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Regional evaluation of hydrocarbon potential in the south Ustyurt region based on integrated geological and geophysical data

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Abstract. A methodology for regional hydrocarbon prospectivity assessment in the South Ustyurt Region (SUR) has been developed through the integration of drilling, seismic exploration, gravimetry, magnetometry, geothermal studies, and airborne gamma-ray spectrometry data. The hydrocarbon potential of the SUR was evaluated using advanced software tools, including IP Seismic, ArcGIS, and others.

The research methodology based on machine learning techniques, specifically Self-Organizing Map (SOM) clustering, to identify correlations between geophysical anomalies, regional and local structures, and predicted hydrocarbon accumulations.

Structural mapping analysis confirmed the block heterogeneity of the sedimentary cover. Airborne gamma-ray spectrometry identified 15 anomalous zones characterized by reduced concentrations of thorium, potassium, and uranium, suggesting potential hydrocarbon presence. Most of these anomalies are concentrated in the Shakhpakhty Steppe. The correlation between airborne gamma-ray spectrometry and seismic data further confirmed the association of radioactive anomalies with fault tectonics.

In the Shakhpakhty Step and Assakeaudan Depression, the Kazgurly, Utezhan, Kozhantay, Western Kozhantay, Otynshy, and Southern Tabyn areas show high probabilities of hydrocarbon accumulation. Exploratory drilling and additional 3D seismic surveys are recommended for these locations.

Furthermore, the research findings require further validation through the integration of remote sensing and well data within a unified 3D model.

The integration of modern digital technologies and artificial intelligence to improve forecasting accuracy and exploration efficiency is recommended for similar studies in Kazakhstan and other regions with comparable geological condition.

Key words: Interpretation, IP seismic, airborne gamma-ray spectrometry, geodensity, geomagnetic and geothermal models, reflecting horizons, geospatial analysis, digital technologies, artificial intelligence.

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Introduction. In the past decade, a clear trend of depletion has emerged in a number of producing hydrocarbon fields in the energy sector of the Republic of Kazakhstan. Therefore, replenishing the country's hydrocarbon resource base is one of the key economic priorities and is reflected in strategic programs approved at the state level, including the *Geological Exploration Development Program for 2021–2025*.

These program documents outline two main directions for geological exploration: (a) further study of underexplored hydrocarbon fields; (b) the discovery of new oil and gas fields.

The first direction focuses on refining the structural, formational, and reservoir characteristics of productive formations in already explored and developed hydrocarbon fields.

However, the potential for replenishing, expanding, or maintaining a competitive hydrocarbon resource base in Kazakhstan is nearly exhausted.

The primary driver for stabilizing and subsequently expanding this resource base lies in the second direction—exploration and development of new oil and gas fields. Key objectives include:

- Advancing and implementing digital technologies, artificial intelligence, and machine learning;
- Developing new theories and concepts of hydrocarbon formation while strengthening the scientific and methodological framework for geological exploration;
- Applying innovative approaches in predictive exploration and acquiring new subsurface data to enhance the reliability of hydrocarbon accumulation forecasts;
- Expanding the role of project management methodologies aligned with international standards.

Implementing regional geological exploration programs in a phased approach is both advisable and justified. Initially, cost-effective large-scale regional methods should be applied, followed by the selection of promising areas for more detailed and resource-intensive geological and geophysical studies.

The choice of exploration and development methods depends on geological specifics, the level of previous studies, and set objectives. A rational complex of geological exploration activities is selected based on prior work analysis, geological science advancements, and technology to ensure reliable geological information at minimal cost.

The choice of exploration and development methods depends on geological characteristics, the extent of previous studies, and specific objectives. A rational combination of geological exploration activities is determined based on the analysis of prior research, advancements in geological science, and technological innovations to ensure the acquisition of reliable geological information at minimal cost.

In regional geological exploration, remote geophysical methods play a key role, forming a basis for “heavy” and expensive seismic surveys and exploratory drilling aimed at localizing hydrocarbon deposits.

Remote geophysical methods offer a cost-effective approach while enabling the exploration of vast areas. These methods include airborne gamma-ray spectrometry (AGSS), geothermal surveys, gravity and magnetic prospecting, as well as integrated data interpretation and modeling within a unified computational platform using advanced software. Our research utilized the innovative IP Seismic software.

1. Study area and geological setting. The South Ustyurt Region (SUR) is located in the southeastern part of the South Mangyshlak Sedimentary Basin, within the same-named oil and gas-bearing region (OGR) of the Turan Epig Hercynian Platform [1].

Tectonically, the South Mangyshlak Sedimentary Basin is situated within a large zone of Mesozoic intracratonic subsidence, known as the South Mangyshlak-Assakeaudan Depression System. It is bounded to the north by the Mangyshlak-Central Ustyurt Dislocation System and to the south by the northern slopes of the Karabogaz Arch and the Tuarkyr Uplift Zone. To the west, the basin extends toward the Caspian Sea, i.e. it covers oil and gas bearing regions and areas of 3 countries: the Republic of Kazakhstan, the Republic of Uzbekistan and the Republic of Azerbaijan.

The axial zone of the South Mangyshlak-Assakeaudan Depression System is characterized by a linear series of basin-like Depressions and depressions, separated by structural saddles. These depressions and synclines vary in size and exhibit irregular, often sub-isometric shapes in plain view [1, 2].

From west to east along the axis of this system, the major Jazgurly and Assakeaudan depressions, as well as the Uchkuduk Depression, can be distinguished. Within these structures, smaller Depressions and subordinate local uplifts have been identified (Fig. 1).

A key characteristic of the tectonic structure of the South Mangyshlak–Assakeaudan Depression System is the stepwise subsidence of rock sequences of different ages from the zone’s margins toward its axial part [2]. On the northern flank, these steps are arranged either parallel to each other or in a staggered pattern, aligning with the general strike of the Mangyshlak–Central Ustyurt Dislocation System (Fig. 1).

These steps are associated with chains of local anticlinal uplifts that act as hydrocarbon traps. The identified local anticlines in the South Mangyshlak petroleum-bearing region exhibit asymmetric structures, characterized by a steep southern wing, a more gently dipping northern limb, and minor faulting [1].

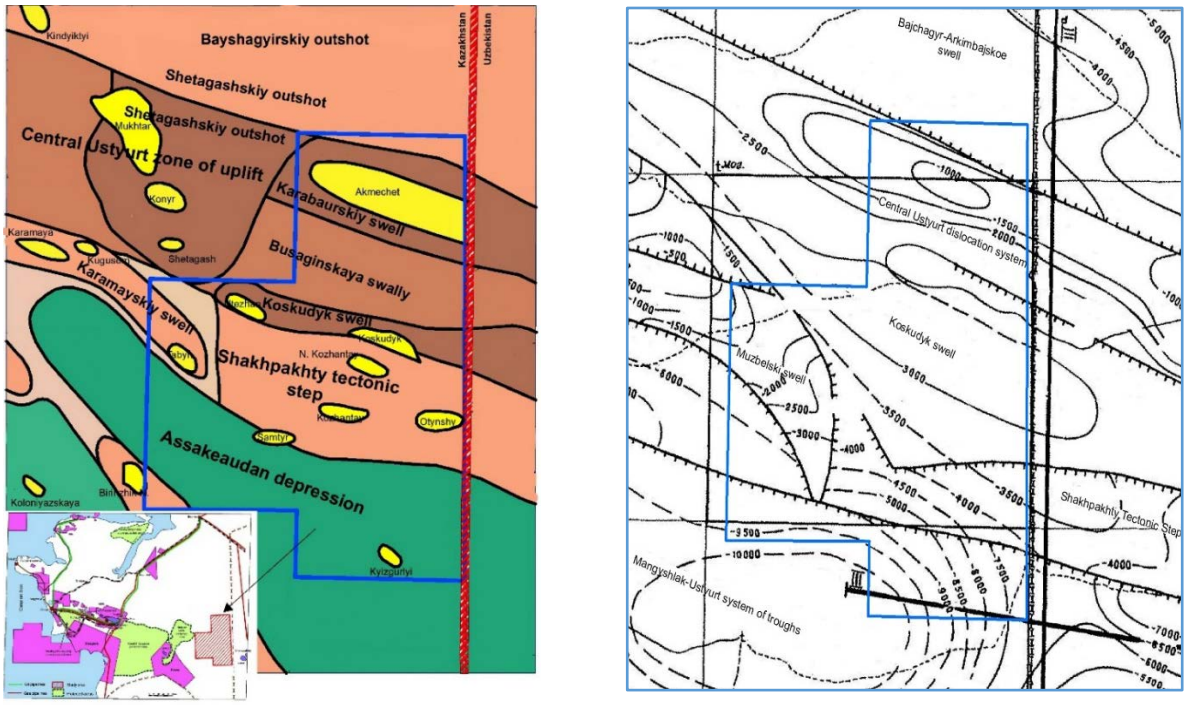


Fig. 1. Scheme of tectonic elements of the study region

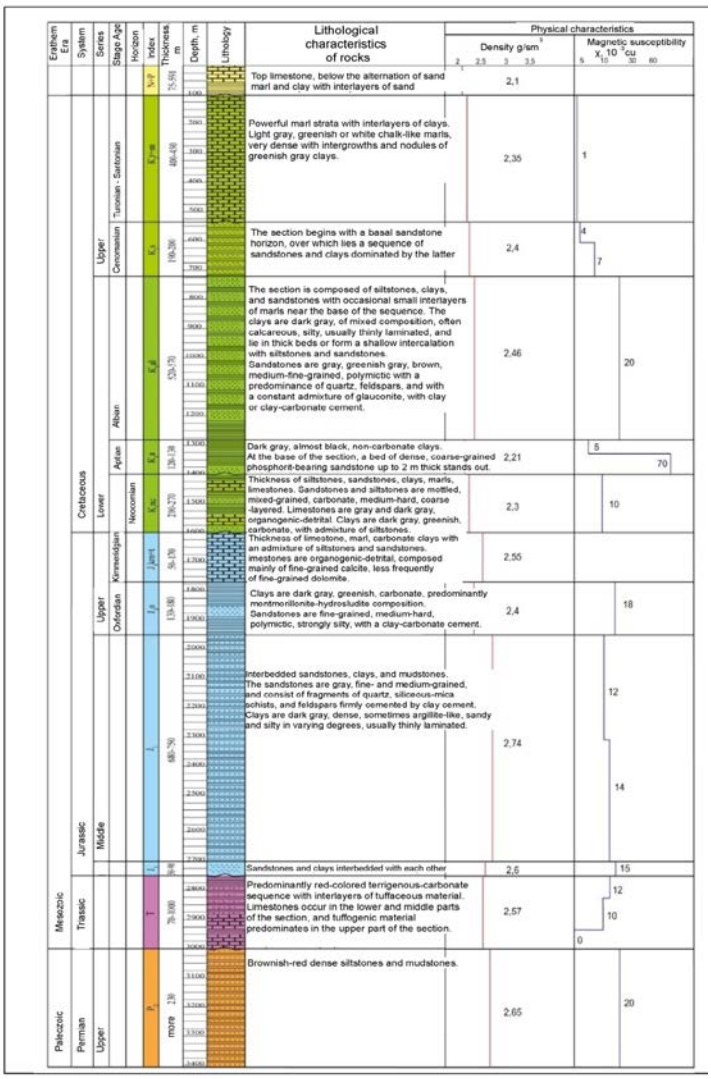


Fig. 2. Consolidated lithological-stratigraphic section of South Ustyurt

The geological section of the study region can be divided into three main structural-formational levels:

- Platform cover of Jurassic-Cenozoic age.
- Transitional complex (intermediate structural level), characterized by more intense, predominantly block-related dislocations. This level includes two subunits: the Permian-Triassic terrigenous-carbonate sequence and the pre-Upper Permian sequence, with a total thickness ranging from 3,500 to 6,000 meters.
- Folded basement, composed of rigid massifs and Paleozoic folded systems

The oldest deposits, represented by thick Upper Permian and Triassic rock sequences, are exposed in the Mountainous Mangyshlak region. These rocks are highly deformed and partially metamorphosed (Fig. 2).

In the central, most subsided part of the South Mangyshlak–Assakeaudan Depression System, these deposits occur at depths exceeding 4 km. Here, they exhibit minimal deformation and a subhorizontal bedding orientation [1].

Above these deposits, a sharp angular unconformity marks the transition to thick Jurassic sediments, which include all three Jurassic series. The Jurassic sequence, in turn, is overlain by Cretaceous deposits with evidence of erosion and angular unconformity. The eroded surface of the Cretaceous is further covered by Paleogene sediments (Fig. 2).

Neogene deposits, which form the uppermost layer of the sedimentary cover, rest unconformably on Paleogene sediments and, in some cases, on older formations, also with signs of erosion and angular discordance.

Mesozoic–Cenozoic sediments are predominantly terrigenous, except for the Upper Turonian–Danian carbonate sequence and interbedded shell limestones within the sand-clay Neogene section (Fig. 2).

The South Mangyshlak-Assakeaudan Depression System represents a typical Mesozoic-Cenozoic basin, characterized by a platform-type, weakly deformed Jurassic–Neogene sedimentary cover overlying a more deformed pre-Jurassic section. The uppermost stratigraphic unit consists of Miocene sediments of the Sarmatian stage. Beyond the study area, along the western escarpment of the Ustyurt Plateau, Jurassic and Triassic deposits are exposed [2].

In the South Mangyshlak petroleum region, Triassic, Jurassic, and Cretaceous formations host commercial oil and gas reserves. The primary productive interval consists of Middle Jurassic terrigenous sediments, which contain the majority of the discovered hydrocarbon reserves.

Eight oil, gas, and gas-condensate fields have been explored within this complex. Hydrocarbon-bearing horizons with minor reserves have also been identified in Upper and Lower Jurassic sediments. Commercial Triassic petroleum potential has been confirmed at fields such as Northen-Rakushechnoye and Southern-Zhetybai. Gas accumulations in Cretaceous sediments have been explored at the Uzen and Kansu fields, while oil fields have been identified at Dunga, Zhozaskan, Spemesai, and others [1].

The pay horizons of the discovered **South Mangyshlak** petroleum region are mainly composed of terrigenous rocks, including sandstones, clayey sandstones, and siltstones. **Cretaceous hydrocarbon-bearing horizons** exhibit effective thicknesses ranging from a few meters to 25 meters, with well flow rates reaching up to **25,000 m³/day.** In contrast, **Jurassic reservoirs** can attain effective thicknesses of up to **65 meters,** with gas well flow rates reaching **800,000 m³/day** [1,3].

The South Ustyurt potentially gas-bearing area is located between the Kansu (in the west) and Shakhpakhy (in the east) gas-bearing areas [1, 24]. Structural-tectonic, lithofacial, geochemical factors, and direct signs of hydrocarbon saturation in the adjacent gas-bearing areas suggest a high probability of gas and gas - condensate fields discovery in the SUR.

2. Vintage data

2.1. Seismic and drilling. In 2019, Tat-Arka LLP conducted MOGT-2D field seismic surveys in the SUR, covering the Central Ustyurt Dislocation System (CUSD), the Shakhpakhy Step, and the northern flank of the Assakeaudan Graben. The objective was to enhance the understanding of the geological structure and assess the oil and gas potential of Cretaceous, Jurassic, Triassic, and Paleozoic sediments.

The processing of MOGT-2D seismic data, along with structural and dynamic interpretation, was carried out by Professional Geo Solutions (PGS) Kazakhstan LLP using Spark (PGS), HoloSeis, GeoGraphix Discovery, DUG Insight, and Petrel software. As a result, final migrated profiles in the time domain were obtained, covering 1,200 full-fold linear kilometers.

