Results of Modeling of Generation and Accumulation Hydrocarbon Systems in the Sedimentary Basins of the Sea of Okhotsk

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Abstract. The paper presents the results of modeling of generation and accumulation hydrocarbon systems in the sedimentary basins of the sea of Okhotsk. The results of modeling HC migration showed that the most likely zones of hydrocarbon accumulation are the side parts of sedimentary basins. The anticline zones located on the border of two or more basins have the most favorable conditions. These areas, in general, are among the most promising in terms of hydrocarbon prospecting. However, such zones are characterized by complex conditions for the formation and preservation of deposits due to the non-synchronous evolution of adjacent sedimentary basins. This leads to uncertainties when assessing their prospects at the regional research level, for example, when predicting the type of fluid in deposits. For example, Vostochno-Shmidtovsk (East Schmidt) anticline zone is located on the border of two large centers of oil and gas generation: Severo-Sakhalinsky (North-Sakhalin) and Deryugin basin. The results of numerical modeling of the regional level allowed us to establish that HC migration towards the anticline zone occurs from the East (from the Deryugin basin) and the West (from the Severo-Sakhalinsky (North-Sakhalin) basin). The type of fluid in the predicted clusters is controlled by the type and maturity of the organic matter of the generation centers.

1. Introduction

Despite a significant period of study of the region, the water area of the sea of Okhotsk still remains unevenly explored. It includes both areas characterized by a high degree of geological and geophysical study, and very poorly studied Central areas.

The tectonic basis of the sea of Okhotsk is formed by the Okhotsk sea plate, the consolidated foundation of which was formed in the late Cretaceous. The foundation consists of blocks of different ages, composed according to the data of dredging by the Precambrian and Paleozoic, and folded zones, which include Mesozoic and Cenozoic rocks. The sedimentary cover of the plate is composed mainly of Cenozoic rocks, whose thickness, insignificant in the central part of the water area (Central Okhotsk sea uplift), increases to the marginal zones of the plate, exceeding 12-14 km in some basins.

Within the water area of the sea of Okhotsk, there are different-scale sedimentary basins. The largest are: Severo-Sakhalinsky (North-Sakhalin), Severo-Okhotsk (North-Okhotsk), Okhotsko-Zapadno-Kamchatsky (Okhotsk-West Kamchatka), Yuzhno-Okhotsky (South-Okhotsk) allocated, Zapadno-Okhotsky (West-Okhotsk). All of them are characterized by a complex structural structure and consist of a system of smaller deflections and elevations.
The large Severo-Sakhalinsky (North-Sakhalin) basin of the North-northwestern stretch, with a length of at least 600 km and a width of 80÷120 km, is located in the North of the island and its North-Eastern shelf. It is bounded by the Eastern Sakhalin Mountains (ridge) and the Schmidt uplift zone, whose Jurassic-Cretaceous sedimentary-volcanogenic base is exposed on the Schmidt Peninsula, in the North of the Sakhalin Island. The maximum capacity of the section in the basin can reach 12.0 km, typical capacities are 5÷8 km.

The basins of the Severo-Okhotsky (North-Okhotsk) zone (Severo-Okhotsky and Lisyansk-Kukhtuyksky), located along the southern edge of the Okhotsk-Chukotka volcanic belt, according to existing representations, were formed on the site of a Cretaceous trough filled with terrigenous or volcanogenic-terrigenous strata. The total thickness of Cenozoic deposits in individual depressions of this zone can reach 5 to 8 km.

The Okhotsko-Zapadno-Kamchatsky (Okhotsk-West Kamchatka) basin is located on the territory of the coastal plain of Western Kamchatka and on the adjacent part of the East Okhotsk shelf. It is bounded on the East by the Central Kamchatka uplift zone, on the South by the Bolsheretsky uplift, and on the West and Northwest, through systems of fault-fold zones, it contacts with the Shelikhovsky and TINRO basins (TINRO /acronym/ - Pacific branch of the all-Russian Research Institute of Fisheries and Oceanography). Typical deposition capacities are 3 to 5 km, but in some local basins they may exceed 7 to 8 km.

The Deryugin, TINRO and Yuzhno-Okhotsky (South-Okhotsk) basins are the areas of the most active deflection, which is assumed to be due to the influence of rifting processes. These basins have accumulated significant sedimentary deposits of 6 to 10 km or more.

