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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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ИЗВЕСТИЯ

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THE EFFICIENCY OF A COMPLEX OF GEOPHYSICAL METHODS BY EXAMPLE OF THE ATASU ORE DISTRICT

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Abstract. The relevance of this research is determined by the increasing complexity of geological conditions and the depth of exploration works, as well as the need to optimize exploration costs for solid mineral deposits. Thus, the application of effective geophysical methods for studying geological structures and predicting deposits has become a critical task. The objective of this study is to evaluate the effectiveness of a complex of geophysical methods using the example of the Atasu ore district in Central Kazakhstan, aimed at improving the accuracy of exploration work while reducing drilling costs.

The study includes the collection and analysis of prior geological information, addressing the geological and geophysical knowledge of the area, the characteristics of its geological structure, and the petrophysical properties of the rocks. A complex approach was implemented, utilizing gravity, magnetic and electrical exploration using the audio-magnetotelluric sounding (AMTS). Gravimetry and magnetometry were particularly effective in mapping geological structures, identifying faults, and distinguishing rock types based on their composition.[2] AMTS proved successful in identifying ore horizons and host rocks, enabling the construction of a detailed geoelectrical model.

The results confirm the high informativeness and accuracy of the selected geophysical methods, facilitating the determination of geological structures and the identification of ore zones. The scientific novelty of this work lies in applying a comprehensive approach to evaluating geophysical methods under the specific conditions of the Atasu region. The practical significance of the research is evident in its potential application for the effective exploration of mineral deposits in Central Kazakhstan.

Keywords: Atasu ore district, polymetallic ores, complex of geophysical methods, processing and interpretation, magnetic prospecting, gravity prospecting, electrical prospecting, AMTS method

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АТАСУ КЕНДІ АЙМАҒЫ МЫСАЛЫНДА ГЕОФИЗИКАЛЫҚ ӘДІСТЕР КЕШЕНІНІҢ ТИІМДІЛІГІ

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Аннотация. Жұмыстың өзектілігі қазіргі жағдайда, іздеу-барлау жұмыстары кезінде зерттелетін геологиялық құрылымның күрделілігі мен тереңдігінің артуымен, сондай-ақ қатты пайдалы қазбалар кен орындарын барлау шығындарын оңтайландыру қажеттілігімен анықталады. Осыған байланысты кен орындарының геологиялық құрылымы мен болжамын зерттеу үшін тиімді геофизикалық әдістерінің кешенің қолдану маңызды

мәселе. Жұмыстың *мақсаты*, Орталық Қазақстандағы Атасу кенді аймағы мысалында геофизикалық әдістер кешенінің тиімділігін бағалау, бұл барлау жұмыстарының дәлдігін арттыруға және бұрғылау зерттеулеріне жұмсалатын шығындарды азайтуға мүмкіндік береді.

Зерттеу жұмысы шеңберінде априорлық геологиялық ақпаратты жинау және талдау бойынша үлкен жұмыс жүргізілді, ауданның геология-геофизикалық зерделеу мәселелері, геологиялық құрылымның ерекшеліктері, тау жыныстарының петрофизикалық параметрлері және т.б. қарастырылды. Нәтижесінде, геологиялық құрылымдарды кешенді зерттеуге мүмкіндік беретін аудиомагнитотеллуриялық зондтау (АМТЗ) модификациясындағы электр барлау, гравибарлау, магниттік барлау әдістерінің нәтижелері пайдаланылды. Гравиметрия мен магниттік барлау геологиялық құрылымдарды карталауда және жарылымдарды оқшаулауда, сондай-ақ тау жыныстарын заттық құрамы бойынша ажыратуда жоғары тиімділікті көрсетті. АМТЗ әдісімен электр барлау кенді горизонттары мен негізгі сыйыстырушы тау жыныстарды анықтауда сәтті болды, бұл зерттелетін аумақтың дәл геоэлектрлік моделін құруға мүмкіндік берді.

Қорытындылай келе, геофизикалық әдістер кешенінің нәтижелеріне жүргізілген талдау осы аймақтағы геологиялық құрылым мен кенді аймақтарды анықтау кезінде әрбір әдістің тиімділігін бағалауға мүмкіндік беріп, осы ауданды зерттеу кезінде геофизикалық әдістер кешенінің айтарлықтай ақпараттылығы мен дәлдігін көрсетеді. Жұмыстың ғылыми жаңалығы Атасу кенді аймағы жағдайында геофизикалық әдістерді бағалау үшін кешенді тәсіл мен алынған деректерді өңдеудің жаңа интерпретациялық әдістерін қолдану болып табылады. Зерттеудің практикалық маңыздылығы Орталық Қазақстан мен геологиялық жағдайлары ұқсас басқа өңірлердегі кен орындарын тиімді барлау үшін осы әдістерді қолдану мүмкіндігінде жатыр.

