15. Doré A., Lundin E., Gibbons A., Sømme T., Tørudbakken B. Transform margins of the Arctic: A synthesis and re-evaluation. *Geological Society, London, Special Publications*. 2015. Vol. 431, Iss. 1. DOI: 10.1144/sp431.8
16. Kosko M. K., Sobolev N. N., Korego E. A., Proskurnin V. F., Stolbov N. M. Geology of the Novosibirsk Islands is the basis for the interpretation of geophysical data on the East Arctic Shelf of Russia. *Neftegazovaya geologiya. Teoriya i praktika*. 2013. Vol. 8, No. 2. DOI: 10.17353/2070-5379/17_2013
17. Pavlovskaia E. A., Khudoley A. K., Ruh J. B. et al. Tectonic evolution of the northern Verkhoyansk Fold-and-Thrust Belt: insights from palaeostress analysis and U–Pb calcite dating. *Geological Magazine*. 2022. Vol. 159, Iss. 11-12. pp. 2132–2156.
18. Prokopiev A. V., Khudoley A. K., Egorov A. et al. Late Cretaceous–Early Cenozoic indicators of continental extension on the Laptev Sea shore (North Verkhoyansk). Norway : Geological Society of Norway, 2013. 170 p.
19. Vasiliev D. A., Prokopiev A. V., Khudoley A. K. et al. Thermochronology of the northern part of the Verkhoyansk fold-and-thrust belt according to the track dating of apatite. *Natural Resources of the Arctic and Subarctic*. 2019. Vol. 24, No. 4. pp. 49–66.
20. Frolov S. V., Korobova N. I., Bakay E. A., Kudrina N. S. Hydrocarbon systems and oil and gas potential prospects of the Anabar–Lena trough. *Georesursy*. 2017. Vol. 19, P. 2. pp. 173–185.
21. Jokat W., Uenzelmann-Neben G., Kristoffersen Y., Rasmussen T. M. Lomonosov Ridge—A double-sided continental margin. *Geology*. 1992. Vol. 20, No. 10. pp. 887–890.
22. Jokat W. The sedimentary structure of the Lomonosov Ridge between 88°N and 80°N. *Geophysical Journal International*. 2005. Vol. 163, Iss. 2. pp. 698–726.
23. Jokat W., Ickrath M., O'Connor J. M. Seismic transect across the Lomonosov and Mendeleev Ridges: Constraints on the geological evolution of the Amerasia Basin, Arctic Ocean. *Geophysical Research Letters*. 2013. Vol. 40, Iss. 19. pp. 5047–5051.
24. Arctic Coring Expedition. Available at: http://www.ecord.org/pub/ACEX (accessed: 10/03/2025).
25. Earle S. Physical Geology—2nd Edition. 2019. Available at: https://opentextbc.ca/physicalgeology2ed/ (accessed: 10/03/2025).
26. Prokopyev A. V., Toro J., Smelov A. P., Miller E. L., Wooden J. et al. Ust-Lena Metamorphic Complex (Northeast Asia): The first U-Pb SHRIMP geochronological data. *Otechestvennaya Geologiya*. 2007. Vol. 5. pp. 26–29.
27. Grantz A., Eittreim S. Dinter D. A. Geology and tectonic development of the continental-margin north of Alaska. *Tectonophysics*. 1979. Vol. 59, Iss. 1–4. pp. 263–291.
28. Grantz A., Hart P.E., Childers V.A. Geology and tectonic development of the Amerasia and Canada basins, Arctic Ocean. *Geological Society, London, Memoirs*. 2011. Vol. 35. pp. 771—799.
29. Somme T. O., Dore A. G., Lundin E. R., Torudbakken B. O. Triassic paleogeography of the Arctic: Implications for sediment routing and basin fill. *AAPG Bulletin*. 2018. Vol. 102, No. 12. pp. 2481–2517.
30. Miller E. L., Toro J., Gehrels G. et al. New insights into Arctic paleogeography and tectonics from U–Pb detrital zircon geochronology. *Tectonics*. 2006. Vol. 25, Iss. 3. DOI: 10.1029/2005tc001830
31. Sokolov S., Bondarenko G. Y., Layer P. W., Kravchenko-Berezhnoy I. R. South Anyui suture: Tectono-stratigraphy, deformations, and principal tectonic events. *Stephan Mueller Special Publication Series*. 2009. Vol. 4. pp. 201–221.
32. Kuzmichev A. B. Where does the South Anyui suture go in the New Siberian Islands and Laptev Sea? Implications for the Amerasia Basin origin. *Tectonophysics*. 2009. Vol. 463, Iss. 1–4. pp. 86–108.
33. Vernikovsky V. A., Dobretsov N. L., Metelkin D. V., Matushkin N. Y., Koulakov I. Y. Concerning tectonics and the tectonic evolution of the Arctic. *Russian Geology and Geophysics*. 2013. Vol. 54, No. 8. pp. 838–858.
34. Vernikovsky V. A., Metelkin D. V., Tolmacheva T. Y. Concerning the issue of paleotectonic reconstructions in the Arctic and of the tectonic unity of the New Siberian Islands Terrane: New paleomagnetic and paleontological data. *Doklady Earth Sciences*. 2013. Vol. 451, pp. 791–797.
35. Gaina C., Roest W. R., Muller R. D. Late Cretaceous–Cenozoic deformation of northeast Asia. *Earth and Planetary Science Letters*. 2002. Vol. 197, Iss. 3–4. pp. 273–286.
36. Shephard G. E., Müller R. D., Seton M. The tectonic evolution of the Arctic since Pangea breakup: Integrating constraints from surface geology and geophysics with mantle structure. *Earth-Science Reviews*. 2013. Vol. 124. pp. 148–183.
37. Alvey A., Gaina C., Kusznir N. J., Torsvik T. H. Integrated crustal thickness mapping and plate reconstructions for the high Arctic. *Earth and Planetary Science Letters*. 2008. Vol. 274, Iss. 3–4. pp. 310–321. EM

