GEOELECTRICAL MODEL OF THE EARTH’S CRUST ALONG THE SHU-SARYSU GEOTRAVERSE ACCORDING TO MAGNETOTELLURIC SOUNDINGS

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Abstract. The study area under consideration is the only purely gas-bearing area in Kazakhstan. The presence of known gas fields such as Amangeledy proves the prospect of the area for the presence of hydrocarbons. Thus, the interest of the state and the prospects of the area in the gas-bearing area show the indisputable relevance of research.

Keywords: geotraverse, sedimentary cover, basement, Shu-Sarysu sedimentary basin, magnetotelluric sounding, geoelectric section

Purpose. To study and assess the possibility of effective application of electrical prospecting by magnetotelluric sounding (MT-sounding) and to determine the range of geological problems to be solved in the geoelectric conditions of the Shu-Sarysu geotraverse.

Methodology. The issues of methodology of modern technologies of field observations, peculiarities of processing and interpretation of MT-sounding data are considered, which showed that modern instrumental and methodical electrical survey technologies of MT-sounding allow obtaining results of field measurements of increased reliability, due to their accuracy, productivity, mobility, noise immunity, level of automation. To identify the main features of the geoelectric structure of the Earth’s crust and the upper mantle, the modern technique of interpreting MT data allows for 1, 2D inversion of the effective curves of apparent resistivity and impedance phase.

Findings. Based on MT-sounding data, a geoelectric section of the Shu-Sarysu geotraverse was constructed, characterizing the position and morphology of five geoelectric boundaries in the crustal section in the 0–40 km depth interval. The identified five geoelectric horizons show good coincidence with the conventional seismic horizons and confidently correlate with the geological references established by GIS data.

Originality. On the basis of MT-sounding studies, the geological interpretation of the structure of suprasalt and subsalt structural-formation complexes is presented; the geological efficiency of MT-sounding electrical prospecting in revealing the complex structures in the conditions of the Shu-Sarysu geotraverse is shown. On the basis of model constructions of the geoelectric section, new data on the deep geological structure of the Shu-Sarysu geotraverse were obtained: new data on the structure of Mesozoic terrigenous-sedimentary rock complexes and the Paleozoic part of the section with the allocation of the supposed faults; on the basis of MT-sounding results, recommendations for further detailed geological exploration work were given.

Practical value. A comprehensive interpretation is recommended of the obtained MT-sounding data together with the results of geological and geophysical research on the regional profile in order to establish search criteria for the discovery of mineral deposits and the prospects of gas content in the area.

Introduction. At present, the study on the deep structure of the Earth’s crust and upper mantle is important not only in terms of the use of geophysics for further development of natural sciences about the Earth. The results of regional studies are used in the construction of deep geological and geophysical 3D models in order to obtain the basis for the assessment of unexploited resources of mineral and hydrocarbon raw materials at the stage of forecasting and prospecting tasks. In some cases, research on geotraverses is even used in the search for new mineral deposits.

Along with national projects aimed at solving these problems and carried out by scientific centers of the United States, Great Britain, Germany, India, Spain, Canada, China, France, Japan, and other countries, there are also a number of international programs and projects implemented on the basis of a corporate combination of efforts of scientists and practitioners from different states. An example of the implementation of such programs in Kazakhstan is geophysical research along the line of the geotraverse that crosses the southeastern part of the Syrdarya basin, the Karatau mountain system and the Shu-Sarysu sedimentary basin (Fig. 1).

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Modern geophysics is characterized by rapid breakthroughs due to the emergence and use of high-precision and high-resolution technologies, allowing for a detailed understanding of the structural features of objects under study [1]. Electrical magnetic-telluric sounding (MT-sounding) is a tool that can successfully solve a range of problems associated with the search for mineral deposits, including hydrocarbon deposits, acting as an essential complement to seismic exploration.
[2]. Structural constructions are close to seismic surveys in terms of accuracy, and constructions when interpreting MT-sounding do not depend on any a priori data (as, for example, in the method of seismic CMP (common midpoint) from velocities).