Түйін сөздер: Атасу кенді аймағы, полиметал кендері, геофизикалық әдістер кешені, деректерді өңдеу, интерпретация, магниттік барлау, гравибарлау, электрлік барлау, АМТЗ әдісі

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ЭФФЕКТИВНОСТЬ КОМПЛЕКСА ГЕОФИЗИЧЕСКИХ МЕТОДОВ НА ПРИМЕРЕ АТАСУЙСКОГО РУДНОГО РАЙОНА

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Аннотация. Актуальность исследования определяется возрастанием сложности геологических условий и глубины поисково-разведочных работ, а также необходимостью оптимизации затрат на разведку месторождений твердых полезных ископаемых. В связи с этим важнейшей задачей является применение эффективных геофизических методов для изучения геологической структуры и прогноза месторождений. Целью работы является оценка эффективности комплекса геофизических методов на примере Атасуйского рудного района в Центральном Казахстане, что позволяет повысить точность разведочных работ и снизить затраты на буровые исследования.

В рамках исследования проведена большая работа по сбору и анализу априорной геологической информации, рассмотрены вопросы геолого-геофизической изученности района, особенности геологического строения, петрофизические параметры пород и т.д. В конечном итоге использованы результаты методов гравиразведки, магниторазведки и электроразведки в модификации аудио-магнитотеллурических зондирований (АМТЗ), которые обеспечивают комплексный подход к изучению геологических структур. Гравиметрия и магниторазведка продемонстрировали высокую эффективность в картировании геологических структур и выделении разломов, а также в различении горных пород по вещественному составу. Электроразведка методом АМТЗ оказался успешным в выявлении рудных горизонтов и вмещающих пород, что позволило построить точную геоэлектрическую модель исследуемой площади.

Полученные результаты подтверждают высокую информативность и точность комплекса выбранных геофизических методов, что способствует успешному определению геологической структуры и выявлению рудных зон. Научная новизна работы заключается в применении комплексного подхода для оценки геофизических методов в условиях Атасуйского рудного района, а также в использовании новых интерпретационных методов для обработки полученных данных. Практическая значимость исследования заключается в возможности применения данных методов для эффективной разведки месторождений в Центральном Казахстане и других регионах с аналогичными геологическими условиями.

Ключевые слова: Атасуйский рудный район, полиметаллические руды, комплекс геофизических методов, обработка и интерпретация, магниторазведка, гравиразведка, электроразведка, метод АМТЗ

Introduction. Today, most of the ore districts and deposits of solid minerals in Kazakhstan are quite well explored from the surface, as a result, the reserves and stocks of shallow, easily accessible deposits are practically exhausted. Therefore, the search and discovery of deposits at medium and great depths becomes the most important task. In connection with the increasing depth of prospecting and exploration work, the complication of the geological and tectonic structure of mineralization zones, the increasing labor intensity and cost of drilling operations, the emphasis is on the widespread use of the results of complex geophysical surveys. Today they are characterized by increasing the quality of hardware-processing complexes and effective measurement technologies. The authors will consider the possibilities of integrated use of geophysical methods by example of one of the deposits of the Atasu ore district.

The study presented in the article is highly relevant, since the Atasu ore district is an important raw material base for the ferromanganese and lead-zinc industries of Kazakhstan. Here one can note the famous deposits of zinc and lead and barite, among them the Mirgalimsay, the Achisay, the Akzhal, the Uzunzhal, the Karagaily, the Shalkiya, the Zhairem fields. The Karazhal, the Kentyube and the Ushkatyn deposits are the richest bases of iron and manganese. Therefore, for many years, geological and geophysical work of various scales has been carried out in this territory. Based on the results of these studies, the North Aktai and the Karatulen magnetic anomalies were discovered. They are confined to the structural complex of the Zhailma syncline, where large deposits of base metals were identified. According to geologists, the deposits located at shallow depths suggest the presence of hidden reserves at great depths. This fact increases the potential prospect of discovering new deposits in the Atasu ore district.

The studied site is located in the Zhanaarka district of the Ulytau region of Kazakhstan, 25 kilometers from the city of Karazhal. The area is characterized by the developed infrastructure and the presence of industrial enterprises, including mining complexes located within the radius of 50 to 150 kilometers from the studied site, such as Zhairem MPP, the Balkhash and the Zhezkazgan MMCs.

