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ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

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CONSOLIDATED GEOLOGICAL AND GEOPHYSICAL CHARACTERISTICS OF URANIUM DEPOSIT ROCKS AND PROSPECTS FOR THEIR UTILIZATION (SHU-SARYSU PROVINCE, KAZAKHSTAN)

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Abstract. The article addresses a scientific and methodological (physico-geological) problem concerning the selection and application of effective geophysical technologies at all stages of geological and mining-geological operations in uranium provinces and deposits of Kazakhstan. Borehole geophysical methods are vital not only due to uranium's radioactive nature but also because of the safe and efficient in-situ leaching (ISL) technology widely used for its extraction.

The study focuses on creating detailed models of the physical properties of rocks and ores forming the geological sections of uranium deposits. Statistical methods were applied to calculate generalized ranges of physical properties and borehole geophysical fields, using data from geological archives and scientific publications on the Shu-Sarysu uranium province. The authors' experience with other deposits and geological challenges further supported this analysis.

The results revealed insufficiently detailed studies of impermeable (barren) and permeable (ore-bearing and barren) rocks, particularly regarding their electrical properties, density, and seismic wave velocities. Detailed investigations into these characteristics would improve the informativeness of geophysical methods and expand their industrial applications, such as optimizing well-logging and ISL technologies.

Integrating advanced geophysical technologies into exploration and development processes enhances workplace safety, reduces operational costs, and increases economic efficiency. These advancements contribute to modernizing geological operations and boosting the long-term sustainability of Kazakhstan's uranium industry.

Key words: Shu-Sarysu province, uranium deposits, physical fields and rock properties, statistical data processing, geophysical technologies

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УРАН КЕНОРЫНДАРЫ ТАУЖЫНЫСТАРЫНЫҢ ЖИЫНТЫҚ ГЕОЛОГИЯЛЫҚ-ГЕОФИЗИКАЛЫҚ СИПАТТАМАЛАРЫ ЖӘНЕ ОЛАРДЫ ПАЙДАЛАНУ ПЕРСПЕКТИВАЛАРЫ (ШУ-САРЫСУ ПРОВИНЦИЯСЫ, ҚАЗАҚСТАН)

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Аннотация. Мақала Қазақстанның уран провинциялары мен кенорындарындағы геологиялық және тау-кен-геологиялық жұмыстардың барлық кезеңдерінде ақпаратты геофизикалық технологияларды таңдау және пайдаланудың ғылыми-әдістемелік (физикалық-геологиялық) проблемаларын шешуге арналған. Уран кенорындары ұңғымаларында геофизикалық

(қашықтық) әдістерді қолдану қажеттілігі уранның радиоактивті табиғатымен ғана негізделмейді. Маңызды өндірістік фактор – жерасты ұңғымалық сілтісіздендіру (ЖҰС) әдісін қолдана отырып, уран кенорындарын игеру мен өндірудің қауіпсіз және озық технологиясының қолданылуы.

Проблеманы шешудің физикалық-геологиялық негіздері кенорындардағы геологиялық қималарды құрайтын таужыныстар мен кендердің неғұрлым көп физикалық қасиеттері мәндерін жүйелеу болып табылады. Ұңғыманың геофизикалық өрістерінің және таужыныстардың физикалық қасиеттерінің жиынтық мәндерін (мәндерінің өзгеру диапазонын) есептеуде статистикалық әдістер мен әдістемелелер қолданылды. Есептеулер үшін геологиялық қорлардың фактілік деректері және Шу-Сарысу уран провинциясы бойынша ғылыми басылымдардың мәліметтері пайдаланылды. Мақаланы жазуда авторлардың басқа кенорындардағы және басқа геологиялық мәселелерді шешудегі тәжірибесі де пайдаланылды.

Алынған көппараметрлі петрофизикалық модельдік көрсеткіштер уран кенорындары бойынша өткізбейтін (сазды) және өткізетін (кенді және кенсіз құмдар) таужыныстарды дәл ажыратуға мүмкіндік беретін зерттеулер қажеттігін көрсетті. Оларға таужыныстарда сейсмикалық толқындардың тарау жылдамдықтары, таужыныстардың электрлік қасиеттері, тығыздықтары жатады. Осы физикалық қасиеттерді тақырыптық және неғұрлым нақты деңгейде зерттеулер геофизикалық әдістердің мәліметтілік деңгейін көтеруге және олардың салада шеше алатын мәселелерінің ауқымын кеңейтуге мүмкіндік береді.

Уран кенорындарын барлау мен игеруде геофизикалық технологиялардың мүмкіндіктерін кеңейту және енгізу персоналдың еңбек қауіпсіздігінің деңгейін көтереді және жалпы саланың экономикалық тиімділігін арттырады.

Түйін сөздер: Шу-Сарысу провинциясы, уран кенорындары, таужыныстардың физикалық өрістері мен қасиеттері, мәліметтерді статистикалық өңдеу, геофизикалық технологиялар

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СВОДНЫЕ ГЕОЛОГО-ГЕОФИЗИЧЕСКИЕ ХАРАКТЕРИСТИКИ ПОРОД УРАНОВЫХ МЕСТОРОЖДЕНИЙ И ПЕРСПЕКТИВЫ ИХ ИСПОЛЬЗОВАНИЯ (ШУ-САРЫСУСКАЯ ПРОВИНЦИЯ, КАЗАХСТАН)

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Аннотация. Статья посвящена решению научно-методической (физико-геологической) проблемы выбора и использования наиболее информативных геофизических технологий на всех этапах геологических и горно-геологических работ в урановых провинциях и месторождениях Казахстана. Необходимость в использовании скважинных (дистанционных) геофизических методов обоснована не только радиоактивной природой полезного ископаемого – урана. Важным фактором является безопасная и передовая технология разработки и добычи месторождений урана способом подземного скважинного выщелачивания (ПСВ).

Физико-геологической основой решения проблемы является составление модельных представлений наибольшего количества физических свойств горных пород и руд, слагающих геологические разрезы месторождений. В статистических методах и методике расчёта сводных значений (диапазонов изменения значений) физических свойств и скважинных геофизических полей использованы фактические данные из геологических фондов и публикаций из научных изданий по Шу-Сарысуской урановорудной провинции. Также использованы опыт авторов статьи по другим типам месторождений и по решению других геологических задач.

