



Review article

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Modern geochemical methods for local oil and gas potential prediction in the Arctic regions of Western and Eastern Siberia: a comparative analysis

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Abstract. This work is devoted to the study and comparative analysis of the effectiveness of geochemical methods for predicting oil and gas potential in the Arctic regions of Western and Eastern Siberia. The features of geological conditions influencing the selection and implementation of exploration methods are considered. The analysis is given to the historical experience of developing oil and gas resources in the region, starting from the Soviet period and highlighting the achievements of renowned scientists such as V.P. Isaev and others. The work thoroughly examines the theoretical foundations of geochemical prediction including the theory of subvertical hydrocarbon migration and the identification principles of geochemical anomalies. The main geochemical research methods applied in Western and Eastern Siberia are described. Special attention is paid to an integrated approach combining geochemical, geophysical, and geological data. The article provides some examples of successful application of geochemical methods such as identification of promising oil and gas zones in the South-Syuldyukar area and confirming significant resources at the Medvezhye field. Recommendations are given for improving forecasting methods, including the creation of a unified database, automation of data processing, and introduction of new remote sensing technologies. The necessity of international cooperation and interaction between scientific organizations and industrial enterprises to accelerate the adoption of advanced technologies and ensure the sustainable development of Russia's oil and gas industry is emphasized.

Keywords: geochemical methods, local prediction, oil and gas potential, Arctic, Western Siberia, Eastern Siberia, integration of methods, geological exploration

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Обзорная статья

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Современные геохимические методы локального прогноза нефтегазоносности в арктических регионах Западной и Восточной Сибири: сравнительный анализ

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Резюме. Работа посвящена исследованию и сравнительному анализу эффективности геохимических методов прогноза нефтегазоносности в арктических регионах Западной и Восточной Сибири. Рассматриваются особенности геологических условий, влияющие на выбор и реализацию методов разведки. Анализируется исторический опыт освоения нефтегазовых ресурсов региона, начиная с советского периода, и подчеркиваются достижения известных ученых, таких как В.П. Исаев и др. В работе подробно рассматриваются теоретические основы геохимического прогноза, включая теорию субвертикальной миграции углеводородов и принципы выявления геохимических аномалий. Описываются основные методы геохимических исследований, применяемых в Западной и Восточной Сибири. Особое внимание уделяется интегрированному подходу, сочетающему геохимические, геофизические и геологические данные. Приводятся примеры успешного применения геохимических методов, такие как выделение перспективных нефтегазоносных зон на Южно-Сюльдюкарском участке и подтверждение значительных ресурсов



на Медвежьем месторождении. Даются рекомендации по совершенствованию методик прогноза, включая создание единого банка данных, автоматизацию обработки данных и внедрение новых технологий дистанционного зондирования. Подчеркивается необходимость международного сотрудничества и взаимодействия научных организаций с промышленными предприятиями для ускорения внедрения передовых технологий и устойчивого развития нефтегазовой отрасли России.

Ключевые слова: геохимические методы, локальный прогноз, нефтегазоносность, Арктика, Западная Сибирь, Восточная Сибирь, интеграция методов, геолого-разведочные работы

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Introduction

Exploration and development of oil and gas resources in the Arctic regions of Western and Eastern Siberia are strategic tasks for the Russian economy. However, these territories are characterized by extreme climatic conditions and complex geological structures, including permafrost rocks and a thick cryolithozone. These factors create significant obstacles to the application of traditional exploration methods, such as seismic surveying, increasing their cost and reducing their effectiveness. Under these conditions, geochemical exploration methods are becoming the most promising direction, providing rapid and relatively cost-effective identification of hydrocarbon indicators directly in the zone of potentially productive layers. Their significance is due to the possibility of direct or indirect detection of hydrocarbon fluids. At the same time, the effective implementation of these methods in the Arctic faces challenges in correctly interpreting data, caused by the uniqueness of the natural environment, which can mask or distort geochemical anomalies.

The aim of the presented study is to conduct a comparative analysis, systematization, and evaluation of the effectiveness of geochemical methods for local oil and gas potential prediction in the Arctic conditions of Western and Eastern Siberia. The main attention in the work is paid to a detailed description of both direct (gas and bituminological surveys, chromatography-mass spectrometry) and indirect (study of trace elements, isotopic compositions) methods, their theoretical foundations, practical implementation, and adaptation to specific regional features.

To address these tasks, it is necessary to

identify the features of applying geochemical methods in Western and Eastern Siberia, which will subsequently allow assessing the strengths and limitations of geochemical methods, proposing recommendations, and improving the processes of sample collection and data processing.

The oil and gas potential of Siberia has long attracted the attention of researchers. Although the first evidence of the presence of hydrocarbons in the region dates back to the mid-19th century, systematic study began during the Soviet period. The start of targeted geological study of the Arctic regions, particularly the territory in the lower reaches of the Yenisei River, was initiated by the expedition of the Main Administration of the Northern Sea Route in 1934 under the leadership of N.A. Gedroits, a representative of the classical school of the Geological Committee [1, 2]. As early as 1934, geologists discovered near-surface outcrops of combustible gases in the area of the Malaya Kheta River mouth. Despite the absence of direct oil shows, Gedroits, relying on the detected gas shows, finds of native sulfur, and the presence of salt lakes, gave a positive assessment of the prospects of the lower Yenisei region [2, 3]. These results drew attention to the region, and in 1935, the Ust-Yenisei oil exploration expedition was organized, operating until 1954. The first industrially significant oil shows were obtained in 1942, when a gas deposit was discovered in the Malokhetskaya structure [2, 4].