MT-sounding is not comparable with seismic survey in terms of resolution, but nevertheless allows one to identify specific resistivity anomalies associated with epigenetic changes in rocks above the hydrocarbon reservoir, conduct a lithological partitioning of sedimentary complexes, identify deep faults, large anticlinal uplifts, foundation structures [3]. In addition, according to the MT-sounding by indirect signs it is possible to predict the zones of horizons, prospective for oil and gas [1].

The purpose of the research presented in the article is to define the range of tasks and study the geological effectiveness of MT-soundings in real geoelectric conditions.

To achieve this goal, the following tasks were accomplished:

1. Collecting, analyzing and summarizing information on the geological characteristics of the fields of the Shu-Sarysu gas-bearing region and adjacent areas.

2. Studying primary geophysical criteria along the Shu-Sarysu geotraverse line.

3. Identifying geoelectric horizons, basement of sedimentary cover, basement roof, identifying structural and material heterogeneities of the consolidated crust and weakly delocalized complexes of the Paleozoic, tracing of faults according to MT-sounding data.

4. Determining the material composition and isolating local geoelectric heterogeneities.

The Shu-Sarysu basin is located in the central part of Kazakhstan, and is geologically connected with the basin of the same name, stretching in the north-west direction for 700 km with a width of 200–250 km. The sedimentary basin in the west and north is bounded by the Ulytau mountain-fold structures and the Sarysu-Teniz uplift, in the northeast it borders on the Shu-Ili anticlinorium, in the south and southwest — the mountain ranges of the Big and Small Karatau, in the east and southeast it borders with the Kendyktas massif and the Kirghiz Alatau. The depression is composed of a complex of Devonian-Permian and Mesozoic sediments with a maximum thickness of up to 6000 m.

The basin is composed of metamorphic rocks of the Proterozoic, and within the individual blocks of the central part of the basin in the upper sections of the basement there are intensely dislocated and intruded strata of Lower Paleozoic rocks.

The sedimentary cover of the basin includes deposits from the Middle Upper Devonian to the Neogene and forms two structural stages separated by large stratigraphic and angular unconformities: Paleozoic (Middle Upper Devonian-Permian) and Mesozoic-Cenozoic (Upper Cretaceous-Paleogene).

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Fig. 1. Structural map of the basement surface of the study area
The electrical properties of deposits of Cenozoic-Mesozoic age have been most fully studied in connection with earlier electrical prospecting work to determine the depths to the Paleozoic. The Paleozoic rock complex proper is poorly studied. The Lower Paleozoic, represented by the sedimentary and intrusive complexes of Cambrian and Ordovician rocks, has a high electrical resistivity and is firmly fixed by the output of the VES curves on the asymptote at an angle of 45°. In the area of development of Lower and Middle Carboniferous sedimentary strata (sandstones, siltstones, mudstones, limestones, dolomites) Paleozoic formations often have low resistivity (from 10–30 to 50–100 Ohm m), close to the resistance of overlap and porosity and displacement to the surface of free water, the resistance of rocks increases [7].

The electrical properties of deposits of Cenozoic-Mesozoic age are shown in the Table. Analysis of a priori geological and geophysical information allowed us to conclude that the rocks in this section are contrasting in their electrical parameters and are favorable for MT-sounding.

**Research methodology.** The presented geological and geophysical criteria were the basis for conducting magnetotelluric soundings along the Shu-Saryusy geotraverse. Gas fields of the Shu-Saryusy gas-bearing region is confined to the fields of domed and brachianticlinal uplifts, complicated by fractures. The uplifts controlling the deposits are complexly built, tense in morphology, often truncated in section, sharply asymmetric, near-faulted.

