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RESULTS OF MODELING HYDROCARBON MIGRATION AND ACCUMULATION PROCESSES IN THE SOUTH CASPIAN BASIN

The implemented 3D modeling of hydrocarbon systems in the South Caspian Basin (SCB) identified the mechanisms of hydrocarbon migration: mud volcanoes and extensional fractures related to diapiric structures are the primary migration pathways. Nearly all deposits in SCB occur in the mud volcanism areas and are complicated by eruptive channels, which implies vertical migration of hydrocarbons. The modeling also indicates that the critical moment and migration of hydrocarbons from the Eocene, Maikop and Diatomaceous oil and gas source rocks (OGSR) comes by the end of the Surakhany time (~3 million years ago), i.e. during formation of the upper portion of the productive series. In the Tarkhan–Chokrak OGSR strata, the critical moment was only passed by at the end of the Akchagyl time (2.2 million years ago). Modeling of hydrocarbon systems identified the oil and gas concentration zones (or accumulation zones) in the productive series. The analysis and typification of hydrocarbon traps and reservoirs in the South Caspian Basin shows that the totality of characteristics, which point at belonging of a deposit in a certain class, relate with one of two factors–structure or sedimentation (lithology–stratigraphy).

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Introduction

It is known that multiple mechanisms of primary oil migration may operate in nature. The movement of hydrocarbons occurs at varying rates and depends not only on the molecular structure of hydrocarbons but also on the mineral composition of the enclosing rocks [1]. As understanding of migration processes has evolved, three main conceptual pathways for primary hydrocarbon migration have been identified: in gas-dissolved, water-dissolved, and free phases. Hydrocarbons never start migrating from the origin of the source rock [2]. The primary mechanisms of hydrocarbon migration can be broadly classified into two categories: migration driven by pressure gradients and migration driven by buoyancy, the latter being a result of density differences between hydrocarbons and formation water.

Various basin modeling approaches have been developed to simulate these processes, among which three key concepts are commonly distinguished:

Darcy Flow—Based on the equations for multiphase flow through porous media (Darcy's Law). This method describes the movement of multicomponent, three-phase fluids while accounting for rock permeability and capillary pressure. Migration velocities and hydrocarbon saturation within reservoirs are calculated in a single procedure. Specialized algorithms are employed to model potential leakage through cap rocks and migration along faults. Diffusion effects can also be incorporated to simulate the transport of gaseous hydrocarbons in the aqueous phase.

Flow Path Analysis—A geometric surface analysis method based on buoyancy-driven migration. The Flow Path is typically used to simulate lateral hydrocarbon migration. It provides insights into drainage areas, hydrocarbon accumulation zones, and phase composition. When combined with the Darcy Flow for low-permeability zones, this hybrid approach enhances simulation accuracy.

Invasion Percolation—A method in which flow is governed solely by capillary forces. This approach assumes that, on geological timescales, hydrocarbons migrate instantaneously under the influence of buoyancy and capillary pressure. Invasion percolation is particularly effective for modeling fluid migration along fault zones and is best suited for simulating single-phase fluids composed of a limited number of components.

The combination of different modeling methods requires the implementation of threshold values that allow the software to determine when a specific approach should be applied. The advantages of each method can thus be integrated, enabling efficient and accurate simulation of hydrocarbon migration and accumulation processes.

Hydrocarbon migration in the South Caspian Basin

Modeling of hydrocarbon migration processes in SCB demonstrates that migration is closely linked to mud volcanism [3–5]. In SCB and adjacent onshore marginal zones—particularly within the Apsheron–Gobustan pericline and the Lower Kura Depression—there are approximately 100 large mud volcanoes, most of which exhibit a predominantly conical morphology [6, 7]. In the offshore area, mud volcanoes tend to be significantly larger in size. For example, the Sharg mud volcano, associated with the Ataturk Ridge, extends over 100 km in length and approximately 7 km in width.

Approximately 50% of mud volcanoes emit exclusively Paleogene–Lower Miocene oils. In 17% of the volcanoes, the emitted oils are primarily derived from the Diatomaceous Complex, while in 33%, a mixed composition is observed, with approximately equal contributions from both the Paleogene–Lower Miocene and Diatomaceous OGSR complexes. The roots of mud volcanoes are situated at depths of 10–12 km, coinciding with zones of active fluid generation [8–21]. Seismic data confirm that these roots are buried no deeper than 10–12 km.

Of particular interest is the spatial distribution pattern of hydrocarbons associated with mud volcanism. Mud volcanoes with a predominantly Diatomaceous oil signature are concentrated in the remote northwestern part of the SCB, in the transitional zone between the Lower Kura and Shamakhi–Gobustan depressions. Tectonically, this boundary is defined by the deep-seated Ajichay–Alyat Fault, along which Paleogene–Lower Miocene sediments of the southwestern flank of the Shamakhi–Gobustan tectonic step have been thrust over Middle–Upper Miocene and Pliocene complexes of the northeastern part of the Lower Kura step.