Outstanding scientists made a significant contribution to the development of the region's



modern geology. For instance, N.A. Gedroits not only dealt with issues of hydrogeology and hydrocarbon migration but also was the first to scientifically substantiate the need for exploration in the Tazovsky district. In 1942–1943, he developed a work program, considering the north of the West Siberian Lowland as a zone of junction between the structures of the Urals and the Siberian Platform. On his initiative, in 1943, the Tazovskaya geological exploration party was organized under the general leadership of M.F. Danilov, which included V.N. Saks and I.P. Luginets [2, 4]. Thus, long before the discovery of the first Tazovskoye gas field in 1962, it was N.A. Gedroits who scientifically substantiated the necessity of conducting geological exploration here [2, 5].

In addition to field research, Gedroits played a key role in synthesizing geological materials. In 1936, he compiled one of the first maps of oil potential prospects in the Arctic sector of Siberia, and in 1944–1945, he headed the Arctic Brigade of the All-Union Petroleum Research Institute to synthesize all data on the oil potential of Siberia [2, 3, 6]. Developing his forecasts, he arrived at important tectonic conclusions: in 1941, he substantiated the presence of two fold systems in the Ust-Yenisei region – Paleozoic (sublatitudinal) and Mesozoic (submeridional, extending towards the Gydan Peninsula). These ideas became a working hypothesis for further exploration [2, 4].

The culmination of geological exploration in the 1960–70s was the discovery of a number of unique and large fields. In 1962, the first Tazovskoye gas field was discovered. It was followed by Zapolyarnoye (1965), Urengoy (1966), Medvezhye (1967), and Yamburg (1969). In the Ust-Yenisei region, the Messoyakha (1967) and Soleninskoye (1969) fields, among others, were discovered [1, 5, 7]. One of the most significant events was the discovery of the Vankor group of fields (1972–1991), the geological exploration planning for which was carried out under the leadership of Academician A.E. Kontorovich. The development of a set of methods for predicting oil and gas potential contributed to the discovery of the largest fields [1, 7, 8].

With the advent of the 21st century, the development of geochemistry reached a new qualitative level. Thanks to computer modeling, laser spectroscopy, and high-precision analytical equipment, it became possible to reassess the prospects of previously abandoned areas and identify new fields in complex regions [9–12]. The vast amount of geological and geophysical information accumulated by the beginning of the 21st century made it possible to move on to solving fundamentally new tasks: identifying factors that were decisive in the formation of giant hydrocarbon accumulations and understanding the processes that led to the formation of fields on the periphery of the sedimentary basin [11–13].

Modern science uses innovative technologies in combination with an integrated approach that unites geochemical and geophysical data, which makes it possible to create high-quality models of oil and gas objects and significantly increase the accuracy of hydrocarbon reserve forecasts [9–14].

Materials and methods

The basis of geochemical exploration for hydrocarbon deposits lies in the concept of fluid migration from reservoirs, leading to the formation of dispersion halos and anomalous geochemical fields (AGFs) in near-surface environments [15–17]. The theoretical foundations of modern understanding of migration were laid in the works of the founders of the sedimentary-migration theory – V.A. Sokolov, N.B. Vassoevich, and A.E. Kontorovich [1, 15, 18]. The formation of AGFs is driven by two main mechanisms [15, 16]:

- 1) diffusion – the scattering of gaseous hydrocarbons (C1–C5) within the pore space of rocks under the action of a concentration gradient [18, 19];

- 2) filtration – lateral and vertical transport of fluids through fracture systems and tectonic disturbances, playing a key role in the formation of contrasting anomalies [16, 17, 20].

The combined action of these processes creates complex anomalies in soils, groundwater, rocks, and the ground-level atmosphere, which can serve as indicators of deep hydro-



carbon accumulations¹ [17, 21, 22]. However, direct and unambiguous interpretation of these anomalies is difficult. The absence of pronounced hydrocarbon components at the surface may not indicate the absence of a reservoir but, on the contrary, may be evidence of the presence of a thick and impermeable seal that reliably screens the fluids. Conversely, bright surface anomalies are sometimes associated with destroyed or insignificant accumulations, or with technogenic interference [16, 19, 23]. This fundamental limitation determines that direct methods, such as gas surveys, are most effective for solving regional and zonal forecasting problems, whereas for local prediction, their data require mandatory comprehensive verification and integration with other methods [9, 21, 22]. In this regard, survey of silt gases from water bodies and watercourses is of particular interest, as it integrates information over an area and allows the influence of local inhomogeneities of the underlying surface to be levelled out [10, 24].

Depending on the migration form and indicator medium, several types of geochemical anomalies are distinguished in practical research [15, 18]:

- gas anomalies (hydrocarbons and non-hydrocarbon gases, such as helium, carbon dioxide);
- bitumen anomalies (bitumoids, micro-oils);
- hydrogeochemical anomalies (changes in groundwater composition);
- lithochemical anomalies (secondary rock alterations);
- biogeochemical anomalies (influence of hydrocarbons on vegetation and microorganisms).

The formation and preservation of anomalies are influenced by a combination of factors:

- geological (presence of faults, seal properties);
- physicochemical (pH, Eh);
- biogeochemical (microbial activity);
- climatic (permafrost conditions, infiltration) [10, 16, 21].

In Arctic conditions, the influence of these factors is particularly pronounced, which requires careful adaptation of methodologies [9, 10, 11].

