MINISTRY OF EDUCATION AND SCIENCE OF THE REPUBLIC OF KAZAKHSTAN

Kazakh National Research Technical University named after K.I. Satbayev

K. Turysov Institute of Geology, Oil and Mining

Department of Oil, Gas, and Ore Geophysics

Suleimenov Bauyrzhan Talgatuly

Kanseit Tileuberdi Imangeldiuly

Topic «Possibilities of using electrical resistivity tomography in the search for ore bodies»

DIPLOMA WORK

Specialty 5B070600 – Geology and exploration of mineral deposits

Almaty 2020

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ADMITTED TO DEFENCE
Head of the Department of Geophysics
Doctor of geological-mineralogical sciences, professor
Abetov A.E.
"_____"_____________2020 y.

DIPLOMA WORK

Topic: «Possibilities of using electrical resistivity tomography in the search for ore bodies»

Specialty 5B070600 – Geology and exploration of mineral deposits

Done by Suleimenov B.T.

Kanseit T.I.

Scientific superviser

Doctor Ph.D

Umirova G.K.

"_____"________2020 y.

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Geophysics Department

APPROVED BY
Head of the Department of Geophysics
Doctor of geological-mineralogical sciences, professor
Abetov A.E.
“_____” _______________ 2020y.

THE TASK
to complete the diploma work

Students Suleimenov B.T and Kanseit T.I

Topic: «Possibilities of using electrical resistivity tomography in the search for ore bodies »

Approved by order of the Rector of the University №762–b from "27" January 2020 y.

Submission deadline of the completed work "15" May 2020 y.

Initial data for the diploma work: were provided by the scientific adviser

Summary of the diploma work:

a) Results of experimental and methodical work;

b) Field observation technique;

c) Data processing and interpretation of ERT;

d) Modeling technique based on electrotomography data

List of graphic material: 20 slides of the presentation of work are presented.

Recommended main literature: Bobachev A.A Electrotomography by the method of resistance and induced polarization.

GRAPH
of diploma work preparation

Name of sections, list of issues to be developed	Submission deadline to scientific adviser	Notation
Results of experimental and methodical work	05.03.20y.-01.04.20y.	
Field observation technique	02.04.20y.-18.04.20y.	
Data processing and interpretation of ERT	19.04.20y.-01.05.20y.	
Modeling technique based on electrotomography data	02.05.20y.-10.05.20y.	

Signatures
consultants and the standard controller for the finished diploma work indicating the sections of work related to them

Name of sections	Consultants, N.P.F. (academic degree, rank)	Date of signature	Signatures
Results of experimental and methodical work	Umirova G.K.		
Field observation technique	Umirova G.K.		
Data processing and interpretation of ERT	Umirova G.K.		
Modeling technique based on electrotomography data	Umirova G.K.		
Standard controller	M.M.Aliakbar		

Scientific supervisor Umirova G.K.

Students fulfilling the task Suleimenov B.T.

Kanseit T.I.

Date "_____"______________2020 y.

АҢДАТПА

дипломдық жұмысқа "Рудалық кен орындарын іздеуде электрлік іздестіру томографиясын қолдану мүмкіндігі"

Жұмыс кіріспеден, 4 тараудан, қорытындыдан, пайдаланылған әдебиеттер тізімінен тұрады.

Осы дипломдық жұмыс, рудалық кен орындарын іздеуде электрлік іздестіру томографиясын қолдану мүмкіндігіне арналған. Электротомографияның бірнеше әдістері қаралып, арасынан өте тиімді әдісі Бенкала және Оңтүстік Бенкала кен орындарын іздестіруде қолданылды. Тарауларда мәліметтерді өңдеу, инверсиялау және интерпретациялау кезеңдері талданып, зерттелді. Далалық бақылау әдістері мен технологиялары жетілдірілді. Қорытындыда далалық бақылаулардың нәтижелері және шешілген мәселелер ұсынылды.

АННОТАЦИЯ

К дипломной работе "Возможности использования электроразведочной томографии при поисках рудных месторождении"

Работа состоит из введения, 6 глав, заключения и списка использованной литературы.

Данная работа посвящена изучению возможностей электроразведочной томографии при поисках рудных месторождений. Было рассмотрено несколько методов ЭТ, и был выбран лучший метод при поиске рудных объектов на месторождениях Бенкала и Южная Бенкала. В главах были проанализированы и изучены этапы обработки, инверсии и интерпретации данных. Методы и технологии полевого наблюдения были усовершенствованы. В заключение представлены результаты полевых наблюдений и решенных задач.

ABSTRACT

To the graduate work "Possibilities of using electrical resistivity tomography in the search for ore bodies"

The work consists of introduction, 6 chapters, conclusion and list of references.

This work is devoted to study possibilities of electrical resistivity tomography in the search for ore bodies. The several methods of ERT were reviewed and was chosen the best method in the search for ore bodies on Benkala and South Benkala deposits. In the chapters steps of data processing, inversion and interpretation were analyzed and studied. Methods and technologies of field observation were refined. In conclusion the results of field observation and solved problems are presented.

CONTENT

INTRODUCTION

Electrical exploration by the resistance method remains one of the main methods in shallow geophysical surveys. The main technique is vertical electric sounding, aimed at the study of horizontally layered sections. Currently, the electrotomography technique is being actively introduced into practice, which allows us to study complexly constructed media and interpret in the framework of two-dimensional models. This technique has been used in the West for more than 10 years, but in Kazakhstan it still has not received wide application due to the almost complete absence of domestic equipment. In English literature, two terms are most often used: Resistivity Imaging and Electrical Resistivity Tomography.

Electrotomography is a whole complex that includes both the technique of field observations and the technology for processing and interpreting field data. Its peculiarity is the repeated use of the same positions of the electrodes fixed on the observation profile as supply and measuring ones. This approach allows, on the one hand, to work with modern high-performance equipment, and on the other hand, to apply effective modeling and inversion algorithms. The interpretation of electrotomography data is carried out in the framework of two-dimensional and three-dimensional models. This fundamentally expands the range of tasks solved by electrical exploration, due to the study of media significantly different from the "classical" horizontally layered.

The resolution (i.e., the number of parts of the geoelectric section stably appearing in the electric field) and, accordingly, the quality of interpretation of the electrotomography data are closely related to the number and density of measurements on one profile. Their number usually reaches the first thousand, so the question of the performance of field measurements is of fundamental importance and largely determines the possibility of practical use of this method. To achieve maximum efficiency during field work, special equipment is used with programmable automatic electrode switching. Further, for brevity, we will use the term multi-electrode equipment.

The recorded data are transferred to a PC for processing. In order to derive a cross-sectional model of true ground resistivity, the measured data are subject to a finite-difference inversion process via RES2DINV software. Data processing is based on an iterative routine involving determination of a two-dimensional (2D) simulated model of the subsurface, which is then compared to the observed data and revised. Convergence between theoretical and observed data is achieved by non-linear least squares optimisation. The extent to which the observed and calculated theoretical models agree is an indication of the validity of the true resistivity model (indicated by the final root-mean-squared (RMS). The true resistivity models are presented as colour contour sections revealing spatial variation in subsurface resistivity. The 2D method of presenting resistivity data is limited where highly irregular or complex geological features are present and a 3D survey maybe required. Geological materials have characteristic resistivity values that enable identification of boundaries between distinct lithologies on resistivity cross-sections. At some sites, however, there are overlaps between the ranges of possible resistivity values for the targeted materials which therefore necessitates use of other geophysical surveys and/or drilling to confirm the nature of identified features.

1 The relevance, goals and objectives of the study

In recent decades, in the field of prospecting and exploration of minerals, there has been a transition to the study of deposits of a more complex structure, with great depths of ore bodies. To study them, it is necessary to create methods that can increase the accuracy, detail, productivity, resolution of the research. One of the rapidly developing methods is electrotomography. As a modification of the direct current resistance method, electrotomography inherited all the fundamental possibilities of the resistance method, allowing us to study complex media and interpret within the framework of two-dimensional models due to the high density of observations, high-tech equipment and modern software technologies. Thus, the relevance of our report is to increase the efficiency of electrical exploration methods through the use of new advanced technologies, modern processing systems and field observation techniques with a high network density, which can significantly increase the resolution of the electrotomography method.

The goal is to study and evaluate the effectiveness of the use of electrotomography in the search of ore bodies and deposits.

Goal is going to be be achieved by solving these tasks:

1) Overview of existing methods of electrotomography and selection of the most optimal monitoring system in the conditions of the Benkala deposit
2) Analysis of the information content of electrotomography data;
3) Isolation of geophysical criteria for the detection of zones promising for porphyry copper mineralization;
4) Recommendations for using ET

2 Review of existing methods of electrotomography and their development

Electrical exploration by the resistance method remains one of the main methods in shallow geophysical surveys. The development of this method has led to the emergence of a new technique that is aimed at studying complexly constructed environments and which allows interpretation within the framework of two-dimensional models. This technique has been used for over 10 years and is called electrotomography. In English literature, two terms are most often used: Resistivity Imaging and Electrical Resistivity Tomography. The mass use of electrotomography began at the end of the 20th century, which is associated primarily with the rapid development of computer technology and digital equipment. Electric resistivity method is one of the electrical exploration methods using the four-electrode AMNB. An electric field in the form of a potential difference (ΔUMN) observed on the surface of the earth when an electric current (I_{AB}) is passed through grounded electrodes MN depends on the distribution of the apparent apparent electrical resistance P_k in a certain section of the section near the installation. The integrated nature of the observed field allows the use of the resistance method in conditions when the studied section has a complex structure. On the other hand, this stability of the method leads to low resolution, in comparison with seismic methods or ground penetrating radar. Electric resistivity methods are a form of geophysical surveying that aids in imaging the subsurface. These methods utilize differences in electric potential to identify subsurface material.

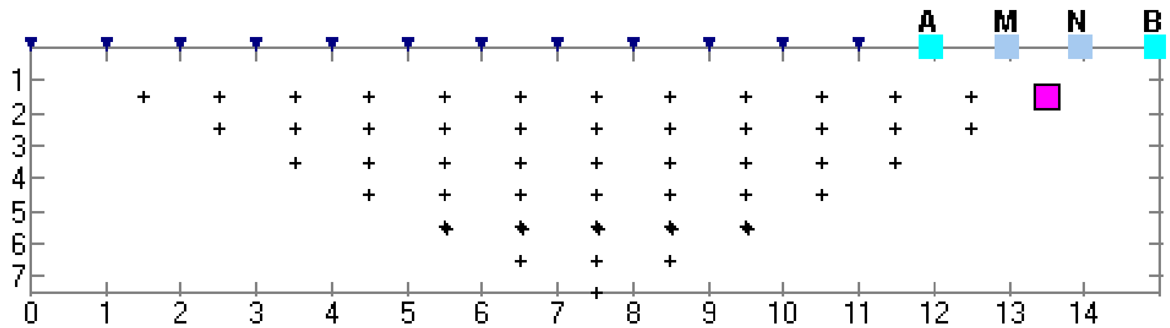

Figure 1 – Arrangement of electrodes for electrical resistivity method

Until the 90s of the last century, the most common direct current methods were vertical electrical sensing (VES-IP) and electrical profiling (EP). However, these methods, which have proven themselves in the study of horizontally layered media, are ineffective in complex, heterogeneous media, which are typical for most ore regions. The resistance method has been used for more than 100 years, it is used in the search for ore deposits, engineering and archaeological surveys. In the cn method, the four-electrode AMNB installation is used, where AB are the supply electrodes, MN is the measuring electrodes.

In the last two decades, classical modifications of the resistance method are increasingly being replaced by electrotomography (ERT) - a complex, including both the methodology of field observations and the technology of processing and interpretation of field data for heterogeneous environments.

Electrotomography is a modern direction of the known and stable methods of resistance and induced polarization, has been used in the West for more than 10 years, is widely used in the search for ore deposits in heterogeneous two-dimensional and three-dimensional spaces. Electrotomography is a high-resolution direct current electrical prospecting, a modern area of resistance methods and polarization exploration-induced geophysics. Mass application of this method falls at the end of the twentieth century. Since geological objects and the structure of the earth are two-dimensional, and in special cases three-dimensional, the outdated one-dimensional method has lost its relevance. Thanks to annual improvements in electrotomography, a 3D image of a geological object is now being made.

Figure 2 – Deployment of a permanent electrical resistivity tomography profile on a longitudinal section of an active landslide.

2.1 History of ERT

The technique evolved from techniques of electrical prospecting that predate digital computers, where layers or anomalies were sought rather than images. Early work on the mathematical problem in the 1930s assumed a layered medium (see for example Langer, Slichter). Andrey Nikolayevich Tikhonov who is best known for his work on regularization of inverse problems also worked on this problem. He explains in detail how to solve the ERT problem in a simple case of 2-layered medium. During the 1940s, he collaborated with geophysicists and without the aid of computers they discovered large deposits of copper. As a result, they were awarded a State Prize of Soviet Union. When adequate computers became widely available, the inverse problem of ERT could be solved numerically. The work of Loke and Barker at Birmingham University was among the first such solution and their approach is still widely used.

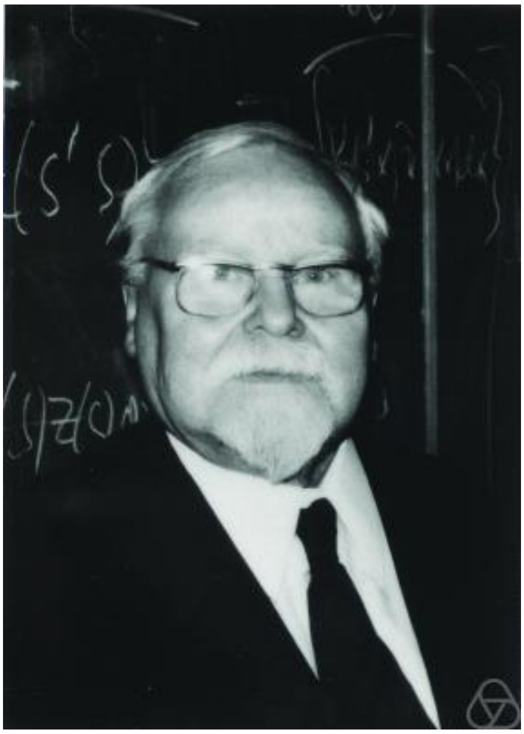

Figure 3 – Andrey Nikolayevich Tikhonov, the "father of electrical resistivity tomography or ‘ERT’"

With the advancement in the field of Electrical Resistivity Tomography (ERT) from 1D to 2D and now-a- days 3D, ERT has explored many fields. The applications of ERT include fault investigation, ground water table investigation, soil moisture content determination and many others. In industrial process imaging ERT can be used in a similar fashion to medical EIT, to image the distribution of conductivity in mixing vessels and pipes. In this context it is usually called Electrical Resistance Tomography, emphasising the quantity that is measured rather than imaged.