The identical carbon isotopic composition of oils found in the thrust sheet and the underlying footwall suggests that the source feeding the mud volcanoes is primarily located within the Diatomaceous Complex of the Lower Kura Depression. This conclusion is further supported by the uniformly low maturity levels of oils in this group of mud volcanic manifestations, which correspond to those found in the northern part of the Lower Kura Depression (e.g., Kalamadyn, Maly Kharami fields).

Thus, mud volcanism in SCB represents the principal mechanism of hydrocarbon migration. The main migration pathways are the eruptive conduits of mud volcanoes and extensional fractures formed during the development of diapiric structures [22–24]. Considering that virtually all hydrocarbon fields located within areas of active mud volcanism are affected by eruptive channels, the mechanism of reservoir charging within the productive series through vertical hydrocarbon migration is convincingly substantiated [25]. These reservoirs are primarily supplied by hydrocarbons migrating from OGSR adjacent to the eruptive channels of mud volcanoes. This key feature of petroleum systems in the SCB has ensured the continued replenishment of hydrocarbon accumulations in producing fields located within mud volcanic zones—even those that have been under development for over a century.

The onset of hydrocarbon expulsion from OGSR into reservoirs begins with the so-called critical moment—the phase of the generative process during which approximately 50% of hydrocarbons are generated and migration commences. Modeling results indicate that the critical moment and hydrocarbon expulsion from the Eocene OGSR (**Fig. 1**) occurred by the end of the Sabunchi time (~3.8 million years ago), while for the Maikop (**Fig. 2**) and Diatomaceous (**Fig. 3**) OGSR, it was reached by the end of the Surakhany time (~3 million years ago), coinciding with the formation of the upper part of the productive series.

Hydrocarbon accumulation

As a result of primary migration, hydrocarbons penetrate into natural reservoirs, which, as a rule, are not strictly horizontal, but have a slope that can provoke the migration of hydrocarbons along the regional rise of the layers. Depending on the intensity of hydrocarbon generation, thermobaric conditions and other factors, hydrocarbons that have penetrated into the reservoir can be in a free state or dissolved in water. Moving in the reservoir up the rise of the layers due to changes in thermobaric conditions, some of them are released into a free phase and, in the presence of traps, can form accumulations of oil and (or) gas. In the zone of oil and gas accumulations in the chain of traps, a distribution of hydrocarbon accumulations of different phase states is quite often observed, formed according to the principle of 'differential capture'. The principle of differential capture of oil and gas is possible only if the traps are located along the migration path and the hydrocarbons migrate in a free state in the form of streams of oil and gas.

Pliocene deposits in SCB in the section of which natural reservoirs of oil and gas were formed are represented by lithological differences of terrigenous formations, the accumulation of which occurs in various facies conditions (marine, coastal) [26]. As paleogeographic reconstructions showed, fluvial–deltaic complexes played a significant role in the formation of sedimentary complexes in the South Caspian Basin [27-36]. The formation of the main oil and gas bearing object of the Lower Pliocene age of the productive strata is associated with three large rivers (Paleo-Volga, Paleo-Uzboy and Paleo-Kura) and dozens of small rivers.

In the South Caspian Basin of oil and gas, generation–accumulation hydrocarbon systems are formed and evolve; within these systems, it is possible to identify zones of oil and gas concentrations (accumulation zones) as reservoirs and pools. Modeling of hydrocarbon systems (HS) allowed identifying such oil and gas concentration zones (accumulation zones) as: Apsheron–Near-Balakhan in the Eocene–Pliocene HS; Island Apsheron, Southeastern Apsheron, Apsheron–Near-Balakhan zone, Baku Archipelago zone, Lower Kura zone and the Shamakhi–Gobustan zone in the Maikop–Pliocene HS; Southeastern Apsheron and Apsheron–Near-Balakhan zone in the Miocene–HS (**Fig. 4**).

The graphs and volumes of accumulated hydrocarbons from OGSR in the productive strata of SCB are given in **Fig. 5** and in **Table**.

An important factor in the accumulation and formation of hydrocarbon reserves is the development of traps, which are closely associated with the folding patterns of the region. The results of the modeling indicate a relatively high density, yet highly uneven distribution of fold-related dislocations within the sedimentary succession—ranging from Mesozoic strata to the present-day surface in SCB. Folding within SCB is characterized by coherent structural patterns that are consistent throughout the entire depth interval, with conformable structural elements. This suggests that the majority of folding can be attributed to the Pliocene–Pleistocene tectonic cycle.