The ultimate goal of the work is studying the efficiency of using a set of geophysical methods in order to optimize geological exploration and to increase the accuracy of detecting mineral deposits.

The goal will be achieved by systematical solving the following tasks:

1. Collecting, synthesizing and analyzing a priori information to highlight the features of the geological structure of the Atasu ore district.

2. Studying the applicability of geophysical methods, the range of tasks to be solved and justifying the composition of the complex of geophysical methods.

3. Studying the results of method-by-method interpretation of geophysical data.
4. Determining the efficiency of a complex of geophysical methods in studying the nature of the gravimagnetic anomaly and identifying ore intervals based on a comprehensive interpretation of geological and geophysical data.

The current state of knowledge of the Atasu ore district

The territory of the Atasu district was studied in different years by various specialists. At the beginning of the 20th century, hydrogeological work was carried out here by A.A. Kozyrev. Later, in 1926, a geological survey on a scale of 1:420,000 was carried out by I.S. Yagovkin, and in 1932 a geological map was compiled under the leadership of I.G. Nikolayev. As a result of those works, deposits of iron and manganese were discovered. After a break in 1951, search work was resumed with the participation of M.E. Kerensky, N.K. Dvoycheko, V.N. Vaitonis and the entire area was mapped on a scale of 1:200,000 in 1960. In subsequent decades, prospecting and evaluation work was carried out for various ores, including barite-polymetallic and ferromanganese ores, which made the Atasu region an attractive object for geological studies (Kayupova, 1974; Ministry of Geology KazSSR., 1953).

Studying the geophysical nature of the Atasu ore district was divided into three stages, covering the time interval from the 1930s to the 1990s. The first stage (1930-1950) was characterized by magnetic prospecting surveys by D.N. Redkin and the formation of the Atasu Geophysical Party, later transformed into the Atasu Geophysical Expedition. The second stage (1950-1970) included gravity exploration work of the Ministry of Geology of the SSAGT, which led to the compiling the maps of the regional gravity field and residual anomalies on a scale of 1:50,000 and 1:25,000. The third stage (1970-1990) included exploratory seismic surveys on a scale of 1:50,000 in the Zhailma trough area (Kayupova, 1974; Ministry of Geology KazSSR., 1953). The results of those works made it possible to discover new ore-controlling structures and to determine the depth of depressions in the base of the Famennian carbonate sequence, which became the basis for formulating recommendations for placing the areas for further research.

The analysis of the geophysical study of the considered area shows that many deposits of base metals and ores have been identified in the Atasu ore district, but there is a potential for further exploration of the largest anomalies associated with the deep occurrence of ore objects of unknown nature. The experience of the past work shows a high information content of using updated geophysical complexes to further study the geological structure of the studied area.

Geological features of the Atasu ore district structure

The studied area is located in the southeastern part of the Zhailma syncline and occupies the intermediate position between the Balkhash region and the Dzhezkazgan-Ulytau region. Geological studies indicate the formation of rift structures on the continental crust of the pre-Middle Devonian age. Basically, there are hydrothermal deposits of lead-zinc and ferromanganese ores concentrated in marine carbonate deposits of the Famennian stage. The main geological formation of the area is the Zhailma graben-syncline that is a first-order prospecting and exploration structure that determines the location of large ore belts. The graben-syncline has an irregular shape and is characterized by an arcuate shape with the width of 12 to 30 km and the length of more than 175 km. The most prominent fault in this structure is the Ashchily tectonic rupture, with the fall amplitude of 300 meters (Ministry of Geology KazSSR, 1953; Kayupova, 1974; Lyubetskiy et.al., 2009).

The rocks of the region are represented by a variety of sedimentary, intrusive and volcanic formations from the Cambrian to the Quaternary deposits. Ferromanganese and lead-zinc mineralization belongs to the deposits of the Upper Famennian substage, where ore bodies underlie layers of iron ores and sometimes alternate with them and are confined to the pigmented carbonaceous horizons of the Upper Famennian. There are two main complexes of rocks of the Upper Devonian period: the terrigenous complex of the Frasnian stage and the carbonate complex of deposits of the Famennian stage. The Frasnian deposits assigned to the Dairen formation have a variety of rock types, including conglomerates, sandstones, gravelites, and subvolcanic liparite bodies. The Famennian stage sediments consist mainly of limestone, clayey-carbonate and carbonaceous-siliceous-carbonate rocks. In this area, sheet-like lead-zinc ore bodies underlie layers of iron ore and sometimes alternate with them, while being confined to pigmented carbonaceous horizons of the Upper Famennian substage (Satpaev, 1968; Kayupova, 1974; Ministry of Geology KazSSR, 1953).