2.2 1D ERT

In the vertical electric sounding (VES) method, an artificial constant electric field is measured, from which information on the distribution of electrical resistivity in the earth is then extracted. The VES method is one of the main ones in geophysical studies of the geological environment to depths reaching one hundred meters. It is used in geo-mapping, in the search and exploration of mineral deposits, in hydrogeological, engineering-geological and environmental studies. A shallow modification of the VES is used to solve archaeological and geotechnical problems. VES is a geophysical method for investigation of a geological medium. The method is based on the estimation of the electrical conductivity or resistivity of the medium. The estimation is performed based on the measurement of voltage of electrical field induced by the distant grounded electrodes (current electrodes).

2.2.1 Measurements

Figure 4 shows the possible configuration of the measurement setup. The electrodes *A* and *B* are current electrodes which are connected to a current source; *N* and *M* are potential electrodes which are used for the voltage measurements. As source, the direct current or low frequency alternating current is used.

The interpretation of the measurements can be performed based on the apparent resistivity values. The depth of investigation depends on the distance between the current electrodes. In order to obtain the apparent resistivity as the function of depth, the measurements for each position are performed with several different distances between current electrodes. The apparent resistivity is calculated as:

$$\rho_k = k\frac{U_{MN}}{I_{AB}}$$

here, *k* is a geometric factor, U_{MN} — voltage between electrodes M and N, I_{AB} — current in the line AB. The geometric factor is defined by:

$$k = \frac{2\pi}{\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}}$$

here *r* is the distance between electrodes.

The application of large electrode arrays allows for reconstructing complex 3D structure of geological media. However, the interpretation of such measurement is rather difficult. In this case, advanced interpretation techniques based on numerical methods can be applied.

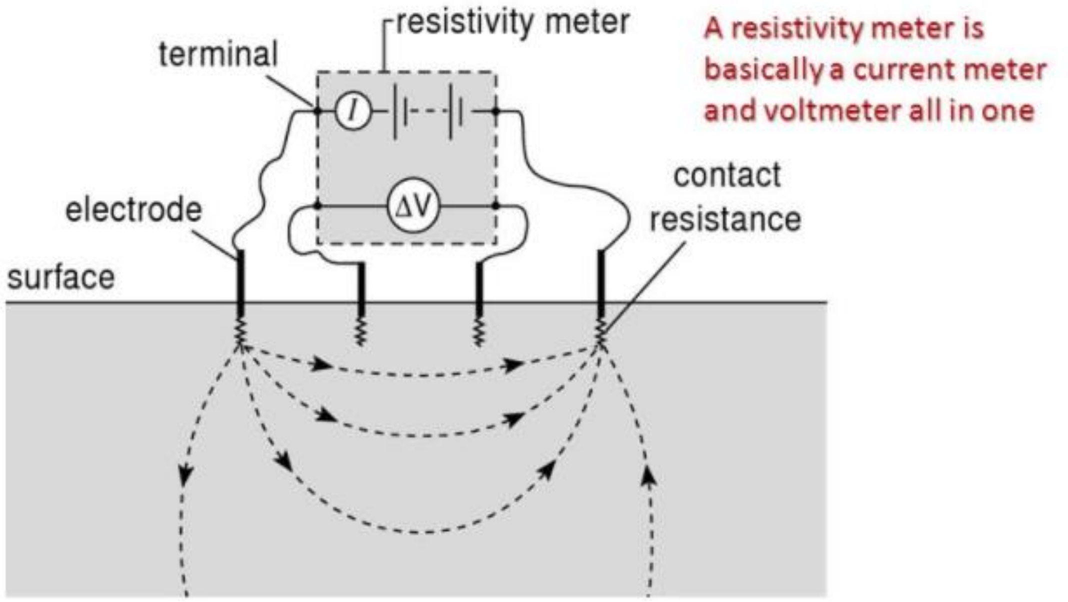

Figure 4 – Showing the basic setup involving a resistivity meter and four electrodes.

Resistivity is fundamentally related to Ohm's Law measuring Resistance. Resistance is defined as the voltage divided by the current (R = V/I) and the value of a material's resistance depends on the resistivity of that material. Resistivity is the value of resisting power of a certain material to the flow of a moving current.

2.2.2 The Wenner Array

Among the four electrodes used with the resistivity meter, two are used to pass the current through while the other two measure the change in potential.
In the Wenner Array, the spacing between each of the four electrodes is the same. The amount of spacing can be changed depending on the depth of the survey. Generally, the depth the survey can measure is related to 1/2 the distance between the outer electrodes. This array is one of the most commonly used.

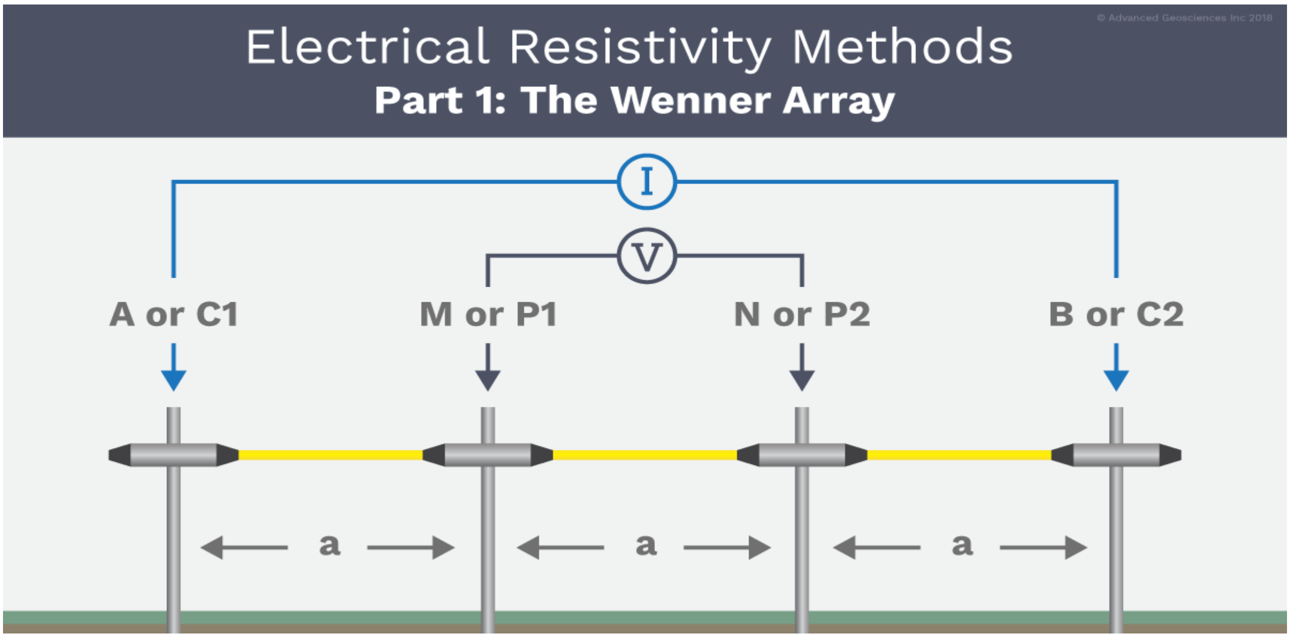

Figure 5 – The arrangement of electrodes for the Wenner array.

2.2.3 The Schlumberger Array

With the Schlumberger array, only the outer two electrodes (the electrodes supplying and receiving the current) are moved. The advantage of this is that it is much faster because only two electrodes have to be moved rather than the 4 with the Wenner array.

In field work, the outer electrodes would keep being moved until the recorded potential is a minimum value. At that point the set up is established in another location and the survey is continued. With the Schlumberger array, for each measurement the current electrodes A and B are moved outward to a greater separation throughout the survey, while the potential electrodes M and N stay in the same position until the observed voltage becomes too small to measure. The Schlumberger array is named for Conrad Schlumberger, founder of the modern-day Schlumberger oilfield services company and pioneer of electrical methods in the early 1900s.

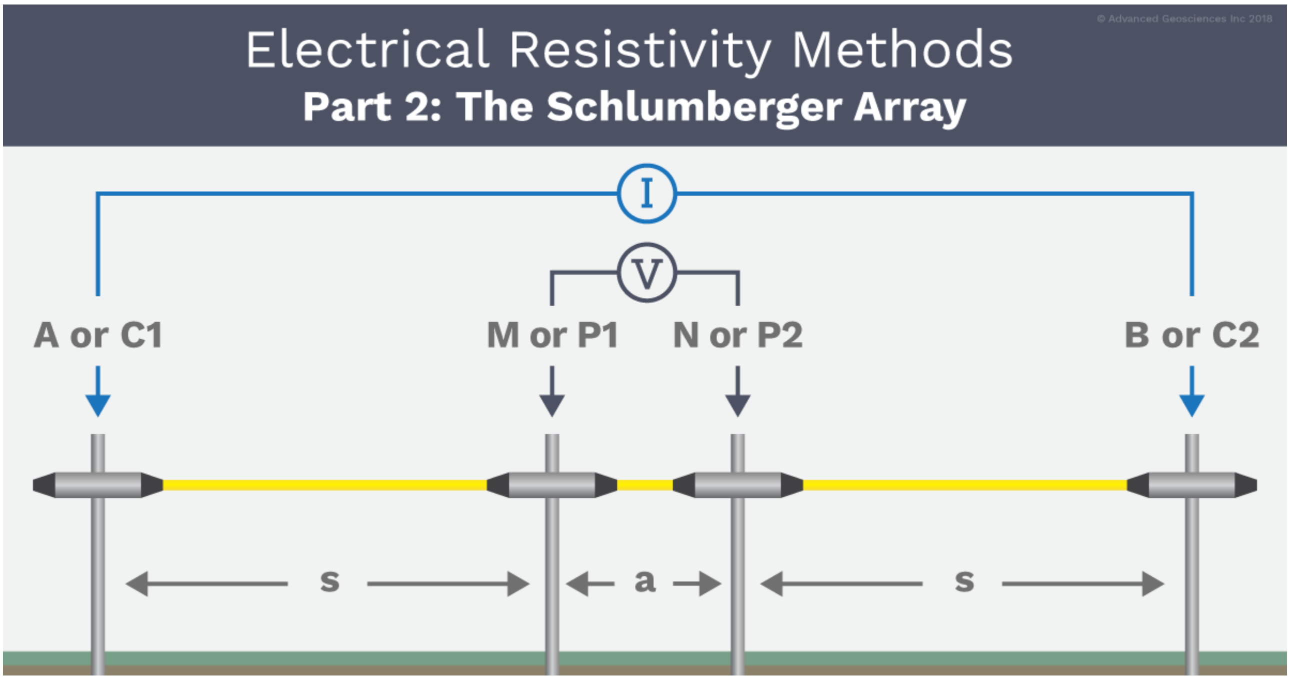

Figure 6 – The arrangement of electrodes for the Schlumberger array.

2.2.4 The Gradient Array

With the gradient array, the spacing of the outer two electrodes is kept constant while the two inner electrodes (the potential electrodes) are moved. The spacing between the inner electrodes is constant but they are moved as a pair in the space between the outer electrodes and measure the potential as they go.

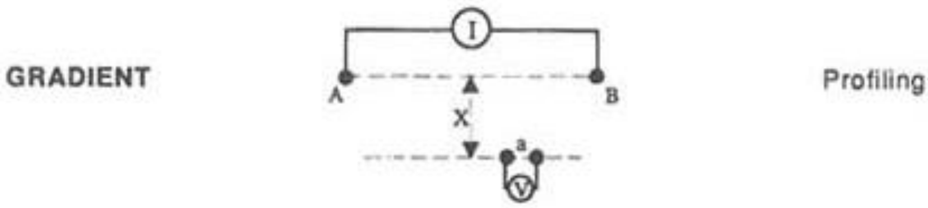

Figure 7 – The arrangement of electrodes for the Gradient array.

2.2.5 Other array spacings

These are not the only array spacings a resistivity survey can have. Others include the dipole-dipole array, the pole-dipole array, pole-pole array, the Lee-partition array, and the square array. Each of these various arrays differs in electrode spacing and the movement of either the current or potential electrodes. Some of the array spacings are depicted down below.

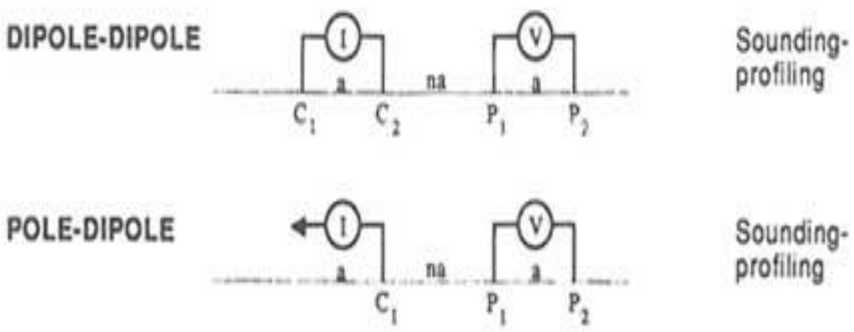

Figure 8 – The arrangement of electrodes for other array spacings.

2.2.6 Methods

The three main methods of electric resistivity surveys are vertical electric sounding (VES), electric profiling, and electric imaging. Each of these utilize one of the array configurations mentioned above.

2.2.7 Vertical Electric Sounding

VES is one of the more commonly used and cost effective resistivity survey methods. Current is moved through the subsurface from one current electrode to the other and the potential as the current moves is recorded. From this information, resistivity values of various layers is acquired and layer thickness can be identified. The apparent resistivity values determined are plotted as a log function versus the log of the spacing between the electrodes. These plotted curves identify thickness of layers. If there are multiple layers (more than 2), the acquired data is compared to a master curve to determine layer thickness. There are a few limitations with VES. First, the depth of the survey is limited to the electrode spacing. Second, layers may vary in resistivity horizontally. This is where a method like electric profiling would be better to use. Lastly, the layers must have consistent thickness. If there is a case where the middle layer is much thinner than the layers above and below it then the resistivity results will be inaccurate. The resistivity of the thin middle layer will affect the reading. This is termed equivalence.

2.2.8 Electric profiling

Where VES focuses on determining resistivity variations on a vertical scale, electric profiling seeks to determine resistivity variations on a horizontal scale. Profiling can use the same electrode spacing configurations as VES. Since changing the spacing between electrodes only affects the depth at which the survey can reach, the profiling method does not involve manipulating electrode spacing. Instead, the electrode spacing is kept constant and the entire survey is moved along a line or a "profile" to measure horizontal changes in resistivity.