2. Research methods
The modeling tasks included: forecast of the distribution of established and probable oil and gas producing rocks (OGPRs), assessment of their ability to generate hydrocarbons, taking into account the features of the thermal regime of sedimentary basins, identification of the main foci of HC generation and zones of their most likely accumulation. The main research methods are numerical space-time basin modeling, which allowed us to create models of hydrocarbon systems in the sedimentary basins of the sea of Okhotsk and identify the conditions for the formation of hydrocarbon deposits. In order to reconstruct the conditions of occurrence and evolution of hydrocarbon generation centers, restore the conditions of their formation and patterns of distribution of oil and gas accumulations in the waters of the sea of Okhotsk, three-dimensional modeling of generation and accumulation of hydrocarbon systems was carried out using basin modeling technology and PetroMod software (Schlumberger, Ltd, USA).

To model the generation and accumulation of hydrocarbon systems in the sedimentary basins of the sea of Okhotsk, three-dimensional digital structural and tectonic models of sedimentary basins of the sea of Okhotsk were created for various geological periods - by the end of the Paleogene period (Fig. 1a), by the end of the Neogene period (Fig. 1b) and for the modern period (Fig. 1c). The formed models include four main sedimentary complexes: lower-middle Paleogene, upper Paleogene-lower Miocene, middle-upper Miocene, and Pliocene-Quaternary.

The results of regional and detailed structural studies performed earlier in the sea of Okhotsk were used to generate the maps. They were linked and adjusted to take into account drilling data and geological surveys. For regional-level models, structural maps were formed for the base and main surfaces of the unconformity of the sedimentary cover of the sea of Okhotsk and adjacent land-near the Eocene roof, the lower Miocene roof, and the Miocene roof, as well as a bathymetric map of the bottom. The regional model was calculated in 1x1 km increments. The start and end times of sedimentation periods were determined in accordance with the International stratigraphic scale.

3. Results and discussion
In accordance with the results of generalization of geological and geochemical data, four oil and gas-producing strata are identified in the sedimentary cover of the sea of Okhotsk: Eocene, upper
Oligocene, lower Miocene, and lower-middle Miocene. In accordance with this, four hydrocarbon systems were modeled – in the Eocene, Oligocene, lower Miocene, and lower-middle Miocene. Fig.2 shows the distribution schemes of vitrinite reflectivity (R0, %) OM showing the degree of maturity of organic matter of rocks of modeled OGPRs.

The figures show that at all stratigraphic levels, the most extensive distribution areas of mature OGPRs are located within the sedimentary basins of the Magadan, TINRO, Shelikhov, Deryugin, Severo-Sakhalinsky (North-Sakhalin) and Pogranichny (Border) basins. The maturity of the OM parent rocks of Eocene age in most of the basins corresponds to the level of the "oil window" (R0 from 0.5 to 1.0%) and higher. In the depots of the TINRO, Deryugin, Severo-Sakhalinsky (North-Sakhalin), and Magadan basins, OGPRs are overheated. In the sediments of the upper Oligocene OM maturity varies from immature in Shantar, Kashevarov, Lisyansk, Gizinsk, Zapadno-Kamchatsky (West
Kamchatka) side pools, to the "overripe" in most submerged parts of the TINRO, Deryugin, Magadan basins.

Figure 2. Distribution of vitrinite reflectance (R0,%):

- a - in the Eocene OGPRs;
- b - Upper Oligocene OGPRs;
- c - Lower Miocene OGPRs;
- d - Middle Miocene OGPRs

Legend: Basins: I - South Pogranichny, II - Pogranichny, III - Makarova-Schmidt, IV - Golyginsky, V - West Sakhalin, VI - North Sakhalinsky, VII - Deryuginsky, VIII - East Deryuginsky, IX - Severo-Deryuginsky, X - TINRO, XI - Central Okhotsk, XII - Lebed, XIII - Kashevarovsky, XIV - Lisyansky, XV - Magadansky, XVI - Shantarsky, XVII - West Kamchatsky, XVIII - Shelikhovsky, XIX - Gizhinsky, XX - Pyaginsky, XXI - Voyampolsky

Up the section (in the Miocene), the maturity of OM oil and gas mother rocks decreases. Vast areas of mature rocks are preserved only in the TINRO, Deryugin, Magadan, Severo-Sakhalinsky (North-Sakhalin), Golygin, and Pogranichny (Border) basins. This significantly reduces the areas where OGPRs can generate predominantly gaseous HC. The vertical distribution of the degree of OM maturity corresponds to the normal trend and indicates the absence of significant vertical movements, opposite to immersion, during the evolution of GAHCs.