Structural and dynamic interpretation of these profiles was conducted in conjunction with digitized “old” MOGT data from 1984-1991, amounting to 2,000 linear kilometers, and was complemented by well log data from 12 wells drilled ш the SUR.

As a result of the conducted work, isochron maps and structural maps were compiled, for ten reflective horizons: I, II, III, IV, IVbt, V, TV1, TV2, TV3, and “b”. These maps served as the basis for identifying and confirming seven gas- and oil-prospective local structures: Kyzgyrly, Samtyr South, Samtyr West, Tabyn South, Kozhantay West, Otynshi, and Kazgyrly South. AVO anomalies were detected at three areas in the SUR—Kazgyrly, Kozhantay West, and Kazgyrly South - which may indicate the presence of gas within these local structures.

Exploration drilling in the SUR was conducted on seven structures - Birinzhik, Birinzhik South, Kozhantai, Utezhan, Samtyr, Mukhtar, and Koskudyk. A total of 15 wells were drilled on the crests and periclines of these structures, penetrating Cretaceous, Jurassic, and pre-Jurassic formations.

The Birinzhik South and Birinzhik structures were identified within the Assakeaudan Depression (Fig.1), while the Kozhantai, Utezhan, and Samtyr structures are located on the

Shakhpakhty Step. The Mukhtar and Koskudyk structures are situated within the Central Ustyurt Dislocation System (CUSD).

A standard well logging (of that time) was conducted in all drilled wells. In addition to various methods used to assess the hydrocarbon potential of the section, it also included uncompensated neutron-gamma logging, which is highly sensitive to gas saturation, typically indicated by abnormally high readings. However, no abnormally high spikes in neutron-gamma log readings were recorded in any of the wells.

The likely cause of this is the heavy drilling mud invasion, with penetration into the reservoir ranging from 2 to 16 wellbore diameters, as well as suboptimal well placement and an underestimation of the structure of the oil and gas-bearing system (see below). Given these factors, the definitive classification of the drilled structures as unpromising remains questionable.

2.2. Gravimetric study. In the 1950s, VNIGRI and the Karakalpak Oil and Gas Exploration Trust conducted a regional gravimetric survey in Ustyurt Region at a 1:200,000 scale. Based on the interpretation of the acquired data: a) The first insights into the structure of the pre-Jurassic rock complex were obtained; b) Structural maps of the Permo-Triassic and pre-Early Permian rock complexes were compiled. The latter was identified by many researchers (V.A.Lapshov, 1963) with the top of the basement.

Gravity survey in the SUR has been conducted since 1954, aiming to provide a detailed analysis of the gravity field characteristics and to identify local anomalies associated with structures in the Permo-Triassic and older sediments. The survey scale ranged from 1:200,000 to 1:50,000.

2.3. Geomagnetic study. Magnetic survey in the Ustyurt region has been conducted since the late 1950s to obtain information on the regional structure of the basement and to support geological and mineral exploration. The survey scale ranged from 1:25,000 to 1:1,000,000.

Based on the results of the aeromagnetic survey conducted in 1954, ΔTa maps at a scale of 1:200,000 were compiled. The potential of magnetic surveying for mapping the top of the crystalline basement was demonstrated, followed by the solution of structural and tectonic zoning objectives.

As a result, new insights into the geological structure of the Ustyurt Region were obtained, magnetic field zoning was conducted, and recommendations for regional prospecting were provided. Promising areas for identifying local structural uplifts favorable for oil and gas exploration were delineated [8,9].

The aeromagnetic survey of the Ustyurt region was conducted by KazAGGE between 1974 and 1976. As a result, anomalous field ΔTa map at a scale of 1:50,000 were compiled. According to some researchers (14, Seifulin et al.), the observed anomalies are associated with magnetically disturbing masses of basement rocks. However, the depths of these formations were systematically underestimated, particularly in areas of deep subsidence. No clear correlation between the magnetic field and structures within the sedimentary cover has been established, which is attributed to the low magnetic susceptibility and lithological differentiation of sedimentary rocks.

Ground magnetic surveys were also conducted in the SUR to develop regional tectonic zoning maps and assess its structural connections with adjacent areas. The results revealed no distinct correlation between the magnetic field and the structures within the sedimentary cover.

Therefore, the results of the magnetic survey were further utilized for structural and tectonic zoning of the region along the crystalline basement surface. In this context, the authors of the article incorporated the results of aeromagnetic surveys at a scale of 1:200,000 (Spirin E.A., Makarova Z.A., 1952; Purgalin A.I. et al., 1958; Dzabaev A.A. et al., 1963) to construct composite digital datasets of the anomalous magnetic field.

2.4. Thermal field study. In the SUR, infrared (IR) survey in the long-wave spectrum (8–14 μm), conducted in 2009, was used to assess oil and gas prospective areas. This wavelength range corresponds to the intrinsic thermal radiation of surface objects, and the acquired data are widely applied in solving various geological targets.

IR survey was carried out in summer, in the pre-morning hours and in cloudless time, when the solar-thermal inertia component, as well as the temperature influence of moistened soil and green vegetation is practically excluded.

Additionally, the influence of terrain is reduced, while the intrinsic radiation of geological objects is enhanced due to the release of internal heat from the Earth's interior through weakened (fractured) zones, creating in thermal anomalies. For thermal field processing, seven spectral channels within the wavelength range of 9.58 to 14.385 µm were selected.

2.5. Aerogamma spectrometry coverage. An aerogamma spectrometric survey (hereinafter referred to as AGSS) was conducted in the South Ustyurt region (SUR) for the first time. However, to the west, on the North Bozashy uplift, a similar survey (experimental-methodological studies) at a scale of 1:200,000 was carried out by the NPO "Neftegeofizika" in 1981–1983 (Gauer Z.E., Tsytovich B.L.). Based on the survey results, the regional gamma field was zoned, and areas promising for further detailed studies were identified.

In 1982–1984, a comprehensive AGSS at a scale of 1:25,000 was conducted over a 4,000 km² area in the western part of the South Mangyshlak Depression. However, the survey results did not yield positive outcomes in the search for hydrocarbon fields.

3. Materials and methods

3.1. General approaches to interpretation and modelling. A comprehensive interpretation of geological and geophysical data, along with a regional prediction of the oil and gas potential of the South Ustyurt region (SUR), was conducted using the inversion-forecasting software package IP Seismic [5,6].

For an in-depth qualitative and quantitative analysis of multi-scale data, the authors utilized drilling, seismic, gravity, and magnetic survey data, as well as AGSS and geothermal data, applying innovative machine learning algorithms and artificial intelligence [8, 14].

The **SOM_Clustering Seis plug-in** was used, developed based on Kohonen’s algorithm to classify geophysical potential field maps within a moving window.

Kohonen's Self-Organising Map (SOM) 1D, 2D or 3D, is a computer modelling technique designed primarily for clustering, visualisation and data analysis of multivariate data. The main purpose of applying SOM is to identify hidden patterns in the data by reducing the dimensionality of the original space. In practice, a two-dimensional space is often used due to its convenience for visualization while preserving the topology of the original data space [8, 10].

As a result of machine learning, the model generates a grid of trained neurons, referred to as a "map" of the original data space [11, 12, 14].

The IP_Prediction 2D module (version 2019.1.0.1) is used for profile modeling of geophysical potential field parameter distributions. This is based on structural maps of key sedimentary cover interface surfaces, well intersection points with these surfaces, and various machine learning algorithms [5, 6]. To enhance the correlation of complex data, an inversion technique was applied to calculate the contrast of geophysical parameters in the vicinity of the target layer.

In the **IP Seismic** software, the prediction process is carried out in two stages:

1. Training – This stage involves the self-learning of neural networks to determine cluster centers (clusters of points representing classification objects in a multidimensional feature space). It uses paired input data: an attribute of potential geophysical fields and a set of map values within sliding windows for forecasting. During this phase, the optimal neural network coefficients are computed by minimizing the objective function.

2. Calculation – At this stage, the attribute of potential geophysical fields is computed across a given set of maps. The distance of current points (objects) to the nearest cluster centers is determined, and each point is assigned to the corresponding cluster.

The output is the values of standard deviation of maps P10, P50, P90 (pessimistic, probable and optimistic forecasts).

The main advantages of using a nonlinear operator based on a neural network include: 1. Modelling complex nonlinear relationships between different types of data, which facilitates more accurate analysis and prediction. 2. Automatically adapting the model to a variety of input data types and conditions, which improves its efficiency. 3. Automatic tuning of model parameters, which helps in achieving optimal results in inversion and prediction objectives [5, 13].

Thus, the combination of a neural network-based nonlinear operator and an evolutionary algorithm provided an effective tool for simultaneously analyzing multiple variables, interpreting complex geological systems, and optimizing forecasting.

In the computations, Surface and Optional Points attributes were utilized. The Surface attribute specifies the surface with classification attributes, the sliding window size, and the number of classes. The Optional Points attribute defines the points used to identify similar locations based on the features applied to the map [7, 11, 12].

In addition, the study of gravity and magnetic fields was performed in the **GraviMag Modeling Inversion** module integrated into IP Seismic software and designed for solving problems of inversion of gravity and magnetic survey data, combining them with seismic data. Geodensity and geomagnetic models were built in the depth range from 100 to 20 000 metres. The input data for modelling were a digital model of gravity field anomalies in Bouguer reduction and a digital model of magnetic field anomalies [5, 6].

The application of the GraviMag Modeling Inversion module enabled the following: 1. Modeling and interpretation of gravity and magnetic data. 2. Construction of mathematical models for calculating gravity and magnetic fields based on predefined geological structures. 3. Inversion processing using observed data, enhancing the accuracy of determining the depth, shape, and composition of gravity- and magnetically anomalous objects.

3.2. Classification of airborne gamma-ray spectrometry data. In oil and gas exploration, the presence of microscopic hydrocarbon microseepages is considered a direct indicator of hydrocarbon accumulations. According to several studies [15, 16, 19, 21], areas above potentially productive structures are often characterized by a decrease in background gamma radiation, accompanied by the formation of halos with relatively elevated radioactivity. These radiogeochemical anomalies can serve as diagnostic markers for identifying prospective hydrocarbon-bearing zones.

Taking this indicator into account, an integration of GIS technologies [7] with statistical and spatial analysis methods was implemented in the ArcGIS environment (Model Builder), utilizing the IP Seismic platform (SOM_Clustering Seis plug-in module). This approach enabled correlation analysis of AGSS datasets, identification of hidden patterns through clustering, visualization of results in 1D and 2D formats, and substantiation of decisions regarding the localization of prospective hydrocarbon targets.

To account for geomorphological, landscape, and soil factors affecting the distribution of surface radioelement concentrations, the study of the South Ustyurt Region (SUR) employed satellite imagery with a spatial resolution of 25×25 meters, along with topographic maps. The primary source was a 2019 GeoEye satellite image from the Esri database, provided in GeoTIFF format and referenced in the WGS coordinate system

The study utilized digital models of potassium, thorium, and uranium concentrations. A self-organizing map (SOM) was subsequently generated using a neural network-based approach to visualize spatial variations in gamma activity. These results substantially augmented conventional geological and geophysical datasets, significantly improving the depth and accuracy of their interpretation [9, 18, 21].

At the initial stage, the airborne gamma spectrometry survey (AGSS) data were interpreted using thorium normalization in the COSCAD software [4]. Subsequently, digital models of radioelement concentrations were integrated into Model Builder, where cell values were extracted at 500-meter intervals and converted into point features.

Subsequently, a classification map was generated based on cluster analysis, dividing the South Ustyurt Region (SUR) into eight statistically homogeneous classes characterized by distinct combinations of radioactive potassium, uranium, and thorium concentrations (Fig. 3). All classes (0–8) were identified within the studied structural units, with sharp boundaries observed along tectonic faults. These boundaries reflect the block-type heterogeneity of the facies composition of the rocks and variations in radioelement enrichment along tectonic contacts.

The analysis of the spatial distribution of gamma activity classes based on AGSS data (Fig. 3) enabled the differentiation of hydrocarbon prospectivity across key structures of the SUR.

The Central Ustyurt System Dislocation (CUSD), which includes the Karabaur Ridge, the Busagin Depression, the Akmechet structure, and others, is predominantly characterized by the development of Class 1 (57%) and Class 2 (33%) (Table 1), together accounting for 90% of its region. This indicates a generally homogeneous and background level of radioelement enrichment (Table 1). Combined with the intense deformation and tectonic disruption of the Paleozoic and Permo-Triassic formations, the classification

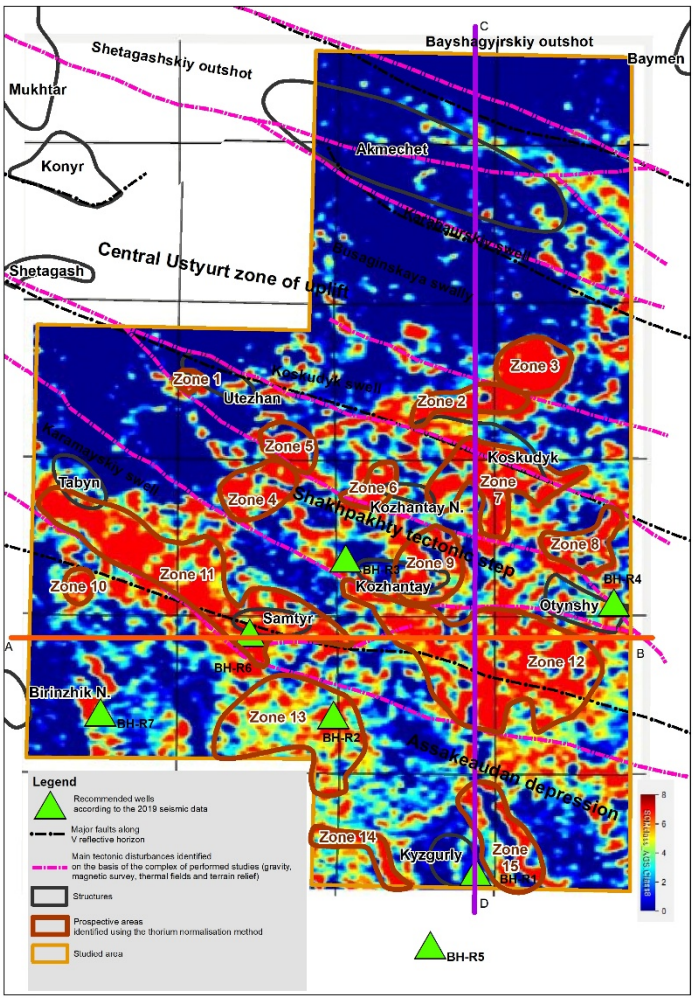


Fig. 3. Distribution of classes based on the content of radioactive elements in the SUR, calculated using the SOM_Clustering module from AGSS data results based on radioactive potassium, uranium, and thorium content suggest that the structures of the CUSD are of low or no hydrocarbon potential.

In the Assakeaudan Depression, classes 5 (32%) and 6 (44%) predominate, reflecting greater spatial differentiation and lower concentrations of radioactive potassium, uranium, and thorium (Table 1). These features, combined with favorable lithofacies, geochemical, and structural characteristics, support the forecast of increased hydrocarbon potential in the Assakeaudan Depression.

In the Shakhpakhty Step, classes 6–7 (35%) and class 8 (47%) dominate, collectively covering 81% of its area (Table 1). The highest-ranking classes were identified in the areas of local structures such as Kozhantay, Otynshy, Koskuduk, and others, indicating their elevated prospectivity for hydrocarbon accumulation (Fig. 3).