Of particular practical interest for Arctic regions is the morphogenetic classification of anomalous geochemical concentration fields developed by G.L. Koryukin, which identifies five main types associated with different geological structures [25]:

- arch-ring type – above anticlinal structures;
- linear-fault type – confined to tectonic disturbances;
- mosaic-monocline type – controlled by the pinching out of oil and gas bearing complexes;
- arch type – above domes of local uplifts;
- fumarole type – above subaqueous gas discharge foci.

This classification is an effective tool not only for establishing the fact of hydrocarbon migration but also for determining the genetic relationship of anomalies to specific types of traps, which is fundamentally important for local prediction [23, 25].

Development of quantitative methods for assessing oil and gas potential. Concurrently with the development of field geochemical methods, approaches to the quantitative assessment of the generative potential of the subsurface have also been improved. In this regard, two complementary methods have played a key role: the volumetric-genetic method and the historical-genetic method (basin modeling)² [21, 26, 27].

The volumetric-genetic method, the foundations of which were laid by A.D. Arkhangel'sky (1927) and developed in the works of V.A. Uspensky, N.B. Vassoevich, A.E. Kontorovich, and S.G. Neruchev, made it possible to estimate the potential hydrocarbon resources based on the organic matter content in oil and gas source rocks [1, 21, 28]. A crucial contribution was the theory of the main phase (zone) of oil formation (N.B. Vassoevich, A.E. Kontorovich), which demonstrated the non-uniformity of hydrocarbon generation processes depending on the stages of catagenesis [1, 15, 28].

¹ Isaev V.P. *Geochemical methods for prediction and exploration of oil and gas fields: a textbook*. Moscow–Vologda: Infra-Inzheneriya; 2022, 196 p.

² Prishchepa O.M. *Geology and geochemistry of oil and gas: a teaching and methodological manual*. St. Petersburg: Mining University; 2023, 157 p.



The logical development of these ideas was the historical-genetic method (basin modeling) [26, 27, 29]. This method allows for the numerical reconstruction of the history of the realization of generation potential over time, taking into account all stages of the geological development of the sedimentary basin: subsidence, rock compaction, changes in the thermal field, generation, migration, and accumulation of hydrocarbons [16, 27, 29]. The modern software products (such as Temis, Petromod) that use this method are based on kinetic models of kerogen transformation developed by B. Tissot and J. Espitalié, as well as the time-temperature index of N.V. Lopatin [20, 23, 27].

It is important to note that even modern historical-genetic methods have their limitations. These include: firstly, the closed nature of the kinetic models, which does not fully reflect real processes in an open system; secondly, the ambiguity in determining kinetic parameters (activation energy and frequency factor), known as the “compensation effect”; thirdly, the high dependence of results on the quality and completeness of the initial geochemical data, especially for poorly studied deep horizons [19, 23, 27]. These factors must be taken into account when interpreting modeling results [9, 29].

Modern suite of methods. The modern arsenal of methods represents an integrated approach combining field, laboratory, and mathematical research techniques. All applied methods are divided into three main groups (Table 1) [21, 22, 30–32].

Standardization of sampling, accounting for background values, elimination of technogenic interference, and comprehensive data interpretation involving geophysics are of key importance for successful prediction [9, 21, 22].

Methodology and evaluation of effectiveness for different regions. The specific geological structures of Western and Eastern Siberia explain the different approaches that have been developed for integrating geochemical methods [7, 9, 11, 14].

Criteria for diagnosing the nature of anomalies for local prediction. To move from regional assessment to local prediction in Arctic conditions, a comprehensive analysis of anomalies is necessary based on a number of diagnostic criteria. The key ones are:

1. Spatial continuity of anomalies across the section and their registration at different levels of exploration sounding [16, 21, 25].

2. An extended spectrum of methane homologs – the presence not only of light (C1–C2) but also of heavy homologs up to pentane (C₅H₁₂) [9, 18, 23].

3. Predominance of saturated hydrocarbons over unsaturated hydrocarbons, indicating the thermocatalytic nature of the gas [17, 18, 26].

4. A regular increase in the content of heavy hydrocarbons down the section [16, 23, 26].

5. The absence of a correlation between hydrocarbon anomalies and the composition of organic matter or the lithological type of rocks confirms their migration, rather than syngenetic, nature [17, 21, 28]. In the complex sections of Eastern Siberia, enriched with carbonaceous material, this criterion makes it possible to separate superimposed anomalies from syngenetic ones [13, 14, 33].

6. Elevated contents of helium and hydrogen as indicators of deep, tectonically controlled migration pathways³ [11, 34]. Helium, due to its inertness and lack of lithological association, is the most reliable indicator of fluid-conducting faults,

Table 1. Groups of methods
Таблица 1. Группы методов

Method group	Example
Direct	Gas surveys, bituminology, chromatography-mass spectrometry
Indirect	Isotopic, lithochemical, hydrogeochemical, biogeochemical methods
Integration	Statistical modeling (including cluster and discriminant analysis), integrated sounding, joint interpretation with geophysics, basin modeling

³Pastukhov N.P. *Relationship between geochemical and geophysical fields in overproductive complexes of oil and gas fields in the South of the Siberian Platform: candidate of geological and mineralogical sciences dissertation: 04.00.13.* Moscow; 1992, 180 p.



especially under conditions of a thick sedimentary cover [10, 24, 25].

7. Spatial coincidence of anomalous geochemical and geophysical fields. It is not just the fact of coincidence that is important here, but the analysis of the structural conditioning of the geochemical fields [34]. The tendency of anomalies to be confined to ring structures, fault zones, and other elements of the tectonic framework identified by geophysical methods significantly increases the predictive significance of geochemical data [9, 17, 20].