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# INTEGRATED GEOLOGICAL INTERPRETATION OF GEOPHYSICAL DATA BASED ON 2.5D VOLUMETRIC MODELING

*The relevance of the research is based on the need to enhance the efficiency of geophysical work in the search for zones of sulfide mineralization in the Northwestern Balkhash region, Kazakhstan. The aim of the study is to analyze, summarize and interpret geological and geophysical materials in order to identify promising areas. A comprehensive set of geological and geophysical methods has been applied, including high-precision gravity and magnetic surveys as well as electrical exploration. As a result of 2.5D volume modeling, taking into account various prerequisites and signs of mineralization, we have identified geological and geophysical criteria for detecting gold mineralization. It has been found that ore mineralization is associated with two types of deposits: terrigenous deposits of carbonates and terrigenous rock masses of the Famennian stage of the Upper Devonian. Geophysical criteria for distinguishing ore zones have been defined for these areas. It is found that non-ore areas show a widespread increase in all parameters of geophysical fields. The conducted research allows forecasting supplementary gold mineralization zones, facilitating future geological exploration for gold and associated metals.*

***Keywords:*** *Northwestern Balkhash region, gold, ore mineralization, 2.5D modeling, geophysical studies*
***DOI:*** *10.17580/em.2025.01.02*

## Introduction

The study area is located within one of Kazakhstan's primary regions. This territory is not only rich in mineral resources but also boasts a well-developed mining infrastructure, including gold extraction plants and mining and processing integrated works. The study area encompasses both actively mined gold deposits and those under exploration, requiring further investigation. This includes the medium, large and unique deposits of the Stepnyak–Bestyubinskaya area, which have been in operation for over 60 years and continue to supply Kazakhstan's economy with valuable minerals. The region has sufficient projected resources to sustain mining operations at these mines for an estimated additional 13 years. Gold reserves in the Maikain region are associated with gold-pyrite deposits. Nearly 20 deposits have been in operation here for over 50 years, with 75% of the mining conducted by opencasting. It is predicted that the reserves of the Maikain group of deposits will last for almost 60 years [1–6].

Seitmuratova E. and colleagues have made significant contributions to the study of Northwestern Pribalkhashye [7–11], where, based on the results of lithochemical and metallogenic analyses, the region's gold potential was confirmed.

The study area presented in this article is considered a reserve for replenishing the raw material base of the region's mining and metallurgical sector and therefore requires further exploration, prospecting and detailed study.

The need for exploration work has become urgent due to the depletion of shallow deposits and the necessity to shift focus towards the search for deep-seated ore deposits. To plan such exploration, information about the structure of the deeper parts of the geological section is crucial. Hence, the relevance of the research presented in this article.

At present, seismic exploration data, in addition to drilling results, are considered the most reliable source of information about deep-seated structures. However, the heterogeneous and complex structure of the ore section can complicate the unambiguous interpretation of seismic data. Therefore, when searching for ore, it is necessary to involve a complex of geophysical data.

The effectiveness of integrated geophysical works in searching for gold deposits is confirmed by the results of numerous field studies [12–14]. Despite the fact that geophysical methods are not direct indicators of gold and that geophysicists face a number of difficulties when searching for gold deposits due to the very nature of gold occurrence, the induced polarization (IP) method (in various modifications), for example, is successfully used to identify accumulations of sulfide minerals, with which gold deposits are most often associated [15–16].

In the conditions of the study area, several factors complicate the integrated geophysical works. Firstly, the conditions of gold localization in rocks are very diverse, and the deposits themselves, as a rule, are part of more complex ore systems represented by mineralizations of various specializations [17]. Secondly, gold-bearing deposits, structures and complexes of rocks to which they are confined, as a rule, do not contrast in geophysical fields with host rocks and ore mineralization of other types [17].

## Materials and methods

The reliability of identifying anomaly-forming objects, the resolution of geophysical methods based on an understanding of the region's geological history, and the accuracy and reliability of detecting areas prospective for gold mineralization significantly increase only with a comprehensive analysis of geophysical results. In our case, the geological interpretation is based on data from potential field methods: magnetic, gravimetric and electrical surveys.

Regional gravity and magnetic surveys were conducted for geological mapping, identifying zones of metasomatic alterations, vein and dike bodies, and areas of fracturing and rock fragmentation.

Electrical exploration was carried out using the induced polarization method in the modifications of dipole electrical sounding (DES-IP) and vertical gradient (IP-VG). DES-IP was performed to trace zones of ore mineralization based on the polarizability parameter with the aim of detailed studying the distribution of sulfide mineralization zones and preparing targets for drilling exploration wells, as well as for mapping zones of low resistivity values associated with ore-bearing rocks [18]. DES-IP was conducted in the modification of profile deep soundings using a pole-dipole system. Measurements were carried out simultaneously using an array of 16 receiving dipoles. The dipole length was 50 m, the step of movement along the profile was 50 m, the distance from the feeding electrode to the first receiving one was 50 m. The distance between profiles was 200 m. The depth of investigation was 400 m.

Induced polarization processes are most intense at the contact between the intrapore electrolyte and minerals with high electronic or hole conductivity. Most sulfides, some oxides and graphite belong to such minerals [19]. Since IP-VG is the most sensitive electrical exploration method for tracing zones of sulfide mineralization, this method was used in the study area. Measurements of the potential difference between the receiving electrodes were carried out using two high-precision VPF-210M IP meters and one EIN-209M device. A GER-5M generator was used as a current source during the work. A small HONDA alternating current power station with a frequency of 50 Hz, an output voltage of 220 V, and a power of 5 kW was used as the primary power source. The IP-VG work technology consisted of the following: measurements were carried out using 3 meters on 7 parallel profiles from a single current line AB, located between the third and fifth profiles. The length of the IP-VG measurement zone was 1600 m.