2.2.9 Electric imaging

In many cases resistivity can change as both depth and horizontal distance increase. Both VES and electric profiling are limited to surveying in one direction. Electric imaging is able to survey both vertical and horizontal changes in resistivity. This method essentially combines the other two methods. Electrode spacing is increased and the survey is moved along a profile in order to measure both vertical and horizontal resistivity. These values are then used to create a pseudosection.
The pseudosection can be used to generate an image of the subsurface. Imaging can be done in both 2D and 3D. 2D area electrotomography is a profile survey of 2D profiles with 2D inversion for each and subsequent interpolation combining of results. 2D area survey, strictly speaking, has no mathematical and physical justification for studying three-dimensional media. This approach is possible only if the required accuracy and detail of the studies allows an approximative two-dimensional approximation of the medium for each profile.

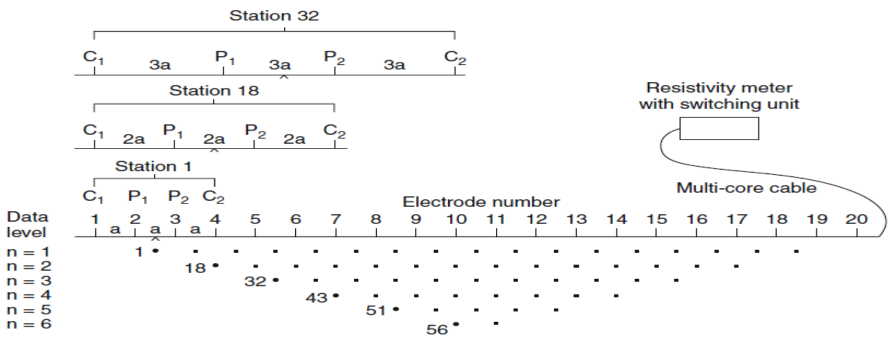

Figure 9 – Schematic diagram of a multielectrode system used for a 2-D electrical survey and an example sequence of measurements used to build up a pseudosection using the Wenner array.

Table 1 – Comparison of Vertical electrical sounding and Electrical resistivity tomography

Method	Method VES	ERT
equipment	single channel	Mostly multi-electrode
spacing step	logarithmic	linear
electrical installation	Schlumberger or dipole	standard, custom or combination settings
number of measurements on one profile	tens and first hundreds	hundreds and first thousands
interpretation	one-dimensional	1D-2D (3D)

2.3 2D ERT

The development of resistivity surveying techniques has been very rapid in the last three decades. The advent of automated data acquisition systems, inversion codes, and easy access to powerful and fast computers has tremendously increased the practical applicability of the geophysical method. Geoelectrical resistivity imaging is increasingly being used in environmental, engineering and hydrological investigations as well as geothermal and mineral prospecting, where detailed knowledge of the subsurface is sought.

2D area electrotomography is a profile survey of 2D profiles with 2D inversion for each and subsequent interpolation combining of results. 2D area survey, strictly speaking, has no mathematical and physical justification for studying three-dimensional media. This approach is possible only if the required accuracy and detail of the studies allows an approximative two-dimensional approximation of the medium for each profile. Nevertheless, in many cases, the preference in research is given to 2D shooting, since it has a number of undeniable advantages over the other two approaches:

- The method of 2D electrotomography has been developing for a long time, therefore algorithms, equipment and techniques have already been developed to obtain the optimal result in solving a wide range of problems;

- the independence of the profiles from each other allows you to choose an arbitrary network of observations;

- the scope of work can be adjusted due to the number of profiles and parameters of the observation network, in general, this makes 2D areal survey relatively cheaper and more productive.

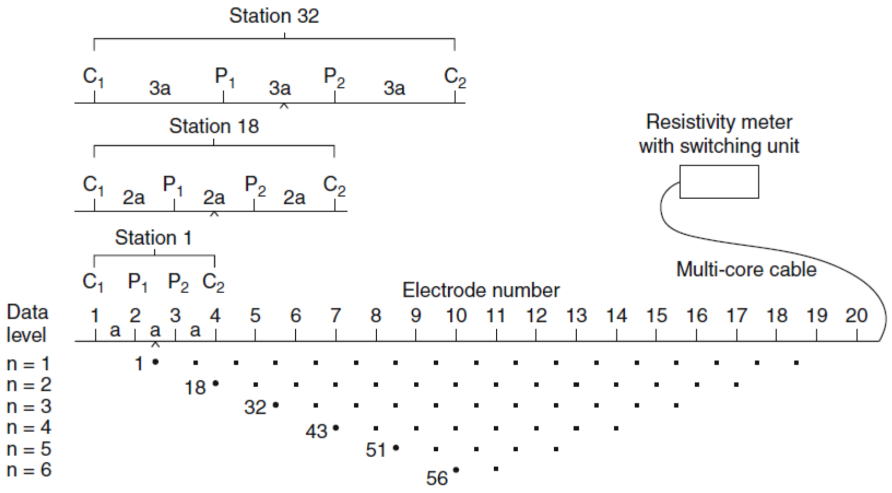

Figure 9 – The arrangement of electrodes for 2D ERT.

Two-dimensional (2D) geoelectrical resistivity imaging can be achieved by integrating the techniques of vertical electrical sounding with that of electrical profiling. It involves apparent resistivity measurements from electrodes placed along a line using a range of different electrode separations and midpoints. The procedure is repeated for as many combinations of current and potential electrode positions as defined by the survey configuration. 2D resistivity imaging can be seen as continuous vertical electrical sounding (CVES) in which a number of VES conducted in a grid are merged together or as a combination of successive profiles with increasing electrode spacing. Two-dimensional (2D) resistivity surveys are usually carried out using large numbers of electrodes connected to multi-core cables. For a system with limited number of electrodes, the area covered by the survey can be extended along the survey line using the roll-along technique. This can be achieved by moving the cables past one end of the line by several units of electrode spacing, after completing a sequence of measurements. A number of arrays have been used in recording 2D geoelectrical resistivity field data, each suitable for a particular geological situation. The conventional arrays most commonly used include Wenner, dipole-dipole, pole-pole and pole-dipole. Most of the pioneering works in 2D geoelectrical resistivity surveys were carried out using Wenner array. The resistivity of the 2D model is assumed to vary both vertically and laterally along the survey line but constant in the direction perpendicular to the survey line. The observed apparent resistivity values are commonly presented in pictorial form using pseudosection contouring which gives an approximate picture of the subsurface resistivity distribution. The shape of the contours depends on the type of array used in the investigation as well as the distribution of the true subsurface resistivity. The pseudosection plot serves as a useful guide for detail quantitative interpretation. Poor apparent resistivity measurements can easily be identified from the pseudosection plot. The pseudo-depth values are based on the sensitivity values or the Frechet derivatives for a homogenous half-space.

To study two-dimensional sections, a method of electrotomography has been developed and is actively used (Table 2). This technology significantly expands the field of application of the resistance method and induced polarization, increases the accuracy, resolution and geological efficiency of the resistance method, allowing reliable interpretation for complexly constructed environments. This quality of interpretation is in many cases unattainable when using the methods of VES and VES-IP.

Table 2 – The differences in the technologies of classic Vertical electrical sounding (VES) and Electrical resistivity tomography (ERT)

Methodological element	VES (1D)	ERT (2D)
Spacing	Geometrical, usually 7 points per decade	Linear, equal to the distance between the electrodes or a multiple
Line length of MN	MN≤AB/3	MN≤AB/3, MN is equal to the step between the electrodes or a multiple of him
VES step by profile	Arbitrary, usually larger AB/2max	Rigidly connected to the grid of electrodes and often equal to the spacing step, smaller AB/2max
Density of the observations on one profile	Ten and first hundred points	Hundred and first thousand points
Interpretation	1D interpretation of each VES curve separately with linking the results for the profile	2D inversion of all profile data with obtaining a single model for the entire profile

All geological structures and spatial distribution of subsurface petrophysical properties are inherently threedimensional in nature. The three-dimensional effects of subsurface structures are more pronounced in environmental and engineering investigations where the geology is highly heterogeneous and subtle. Model images resulting from 2D resistivity surveys often contain spurious features due to 3D effects and violation of the 2D assumption. This usually leads to misinterpretation of the observed anomalies in terms of magnitude and location (Bentley and Gharibi, 2004). Hence, a 3D survey with a 3D interpretation model in which the resistivity is allowed to vary in all directions should, in theory, give the most accurate and reliable results especially in subtle heterogeneous subsurface. 2D area electrotomography is a profile survey of 2D profiles with 2D inversion for each and subsequent interpolation combining of results. 2D area survey, strictly speaking, has no mathematical and physical justification for studying three-dimensional media. This approach is possible only if the required accuracy and detail of the studies allows an approximative two-dimensional approximation of the medium for each profile.

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- the independence of the profiles from each other allows you to choose an arbitrary network of observations;
- the scope of work can be adjusted due to the number of profiles and parameters of the observation network, in general, this makes 2D areal survey relatively cheaper and more productive.

A methodology to locate automatically limits or boundaries between different geological bodies in 2D electrical tomography is proposed, using a crest line extraction process in gradient images. This method is applied on several synthetic models and on field data set acquired on three experimental sites during the European project PALEOSIS where trenches were dug. The results presented in this work are valid for electrical tomographies data collected with a Wenner-alpha array and computed with an l1 norm (blocky inversion) as optimization method. For the synthetic cases, three geometric contexts are modelled: a vertical and a dipping fault juxtaposing two different geological formations and a step-like structure. A superficial layer can cover each geological structure. In these three situations, the method locates the synthetic faults and layer boundaries, and determines fault displacement but with several limitations. The estimated fault positions correlate exactly with the synthetic ones if a conductive (or no superficial) layer overlies the studied structure. When a resistive layer with a thickness of 6 m covers the model, faults are positioned with a maximum error of 1 m. Moreover, when a resistive and/or a thick top layer is present, the resolution significantly decreases for the fault displacement estimation (error up to 150%). The tests with the synthetic models for surveys using the Wenner-alpha array indicate that the proposed methodology is best suited to vertical and horizontal contacts. Application of the methodology to real data sets shows that a lateral resistivity contrast of 1:5–1:10 leads to exact faults location. A fault contact with a resistivity contrast of 1:0.75 and overlaid by a resistive layer with a thickness of 1 m gives an error location ranging from 1 to 3 m. Moreover, no result is obtained for a contact with very low contrasts (~1:0.85) overlaid by a resistive soil. The method shows poor results when vertical gradients are greater than horizontal ones. This kind of image processing technique should be systematically used for improving the objectiveness of tomography interpretation when looking for limits between geological objects.

Among all geophysical techniques dedicated to image the near surface, 2D or 3D resistivity surveying has been increasingly used for environmental, engineering and geological purposes this last decade . To adequately image the subsurface, the pseudo-section resistivity data set must be inverted using a cell-based inversion technique (see, for example, Loke and Barker, 1996). The principle consists in subdividing the studied 2D surface into a number of cells and in determining the resistivity within the cells that would provide a model response fitting well the measured data. Even if the inversion is a quasi-automatic process, there remains uncertainty in the reliability of the final obtained image.

First, options within the inversion process can highly influence the final sections, as the choice of the optimization norm and the way of computing the partial derivatives. Two optimization methods are commonly used to solve the inversion process: the l2 norm (smoothness-constraint) which is well adapted for areas where the resistivity varies in a gradual manner, and the l1 norm (blocky optimization), which gives significantly better results when sharp boundaries are present. In the same way, to solve the least-square equation, the Jacobian matrix of partial derivatives must be computed for all iterations. For this purpose, the Gauss–Newton method gives significantly more accurate results than the quasi-Newton method when the survey area exhibits large resistivity contrasts, and almost similar results for moderate contrasts.

Second, the inversion of electrical data is a non-linear problem which is usually solved by linearized methods. These techniques require a starting model, which can highly influence the solution if the misfit function exhibits several minima. A way of addressing this problem is to use direct search algorithms like the simulated annealing technique. However, due to the long computation time required, these techniques are limited so far to a small number of parameters, and have been rarely applied to electrical imaging.

Third, delineating the exact position of boundaries in an electrical tomography is often a difficult task, depending on the colour scale and on the eye sensitivity of the interpreter. Indeed, when the final image presents smooth resistivity variations, boundaries appear as continuous transitions between zones of different resistivities. For example, the response of a vertical contact model with a conductive superficial layer has been computed and inverted using the RES2DINV software The smoothed electrical tomography is shown in Fig.1B and C with a logarithmic and a linear colour scale, respectively. Depending on the interpreter, the geometry can be very different from the two images. Moreover, these images also depend on the interpolation technique used for the smoothing. Image and signal processing techniques are commonly used in wave methods to help the user to have an objective interpretation. For example, Morozov and Smithson (1996) used image processing techniques (histogram equalization technique) on seismic signals to compare and plot coherency measures. A 3D skeletonization technique was developed by Vasudevan et al. (1997) to allow automatic event detection and mapping of surfaces in 3D volume of reflection seismic data. Another example can be found in Bergeron and Yuen (2000) who used wavelet transforms to detect plume-like structures from 3D seismic tomography. Other object or event detection algorithms were developed in Al-Nuaimy et al. (2000) and Carter and Lines (2001). Demanet et al. (2001a) used image processing algorithms to automatically detect faults in electrical and seismic tomography images. Based on two synthetic models and one experimental study, they present preliminary results showing that a crest line location method applied on morphological gradient images is successful in identifying sharp lateral contrasts (for example, generated by faults). However, the authors do not make a clear comparison between the identified faults resulting from the image processing, and the known synthetic limits.

It has been a long time since geophysics used vertical electrical sounding in the search for ore bodies, archeological places and water places. VES also has been used and sometimes nowadays it also used to find karst-suffusion processes, it is very important to find this places with karst-suffusion process, because if people are going to build house or engineer buildings then the rest of the situation can be really sad, because the house or building can be pulled underside of the ground. Thankfully, due to the scientists and geophysics method of sounding have been improved and it is also growing up, it means the possible sides of vertical electrical sounding and 2D ERT and 3D ERT are getting wider and wider. It means in the near future students, geophysical companies, geophysics are going to work with 2D electrotomography, then approximately in the next maybe ten decades only with 3D resistivity imaging. Nowadays, 3D resistivity imaging is not the best variant to do measurements, due to the high price of technologies, also it takes a very long time to do measurements by comparing with vertical electrical sounding or 2D electrical resistivity tomography, and the place of where it can be measured is very small by comparing with other methods of resistivity imaging.

2D electrical resistivity tomography is widely used, because it can be done faster than 3D method and can give more information about the underground layers than vertical electrical sounding. By the way, electrical resistivity tomography is the new way, which came from the method of resistivity and polarization. On the west continents like USA and Canada, electrical resistivity is very popular and has been used for almost 20 years, while in our region, in Kazakhstan and Russia this new type of resistivity method and polarization just has been started using. The main reason why electrical resistivity tomography was not so popular in Kazakhstan was lack of domestic equipment. But, geophysics of Russia with scientists and geophysics of our country find a way to avoid from this big deal. They have made our own domestic technologies, equipment. These products need to be improved and group of scientists working on it. Geophysical companies by working with engineers are creating new programs, which can significantly increase the results of 2D and 3D inversion, to avoid false anomalies. It will help us and our geophysics to avoid from false geological objects which can be laid in hundreds of meters.