Полученные многопараметровые модельные представления петрофизических свойств пород урановых месторождений района показали, что существует проблема недостаточно детальной изученности непроницаемых (безрудных) и проницаемых (рудных и безрудных) пород района по электрическим свойствам, плотности, скорости распространения сейсмических волн. Тематическое и более детальное изучение указанных свойств позволит поднять уровень информативности геофизических методов и расширить круг ими решаемых задач в отрасли.

Расширение и реализация возможностей геофизических технологий при детальной разведке и разработке урановых месторождений повышают уровень безопасности труда персонала в разведке и освоении месторождений урана и экономическую эффективность отрасли в целом.

Ключевые слова: Шу-Сарысуская провинция, месторождения урана, физические поля и свойства пород, статистическая обработка данных, геофизические технологии.

Introduction

Kazakhstan ranks among the top countries in the world for uranium resources. Its territory hosts exogenous (Shu-Sarysu, Syrdar'ya, Ile provinces, and the Caspian region) and endogenous (primarily in the North Kazakhstan province and Betpakdala-Shu-Ile) types of deposits. These include strata-bound, groundwater infiltration, sedimentary-diagenetic, and hydrothermal types of uranium mineralization (Mineral resources of Kazakhstan, Explanatory note for the Map of the Mineral Resources of Kazakhstan, 1:1000 000 scale, 2002; Uranium Production by Country, 2023; Franz, 2009; Petrov, et al, 2008). Information on the geological structure of the region, the genesis of the deposits, mineralization features, ore deposit characteristics, and associated minerals has been detailed in numerous scientific works by researchers (Uranium Production by Country, 2023; Franz, 2009; Petrov, et al, 2008; Brovin, et al, 1997; Uranium Mining in Virginia, 2012). On an international scale, the geological-structural and genetic characteristics of uranium deposits, as well as the technologies for their exploration and development, have been extensively studied (Franz, 2009; Uranium Mining in Virginia: Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in Virginia, 2012; Mwenifumbo, et al, 2013; Kalashnyk, 2013; Zhanchiv, et al, 2013; Kolbenkov, 2010; Erofeev, et al, 2009). For example, the literature classifies them differently according to ore formation. According to the IAEA classification, uranium deposits are categorized as Unconformity-Related Deposits, Fracture-controlled, dominantly basement-hosted deposits, Clay-Bound Massive Ore, Sandstone Deposits, Roll-front deposits, Tabular deposits, Paleovalleys, and Tectonic/lithologic deposits (Uranium Mining in Virginia: Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in Virginia, 2012).

Currently, exogenous strata-infiltration hydrogeological type deposits account for about 75% of Kazakhstan's proven uranium reserves. The Shu-Sarysu uranium province hosts around ten known deposits of this type. Among these, the Mynkudyk, Inkay, and Budenovsk deposits are unique, while the Zhalpak, Akdala, Uanas, Tortkudyk, Moyynkum, and Kanzhugan deposits are considered large (Mineral resources of Kazakhstan, Explanatory note for the Map of the Mineral Resources of Kazakhstan, 1:1000 000 scale, 2002). These deposits are located in the northern and eastern uranium clusters of southern Kazakhstan (Figure 1).

Geological map of the Shu-Sarysu and Syrdar'ya uranium provinces showing oxidation-reduction fronts and uranium deposits. The map highlights oxidation zones in Paleogene and Cretaceous deposits, key deposits such as Mynkudyk and Inkay, and major geological features including the Karatau Range and Syrdar'ya Depression. Similar deposits include Crow Butte and Smith Ranch in the USA. They are also comparable in terms of resources, ranging from several hundred to several tens of thousands of tonnes of uranium, with grades from 0.015 to 0.25 percent (Uranium Mining in Virginia: Scientific, Technical, Environmental, Human Health and Safety, and Regulatory Aspects of Uranium Mining and Processing in

Virginia, 2012). The safety, efficiency, and profitability of mining ore horizons in exogenous deposits are ensured by the use of well-logging technologies and in-situ leaching (ISL) (Mwenifumbo, et al, 2013; Erofeev, et al, 2009; Shayakhmetov, et al, 2023; Wei, et al, 2023; Huang, et al, 2021; Sharapatov, et al, 2023).

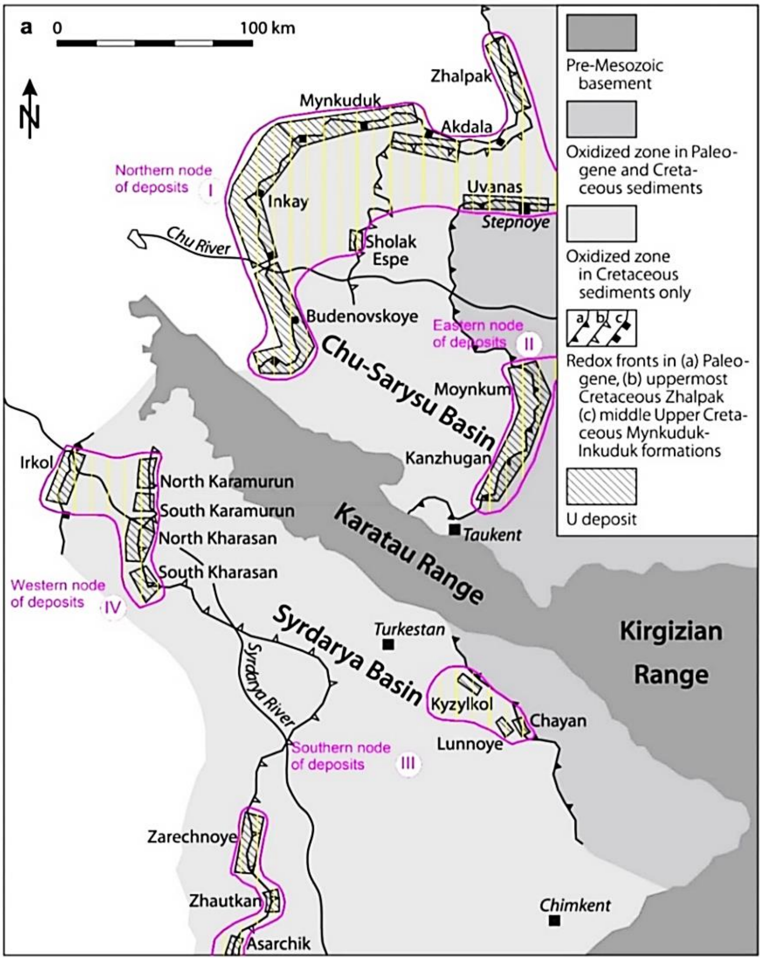

Figure 1 – Geological map of the Shu-Sarysu, Syrdar'ya uranium provinces and the location of the redox potential fronts and related deposits, compiled by Assirbek N. using published data's (Mineral resources of Kazakhstan, Explanatory note for the Map of the Mineral Resources of Kazakhstan, 1:1000 000 scale, 2002; Franz, 2009; Petrov, et al, 2008)