The dominant mechanism responsible for folding in the SCB is the redistribution of volumes of low-viscosity, clay-rich Maikop horizons within the stratified basin fill. These layers tend to deform plastically under the load of the overlying thick Upper Miocene, Pliocene and Pleistocene sediments. In the marginal zones of the basin, as well as above major buried and likely relatively rigid structures within the basin interior, the formation and zonal arrangement of folding and faulting are further influenced by geodynamic factors. These are controlled by external stress regimes, including compression, extension, shear, or their combinations.

The analysis and classification of hydrocarbon traps and accumulations in SCB indicate that the full range of characteristics defining a field's typology can be grouped according to two principal factors: structural and sedimentary (lithological–stratigraphic). The structural factor determines the overall spatial configuration of the field within the geological environment—essentially the generalized morphology of the area it occupies. The sedimentary factor, either independently or in combination with the structural one, controls the internal architecture of the field, typically composed of one or more discrete accumulations.

The sedimentary (lithological–stratigraphic) factor is represented by four main types of elementary (individual) traps: lithologically bounded (LB), lithologically sealed (LS), stratigraphically sealed (SS), those associated with biogenic buildups (BB). For the purposes of analysis, lithologically sealed and lithologically bounded traps are collectively grouped into a single conditional category: lithologically controlled traps.

In the course of analyzing the obtained characteristics, it became necessary to introduce an additional criterion based on the observed combinations of sedimentary and structural factors in the architecture of hydrocarbon fields. As a result, three main variants can be distinguished, each defining the type of trap that characterizes the field as a whole:

1. The field is controlled solely by the sedimentary factor, with no structural expression evident in its configuration.
2. Conversely, the field is formed exclusively due to structural control, with no significant sedimentary influence.
3. The field results from a combination of both structural and sedimentary factors.

In the first case, the entire trap—including the accumulation—is classified as non-structural, i.e., lithological, stratigraphic, or lithostratigraphic. In the second case, the trap is considered structural. In the third, it is categorized as a combined structural–lithological–stratigraphic trap.

Within the stratigraphic section of the productive series in SCB, wedge-out (clinoform) bodies forming lithological and stratigraphic traps are widely developed, as confirmed by seismic and geological data.

Thus, based on the analysis and numerical modeling of petroleum systems in SCB, three classical generation–accumulation systems have been identified, namely: the Eocene–Pliocene system, the Maikop–Pliocene system and the Miocene–Pliocene system (**Fig. 6**).

Conclusions

The main mechanism of hydrocarbon migration in SCB is mud volcanoes, whose eruptive channels serve as channels for hydrocarbon migration. Migration processes are also provided by a network of tension cracks created by the formation of diapir structures. Almost all of SCB deposits are located in areas of mud volcanism development and are complicated by their eruptive channels, which indicates that the reservoirs of the productive stratum are filled due to the vertical migration of hydrocarbons. This property of the hydrocarbon systems of the South Caspian Basin ensures the replenishment with hydrocarbons of deposits developed over more than a century of deposits located in the zone of development of mud volcanism.

The onset of hydrocarbon expulsion from OGSR into reservoirs corresponds with the so-called critical moment—defined as the phase of the generative process during which approximately 50% of hydrocarbons are generated and expulsion begins. According to modeling results, the critical moment and hydrocarbon expulsion from the Eocene OGSR occurred by the