Vertical electrical sounding or just VES is not as important as it has been in XIX century. But, due to its very low price, nowadays it is used to help students for better understanding of electrical resistivity tomography and the underground layers of our Earth and about Earth's electric field. Also, vertical electrical sounding is used to take information about the first and approximately hundred meters of the geological subsurface and its first layers. There are several ways of combination of electrodes to do measurements with vertical electrical sounding, such as: the wenner array, schlumberger array, gradient array, pole-pole array pole-dipole array, dipole-dipole array and etc. When we were working in Karaganda we had a deal with pole-dipole array and worked with 12 profiles, in Balkash we worked with dipole-dipole array and there were 6 profiles at all, both of measurements were aimed to find out the location, size, length, depth, width and geographical information of copper geological objects.

These measurements have been done in Benkala and South Benkala deposit, which is located in west Kazakhstan. These deposits is also very rich with copper. Nowadays these deposits are being mined opened pit with workers. More information about the results of cross-section, pseudo-section and results of data processing, inversion and interpretation will be in the next chapters.

2.4 3D ERT

Traditional 2D profile electrotomography is the most effective technology in the resistance method used in detailed studies of two-dimensionally inhomogeneous media. But recently, interest in the study of 3D objects has increased, and multi-electrode multi-channel hardware systems and 3D inversion algorithms have begun to develop rapidly. This, in turn, entailed the development of various data collection and processing techniques for studying directly three-dimensionally inhomogeneous media. The specificity of each such technique is determined by the difference between spatial approaches to the study of the environment. 3D electrical resistivity tomography has the highest degree of information when studying three-dimensional objects. But at the same time, it has a number of significant drawbacks, and the main one is difficulty. What constitute a 3D data set that would yield significant 3D subsurface information for geoelectrical resistivity imaging is not clearly understood. Ideally, the measurements of apparent resistivity values that would constitute a complete 3D data set should be made in all possible directions. The techniques for conducting 3D electrical resistivity surveys have been presented by Loke and Barker (1996). The use of pole-pole and pole-dipole arrays in 3D electrical resistivity surveys have been reported. Square and rectangular grids of electrodes with constant electrode spacing in both x- and y-directions, in which each electrode is in turn used as current electrode and the potential measured at all other electrode positions, were commonly used. For n number of electrodes in a grid, the maximum number of independent data points (a complete 3D data set) that can be measured is given by:

$$d_{max} = \frac{n(n-1)}{2} .$$

Currently, it is characterized by the rapid development of geophysical methods and their active application in various related fields, such as ecology, archeology, engineering geology, hydrogeology, engineering and geological surveys for construction, urban utilities, etc. In particular, such a method as electrotomography has recently been developed and introduced. The resistance method is one of the oldest electrical prospecting methods; its history has been around for a hundred years [Schlumberger, 1920]. For many decades, a limited number of electrodes were grounded and carried by hand, which determined the performance of electrical exploration. In the 1980s, multi-electrode measurement systems appeared, first with manual, and later with automatic switching. Such systems made it possible to perform fully automatic measurements and data quality control. Thus, at the end of the 20th century, electrical exploration by the resistance method reached a qualitatively new level. In place of or in addition to traditional vertical electrical sensing and electrical profiling, so-called solid electrical sounding has been developed. In foreign literature, two terms are most often used - Resistance Imaging and Electrical resistivity tomography. The paper gives a brief overview of the development of the method. In Kazakhstan, to date, the term electrotomography has been fixed, which is included in the "Code of Rules" of the Gosstroy of Kazakhstan. Electrotomography allows you to solve a wide range of problems with a high degree of economic efficiency. A detailed study of the structure of the soil to a depth of several hundred meters, exploration of ore minerals, mapping of the alluvial deposits, determining the topography of bedrock when designing the foundations of buildings, studying the state of industrial facilities such as dams, dams, mine tailings, etc. Electrotomography is based on the use of multi-electrode electrical prospecting braids connected to equipment capable of switching current and measuring electrodes to arbitrary braid leads. Such technology increases the productivity and resolution of studies by the resistance method by an order of magnitude, especially if the equipment has several measuring channels that allow measuring the potential difference simultaneously from several receiving lines. Until recently, in Kazakhstan, equipment for electrotomography was not produced, which, together with the lack of regulatory documentation, leads to the fact that the technique is practically not used in the industry. Thus, the corresponding niche, which is actively developing abroad, is practically empty in Kazakh geophysics. There are several ways to do measurements with 3D electrical resistivity tomography and lots of ways for arrangements of electrodes for 3D electrical resistivity tomography. For example,

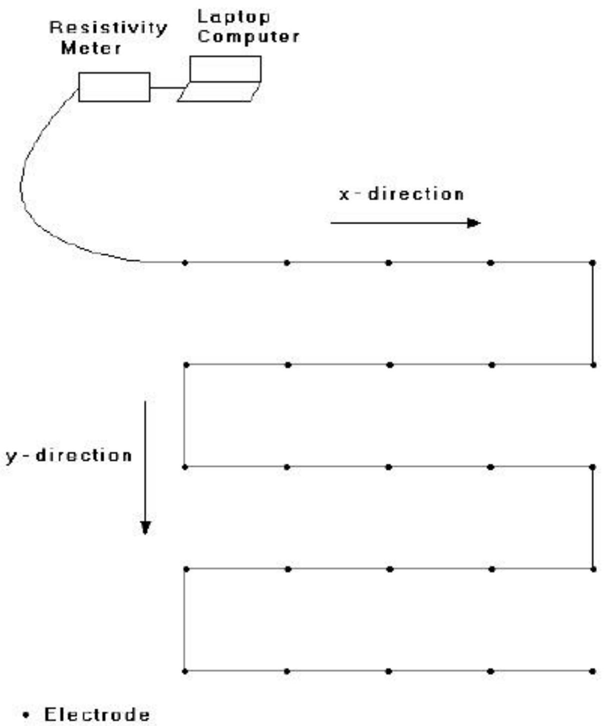


Figure 10 – The arrangement of electrodes for 3D electrical resistivity tomography

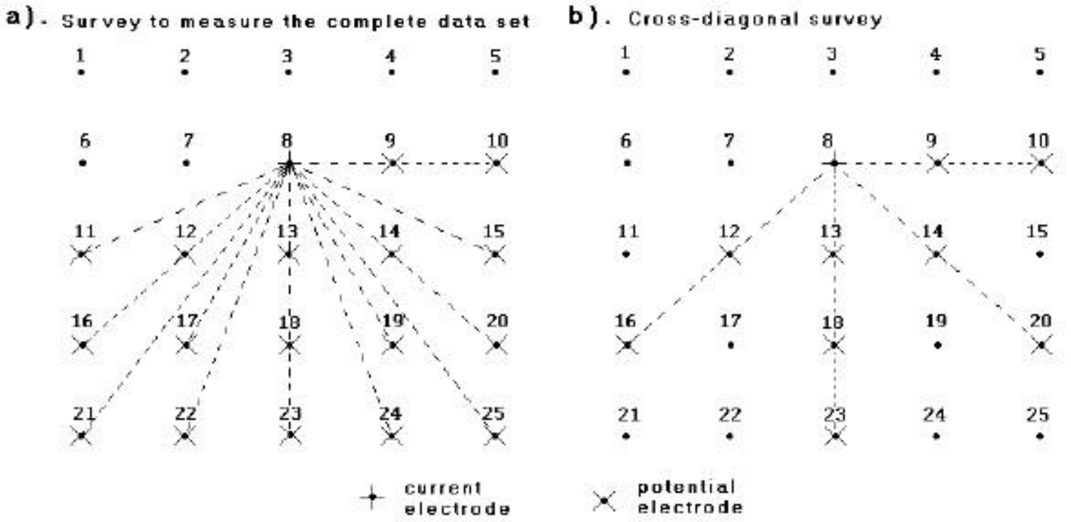


Figure 11 – The two possible measurement sequences for 3D survey. The location of potential electrodes corresponding to a single current electrode in the arrangement used by (a) a Survey to measure the complete data set (b) Cross-diagonal survey.

As can be seen in Figure 10, the electrodes of three-dimensional tomography of resistivity are lengthened not only along the x axis, but also along the y axis and the h is going to be the depth of the measuring object. The results of 3D electrical resistivity tomography are very useful and popular if the geological object which we are going to look at is three dimensional, because the results of this measurement will be very good, but here is one thing, the place where 3D electrical resistivity tomography is going to be measured is very small by comparing with the size of vertical electrical sounding or 2D resistivity imaging. Also, 3D resistivity imaging takes a very long time to take measurements, rather than 2D electrical resistivity imaging or vertical electrical sounding which is the fastest in measuring, as we wrote before. As can be seen in figures above, current comes from cable and goes to the current electrodes, and the current, in turn, goes to the geological object which is located under hundreds of meters the ground and back to the electrodes which work to measure the data which came from the geological object. The data from geological object, which is located underground, comes in resistivity meter and geophysicists can see the characteristics of the geological object, then decide what kind of ore-body this is. There are a lot of minerals, rocks and clays which can show us approximately the same results of resistivity, that is why modern geophysicists use modern technologies, field observation techniques, modern processing systems, programs which can work very fast with a lot of data set and give us better quality of inversion, interpretation and help to avoid from false anomalies.

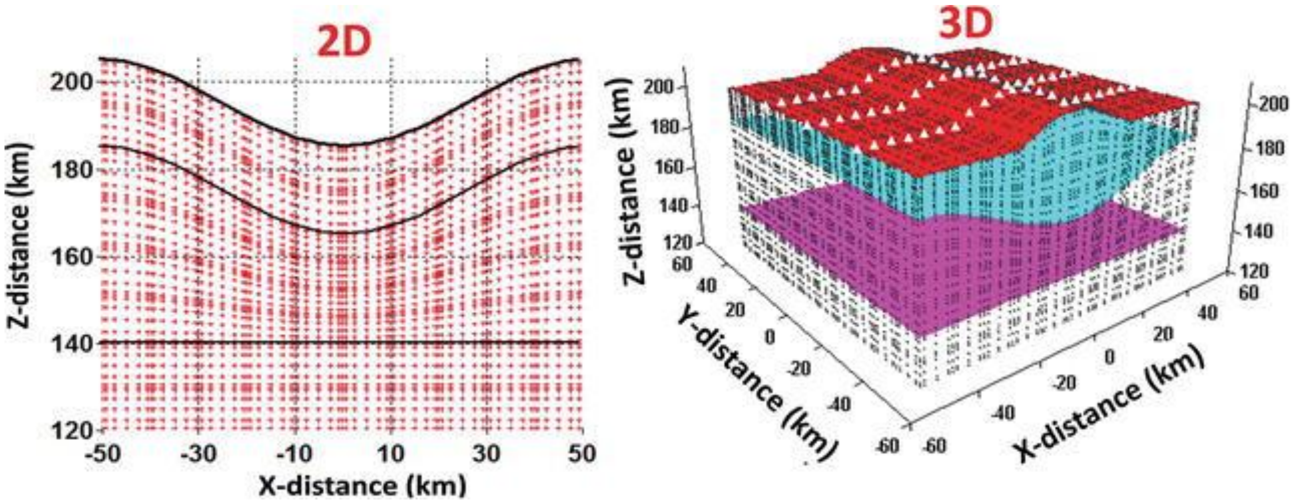
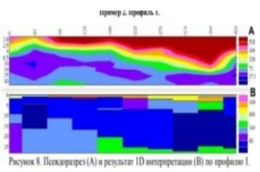
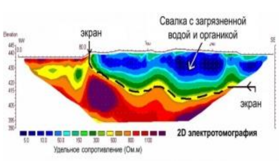
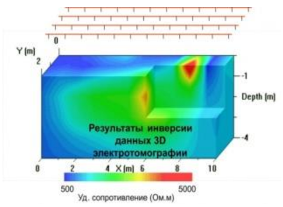


Figure 12 – The comparison of 2D resistivity imaging and 3D resistivity imaging results.

As its seen here in Figure 12, there are a lot of differences between 2D electrical resistivity imaging and 3D electrical resistivity imaging. Each of them have advantages and disadvantages of their own, one of them can not see three dimensional structures of the underground, while another one measures the polarization and resistivity of the geological object in a very long time. In the next table will be shown the advantages and disadvantages of each method in electrical resistivity tomography:

Table 3 – Advantages and disadvantages of electrical resistivity tomography (1D, 2D, 3D)

Type	Advantages	Disadvantages
1D ERT 	1) Used to evaluate the upper horizontal layers of the earth's crust 2) High speed of work 3) Low price compared to 2D and 3D shooting	1) two-dimensional and tectonically complex three-dimensional inhomogeneities manifest as distortion or false anomalies

2D ERT 	1) A wide range of tasks and the study of linear and local heterogeneities 2) High speed of work 3) Affordable price	1) Tectonically complex three-dimensional heterogeneities manifest as distortion or false anomalies
3D ERT 	1) Well displays termer-heterogeneity	1) Difficulty 2) High price 3) Low current profitability 4) Small resolution

Due to the fact that Vertical electrical sounding has been used for up to 100 years, since XIX century, nowadays we use it just to see the upside of geological structure of the of the underground. 1D ERT or VES has its own good sides and bad sides, as it is shown in the table 3, VES is used to study and learn the first horizontal layers of the underground and to figure out what kind of rocks minerals we have there. There is no method which can compare with the high sped of work of vertical electrical sounding, it works really fast than other methods of electrical resistivity sounding and one of the biggest advantages of this method is low price by comparing with 2D resistivity imaging and very low price by comparing with 3D ERT. But, nothing is perfect as the vertical electrical sounding is, so the biggest weak side of 1D method is VES can not see two-dimensional and tectonically complex three-dimensional inhomogeneities manifest as distortion or false anomalies.

The method which is widely used than others, golden middle, 2D electrical resistivity tomography. This method is highly recommended with geophysicists around the world, because it has a wide range of tasks and study of linear and local heterogeneities, it means this method can solve lots of problems which is connected to the geological object or structure of the underground. 2D resistivity imaging has a high speed of work of vertical electrical sounding, but it is not faster than VES. 2D electrical resistivity tomography has a very cheap price rather than 3D ERT. Of course, it also has its own black sides which brings us a problem when we face tectonically complex three-dimensional heterogeneities and the results of the final cross-section or model manifest as distortion or false anomalies. Though there is a real problem of 2D resistivity imaging with three dimensional structures and geophysical objects, but it continues to be done by a lot of geophysical companies and this method gets better and better every year, just because companies ask for geophysicists to use it and scientists with engineers developing this method and its inversion, data processing and interpretation programs. We also used 2D electrical resistivity imaging in the search for ore bodies in Benkala and South Benkala deposit.