8. Presence of geochemical zoning. For local prediction, it is fundamentally important not only to identify an anomaly but also to analyze its internal structure. A regular change in the composition of hydrocarbon gases (for example, an increase in the proportion of heavy homologs or a regular change in the carbon isotope composition of methane) towards the supposed source is a reliable sign of its proximity [9, 15, 17, 23, 26].

9. Adequate choice of sampling medium taking into account landscape-geochemical conditions. In Arctic regions, characterized by the development of the cryolithozone and specific biogeochemical barriers (peatlands, moss cushions), traditional lithochemical sampling can be supplemented or replaced by biogeochemical and hydrogeochemical methods, which makes it possible to detect low-contrast but stable superimposed dispersion halos [10, 24, 35].

The reliability of local prediction increases many times over when this set of criteria is fulfilled [9, 21].

Results and discussion

Western and Eastern Siberia, being key oil and gas provinces of Russia, are characterized by fundamental differences in geological structure, which necessitates the application of different methodological approaches to prediction [7, 8, 14]. The methods are based on the theory of subvertical hydrocarbon migration, aimed at identifying and interpreting geochemical anomalies above reservoirs [15, 16, 19].

Effective prediction in these regions requires different technological emphases, which are systematized in Table 2 [9, 11, 14, 17, 34].

A rational suite of prediction methods in Western and Eastern Siberia includes the following stages (Table 3) [9, 16, 21, 29].

Evaluation of effectiveness and justification of a rational suite of methods. The effectiveness of geochemical prediction methods in Western and Eastern Siberia is determined not so much by technical equipment as by the synergistic effect of data integration [11, 29, 35]. Key success criteria:

1. Stratified choice of methods – correspondence of the methodological apparatus to regional geological conditions [9, 14, 17]:

- for Western Siberia: emphasis on gas chromatography and biomarkers [5, 36];
- for Eastern Siberia: priority of isotopic studies and trace element analysis [33, 34].

2. Multi-level verification – cross-checking of results [11, 16]:

- comparison of geochemical anomalies with seismic data [9, 37];

Table 2. Comparison of oil and gas potential forecasting technologies in Western and Eastern Siberia
Таблица 2. Сравнение технологий прогнозирования нефтегазоносности в Западной и Восточной Сибири

Technology	Western Siberia	Eastern Siberia
Gas and bituminological logging	Important for assessing the quality of productive horizons	Necessary for studying complex geological conditions
Luminescence-bituminological analysis	Diagnosis of residual hydrocarbon presence	Used to refine the composition and preservation of hydrocarbons
Cluster analysis	Effective for data systematization	Useful for processing large volumes of heterogeneous data
Discriminant analysis	Modeling of complex oil and gas formation processes	Recommended for testing hypotheses about reservoir formation mechanisms
Neural networks	Modeling of complex oil and gas formation processes	Recommended for analyzing multiple variables and searching for relationships



Table 3. Stages and phases of geochemical work
Таблица 3. Этапы и стадии геохимических работ

Stage	Phase	Main objectives
Regional	Prediction of oil and gas potential	1. Study of regional geochemical anomalies. 2. Compilation of predictive oil and gas potential maps. 3. Delineation of zones of probable hydrocarbon accumulation
	Assessment of oil and gas accumulation zones	1. Detailed investigation of the spatial distribution of tracer hydrocarbons. 2. Quantitative assessment of the content of volatile components. 3. Development of a strategy for detailed evaluation of promising areas
Exploration-appraisal	Identification of targets for exploratory drilling	1. Localization of reservoirs using detailed gas-geochemical surveys. 2. Search for new promising geochemical signals. 3. Selection of optimal points for positioning exploratory drilling
	Preparation of targets for exploratory drilling	1. In-depth study of the composition of soil, rock, and water samples. 2. Assessment of risks and probability of successful oil and gas potential of the area. 3. Optimization of the plan for subsequent drilling stages
Exploration	Exploration and pilot production	1. Monitoring of changes in geochemical profiles. 2. Data collection on the state of hydrocarbon reserves. 3. Confirmation and transfer of reserves to the proven category

– correlation of surface manifestations with data from structural drilling [7];

– statistical processing of heterogeneous data (cluster and discriminant analyses) [35].

3. Economic feasibility – optimization of exploration costs [9, 11, 27]:

– reduction in the number of dry wells by 25–40% [5, 8];

– reduction in the time required for localizing promising targets by 30% [9, 10, 37];

– increase in the accuracy of predictive estimates to 85–90% [11, 14, 29].

A rational suite of methods is formed based on the principle of “sequential focusing” [9, 16, 36]:

– regional stage: identification of oil and gas basins [10, 11, 13];

– exploration stage: delineation of promising zones [9, 14];

– detailed stage: localization of targets for exploratory drilling [5, 7, 37].

This approach ensures a reduction in overall risks by 35–50% compared to traditional prediction methods, which is confirmed by successful testing at the Vankor group fields in Western Siberia and the Chayandinskoye field in Eastern Siberia [5, 8, 13, 14].

Thus, maximum efficiency is achieved not by simple summation of methods, but by their

systemic integration within a unified predictive model adapted to the specifics of each region [9, 16, 29].