Iron electrodes (5 at points A and B) with a length of 1.2 m were used as electrodes on the AB line, and brass electrodes with a length of 0.4 m were used on the MN line. A HONDA 5 kW power station was used as a current source. As a result, at each point (station) of the profile, two values were measured: the amplitude (signal voltage) and the phase shift of IP (phase) determined by the phase shift of the voltage at the receiving electrodes relative to the phase of the current in the supply line. Further processing allowed calculating the values of $\rho$k (apparent resistivity) and Eta (polarizability) from these values.

For gravimetric observations, automated CG-5 AutoGrav Scintrex gravimeters (Canada) were used, which are widely recognized and used

*a* *b*

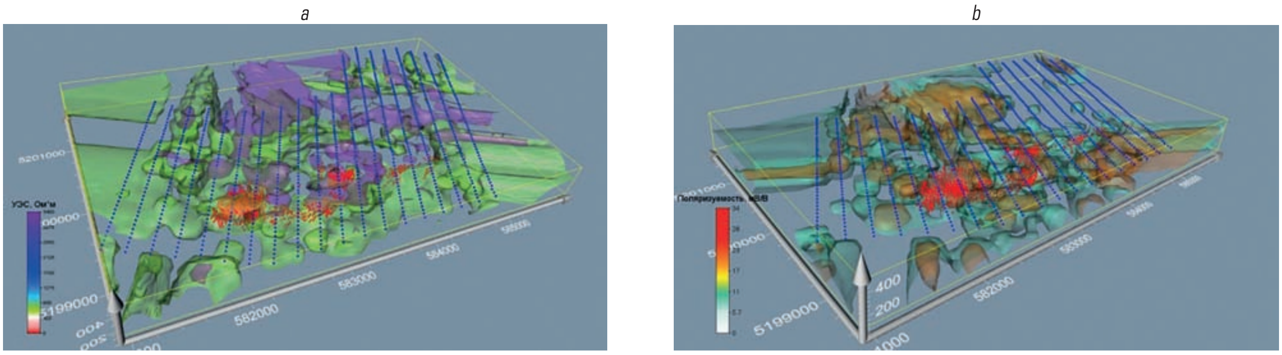


**Fig. 1. 2.5D model of polarizability (*a*) and specific electrical resistance (*b*) built in the Voxler Golden Software program based on the ESD-VP data**

in world practice for high-precision ground gravimetric surveys [18, 20]. Measurements were carried out along profiles with a step of 50 m, the distance between profiles was 100 m.

Magnetic surveying was carried out using G-859 quantum magnetometers (Geometrics, USA). The GPS receiver included in the device allowed measurements to be taken along the profile in continuous mode with an interval of 4 s, which, under the conditions of this section, corresponded to a measurement step along the profile of 3–5 m with an inter-profile distance of 100 m. The errors of the planimetric coordinates did not exceed 5–6 m. To account for daily changes in the geomagnetic field, magnetic surveying was accompanied by recording geomagnetic variations at a ground base station. A proton magnetometer of the MV-07 type was used as a magnetic variation station.

## Procedures

Field and office studies involved preliminary processing of gravity observations of the base network, analysis of the initial gravimetric and topographic-geodetic data, rejection of substandard measurements, calculation of average values of measured readings and calculation of gravity anomalies. All these procedures were carried out using the Trimble Business Center program and specialized modules of the Geosoft Oasis Montaj software complex [21].

Processing of the results of vertical electrical sounding (VES) was carried out according to the following scheme: for each AB array, a folder was created with raw measurements related to this current line. Then, the values of apparent resistivity and polarizability (phase shift) were calculated, and maps of polarizability and apparent resistivity were constructed. Data quality control for outliers and incorrect values was checked in the IP Section module of Oasis Montaj. Here, data on individual blocks related to a specific AB current line array were combined into a common map.

Processing of induced polarization (IP) data involved checking the measured data, constructing pseudo-sections of apparent polarizability and resistivity; solving the inverse problem for geophysical profiles using successive approximations of models for polarizability and resistivity (geophysical inversions); constructing maps of polarizability and resistivity after inversion at various geoelectric levels; and creating a database of polarizability and resistivity [22].

Magnetometer data was daily transferred to a computer and imported into the Geosoft Oasis Montaj database for editing and correction. Magnetic Variation Station (MVS) data was loaded into the same database with time synchronization. Corrections for diurnal variations were applied by simply subtracting the MVS value from the edited magnetic field. For the calculation of the magnetic anomaly, the International Geomagnetic Reference Field (IGRF) was adopted as the normal magnetic field of the Earth. The normal field was calculated using Oasis Montaj.

The value of the normal magnetic field of the Earth, TnMVS, in the area of the MVS location within the study area was –55899.0 nT.

As a result of the office processing of magnetic data, the following maps were obtained: a map of the magnetic anomaly field, a map of magnetic field graphs, and a map of gradient characteristics of the magnetic anomaly field.

To evaluate the regional position of the study area, a comprehensive analysis of the available geological and geophysical data was conducted. The specific features of the geological structure were identified, and the level of exploration of the territory was assessed. Based on the study of the geological structure, the following geological-tectonic criteria for searching for zones of sulfide mineralization were identified: the objects of study are complexes composed of the Upper Devonian terrigenous deposits. Stockwork gold-bearing mineralization is confined to places of contact between intensely compressed, sublatitudinal folds at the contact of the Devonian and Carboniferous deposits. Their formation led to the formation of a dome-like bending of the hinges of intersecting folds with a gentle dip from the fault zone to the west and east. This process led to the significant development of alpine-type quartz veins and veins with poor gold-bearing mineralization in the rocks. Based on the results of the first stage of interpretation, a geological basis was chosen for further interpretation of the obtained geophysical data.

As a result of qualitative interpretation, old (based on the results of previously performed works) and new maps of gravity and magnetic fields were combined. Thus, summary digital models of magnetic and gravitational fields were obtained, which made it possible to calculate sets of transforms of potential fields, to construct schemes of faults based on lineament analysis, and to construct a resulting scheme of geological interpretation of geophysical data.