The wide range of differentiation of the Shakhpakhty Step in terms of classes of radioactive potassium, uranium, and thorium content reflects the presence of zones with both minimal and maximal concentrations of these elements. The spatial distribution of these classes, taking into account deep-seated faults and the structural-formational composition of the sedimentary cover and

intermediate structural tier, indicates the development of microseepage, migration, and accumulation processes of hydrocarbons within the gas- and oil-prospective local structures of this step [16, 18, 20].

Thus, the integration of AGSS data with spatial analysis and statistical classification techniques has enabled the identification of consistent patterns in the distribution of radioactive elements and their correlation with potentially hydrocarbon-bearing structures situated along inferred migration pathways. Among the studied areas, the Shakhpakhty Step demonstrates the highest exploration potential, whereas the Assakeaudan Depression exhibits less distinct geochemical and structural indicators of hydrocarbon accumulation.

3.3. Classification of Gravity and Magnetic Data. The integration of ArcGIS (Model Builder) with the inversion and predictive modeling software package IP Seismic (SOM_Clustering Seis plug-in) has facilitated the classification of gravity and magnetic datasets, their visualization in both 1D and 2D formats, and the subsequent analysis of their correlation with regional variations in the thickness of the sedimentary cover and the intermediate structural level. This approach enhances the interpretation of geophysical anomalies in relation to subsurface geological architecture.

The CUSD exhibits well-expressed heterogeneity in the vertical gradient of the anomalous gravity field, with classes 7-8 covering approximately 69% of its area. A similar pattern is observed in the distribution of the vertical gradient of the magnetic field, where classes 6-7 are identified across 67% of the domain's territory (see Table 1).

Table 1. Class Values Computed from 2D IP Prediction across Geophysical Survey Types *(percentage of area covered indicated in parentheses)*

Types of geophysical surveys	Airborne gamma spectrometry	Gravimetry	**Magnetometry**	Geothermics	Structural models
Assakeaudan Depression	5 class (32%) 6 class (44%)	1-2 classes (75%)	2 class (34%)	5 class (32%)	4-5 classes (25%)
Shakhpakhty Step	6-7 classes (35%) 8 class (47%)	2 -3 classes (82%)	3-4 classes (47%)	6-7 classes (52%)	5-6 classes – (34%)
Central Ustyurt System Dislocation (CUSD)	1 class (57%) 2 class (33%)	7 class (44%) 8 class (25%)	6-7 classes (67%)	7 class (25%)	7-8 classes – (62%)

The integrated analysis of gravity and magnetic anomalies indicates a well-expressed anisotropy in the section regarding density and geomagnetic properties, reflecting the saturation of the stratigraphic succession with bodies exhibiting gravity and magnetic disturbances [22, 23].

The results of cluster analysis, combined with the high degree of structural disruption and tectonic deformation of the rocks, suggest that the CUSD is a region with low or negligible hydrocarbon potential. This conclusion is further supported by the spatial distribution of radioactive elements, with the majority of the area characterized by minimal concentrations of potassium, uranium, and thorium - classes 1 and 2 account for 90% of the domain's surface.

In contrast to the CUSD, the local structures within the Shakhpakhty Step exhibit geophysical characteristics more conducive to hydrocarbon accumulation. The vertical gradient of the gravity field is dominated by classes 2–3, covering up to 82% of the area, while the magnetic field gradient is primarily represented by classes 3–4, occupying approximately 47% (Table 1). When considered alongside elevated concentrations of radioactive elements, these parameters collectively indicate more favorable geological conditions for the accumulation of hydrocarbons within both the sedimentary cover and the intermediate structural level.

The Assakeaudan Depression is characterized by minimal values of both the vertical gravity gradient (classes 1–2 covering 75% of the area) and the magnetic field gradient (class 2 covering 34% of the area). This is likely attributed to the orthoplatform nature of its thick sedimentary cover, which is marked by more homogeneous lithofacies and other geophysical properties. Additionally, the predominance of lower classes in the distribution of radioactive elements may further indicate the presence of effective reservoir sealing capacities and the absence of microseepage signals typically associated with hydrocarbon migration.

Overall, the analysis of the spatial localization of gravity and magnetic anomalies indicates a consistent decrease in gradients and their cluster classes from south to north - from the tectonically active and geologically and geophysically anomalous CUSD toward the more stable structures of the Shakhpakhty Step and further to the Assakeaudan Depression.

And furthermore, gravimetric and magnetic anomaly-generating features are most prominently expressed within the CUSD, become less contrasted in the Shakhpakhty Step, and are weakly developed in the Assakeaudan Depression. This gradation reflects the degree of structural, density, and other types of differentiation within the sedimentary cover, as well as its hydrocarbon prospectivity.

The identified geological phenomenon represents a transition from intensely deformed fold structures to an orthoplatform-type sedimentary cover characterized by decreasing levels of dislocation and structural contrast. This transition correlates clearly with the tectonic framework of the SUR. Similar cases have been discussed in [29, 31, 32], supporting the observations made in this study.

Analysis of classification data obtained from AGSS, gravimetric, and magnetic surveys reveals a stable inverse correlation: higher classes of vertical gradients in gravity and magnetic fields correspond to lower classes in the distribution of radioactive elements, and vice versa. This relationship may serve as an informative indicator of hydrocarbon potential - elevated concentrations of radioactive elements are associated with diminished gravimetric and magnetic anomalies, which may reflect the presence of sealing reservoirs and the absence of deep-seated density and magnetic contrasts.

3.4. Classification of Infrared Survey Data. The integration of neural networks with subsequent clustering of infrared data using the SOM_Clustering module in IP Seismic enabled the development of 1D and 2D classification models based on the local component of the thermal field, aimed at predicting hydrocarbon potential across the SUR. These results have substantially augmented the conventional set of geological and geophysical data, including the work of Petrovsky V.B. (2019).

In the CUSD, only 25% of the area could be confidently classified, primarily falling into Class 7. This classification indicates a high level of endogenous geodynamic activity, an unstable thermobaric regime, and intense tectonic deformation (see Table 1). Such conditions are typically unfavorable for the generation and accumulation of hydrocarbons. An additional risk factor is the increased rock density and magnetization, which are often indicative of crystalline and metamorphic basement lithologies.

In the Assakeaudan Depression, 32% of the area was classified as Class 5, while on the Shakhpakhty Step, 52% of the territory fell within Classes 6–7 (Table 1). These results point to comparatively more stable thermal conditions across both zones, which are conducive to the generation, migration, and long-term preservation of hydrocarbon systems. The higher classification percentages, particularly in the Shakhpakhty Step, suggest favorable geothermal regimes that enhance the prospectivity of these structures for hydrocarbon accumulation.

Significant correlation patterns have been established:

- In the Shakhpakhty Step and Assakeaudan Depression, direct correlations are observed between geothermal and radioactive anomalies, while inverse correlations are noted with gravity and magnetic anomalies.
- Conversely, within the CUSD, geothermal and radioactive anomalies exhibit inverse relationships, and positive correlations are observed with gravity and magnetic field anomalies.

Of particular importance are the localized geothermal anomalies identified within the Shakhpakhty Step, which extend into adjacent areas of Uzbekistan. In similar structural and geological settings, Jurassic-aged gas fields such as Shakhpakhty and Dzhel have been discovered and developed. This cross-border geothermal continuity strongly supports the hydrocarbon prospectivity of the Shakhpakhty Step and underscores its high potential for further exploration efforts within the SUR.

3.5. Classification of Structural Model Data. As part of the study of the SUR, structural models were classified using artificial intelligence techniques, followed by a comprehensive analysis of their correlations with gravimetric, magnetic, geothermal, and surface radioactive element distribution data. The results were visualized in both 1D and 2D formats and employed to assess the hydrocarbon prospectivity of local structural features.

Comparable cases have been examined in studies [6, 7], confirming the relevance and practical applicability of an integrated approach combining geophysical data with artificial intelligence methods.

The foundation for this analysis consisted of structural maps based on reflective seismic horizons compiled from the works of Ibragimov A.A. et al. (2019), Akchulakov A. et al. (2011), and Godin Yu.N. & Tal-Virsky B.B. (1969). These included:

– Horizon III: boundary between the Lower Cretaceous and the top of the Upper Jurassic;

– Horizon V: base of the Jurassic / top of the Permian or Triassic;

– Horizon "b": base of the Upper Permian / top of the Upper Paleozoic carbonate–terrigenous sequence.

These maps were digitized using Surfer and ArcGIS software [7, 13]. Loading the data into the *SOM_Clustering 2D* module enabled the construction of a multilayered structural model of the SUR, reflecting key tectonic and lithological features. This integrative model provides a valuable tool for forecasting hydrocarbon-bearing zones and significantly enhances the geoscientific basis for exploration targeting in the region.

Analysis of classifications derived from structural horizons maps using artificial intelligence techniques has revealed well-expressed differences in the geological architecture of the key tectonic units within the SUR.

The CUSD is dominated by high classification levels (Classes 7–8), covering up to 62% of its total area (Table 1). This predominance reflects a high degree of tectonic dislocation and fragmentation, strongly associated with metamorphic overprinting and a widespread presence of intrusive and effusive igneous bodies. These characteristics, when coupled with the unfavorable distribution of radioactive elements at the surface, indicate minimal or absent hydrocarbon accumulation potential in this domain.

In contrast, the Shakhpakhty Step exhibits a notable decrease in classification levels, primarily within Classes 5-6, which account for up to 34% of the area (Table 1). This suggests a moderate degree of deformation and a more coherent structural expression of the seismic reflectors. When considered alongside favorable lithofacies assemblages, geochemical signatures, paleogeographic evolution, and thermobaric conditions, the Shakhpakhty Step demonstrates a significantly enhanced potential for hydrocarbon entrapment. Prospective targets include both the sedimentary cover and the underlying Indermediate Structural Level, affirming the region’s importance for further exploration.

The Assakeaudan Depression is characterized by predominantly low prospectivity classes (4–5), occupying about 25% of its area, primarily along the northern flank. This structural configuration indicates limited development of local traps; however, the potential presence of hydrocarbon accumulations within the sedimentary cover cannot be excluded, especially if additional favorable geological conditions are present.

The analysis of structural model classification results (Table 1) reveals a direct correlation with geothermal anomalies and the distribution of radioactive elements, and an inverse correlation with gravity and magnetic anomalies for both the Assakeaudan Depression and the Shakhpakhty Step.

In contrast, the CUSD exhibits a strong correlation between high structural differentiation classes and gravity, magnetic, and geothermal anomalies, accompanied by an inverse relationship

with the distribution of radioactive elements. These patterns underscore the subdued tectonic expression of the Assakeaudan Depression, while highlighting the CUSD as the most structurally complex zone in the region.

The findings provide important predictive insights for refining the geological framework of the South Ustyurt Region and for evaluating the hydrocarbon potential of the studied structures.

4. Research finding

4.1. Airborne Gamma-Ray Spectrometry. Analysis of AGS data using thorium normalization enabled effective suppression of regional background levels and enhanced the identification of local variations in the distribution of radioactive elements. The normalized data revealed a marked decrease in potassium concentrations and a relative increase in uranium, which is attributed to lithological control and may serve as a diagnostic indicator in the interpretation of geophysical anomalies, as demonstrated in studies [16, 17, 20].

Using GIS technologies (ArcGIS) and the SOM_Clustering module of the IP_Seismic software suite, 15 areas with reduced radioactivity background were identified in the South Ustyurt Region. These areas are characterized by low concentrations of potassium, uranium, and thorium.

To assess the spatial distribution of radioactive elements, orthogonal profiles A–B and C–D were generated using the IP_Prediction 2D module (Figures 8 and 9). These profiles clearly delineate the Shakhpakhty Step by zones of decreased concentrations of radioactive elements. When integrated with geothermal and seismic data, this pattern indicates potentially favorable conditions for hydrocarbon accumulation.

In contrast, the CUSD is characterized by background concentrations of radioactive potassium, uranium, and thorium, which likely reflect its elevated tectonic activity and the advanced metamorphic grade of its basement rocks.

The Assakeaudan Depression is characterized by an elevated background of radiogeochemical anomalies, which show a correlation with the complex structural architecture of its northern board.

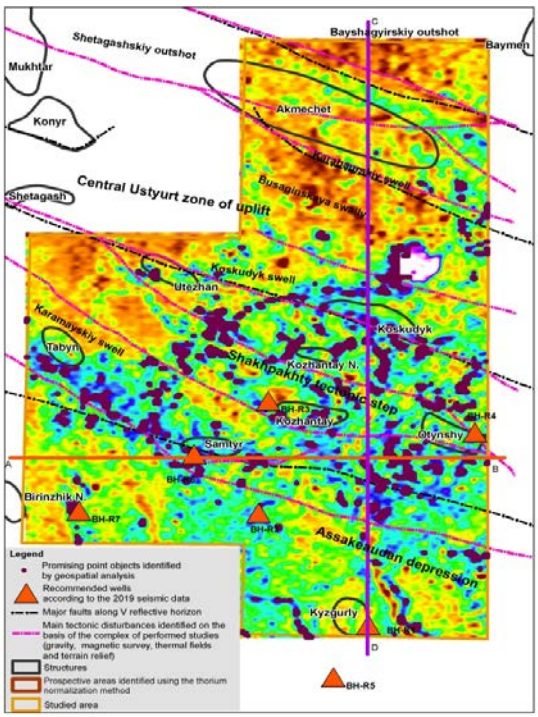


Fig. 6. Location of prospective point targets identified by airborne gamma spectrometry and layout of survey profiles (plan view).

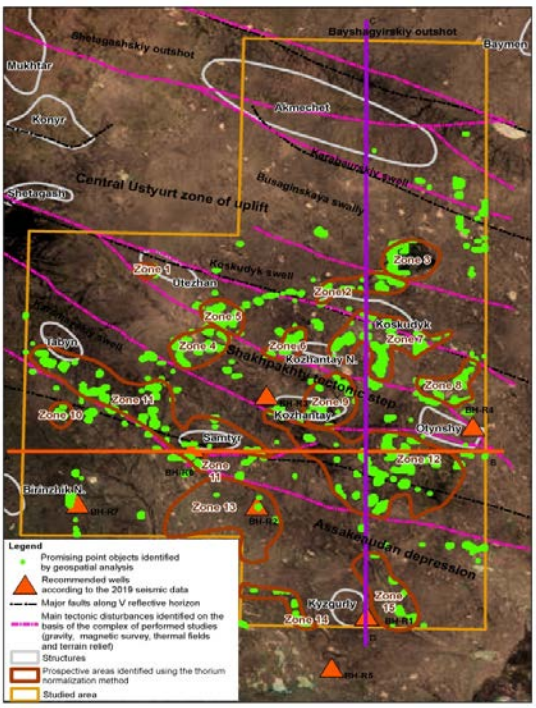


Fig. 7. Distribution of prospective point anomalies from airborne gamma spectrometry overlaid on satellite imagery.

Importantly, the identified radioactive anomalies generally do not coincide with local structural features interpreted from MOGT-2D seismic data and previously targeted by exploration drilling. This misalignment may point to the presence of non-structural hydrocarbon traps or suggest that the placement of certain exploration wells may have been suboptimal.

The analysis of the spatial distribution of radioactive elements (K, Th, U) revealed that zones of anomalously low concentrations are associated with deep fault systems as supported by the findings in [19, 21]. This observation suggests that these structures may have acted as conduits for vertical hydrocarbon migration, subsequently leading to the saturation of overlying reservoir formations. This interpretation is supported by the radiogeochemical data presented in Figures 8 and 9.