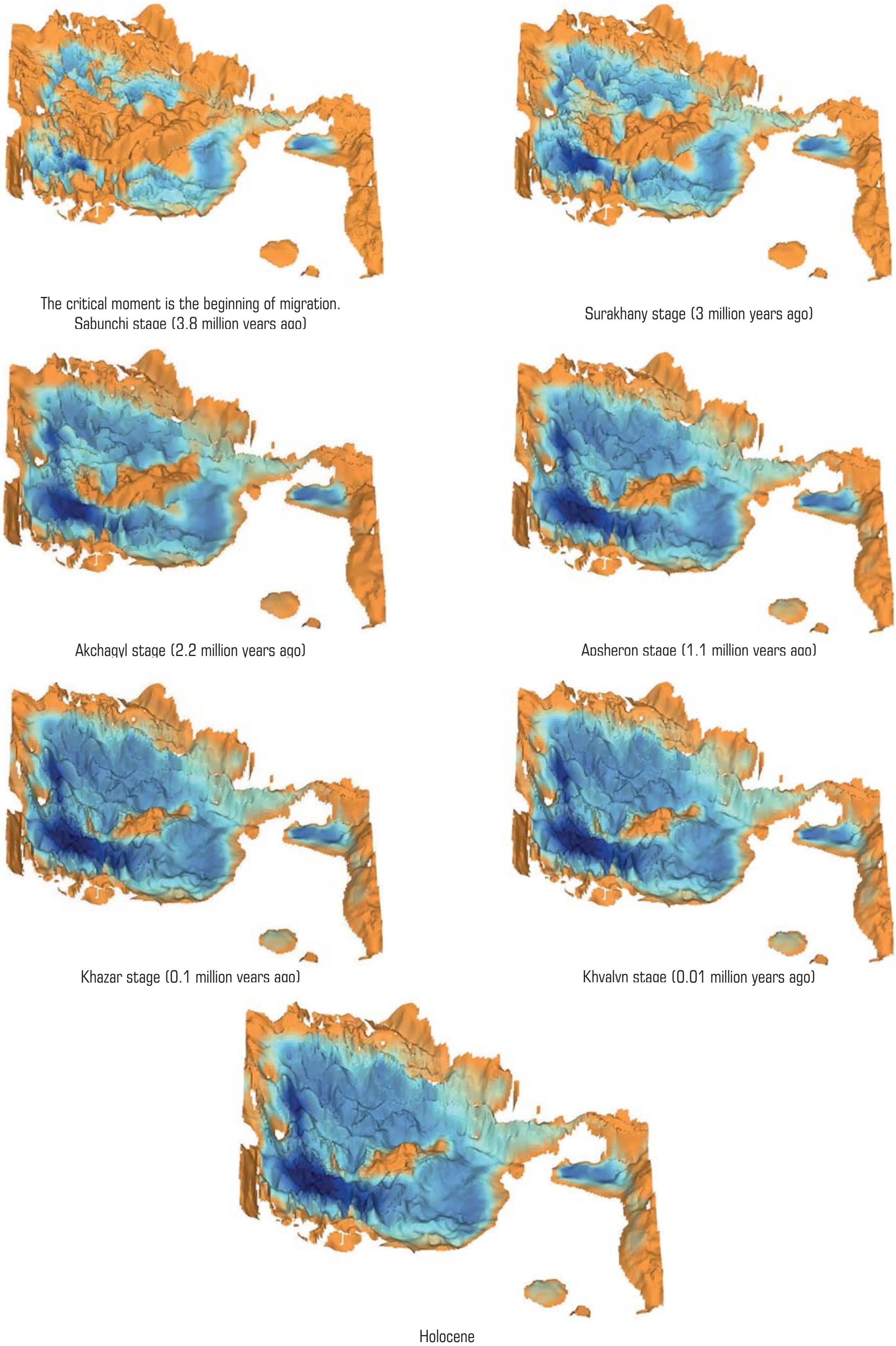

Fig. 1. 3D models of hydrocarbon migration from the Eocene OGSR

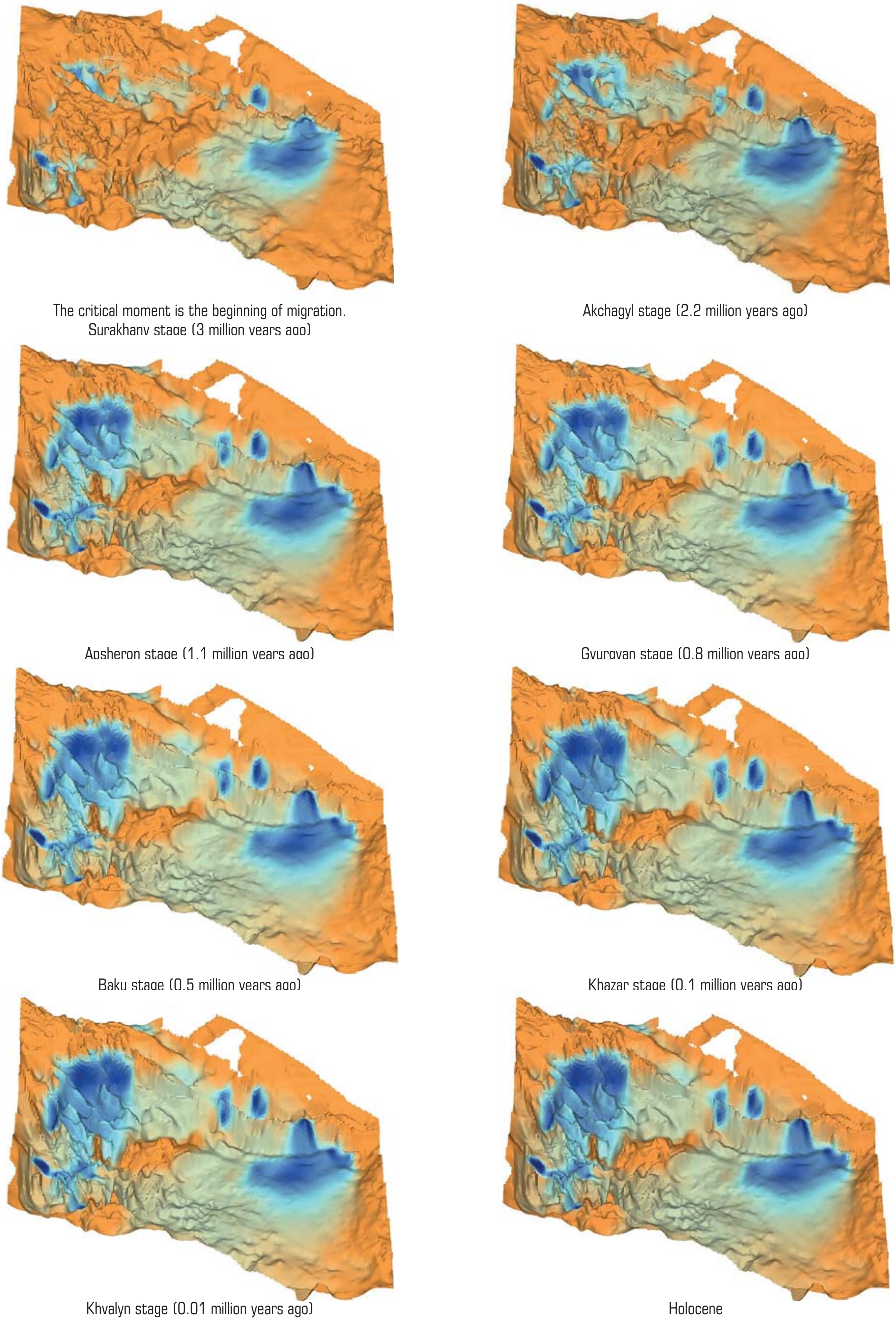

Fig. 2. 3D models of hydrocarbon migration from the Maikop OGSR

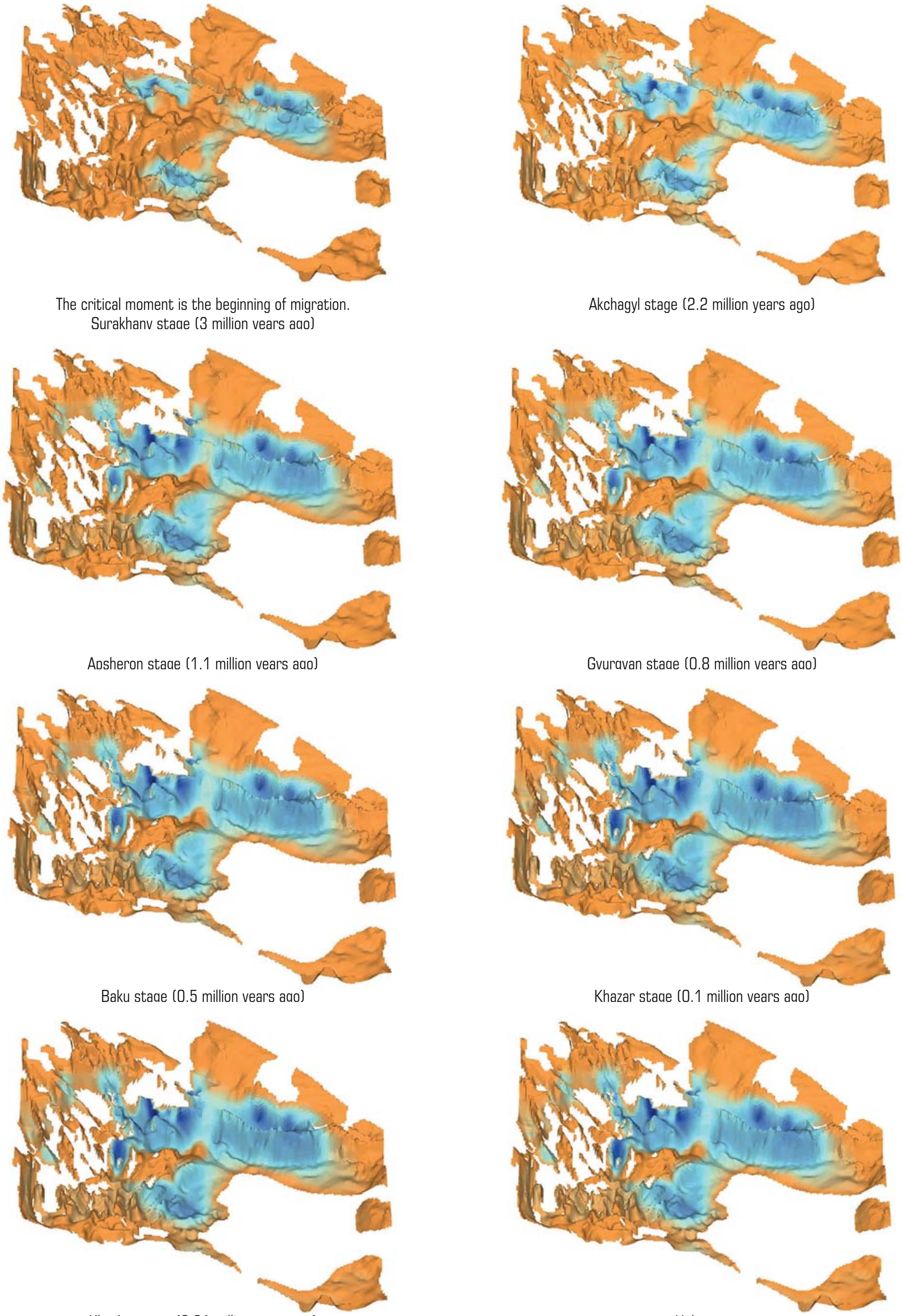

Fig. 3. 3D models of hydrocarbon migration from Diatomaceous OGSR