Figure 3 shows three-dimensional digital models of the catagenetic evolution of OGPRs in sedimentary basins of the sea of Okhotsk. Modeling allows us to determine the degree of
transformation of organic matter of the studied oil and gas-producing rocks and estimate the specific density of generation and emigration of HC.

Fig. 4 shows maps of the degree of transformation of organic matter of the studied oil and gas mother rocks, which, along with the level of maturity, are an important indicator of the realization of their generating potential. It can be seen that in general, the highest generation potential is characterized by the Eocene parent strata, which began to generate HC from the middle of the Oligocene. The generation potential of all OGPRs studied is maximal at the current stage of GAHCSs development.

![Figure 3](image-url)

**Figure 3.** Three-dimensional digital models of the catagenetic evolution of OGPRs of sedimentary basins in the Sea of Okhotsk: a - by the end of the Paleogene period; b - by the end of the Neogene period; c - at the present time.

The Largest centers of hydrocarbon generation are the TINRO, Shelikhov, Deryugin and Severo-Sakhalinsky (North-Sakhalin) basins. The degree of realization of the generation potential of all OGPRs studied in these basins varies from 40 to 90%.

At the same time, the potential of deposits of the lower structural floor (Eocene-Oligocene) has been fully realized to date. The conversion index (TR) of all basins varies from the first percent to one hundred, depending on the current depth of occurrence of oil and gas-producing rocks, which is the
maximum in the history of the development of hydrocarbon systems (Fig. 4 a and b). Significant productivity of the Miocene part of the sedimentary cover is expected only within the TINRO, Shelikhov, Deryugin, Pogranichny (Border), and Severo-Sakhalinsky (North-Sakhalin) basins (Fig. 4 c and d).

The distribution of specific densities of generation (Qgen) of hydrocarbons generally corresponds to the level of maturity of the OM and the degree of their transformation, with the exception of Eocene deposits. Specific densities of Eocene OGPRs generation are determined mainly by the facies type of kerogen. The highest values are marked for carbon-reducing OGPRs (PM_TIII_Tertiary_Coal_2C) with a high initial generation potential for liquid HC. Specific generation densities reach values of 8-11 million tons of oil equivalent/km²).

**Figure 4.** Distribution of the degree of transformation of organic matter (TR,%); a - Eocene OGPRs; b - Upper Oligocene OGPRs; c - Lower Miocene OGPRs; d - middle Miocene OGPRs.

**Legend:** Basins: I - Yuzhno-Pogranichny, II - Pogranichny, III - Makarova-Schmidt, IV - Golyginsky, V - West Sakhalin, VI - North Sakhalin, VII - Deryuginsky, VIII - East Deryuginsky, IX - North Deryuginsky, X - TINRO, XI - Central Okhotsk, XII - Lebeda, XIII - Kashevarovsky, XIV - Lisyansky, XV - Magadansky, XVI - Shantarsky, XVII - West Kamchatsky, XVIII - Shelikhovsky, XIX - Gizhinsky, XX - Pyaginsky, XXI - Voyampolsky.
Kerogen type II of upper Oligocene deposits, taking into account the current maturity, can provide specific densities of generation not exceeding 4 million tons of oil equivalent/km². At the same time, these OGPRs are widely distributed within the water area of the sea of Okhotsk and can provide a significant contribution to the overall hydrocarbon potential of the sedimentary cover.

Marine oil and gas-producing strata of the Miocene are characterized by fairly high values of specific generation densities, which average 4-7 million tons of oil equivalent/km². However, taking into account the performed forecast, they have a limited distribution within the water area and can provide a contribution to the oil and gas content of the TINRO, Severo-Sakhalinsky (North-Sakhalin), Shelikhov and Pogranichny (Border) basins.