Results of research using a suite of geochemical and geophysical methods in Arctic regions. In Western Siberia the research was conducted on the territory of the Medvezhye license area (LA), which is located in the Nadym District of the Yamalo-Nenets Autonomous Okrug. The area of the site extends in the meridional direction for 120 km with a width of 25–35 km [5], with the aim of rapidly assessing the oil and gas potential of exploration targets in the Neocomian and Middle Jurassic deposits identified by seismic surveying, as well as testing the methods under conditions of thick permafrost [9, 10]. The main tasks included:

– identification of intervals with increased gas saturation [9, 33];

– study of the composition and nature of hydrocarbon gases [10, 18];

– assessment of the potential of targets and integration of data with the results of geophysical well logging (GWL) [20, 21, 37].

For effective prediction of oil and gas potential in Arctic conditions, a specialized suite of geochemical methods was developed, adapted to the complex geological and climatic features of the region [9, 11, 29]. The suite includes three main



groups of methods, each solving specific geological problems [29, 34].

Gas-geochemical methods (thermal vacuum degassing of core, gas logging of drilling fluid, analysis of silt and soil gases) make it possible to determine the concentrations of methane, its homologs (C_2-C_6), carbon dioxide, hydrogen, helium, as well as to calculate dryness coefficients ($C_1/\Sigma C_2^+$) and $i-C_4/n-C_4$ [9, 10]. These parameters are used to identify intervals of increased gas saturation, assess the phase state of fluids, and identify zones of vertical hydrocarbon migration [16, 17, 19].

Isotope-geochemical methods (carbon isotope analysis of methane $\delta^{13}C$, biomarker diagnostics, determination of catagenesis degree Ro) provide determination of hydrocarbon genesis, identification of the relationship between oils and dispersed bitumoids, as well as assessment of organic matter maturity [18, 21, 26].

Integration and modeling methods (3D geochemical modeling, joint interpretation with GWL and seismic data, statistical analysis) allow for stratigraphic correlation of anomalies with target horizons, prediction of reservoir properties and saturation zones, and optimization of the location of exploration and appraisal wells [9, 27, 29].

The implementation of the methodological suite is carried out in stages during geological exploration (GE). At the regional stage, luminescence-bituminological surveying at a scale of 1:200,000, gas logging, and isotopic analysis of formation fluids are applied, which makes it possible to create predictive geochemical maps and establish regional gas-geochemical zones [9, 22].

At the exploration stage, detailed gas-geochemical surveying at a scale of 1:50,000, chromatography-mass spectrometry analysis of biomarkers, and microbiological studies are used, which ensures the identification of local anomalous geochemical zones and increases the reliability of the prediction by 30–40% [9, 10].

At the exploration (appraisal) stage, 3D geochemical modeling of productive sequences, monitoring of changes in hydrocarbon composition during drilling, and integration with GWL and seismic data are applied, which makes it possible to identify intervals for testing, predict

the phase state of fluids, and reduce GE risks by 25% [9, 27, 37].

In the section of well no. 50, classical zoning of hydrocarbon gas distribution was revealed, with increasing concentrations and predominance of saturated hydrocarbons over unsaturated ones with depth, especially in the deposits of the Tangalov Formation (Neocomian). Based on the complex of data (gasometry + GWL), 9 intervals of increased gas saturation were identified. The most promising were recognized as layers BN2, BN4, BN7, BN8, and BN9 [5, 37].

Carbon isotope analysis of methane ($\delta^{13}C$ from -40.09 to -38.91‰) for the Tangalov Formation indicated its thermocatalytic nature. At the Medvezhye field, isotope-geochemical analysis revealed different genesis of hydrocarbons: a biogenic gas genesis was established for the upper intervals ($\delta^{13}C$ from -65 to -70‰), while a mixed thermogenic-biogenic origin ($\delta^{13}C$ from -45 to -55‰) was found for the lower horizons [5, 26].

Multi-level gas-geochemical surveying established a clear stratigraphic differentiation of the Senonian deposits. The upper part of the section is characterized by background hydrocarbon concentrations (0.0001–0.001%), while anomalous contents (0.01–0.1%) were recorded in the lower part. Biomarker diagnostics confirmed the autochthonous origin of dispersed bitumoids and the low degree of organic matter catagenesis ($Ro = 0.3-0.5\%$) [5, 18, 22].

Figure 1 presents a comparison of intervals of increased gas saturation in the section of wells 6C, 5C, 3C, and 4C at the Medvezhye oil and gas condensate field [22, 34].

The implementation of the proposed suite of geochemical methods made it possible to:

- increase the reliability of predicting productive intervals by 30–40% due to the integrated approach (geochemistry + GWL);
- reduce the risks of geological exploration by 25% through ranking targets based on geochemical criteria;
- obtain fundamentally new data on the gas-geochemical zoning of the section and the nature of hydrocarbons;
- optimize well placement based on comprehensive data interpretation.