Last method of electrical resistivity tomography is 3D method. This method is the best one if geological object has three dimensional characteristics and the size of this object is very small. But, as everybody know the size of the geological objects underground are very big, even sometimes size reaches tens of kilometers. As far as this 3D method is the best decision if your geological object that you are looking for has termer-heterogeneity, because 3D resistivity imaging has best sides in this area. Unfortunately, this is the first and the last best side of 3D electrical resistivity tomography and it is time to transfer the disadvantages of 3D survey. To take measure by using 3D method is very difficult, because this method has a lot of cabels and electrodes, just to sort them by profiles geophysicists can waste a long time. Also this type of survey has a very small resolution by comparing with other methods of electrical resistivity tomography. 3D-electrotomography has the highest degree of information when studying three-dimensional objects. But at the same time, it has a number of significant drawbacks, and the main one is difficulty. Due to these big 3 disadvantages of 3D electrical resistivity tomography, this method has low current profitability. The complexity of the installation and the one-time use of the grid of electrodes is the main disadvantage of the 3D method. For example, when we use a 64-channel station, we can cover no more than 8x8 electrodes, which, depending on the step, will give us either poor resolution or a very small coverage area.

2.4.1 Idea of ERT

Now we know all methods of electrical resistivity tomography and it is time to talk about how field observation with electrical resistivity tomography is done. First things first, before geophysicists start measuring work they have to do experimental and methodical work. It means must be chosen the most effective distance between electrodes, selected working observation method, distance between profiles with high effectiveness and spacing grid.

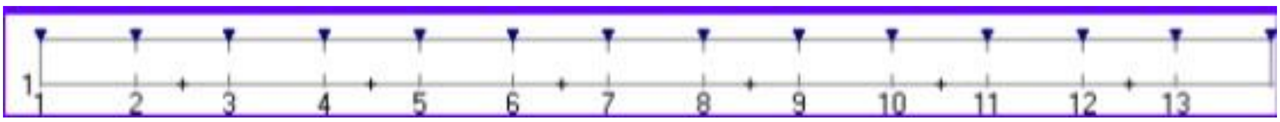


Figure 13 – The optimal distance between electrodes.

After choosing effective distance between profiles and electrodes, it is time to start measuring work in field. Measuring works were done with 2D electrical resistivity tomography and after conducting field observation geophysicists are going to have the results of pseudo-section as resistance and polarizability.

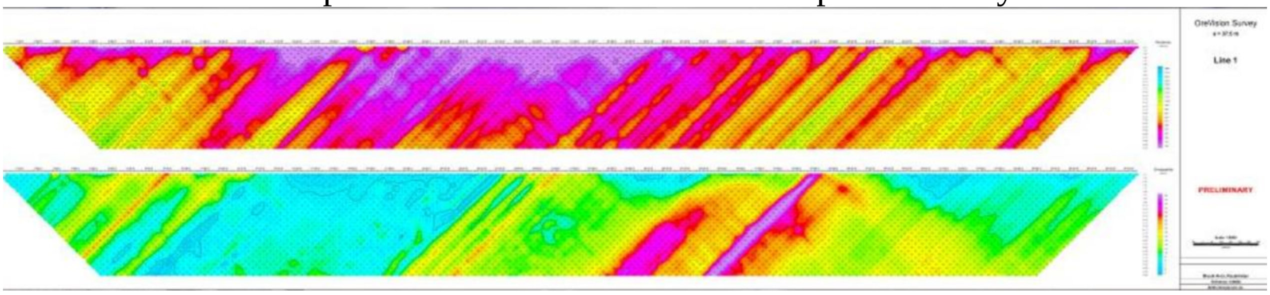


Figure 14 – Pseudo-section as resistance and polarizability.

The data set about geological object or structure of the crust can be and in most of the situations are with false anomalies, due to the three dimensional heterogeneities. This is why data processing programs as Res2Dinv, inversion programs as ZondRes2D and interpretation programs exist.

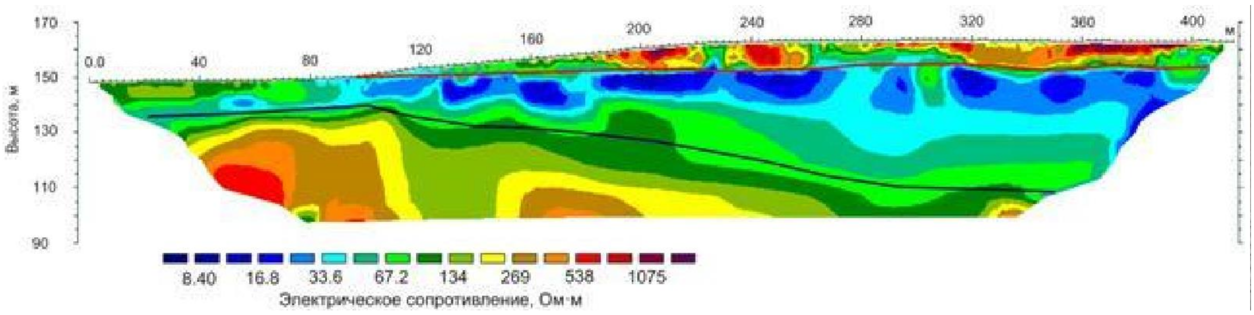


Figure 15 – Geoelectric section after 2D inversion (ZondRes2D).

Generally, after inversion false anomalies and three dimensional heterogeneities will be solved and the results pseudo-section, cross-section and geoelectric section is going to be much more better.

3 Results of experimental and methodological work

Before we start conducting field observation, there must be done experimental and methodical work. The meaning of experimental and methodical work are choosing the best, optimal, most effective distance between profiles, effective distance between electrodes, spacing grid and to select a working observation network. These works are done because if geophysics do not choose the optimal distance between electrodes, pickets and profiles then as practice shows the chance of missing the boundaries of the geological object, in our situation this is copper deposit, is very high. If they miss the boundaries of the geological object and sometimes even programs can not help here, just because due to the wrong data set, then there is a high risk of sending wrong data set to a customer. Experimental and methodical works and measuring works were done in two deposit they are Benkala and South Benkala.

The Benkala deposit of copper-porphyry ores is located in the Aktobe region at 113 km. southeast of the city of Zhetygar and 103 km. southwest of the Krasnooktyabrsky bauxite mine and is located 16 km. southwest of the Sholaksky railway junction. The relief of the region is a slightly hilly plain with absolute elevations from 229 m to 284 m. Numerous drainless depressions are 3-5 m deep. Land on the area of the deposit was previously occupied by spring crops. The region does not have its own energy and labor resources, the nearest highway runs 6 km to the east, with the completion of the construction of a new railway, the district's infrastructure has improved significantly. In addition, iron ore, bauxite, gold, nickel and various building materials are known in the area. The geographical coordinates of the license area are as follows:

Table 4 – The geographical coordinates of the license area

Corner points	**Corner point coordinates**	
	northern latitude	**Eastern longitude**
1.	51º 12′ 42′′	61º 45 ′25′′
2.	51º13′ 35′′	61º 45′ 25′′
3	51º 13′ 35′′	61º 46′ 45′′
4.	51º 12′ 42′′	61º 46 ′45′′

The Benkalinskoye deposit was discovered in 1969 by the Steppe GRE (Yanovsky V.I.), which conducted detailed searches for copper in the area. As a result of the work, the geological structure of the ore occurrence was clarified, industrial copper ores were discovered by a number of wells, which allowed the

author to provide a predictive assessment of the ore occurrence to a depth of 250 m and to outline the further direction of prospecting and evaluation work.
In the years 1976-80. Dzhetygarinskaya GRE (Gachkevich I.V.) at the field, prospecting and evaluation work was carried out. As a result of these works, ore and metal reserves were calculated for category C2 (author's calculation).
In 2007, the company “U.S. Megatex, Inc. » concluded a contract No. 2482 of 11/15/2007. for the exploration and production of copper at the Benkala deposit in the Aktobe region, which drafted and agreed with the Zapkaznedra technical university for a 4-year exploration project (exploration period) and an annual work program for 1 year of exploration until November 15, 2008. In 2008, in connection with the liquidation of the company “U.S. Megatex, Inc. » subsoil use contract No. 2482 reissued to KazCopper LLP (supplement No. 1 of 08/13/2008).
In 2010, KazCopper LLP compiled a Report on the “Geological and Economic Assessment of Secondary Ores of the Benkala Copper Deposit in the Aktobe Region (Contract No. 2482)." The result of this work is the calculation of reserves and geological and economic evaluation of secondary copper ores of the Benkala deposit.
Ore and metal reserves at the Benkala deposit have been reviewed and tested at the State Reserves Committee of the Republic of Kazakhstan.

Table 5 – Ore and copper reserves calculated at the Benkala deposit as of 01.01.2011y.

Parameters	Unit	Category C2 reserves
Secondary ores:		
Balance stocks:		
Ore	Thousand tons	37656,0
Copper	Thousand tons	198,9
Average content	%	0,53
Off-balance reserves:		
Ore	Thousand tons	763,2
Copper	Thousand tons	3,0
Average content	%	0,39
Total balance + off-balance reserves		

Ore	Thousand tons	38419,2
Copper	Thousand tons	201,9
The average content,%	%	0,53

The State Reserves Committee of the Republic of Kazakhstan recommended that geological exploration work be continued at the deposit in order to study flanks and deep horizons, to study the technological properties of secondary and primary ores, as well as pilot production of oxidized ores for heap leaching technology of copper in semi-industrial conditions, and the terms and volumes should be determined by the project.

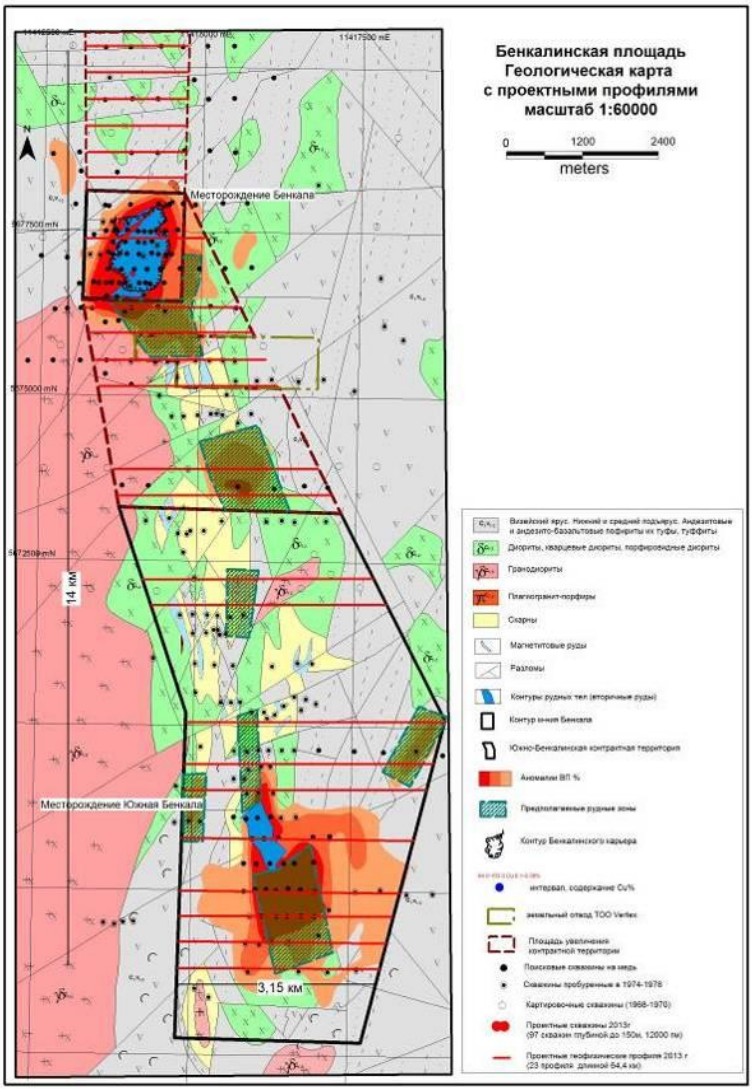


Figure 16 – Geological allotment of Benkala and Benkala South sites.

Experimental and methodical work and measuring work were carried out in two areas. In the South Benkala section, measurements were carried out according toprofiles 0-950, and in the Benkala section, measurements were taken from profiles 1025-1525. As it is shown in figure 16, the scale of the map is equal to 600 hundred meters per one centimeter and the location of profiles and pickets on Benkala and South Benkala deposit. According to preliminary results of geological studies on Benkalinskaya area, local anomalies of high polarizability of rocks are identified. The results of the analysis of geophysical materials made it possible to draw a conclusion about the continuation of the identified anomalous zones to the north and northeast of the site. To delineate the identified anomalies, it was decided to continue the electrical exploration by the method of electrotomography beyond the northern and northeastern borders of the project circuit. Additionally, it was carried out: electrical exploration in increments of 250x50 - 25 linear kilometer.

There were done not only electrical resistivity tomography on Benkala and South Benkala, also magnetic exploration, surveying work and electrical exploration IP-MG about types and volumes of these works you can see in the next table.

3.1 Methodology

№ MN	B	A	M	N	MN	Spacing
1	-1000	0	10	20	10	15
2	-1000	0	20	30	10	25
3	-1000	0	30	50	20	40
4	-1000	0	50	70	20	60
5	-1000	0	70	100	30	85
6	-1000	0	100	150	50	125
7	-1000	0	150	250	100	200
8	-1000	0	250	350	100	300
9	-1000	0	350	550	200	450
10	-1000	0	550	750	200	650
11	-1000	0	750	950	200	850
12	-1000	0	950	1250	300	1100
13	-1000	0	1250	1650	400	1450

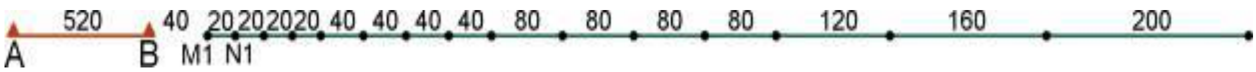


Figure 17 – Installation of electrotomography. Distances are in meters.