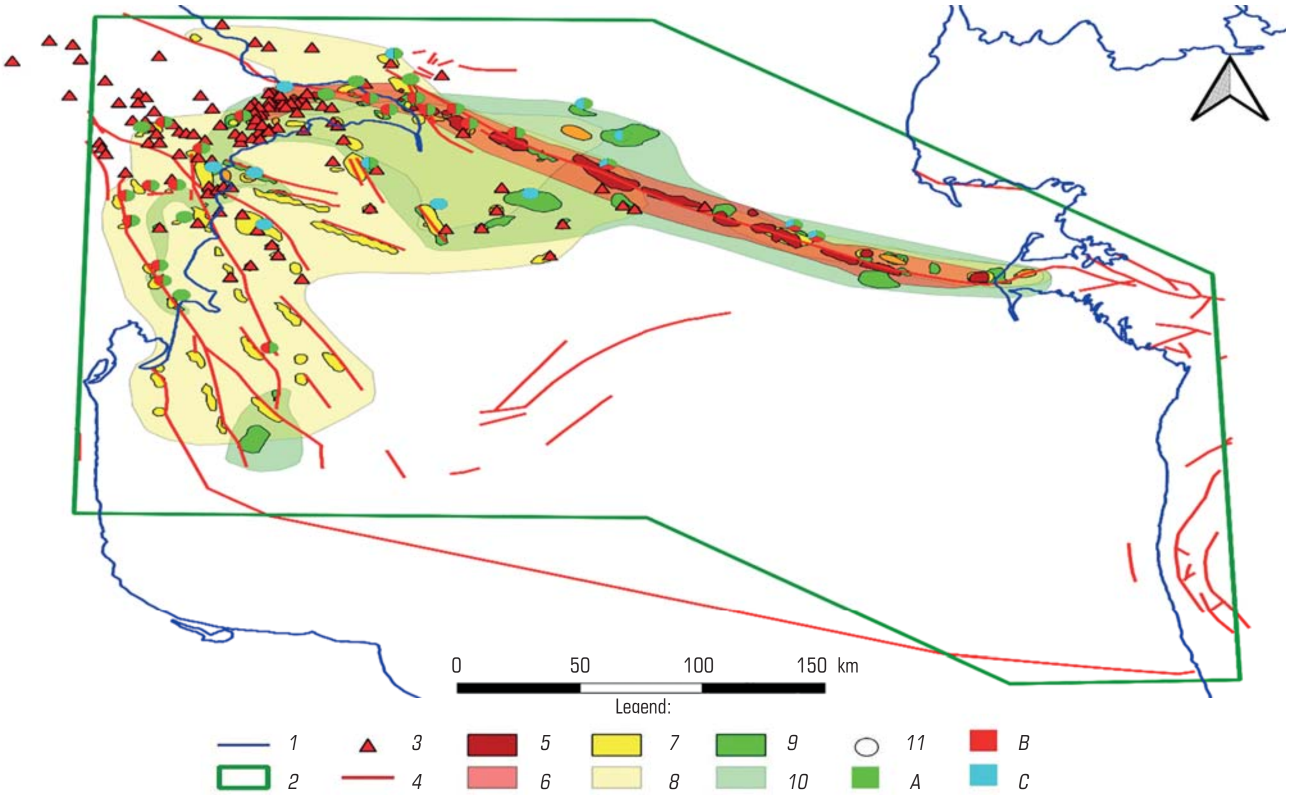

Fig. 4. Distribution maps of oil and gas concentrations (accumulation zones) in productive series in SCB, covering all hydrocarbon systems:
1–coastline; *2*–study area; *3*–mud volcanoes; *4*–faults; *5*–Eocene–Pliocene HS oil and gas concentrations; *6*–Eocene-Pliocene HS accumulation zones (oil and gas concentrations); *7*–Maikop-Pliocene HS oil and gas concentrations; *8*–Maikop–Pliocene HS accumulation zones (oil and gas concentrations); *9*–Miocene–Pliocene HS oil and gas concentrations; *10*–Miocene–Pliocene HS accumulation zones (oil and gas concentrations); *11*–fields: *A*–oil; *B*–gas; *C*–gas condensate