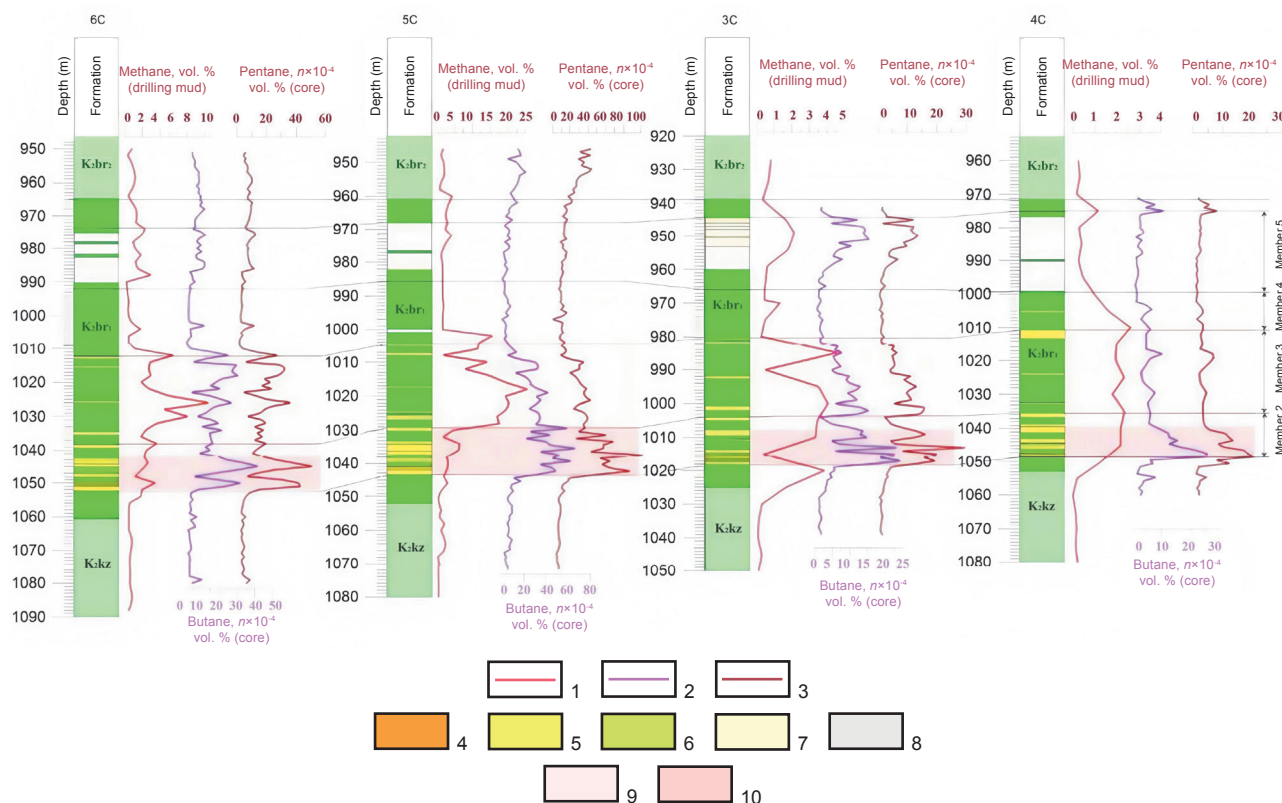


Fig. 1. Comparison of intervals of increased gas saturation and rock units in the section of wells 6C, 5C, 3C and 4C (pilot borehole) at the Medvezhye oil and gas condensate field:

- 1–3 – hydrocarbon component concentration curves: 1 – methane (drilling mud), 2 – butane (core), 3 – pentane (core); 4–8 – rock classes: 4 – best reservoir properties, 5 – good reservoir properties, 6 – poor reservoir properties, 7 – flasks with good reservoir properties, 8 – flasks with poor reservoir properties; 9, 10 – intervals of elevated hydrocarbon concentrations:
9 – interval 1, 10 – interval 2

Рис. 1. Сопоставление интервалов повышенной газонасыщенности и пачек пород в разрезе скважин 6С, 5С, 3С и 4С (пилотный ствол) на Медвежьем нефтегазоконденсатном месторождении:

- 1–3 – кривые концентрации углеводородных компонентов: 1 – метан (буровой раствор), 2 – бутан (керна), 3 – пентан (керна); 4–8 – классы пород: 4 – с наилучшими коллекторскими свойствами, 5 – с хорошими коллекторскими свойствами, 6 – с ухудшенными коллекторскими свойствами, 7 – опоки с хорошими коллекторскими свойствами, 8 – опоки с низкими коллекторскими свойствами; 9, 10 – интервалы повышенных концентраций углеводородов:
9 – интервал 1, 10 – интервал 2

The conducted research confirmed the high effectiveness of the developed suite of geochemical methods for exploration and appraisal of fields in the Arctic conditions of Western Siberia. Specific intervals in layers BN2, BN4, BN5, BN7, BN8, and BN9 are recommended for testing. The most probable hydrocarbon accumulations are predicted in intervals BN2, BN4_1, BN8_1, and BN8_2 [36].

Widespread implementation of these methods in geological exploration practice is recommended, including:

– mandatory gasometric monitoring during drilling of all exploration and appraisal wells;

– use of isotope-geochemical methods to establish the genesis of hydrocarbons;
– implementation of 3D geochemical modeling at all stages of GE;
– creation of integrated databases combining geochemical and geophysical information.

The proposed suite of methods makes it possible to significantly increase the efficiency and reduce the costs of geological exploration in the Arctic conditions of Western Siberia [5, 9, 11].

In Eastern Siberia the South-Syuldyukar license area (LA), located in the Mirninsky Dis-



tract of the Republic of Sakha (Yakutia), northwest of the town of Lensk and west of the town of Mirny, was considered. The area covers 2,450 km², is included in the regional oil and gas accumulation zones of the Nepa-Botuoba Antecline, and encompasses the Mirninsky and Syuldyukar uplifts [13, 14, 33].

The methodological basis of the work is the concept of vertical migration of hydrocarbon fluids from reservoirs, leading to the formation of dispersion halos and AGFs in near-surface environments [16, 17, 29]. To identify low-contrast anomalies in complex geological conditions, an integrated approach was developed based on complementary methods of direct hydrocarbon exploration [14, 29, 33, 34].