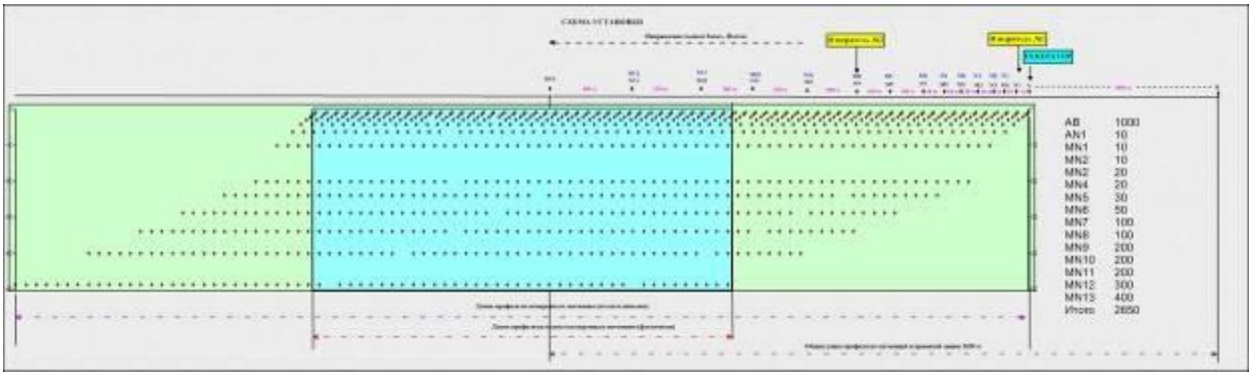


Figure 18 – The length of the supply line AB is 1000 m. The length of the receiving lines is from 10 to 400 m. The plant spacing is from 15 to 1450 m. The step along the profile between the sensing points was 50 m.

Types and volumes of field work

South Benkala

№ n/w	Type of work	Unit	Volume		
1.	Surveying work (breakdown of profiles)	Lin. km	120,0		
2.	Electrical exploration IP-ChZ, SG: AB = 3km, MN = 50m, network 250x50m	Lin. km	120,0		
3.	IP electrical exploration, profile electric tomography, step of receiving electrodes 10m, step of feeding 50m	Lin. km	35,0		
4.	Magnetic exploration, network 100x10m	Lin. km	350,0		

Benkala

№ n/w	Type of work	Unit	Volume		

1.	Surveying work (breakdown of profiles)	Lin. km	65,0		
2.	Electrical exploration IP-CZ, SG: AB = 3km, MN = 50m, network 250x50m	Lin. km	65,0		
3.	IP electrical exploration, profile electric tomography, step of receiving electrodes 10m, step of feeding 50m	Lin. km	20,0		
4.	Magnetic exploration, network 100x10m	Lin. km	250,0		

Additional electrical exploration works

№ n/w	Type of work	Unit	Volume		
5.	IP electrical exploration, profile electric tomography, step of receiving electrodes 10m, step of feeding 50m	Lin. km	25,0		
	Overall:				

3.2 Electrical exploration with IP-MD

Electrical exploration using the mid-gradient method with the measurement of induced polarization (IP-MG)

The IP-MG work technology consisted of the following: the work was carried out by 3 AGE-xx1-4h meters on 3 parallel profiles from a single current line AB 3000 m long. In this case, only the central part of the tablet with a length of 1000 m was worked out, then the AB line moved along the profile and the tablet shifted in area. The length of the receiving line for each meter was 200 m. On each measurement cycle, 4 points were worked out (4x50m = 200m). The technology of continuous movement of the current line AB was used. Electrical exploration of the

IP-MG was carried out by a set of equipment AGEXX1 consisting of the following elements:
1. 2 stand-alone meters.
2. 4-channel meters.
3. Generator UCM -02 kW.
4. Generator UCM-30 kW.
5. 2 power stations HONDA.
6. Universal braids, current and receiving electrodes, chargers and batteries.
7. 8 personal computers.
8. The works were serviced by 5 UAZ vehicles and the ZIL-131 vehicle was used as a generator station.

The stand-alone field meter AGE-xxl-4-h is a part of the AGE-xxl electrical exploration complex and is designed to measure and record the signals of various components of the electromagnetic field when performing geophysical field exploration by any methods. Main technical characteristics of AGE-xxl-4-h:

- number of simultaneously measured “l” channels: 4;
- number of simultaneously measured “h” channels: 1;
- amount of internal data memory: 512 MB;
- number of offline records - up to 256;
- constant field compensation - up to 250 mV;
- maximum measured input voltage - up to 100 V;
- minimum measured input voltage - from 10 nV;
- availability of interfaces for communication: USB, RS-485, SPI;
- voltage of standby power (internal source-battery): 3.6 V;
- voltage of working power supply (internal source - battery) - 12 V;
- capacity of the internal power supply: 9 A / hours
- consumption in operating mode - not more than 200 mA;
- range of working temperatures: from -40 to +60 degrees C.

Technical characteristics of the high-frequency “h” channel:

- cutoff frequency of the analog low-pass filter - 2 MHz or 500 kHz;
- ADC time sampling (minimum value) - 1/12 μs;
- the number of bits of the ADC - 16;
- maximum input signal - 2.5V / 25V / 100 V;
- programmable amplifications in the channel (for the input range of 2.5 V) - 1/10/100;
- input channel resistance - more than 300 mOhm / 2.5 kOhm.

Technical characteristics of the low-frequency “l” channel:

- ADC time sampling (minimum value) - 125 μs;
- the number of bits of the ADC - 24;
- maximum input signal - 2.5 V;

- programmable amplifications in the channel - 1/10/100/1000;
- input channel resistance - more than 300 mOhm.

The UCS-02M-37 switch is designed to form rectangular current pulses of different polarity and duration in the load circuit. The switch provides stable and reliable operation over a wide range of load resistances.

The scope of the switches is work as a part of generator electrical prospecting installations (Fig. 2.1-2.2).

Main technical data of the UCS-02M -37 switch:

Maximum load current: 75 A.

- Maximum voltage (constant): up to 750 V
- Maximum switching frequency: 1 kHz
- The duration of the current shutdown front (at active load) is not more than 10 μs.
- Type of power supply: constant or variable (50 Hz, 400 Hz).
- Necessary working power supply: 220V, 50Hz.
- Power consumption: no more than 300 W.
- Range of working temperatures: from 0 to +40.
- Weight: 60 kg.
- Average life: at least 3 years.

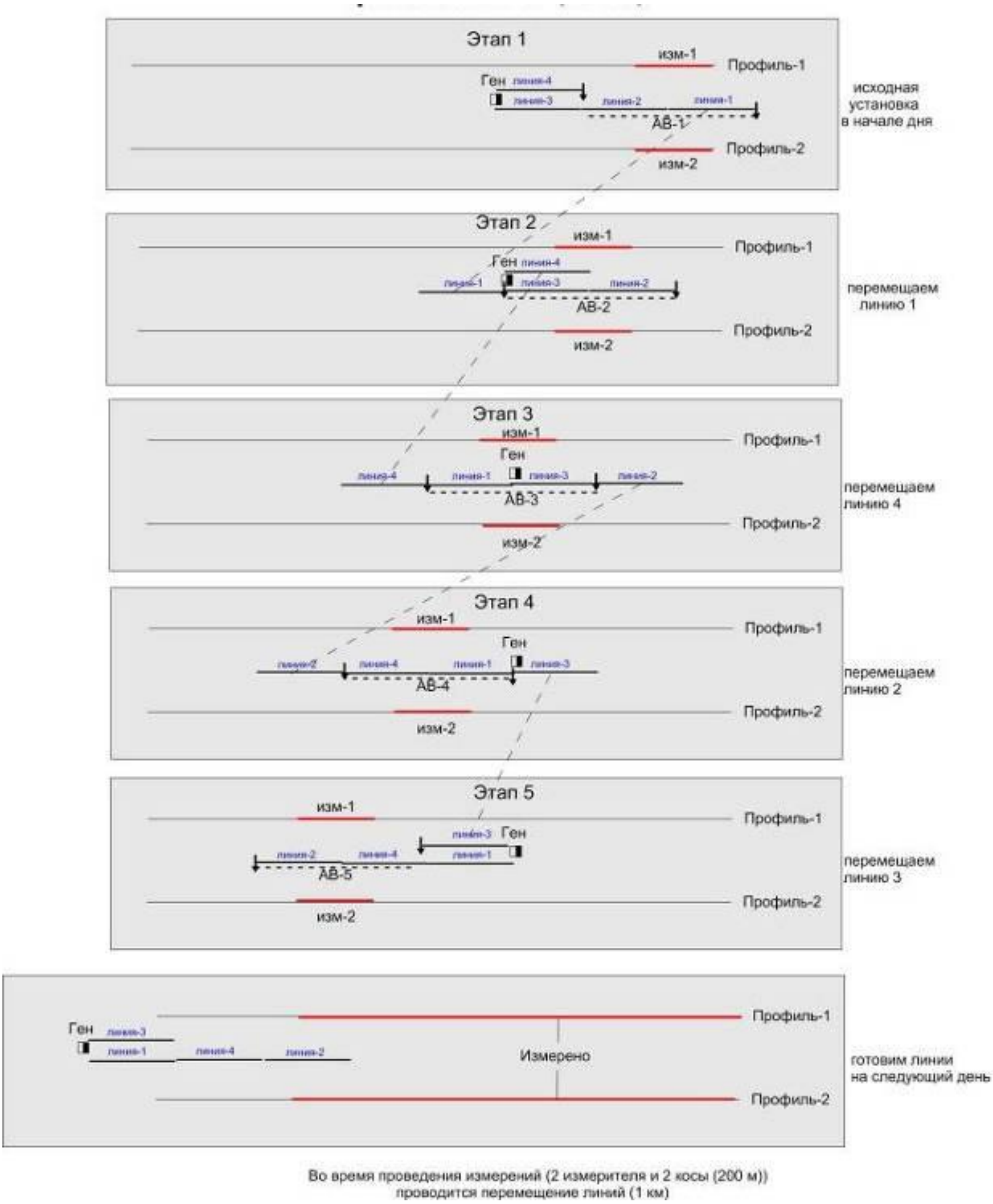


Figure 19 – Installation diagram for continuous IP-MG

All of these equipments have been used in the search for ore body, to find out the location of copper. These and other equipments are used on both deposits Benkala and South Benkala. By the final results of electrical resistivity tomography, cross sections of the each profile and three dimensional model of the both deposits we can see that there is a geological object underground approximately 200 meters. Three dimensional model has been done with the program Voxler three dimensional visualization system. All together on both deposits going to be drilled 6 boreholes, all of them will be drilled strictly upright and until they reach 200 meters.

Figure 20 – Switch UCS-02M -37.

Application: any methods of electrical exploration with artificial field sources; performance of work to increase oil recovery; conducting research on the study of seismic-electrical effects; physical modeling of electromagnetic fields; Functional features: a number of current switches of various power (from 15 to 150 kW), containing a two-link frequency converter on a transistor inverter (IGBT); arbitrary choice of power supply: direct current source, either 380V-50/60 Hz, or 380V - 400 Hz, or 660V-50/60 Hz; possibility of field execution with degree of protection IP-54 (option); digital control of UCS operation - from a 4-channel AGE-xxl meter with the formation of an arbitrary time diagram of the current in the load; registration of current and voltage signals; software control of load resistance, hardware protection for current and voltage at the output of UCS; GPS measurement synchronization; The original Control Program provides a graphical display of current and voltage signals in real time; processing software allows you to take into account the shape of the current when processing electrical exploration data; Main technical characteristics: maximum current in the load - from 30 to 300 A (from the model); maximum load voltage - up to 900 V (from the model); maximum power - up to 150 kW (from model); maximum switching frequency (at active load) - up to 50 kH.

Figure 21 – Equipment set of the measuring installation AGE-xxl-4-h.

3.3 Electrical resistivity tomography

Until recently, the main techniques of the resistance method in ore geophysics were vertical electric sounding (VES-IP) and the mid-gradient method (MG). These techniques, developed in the first half of the last century, are aimed at interpretation within the framework of simple models. This limits the effectiveness of their use in the study of complex sections that are significantly different from one-dimensional.

The rapid development of computer technology, special software and field equipment has allowed us to move from one-dimensional measurements of electrical resistance to two-dimensional (2D) measuring circuits. Two-dimensional measurements are a whole complex that includes both the methodology of field observations and the technology for processing and interpreting field data. Usually multi-electrode installations are used. The measuring complex consists of a current source, current and difference potential meters, and receiving electrodes connected by means of an electric prospecting braid to the switch. Two-dimensional observation schemes can be represented as a combination of a large number of vertical electrical soundings with a frequent step. In this case, the value of the maximum separation for the obtained curves varies along the profile. The maximum spacing for one arrangement is possible only in the central part of the profile. At the edges of the arrangement, the maximum spacing and, accordingly, the depth are reduced to zero. As a result, the apparent resistance pseudo-cuts and the interpreted geoelectric section have a characteristic trapezoidal shape or parallelogram shape (with one-sided installation). When moving the arrangement along the profile, a half-length overlap is used to provide sufficient depth along the profile. The maximum separation is determined by the length of the installation, and the minimum distance between the electrodes.

Data interpretation is carried out in the framework of two-dimensional models using special two-dimensional inversion algorithms. In contrast to the VES method, in which individual curves on the profile are interpreted, in multi-electrode soundings, inversion is performed for the entire measured data set. The result is a distribution of resistivity in depth.

Electrical resistivity tomography was performed in two areas. In the South Benkala section, measurements were carried out according to profiles 0–950, and in the Benkala section, measurements were taken from profiles 1025–1525.

Electrical resistivity tomography installation is shown in figure 17. The length of the supply line AB is 1000 m. The length of the receiving lines is from 10 to 400 m. The plant spacing is from 15 to 1450 m. The step along the profile between the sensing points was 50 m. The total volume of measurements was: main work according to the contracts - 55 linear meters. km, under an additional agreement - 25 p. km. The volume of control measurements was 5%. The error in the determination of apparent resistance and apparent polarizability, determined from control measurements, was 1.51% and 4.16%, respectively.

4 Methods of processing and interpretation electrical exploration data ET

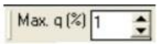
Modern software for modeling and inversion of electrotomography data. Before the introduction of field and area tomographic measurement systems into practice, the resistance method was carried out on a per-unit basis basis and mainly 1D and 1.5 inversion systems were used. With the advent of electrical prospecting stations that implement dense 2D and 3D tomographic measurements, the need has arisen for multidimensional inversion. So in 1996, published works [Loke and Barker, 1996a; 1996b], which provides algorithms for practical 2D and 3D inversion. At the same time, the first versions of Res2DInv, Res3DInv programs are released, see table. 2) that implement these algorithms. To date, there are many programs specialized for modeling and inversion of electrotomography data. In the table. Figure 2 shows a list of commercial software for modeling and inversion of 1D, 2D, and 3D electrotomography data. For processing field records and calculating apparent polarizability and apparent resistance, we used the certified Res2Dinv program developed in Malaysia. In this section, we will consider the main processing steps and signal processing algorithms implemented in this program. There are a lot of aps and programs which can help geophysicists to do data processing of the electrical resistivity tomography data. One of them which is widely used is Res2Dinv. There are 4 ways of data processing in this program. In Res2Dinv reprocessing restores data, it is very convenient because other programs which are also used to take data processing of electrical resistivity data can not show such a big advantage of their own program. Processing deliberately bad measurements can significantly improve the quality of the inversion and avoid false anomalies. Res2Dinv program helps to achieve the best results by removing false anomalies and improving the results of data processing. So, customers can see their order very clear. In the Res2Dinv program, the data can be processed in four ways, then these processed data are saved in the ‘Res2dinv’ format, after which the edited data is opened in the ZondRes2dp or ZondRes2d program to interpret the received data.