The studied area is characterized by the presence of ferromanganese and lead-zinc mineralization that belongs to the deposits of the Upper Famennian substage. Iron ores usually contain high concentrations of germanium and consist of magnetite, hematite and ferruginous jasper, sometimes with traces of lead, arsenic and the other elements. Manganese ores include in turn braunite, hausmannite, jacobsite and pyrolusite. In addition to lead and zinc, lead-zinc ores can contain silver, cadmium, mercury, copper, thallium, antimony and arsenic (Kayupova, 1974; Lyubetskiy et.al., 2009).

Studying the geophysical fields and anomalies in the Zhailma graben-syncline requires knowledge of the physical parameters of rocks and ore bodies that make up the geological structure of the area. The analysis of a priori information shows that the density of various rocks is unique: gabbrodolerites have the highest density on average 2.8 cm/g^3, deposits of the Posidonian formation (D_3-$C_1 ps_2$) and the Famennian stage ($D_3 fm$) have approximately the same density values of 2.4 cm/g^3. Most of the rocks in the study area are mainly classified as non-magnetic. The deposits of the lower Famennian stage ($D_3 fm$) have average values of magnetic susceptibility. Gabbrodolerite intervals have high magnetic sensitivity with average values of $120 \cdot 10^{-5}$ SI units (Kurskeev, 1983; Lyubetskiy et.al., 2009). High gravity values are associated with the influence of productive deposits of the Famennian stage, which makes this parameter a significant feature for prospecting and exploration work.

Justification of carrying out a complex of geophysical methods in the studied area

Analyzing a priori information made it possible to conclude that the study area is promising for ferromanganese mineralization. The following factors indicate this conclusion.

1. The proposed ore body is confined to the Zhailma graben-syncline and is associated with large barite-base metal deposits Bestobe, Eastern Zhairem and Western Karazhal. Barite lead-zinc and iron ores are located at a great depth in the central part of the trough. Geological evidence indicates a similar uplift surrounded by major faults.

2. Structural tectonic control is represented by two faults surrounding the inferred ore body, which act as ore conduits for hydrothermal solutions.

3. Lithological control is characterized by the development of silts and depression-type sections that are typical for the Zhairem deposit complex. In this complex mineralization occurred in gray-colored deposits of the Upper Famennian that are distinguished by petrophysical characteristics (Kayupova, 1974).

Traditionally, in prospecting and exploration for ferromanganese mineralization, electrical, magnetic and gravimetric methods are most widely used. Gravity prospecting and magnetic prospecting are used as part of a geophysical complex when solving problems of deep mapping the structures, additional study of the geological structure and solving the problem of detailed surveying of ore-controlling complexes or ore objects. Electrical prospecting still remains the main method of exploring ore objects and mineralization zones. It is most effective at medium depths (up to 500-1,000 meters) when searching for deposits covered by loose strata. Analyzing the entire volume of information makes it possible to substantiate a complex of geophysical methods, including ground-based magnetic and gravity surveys, as well as electrical prospecting using the AMTS method (Lyubetskiy et.al., 2009; Umirova, et.al., 2018).

Materials and basic methods

Ground magnetic survey work was carried out in area and profile versions with a profile step of 25 m, using high-precision Overhauser magnetometers GEM GSM-19W. Gravity survey work was also carried out in profile and area versions with the use of SCINTREX CG-5 Autograv gravimeters with a profile step of 25 m. Processing the field magnetic survey and gravity survey data included introducing of various types of corrections and was carried out in the specialized Geosoft Oasis Montaj software (Khesin B, et.al., 1996; Balk P, 2021; Ibraheem et.al., 2023).

Electrical prospecting AMTS studies were carried out in profile (step 100 m) and area versions using the 500×200 m net. Audio-magnetotelluric soundings were carried out using high-precision equipment MTU-5A "Phoenix Geophysics". The work was carried out according to the scheme with a remote base point and several stations simultaneously.