Field work included two main directions: litho-gas-geochemical sampling and hydro-gas-geochemical surveying [24, 35].

The aim of the sampling was to identify anomalous fields of sorbed and free hydrocarbon gases, helium, and hydrogen associated with diffusion and filtration flows from deep reservoirs [17]. The work was carried out along a network of seismic profiles with a step of 0.5–1 km. Drilling of shallow wells (1–2 m) was performed with GPS positioning. A key element of the methodology was thermal vacuum degassing of cuttings samples directly in the field, which made it possible to eliminate hydrocarbon oxidation and loss of light components. Free gas sampling was carried out using a VGS-01 vacuum sampler [13, 14, 33].

To identify zones of deep fluid discharge, surface water sampling was carried out in winter. A complete set of indicators was analyzed: organoleptic properties, physicochemical parameters (Eh, pH, electrical conductivity), ionic-salt composition, and dissolved gases (hydrocarbons, helium) [10, 24].

Laboratory studies were performed on a gas chromatograph with a detectable concentration range of 10⁻⁷–10⁻¹² vol.%. A wide range of components was determined: hydrocarbon gases (C¹–C⁶), aromatic hydrocarbons (benzene), and non-hydrocarbon gases (hydrogen, helium, carbon dioxide) [9, 10, 18].

For data processing, a suite of modern approaches was applied:

1. Statistical analysis – correlation and cluster analyses to identify associations of geochemical indicators and assess the degree of potential of anomalous geochemical zones (AGZs) relative to the reference Syuldyukar field [13, 14, 35].

2. Geochemical modeling – analytical continuation of hydrocarbon and helium concentration fields to the level of productive horizons (Vendian–Lower Cambrian complex) using proprietary software packages (“Geoprognoz”) based on a diffusion mass transfer model (Fick’s law) [16, 17, 29].

3. Mapping of tectonic disturbances – anomalous helium content (exceeding background by two times or more) was used as the main indicator of fluid-conducting zones [10, 25, 34].

4. Prediction of phase saturation – determination of fluid type (oil, gas, gas condensate) was carried out based on a system of geochemical coefficients, including the gas dryness coefficient (CH₄/C₂₊), butane (iC₄/nC₄) and pentane (iC₅/nC₅) coefficients, as well as analysis of “edge effects” [17].

Figure 2 presents the distribution of geochemical indicators along seismic profiles of the South-Syuldyukar LA [13, 14, 34].

As a result of the work carried out on the territory of the South-Syuldyukar LA, several complex AGFs were identified and delineated. These zones are characterized by stable anomalies not only of methane but also of its homologs (C₂–C₆), helium, and hydrogen, which indicates their “epigenetic”, migration nature and connection with deep sources [13, 33, 34].

Based on calculations of geochemical coefficients, an assessment was made of the phase state of fluids in the predicted reservoirs. For different AGZs, the following was established:

1. Oil saturation – characterized by low values of the dryness coefficient (less than 5) and the butane coefficient (less than 0.4).

2. Gas condensate saturation – butane coefficient in the range of 0.4–0.8.

3. Gas saturation – high dryness coefficient (greater than 9–10) and butane coefficient (greater than 0.8).

A map of tectonic disturbances was constructed, which showed that most of the iden-