Figure 8. Graph illustrating the distribution of radioactive potassium (purple), thorium (red), and uranium (green) concentrations along profile A–B

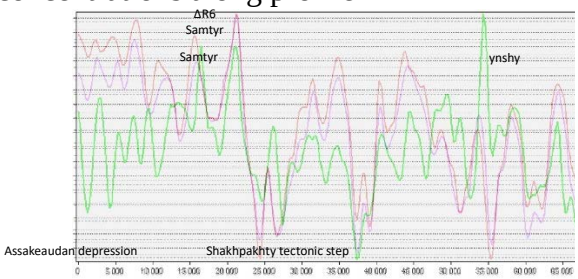
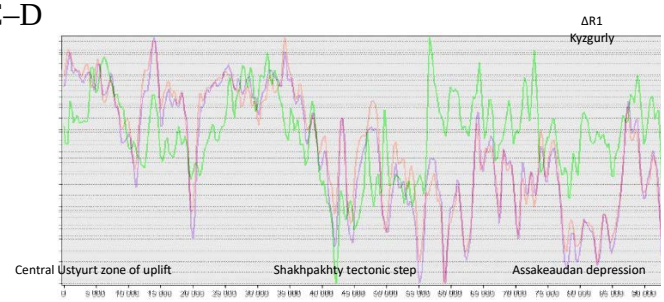


Figure 9. Graph illustrating the distribution of radioactive potassium (purple), thorium (red), and uranium (green) concentrations along profile C–D



The observed pattern of radiogeochemical anomalies underscores the applicability of AGSS for direct hydrocarbon prospecting. Exploration efforts should prioritize areas exhibiting low background levels of total radioactivity, as well as localized anomalies spatially associated with tectonic faults.

These findings establish a reliable geophysical basis for defining and justifying targets for exploration and seismic surveys, thereby enhancing the focus, efficiency, and effectiveness of subsequent subsurface investigations.

4.2. Thermal Field. The processing of infrared survey data using thermal field separation methodologies [36, 39] facilitated the development of digital models representing the spatial distribution of heat flow density throughout the South Ustyurt Region (SUR).

Analysis of the regional thermal component identified linear anomalies interpreted as deep-seated fault systems. The local thermal component revealed a consistent spatial correlation between positive geothermal anomalies and Jurassic stratigraphic units, previously delineated based on MCDP-2D seismic data.

Geothermal modeling results obtained using the IP_Prediction 2D module along profiles A–B and C–D confirm that the major tectonic features of the region possess distinctive geothermal signatures. The Assakeaudan Depression is distinguished by an extensive zone of suppressed geothermal anomalies extending to depths of approximately 5 km, punctuated by localized maxima at shallower depths of up to 2 km [37] This distribution indicates the presence of a substantial sedimentary succession characterized by low thermal conductivity and a high proportion of potentially oil-prone source formations.

The fault systems transecting the depression likely serve as pathways for deep heat and mass transfer, as well as vertical hydrocarbon migration [33, 34, 35, 38]. The established correlation between geothermal lows, deep basement configurations, and thick sedimentary cover likely reflects the structural inheritance of elements from a Paleozoic rift system.

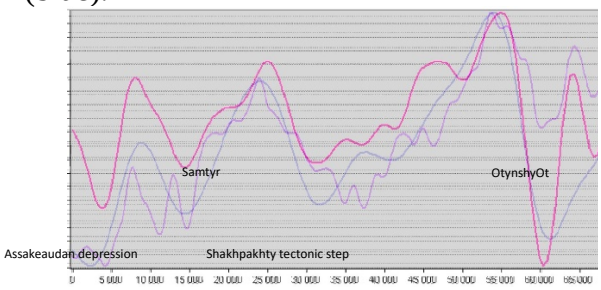
Figure 10. Plot of the thermal field (purple), extrapolated into the lower half-space. Cross-sections along profile A–B are

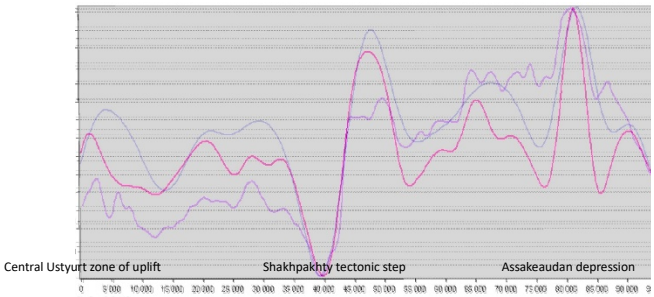
Figure 11. Plot of the thermal field (purple), extrapolated into the lower half-space. Cross-sections along profile A–B are shown at depths of 1,500 m (pink) and 2,500 m (blue).

ΔR6
Samtyr

ΔR1
Kyzgurly

shown at depths of 1,500 m (pink) and 2,500 m (blue).





Interpretation of thermal field data at subsurface depths of 1,500 and 2,500 meters has identified the Shakhpakhty Step, distinguished by persistent positive geothermal anomalies. These anomalies indicate the presence of rocks with elevated thermophysical properties (Figures 10 and 11).

The step is morphologically confined by a system of deep-rooted faults, delineated based on gradient anomalies in regional geophysical fields. Three major fault zones extend in a northwestern direction. Along the southeastern flank of these structures are the discovered Shakhpakhty and Zhel gas fields [4, 33], while to the west, several prospective local structures have been identified, including Otynshy, Kozhantay, North Kozhantay, Utezhan, and others.

The identified local structures are regarded as potential traps for hydrocarbon accumulations, provided an effective seal is present. Based on these considerations, geothermal and structural criteria support prioritizing the Shakhpakhty Step for geological exploration.

Thermal field anomalies show a strong correlation with airborne gamma-ray spectrometry (AGRS) data interpreted using thorium normalization. The observed increase in heat flow amplitude with depth may indicate a block-faulted structural framework and contrasting thermophysical properties within deformed zones. A similar judgment can be found in the publication [35].

In the zones of deep faults, high vertical and horizontal gradients of the thermal field and local minima of heat flow are observed. This is interpreted as a result of the abrupt change in thermophysical properties and the functioning of these faults as channels for deep heat and mass transfer. The faults are predominantly oriented in a northwest direction, although submeridional elements are also identified.

A geothermal phenomenon has been identified on a cross-section through the Shakhpakhty gas field (Uzbekistan), manifested as a relative heat flow minimum at depths of up to 3,000 m, complicated by two positive anomalies at depths of 2,200–2,500 m [33]. According to the literature [36, 37], such geothermal signatures are characteristic of major gas accumulations and may be associated with the presence of compacted cap rocks. Nevertheless, the interpretation of these anomalies requires additional integrated analysis using high-resolution gravity surveys, seismic data, and drilling information.

The CUSD is characterized by distinct minima in heat flow density at depths of approximately 1,500 and 2,500 meters, as revealed by heat flow mapping and the results of regional and local geothermal transform analysis. These low heat flow areas likely reflect a combination of geological and thermophysical factors. In particular, they may indicate the presence of thick, low-conductivity rock sequences that inhibit upward heat transfer.

The spatial correlation of these heat flow minima with structural features such as deep-seated faults and flexural zones further suggests that they may represent areas of restricted vertical migration of fluids and heat. These features underscore the importance of the thermal field as a valuable exploration criterion for predicting hydrocarbon saturation in the SUR.

4.3. Gravitational and magnetic fields. The inversion of gravity and magnetic data was based on forward modeling equations in the frequency–wavenumber domain developed by R.L. Parker (1973), as well as an optimization technique introduced by A.I.Kobrunov (1981). These methodologies underpin the **GraviMag Modeling Inversion** module, which is integrated into the **IP_Prediction 2D** software package [5].

Using this module, profiles A–B and C–D were generated to model the distribution of gravity and magnetic anomalies across the SUR. The results clearly demonstrate a marked geophysical differentiation between the Shakhpakhty tectonic step, the Assakeaudan Depression, and the CUSD), as evidenced by the distinct patterns and intensities of gravity and magnetic anomalies (see Figures 10 and 11).

Analysis of deep slices at levels of 5, 10, and 20 km revealed a consistent trend of increasing size of gravity and magnetic anomalies with depth, accompanied by a decrease in their spatial concentration. This effect is interpreted as reflecting the consolidation and coalescence of anomalously dense and/or magnetized bodies within the deeper layers of the lithosphere [24].

Numerical values of density and geomagnetic parameters for the main tectonic elements of the SUR at various depths are presented in Table 2.

Table 2. Statistical summary of geodensity and geomagnetic models' parameters along profiles A-B and C-D

Potential fields data	Depth	Profile A-B		Profile C-D		
		Assakeaudan depression	Shakhpakhty step	Central Ustyurt System Dislocation	Shakhpakh-ty Step	Assakeaudan Depressi-on
Geodensity model, mGal	0-5 km	**Up to 1 km:** heterogeneous surface, values range from -25 to 60 **From 1 km to 3 km:** values range from -10 to 40 **Below 3 km:** values range from -10 to 30	from -30 to 50	from -70 to 70	from-30 to 30	from -40 до 40
	5-10 km	from -30 to 30	from -20 to 30	from -60 to 60	up to -20	from -20 to 10
	10-20 km	Down to a depth of -13 km: from -30 to 15 From -13 to -20 km depth: from 0 to -40	from -20 to 10	from -50 to 20	from -30 to 0	from -20 to 10
Geomagnetic model, nT	5 km	Down to a depth of -2.3 km: from -50 to 80 Below -2.3 km: up to -50	Down to a depth of -3.5 km: from -50 to 50 Below -3.5 km: from -50 to 100	from -200 to 200	from -80 to 80	from -80 to 100
	10 km	from -50 to 50	from 20 дто120	from -80 to 80	from -130 to -20	from -100 to 100

	20 km	Up to 120	from -100 to 100	from -120 to 100	from -200 to -80	from -20 to 100

To enhance the reliability of geological interpretation, the vertical distribution of geodensity and geomagnetic heterogeneities was correlated with the positions of key seismic reflecting horizons: III, V, and “b” (see Figures 10 and 11).

The Shakhpakhty tectonic step is distinguished by an alternation of local positive and negative Bouguer gravity anomalies of moderate to low intensity (reduced to an elevation of 2.5 km). In our previous studies, it was established that this zone is characterized by low values of horizontal gradient transforms and elevated values of the vertical gradient of the Bouguer gravity field, which indicates the presence of significant density contrasts at depth [23, 28].

The Assakeaudan Depression is characterized by a relatively homogeneous geological structure, as reflected in the low gradients of both gravity and magnetic fields. This uniformity likely indicates the predominance of sedimentary sequences with minimal density and magnetization contrasts. Accordingly, the region exhibits predominantly local negative gravity anomalies with low horizontal and vertical gradients.

In contrast, the CUSD exhibits elevated values of local gravity anomalies and intermediate values of horizontal and vertical gradient transforms [23], indicating a complex combination of structures with varying densities and tectonic origins.

The density heterogeneity of the subsurface down to depths of 8 km is supported by the distribution of Euler solutions derived from gravity data using Geosoft Oasis Montaj™ software [29].

In the CUSD, gravity-disturbing bodies predominantly exhibit a northwest trend; in the northern part of the Shakhpakhty Step, their orientation shifts to northeast, while in the southern part of the step and within the Assakeaudan Depression, they display northwest to submeridional trends. These structural patterns are corroborated by the distribution of anisotropic transform values [23].

The CUSD is marked by elevated local gravity anomalies combined with intermediate vertical gravity gradient values, reflecting the superposition of geologic structures with contrasting densities and tectonic origins, including both thrust-related and block-fault systems.

The density heterogeneity of rocks down to depths of 8 km is confirmed by the distribution of Euler’s special points in the gravitational field, calculated using **Geosoft Oasis Montaj™ software [41].** In the northern part of the Shakhpakhtinsky step, gravity-disturbing objects exhibit a northeastern trend; within the CUSD - a northwestern trend; and in the southern part of the step and the Assakeaudan Depression - both northwestern and sub-meridional orientations. **This is confirmed by the spatial distribution of anisotropic transformant values [23].**

In the CUSD, these objects are characterized by a northwestern orientation. In the southern part of this tectonic step and in the Assakeaudan Depression, they are oriented northwestward and sub-meridionally, **which is also supported by the distribution of anisotropic transformant values.**

The Assakeaudan trough is characterized by a relatively homogeneous geological structure, which is reflected in the reduced gradients of both the gravimetric and magnetic fields. Such homogeneity may indicate the predominance of sedimentary cover layers that are weakly differentiated in density and magnetization [22, 23].

In the Assakeaudan Depression, gravity anomaly interpretation has revealed zones of increased Euler solution concentration aligned with the stratigraphic boundary between Upper Jurassic and Lower Cretaceous sediments. This clustering is likely attributed to lithological contrasts between the weakly consolidated Cretaceous and the denser Jurassic formations, as well as the presence of concealed tectonic faults.

Interpretation of gravity anomalies revealed zones of increased concentration of Euler points, confined to the stratigraphic contact between Upper Jurassic and Lower Cretaceous deposits. The concentration of points in this area is probably due to both lithological contrasts between poorly consolidated Cretaceous and denser Jurassic rocks, and the presence of hidden tectonic faults.

The highest density of Euler solutions corresponding to the boundaries of gravity-anomalous bodies is observed at depths of 1000–2000 m. Within this interval, MCDP-2D seismic data delineate

the reflective horizon III, whose geophysical properties and spatial correlation with anomalies in potential fields suggest it may play a key role in controlling fluid migration and the formation of hydrocarbon traps [23].

It is noteworthy that at depths exceeding 8–10 km, the density structure of the Shakhpakhty Step exhibits characteristics similar to those of the Assakeaudan Depression: in both cases, gravity anomaly values range from –5 to –30 mGal (see Table 2).

The CUSD is characterized by increased values of local gravity anomalies in combination with intermediate values of gravity gradients, which reflects the superposition of geological structures of different densities and tectonic nature, including both thrust and block-fault elements.

In the Assakeaudan Depression, the upper boundary of magnetically anomalous bodies descends to depths of 8–10 km, corresponding to the top of basement as identified by MCDP-2D seismic data. This depth level likely reflects the occurrence of mafic and ultramafic rock assemblages within the basement composition [22].

In the Shakhpakhty Step, the upper boundary of magnetically anomalous bodies is traced at depths of 8–12 km, while gravity-anomalous masses are primarily concentrated within the 6–7 km range. This vertical separation reflects the presence of two structural levels — a fragmented crystalline basement and an intermediate structural level. Beyond depths of 12 km, a well-expressed decrease in the variability of Euler depth solutions is observed, suggesting a relatively homogeneous geological structure in the deeper horizons.

The magnetic field over the Shakhpakhty Step is characterized by reduced magnetization values at depths of 6–20 km, in marked contrast to the higher magnetic anomalies observed in the adjacent Assakeaudan Depression. This contrast likely reflects differences in the petrological composition and magnetic properties of the basement rocks, possibly due to a higher concentration of mafic and ultramafic lithologies within the depression [22].

Of particular scientific interest is the persistent deepening of the magnetically active layer beneath the Shakhpakhty Step, which highlights the distinct tectonic architecture of the region. This geophysical configuration - manifested by deep gravity and magnetic anomalies and a well-defined stratification of tectonic levels - suggests favorable geological conditions for the development of hydrocarbon traps, both within the sedimentary cover and the intermediate structural level. Together, these features underscore the elevated petroleum potential of the Shakhpakhty Step.

Against this background, an integrated analysis of gravity and magnetic anomalies has confirmed the consistency between basement depths interpreted from potential field data and the crystalline basement surface delineated by MCDP-2D seismic surveys. This correlation significantly enhances the reliability of the geological interpretation and indicates that the observed anomalies are tectonically controlled, associated with heterogeneities in the composition and structure of the basement rocks.