A pressing task in geological and mining-technological work at deposits is the optimization of their volume and execution time. The primary tool for providing information at deposits with well mining is geophysical technologies. To establish the physical basis for selecting and/or evaluating the informativeness of geophysical methods, a detailed study of the physical properties of rocks and their manifestations in observed physical fields is necessary (Sharapatov, et al, 2017).

Statistical processing and the creation of a generalized data database for the region's deposits enable the use of information at various stages of deposit operations.

The aim of the study is to compile generalized (model) information on the physico-geological parameters of ore deposits and host rocks for exogenous type deposits. To achieve this research objective, a series of tasks were accomplished in a specific sequence (Figure 2):

1. Collection of scientific and archival materials, grouping of deposits' rocks and ores by attributes (age, stratigraphic unit, ore horizon, composition);
2. Systematization of the parameters of observed geophysical fields and results of geological interpretation of well log diagrams in conjunction with laboratory core study data – physical properties, composition, and parameters of ore-bearing and barren horizons, highlighting the main interpretative characteristics of the geological section;
3. Analysis of actual geodata: statistical processing and averaging of the physical properties of rocks, determination of the ranges of physical field variations;
4. Compilation of generalized geological and geophysical information on uranium deposits in the Shu-Sarysu uranium province in a text-table format;
5. Evaluation of the sufficiency level of existing data, recommendations for the content of further research.

The presence of a digital integrated database of geological, geophysical data, and petrophysical parameters of rocks and ores of deposits – a geological-geophysical (technological) model of uranium deposits for the ore district – enables: a) the selection of effective geophysical technologies, ensuring the optimization of geological work volumes (including drilling) when identifying new uranium deposits and areas; b) information support for conducting geotechnological operations (mining-geological and technological works) in the development of uranium deposits using the in-situ leaching (ISL) method.

The practical value of the research results lies in the fact that the expansion and utilization of geophysical methods' capabilities can impact the technological development and economic performance of the industry as a whole.

Materials and methods. In compiling the comprehensive geological-geophysical/petrophysical characterization of the rocks of uranium deposits, textual and graphic materials from geological fund reports on the deposits were used, as well as normative and technical documentation of the uranium industry. The comprehensive characterization is the result of analysis, grouping, statistical processing, and generalization of data on characteristic rocks and ore horizons of deposits in the northern and eastern nodes of the Shu-Sarysu uranium province (Figure 2). The flow chart illustrates the process of creating a consolidated geological and geophysical characteristic. It starts with factual materials from reports, articles, and monographs, followed by systematization and statistical analysis of data, and ends with a consolidated model of geological and geophysical characteristics of uranium deposits.

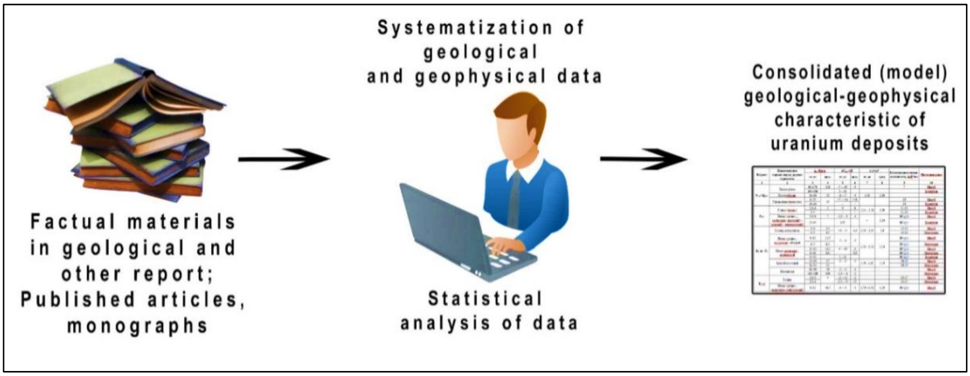

Figure 2 – General principle for creating summary/model geological and geophysical characteristics

The relevant parameters for addressing geological and mining-technological tasks in the development of hydrogeological-type uranium deposits include lithology, horizon thicknesses, and the filtration-capacity properties (FCP) of the rocks; the contours and sizes of ore deposits, and their uranium content. These are determined based on the interpretation of geophysical field diagrams along the wellbore. The interpretation of well logging data (WLD) is conducted based on laboratory studies of the physical properties and parameters of a sufficient quantity of rock core samples and the establishment of a correlation between WLD and core data.

Lithological subdivision of the section is performed using the apparent resistivity of the rocks (apparent resistivity method – AR; ρ_a, Ohm·m – blue line) and the potential of the natural field (self-potential method – SP, U_{sp}, mV – green line). When interpreting the SP data, the potential readings for Chegan clays are conventionally taken as the zero level of the natural electric field (above this level are positive field values, below it are negative field values). The Chegan clay horizon (upper-middle Paleogene $₽_{1-2}$) has a regional distribution and serves as a reference horizon in the analysis and geological interpretation of WLD data.

Uranium horizons are identified based on the exposure dose rate (gamma logging – GL; R, μR/h – red lines in two scales). The specific electrical conductivity values (induction logging – IL; g, mS/m – pink line) are used to study the position of the borehole bottom and the integrity of the casing (Figure 3). The example logs and their geological interpretation results shown in Figure 3 show stratigraphy, gamma ray logs and conductivity/resistivity measurements at different depths. Lithology is depicted in the central column, showing the variations in rock types, while the logs on either side indicate the relevant geophysical properties needed to identify ore horizons. IL data are also informative for monitoring the spread of technological solutions across the area during the exploitation phase of uranium deposits using the in-situ leaching (ISL) method (Sharapatov, et al, 2023).