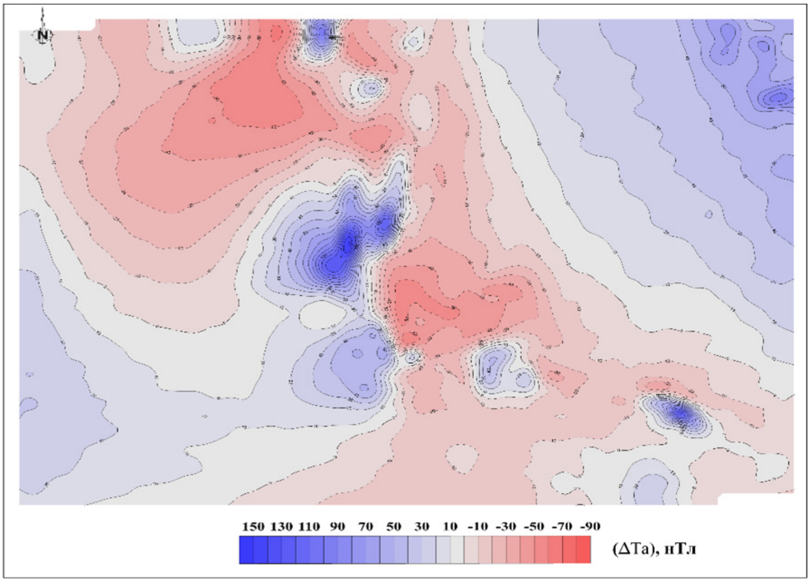

Figure 1 – Isodynamic map of the anomalous magnetic field of the ΔTa

Based on the results of the area magnetic exploration work, maps of isodynamics of the anomalous magnetic field were compiled (Figure 1). Magnetic susceptibility of rocks in the studied area is characterized by slight differentiation, therefore the magnetic field of the area is calm and is characterized by relatively small values of the magnetic intensity vector ΔT_a from -100 to 150 nTl. There are no sharp gradient zones that allow clear mapping tectonic disturbances. In the central part of the site, a submerial fault can be traced that is considered the axial part of the rift structure. The Karatulen anomaly is confined to this fault. The central and eastern parts of the site, represented mostly by deep-sea Famennian-Tournaisian sediments, are mapped with average magnetic field values (0-40 nTl). The western part of the site is represented by the Lower Carboniferous deposits and is characterized by a negative magnetic field. The most intense zone (more than 130 nTl) is located in the central part of the site. To the south of it, another intense zone of up to 50 nTl is recorded (Kayupova, 1974; Balk P, 2021). In the southeastern part of the site, an anomalous region of medium intensity (up to 120 nT) of the magnetic field is observed.

To obtain a map of local components ΔT_a, a set of magnetic field transformants was calculated (high-frequency filtering, local component after recalculation of the original field into the upper half-space), which made it possible to most clearly identify and trace geological boundaries and bodies with increased magnetic characteristics (Balk P., 2021). The boundaries of anomaly-forming objects are clearly visible on the map of the local component. The shape of the transformed field does not differ much from the original field, which indicates the deep occurrence of large geological objects, and therefore is not presented in the article (Ibraheem et.al., 2023; Eppelbaum, 2024).

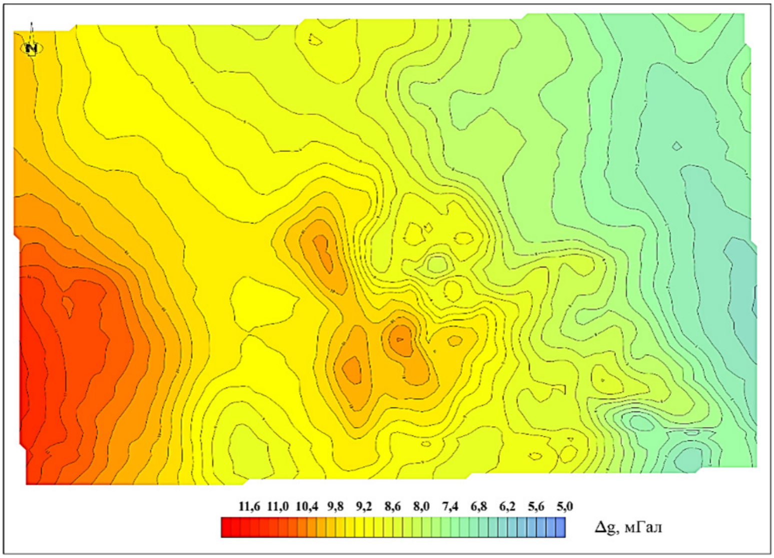

Figure 2 – Map of local gravitational anomalies (Hw=1000 m)

Based on the results of area gravity surveys, the maps of the anomalous gravitational field and local component were obtained (Figure 2); horizontal and vertical gradients of the gravitational field were calculated to clearly identify and trace geological objects with increased density characteristics. The local field intensity varies between -1.2 and 1.4 mGal. On the map of the local component of the gravitational field, increasing the intensity of the gravitational field at the eastern boundary of the site from 6.6 mGal in the sublatitudinal direction to 11.4 mGal in the extreme west is clearly visible (Balk P, 2021; Abdoldina et.al., 2021).