One of the most important geological phenomena is the contact zone of the CUSD and the Shakhpakhtinskaya step, revealed in the process of interpreting geophysical data. Here, along the meridional profile, a thrust of decompressed rocks of the Shakhpakhtinskaya step onto the compacted complexes of the CUSD with an angle of 50–70° and an established depth of up to 8–10 km is recorded, which indicates large-scale nappe-thrust processes [22, 23].

The results of the analysis of the transforms of gravity-magnetic fields confirm the presence of deep tectonic activity. Thus, in the area of the Karabaur swell, an area of concentration of Euler points was identified, interpreted as a manifestation of the effect of a "double" crust caused by its submersion under the South Ustyurt region. These findings are consistent with the results of our previous works (2022).

Within the CUSD, localized gravity anomalies with intermediate gradient values are observed, reflecting a combination of different structural types, including both thrust-related and fault-block features. Notably, there is a spatial correlation between the depths of gravity and magnetic anomaly sources, indicating their association with the surface of the crystalline basement. The position of this basement surface was determined based on data from MCDP-2D.

In the area of the Karabaur Ridge, a concentration zone of Euler solutions has been detected, interpreted as evidence of a "double crust" effect resulting from underthrusting beneath the South Ustyurt massif. This interpretation is consistent with the results of our earlier studies [5, 6, 8].

Furthermore, magnetic field transformant analysis within the CUSD revealed two distinct depth intervals of magnetically active bodies: 4,000-6,000 m and 10,000-12,000 m. These reflect vertical structural segmentation associated with thrust and overthrust deformation.

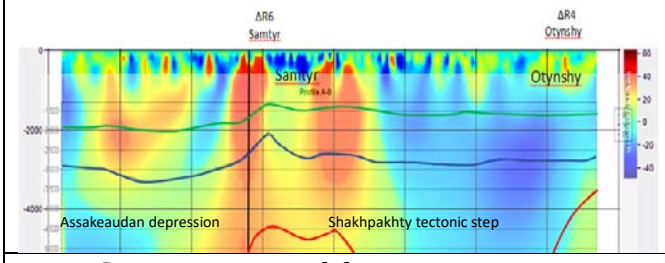
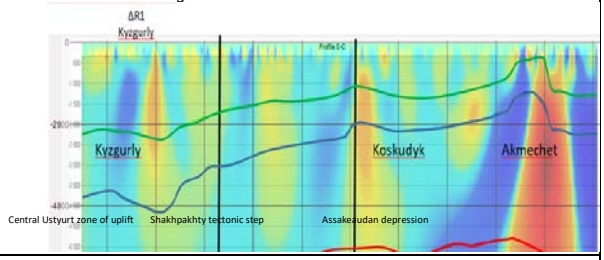
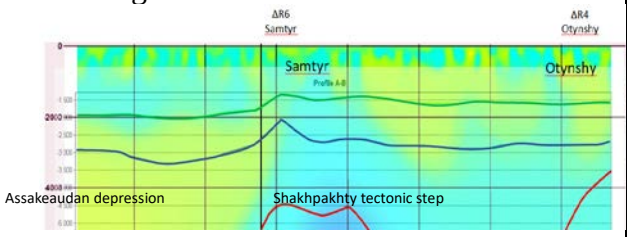
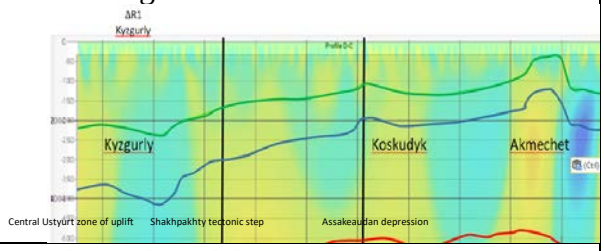
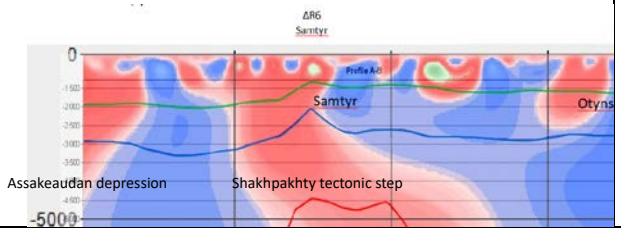
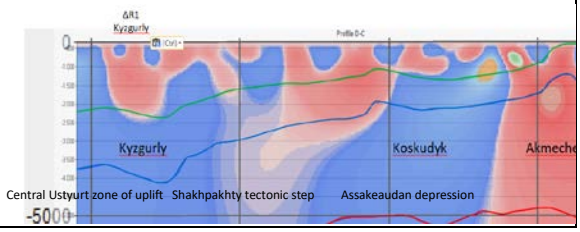
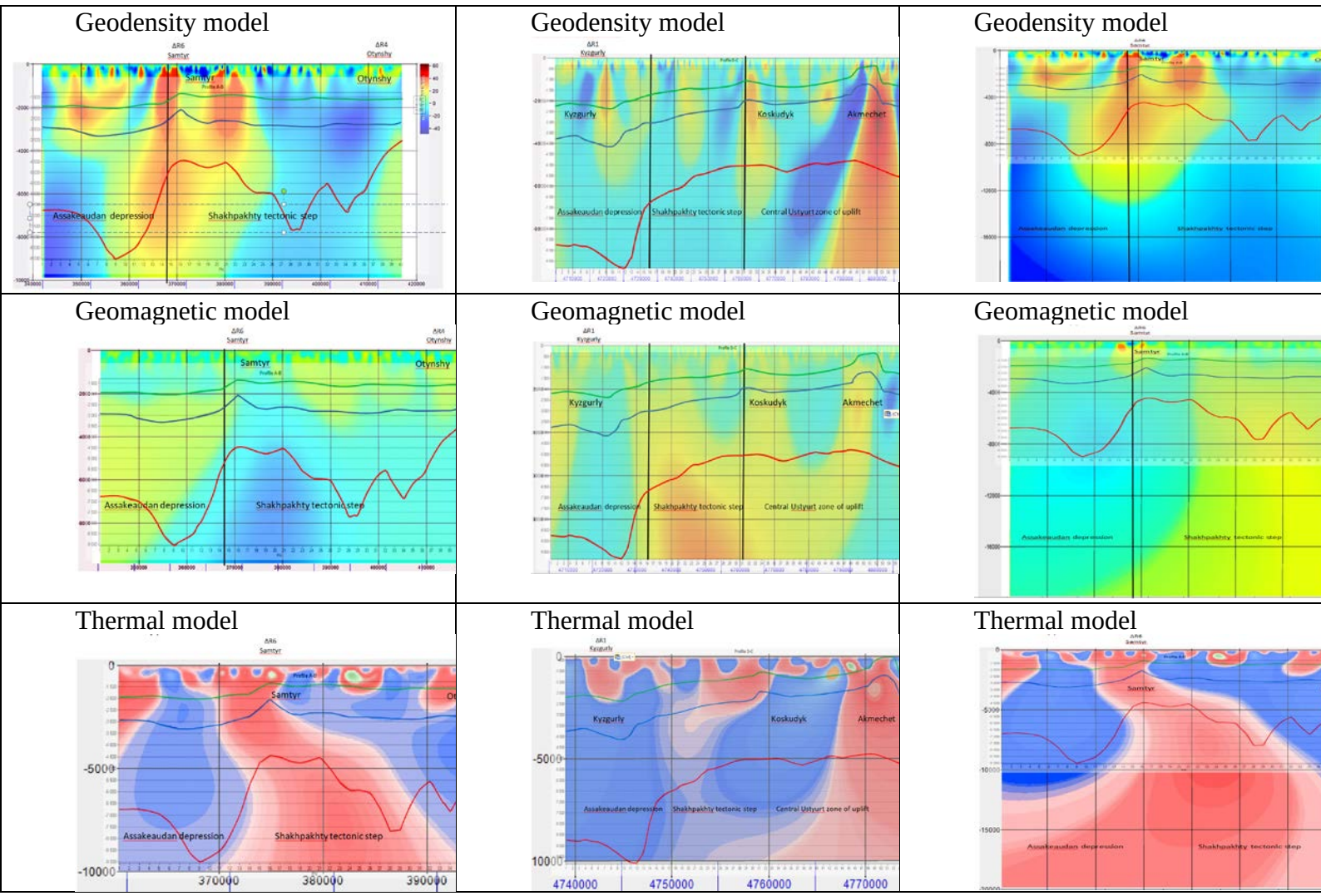
Fig. 10.1. Profile geodensity, geomagnetic and thermal models along A-B combined with the relief of OG up to 5 km	Figure 11.1. Profile geodensity, geomagnetic and thermal models along C-D combined with the OG plot up to 5 km
Geodensity model 	Geodensity model 
Geomagnetic model 	Geomagnetic model 
Thermal model 	Thermal model 

Fig. 10.2. Profile geodensity, geomagnetic and thermal models along A-B combined with the relief of OG up to 10 km	Figure 11.2. Profile geodensity, geomagnetic and thermal models along C-D combined with the OG plot up to 10 km	Fig. 10.3. Profile geodensity, geomagnetic and thermal models along A-B combined with the relief of OG up to 20 km



The spatial correlation between the sources of gravity and magnetic anomalies within the CUSD confirms their association with the crystalline basement top. The spatial coincidence of the depths of gravity and magnetically disturbing bodies in the CUSD confirms their confinement to the basement surface [22, 23].

The integrated interpretation of gravity, magnetic, and seismic data indicates that the Shakhpakhty Step holds high hydrocarbon potential. A key factor contributing to this prospectivity is the substantial cumulative thickness of the sedimentary cover and the intermediate structural tier. These geological conditions favor the development of high-capacity reservoirs and various types of traps, as well as the presence of effective seals with good insulating properties.

Consequently, the combination of critical factors - marked structural differentiation, deep subsidence of tectonic elements, the presence of a thick sedimentary succession, and the correlation of geophysical anomalies with seismic reflectors - justifies classifying the Shakhpakhty Step as a priority target for future hydrocarbon exploration and appraisal activities. The obtained data reveal additional opportunities for exploration and emphasize the necessity of continued investigation to refine the geological structure and improve the prediction of potential hydrocarbon accumulations.

This conclusion is supported by AGSS data, processed and interpreted using the thorium normalization method within the COSCAD software. The results substantiate the rationale for continuing integrated investigations in the Shakhpakhty Step. Similar conclusions were drawn based on the results of high-precision magnetic and radiometric surveys conducted in Western Canada [32].

An integrated interpretation of gravity and magnetic field transformants has significantly enhanced the understanding of the structural framework of the South Ustyurt region, enabling the identification of several local zones with high hydrocarbon potential. The effectiveness of

transformant analysis has been confirmed through the detection of previously unrecognized tectonic features and anomalies associated with potential hydrocarbon traps, thereby increasing the reliability of geophysical interpretation [31, 32].

A key result of the study is the recognition of a systematic deepening of the magnetically active layer within the Shakhpakhty Step, accompanied by reduced magnetization relative to the neighboring Assakeaudan Depression. This contrast highlights the differing geological compositions of these zones and points to favorable conditions for hydrocarbon accumulation within the Shakhpakhty Step.

In addition, the deep burial of the magnetically active layer, coupled with elevated thermal gradients, indicates the presence of deep thermal and fluid migration processes - favorable conditions often associated with hydrocarbon generation. These conclusions are further supported by thorium-normalized airborne gamma spectrometry data and thermogradient analysis.

Overall, the integration of geophysical and radiogeochemical patterns - together with the region's complex stratigraphic architecture, tectonic block segmentation, structural heterogeneity, and lithofacies variability - strongly supports the high hydrocarbon potential of the Shakhpakhty Step. These findings form a solid scientific foundation for the targeted planning of future geological exploration efforts in the South Ustyurt region.

4.4. Applied aspects of regional geophysical field modeling. Along profiles A-B and C-D (Figs. 10–11), constructed based on gravity, magnetic, and thermal data, a comprehensive interpretation of the deep structure of the SUR was carried out using the **GraviMag Modeling Inversion** module of the *IP_Seismic* software package. The obtained results were correlated with outputs from automatic classification and predictive modeling conducted using *IP_Prediction 2D*, which significantly enhanced the reliability of the geophysical interpretation and refined the assessment of hydrocarbon potential across the SUR.

The results confirm the presence of major tectonic elements in the region, including the Assakeaudan Depression, the Shakhpakhty Step, and the Central Ustyurt Structural Domain (CUSD). Within these zones, several local structures—such as Samtyr, Otynshy, Kyzgyrly, Koskudyk, and Akmechet - have been identified, showing the highest contrasts in geophysical anomalies within the upper 5 km of the sedimentary cover and intermediate structural level.

Along the sublatitudinal profile A–B, the Samtyr structure is characterized by prominent positive gravity (+60 mGal) and magnetic (+150 nT) anomalies, reflecting the presence of a high-density, magnetically susceptible block extending to depths exceeding 12 km. The combination of elevated rock densities, well-developed faulting, and increased magnetic susceptibility - affecting both the lower horizons of the sedimentary cover and the intermediate structural level-suggests the presence of compacted lithologies with poor reservoir potential. Consequently, despite the presence of a favorable structural high, the Samtyr high is considered to have low prospectivity for oil and gas exploration.

Along the meridional profile C–D, the local structural highs of Akmechet, Kyzgurlu, and Koskudyk are clearly delineated, along with a well-expressed boundary separating the Shakhpakhty Step from the Central Ustyurt Depression. This boundary is expressed as a regionally significant gravity step and is interpreted as a deep-seated fault zone or a major overthrust (sharyazh) structure.

Within the Shakhpakhty Step, consistently negative magnetic field values - reaching as low as –150 nT from depths of approximately 2.5 km - indicate the presence of lithologies with low magnetic susceptibility. This geophysical signature is characteristic of rock types depleted in ferromagnetic minerals, such as clay-rich, siliceous, and carbonate formations.

The observed magnetic attenuation may also reflect diagenetic or hydrothermal alteration processes, during which primary magnetically active minerals are replaced by non-magnetic phases. These petrophysical characteristics, although indirect, serve as important indicators of potential reservoir development and support a favorable assessment of the Shakhpakhty Step within the regional hydrocarbon prospectivity framework.

The results of thermal modeling indicate the presence of abnormally high geothermal activity at depths of 12–20 km within the Shakhpakhty Step and along the northern margin of the Assakeaudan

Depression. These thermal anomalies may reflect deep-seated heat-generating processes and/or zones of thermal fluid discharge, potentially contributing to the formation of conditions favorable for hydrocarbon generation and migration.

Localized anomalies of elevated heat flow have been identified within the CUSD, likely associated with the reactivation of deep-seated faults, including thrust zones. The spatial correspondence between these thermal anomalies and major tectonic features suggests the operation of heat and mass transfer channels facilitating the upward migration of deep-sourced thermal fluids.

The integration of gravity, magnetic, and geothermal models has revealed a block-type heterogeneity in the Earth's crust of the CUSD, alongside the relative tectonic stability of the Shakhpakhty Step and the Assakeaudan Depression.

Regional gravity and magnetic anomalies clearly define the boundaries of the Shakhpakhty Step, which extends southward into Uzbekistan, where analogous Jurassic formations host the Shakhpakhty and Djel gas fields.

Modeling using the **IP_Prediction 2D** technology has confirmed the prospectivity of several local structures within the Shakhpakhty Step, which are recommended as priority targets for further exploration and appraisal activities.

5. Discussion

5.1. Artificial Intelligence and Machine Learning. A comprehensive evaluation of the hydrocarbon potential of the SUR, based on the integration of drilling data, seismic surveys, gravity and magnetic exploration, airborne gamma spectrometry, and geothermal studies, combined with advanced digital techniques, enabled a refined understanding of the geological structure and the identification of prospective hydrocarbon accumulation zones.