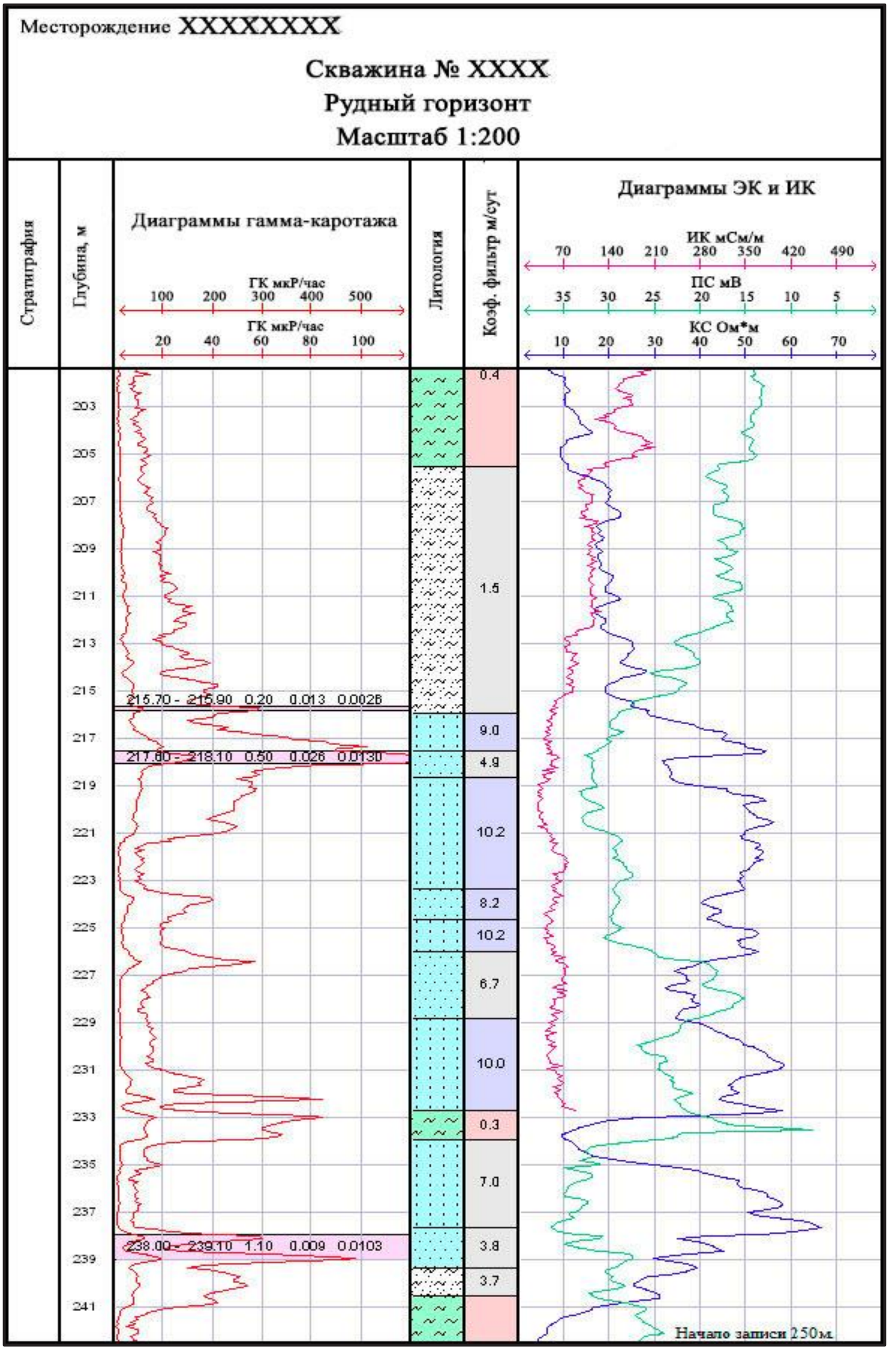

Figure 3 – Example of logging diagrams and the results of their geological interpretation

The interpolation of geological, geometrical, and filtration-capacity (technological) parameters of rocks and deposits, based on the interpretation of logging method diagrams, allows for the delineation of their boundaries and contours along the profile in section format (Figure 4). The section in Figure 4 is the result of combining and interpolating borehole log and core data, showing various rock types, ore bodies and uranium deposits. Also shown are gamma ray, resistivity and spontaneous potential logs with contours indicating permeable and impermeable zones within the stratigraphic profile.

Data analysis should not be considered merely as information processing after collection. Instead, data analysis is a means of testing hypotheses and solving research problems. The necessity of summarizing and collectively representing the properties, parameters, and features of an object or phenomena leads to the use of models.

Typically, various mathematical methods, including statistical analysis of measurement results, are used for geodata analysis. Different types of statistical computations using geophysical (petrophysical) data are conducted depending on the stages of geological object studies and the tasks at hand. These computations cover all stages of geological and geophysical work: from planning to developing field observation methodologies; from assessing the required survey accuracy to interpreting geophysical data to determine the nature of anomalies. Computational work defines probabilistic-statistical parameters of physical properties and fields. These parameters are used to select informative methods and create a rational geophysical complex to enhance the efficiency of exploration tasks and address the problem of classifying geophysical anomalies as ore-bearing or barren (Sharapatov, et al, 2020).

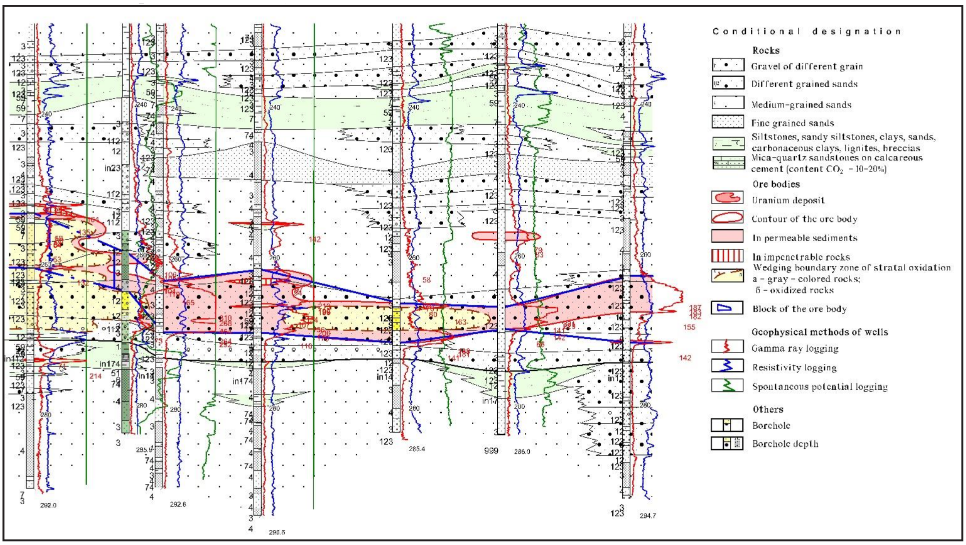

Figure 4 – Example of a lithological-filtration cross-section based on laboratory core material studies and well-logging data along the profile of the operational site, Shu-Sarysu Uranium Ore Province.