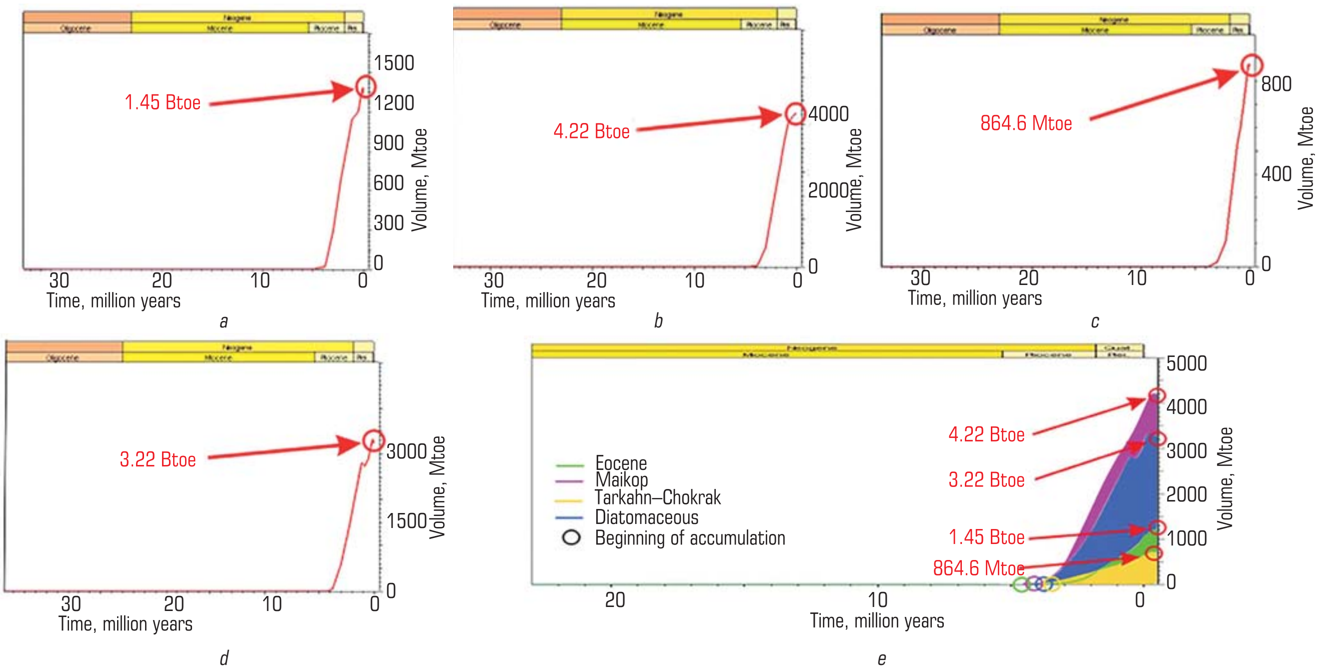

Fig. 5. Graphs and volumes of hydrocarbons accumulated from OGSR in productive strata in SCB:
a–Eocene; *b*–Maikop; *c*–Tarkhan–Chokrak; *d*–Diatomaceous; *e*–cumulative of all four OGSR

Quantitative assessment of accumulated hydrocarbons

OGSR	Volume of HC accumulated in reservoirs, Btoe				
	Sabunchi suite	Fasila suite	Over-Kirmaki suite	Kalin suite	Total for productive series:
Total per suites:	111,49	1,8	0,9	36,06	150,25
Total hydrocarbon potential 150.25 Btoe					