### Table

<table>
<thead>
<tr>
<th>Age</th>
<th>Lithology of rocks</th>
<th>Electrical resistances, Ohm · m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sandstones, clays, limestones</td>
<td>50–80</td>
</tr>
<tr>
<td>C&lt;sub&gt;N&lt;/sub&gt;</td>
<td>Massive limestones and sandstones</td>
<td>200–300</td>
</tr>
<tr>
<td>C&lt;sub&gt;A&lt;/sub&gt;</td>
<td>Sandstones, limestones, mudstones</td>
<td>70–80</td>
</tr>
<tr>
<td>C&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Sandy-argillite pack</td>
<td>20–30</td>
</tr>
<tr>
<td>C&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Lime-sandy strata</td>
<td>200–300</td>
</tr>
<tr>
<td></td>
<td>Coal-bearing strata</td>
<td>20–30</td>
</tr>
<tr>
<td></td>
<td>Rock salt</td>
<td>100</td>
</tr>
<tr>
<td>D&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Sandstones</td>
<td>70–60</td>
</tr>
<tr>
<td>D&lt;sub&gt;1&lt;/sub&gt;/2</td>
<td>Porphyrites, quartz porphyrites, sandstones</td>
<td>300 and more</td>
</tr>
</tbody>
</table>
influence of a powerful flux of charged particles there are variations in the magnetic field of the earth and there are current vortices in the ionosphere. This results in a magnetotelluric field, which contains a wide range of frequencies. Ultra-low frequencies penetrate hundreds of kilometers deep, making this method one of the deepest of all electrical exploration methods [8].

The measured quantities are the electrical (Ex and Ey) and magnetic (Hx, Hy and Hz) components. The resistance value of the medium is determined by the impedance—the ratio of the horizontal components of the electromagnetic field—electric to magnetic (Ex/Hy) and (Ey/Hx) at different periods (frequencies) of the field fluctuations [9].

Submeridional direction of the geotraverse was chosen and justified based on the results of large-scale works on “Comprehensive Study of Sedimentary Basins of Kazakhstan. Shu–Sarysu Basin” performed in 2012. Gravimetric and aeromagnetic surveys were conducted in the area of the 60–100-km wide geotraverse, and seismic and electrical surveys were conducted along the axis of the profile. The study on deep horizons of the Earth’s crust along regional profile lines (geotraverses) by a complex of methods is one of the most effective ways to study the tectonic development of the Earth, its geodynamic regime, the connection between deep processes and surface phenomena, the development of deep criteria for prediction of minerals and, in the future, to combine these factors within a unified theory of deposit formation processes [10].

Interpretation of electrical prospecting data consists of two main steps: inversion with obtaining geoelectric models of the medium (solving the inverse problem, that is, the transition from the dependence of the apparent electrical resistivity on frequency to the dependence on the specific resistance depth) and the subsequent “geological interpretation” of geoelectric sections [11]. According to the results of the analysis, the medium has a 3D effect caused by regional inhomogeneity of conductivity distribution. Thus, to obtain reliable data on the electrical resistivity distribution in the target depth interval it is necessary to apply a 2D inversion [4]. Application of the 1D approach is limited because the mismatch of the inverse problem dimensionality with the medium dimensionality can lead to incorrect definition of the electrical resistivity of the layers. However, the transition to an inverse problem of a larger dimension leads to an increase in the instability of its solution. Compared to one-dimensional inversions, two- and three-dimensional inversions are less stable. This is because the adequate description of 2D and 3D models requires a much larger number of parameters than for a 1D model. Therefore, to keep the detail of the dissection, on the one hand, and to ensure the reliability of the electrical resistivity determination, on the other hand, a staged interpretation was applied, which included both 1D and 2D (controlled multistage 2D inversion with a starting model built from the results of one-dimensional fitting) [12].

Using this approach allows us to obtain a single geoelectric model for the entire depth interval under study, including a detailed horizontal-layered top and a heterogeneous bottom. In this case, the model satisfies the observed data in the whole range of periods, and there is no loss of model detail in the upper horizontal-layered part, nor loss of validity of results in the lower inhomogeneous part, related to the incompatibility of the dimensional inversion procedure and the medium model, to which the MT field corresponds.

