocene-Lower Miocene (clay deposits of the Maikop Series).

The phase composition of generated fluids depends on the degree of catagenetic transformation of the oil source rocks in combination with the type of original organic matter. According to the classification proposed by N.B. Vassoevich, the boundaries of the “oil window” correspond to the MC_1-MC_3 catagenetic phases, which in turn correspond to the reflectance of vitrinite in oil (R_o) of 0.55–1.2 %. The peak of oil production falls within the MC_2 phase (R_o is 0.65–0.85 %). The “gas window” (the main zone of gas generation) corresponds to R_o = 1.2–4 %. At the beginning of the “gas window”, predominantly “wet” gas is generated (up to R_o = 2 %),

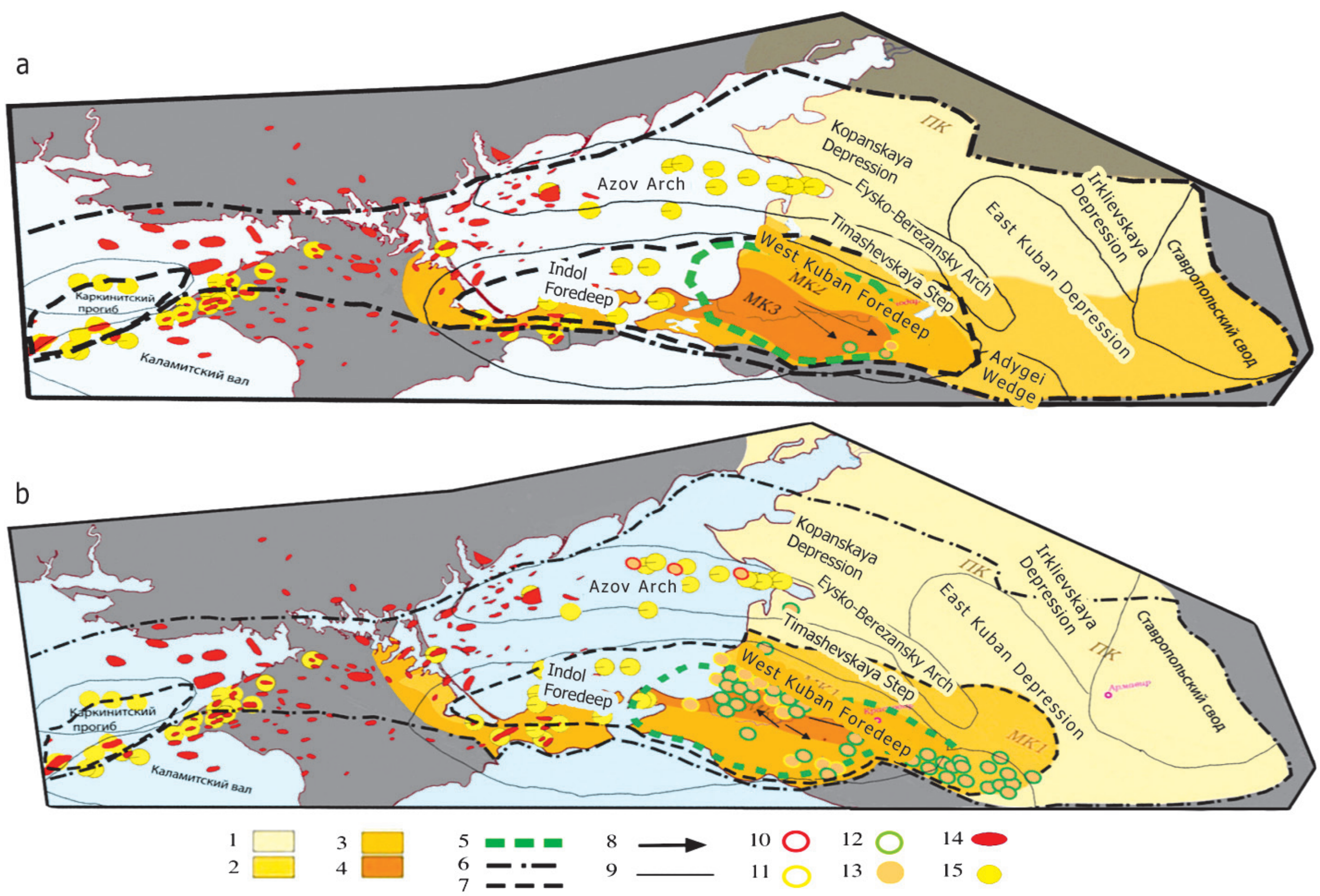

Fig. 11. Map of the Crimean-Caucasian Cenozoic GAHS: a – Eocene, b – Maikop. 1–4 – phases of catagenesis: 1 – PC; 2 – MC_1; 3 – MC_2; 4 – MC_3; 5 – boundary of the «oil window»; 6 – boundaries of the hydrocarbon system; 7 – boundaries of the HC source; 8 – direction of migration; 9 – boundaries of structural and tectonic elements; 10 – gas deposit; 11 – gas-condensate deposit; 12 – oil deposit; 13 – field confined to the deposits of the Kumskaya and Maikop formations; 14 – perspective elevated areas; 15 – oil and gas showings in the Cenozoic sediments

followed by “dry” gas rich in methane (Vassoevich, 1986).