Quantitative interpretation involves determining the shape, depth of occurrence, magnetic, density, and electrical properties of geological objects, which are estimated by numerical values. The method of quantitative interpretation consisted in comparing the observed data with the results of repeated solution of the direct and inverse problems of gravity-magnetic exploration and electrical prospecting [23]. At the stage of quantitative interpretation, using tomographic interpretation methods, volumetric models of the electrical, density and magnetic properties of the geological medium were calculated.

To obtain a 3D representation of magnetic susceptibility and density distribution within the geological medium, a gravity and magnetic data modeling was performed using the approximate tomography algorithm [24]. Calculations were carried out using the SIGMA 3D software package, DVOP module.

The essence of approximate tomography lies in the sequential selection of the density (magnetic susceptibility) distribution of a horizontally layered model. Layer-by-layer selection of model parameters begins with the bottom layer. The size of the approximation elements in the plan for each layer is equal to the depth of the layer's sole. The program calculates horizontal planes of density (magnetic susceptibility), which are then combined into a single 3D model. The initial gravity and magnetic field was used as input data for modeling [24].

Starting from the bottom layer (5000 m), the distribution of magnetization of a horizontally layered model was selected. The thickness of each layer is 100 m. The size of the approximation elements in the plan for each layer varies and is equal to the depth of the sole of the i-th layer. The program calculates horizontal planes of magnetization, which are then combined into a single 3D model. As a result, a model of magnetization values (in arbitrary units) was constructed, from which vertical sections in the meridional direction and along a given line were extracted.

For the calculation of the geo-density model, the depth to the bottom of the lower layer was assumed to be 1000 m. The thickness of each layer is 25 m. A pentagonal prism with triangular top and bottom bases and vertical side faces was chosen as the elementary cell of the model.

To implement the inversion transformations of the VES data, the ZondRes2D program (author A. Kaminsky, Saint Petersburg, Russia) was used. The program represents an automatic two-dimensional inversion calculation within the framework of 'smooth' models and allows formal interpretation without taking into account a priori data. Mathematically, an iterative selection of a physical model is performed based on the observed distribution of potentials at the receiving dipoles, taking into account the location of current sources. The lower half-space is divided into many elementary cells that approximate the physical parameters of the lower half-space. First, geoelectric models are calculated based on the results of the inversion of apparent resistivity profiles. Inversion of apparent polarizability profiles is carried out based on the calculated geoelectric resistivity model.

## Results and discussion

**Figure 2** presents a layout of interpretation profiles along which geological and geophysical sections were constructed and a comprehensive interpretation was carried out. Since numerous zones of quartzification, gold-bearing halos, and areas with increased gold content were identified in the study area, the interpretation profiles were selected in the southern part of the study area. The direction of the profiles was chosen so that they intersected the ore zone in a meridional direction.