**Research results.** The results of magnetotelluric soundings along the Shu–Sarysu geotraverse line are presented in the form of the electrical resistivity geoelectric section. The electrical resistivity of the section varies in a very wide range from 0.1–1 to 10,000 Ohm·m. In this regard, the isolines on the geoelectric section are given in values of the decimal logarithm of resistance (LgR from -1 to +4). In order to improve the clarity and information content of the obtained electrical survey data, a generalized parametric geoelectric model was built in addition to the geoelectric sections, on which the lineaments of the tracing axes of the logarithm of resistance gradients and zones were superimposed. To calculate additional parameters (transformant) of the geoelectric section, specialized software packages Epi–Kit, MTS Prof Inv, MT 2D Tools, GeoSoft Oasis MontajTM, COSCAD 3D and several others were used. Above the geoelectric section there are diagrams of magnetic and gravitational field parameters; elements of geological structures of the first and higher orders (Syrdarya and Shu–Sarysu sedimentary basins, Karatau mountain system, borders of Zhaihlair–Naima folding zone, Baikadam and Tashbulak troughs, Leonitiv graben, Talas–Tusty uplift area, Lower Syrdarya Graben, etc.) are marked, crossed by the geotraverse line (Fig. 2).

In the southwestern part of the profile (interval from 0 to 80 km) in the upper part of the geoelectric section a contrasting well conductive horizon is mapped by the Meso–Cenozoic sediments. Within the Arys trough of the Syrdarya sedimentary basin, the resistivity of this horizon is 3–10 Ohm·m, up to 1.5 km thick. These formations lie on rocks, for which the resistance with depth increases gradually from 10 to 50–60 Ohm·m. In the depth range of 4–11 km, the resistance varies within a small range (60–160 Ohm·m) and averages 100 Ohm·m. In the depth interval of 10–20 km, there is a relatively conductive horizon, with resistance values ranging from 10–30 Ohm·m. Below this horizon, at depths of 20–40 km, the resistivity of the geoelectric section is relatively elevated and is 300–500 Ohm·m.

The interval of the geotraverse profile (interval 80–160 km), which crosses the Karatau mountain massif on the geoelectric section is characterized by a general anomalously high level of values of resistivity 1000 Ohm·m. The block has a complex geo-electric structure, with sub-vertical zones of maximum resistance (up to 10,000 Ohm·m), and sub-horizontal layers with zones of lower resistance (from 1000 to 100 Ohm·m). In the upper part of the section, a local anomaly of reduced resistivity (10–100 Ohm·m) marks the position of the Leonitiv graben. A certain zonality of...
Electrical properties of the block is also noted in its subhorizontal-layered structure. In the depth interval of 0–5 km stands out a horizon with resistance from 500 to 1500 Ohm-m, the underlying horizon (depth 5–17 km), divided by subvertical boundaries into zones of low and high resistance, in general, has a reduced level of average resistance. The lower horizon (from 17–20 to 40 km depth) is of relatively high resistivity; in the southwestern part of this interval of a profile, resistance reaches 1000–5000 Ohm-m, in the northeast it goes down to 120–150 Ohm-m.

In the interval of the profile (160–200 km) corresponding to the northeastern slope of the Small Karatau, the Itmuryn stage and the southwestern part of the Buykadam trough are distinguished as a conductive horizon (resistivity 2–10 Ohm-m) in the upper part of the geoelectric section. The Paleozoic roof is marked by a high gradient zone, below which, in the interval of depths from 2 to 10–12 km, a high-resistance horizon (100–10,000 Ohm-m, with an average value of 1000 Ohm-m) is distinguished. In the depth interval from 10–12 to 25–30 km, the average resistivity of the section decreases to 100 Ohm-m. By subvertical gradient zones, the horizon is divided into high-resistance (up to 1000 Ohm-m) southwestern and low-resistance (10–100 Ohm-m) northeastern parts. The lower part of the section in the depth interval from 25–30 to 40 km is characterized by moderate resistance values of 150–300 Ohm-m.

The profile interval (200–360 km) corresponds to the central and eastern parts of the Shu-Sarysu basin, crosses the Buykadam trough, Talas and Tasty rises, the Lower Shu saddle and the northeastern slope of the Small Karatau, the Itmuryn stage, and the southern end of the Tasbulak trough in the southwest-eastern part. The upper part of the section in the depth interval of 0–2 km stands out as a conductive horizon with resistivity from 4–5 to 100 Ohm-m, the base of the horizon almost coincides with the Paleozoic roof. The underlying high-resistance (resistivity from 700 to 2000–3000 Ohm-m) horizon occupies the interval of depths from 1–2 to 5–8 km, its upper gradient part corresponds to the sediments of the Upper Paleozoic quasiplatym form. Below the 5–8 km depth level, the horizon without sharp geoelectric boundaries is underlain by a horizon of moderate resistivity (700–1200 Ohm-m). In the interval of depths from 15 to 35 km, a relatively conductive horizon with a resistance of 50–100 Ohm-m is distinguished.