When delineating petrophysical groups of rocks, the method of grouping by the most general and stable characteristics (such as age, composition, and filtration-capacity properties) is applied. Statistical processing of petrophysical properties allows establishing the main patterns of changes in the physical parameters of the studied rocks and objectively characterizes their groups and associations.

With numerous values of the same rock properties, there arises a need to average empirical data separately for each rock type. An important factor in this process is representativeness – the number of tested rock samples. A variation chart is constructed based on the dependence of the ratio $\frac{n_i}{N}$ on the studied property x): n_i is the number of rock samples in the i- th interval of property values, n_i is the total number of rock samples, and x_i are the values of the studied property. The width of the rock property value intervals (h) depends on the overall range of their variation and is determined according to the rules of Scott 1979, Friedman, and Diaconis 1981 (Hyndman, 2023).

The average values of the studied rock properties reflect their typical level per unit of the population under specific conditions of place and time, ignoring differences between individual units. It serves as a measure of the attribute per unit of the population (unlike relative values, which serve as a measure of the ratio of indicators) (Kovaleva, et al, 2019). Based on the data processing results, generalized/model values of physical properties are assigned to each rock type in the geological section. Statistical processing can be used to assess the geological exploration informativeness of geophysical fields (Sharapatov, et al, 2020) and in the analysis of spatial quantitative data in other geosciences (Mukayev, et al, 2022; Tereshchuk, et al, 2017).

The most common summary indicator of the distribution character of a physical parameter is the arithmetic mean (x_α)

$$x_a = \frac{x_1 + x_2 + \ldots + x_N}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (1)$$

where x_i is the physical parameter of the sample (sample data); n_i is the total number of samples.

The values of x_α are used when calculations are performed on ungrouped statistical data.

When identifying groups (associations) of rocks, the calculation of the most probable values of physical parameters is conducted considering the recurrence («weight») of the parameter values (frequency). The weighted average $x_{w\alpha}$ is calculated using the formula:

$$x_{wa} = \frac{1}{m}\sum_{i=1}^{N} x_i\, n_i \qquad (2)$$

Where x_i -physical parameter of the sample; n_i - number of samples in separate groups; m - number of groups.

As an indicator of the magnitude of the deviation of individual values from the average and the difference of individual values from each other, that is, the variation of a parameter, is the dispersion or standard (standard deviation S, which is calculated by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{N}(x_i - x_{wa})^2}{N-1}} \quad (3)$$

Results and discussion. *In the "Generalized Geological-Geophysical/ Petrophysical Information on Ore-Bearing and Host Rocks of Uranium Deposits in the Shu-Sarysu Depression of Kazakhstan" the data cover the deposits of the northern and eastern ore nodes of the region (Figure 1).*

Figures 5-8 detail the results of statistical data processing, exemplified by the values of apparent electrical resistivity ρ_a. In this case, the statistical data processing results are used to solve a technological problem: determining the dependence of ρ_a on C_f (filtration coefficient of permeable rocks – sands). For this purpose, intermediate parameter correlations – median grain diameter of sands D_{50} with C_f and D_{50} with ρ_a – were utilized.

Overall, the most important result is the fact that impermeable rocks (clays, siltstones) can be reliably and unequivocally distinguished from permeable rocks (sands of varying grain size and sorting). Thus, based on the modal values of ρ_a for lithological varieties of rocks, two groups of rocks are identified:

- rocks of clay composition – these include clays, siltstones, clayey siltstones, and silty clays;
- rocks of sand composition – these include fine to medium-grained sands, varied and medium-grained sands, sand-gravel, and gravel-pebble formations.

Poorly sorted sands with gravel, which occupy an intermediate position in terms of ρ_a values, can be identified with less reliability and greater error. Sand-gravel and gravel-pebble formations exhibit intermediate apparent electrical resistivity values due to the presence of clayey-silty particles, which makes their identification prone to determination errors (Figure 5).

Figure 5 shows a graph of the variation in the distribution of apparent specific electrical resistivity for different types of rocks in the Mynkudyk ore horizon of the Budenovsk deposit. The graph depicts distinct curves for clays, aleurites, fine-grained, medium-grained, mixed-grained, and gravelly-pebble rocks, highlighting the modal values of their petrophysical properties.

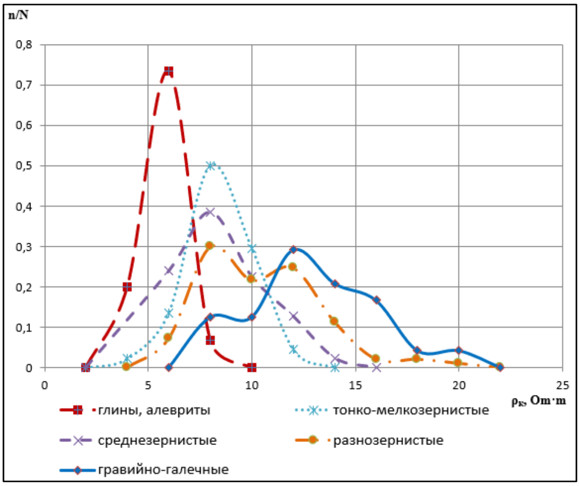

Figure 5 – Example of grouping rocks and determining the modal values of the petrophysical properties of the section (variation graphs of the distribution of apparent electrical resistivities, Mynkudyk ore horizon of the Budenovsk deposit)

In the data processing, sufficient representativeness of the number of determinations was ensured. The sample size (N) and the standard deviation (S) of ρ_a values in Ohm·m were as follows: gravel-pebble deposits – 23 and 3.2; poorly sorted sands, poorly sorted sands with gravel – 97 and 2.69; medium-grained sands – 213 and 2.05; fine to very fine-grained sands – 44 and 1.51; clays, siltstones – 15 and 1.02.