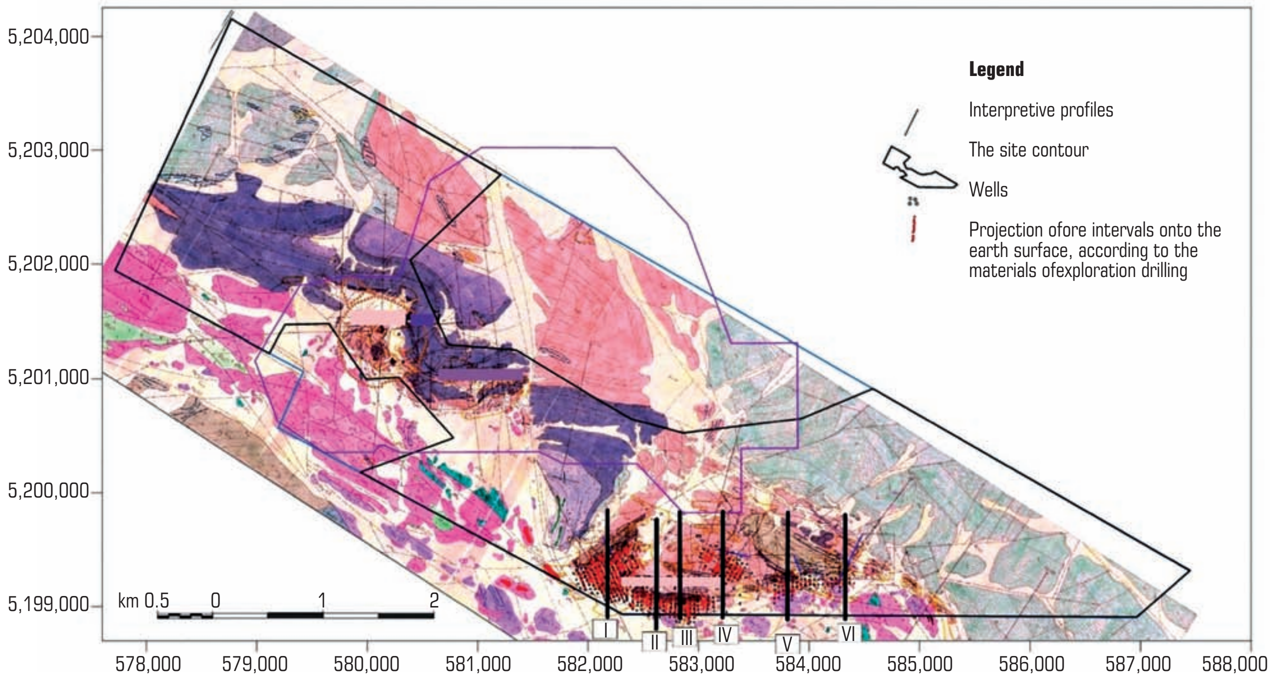


**Fig. 2. Interpretation layout of profiles**

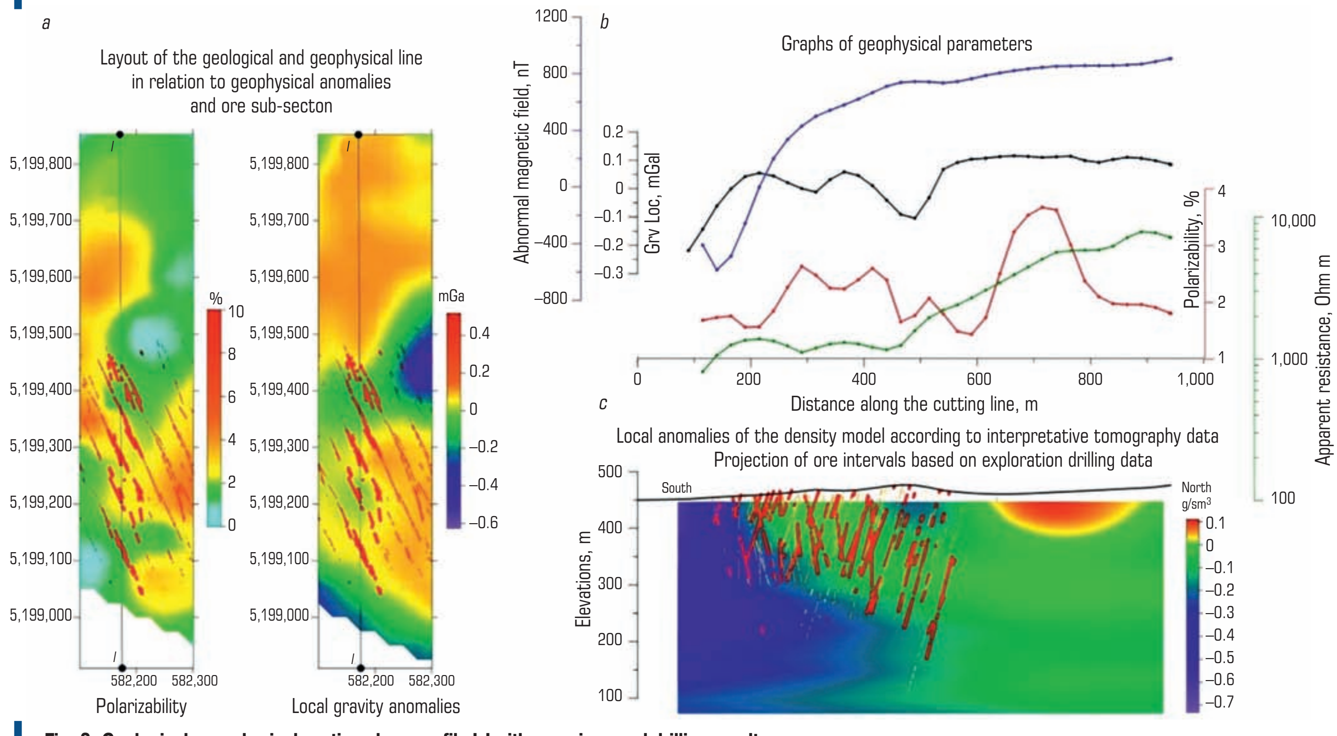


**Fig. 3. Geological–geophysical section along profile I-I with superimposed drilling results:**
*a* – location of the geological–geophysical section line relative to geophysical anomalies and ore shoots; *b* – graphs of geophysical parameters;
*c* – local density anomalies according to the data of interpretational tomography

The geological and geophysical sections include: a set of graphs of geophysical fields along the profile, a geo-density section calculated using approximate tomography, the plan position of the profile relative to geophysical anomalies and ore shoots, as well as projections of ore intervals according to exploration drilling data.

Some profiles were selected along a series of geological cross-sections compiled in previous years during detailed gold exploration and evaluation works (I. V. Stasiv, V. V. Voloshin, et al. 1983).

**Figure 3** shows the geological and geophysical section of profile I-I. It is located on the eastern flank of the study area.

Profile I-I crosses the deposits of the Famennian stage of the Upper Devonian, overlain by Carboniferous terrigenous rocks, in which quartz veins with zones of pyritization and silicification were identified [25]. An analysis of the geological–geophysical section allowed us to form information about the characteristics of geophysical fields in ore zones and non-ore areas based on the survey data obtained in 2018 (**Table 1**).

**Table 1. Results of interpretation of geophysical data along profile I-I**

| Field characteristics | Field value in the ore zone | Characteristics of the field beyond the ore zone contour |
|---|---|---|
| Zone of low magnetic field values | –600–+800 nT | Increase in magnetic field to 1200 nT |
| Zone of local low gravitational field values | –0.25–+0.1 mGal | Increase in gravitational field to 0.3 mGal |
| Zone of high polarizability values | 2.5% on the background of 1.5% | Increase in polarizability to 4% |
| Zone of low resistance values | 150 Ohm m vs 70 Ohm m | Increase in resistance to 800 Ohm m |