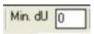
As it was written above there are 4 ways of data processing in Res2Dinv program. They are:

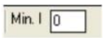
- Automatical
- Delete selected electrodes
- Manual removal of individual spacing
- Manual rebound removal

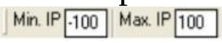
Then after going through each one of these steps, geophysicists are going to have ‘data’ which they need to save in ‘res2dinv’ format in order to do an interpretation of these data set.

Automatical

Automatic deletion of data that does not meet the criteria specified in the “Data” tab of the Table window: Calculated measurement accuracy (q, quality factor. 

Dev) is greater than the specified value.The measured potential difference is less than the set value. The minimum acceptable signal depends on the accuracy of the equipment used and the level of interference, usually 0.1-10 mV 

The current in the supply line was less than the set value. This 

usually indicates poor grounding quality. The measured value of the polarizability does not meet the specified limits. These values usually indicate a high level of interference 

Delete selected electrodes

{  Delete selected electrodes}, {[Del] in the table with a description of the electrodes}. Discarding data received with a bad electrode. This is usually due to poor grounding of the electrode, improper connection or problems in the measuring equipment. In fig. An example of data is shown before and after removal of two electrodes (MNB installation).

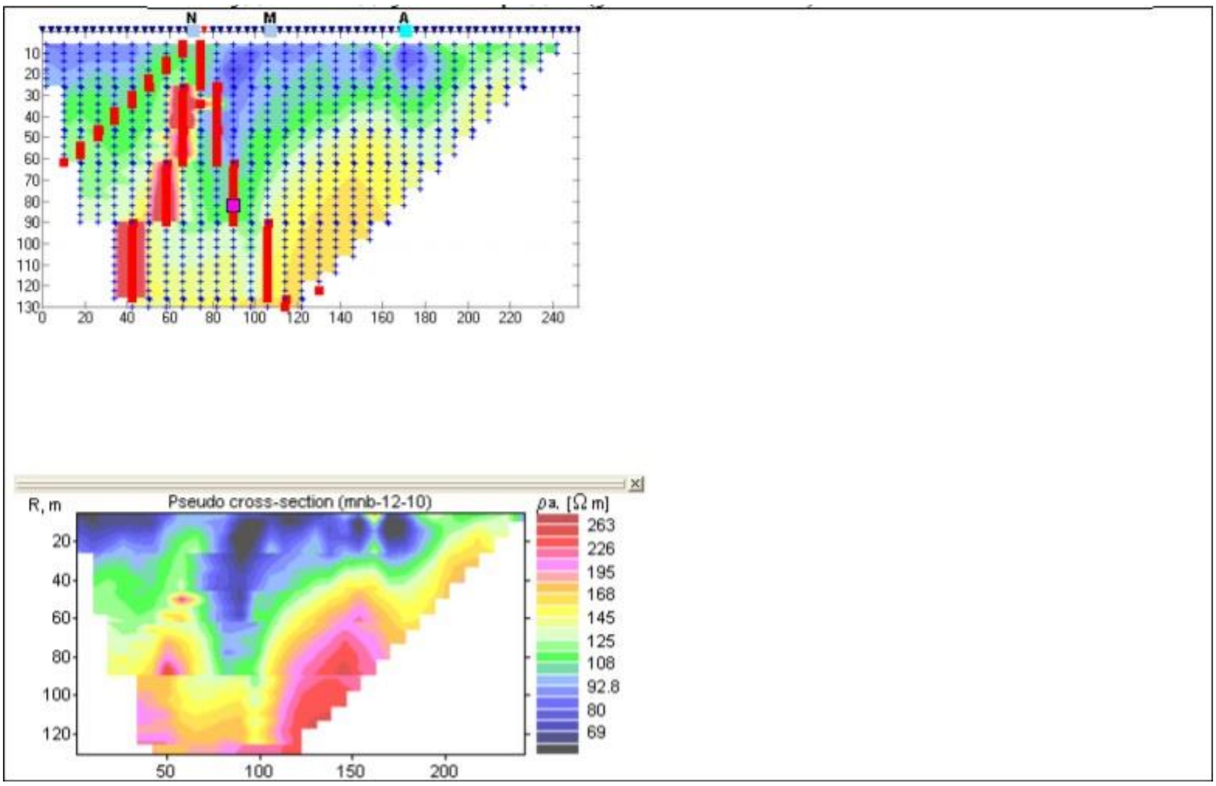


Figure 22 – The process of deleting selected electrodes.

Manual removal of individual spacing.

It is sometimes necessary if at some spacings an excessively large ratio of AB to MN was used. Delete selected spacings in the Spacings tab of the Table window

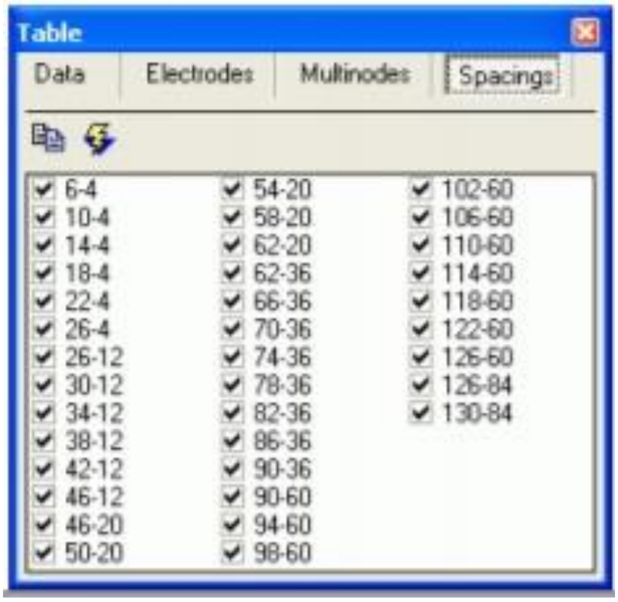


Figure 23 – Process of manual rebound removal.

Mark the desired measurement in the Data and installation configuration window or in the data table and press the [Del] key.
ATTENTION! When data is rejected by the methods described in b) and d), the section is not automatically redrawn. Click the{ Redraw contours} button to redraw the pseudo section.

Saving Edited Data

After editing the field data, it is recommended to save the results in the data format Res2dInv Menu - “Converter | Res2DInv”; [Ctrl-R]; {}
By opening several data files received on one profile, they can be saved in one common file. If the measurements were obtained with different settings, then you need to use the General format Res2dInv: Menu - “Converter | Res2DInv (general)"; [Ctrl-G]; { }.
If the input file contained data for several electrical exploration installations, then you can save the highlighted installation to a separate file: Menu - “File | Extract array”.

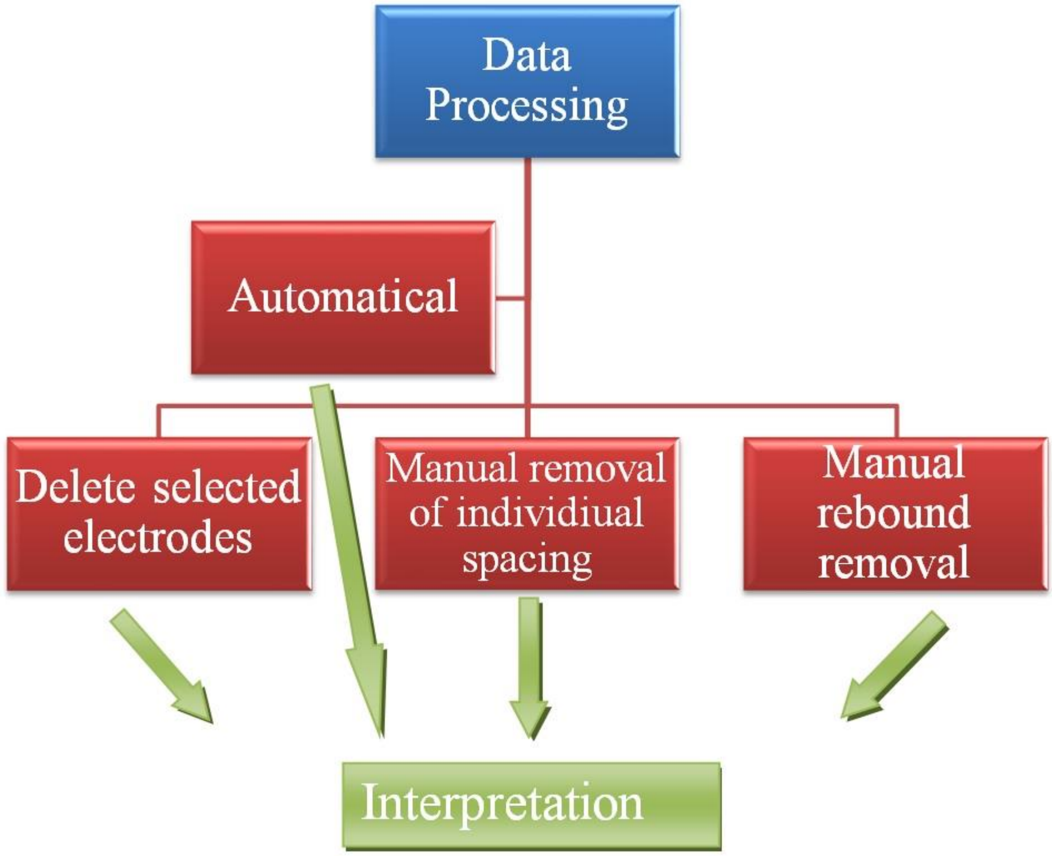


Figure 24 – The process of data processing with program Res2Dinv.

There are also other programs which can do almost the same work as the program for data processing and inversion Red2Dinv. The program Res2Dinv was made in Malaysia and widely spread around the world. Nowadays, other countries also doing their best to create such a simple in use and program with high speed of processing data. In the next table you can see other programs which are also used to process the data of electrical resistivity tomography, especially 2D and 3D.

Table 6 – Software for modeling and inversion of electrotomography data.

Software Name	**Description**	**Developer**	**Site**
Res2DInv, Res3DInv	First and most popular 2D and 3D inversion software ETM data	Geotomo SOFTWARE (Malaysia)	www. geoelectrical.com

Res2DMod, Res3DMod	Data modeling software ETM	Geotomo SOFTWARE (Malaysia)	www. geoelectrical.com
SensInv1D, SensInv2D, SensInv3D	Software for 1D, 2D, 3D modeling and inversion ETM data	Geotomographie GmbH (Germany)	www. geotomographie.de
DC2DInvRes, DC3DInvRes	Software for 2D, 3D inversion and permits ETM data capabilities	Thomas Günther (Germany)	www. resistivity.net
ZondIP1D, ZondRes2D, ZondRes3D	Software for 1D, 2D, 3D modeling and inversion ETM data	Alexander Kaminsky (Russia)	www. kaminae.narod.ru
Earth Imager 1D, 2D, 3D	Software for 1D, 2D, 3D modeling and inversion ETM data	Advanced geophysics (USA)	www.agiusa.com
ERT Lab	3D data inversion software ETM	MPT & GEOStudi Astier (Italy)	www.ertlab.com
Emigma	3D modeling software and 1D inversion of ETM data	PETROSEIKON Inc. (Canada)	www.petroseikon.com
Ie2Dp, X2ipi, Ip2Win	Software for 1D and 2D modeling and processing 1D inversion of ETM data	Moscow State University (Russia)	www. geoelectric.ru

4.1 Interpretation of ERT

The interpretation of electrical resistivity tomography data was done with ZondRes2D program. The ZondRes2D program is designed for two-dimensional interpretation of electrotomography data by the method of resistance and induced polarization in the ground, borehole and aquatic versions. The resolution and, consequently, the quality of interpretation of the electrotomography data are closely related to the number and density of measurements on one profile. Their number usually reaches the first thousand, so the question of the performance of field measurements is of fundamental importance and largely determines the possibility of practical use of this method. To achieve maximum efficiency during field work, special equipment is used with programmable automatic electrode switching.

ZondRes2d presents a turnkey solution for electrical tomography, and solves a wide range of tasks from mathematical modeling, selection of an observation system, analysis of data quality and sensitivity, to processing and interpretation of field data. A convenient interface and ample opportunities for presenting data make it possible to most effectively solve the geological problem. The system of analysis of the quality of electrical tomography data allows you to quickly and efficiently identify problematic measurements in automatic and semi-automatic modes.

ZondRes2d uses a simple and understandable data format that makes it easy to combine various electrical exploration observation systems, including various options for setting the terrain (including the bottom topography for bottom and aquator electrotomography) and other supporting information. The well-known formats of data inversion programs for the resistance method and induced polarization (res2dinv, earthimager, etc.) are supported, as well as the output files of well-known manufacturers of electrical prospecting equipment (SysCal, ABEM, AGI, Skala-48, Omega-48). The program works with any types of installations (two, three and four - electrode) used in electrical exploration, or their combinations on the surface of the earth and water in a well or under water. It is possible to set all three coordinates for each of the electrodes and work with arbitrary profile geometry. An important stage preceding field measurements is the mathematical modeling of the geoelectric structure of the site. Modeling makes it possible to evaluate the signal level and select the optimal installation parameters to solve the geological problem. ZondRes2d has a large set of tools for mathematical modeling and sensitivity analysis of DC fields and induced polarization. Two variants of modeling the electrical tomography data are implemented - in grid or polygon mode.

Since the main task of the program is to restore the parameters of the geoelectric section, ZondRes2d implements several options for solving the inverse problem, the most important of which are: smoothing inversion - to obtain a smooth, block inversion to obtain a block and focusing - to obtain a piecewise-smooth distribution of geoelectric parameters with depth. When developing the program, special attention is paid to the accounting of a priori information. Due to the equivalence of inverse geophysical problems, the quality of the results obtained directly depends on the amount of a priori data used. In ZondRes2d there is the possibility of assigning weights to measurements, fixing and setting the limits of changes in the properties of individual cells, using an a priori model as a reference model in inversion.