The maximum emigration potential is characterized by Eocene OGPRs. The emigration of hydrocarbons from these deposits began at the beginning of the Miocene, and only at the end of the Miocene hydrocarbons could enter the traps from the overlying parent strata. All the studied hydrocarbon systems are quite young. The critical moment of the Eocene systems was overcome from 15 (TINRO, Magadan basins) to 8.5 (Severo-Sakhalinsky (North-Sakhalin), Deryugin, Pogranichny (Border) basins) million years ago, and the upper Oligocene systems - about 5 million years ago. Most Miocene hydrocarbon systems have not yet overcome this critical point, despite the relatively high modern maturity of organic matter in the generation centers. The volume characteristics of the generation and emigration potential of the studied OGPRs are presented in Table 1.

| OGPRs            | Residual potential, million tons of oil equivalent | Generational balance, million tons of oil equivalent | Accumulated in OGPRs, million tons of oil equivalent | Emigration balance, million tons of oil equivalent |
|------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| Early-middle Miocene | 270,167.77                                          | 41,644.67                                           | 19,290.07                                            | 22,354.61                                           |
| Early Miocene    | 101,567.57                                           | 33,995.73                                           | 1,375.99                                             | 32,619.74                                           |
| Upper Oligocene  | 297,931.98                                           | 69,904.59                                           | 33,512.91                                            | 36,391.69                                           |
| Eocene           | 666,170.88                                           | 292,280.6                                           | 16,239.69                                            | 276,040.91                                           |
| Total:           | 1,335,838.2                                          | 437,825.6                                           | 70,418.65                                            | 367,406.94                                           |

Generational and emigration indicators of the Eocene OGPRs are much higher than all others. Fig. 5 shows three-dimensional digital models of HC migration in sedimentary basins of the sea of Okhotsk in various geological periods.
4. Conclusion
The results of modeling HC migration showed that the most likely zones of hydrocarbon accumulation are the side parts of sedimentary basins (Fig. 5).

The anticline zones located on the border of two or more basins have the most favorable conditions. These areas, in general, are among the most promising in terms of hydrocarbon prospecting. However, such zones are characterized by complex conditions for the formation and preservation of deposits due to the non-synchronous evolution of adjacent sedimentary basins. This leads to uncertainties when assessing their prospects at the regional research level, for example, when predicting the type of fluid in deposits. For example, Vostochno-Shmidtovsk (East Schmidt) anticline zone is located on the border of two large centers of oil and gas generation: Severo-Sakhalinsky (North-Sakhalin) and Deryugin basin. The results of numerical modeling of the regional level allowed us to establish that HC migration towards the anticline zone occurs from the East (from the Deryugin basin) and the West (from the Severo-Sakhalinsky (North-Sakhalin) basin). The type of fluid in the predicted clusters is controlled by the type and maturity of the organic matter of the generation centers.

In general, the source strata of Deryugin basin are in more favorable conditions for the generation of liquid hydrocarbons compared to the Severo-Sakhalinsky (North-Sakhalin), which is due, in particular, differences in paleogeographical conditions of their formation: throughout the Cenozoic history of the development of sedimentary basins, Deryugin basin was farther from the main source demolition sediment (river system of paleo Amur). The presence of a narrow deflection that divides the Vostochno-Shmidtovsk (East Schmidt) anticline zone into two parts (Western and Eastern) complicated the structural plans of the reservoirs and caused the peculiarities of hydrocarbon migration within it. This has led to the fact that hydrocarbons migrating from the Deryugin basin can fill promising objects (traps) located only in the Eastern part of the anticline zone, and HC migrating from Severo-Sakhalinsky (North-Sakhalin) trough can only fill traps located in its Western part. This
means that the field discovery in the Western part of the Vostochno-Shmidtovsk (East Schmidt) anticlinal zone and perspective objects of its Eastern part belongs to a different hydrocarbon system, characterized by significant differences in conditions of formation of the elements of hydrocarbon systems and evolution, i.e., they are not geological analogues. Modeling of hydrocarbon systems in the sea of Okhotsk shows, in general, a consistent increase in HC volumes in reservoirs of all stratigraphic levels. This pattern is observed for most of the studied sedimentary basins, with the exception of basins located on the shelf of North Sakhalin, where neotectonics is actively manifested. A significant change in the structural plans in the second half of the Miocene led to the re-formation of HC clusters formed earlier. This mainly applies to reservoirs of the Eocene hydrocarbon system, where the volume of some predicted deposits in the Northern part of the East Schmidt anticline zone has decreased by almost 4 times, and to a lesser extent - to reservoirs of the upper Oligocene system.