The application of machine learning algorithms, including Kohonen self-organizing maps and neural network-based modules (SOM_Clustering Seis, IP_Prediction, IP Seismic), facilitated the detection of hidden geological patterns and provided spatial differentiation of potentially productive areas [5, 6, 12].

The application of advanced inversion technologies, including the specialized **GraviMag Modeling Inversion** module, played a crucial role in enhancing the integrative interpretation of heterogeneous geoscientific datasets - gravity, magnetic, seismic, and geothermal. These methods significantly improved the correlation between diverse data sources and enabled more accurate modeling of the deep structure of the sedimentary cover, including the reconstruction of the geometry and depth of potential hydrocarbon traps.

The use of neural network operators added further analytical depth by effectively handling high-dimensional, nonlinear relationships between geophysical parameters. This not only improved the reliability of the resulting models but also helped uncover hidden patterns in the distribution of anomalous features [8-10, 13, 14].

Of particular importance was the integrated analysis of inversion results, geothermal anomalies, and radiogeochemical data, which made it possible to localize zones of active fluid mobility. These zones are likely associated with deep-seated tectono-magmatic conduits that may serve as migration pathways for hydrocarbons. Altogether, this approach provides a robust basis for identifying high-potential targets for subsequent exploration and drilling.

The supplementary analysis of thermogeophysical and radiogeochemical anomalies uncovered robust indicators of active fluid migration linked to hydrocarbon transport [19, 35]. The integrated application of these methodologies enabled a precise and well-substantiated forecast of prospective hydrocarbon-bearing zones, thereby establishing a strong scientific framework to guide the optimization and improve the effectiveness of exploration efforts in the SUR.

5.2. Airborne Gamma Spectrometry. An analysis of normalized radioelement fields, conducted using ArcGIS and IP_Seismic (SOM_Clustering), revealed 15 areas with decreased concentrations of potassium (K), uranium (U), and thorium (Th), predominantly localized within the Shakhpakhty Step.

These anomalously low concentrations consistently correlate with zones of deep-seated faulting, likely reflecting the upward migration of deep fluids, including hydrocarbons, which facilitate the removal or redistribution of radionuclides. This interpretation aligns with the findings of previous studies [15, 18], which describe radiogeochemical transformation processes induced by the presence of hydrocarbon-bearing fluids.

Profile-based modeling has confirmed the regular spatial distribution of radioactive elements and the presence of well-expressed negative anomalies over the Shakhpakhty Step, supporting its interpretation as a territory with potential hydrocarbon accumulations. The diagnostic significance of such anomalies is emphasized in previous studies [19].

It is important to note that a significant portion of the identified radiogeochemical anomalies does not coincide with previously mapped local structures based on MCDP-2D data. This discrepancy may indicate the presence of non-structural hydrocarbon traps (such as lithological, stratigraphic, or fault-sealed types), or suggest that geochemical criteria were insufficiently considered during the planning of exploration wells.

Based on the above, the following scientific and practical conclusions can be drawn:

- The AGS (Airborne Gamma Spectrometry) method, particularly when normalized to thorium, has demonstrated high effectiveness in direct hydrocarbon prospecting, as corroborated by several regional studies [16, 20].
- Areas exhibiting reduced concentrations of K, U, and Th should be considered priority targets for further geological exploration.
- The spatial correlation between deep fault zones and radiogeochemical minima highlights their potential role in hydrocarbon migration pathways.
- Integrating radiogeochemical data provides a valuable tool for refining seismic survey models and optimizing the placement of exploration wells.
- The results obtained offer a reliable foundation for improving the design of seismic acquisition programs and for revising exploration drilling plans, incorporating both radiogeochemical and structural information in a comprehensive manner.

5.3. Geothermal Surveys. Geothermal study carried out in the SUR led to the development of thermal flux distribution models, the identification of geothermal anomalies, and the establishment of their correlation with major tectonic structures and the lithological composition of the subsurface. The analysis demonstrated that each principal structural element of the region is characterized by a distinct geothermal signature.

In particular, the Assakeaudan Depression exhibits consistently low heat flow values down to depths of 5 km, which is attributed to a thick sedimentary cover composed predominantly of low-thermal-conductivity, hydrocarbon-generating source rocks. Similar patterns have been previously documented in deep marine basins with organic-rich sediments [34, 38].

Conversely, the Shakhpakhty Step is marked by stable positive geothermal anomalies at depths of 1.5–2.5 km. These are associated with elevated thermophysical properties of the host rocks and an extensively developed system of disjunctive faults, which likely enhance vertical fluid migration. Such anomalies are considered potential indicators of hydrocarbon accumulation zones [42, 43], particularly within stepped uplifts and active fault networks.

A localized heat flow minimum observed in the area of the Shakhpakhty field **(Uzbekistan)**, combined with positive anomalies in the upper stratigraphic section, is of particular interest. This pattern likely reflects the presence of dense, low-permeability cap rocks that inhibit vertical heat transfer and help preserve hydrocarbon accumulations [36].

On the southeastern flank of the associated fault zones, the Shakhpakhty and Djel fields **(Uzbekistan)** have already been discovered. Meanwhile, the western flank hosts several promising structures - such as Otynshy, Kozhantay, and Utezhan **(Kazakhstan)** - which are recommended as priority targets for exploration, provided the presence of effective sealing formations is confirmed.

The integration of geothermal indicators with gravity-magnetic and seismic data significantly enhances regional hydrocarbon prospectivity assessments. This conclusion is strongly supported by the present study and corroborated by international research findings [33, 39].

5.4. Gravity and Magnetic Surveying. The application of gravity and magnetic field transformants - including horizontal and vertical gradients, TDR-type derivatives, ΔTa, and automated anomaly axis tracing - significantly enhanced the interpretive capacity of geophysical data for the SUR. This approach greatly improved the understanding of the geological framework and increased the efficiency of exploration targeting.

The use of these methods enabled the identification of previously undetected structural features, localized density and magnetic anomalies, and hydrocarbon-prospective zones, thereby confirming the high diagnostic value of such techniques. Notably, this methodology proved particularly effective for interpreting fault and fracture zones that control fluid migration and accumulation.

The results are consistent with international studies [26, 27], where transformant-based analysis is recognized as a sensitive and reliable tool for structural interpretation in petroleum geophysics.

Distinct geophysical signatures differentiate the CUSD, the Shakhpakhty Step, and the Assakeaudan Depression.

The Shakhpakhty Step is characterized by low remanent magnetization, alternating gravity anomalies of contrasting polarity, and the presence of a deep-seated magnetically active layer at depths reaching up to 12 km, accompanied by an elevated geothermal gradient. These features indicate favorable conditions for hydrocarbon accumulation both within the sedimentary cover and in underlying structural levels - comparable to inverted basin settings observed in regions with active tectonic inversion regimes [30].

In the Assakeaudan Depression, magnetically active bodies are found at depths of 8–10 km, which correlate with the crystalline basement top. Their geophysical expression suggests an association with ultramafic intrusions, indicating the possible presence of diapiric structures similar to those identified in the Precaspian Basin [45].

The contact zones between Upper Jurassic and Lower Cretaceous formations exhibit a high density of Euler solution clusters, reflecting well-expressed lithological contrasts and likely indicating the presence of concealed fault systems. These structures may have influenced sedimentation patterns and played a key role in the development of stratigraphic and structural hydrocarbon traps.

In the CUSD, deep-seated gravity and magnetic anomalies correlate closely with the basement surface delineated by MCDP-2D seismic data, thereby confirming the tectonic origin of the detected geophysical heterogeneities [30].

A notable anomaly identified over the Karabaur Ridge is interpreted as a manifestation of a "double crust" phenomenon, likely caused by the overthrusting of the South Ustyurt block onto the deformed complexes of the CUSD [30]. Magnetic data reveal the presence of two distinct magnetically active horizons at depths of 4-6 km and 10–12 km, which are interpreted as expressions of thrust-and-fold tectonics - analogous to structures previously described in the Turkestan orogenic belt [44].

These results demonstrate the diagnostic value of potential field transforms in resolving deep geological architecture and delineating prospective hydrocarbon-bearing structures that may remain undetected using conventional interpretation methods. The observed correlations among deep density heterogeneities, magnetically active bodies, fault zones, and potential hydrocarbon traps emphasize the applied relevance of this approach.

Taken together, the findings substantiate the need to systematically integrate transform-based potential field analysis into three-dimensional geological modeling and exploration planning, particularly in geologically complex and underexplored regions such as South Ustyurt.

5.5. Integration of Geophysical Methods. A comprehensive interpretation of gravity and magnetic field transformants has considerably refined the tectonic framework of the South Ustyurt Region (SUR) and allowed the identification of new areas with significant hydrocarbon prospectivity. The use of horizontal gradients, second-order derivatives, and Euler solutions has enabled detailed delineation of concealed fault-block structures and lateral boundaries of tectono-stratigraphic complexes.

The integration of gravity and magnetic data with airborne gamma-ray spectrometry and geothermal modeling has revealed strong and consistent spatial correlations among geophysical

parameters that capture both physical properties and tectono-thermal characteristics of the subsurface. These correlations underscore the high diagnostic value of the integrated dataset for elucidating the structural architecture of the South Ustyurt Region and affirm its critical role in developing geologically sound predictive models of hydrocarbon prospectivity.

Radiogeochemical anomalies - particularly the depletion of potassium and uranium - demonstrate spatial association with potential hydrocarbon traps, indicating their utility as supplementary indicators in petroleum system analysis. The combined use of these data through advanced machine learning algorithms (e.g., Self-Organizing Maps, SOM) and conventional geophysical techniques (gravity, magnetometry, seismic surveying) provides a scientifically robust platform for constructing high-resolution predictive models and prioritizing exploration targets at early stages of geological prospecting. Stable spatial connections between anomalies of geophysical fields and tectonic elements of various orders have been established, which made it possible to substantiate the high oil and gas potential of the Shakhpakhtinsky stage and, to a lesser extent, the Assakeaudan Depression.

The integrated interpretation of geophysical, geothermal, and radiogeochemical datasets - employing multiparametric analysis and advanced data processing techniques, including state-of-the-art machine learning algorithms - has substantially improved the accuracy and reliability of predicting potential hydrocarbon accumulation zones within the South Ustyurt Region.

This comprehensive approach has yielded a significantly refined understanding of the region's geological architecture, including the reconstruction of deep crustal structures, delineation of concealed fault-block systems, and characterization of geophysical heterogeneity across major geostructural domains.

A key outcome of the study was the identification of consistent spatial correlations between gravimagnetic, geothermal, and radiogeochemical anomalies and tectonic features of varying hierarchical levels. These correlations underpin a set of robust predictive criteria for hydrocarbon prospectivity and have enabled the delineation of the most favorable structural settings for trap formation. The Shakhpakhty Step stands out as the most prospective zone, exhibiting clear structural segmentation and strong evidence of deep fault control on hydrocarbon entrapment. The Assakeaudan Depression also demonstrates moderate exploration potential.

Conversely, the **CUSD** is characterized by well-expressed tectonic and geophysical heterogeneity, suggesting limited favorability for the development of significant hydrocarbon accumulations.

These findings form the basis for a scientifically grounded revision of the regional geological model and support the design of a strategically targeted exploration framework. This approach not only enhances the overall efficiency of exploration programs but also reduces geological uncertainty and economic risk at the early stages of hydrocarbon resource development.

The most promising targets for further investigation within the SUR are the Shakhpakhty Step and, to a lesser extent, the Assakeaudan Depression. These structural domains exhibit well-expressed radioactive heterogeneity, contrasting anomalies in gravity, magnetic, and geothermal fields, as well as indications of active deep fluid dynamics. The convergence of these geophysical and geochemical features is interpreted as a reliable indicator of enhanced hydrocarbon saturation.

Notably, the Shakhpakhty Step is distinctly manifested across gravity, magnetic, and thermal data, with localized geothermal anomalies interpreted as zones of deep fluid discharge. These zones are believed to promote the formation of hydrocarbon traps within the sedimentary succession. The southern continuation of the step into the territory of Uzbekistan shows spatial correlation with major Jurassic gas fields - Shakhpakhty and Dzhel **(Uzbekistan)** - underscoring the regional extent of the petroleum system and its strong structural control.

The integration of gravimagnetic modeling with thorium-normalized airborne gamma-ray spectrometry has facilitated the identification of several local structures with high exploration potential, including Utezhan, Kozhantay, North Kozhantay, and Otynshy **(Kazakhstan)**.

The exploration significance of these targets is further substantiated by a combination of geological criteria, including favorable lithofacies distributions and structurally controlled settings,

both of which increase the likelihood of hydrocarbon trap formation. Consequently, these structures are justifiably regarded as priority targets for the next phase of exploration, aimed at identifying and evaluating new hydrocarbon accumulation zones.

5.6. Gravimagnetic modeling and geostructural features of the South Ustyurt Region: Hydrocarbon potential assessment using the SIGMA DVOP software platform. To ensure the reliability of the interpretation and validate the outcomes, a comparative analysis was performed using our own data alongside geophysical models constructed in the **SIGMA DVOP** software platform. This system is based on the method of interpretational tomography and was applied in earlier studies of the SUR, including work conducted by P.N. Kovrizhny, who utilized this approach for deep structural modeling.

The analysis relied on an integrated dataset that included gravity and magnetic survey data, as well as seismic information from CDP and CMRW methods. For additional verification, these data were cross-referenced with borehole results, AGSS and geothermal measurements.

The resulting geodensity and geomagnetic models provided a more detailed representation of both vertical and lateral heterogeneities within the sedimentary cover and crystalline basement. These models enabled spatial interpretation of anomalies associated with major structural elements and potential hydrocarbon traps. A consistent increase in sediment density with depth was observed, reaching values of approximately 2.60 g/cm³ near the basement surface - reflecting progressive compaction and porosity reduction in the deepening sedimentary succession.