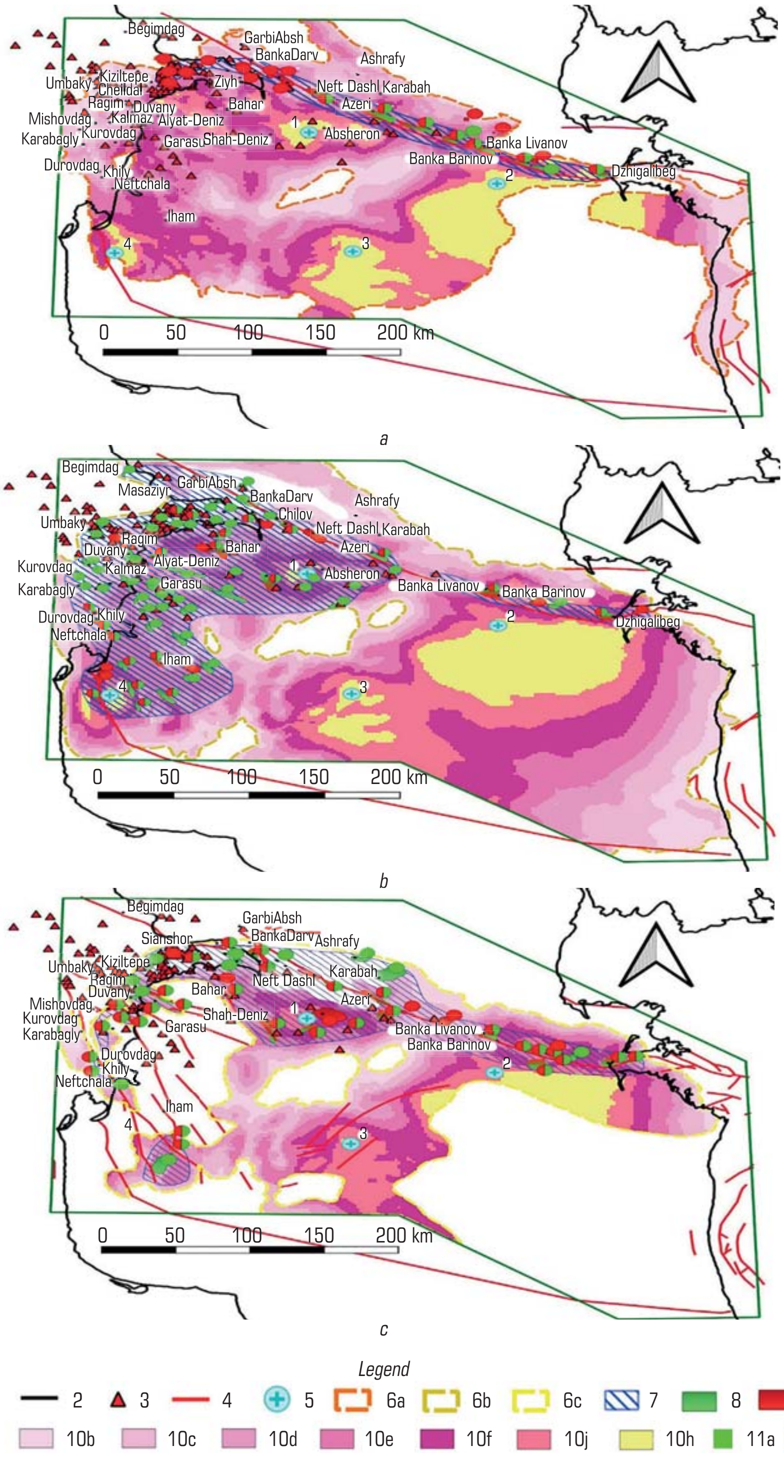

Fig. 6. Generation–accumulation hydrocarbon systems (GAHS) of SCB:
Hydrocarbon systems: a–Eocene–Pliocene; b–Maikop–Pliocene; c–Miocene–Pliocene; 1–study area; 2–modern coastline; 3–mud volcanoes; 4–faults; 5–pseudo wells; 6–boundary of GAHS: 6a–Eocene–Pliocene; 6b–Maikop–Pliocene; 6c–Miocene–Pliocene; 7–accumulation zones (oil and gas concentrations); 8–liquID hydrocarbon accumulations; 9–gaseous hydrocarbon accumulations; 10–organic matter maturity in the generative center (R_0, %): 10a–≤ 0.5%; 10b–0.55–0.75%; 10c–0.75–1%; 10d–1–1.3%; 10e–1.3–2%; 10f–2–3%; 10g–3–4%; 10h–4–5%; 11–confirmed fields: 11a–oil fields; 11b–gas fields

end of the Sabunchi time (~3.8 million years ago), while for the Maikop and Diatomaceous OGSR, it was reached by the end of the Surakhany time (~3.0 million years ago), coinciding with the formation of the upper productive series. In the Tarkhan–Chokrak OGSR, this stage was achieved only by the end of the Akchagyl time (~2.2 million years ago).

As a result of the analysis and numerical modeling of petroleum systems in SCB, three classical generation–accumulation petroleum systems were identified: the Eocene–Pliocene, Maikop–Pliocene and Miocene–Pliocene systems.

Modeling the Eocene–Pliocene, Maikop–Pliocene and Miocene–Pliocene hydrocarbon systems enabled identification of hydrocarbon accumulation zones within the reservoirs of the productive series. Formation of natural oil and gas reservoirs in SCB was significantly influenced by fluvio-deltaic complexes associated with three major paleorivers—Paleo-Volga, Paleo-Uzboy, and Paleo-Kura—as well as numerous smaller river systems. The analysis and classification of hydrocarbon traps and accumulations in the SCB indicate that the full range of characteristics determining a field's typology is governed by two main factors: structural and sedimentary (lithological–stratigraphic).

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