The minimum values of the gravitational field (up to 8-8.4 mGl) are observed in the Lower Famennian deposits in the eastern part of the site, starting in the southern part and ending in the north. The central and western parts of the site composed of the Famennian-Tournaisian and Visean-Serpukhovian deposits, are mapped with average values (8-10 mGl). The southwestern part is distinguished by a sharp increase in the gravitational field of more than 11 mGal. On the map of the Paleozoic basement, in this area a fault is observed and a sharp field gradient is associated with the gravitational effect of this fault. In the central part of the site, there is a zone of increased gravitational field values (more than 9.6 mGal) that has an irregular shape, with epicenters of more than 10.2 mGal (Balk P, 2021; Abdoldina et.al., 2021).

The main geological objectives of the AMTS electrical prospecting method was studying and identifying deep-seated ore objects, mapping and studying tectonic disturbances, clarifying the boundaries between a lot of lithological varieties and identifying ore bodies (Garcia X, 2002). To obtain the results described above, a multi-level complex of processing and interpreting the data obtained was performed.

The AMTS data was processed and interpreted in several stages, using the latest software systems. At the first stage, the AMTS inversion was calculated using the ZondMT2D program. Using this program, an express interpretation of the data obtained were carried out, and a primary model of the environment was developed. For quantitative calculations of the resistivity distribution over the studied area, the 1D inversion was carried out. This problem was solved sequentially using a set of programs: the MT_PROV, the MT_PROV_INV and the IPI2DWIN_MT. First of all, preparations were made for the construction of the primary model, then a priori geological and geophysical data were added, binding and correlation of geological and geoelectric sections with each other that were obtained during the processing of materials (Lyubetskiy et.al., 2009; Umirova, et.al., 2018).

After constructing the primary model and calculating the one-dimensional inversion, the 2D two-dimensional inversion was calculated taking into account a priori geological information, the procedure was carried out in ZondMT2D software. In Figure 3, you can see resistivity sections along profiles constructed after calculating the 2D two-dimensional inversion. Based on resistivity maps and sections, it is possible to identify zones of different shapes and sizes with low and high resistivity that are tentatively related to the ore-bearing horizon and lithological boundaries (Umirova, et.al., 2018).

According to the results of the AMTS interpretation and resistivity sections in Figure 3, horizons of polymetallic ores are identified at the depth of 300-400 meters that are characterized by low resistivity values of 10-30 Ohm•m and are distributed in the western part of the area. In turn, zones of high resistivity from 100 Ohm•m are localized in the eastern part of the area and located at a greater depth, which indicates the deep nature of the source rocks of ore objects limited by faults. Tectonic disturbances and faults are marked by abnormally low resistivity values in the geoelectric field (Lyubetskiy et.al., 2009; Umirova, et.al., 2018).

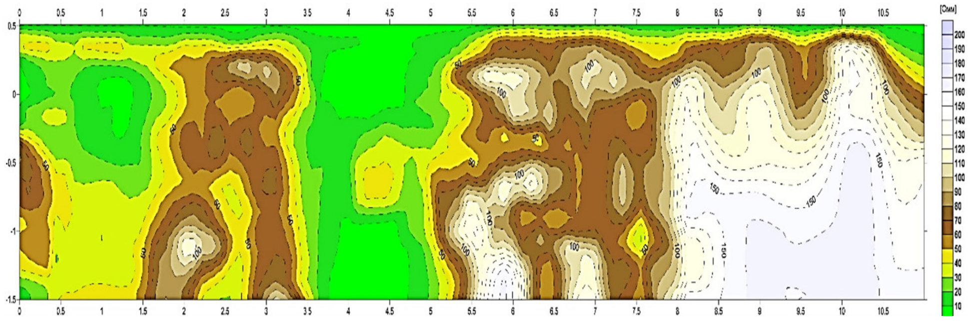

Figure 3 – Geoelectric section according to profile No. 1

After calculating the inversion, on the geoelectric resistivity sections and on the resistivity depth maps, the following features can be identified that characterize the geological and geophysical structure of the studied area.

1. Ore horizons represented by the Cenozoic deposits are distinguished by low resistivity (up to 50 Ohm•m) at the depth of 300 m.