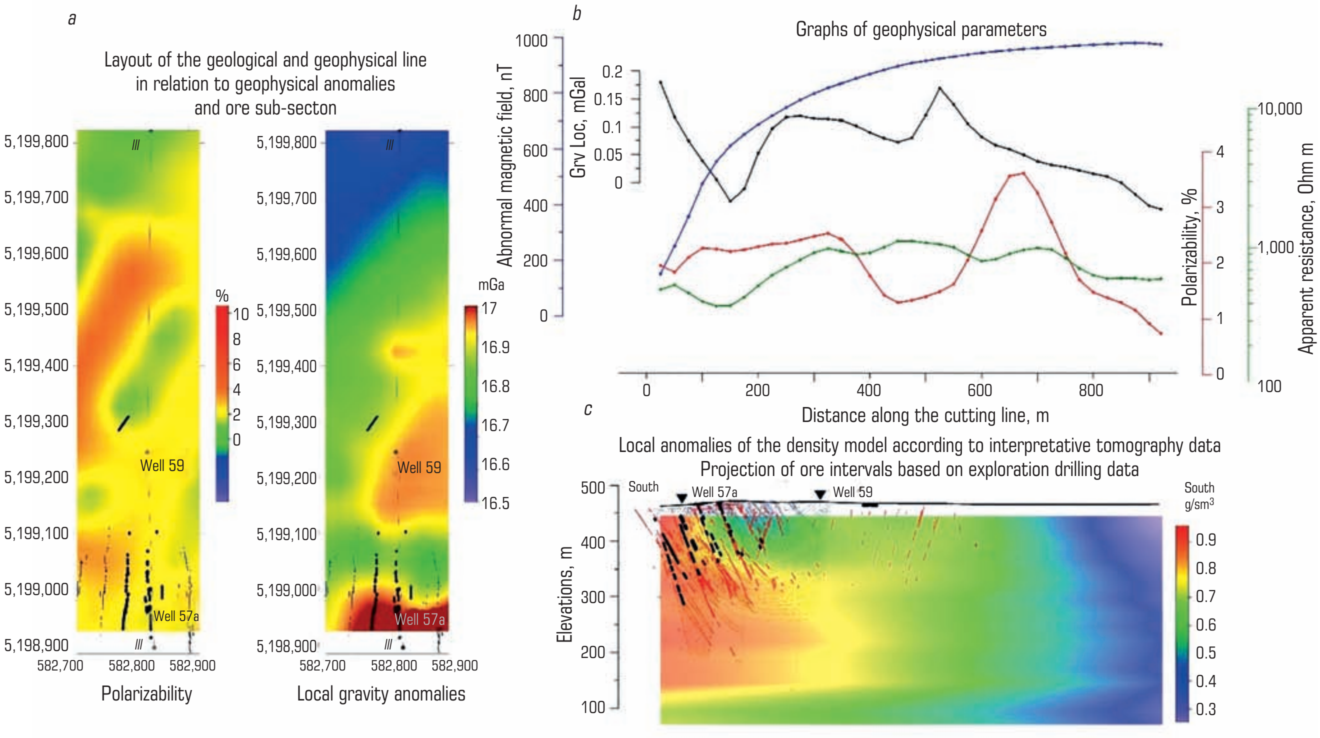


**Fig. 4. Geological–geophysical profile III-III:**
*a* – location of the geological–geophysical profile relative to geophysical anomalies and ore intersections; *b* – graphs of geophysical parameters;
*c* – local anomalies of the density model according to the data of interpretative tomography

**Table 2. Results of geophysical data interpretation for profile III-III**

| Field characteristics | Field value in the ore zone | Characteristics of the field beyond the ore zone contour |
|---|---|---|
| Zone of reduced magnetic field values | +100–+800 nT | Increase in magnetic field to 1000 nT |
| Zone of reduced gravity field values | –0.05 mGal | Increase in gravitational field to 0.2 mGal |
| Zone of increased polarizability values | 2.5% against 1.5% | Increase in polarizability to 3% |
| Zone of low resistivity values | less than 130 Ohm m | Increase in resistance to 1000 Ohm m |

An analysis of the complex geophysical data indicates that within the zone of ore-bearing sections intersected by exploration boreholes, the magnetic field increases along profile I-I from a deep minimum of –600 nT to 1200 nT at the northern end of the profile. Directly within the ore zone, magnetic field intensity values are lower. The same can be said for the gravitational field. In the ore zone, gravitational anomalies are characterized by lower values.

Values of gravitational anomalies vary depending on lithological changes. This is evident in the density cross-section of profile I-I, where we observe density heterogeneity in the ore zone. Here, the effective density increases laterally by a few tenths of a unit. This effect is attributed to the influence of denser Devonian sediments. We have repeatedly emphasized that the density values calculated based on interpretive tomography should be considered as conditional, relative values.

Regarding the electrical parameters of the medium, the section of the profile with the development of quartz veins, pyritization, etc., corresponds to an increase in polarizability up to 4% against the background of a decrease in apparent resistivity. Resistivity values are quite low (up to 200 Ohm·m).

Another aspect that was noted during the interpretation is the behavior of geophysical parameters outside the ore zone. Figure 3 shows a significant increase in the characteristics of all fields beyond the development of quartzification and pyritization processes.

The identified field trends are preserved for profile II-II but differ for profile III-III (**Fig. 4**).

High values of the gravitational field on the southern flank of profile III-III are caused by the influence of listvenites and pyroxenites (see Fig. 4). Further along the profile, a gravitational minimum with an intensity of –0.05 mGal is observed (**Table 2**), caused by the influence of mineralization processes associated with pyritization, serpentinization, which occurred in zones of fracturing and active intrusion of products of tectonic processes.

Further along the profile, a mineralized zone begins again, characterized by a decrease in the intensity of the gravity field. Subsequently, denser Devonian sediments influence the formation of the gravity anomaly amplitude. Thus, we observe that a rather stable criterion for highlighting mineralization zones is formed—a local decrease in the intensity of the gravitational field.

The shape of the magnetic field graph along profile III-III remains the same: a trend of increasing magnetic field intensity from south to north is observed. However, it is necessary to note a change in the level of magnetic field strength. If in the previously considered profiles the magnetic field intensity in the zones of mineralization development varied within the range from -200 to +600 nT, then in profile III-III these values range from +100 to +800 nT.

The parameters of the electric field in the ore zone behave quite standardly: an increase in polarizability up to 2.8% is observed against the background of a decrease in apparent resistivity (up to 130 Ohm·m). This mineralization is confined to a package of terrigenous rocks, predominantly of Carboniferous age. Further along the profile, in the Famennian deposits, another gold halo is observed. And in the rocks of the Upper Devonian, there is a sharp change in the shape of the graphs of electrical field parameters: the apparent resistivity increases to 1100 Ohm·m. Apparently, this is due to the confinement of this halo to the Devonian formations. The density of the Devonian is higher than that of the sandstones and siltstones of the Carboniferous. This probably leads to a decrease in the level of mineralization, which, in turn, leads to a decrease in the intensity of polarizability to 1%.