For systems with later generation and HC emigration, such risks are not typical. However, given the ongoing tectonic activity in the region, it is advisable to carefully analyze and map all the surfaces of the Pliocene-Quaternary floor inconsistencies, assess possible local washouts, and assess the risks of preservation of Miocene deposits in the section within the framework of detailed modeling.

5. References

[1] Blumenberg M, Oppermann B, Guyoneaud R, Michaelis W 2009 Hopanoid-production by Desulfovibrio bastini isolated from oilfield formation water. FEMS Microbiol. Lett. Vol 293 pp 73-78
[2] Bogoyavlensky V I, Kerimov V Yu, Olkhovskaya O O 2016 Dangerous gas-saturated objects in the world ocean: The Sea of Okhotsk. Oil Industry pp 43-47
[3] Gavrilov V P 2010 Netradicionnaya model' obrazovaniya granitov i ih neftegazonosnosti (na primere yuzhnogo shelf'a V'etnama) Geologiya nefti i gaza 1 pp 51-58
[4] Gordadze G N, Kerimov V Yu, Gaiduk A V 2017 Hydrocarbon biomarkers and diamondoid hydrocarbons from late Precambrian and lower Cambrian rocks of the Katanga saddle (Siberian Platform) Geochemistry international 55 4 pp 360-366
[5] Guliev I S, Mustaev R N, Kerimov V Y, Yudin M N 2018 Degassing of the earth: Scale and implications. Gornyi Zhurnal 11 38-42
[6] Hall R 2002 Cenozoic geological and plate tectonic evolution of SE Asia and SW Pacific: computer – based reconstructions, model and animations. Journal of Asian Earth Sciences 20 pp 353-431
[7] Kerimov V, Rachinsky M, Mustaev R, Serikova U 2018 Geothermal conditions of hydrocarbon formation in the South Caspian basin. Iranian Journal of Earth Sciences 10(1) pp 78-89
[8] Kerimov V Y, Leonov M G, Osipov A V, Mustaev R N, Hai V N 2019 Hydrocarbons in the Basement of the South China Sea (Vietnam) Shelf and Structural–Tectonic Model of their Formation. Geotectonics 53(1) 42-59
[9] Kerimov V Y, Bondarev A V, Mustaev R N 2017 Estimation of geological risks in searching and exploration of hydrocarbon deposits. Oil Industry 8 36-41
[10] Kerimov V Yu, Gorjade G N, Mustaev R N, Bondarev A V 2018 Formation conditions of hydrocarbon systems on the Sakhalin shelf of the sea of okhotsk based on the geochemical studies and modeling. Oriental Journal of Chemistry 34(2) 934-947
[11] Leonov M G 2008 Tektonika konsolidirovannoy kory (M.: Nauka) 464 p
[12] Luk'yanov A V 1991 Plasticheskie deformacii i tektonicheskoe techeni v litosfere (M.: Nauka) 144 p
[13] Mustaev R N, Hai W N, Kerimov V Y, Leonova E A Generation and Conditions Formation of Hydrocarbon Deposits in Kyulong Basin by Simulation Results. Hydrocarbon Systems Geomodel 2015 - 17th Scientific-Practical Conference on Oil and Gas Geological Exploration and Development
[14] Pospelov G L 1972 Dispergity i avtodispersgaciya kak vazhnaya problema fiziki lito-petro- i tekstogeneza. Geologiya i geofizika 12 pp 53-73
[15] Varnavskij V G, Tronov Yu A, Harahinov V V, Kononov V E 1987 i dr. Severo-Tatarskij neftegazonosyj bassejn Tihookeanskaya geologiya 6 pp 45-49

[16] Vu N, Kerimov V Y 2016 3D Structural-Tectonic Modelling of the Hydrocarbon System of the Cuu Long Basin (Vietnam) Geomodel 2016 - 18th Science and Applied Research Conference on Oil and Gas Geological Exploration and Development

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