In studying the dependence of ρ_a on the granulometric composition, the closest correlation was found with the median diameter D_{50}. An example of the dependence of ρ_a on D_{50} is presented in Figure 6.

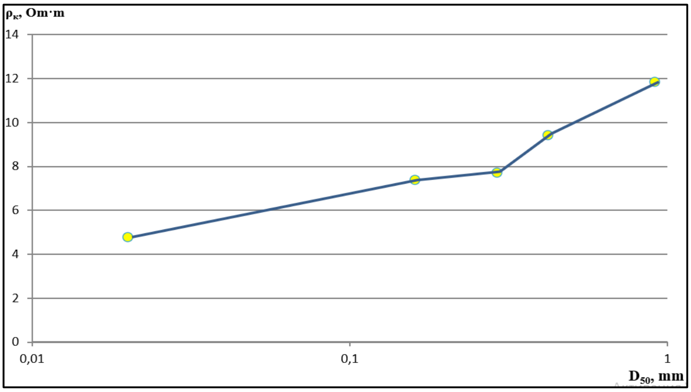

Figure 6 – Graph of the dependence of apparent electrical resistivity ρ_a on the median diameter D_{50} of medium- and different-grained sands, Inkudyk horizon of the Budenovsk deposit

A graph (Figure 6) showing the relationship between apparent electrical resistivity (ρ_a) and the median grain diameter (D_{50}) of medium- and different-grained sands in the Inkudyk horizon of the Budenovsk deposit. The graph indicates a positive correlation, with resistivity increasing as the grain diameter increases.

Based on the results of experimental pumping from hydrogeological wells, the interpretation of flow meter data, and laboratory work, the dependence of the filtration coefficient (C_f) on the median diameter (D_{50}) was established. The results of these studies are presented in Figure 7.

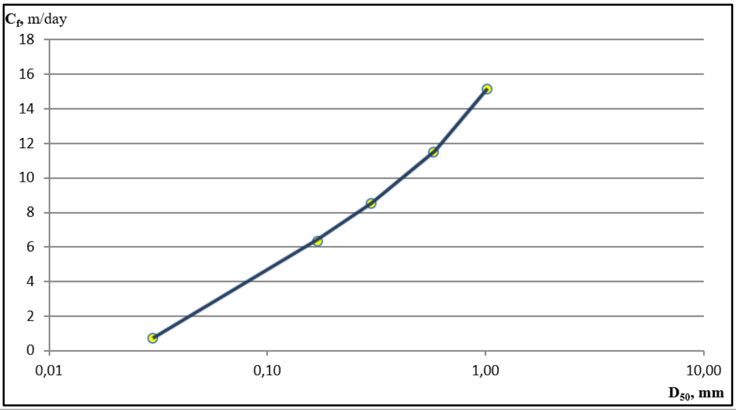

Figure 7 – Graph of the filtration coefficient (C_f) depending on the median diameter (D_{50}) of medium- and different-grained sands

A graph (Figure 7) depicting the relationship between the filtration coefficient (C_f) and the median grain diameter (D_{50}) of medium- and different-grained sands. The graph shows a positive trend, indicating that the filtration coefficient increases with the increase in median grain diameter.

Since the parameter D_{50} is common, the dependence $C_f = f(\rho_a)$ can be represented in an analytical form, as a regression equation, which is subsequently used for calculating C_f values based on apparent resistivity ρ_a data. A graph (Figure 8) showing the relationship between the filtration coefficient (C_f) and apparent resistivity (ρ_a). The graph displays a positive correlation, indicating that as the apparent resistivity increases, the filtration coefficient also increases.

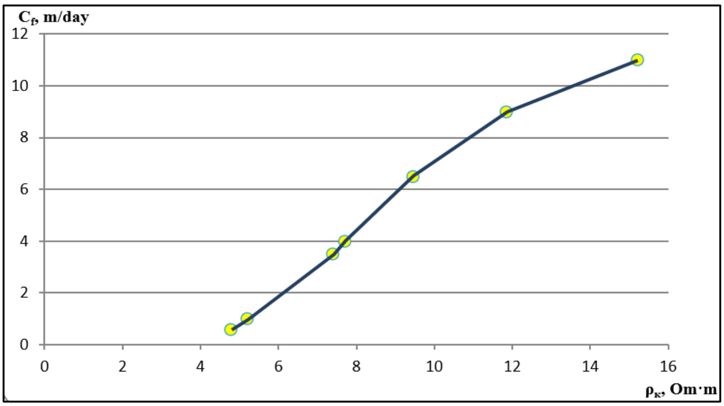

Figure 8 – Graph of filtration coefficient (C_f) versus apparent resistivity (ρ_a)

Geophysical fields (U_{sp}, P) in the wells are presented with coverage of their minimum and maximum values as well as averaged values. Representing the field values in this format is related to the wide range of field value variations and their multifactorial dependence. The minimum value for the exposure dose rate anomalies, according to gamma logging, was set at 80 μR/h (0.8 μSv/h). This threshold was chosen because it generally reflects the minimum industrial uranium content in the ore-bearing horizons of the deposits (Figures 3-4, Table 1).