The areas without mineralization are distinguished by a characteristic increase in all parameters of geophysical fields: polarizability up to 3.5%, apparent resistivity up to 1000 Ohm m, gravity anomalies up to 0.2 mGal and anomalous magnetic field up to 1000 nT. Similar characteristics describe geophysical fields along profiles IV-IV and V-V. Based on the results of a comprehensive interpretation in accordance with certain criteria for searching for sulphide mineralization, anomalous zones of conductivity and polarizability were identified, recommended for further study and assessment for gold mineralization. The obtained materials indicate the complete achievement of the set goal.

## Conclusions

As a result of the geological interpretation conducted in the study area, the search criteria and indicators of ore deposits have been refined. An assessment of the exploration efficiency of geophysical methods has been provided, and a complex of geophysical methods optimal for searching for ore zones has been substantiated. It was found that the intrusive rocks of the Itmurundinskaya Suite, according to the data of induced polarization and magnetotelluric sounding, are characterized by low values of polarizability (1–2%) and apparent resistivity (no higher than 200 Ohm·m). This is most likely due to the fact that the formation of these rocks is closely related to the development of active metamorphism along a deep fault controlling ore formation, when rocks are maximally mixed, altered, and subjected to processes of fragmentation and serpentinization. It is shown that zones of tectonic faults are marked by a sharp change in apparent resistivity values, with contrasting local lows. In geological–geophysical sections, the presence of tectonic disturbances, as well as contact zones of lithological varieties, is marked by the intersection of anomalous magnetic and gravitational field graphs. Zones of silicification, confined to the sedimentary rocks of the Tournaisian and Famennian stages, are distinguished by an increase in apparent resistivity values up to 900-1000 Ohm·m and are confined to the flanks of anomalous resistivity and polarizability values. It has been revealed that extensive polarizability anomalies quite reliably map the Lower Carboniferous deposits with high values, which may be associated with the presence of sulfide mineralization. It was found that in the conditions of the study area, for non-ore zones (based on the consideration of geological–geophysical sections), a widespread increase in all parameters of the geophysical fields is observed.

The obtained materials demonstrate the sufficient effectiveness of the completed geophysical works and the high prospects of the Northwestern Balkhash region for the exploration of large industrial gold deposits. In general, the existing airborne geophysical, gravimetric, and magnetic materials are quite sufficient to solve the problem of creating a modern geophysical foundation, but the collected mass of geological and geophysical information needs to be generalized, correlated, analyzed, and interpreted in the light of modern stratigraphic, geodynamic, metallogenic and other concepts. The interpreted geological and geophysical data can be taken as a basis for planning further exploration work, identifying promising areas, justifying the volumes and methods of exploration geophysical work, and contributing to the increase in reserves and production volumes at ore deposits.

Analysis of the research conducted in the article showed that physical and geological modeling, the elaboration of geological and tectonic conditions for gold ore formation, the study of the relationships between measured geophysical parameters and the physical properties of the rocks that make up the section of the study area, and the establishment of search criteria for quartz-vein-type gold deposits increase the efficiency of discovering new (previously unknown) gold-bearing zones. In quartz-vein and stockwork deposits under the conditions of the North-Western Balkhash region, gravity-magnetic methods show good results, since granitic intrusions are clearly distinguished in the area in the form of local negative anomalies of gravitational fields, and zones of exocontacts, as gradient zones of these fields. Tectonic nodes are mapped in the magnetic field according to characteristic shifts of isolines (a change in directions from meridional to latitudinal). Zones of metasomatism affect the gravity-magnetic field in different ways depending on its type. For example, carbonatization increases, while sericitization and argillization decrease the gravitational field. Fixing the intrusion itself in the gravitational field is associated with a violation of its integrity. The most stable is the geoelectric model, which in the form of a high-resistance plug in a relatively non-conductive environment reflects the intensity of quartz-carbonate metasomatism and the degree of its quartz saturation. When searching directly for quartz veins and zones of sulfide mineralization, it is necessary to use the feature of the geoelectric model, which is expressed in the difference in resistance of quartz veins and zones of sulfide mineralization from the resistance of enclosing rocks and intrusive bodies. As a recommendation, we can propose the application of the method of sounding by the formation of a field in the near zone (ZSB), since this method has a clearly expressed ability to detect quartz veins under a powerful cover of loose sediments.

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### *References*

1. Bespayev H. A., Globa V. A., Abishev V. M., Gulyayeva N. Ya. Gold deposits of Kazakhstan. Directory. Almaty, 1997. 232 p.
2. Rafailovich M. S. Gold of the Bowels of Kazakhstan: Geology, Metallogeny, Predictive and Search Models. Almaty, 2009. 304 p.
3. Rafailovich M. S. Epithermal gold deposits of Kazakhstan. *Geology and exploration of the Subsoil in Kazakhstan*. 1997. No. 5-6. pp. 12–18.
4. Abishev V. M., Aubekerov B. Zh., Bespaev H. A. et al. Placers of gold in Kazakhstan. Directory. Almaty, 1999. 228 p.
5. Umirova G. K., Zakariya M. K., Abdullina A. K. Review of the current state of knowledge in forecasting and searching for gold deposits in the North-Western Balkhash region. *Complex Use of Mineral Resources*. 2024. Vol. 332, No. 1. pp. 62–69.
6. Narseyev V. A., Globa V. A., Grazhdancev N. G., Sinev O. A. Geological and industrial types of gold deposits in Kazakhstan. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*. 1970. Vol. 239. pp. 274–280.
7. Li C., Shen P., Pan H., Seitmuratova E. Control on the size of porphyry copper reserves in the North Balkhash–West Junggar Metallogenic Belt. *Lithos*. 2019. Vol. 328-329. pp. 244–261.