2. The zone of high resistivity values (from 100 Ohm•m and above) is characterized by the impact of carbonate rocks of the Carboniferous and Devonian deposits.

3. At the depth of 250-280 m there is a zone of high resistivity up to 200 Ohm•m that maps red limestones.

4. The zone of maximum resistivity values is observed at the depth of up to 2,000 meters, it maps the deposits of the Lower Famennian substage.

At the last stage, after receiving all the results of geological and geophysical work, gravity exploration, magnetic exploration, as well as electrical exploration using the AMTS method, a comprehensive interpretation of the complex of geophysical methods was carried out by solving the inverse problem. Using the ZondGM2D program for the two-dimensional multi-profile interpretation of magnetic and gravity survey data, mathematical modeling was performed along profile 1 in the gravimetric anomaly interval (Lyubetskiy et.al., 2009; Umirova, et.al., 2018).

To assess the quantitative characteristics of the nature of the gravimagnetic anomaly, 2D inversions were calculated. The program included a priori geological data obtained from the results of drilling an exploratory well (Figure 4). Based on the results of solving the inverse problem, there was determined the nature of the gravimagnetic anomaly previously associated with gabbroic objects with an effective density of 0.16-0.25 conv. units and magnetic susceptibility of 480•10-5 SI units.

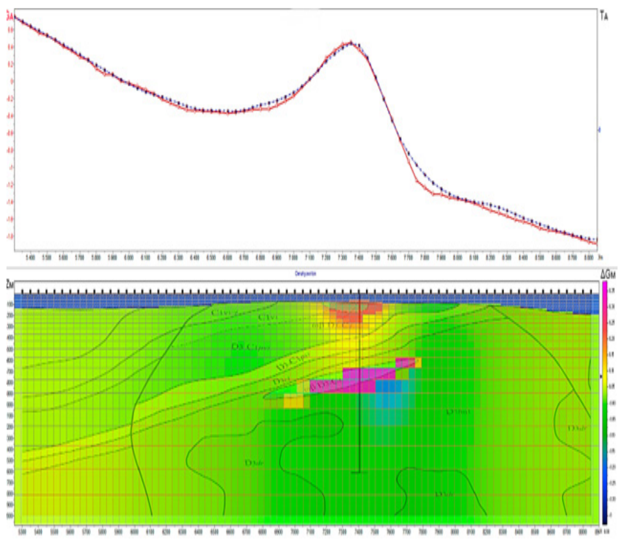

Figure 4 – Result of solving the inverse problem of the gravimagnetic field with introducing a priori data (block model)

The calculated field marks a transition zone of increased density between the first and the second gabbroic objects. This is consistent with the obtained density parameters for limestones, siliceous rocks and sandstones, the maximum density of which reaches 3.02-3.44 g/cm^3.

Thus, calculations confirm that local gravimagnetic anomalies in well No. 1 are associated with gabbroic bodies. Based on calculated geological models based on gravimagnetic data and the results of resistivity inversions according to AMTS, a geological and geophysical section was constructed using interpretive profiles (Figure 5).

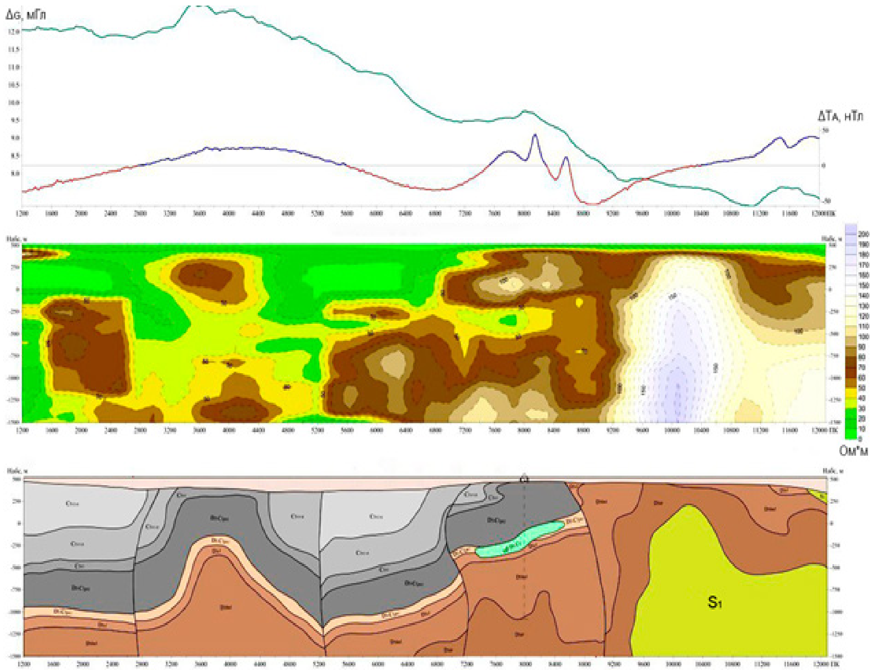

Figure 5. The result of the interpretation of a complex of geophysical methods. Geological and geophysical section according to profile No. 1