Table 1. Generalized geological-geophysical/petrophysical information on rocks of ore and barren horizons of uranium deposits of the Shu-Sarysu depression of Kazakhstan according to P (μR/hour), ρ_a (Ohm·m) and U_{sp} (mV)

Age	Name of rocks; *ore horizon*	P , μR/ hour	ρ_a, Ohm·m		U_{sp}, mV		Field
			min.-max.	avg.	min.-max.	avg.	
₽$_{1-2}$	Clays (Chegan)	7 – 11	2.2 – 4.3	3	0	0	Mynkudyk
	Sands are medium- and fine-grained; ***ikan – uyyk – kanzhugan***	80 ≤	5.5 – 9	7	-5 – -2.5	-3	Uvanas
			12 – 20	16	0 – 4	2	Moyynkum
			20 – 40		3 - 30		Kanzhugan
K$_{2m}$ - ₽$_1$	Clays, silts	12 – 13	3 – 7	5	-5 – 3	-3.5	Inkay
			3.6 – 6.6	5.1	-2 – 1	-1	Mynkudyk
	Sands are medium- and fine-grained; ***motley***	80 ≤	9 – 13	11	-1 – 7	-4	Inkay
			4.8 – 12.4	7.4	-6 – 0	-5	Mynkudyk
	Sands of various grains; ***zhalpak***		5 – 12	8.1	-3 – -1	-2	Zhalpak
			6.3 – 15.3	9.89	-10 – -4	-5.5	Akdala
					3 – 30		Kanzhugan
	Sandy gravel	39 – 42	15 – 19	17	- 1 – 3	-2	Inkay
			8.0 – 15.2	10	-5 – 10	-6	Mynkudyk
	Sandstones	18-21	20 – 90	50	-4 – -2	-3	Inkay
			160 – 200	180	-4 – -1.5	-2	Mynkudyk
K$_2$ st	Clays	15 – 17	3.5 – 5	4	- 2 – 3	-0.5	Inkay
		15 – 17	3.6 – 6.6	5.4	-2 – 3		Mynkudyk
	Sands are medium- and fine-grained; ***inkudyk***	80 ≤	8 – 12	10.5	-3 – -1	-2	Budenovsk
		80 ≤	6.6 – 10	7.8	-3 – 1	-2	Mynkudyk
	Sand of different grains; ***inkudyk***	80 ≤	12 – 15	13.5	-1.5 – 0.5	-0.5	Budenovsk
		80 ≤	8.2 – 12	10	-1 – 0.5		Mynkudyk
	Sandy gravel	33 – 35	14 – 19	15.5	-2 – -1	-1	Inkay
		32 – 35	10 – 15	11.2	-0.5 – 0.8	-0.5	Mynkudyk
	Sandstones and gravelites with carbonate and siliceous cement	20 – 25	20 – 70	30	2 – 3	2	Inkay
		20 – 25	100 – 150	140	2.5 – 3	2.5	Mynkudyk
		20 – 25	25 – 250	110	0 – 5	2	Kanzhugan
K$_2$t	Clays, silts	22	3 – 6	4.5	3 – 4	3	Inkay
		22	3 – 6.6	4.8	2.5 – 4	3.5	Mynkudyk
	Sands medium-, fine-grained	18 – 20	7 – 1 2	9.5	-12	-2	Inkay
		18 – 20	6 – 11	7.6	-1 – 2.5		Mynkudyk
	Sand of different grains; ***mynkudyk***	80 ≤	8 – 12	11.8	-3 – -1	-2	Budenovsk
		80 ≤	7 – 14	8.9	-12	-1.5	Mynkudyk

	Sandy gravel	35-37	10 – 1 6	13	-3 – -2	-3	Inkay
	Sandy gravel with pebbles; ***mynkudyk***	80≤	8 – 15	10.5	-2.5 – 3	-2.8	Mynkudyk
	Sandstones and gravelstones with carbonate cement	28 – 31	15 – 40	20	- 2 – 2	2	Inkay
		22 – 25	140 – 190	180	1.5 – 2.5	1.8	Mynkudyk

Information on the number of samples and diagrams for summarizing data and statistical calculations when compiling Table 1 is given in the text

Analysis of literature and archival materials showed that the densities (σ, g/cm^3) of rocks in the study area have been most thoroughly studied for the productive horizons (densities of dry and naturally moist sands with different grain sizes). This necessity is linked to solving technological tasks during the development of uranium sites, such as determining the coefficient of radioactive equilibrium (C_{re}). C_{re} is calculated from the dry rock core and is used to differentiate the influences of radium and uranium on gamma logging (GL) readings. Uranium content, as interpreted from GL logs, is based on the natural (i.e., moist) state of the ore. Therefore, when calculating uranium content from GL data, a correction for moisture is applied.

The densities of ore-bearing (moist) sands range from 1.79 g/cm^3 (Kanzhugan ore horizon, Moyynkum deposit) to 2.04 g/cm^3 (Mynkudyk ore horizon, Inkay deposit). The moisture level (C_m) varies between 14.54% and 22.00%. The density of dry ore-bearing sands ranges from 1.52 to 1.74 g/cm^3. Additionally, data on the densities of dry, barren sands with different grain sizes indicate values of 1.6 g/cm^3 and above.

An analysis of the density characteristics of rocks in the barren horizons of the region ($σ_b$, g/cm^3) was also conducted. The findings indicate that in various petrophysical studies and reports, sedimentary rock groups are categorized differently by age and stratigraphic units. The accuracy of measurement work also varies. Consequently, it is incorrect to compare and identify contrasts between the values of $σ_b$ and $σ_o$ (density of ore-bearing permeable rocks).

Table 2 presents data on barren rocks/horizons from reports on petrophysical studies of core materials (Petrov, et al, 2008).

Table 2. Generalized geological-geophysical/petrophysical information on rocks of ore and barren horizons of uranium deposits of the Shu-Sarysu Depression of Kazakhstan by σ (g/cm ^{3})

Age	**Name of rocks; *ore horizon***	**σ, g/cm3**		***Number of samples**	**Field**
		min.-max.	**avg.**		
₽$_{1-2}$	Clays (Chegan)	1.86 – 2.02	1.96	4	in general for the region
	Sands are medium- and fine-grained; ***ikan*^{1} – *uyyk* ^{2} – *kanzhuga*^{n}3**	1.79 – 1.98	1.91^1, 1.94^2, 1.79^3	-	Moyynkum
		1.89 – 1.93	1.91^2, 1.92^3	-	Kanzhugan