The northeastern part of the geoelectric section corresponds to the Zhahair-Naiman anticline and stands out as a high-resistance block with resistivities from 1000–3000 to 30,000–50,000 Ohm-m throughout the depth interval from 0 to 40 km.

Generalization of the materials of previously performed electrical exploration and electrical logging in the Shu-Sarysu sedimentary basin allowed us to perform a geological interpretation of the MT-sounding electrical exploration data. The generalized geoelectric section of the work area is presented in a five-layer structure (from top to bottom):

Layer 1 (upper) is represented by proluvial, alluvial and aeolian deposits of Quaternary age (clays, loams, sandy loam, crushed stone, gravel, boulders, and pebbles). Its resistance varies from 2–20 to 300–600 Ohm-m. Layer thickness up to 10–20 m. According to the logging data, the following resistivity values were obtained for different rocks: clay 3–5 Ohm-m; sandy loam, loam 5–20 Ohm; boulder and pebble 100–200 Ohm and more.

Layer 2 of increased resistance is represented by Neogene sands, conglomerates, boulders, and pebbles. According to drilling data, their thickness reaches 50 m. Resistivity of the layer (by VES) 10–25 to 650 Ohm-m. According to well logging data, resistance of clayey sands 5–10 Ohm-m; sands 10–15 Ohm-m; gravel-pebbles, sandstones, conglomerates 30–70 Ohm-m. In outcrops of conglomerates in the Kutyrgan area, parametric measurements yielded values of 1300–1400 Ohm-m.

Layer 3 has relatively low resistances. This layer is marked by the Paleogene and Upper Cretaceous deposits poorly differentiated by electrical properties, represented by a complex of interstratified rocks - clay, sand, clayey sand, gravel and pebble deposits, siltstones, sandstones on clay cement, porcellain-like limestone, breccias, as well as bauxite-like rocks and bauxites. The electrical resistance of the entire thickness is characterized by values of 2–50 Ohm-m. Its thickness varies from the first tens of meters to hundreds of meters, reaching 400–600 m. When probing in this stratum, only rock horizons of sufficient thickness can be detected in separate layers.

Layer 4 of high resistivity (80–280 Ohm-m) is associated with conglomerates, boulders, and pebbles of the lower horizons of the Upper Cretaceous and weathering crust of Jurassic sediments. It is distinguished only in the case of high thickness. It often lies on the surface of Paleozoic sediments and plays the role of a reference horizon, which sometimes leads to errors in determining the depth of occurrence of the roof of the Paleozoic sediments.

Layer 5 of "infinitely" large resistance serves as a reference electrical horizon, which allows the methods of field electrical prospecting to determine the depth of occurrence of the Paleozoic roof. Paleozoic limestones and dolomites, whose resistivity varies from 700 to several thousand ohm-m (accord-
Геоелектрична модель земної кори вздовж геотраверсу Шу-Сарису за даними магнітотелуричного зондування

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Мета. Полягає у вивченні та оцінці можливості ефективного застосування електророзвідувальних технологій шукальніх профілів з метою встановлення пошукових критеріїв виходу корисних копалин і визначення перспектив газодобувних ділянок.

Результати. За даними МТЗ побудовано геоелектричний розріз геотраверсу Шу-Сарису, що характеризує положення й морфологію п'яти геоелектричних границь у розрізі земної кори в інтервалі глибин 0–40 км. Виділені п'ять ефективних кривих уявного опору та фази імпедансу.

Загальна здатність геоелектричних горизонтів вказують на гарний збіг з умовами геотраверсу Шу-Сарису.

Практична значимість. Розглянуто питання методики сучасних технологій геоелектричного розрізу, що впливає на точність і стабільність результатів зондування. Розроблено рекомендації щодо подальших детальних геологорозвідувальних робіт.

Ключові слова: геотраверс, ефективність, автоматизація, геоелектричні розрізи, магнітотелуричні зондування, геоелектричні горизонти.