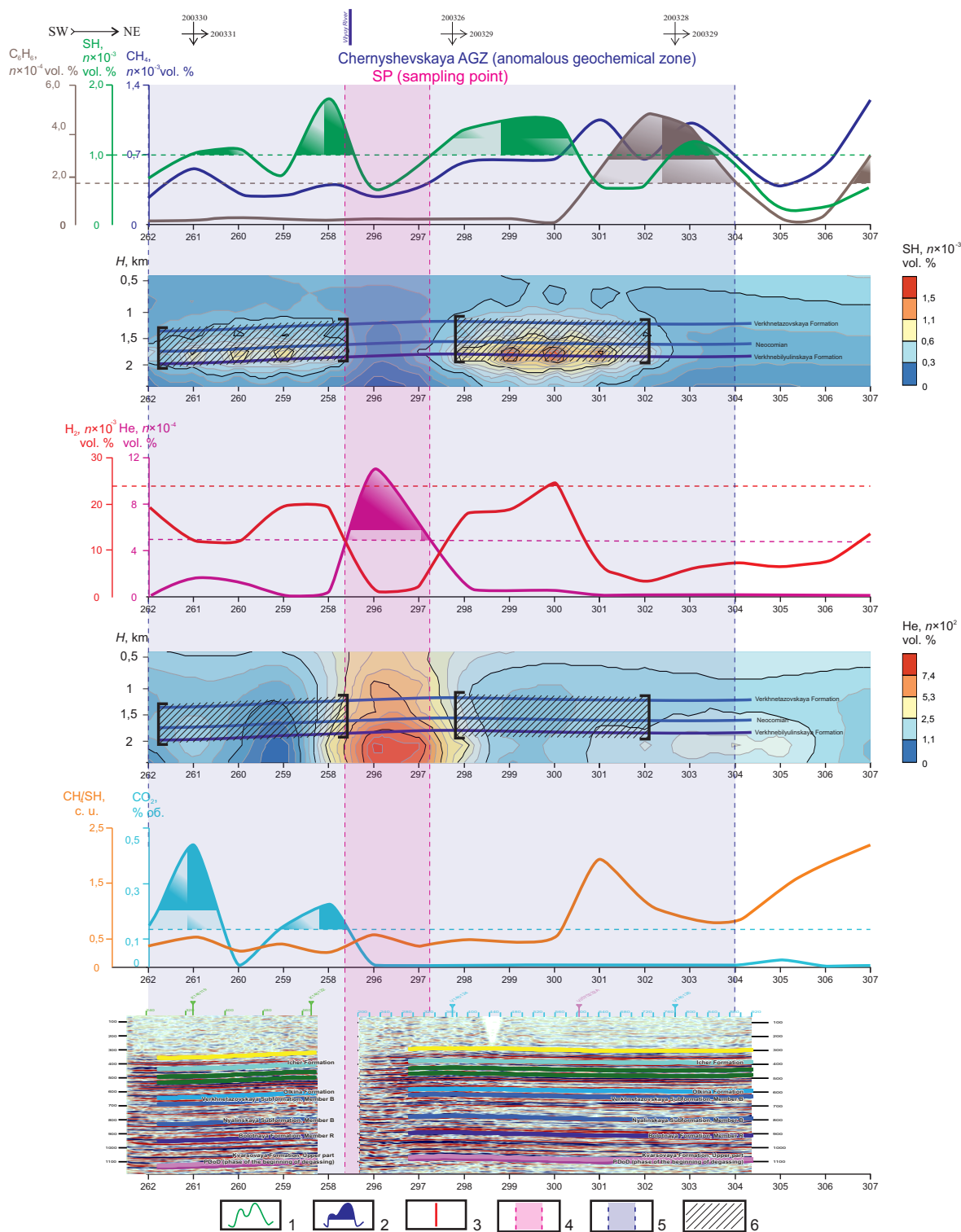


Fig. 2. Distribution of geochemical indicators along seismic profiles of the South-Syuldyukar license area:

- 1 – plots of geochemical indicators; 2 – plots of geochemical anomalies; 3 – tectonic faults;
- 4 – tectonically weakened zone (identified by helium content); 5 – anomalous geochemical zone;
- 6 – zones of distribution of oil- and gas-saturated reservoirs

Рис. 2. Распределение геохимических показателей вдоль сейсмопрофилей Южно-Сюльдюкарского лицензионного участка:

- 1 – графики геохимических показателей; 2 – графики геохимических аномалий;
- 3 – тектонические нарушения; 4 – тектонически ослабленная зона (выделена по содержанию гелия);
- 5 – аномальная геохимическая зона;
- 6 – зоны распространения нефтегазонасыщенных коллекторов



tified AGZs are confined to zones of increased fracturing and faults, which serve as conduits for the migration of hydrocarbon fluids. This is confirmed by their correlation with helium anomalies (see Fig. 2) [10, 24, 34].

Reprocessing of archival gas logging data from nine deep wells made it possible to construct geological-geochemical sections and confirm the increased gas saturation of the subsalt Vendian–Lower Cambrian deposits within the identified zones. Deep seismo-geochemical modeling provided stratigraphic correlation of near-surface anomalies with target productive horizons (Osinsky, Botuobinsky, Ulakhansky) [14, 29, 34].

Thus, the suite of geological-geochemical methods developed and tested at the South-Syuldyukar LA has proven its high effectiveness for solving exploration geology problems in the Arctic regions of Eastern Siberia. The integration of modern geochemical methods with traditional geophysics is a powerful tool for the direct assessment of oil and gas potential and optimization of geological exploration in complex and remote regions [9, 11, 14].

Conclusion

The conducted study has confirmed the high effectiveness of geochemical methods for local oil and gas potential prediction in the Arctic regions of Western and Eastern Siberia, despite significant differences in their geological structures. The comparative analysis revealed regional specificities that require a differentiated approach to the selection and application of methods.

In the conditions of Western Siberia, with its relatively simple sedimentary cover structure, traditional gas-geochemical and bituminological methods in combination with modern chromatography-mass spectrometry have shown the greatest effectiveness. Using the example of the Medvezhye field, the possibility of increasing prediction reliability by 30–40% and reducing GE risks by 25% through the integration of geochemical data with the results of seismic surveying and GWL has been demonstrated.

For Eastern Siberia, characterized by complex tectonics and deep erosional dissection, a

specialized suite of methods has been developed with an emphasis on the analysis of noble gases (helium), indicator trace elements, and isotopic systems. Testing of the methodology at the South-Syuldyukar license area made it possible not only to identify promising anomalous zones but also to predict the phase state of fluids, determining oil, gas condensate, and gas saturations.

The key factors for the successful application of geochemical methods in Arctic conditions are:

- adaptation of methodologies to the specific features of permafrost rocks and complex tectonic structures;
- integrated use of direct and indirect exploration methods;
- integration of geochemical data with geophysical and geological information;
- application of modern methods of mathematical modeling, statistical analysis, digital technologies, and artificial intelligence;
- consideration of the specific features of the formation of geochemical concentration fields in the Arctic, including phenomena such as quasi-stationary “thermal windows” – zones of deep fluid discharge recorded in the water column.

The prospects for the development of geochemical methods for predicting oil and gas potential in Arctic regions are associated with the creation of a unified geochemical database, the implementation of automated information processing technologies, the development of new high-sensitivity analytical techniques, and the expanded use of remote sensing. International cooperation and close interaction between scientific organizations and industrial enterprises are of particular importance for the accelerated implementation of advanced technologies into geological exploration practice.

Thus, a rationally selected suite of geochemical methods adapted to regional conditions represents an effective tool for solving strategic tasks of developing the oil and gas potential of the Arctic regions of Russia, ensuring a significant increase in economic efficiency and a reduction in risks at all stages of the geological exploration process.



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