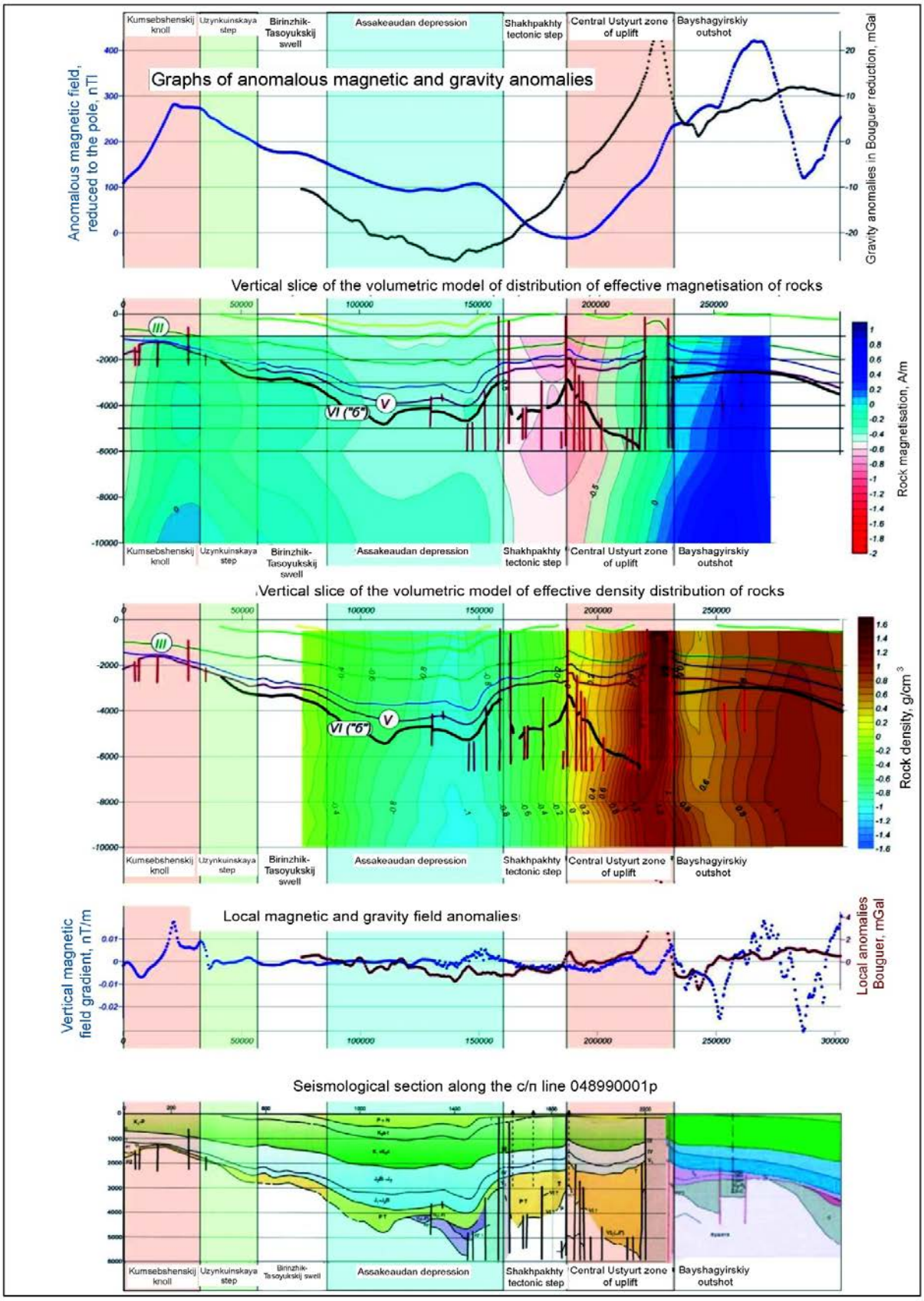
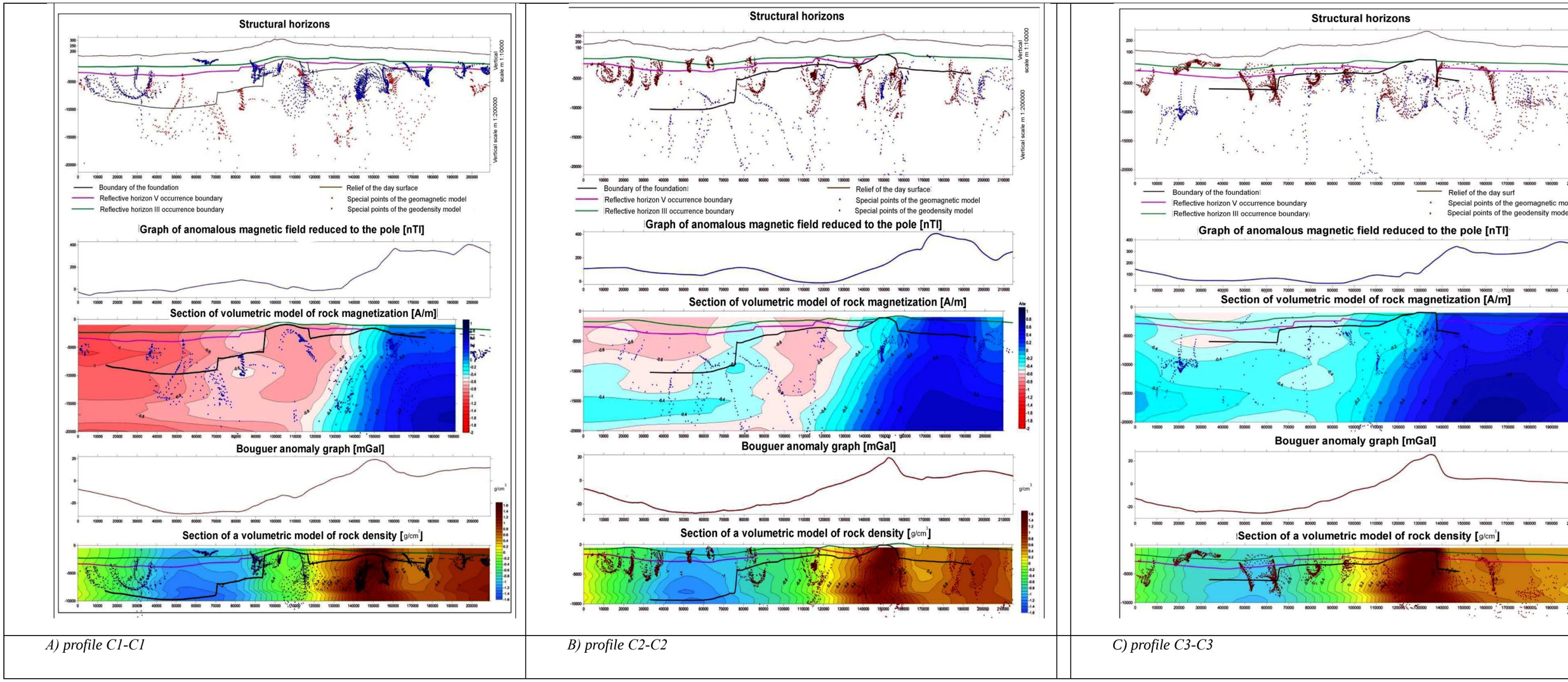


Fig. 12. Vertical section of volumetric models of density and magnetic induction along seismic profile line 048990001 (according to data from Kovriznyh P.N.)



A) profile C1-C1 | *B) profile C2-C2* | *C) profile C3-C3*

Fig. 13. Display of geomagnetic and geodensity volume models in structural constructions along arbitrarily selected lines through the Samtyr area. SIGMA DVOP constructions (based on data from Kovriznyh P.N.)

Gravimagnetic modeling of the CUSD, the Shakhpakhty Step, and the Assakeaudan Depression revealed that the depth to the crystalline basement ranges between 7 and 10 km - significantly deeper than previous estimates of 5–6 km. This finding highlights a more well-expressed and complex gravitational expression of the basement and emphasizes its active geodynamic role in shaping the regional structural framework and influencing the localization of hydrocarbon accumulation zones.

The comparison of gravity (ΔGa) and magnetic (ΔTa) anomalies with seismic profile 048990001 revealed a stable spatial correlation between gravimagnetic expressions and the deep geological structure of the South Ustyurt Region. Elevated ΔGa values are observed over the Karabaur Uplift and the Baishagyr High, which are confirmed by seismic data and reflect the presence of dense crystalline basement rocks.

In the Assakeaudan Depression - the deepest part of the region - well-expressed ΔGa minima and reduced ΔTa values are recorded, indicating decreased rock density and significant basement depth (Figs. 12, 13).

Magnetic anomalies (ΔTa) show consistent correlation with tectonic boundaries and local structural features. The Baishagyr High and the Samtyr structure are characterized by elevated magnetic activity, likely associated with intrusive bodies or volcanic-sedimentary sequences. In contrast, the Shakhpakhty Step exhibits negative ΔTa anomalies (down to –150 nT), which may be attributed to lithological variations or zones of deep fluid discharge (Figs. 12, 13).

These observed patterns confirm the diagnostic value of gravimagnetic data in refining tectonic models and in predicting potential hydrocarbon accumulation zones.

Correlation analysis has identified nonlinear relationships between ΔGa, ΔTa, and the depth to the crystalline basement, as derived from MOGT-2D seismic survey data. These patterns are attributed to the block-faulted structure and petrological heterogeneity of the SUR. Deviations from expected statistical correlations are explained by both the inherent variability of the geological model and uncertainties in seismic data interpretation.

Further evidence supporting the hydrocarbon potential of the SUR was obtained through the correlation of ΔGa with the depth of Jurassic sediments along the top of Seismic Horizon III, revealing a consistent functional relationship (Figures 11 and 12). The development of thick quasi-platform sedimentary sequences within the Shakhpakhty Step and the Assakeaudan Depression suggests favorable geological conditions for the formation of traps and hydrocarbon accumulation.

A comprehensive geophysical analysis of the SUR, conducted using the SIGMA DVOP software suite and integrating gravity, magnetic, seismic, and well data, allowed for a more precise delineation of the morphology and spatial configuration of the crystalline basement. Additionally, several local structures with indicators of hydrocarbon potential were identified.

Particular attention is paid to the Shakhpakhtinsky step and the Assakeaudan Depression, where stable statistical relationships between gravity field anomalies and basement morphology have been established. These patterns formed the basis for geological and geophysical criteria for predicting zones of possible hydrocarbon accumulation.

The results of the study indicate strong potential for further exploration and appraisal activities, particularly in areas of localized positive gravity anomalies associated with zones of tectonic activation. While thick sedimentary cover typically corresponds to regional gravity lows due to lower rock densities, its combination with active tectonics may contribute to the formation of structural traps and favorable conditions for hydrocarbon accumulation. The identified zones exhibit stable geophysical indicators supporting their hydrocarbon prospectivity.

A comparative analysis of interpretational tomography data from SIGMA DVOP and classification-based modeling using the IP_Prediction 2D module revealed consistent geophysical and structural correlations, confirming the reliability of an integrated approach to hydrocarbon prospectivity assessment.

One of the key findings is the characterization of the deep block structure: tomographic modeling clearly delineates the block segmentation of the crystalline basement at depths of 7–10 km. The predictive model in IP_Prediction 2D identifies similar structural boundaries and further refines the interpretation by outlining sub-parallel horizons with high hydrocarbon accumulation potential.

Several key areas with contrasting prospectivity were identified:

1. Deep block structure: Tomography records the block discreteness of the basement at depths of 7–10 km. The IP_Prediction 2D prognostic model identifies similar structural boundaries, additionally specifying subparallel horizons with high hydrocarbon accumulation potential.

2. Prospective structures (Karabaur, Bayshagyr, Kyzgurlu): SIGMA DVOP tomography revealed positive gravimagnetic anomalies in the Karabaur, Bayshagyr, and Kyzgurlu areas, which are interpreted as potential targets for further explorationIn addition, the IP_Prediction 2D model highlights other targets, including local structures within the Shakhpakhty Step such as Otynchi, Utezhan, and others.

3. ***Low-prospectivity zone (Samtyr):*** Tomographic analysis using SIGMA DVOP reveals several unfavorable geological features in the Samtyr area, including an ineffective seal, well-expressed tectonic disruption, and thermal instability. These findings are consistent with the results of the IP_Prediction 2D model, which classifies the zone as having low hydrocarbon prospectivity.

4. High-Prospectivity zone - Shakhpakhty step: **This area is confidently identified by both approaches as one of the key hydrocarbon-prospective regions. It is characterized by stable gravimagnetic and thermal anomalies, as well as the development of Jurassic sedimentary complexes. The IP_Prediction 2D model classifies it as a territory with a high probability of hydrocarbon accumulation.**

5. Assakeaudan depression: Interpreted as a deep subsiding zone with well-expressed density and thermal contrasts, suggesting favorable conditions for the development of source rocks and trap formation in the upper parts of the sedimentary section (particularly in flank zones). These findings align closely with the IP_Prediction 2D model, which also highlights the hydrocarbon potential of this depression.

An integrated analysis of radiogeochemical, gravimetric, magnetic, geothermal, and seismic data, combined with advanced artificial intelligence and machine learning techniques, has significantly improved the geological understanding of the SUR and enabled the identification of priority targets for further exploration and appraisal activities.

The key outcomes of the study include:

- Detailed mapping of the crystalline basement morphology and the delineation of its deep block structure;
- Identification of zones with elevated hydrocarbon potential, primarily within the Shakpakhty Step and, to a lesser extent, along the northern margin of the Assakeaudan Depression;
- Development of geophysical and geochemical criteria for hydrocarbon trap prediction, based on the spatial integration of density, magnetic susceptibility, heat flow, and radiogeochemical anomalies;
- Validation of machine learning-based modeling results (IP_Prediction 2D), supported by geological interpretation and deep geophysical verification.

Overall, the results point to a high hydrocarbon prospectivity of the SUR, particularly in areas characterized by the intersection of deep faults, positive gravimagnetic anomalies, thick sedimentary sequences, well-developed reservoirs, and effective clay seals forming promising hydrocarbon traps.

5.7. Reliability and Verifiability of the Research Results. The reliability of the research findings is ensured through the deep integration of artificial intelligence (AI), machine learning (ML) techniques, and comprehensive interpretation of geological and geophysical data. This approach significantly enhances the objectivity of interpretations, minimizes human bias, and enables the identification of hidden patterns within complex, high-dimensional, and heterogeneous datasets.

According to studies [9, 10], the synergy between physically based geological models and adaptive machine learning algorithms results in markedly higher accuracy in predicting geological structures and fluid-bearing zones compared to conventional analytical methods.

Particularly effective has been the integration of diverse geodata types - seismic, gravity and magnetic, geothermal, and geochemical - using advanced algorithms such as self-organizing maps (SOM), artificial neural networks, principal component analysis (PCA), stochastic inversion

modeling, and deep learning. Publications [11, 13] provide compelling examples of the successful application of these approaches for constructing reliable geological models, identifying anomalous fluid accumulations, and increasing the efficiency of exploration programs.

Thus, the credibility of the dissertation's conclusions is determined not only by the comprehensiveness and representativeness of the geological data employed, but also by the application of modern analytical tools that enable their rigorous integration and interpretation. This aligns with global standards of reproducibility and the principles of data-driven science in geosciences [12].

5.8. Hydrocarbon Systems of South Mangyshlak and the South Ustyurt Regions: Geological framework and generative potential

South Mangyshlak region. A major outcome of our study was the refinement of the regional geological model for the Jurassic and Triassic petroleum systems of the Southern Mangyshlak Petroleum Province and the South Ustyurt Region. Central to this model is the stratigraphic positioning of the principal petroleum source rock formations (PSRFs), which plays a critical role in determining the generative potential of the basin.

The most favorable conditions for organic matter accumulation and sediment deposition were associated with the Mangyshlak and Karaaudan grabens and their flanking structural zones. Geological data indicate the presence of deep, anoxic palaeodepressions with restricted water circulation, which promoted the preservation of organic-rich sediments and the development of effective source rock facies.

Stratigraphic analysis, lithofacies reconstruction, and analog-based geological modeling indicate that the main PSRFs Petroleum Source Rock Formations in Southern Mangyshlak are confined to the basal facies of the Upper Olenekian to Middle Triassic carbonate–terrigenous complex. Of particular significance is the Karadzhatyk Formation, which displays high organic content and laterally persistent facies characteristics [46, 47].

This formation is composed of interbedded dark shales, carbonates (limestones and dolomites), and tuffs. Its thickness reaches up to 750 meters in the southern part of the Zhetybai Step and tapers to 250–300 meters in the Peschanymys Uplift [46], reflecting a structurally and sedimentologically heterogeneous depositional environment.

The stratigraphic position, composition, and lateral extent of the Karadzhatyk Formation support its role as a key generative unit within the regional petroleum system.

The black bituminous shales of the Karadzhatyk Formation are distinguished by a high content of dispersed organic matter, reaching up to 9.8% [47], and a predominance of Type II kerogen. These characteristics point to a strong generative potential, particularly for liquid hydrocarbons [48].

By contrast, the source rock formations of Lower Induan (T_1) and Upper Triassic (T_3) age exhibit significantly lower organic richness and thus a much more limited capacity for hydrocarbon generation [50, 51].