K_2m - P1	Clays,	1.85 – 2.24	2.02	20	in general for the region
	Silts	1.80 – 2.17	1.97	5	
	Sands are medium- and fine-grained; ***motley***	1.99		-	Inkay
					Mynkudyk
	The sands are of different grains; ***zhalpak***	1.95		-	Zhalpak
		1.98		-	Akdala
					Kanzhugan
	***Sandy gravel	1.87 – 2.31	2.13	59	in general for the region
	Sandstones	1.79 – 2.42	2.19	13	
K_2st	Clays	1.90 – 2.13	2.04	20	in general for the region
	Sands are medium- and fine-grained; ***inkudyk***	1.97 – 2.02	2.00	-	Budenovsk
		2.02 – 2.03	2.02		Mynkudyk
	Sand of different grains; ***inkudyk***	1.97 – 2.02	2.00	-	Budenovsk
		2.02 – 2.03	2.02		Mynkudyk
	Sandy gravel	1.87 – 2.31	2.13	59	in general for the region
	Sandstones and gravelites with carbonate and siliceous cement	2.45		13	in general for the region
K_2t	Clays	1.90 – 2.13	2.04	20	in general for the region
	Silts	2.00 – 2.10	2.05	5	
	Sands medium-, fine-grained	1.79 – 2.14	2.02	121	
		1.81 – 2.22	2.04	398	
	Sand of different grains; ***mynkudyk***	1.97 – 2.04	2.00	-	Budenovsk
		1.99		-	Mynkudyk
	Sandy gravel	1.87 – 2.31	2.13	59	in general for the region
	Sandy gravel with pebbles; ***mynkudyk***	1.98 – 1.99	1.99	-	Mynkudyk
	Sandstones and gravelites with carbonate cement	2.45		13	in general for the region

** The number of samples is given for non-metallic rocks; ** Rock density values for all uranium horizons were obtained from data from a special technological study of sands by mining companies; *** in petrophysical materials sandy gravel and sandstones of all tiers of the Upper Cretaceous K_2 (K_2m, K_2st, K_2t) are considered together (Petrov, et al, 2008).*

Within the framework of these studies, the investigation of rock densities (σ, g/cm³) at the deposits aims to identify contrasts in the velocities of seismic wave propagation (V_P , km/s). There is a need to evaluate the potential of seismic methods for section delineation. Velocity parameters in scientific works are provided for rocks of deeper zones (Urazaev, 1971; Kurskeev, 1983); however, V_P and σ in sections have been studied less thoroughly, and detailed information on each rock type is lacking. Only with detailed data on σ_b can the prospects and informativeness of surface-to-borehole seismic methods be evaluated and substantiated when studying ore-bearing and adjacent environments.

Conclusions. The results of compiling the generalized (model) geological-geophysical/petrophysical characteristics showed:

1) the relevance of more detailed studies and the identification of contrasts in the values of apparent resistivity (ρ_a), dielectric permittivity (ε), density (σ), and seismic wave velocity (V_p) of permeable (sands/sandstones of various degrees of sorting) and impermeable (clays, siltstones) rocks (zones 1-7 in Figure 9). These contrasts can serve as the physical basis for selecting well-logging methods: seismic and/or electromagnetic methods in artificial fields for surface-to-borehole and interwell modifications. These methods include vertical seismic profiling (VSP), interwell seismic tomography (IST), and electromagnetic methods (radio-wave profiling, radio-wave geointroscopy, and others) (Istratov, 2008; Belenkiy, et al, 2010). Expanding the use of well-logging technologies at uranium deposits can allow for detailed studies of the geometry and parameters of deposits around and between wells. Consequently, geophysical data can optimize the volume of drilling operations at various stages of uranium site exploration.

The Schematic Section of the Radiological Zoning of a Roller Uranium Ore Deposit shows uranium ores, sands, clayey sandstones, clays, oxidized rock zones, as well as radium diffusion and residual halos (Figure 9). The figure shows the radioactive equilibrium coefficients for different sections of the deposit, the arrow indicates the direction of formation water movement.

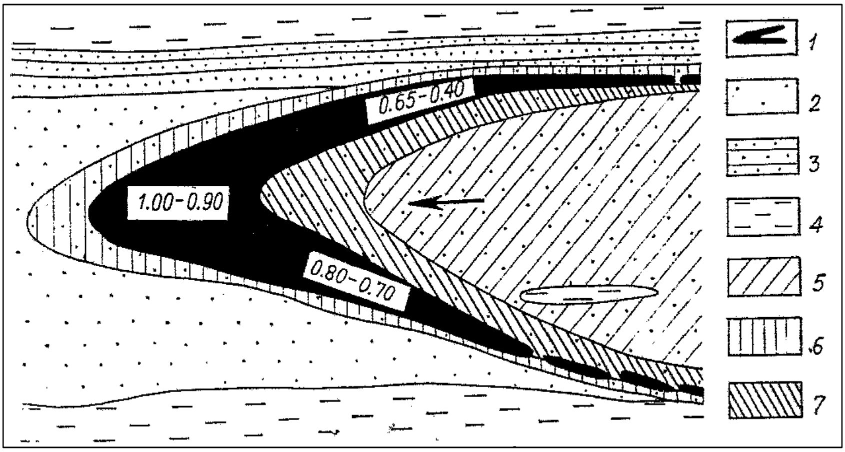

Figure 9 – Scheme of the radiological zoning of the roll uranium ore deposit in the section: 1 – uranium ores; 2 – sands; 3 – clayey sandstones; 4 – clays, silts/siltstones; 5 – zone of oxidized rocks; 6 – diffusion halo of radium; 7 – residual radium halo. The arrow shows the direction of movement of formation waters. The numbers on the black field are the values of the radioactive equilibrium coefficient in different parts of the uranium ore deposit

2) for developing a universal geodata database, additional and more detailed information is necessary. Ensuring the database is updated with relevant information is possible only through a thematic or targeted approach to obtaining

and processing geological-geophysical and laboratory-analytical data. One such theme could be the detailed study and identification of contrasts in the physical properties of rocks throughout the entire section of uranium deposits. These can serve as the physical basis for applying well-logging methods in solving detailed exploration and geotechnological tasks, as well as for petrophysical justification of well-logging diagram interpretations.

3) After selecting the logging method, preliminary calculations of the parameters of the geophysical observation system and experimental-methodological works on characteristic objects and sections should be conducted. During experimental works, the effective parameters of the observation system, and the parameters of the primary signals (from sources) and the recorded seismic/electromagnetic field are refined. Modern geophysical equipment and adapted measurement methodologies allow the registration of small changes in the observed field, related to slight differences in the physical properties of rocks. The results of testing well-logging methods at deposits will enable the development of methodological recommendations for the use of geophysical technologies in solving specific geological and mining-technological tasks.

4) The results of solving the listed tasks can enhance the database used in AI technology for machine and deep learning of geological section models and predictive objects (Sharapatov, et al, 2023).

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CONTENT

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