8. Shen P., Pan H., Hattori K., Cooke D. R., Seitmuratova E. Large Paleozoic and Mesozoic porphyry deposits in the Central Asian Orogenic Belt: Geodynamic settings, magmatic sources, and genetic models. *Gondwana Research*. 2018. Vol. 58. pp. 161–194.
9. Seitmuratova E. Y., Goryaeva V. S., Arshamov Y. K. et al. Results of survey works on gold mineralization revaluation for the Zhungar–Alkhash fold belt. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*. 2019. Vol. 1, No 433. pp. 206–215.
10. Li Ch., Pan H., Suo Q., Chu X., Seitmuratova E. Comparison of natures of barren and fertile intrusions in the Kounrad ore district, Kazakhstan and its implication for mineralization. *Acta Petrologica Sinica*. Vol. 39(11). pp. 3263–3283.
11. Seitmuratova E. Y., Goryaeva V. S., Shaidasheva F. F. et al. The current state of research on secondary quartzites of the Northern Segment of the Jungar-Balkhash Folded system and their Au mineralization (Central Kazakhstan). *Mineral*s. 2023. Vol. 13, Iss. 6. ID 813.
12. Faye Ch. I., Ndiaye A. A., Dia I., Gueye M., Moritz R. Geological, geophysical and surface geochemical guides for gold exploration in the Falémé Volcanic Belt, West African Craton, Senegal. *Journal of Geochemical Exploration*. 2023. Vol. 245. ID 107145.
13. Tchokpon K. G., Kaki Ch., Kourouma M., Yalo N. Detection of gold-bearing quartz veins in the meta-sedimentary formation in the North-Eastern Guinea using remote sensing and geophysical exploration. *Journal of African Earth Sciences*. 2020. Vol 168. ID 103869.
14. Hesselbom A. Geophysical methods in the exploration for gold-bearing quartz veins in Nicaragua. *Geoexploration*. 1985. Vol. 23(3). pp. 416–417.
15. Sono P., Nthaba B., Shemang E. M., Kgosidintsi B., Seane T. An integrated use of induced polarization and electrical resistivity imaging methods to delineate zones of potential gold mineralization in the Phitshane Molopo area, Southeast Botswana. *Journal of African Earth Sciences*. 2021. Vol. 174. ID 104060.
16. Zeinedinov D. T., Zhonys N. B., Umirova G. K. Fundamentals of rational integration of geophysics methods to improve their geological efficiency in forecasting, prospecting and further study of polymetal deposits in central Kazakhstan. *17th Conference and Exhibition Engineering and Mining Geophysics*. 2021. Vol. 2021. pp. 1–11.
17. Shherba I. G. Hercynian Structure of the Northern Balkhash Region. Moscow: Nauka, 1973. 249 p.
18. Jukebayev M., Umirova G., Marinenko V. Results of using Kazakhstan high-precision electro-prospecting equipment for solving ore problems. *14th Conference and Exhibition on Engineering and Mining Geophysics 2018 Almaty*. 2018. Vol. 2018. pp. 1–6.
19. Ivanov A. A., Novikov K. V., Novikov P. V. Electrical Prospecting. Moscow : MGRI, 2019. 79 p.
20. Sarsengaliyev A. M., Umirova G. K. Efficiency of gravity and electrical exploration using the audio-frequency magnetotellurics survey in the conditions of the Atasu deposits type. *E-Scio*. 2022. No. 4(67). pp. 146–164.
21. Genik I. V. Functional comparison of programs for solving problems of gravimetry and magnetometry. *Gornoye eho*. 2021. No. 2. pp. 42–51.
22. Hasan Zaid H. A., Arifin M. H., Kayode J. S. et al. Application of 2-D electrical resistivity imaging, and induced polarization methods for delineating gold mineralisation at Felda Chiku 3, Kelantan, Malaysia. *Sains Malaysiana*. 2023. Vol. 52, No. 1. pp. 305–320.
23. Kostitsyn V. I., Khmelevskoy V. K. Geophysics. Perm : PGNIU, 2018. 428 p.
24. Dolgal A. S. Gravimetry and Magnetometry: Transformations of Geopotential Fields. Perm: PGNIU, 2022. 140 p.
25. Yanovskaya T. B., Porohova L. N. Inverse Problems of Geophysics. Saint Petersburg : Izdatelstvo Sankt-Peterburgskogo gosudarstvennogo universiteta, 2004. 216 p. EM


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# FORECASTING ROLL-FRONT URANIUM PROVINCES BASED ON INTEGRATED GEOLOGICAL AND SATELLITE REMOTE SENSING DATA


*An innovative approach has been developed to predict prospective areas for the exploration of roll-front uranium deposits. This method is based on the infiltration model of ore formation and incorporates the advanced exploration practices of roll-front uranium deposits in Kazakhstan, compared with global experience. The approach employs publicly available satellite Earth observation data alongside global geological datasets. Applying this methodology has allowed the identification of prospective areas for roll-front uranium ore exploration and provided a brief characterization of the most significant ones. Special attention is given to large depressions conducive to infiltration conditions, ranging from regions of atmospheric water recharge in arid and semi-arid climates to sedimentary areas under reverse climatic conditions with favorable environments for the formation of reductive geochemical zones. These zones are characterized by active sulfate-reduction processes mediated by microorganisms and the generation of hydrogen sulfide fluids.*



***Keywords:*** *uranium mineralization, roll-front, forecasting, ore formation model, exploration*
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## Introduction

The development of nuclear technologies in the 20th century enhanced the industrial importance of uranium resources, increasing global attention to them [1]. In the latter half of the 20th century, large-scale exploration and prospecting activities for uranium led to the discovery of numerous deposits worldwide [2]. By the late 20th century, the rate of new discoveries had declined, while sustained high demand for uranium continues to drive the depletion of mineral resources [3]. In the 21st century, uranium production has outpaced the replenishment of its mineral resource base [4], prompting the need for innovative approaches to uranium ore exploration. The highest demand is most effectively met by deposits mined using the advanced in-situ recovery (ISR) method [5], predominantly represented by roll-front uranium deposits in Kazakhstan [6].

The genesis of roll-front uranium deposits is influenced by the solubility of uranium in atmospheric and carbonated waters, its migratory capacity in artesian aquifers, and ore-forming precipitation at geochemical barriers in reductive environments (**Fig. 1**). The depths of such deposits range from tens to over a thousand meters. Their exploration is complicated by deep burial under thick sedimentary cover, which significantly limits the effectiveness of