In the central part of the Mangyshlak palaeorift, the organic matter contained in the Middle Triassic strata has undergone advanced catagenesis, accompanied by structural deformation and partial denudation of the host sediments as a result of pre-Jurassic erosion. Despite these processes, petroleum source rocks have been preserved in the southern part of the Zhetybai Step and within the Karaaudan Rift [50].

It is noteworthy that during the Triassic period, the Karaaudan Rift likely represented a shallow marine platform with limited organic productivity and suboxic to anoxic conditions, which constrained the development of high-quality source rocks and reduced the overall generative potential of this zone.

An alternative model suggests that Middle Triassic petroleum source rock formations are extensively developed across the region, ranging from the Zhetybai Step to the Southern Mangyshlak depressions. However, hydrocarbon generation and subsequent migration into Jurassic reservoirs may have been significantly impeded by the presence of Upper Triassic seal rocks and the isolating properties of disjunctive fault systems, which acted as effective barriers to vertical migration.

In contrast, Lower and Middle Jurassic source rocks are generally considered to exhibit low generative potential. These intervals are dominated by Type III kerogen, and the total organic carbon (TOC) content in the shales ranges from 0.5% to 1%, with maximum values reaching 1.5% in the central part of the Segenydek Depression [52]. Despite these modest values, these formations may have contributed limited volumes of dry gas, which later mixed with liquid hydrocarbons migrating from older, Paleozoic source intervals.

Based on lithostratigraphic and tectonic similarities, a structural and genetic correlation has been proposed among the Jazgurlin, South Mangyshlak, and Assakeaudan depressions. These basins are thought to host petroleum source rocks that served as hydrocarbon contributors not only to the Uzen and Zhetybai fields **in Kazakhstan**, but also to the Shakhpakhty and Dzhel fields **in Uzbekistan.**

This interpretation is further supported by biostratigraphic subdivision of Jurassic deposits conducted in accordance with the International Stratigraphic Guide [54, 55], which allowed for the identification of potentially productive horizons and refinement of the regional assessment of hydrocarbon prospectivity

South Ustyurt Region. An integrated interpretation of stratigraphic, lithofacies, and tectonic data for the SUR has enabled the reconstruction of the principal elements of its petroleum systems.

Source rocks are primarily associated with Middle Triassic (T_2) deposits, with potential analogs inferred in the Lower and Middle Jurassic successions. Reservoir units have been identified within the Upper Paleozoic (PZ_3), Middle Triassic, Jurassic, and, locally, Cretaceous formations. Seals are predominantly composed of clay-rich Upper Triassic and Upper Jurassic sediments, which provide effective caprock integrity and trap preservation [47, 49, 52].

Hydrocarbon traps developed in multiple tectono-sedimentary phases, notably during the Late Triassic (T_3), Late Jurassic (J_3), and later during the Late Cretaceous and Pliocene (N_2) periods.

Hydrocarbon generation and accumulation occurred in discrete stages: the principal phase of generation is attributed to the Late Cretaceous–Paleogene interval, while major hydrocarbon accumulation likely took place during the Neogene. The preservation of hydrocarbon accumulations is supported by the presence of all critical elements of a working petroleum system - including mature source rocks, effective reservoirs, competent seals, structurally and stratigraphically defined traps, and viable migration pathways [46, 48].

From a regional perspective, sediments of the intermediate structural level are extensively developed throughout the area, with the notable exception of Triassic formations, which are predominantly confined to the Assakeaudan Depression. Lower Jurassic sequences are primarily associated with tectonic depressions, while Middle and Upper Jurassic, as well as Cretaceous strata, exhibit widespread stratigraphic and structural distribution across the region. The absence of Paleogene–Neogene formations on uplifted blocks is indicative of well-expressed tectonic reactivation during the Late Cenozoic [52].

The presence of a complete and geologically coherent set of essential petroleum system elements - including mature source rocks, high-capacity reservoir intervals, regionally effective seals, structurally and lithologically diverse traps, and well-established hydrocarbon migration conduits - provides compelling evidence for the existence of fully developed, operational petroleum systems. This integrated geodynamic and petroleum-geological framework substantiates the region's high oil and gas potential and provides a robust scientific rationale for prioritizing and intensifying prospecting and appraisal-stage exploration efforts.

Geological analogues. In the southeastern sector of the South Ustyurt Region (SUR), within the territory of ***Uzbekistan***, the Shakhpakhty Step and the Assakeaudan Depression continue their structural development, while the Koplankyr Step is distinctly delineated. Between 2006 and 2014, PJSC «Gazprom» carried out a substantial program of geophysical surveys, exploration and appraisal drilling, and thematic geological studies in this area, which led to a significant revision of the region's assessed hydrocarbon potential [4].

Within the Shakhpakhty Step, two gas fields have been discovered - Shakhpakhty (1964) and Djel (2009) - both associated with Lower, Middle, and Upper Jurassic formations. The accumulations

are confined to anticlinal traps at depths ranging from 1,700 to 2,400 meters, hosted in sandstones and siltstones with porosity values of 16–20% and permeability ranging from 0.109 to 0.312 μm². The Shakhpakhty gas field is classified as medium-sized [1], while Djel is categorized as a small gas field.

The portfolio of undrilled structures within the Uzbek sector of the Shakhpakhty Step includes seven identified prospects, among which the North Karaaudan and Ergazy structures are of particular note; the latter has already been prepared for exploratory drilling. Jurassic strata remain the principal focus of exploration, while Paleozoic formations and non-anticlinal trap types are also considered promising targets, though they require further geophysical delineation and evaluation [4].

In the southern sector of the Shakhpakhty Step and the Assakeaudan Depression, a series of local uplifts have been identified within the Permian–Triassic stratigraphic complex, including Kumoy I, Kumoy II, Ergazy Prirazlomnaya, Nikolaevskaya, and Assake-Audan. These structural uplifts, complicated by faulting, form anticlinal and drape-type hydrocarbon traps. Reservoir quality within these features is largely determined by the development of secondary porosity in Paleozoic formations, associated with processes of chemical and mechanical weathering. Effective regional seals are provided by dense, low-permeability rocks of the lower Permian-Triassic sequence.

Hydrocarbon entrapment in the Upper Paleozoic complex is controlled by the internal architecture of reservoir units, the presence of structural and lithofacies traps, the development of effective secondary reservoirs, and the integrity of overlying sealing formations. Among the most prospective targets for further exploration are the local structures of Karaaudan, Chuymak, Ergazy, Shakhty, Tamarly, and Zhaptyr.

Seismic interpretation suggests the possible presence of biohermal buildups within the Paleozoic section, which enhances the exploration potential of areas such as Kumoy II and Zhaptyr by indicating the likelihood of stratigraphically and lithologically controlled unconventional traps.

Recommendations for Exploration and Appraisal in the South Ustyurt Region. The South Ustyurt Region (SUR) contains several priority targets for hydrocarbon exploration, including the Utezhan, Kozhantay, North Kozhantay, and Otynshy structures within the Shakhpakhty Step, as well as the Kyzgyrly and South Kyzgyrly structures located in the Assake-Audan Depression. According to estimates by the Geoken Research Center [15], the combined prospective gas resources for these structures are approximately **96.9 billion cubic meters,** underscoring the region's significant resource potential.

Hydrocarbon generation in the area is thought to be primarily associated with Triassic source rocks, which may have produced hydrocarbons that subsequently migrated into traps formed within Jurassic and Paleozoic reservoirs. Despite encouraging geological settings, some previously drilled structures have not yielded commercial discoveries, highlighting the need for further investigation into source rock presence, maturity, and migration dynamics.

In this context, additional integrated geological studies are recommended, with a particular emphasis on basin modeling to better assess the petroleum systems. These studies should aim to:

- characterize the thickness, composition, and thermal maturity of potential source rock intervals in the Triassic, Jurassic, and Paleozoic strata;
- reconstruct hydrocarbon generation and migration pathways;
- identify the geological and structural factors that may explain the absence of accumulations in previously tested prospects.

The application of advanced basin modeling techniques, supported by integrated geological, geophysical, and geochemical data, will enhance the reliability of subsurface interpretations. A data-driven, multidisciplinary approach will be critical to improving the predictive accuracy of reservoir presence and quality, thereby increasing the efficiency and success rate of future exploration and appraisal activities across the South Ustyurt Region.

Based on the results of integrated geological and geophysical analysis, it is recommended to drill an exploratory well on the Kyzgyrly structure to test for potential gas accumulations within the Jurassic –Triassic interval. The planned total depth of the well is approximately 4,320 meters. The estimated geological resources are 42 billion cubic meters, distributed across nine prospective

reservoir horizons -eight within the Jurassic and one within the Triassic - with a projected probability of geological success of 22.6% [15].

In addition to Kyzgyrly, several other local structures have been identified as promising targets for further exploration, including West Kozhantay, Otynshy, South Samtyr, West Samtyr, South Tabyn, and South Kyzgyrly. Among these, Otynshy (estimated at 6.5 bcm) and Tabyn (5.7 bcm) are considered high-priority targets, with potential hydrocarbon accumulations expected in Middle Jurassic reservoirs.

To improve the efficiency and accuracy of drilling and subsurface evaluation, the implementation of advanced drilling and data acquisition technologies, as outlined in [56, 57], is recommended.

The structural geometry has been defined based on a sparse grid of CDP-2D seismic profiles (with line spacing exceeding 3 km), which necessitates refinement of trap parameters.

This limited resolution introduces uncertainty in the delineation of trap morphology and closure. Therefore, to enhance the reliability of structural interpretation and reduce exploration risk, additional high-density 3D seismic acquisition (CDP-3D) is strongly recommended.

At this stage, proposed well locations are preliminary and should be refined and validated based on the results of detailed geophysical surveys and updated seismic interpretation.

Conclusion

1. An integrated approach to regional hydrocarbon prospectivity assessment in the South Ustyurt Region (SUR) has been developed and successfully tested. This methodology is based on the comprehensive interpretation of drilling data, MOZT seismic surveys, gravimetry, magnetometry, airborne gamma spectrometry, and geothermal data.

2. The approach incorporates advanced digital technologies using specialized software platforms such as IP Seismic, ArcGIS, and others, alongside machine learning algorithms, including self-organizing maps (SOM clustering). This has enabled the identification of robust correlations between geophysical anomalies, tectonic structures, and potential hydrocarbon traps.

3. The analysis has revealed a stable correlation between geophysical anomalies, deep-seated faults, and zones of reduced natural radioactivity, which can be used as reliable indicators for early-stage hydrocarbon prediction.

4. The use of self-organizing maps (SOM) in combination with geospatial analysis has proven highly effective in detecting hidden patterns and improving the accuracy and automation of subsurface interpretation.

5. Key structural features influencing hydrocarbon prospectivity include: thrust and overthrust zones, subvertical basement faults, and thermal and radiogeochemical anomalies. These elements define a complex but promising tectonic framework in the South Ustyurt Region, providing a solid basis for targeted drilling, risk reduction, and exploration optimization.

6. Geophysical modeling has identified density, magnetic, and geothermal heterogeneities at depths of 5, 10, and 20 km, spatially aligned with mapped hydrocarbon traps. Additionally, airborne gamma spectrometry has detected 15 anomalous zones with low thorium, potassium, and uranium concentrations - primarily associated with the Shakhpakhty Tectonic Step, confirming its high exploration potential.

7. Integrated analysis of seismic and radiogeochemical data has revealed a stable spatial correlation between radioactive anomalies and deep-seated tectonic faults, supporting their use as reliable indicators in early-stage hydrocarbon exploration.

8. The most prospective structures include the Shakhpakhty Step and, to a lesser extent, the Assake-Audan Depression, where a deeply buried magnetically active layer has been identified. This is interpreted as a favorable geodynamic condition for the formation of petroleum systems within the sedimentary cover.

9. In the Shakhpakhty Step, localized thermal anomalies - associated with deep faults and potential traps - have been detected through geothermal surveys. These are interpreted as signs of vertical fluid migration, suggesting the presence of hydrocarbon accumulations. A geothermal-based

criterion for hydrocarbon prediction has been developed, improving the accuracy of prospect assessment at early exploration stages.

10. Additionally, the junction zone between the CUSD and the Shakhpakhty Step exhibits confirmed thrust-and-overthrust tectonics, with fault planes dipping at 50–70°. This is supported bythe presence of paired magnetically active bodies, and a high concentration of Euler solution points, indicating structural complexity. Together these features define a tectonically active and promising setting for trap formation and hydrocarbon accumulation.

11. Key tectonic and lithofacies factors controlling the formation of potential hydrocarbon accumulations have been identified. A genetic relationship has been established between the Assakeaudan, Zhazgurlin, and South Mangyshlak depressions, reflecting a common mechanism of petroleum system development. The primary productive horizons are associated with Triassic, Jurassic, and Cretaceous formations.

12. A comprehensive, multi-method approach - incorporating seismic surveys, drilling, gravimetry, magnetometry, airborne gamma spectrometry, and geothermal studies - has made it possible to refine the positioning of prospective structures and improve previously proposed models of hydrocarbon distribution.

13. Automated interpretation has significantly enhanced predictive accuracy, revealing block-faulted architecture within the sedimentary cover (an important indicator of possible hydrocarbon migration pathways) and supporting the delineation of targets for exploration and appraisal drilling.

14. As a result, several promising local structures have been identified - Kyzgyrly, Utezhan, Kozhantay, Otynshy, and South Tabyn - located within the Shakhpakhty Step and Assakeaudan Depression. Their hydrocarbon potential is supported by a consistent set of geophysical, lithological, and structural indicators.

15. The results obtained hold substantial practical significance and can inform the planning of subsequent phases of exploration and appraisal activities. While the integrated geological and geophysical analysis yielded promising insights, the findings require further validation. This necessitates exploratory drilling, acquisition of high-resolution 3D seismic data (CDP-3D), and refinement of key parameters such as fault architecture, source rock maturity, and fluid migration pathways.

16. Future investigations should incorporate a comprehensive analysis of deep-seated fault zones as potential vertical conduits for hydrocarbon migration, as well as fluid flow modeling and basin modeling. These methods will improve our understanding of the thermal maturity of Jurassic, Triassic, and Paleozoic source rocks, help reconstruct migration routes, elucidate trap formation mechanisms, and clarify the absence of accumulations in previously drilled structures.

17. A fully integrated approach will significantly improve the reliability of hydrocarbon prospectivity assessments, reduce geological uncertainty, and provide a robust foundation for optimized exploration planning.

18. It is also important to investigate the causes of hydrocarbon absence in previously drilled structures. A recommended approach involves the integration of remote sensing (RS), well logging, and drilling data into a unified 3D conceptual model, enabling a comprehensive evaluation of hydrocarbon prospectivity across the SUR. The adoption of digital technologies and artificial intelligence (AI) offers the potential to significantly improve forecast accuracy, reduce exploration costs, and minimize environmental risks.

19. The findings confirm that the integration of conventional geophysical methods with advanced digital tools - including potential field analysis, remote sensing, AI, machine learning (particularly self-organizing maps, SOM clustering), and well logging - substantially enhances the reliability of hydrocarbon prospecting, especially in underexplored areas with complex geological frameworks.

20. The developed methodology has demonstrated high efficiency and scalability, allowing it to be effectively applied to other regions of Kazakhstan with similar geological conditions. These results represent a meaningful contribution to the evolution of modern exploration strategies and may serve as a methodological foundation for both public-sector programs and private operators.

21. Looking ahead, further development of AI- and machine learning-based interpretation techniques, including nonlinear modeling of geoscientific data, should be prioritized. This will increase predictive confidence, reduce geological uncertainty, and optimize investment in exploration activities

Conflict of interest.

The authors declare that they have no conflict of interest in relation to this research.

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