Results

Thus, based on the results of studying the efficiency of a complex of geophysical methods by example of the Atasu ore district, the following conclusions can be drawn:

1. Magnetic and gravity prospecting methods are of decisive importance in prospecting for solid minerals, especially polymetallic ores. The data from these methods map geological structures, identify regional and local faults, and make it possible to distinguish rocks by their material composition.

2. Analyzing the magnetic survey results shows that a submerional fault can be traced in the central part of the area that is considered the axial part of the rift structure.

The Karatulen anomaly is confined to this fault. The central and eastern parts of the site represented mostly by the deep-sea Famennian-Tournaisian sediments, are mapped with average magnetic field values (0-40 nTl). The western part of the site is represented by the Lower Carboniferous deposits and is characterized by a negative magnetic field.

3. The results of electrical prospecting using the AMTS method show a good information content when studying the geological structure of the area, in which ore horizons and enclosing rocks are clearly distinguished. A feature of the geoelectric model of this area is that the ore horizons are located between the areas of high resistivity values, and these ore segments are distinguished by low and gradient electrical resistivity values. According to these data, ore horizons of the Cenozoic deposits with low resistivity values of 30-50 Ohm•m at the depth of 300 m are distinguished, as well as ferromanganese ore members with low resistivity up to 20 Ohm•m at the depths from 400 to 700 m. In the intermediate layers between ore horizons there are revealed packs of red-colored limestones of the Upper Famennian stage with electrical resistivity up to 200 Ohm•m. In addition, the lower part of the geoelectric section is represented by clayey-siliceous-calcareous deposits of the Lower Famennian substage with maximum resistivity of up to 2000 Ohm•m. It is the underlying layer of the ore-bearing formation.

4. In the conditions of the Atasu ore district, tectonic faults, zones of crushing and fracturing, according to the complex of geophysical methods, are manifested through heterogeneities of rocks both in the lateral, and in the submeridional and sublatitudinal directions.

Discussion

Based on the results of this work, it can be concluded that the main ore-controlling factor of the Atasu metallogenetic type deposit is the confinement of ore objects to sediments of the Devonian-Carboniferous age, in particular the Famennian-Frasnian stage of the Upper Devonian, as well as the structural and tectonic control of ore objects that are tectonically limited faults and disturbances. The block structure of the Zhailma graben-syncline has raised wings on the flanks and a lowering of the central part of the trough. Basically, ore bodies occur in gray-red limestones, red conglomerates, sandstones, and siltstones.

Based on the results of geophysical work carried out on interpretation profiles Nos. 1 and 2, a positive gravimagnetic anomalous area has been identified that is characterized by the values of magnetic susceptibility of up to 65 nT. In this area, the nature of the graphs of magnetic and gravitational fields indicates a deep disturbing object. The results of electrical prospecting using the AMTS method on profile No. 1 within the gravimagnetic anomaly indicate an area with reduced resistivity, the upper edge of which is located at the depth of about 1,000 m. From the geological point of view, this anomalous area is confined to the Karatulen anticline and can be associated with ferromanganese and lead-zinc ore bodies in productive deposits of the Clymenian Formation and the Lower Famennian.

Conclusion

Thus, this article examines the issues of studying the efficiency of a complex of geophysical methods in the course of prospecting and exploration of polymetallic ores using the example of the Atasu ore district. Based on the results of this work, a positive assessment has been given to the complex of geophysical methods that consists of magnetic prospecting, gravity prospecting, and electrical prospecting using the AMTS method. Selecting the most optimal set of geophysical methods with a high geological efficiency for prospecting and exploration work in the Atasu ore district has also been proposed.

Ultimately, the results obtained significantly complement the understanding of the genesis of ferromanganese deposits of the Atasu type, and can also be used to evaluate searching for and forecasting ferromanganese ores. In the case of industrial development of the area, the issues of additional expansion of the raw material base in the studied area, which are the basis of the results obtained, become particularly relevant.

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