The adequacy of the results was assured through comparing the calculated and measured indices of organic matter maturity (T_{max}; R_o, %). Vitrinite reflectance, which is the most reliable indicator of the transformation degree, was not only measured using the carbon petrographic method, but also calculated based on the T_{max} of pyrolysis: R_o, % = 0.018 * T_{max} – 7.16.

Petroleum source beds located in the main zone of oil generation are usually considered as the core of petroleum generation (Bazhenova et al. 2004). As a rule, these cores are located in the lowest parts of the sedimentary basin with rough PT conditions. This is the reason for hydrocarbons to migrate from these areas. Structural and tectonic studies showed that the southern edge of the West Kuban Trough is the most subsided area in the region and can be considered the main source of hydrocarbons. Several local sources were also found in the depressions separating the Sunzhenskaya and Terskaya anticlines.

In general, Mesozoic oil source rocks are characterized by extremely differentiated thermal fields and, consequently, the main petroleum generation zone is located at different depths. A large part of the Western Pre-Caucasian is characterized by an extended catagenetic zonal sequence, and generally the main oil generation zone is located at great depths. The main consequence of this is that petroleum producing beds can be located at a wide range of depths: from 2–3 km to 6 km for oil sources, and up to 9 km for gas sources. The modeling results showed that the upper boundary of the main zone of oil generation runs at a depth of about 2000 m, which in the central part of the West Kuban Trough corresponds to the top of the Upper Miocene or the base of the Pliocene (Yandarbiev et al., 2014). The lower boundary of the “oil window” is located at a depth of about 5000 m, which in the lower part of the trough corresponds to the base of the Maikop Series.

The main phase of oil generation in the Western Pre-Caucasian began the end of the Jurassic. Its completion and the onset of the main phase of gas generation began in the Cenozoic. In the Scythian Plate, however, there are exceptions: within the Adygei Wedge, the Kanevsko-Berezansky Arch and the southwestern part of the East Kuban Depression, Middle Jurassic and

Lower Cretaceous deposits are in the middle of the "oil window" and in the final stages of gas generation; Upper Cretaceous deposits are at the end of the protocatagenesis, i.e. in the beginning of the "oil window".

Thus, it was found that extended catagenetic zonal sequence is typical for depressions. It is caused by high rates of sedimentation and subsidence, and, therefore, large thickness of oil source beds (not less than 2.5 km).

Generation of HC depends not only on innate characteristics of oil source rocks and the degree of their catagenetic transformation, but also on the degree of OM depletion which defines the residual HC generation potential of oil source rocks. At present, Jurassic petroleum source rocks of the West Kuban Trough have almost completely exhausted their potential. They can still generate hydrocarbons, but only within the platforms where they (together with Triassic deposits) are at the MC_{3-4} phase and have sufficient (50–60 %) generation potential. The degree of kerogen depletion in Aptian-Albian petroleum source rocks decreases from 90 % in the depocenter of the West Kuban Trough to 70–80 % at its sides. Within the platforms, they almost completely preserved their generation potential. A similar pattern can be seen in the deposits of the Kumskaya Formation.

Clays of the Maikop Series almost completely preserved their generation potential within the trough. Based on specific features of organic matter and the degree of catagenetic transformation of petroleum source complexes (Zaicev et al., 2017, Mustaev et al., 2017), it can be assumed that the main sources of oil today are deposits of the Maikop Series and the Kumskaya Formation (occasionally of the Lower Cretaceous as well). Gas hydrocarbons are generated mostly by source rocks of the Jurassic complex. Starting from the Late Miocene, Jurassic oil source beds have not been making a significant contribution to the petroleum content of the foretrough. However, they are probably still capable of generating dry gas.

At present, migration processes in the foretrough are multidirectional. The fluids flow from the main oil source located in the lowest part of the region towards the platform part and the southern side of the trough. Major hydrocarbon deposits developed in the anticlinal structures in the central part of the foretrough. According to the modeling results, the main natural reservoir here is chemogenic limestones of the Upper Cretaceous, into which hydrocarbon fluids entered mainly from oil source beds of the Bathonian-Bajocian and Aptian-Albian.

Conclusion

Geological and geochemical modeling of the Azov-Kuban Trough revealed several depocenters within this area which are merged into four generation-accumulation hydrocarbon systems: Triassic-Jurassic, Cretaceous, Eocene and Maikop. Prospectivity of the trough stems from the large thickness of the sediments located in the main zone of oil (and possibly gas) generation.

Basin modeling showed that the Upper Jurassic subsalt carbonate assises on the northern side of the foretrough are the promising exploration targets. Large amount of hydrocarbons can be found in the Upper Jurassic subsalt folds, and the estimated oil saturation can exceed 80 %. Thus, GAHS located in the Mesozoic part of the sedimentary section can promote the formation of hydrocarbon reservoirs in the Jurassic carbonate (presumably) beds of the northern side of the Indolo-Kuban Trough and, possibly, in non-anticlinal traps situated within the fringe zone of Cretaceous rocks on the southern side of the Azov Arch. The expected fluid type is gas.

The modeling results imply that all promising targets of the Cenozoic part of the section within the Indolo-Kuban Trough draw hydrocarbons from the Cenozoic GAHS: Kumskaya, Khadumskaya and Maikop formations. Gas/oil and oil/gas deposits should be expected in this area. Geological reconstructions, basin modeling and the analysis of OM made it possible to identify the areas where hydrocarbon systems can be situated within the sedimentary cover and transient formations.

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