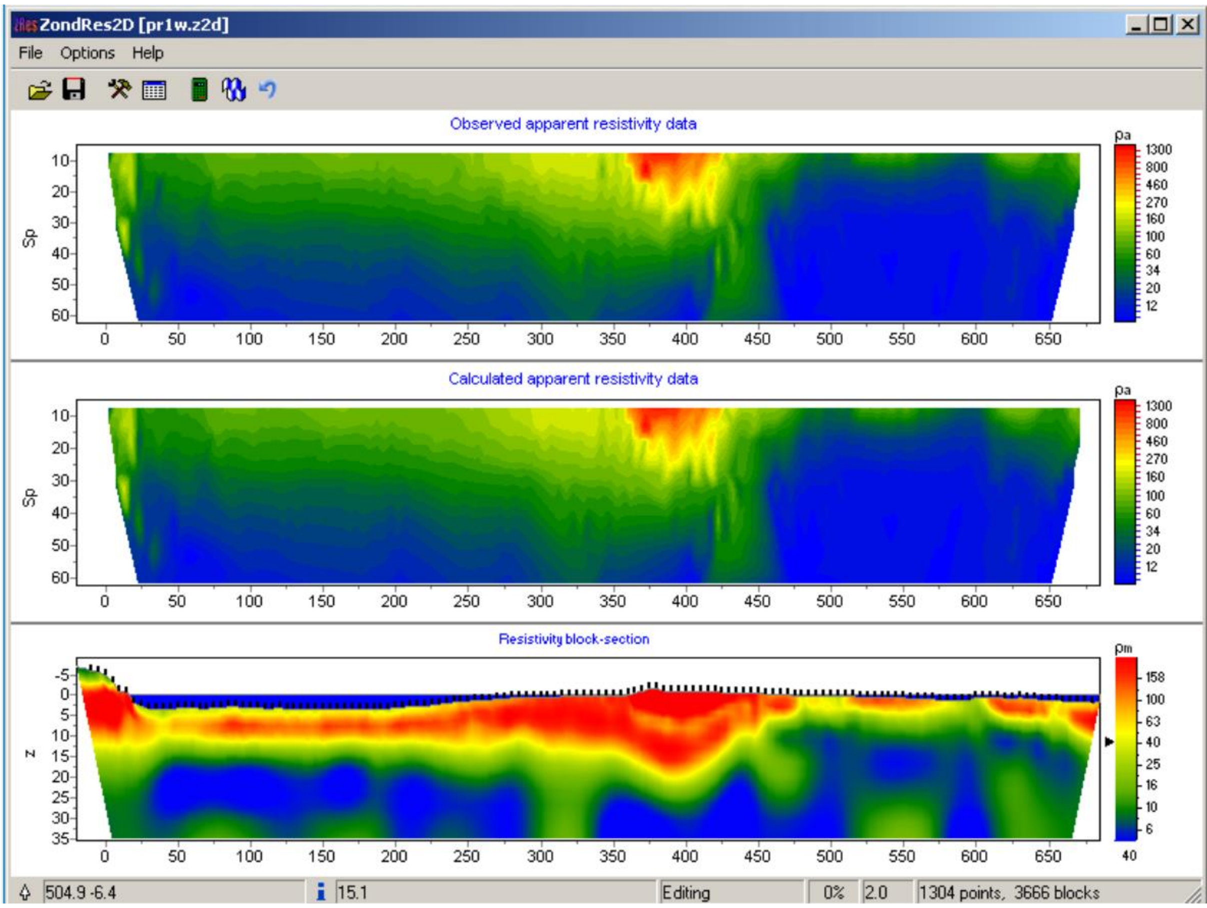


Figure 25 – Results of the interpretation of the data of electrotomographic measurements in Zondres 2D.

In addition, the program implements robust schemes for estimating the noise component. It is also possible to import and display measurement results by other methods and well data, which contributes to a more comprehensive approach to data interpretation. The module gravity exploration, magnetic exploration and the natural field method allows you to effectively combine these methods with a geoelectric section based on a single framework. The frame is built on the basis of the section obtained according to electrotomography, and then is filled with density and magnetic properties in automatic or manual mode.

Features of the program:

- Support for any electrical prospecting installations or their combinations with an arbitrary spacing system and electrode positions. Ability to work with different (by the number of electrodes) installations on one profile.
- Measurements in the water layer and at the bottom of the reservoir. Downhole and crosshole observations.
- Four options for setting topography.

- The ability to interpret the data of the method of induced polarization, both according to the standard scheme, and in the time or frequency domain with the restoration of Cole-Cole parameters.
- Block for quality control and rejection of electrotomography data.
- Joint inversion with magnetotelluric data.
- A set of tools for mathematical modeling of various geological situations. Standard “raster” and polygonal options.
- Integrated polygonal modeling for magnetic exploration of gravity exploration and the natural field method.
- Several options for inverting field data: smooth, focusing, robust, block. Defining a reference model for inversion. Estimation of the noise component during inversion.
- Suppression of P / C effects during inversion. Work with abnormal settings (method of pure anomalies).
- Fixing and setting the limits of parameter changes, the introduction of several a priori geological boundaries or well profiles. Setting weights and rejecting measurements. Measurement Editor.
- Assessment of the quality of a solution based on a sensitivity matrix. Calculation of the quality parameter of the resulting solution, DOI index.
- Trimming the edges of the model: by angle or by sensitivity level.
- Several options for visualizing data, models, and a priori information. Ability to set a translucent background for the section (geological, seismic sections).
- Three-dimensional visualization of geoelectric sections along an arbitrary system of profiles. Maps of slices of various parameters by depth.
- Geological section editor, a system for creating well information.
- Export to raster and vector graphic formats, excel, surfer, CAD. Setting the scale of exported images. Print images and create reports.

After primary processing of our data set of electrical resistivity tomography, here we have initial pseudo-cuts of apparent polarizability and resistance.

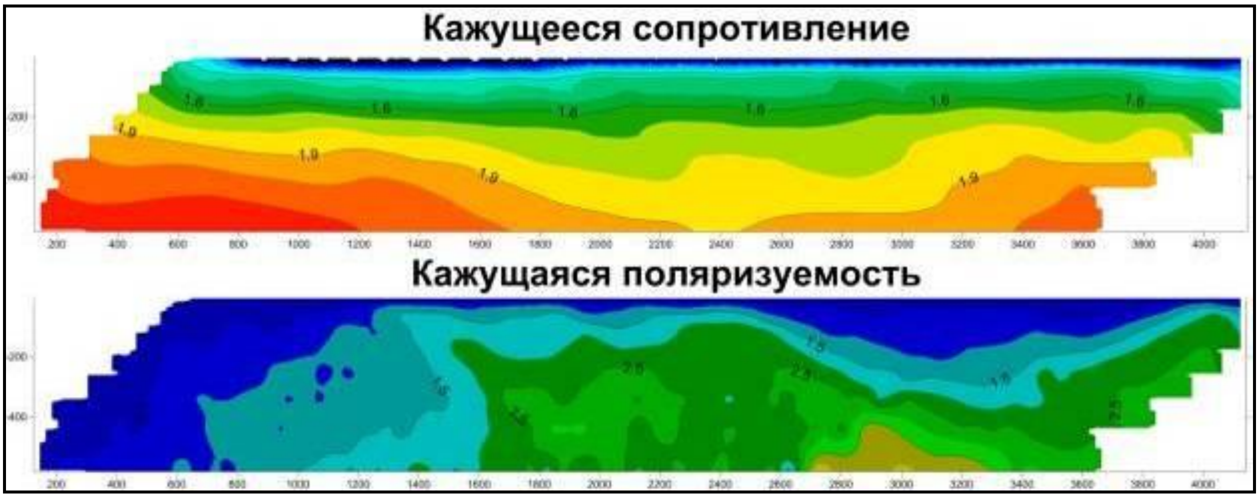


Figure 26– Pseudo-cuts of the profile 1475 .

5 Modeling technique based on electrophotography data

The program “ZondRes2D” (A. Kaminsky) was used to invert the data of electrotomography. This is an automatic two-dimensional inversion program within the framework of “smooth” models. Two-dimensional inversion is an algorithm that recalculates the observed electric field into the corresponding two-dimensional distribution of resistivity in the section. Since this problem is incorrect, the solution is regularized due to models with a smooth change in resistivity. This approach allows for a formal interpretation without taking into account a priori data. Due to the integral nature of the resistance method, the obtained solutions, as a rule, simplify and smooth out the real details of the geological structure of the section, overstating the thickness of the layers. In addition, false anomalies associated with objects located near the observation profile and inversion instability can appear in the section. Depths based on the results of surface geophysical surveys are determined evaluatively, due to the presence of equivalent relationships between resistance and rock thicknesses. All of the above difficulties of geophysical interpretation are common to most geophysical methods. At the same time, using the technique and electrotomography, we can confidently study not only horizontally layered structures, as in the VES method, but also vertical and inclined structures, we can distinguish local inhomogeneities. This is all possible, since the density of observations with this approach is quite high

In addition, the reliability of localization of objects with increased polarizability is significantly increased. The apparent apparent polarizability is complexly related to the distribution of resistivity and polarizable rocks. This leads to a significant ambiguity in the interpretation of the mid-gradient data. In tomography methods, thanks to the knowledge of the distribution of resistivity in the section, it is possible to obtain the spatial distribution of polarized rocks. ZONDRES2D Program
The ZONDRES2D program is intended for the 2.5-dimensional interpretation of the profile data of electrotomography using the resistance method caused by polarization and the charge method. A convenient interface and ample opportunities for presenting data make it possible to most effectively solve the geological problem. When solving the direct and inverse problems, the mathematical apparatus of the finite element method is used, which gives better results compared to grid methods. When modeling the field of a point source, the medium is divided by a network of triangular cells with different resistivities. The behavior of the potential inside the cell is approximated by a linear basis function. The field of a point source inside a two-dimensional medium has a three-dimensional structure.

$$N(x,z)=\frac{(a+bx+cz)}{2A}$$

$$\frac{\partial}{\partial x}\left(\sigma\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial z}\left(\sigma\frac{\partial\phi}{\partial z}\right)-\lambda^2\sigma\phi=-I\delta(x)\delta(z)$$
$$\frac{\partial\phi}{\partial n}+v\cdot\phi=0$$

Using the Fourier transform, the solution of the problem can be transferred to the spatial frequency domain. Where ϕ is the spectral potential value, λ is the spatial frequency, I is the current strength, σ is the medium conductivity, δ is the Dirac delta function. The subsequent solution for the set of spatial frequencies and the application of the inverse Fourier transform to the obtained spectral potential values gives the desired point source potential values at the grid nodes.

$$U(x,y,z)=\frac{2}{\pi}\int_0^{\infty}\phi(x,\lambda,z)\cos(\lambda\cdot y)d\lambda$$

To solve the inverse problem (inversion), the Newton method (or the Quasi-Newton method) with regularization is used. Regularization increases the stability of the solution and allows a smoother distribution of resistance or polarizability in the medium.

Where A is the matrix of partial derivatives of the measured values with respect to the cut parameters (Jacobian), C is the smoothing operator, W is the matrix of relative errors measurements, m is the section parameter vector, μ is the regularizing

$$\left(A^TW^TWA+\mu C^TRC\right)\Delta m=A^TW^T\Delta f-\mu C^TRCm$$

parameter, Δf is the residual vector between the observed and calculated values, R is the focusing operator. In developing the inverse problem, special attention is paid to accounting for a priori information (weights of individual measurements, ranges of parameter changes).

5.1 Two-dimensional inversion results for the Benkala object

When conducting geometrical soundings using a dipole axial installation, the sizes of the receiving and supply lines, the spacing step and between the sensing points are chosen so that the grounding of the receiving and supply electrodes takes place in the same places. In this case, we can use two-dimensional inversion and separate near-surface anomalies from deep ones. This technique imposes some restrictions on the length of the profile. The greater the spacing, and, accordingly, the depth of the installation, the greater should be the length of the profile. For example, for the installation that was used in the Benkala section, the distance between the first and last receiving electrodes was 1640 m, which means that if we want to obtain a stable inversion result in the 2000 m section, then the required profile length will be 3640 m. For example, the profile 200. 34 soundings were performed on it, which at a step of 100 m will amount to 3400 m. However, a real two-dimensional inversion is possible for a section 1770 m long. The model obtained at the edges of the profile is less reliable. In addition, when using a dipole setup, the actual recording point is between the centers of the receiving and supply lines. Those. “dead zones” appear on the edges of the profile, where, in fact, there were no measurements. On one side of the profile on small spans, on the other - on large. In this case, one must either blank the model obtained for these sites or take into account its low reliability. Two-dimensional inversion was performed using the program A.E. Kaminsky Zond2DRes. The inversion parameters remained almost the same for the entire area of work. Vertical grid: first cell 5m, depth - 600m. Horizontal grid: cell size 5m, grouping cells up to 10m starting from 2-3 cells. The number of iterations inversions was usually about 10, varying depending on the accuracy and nature of the selection. It is important to note that on all profiles we did not associate the inversion in apparent resistance with apparent polarizability. Those. the resulting models are completely independent. Below we show what role this approach plays in the study area. Half-space has always been the starting model. The resistivity and polarizability values for the starting model were calculated automatically in the Zond2DRes program. The accuracy of the selection was different. The discrepancies obtained for ρк and ηк we will indicate for each profile below.

All profiles of work using the ET method at the Benkala deposit can be grouped into several sections. The largest volume of work was performed at the Benkala Yuzhnoye ore occurrence: ET profiles 0–550. The second largest site was located north of the Benkala deposit: profiles 1325-1375 and profiles 1475-1525. One profile 1175 crossed the Benkala North field itself. Several profiles were performed between the southern and northern Benkala to verify a large area airspace anomaly identified during the area work using the airspace-gas method. Below is a brief description of the results of the inversion for individual sections.

Northern section. Profiles 1325-1375 and 1475-1525

Given the "dead zones" on the flanks of ET profiles, we "cut off" the final models. From the western edge 1200 m from the last position of the receiving electrode, from the eastern edge - 1200 m from the last position of the supply electrode. For example, for the profile 1500, the total length of the model was 3550 m, taking into account the fact that the extreme position of the receiving electrode is 800 m, and the supply electrode 5150 m. If you look at the number of measurements taken - 66 ft. profile length should be 3300m. Thus, the models obtained by the results of the inversion will give us more by mileage than by the number of fn.

1450-1525

The most northern profiles of works No. 1450 - 1525 are located practically outside the area work area. According to the geological map, individual bodies of porphyritic diorites are distinguished here. Even at the level of a qualitative analysis of data on pseudo-sections of apparent resistance and apparent polarizability, it can be seen that the sounding results for profiles 1525 - 1450 are close figure 26. The resulting inversion models are also similar.

It should be noted that on the northern flank of the area of work, horizontal layering is most pronounced in the sections of apparent resistance. In the inversion toga, pronounced subhorizontal interfaces that are not related to the lithological composition of the rocks appear on the resistivity models. In our opinion, these boundaries may correspond to groundwater horizons. Groundwater provides the electrical conductivity of most rocks in the earth. Fresh water conducts current poorly, the higher the salinity of groundwater, the lower the resistance. Judging by the information provided in the project on exploration of the Benkalinsky copper deposit (2014-17), three main aquifers are distinguished in the deposit area: Quaternary, Oligocene and fractured waters of folded basement rocks.

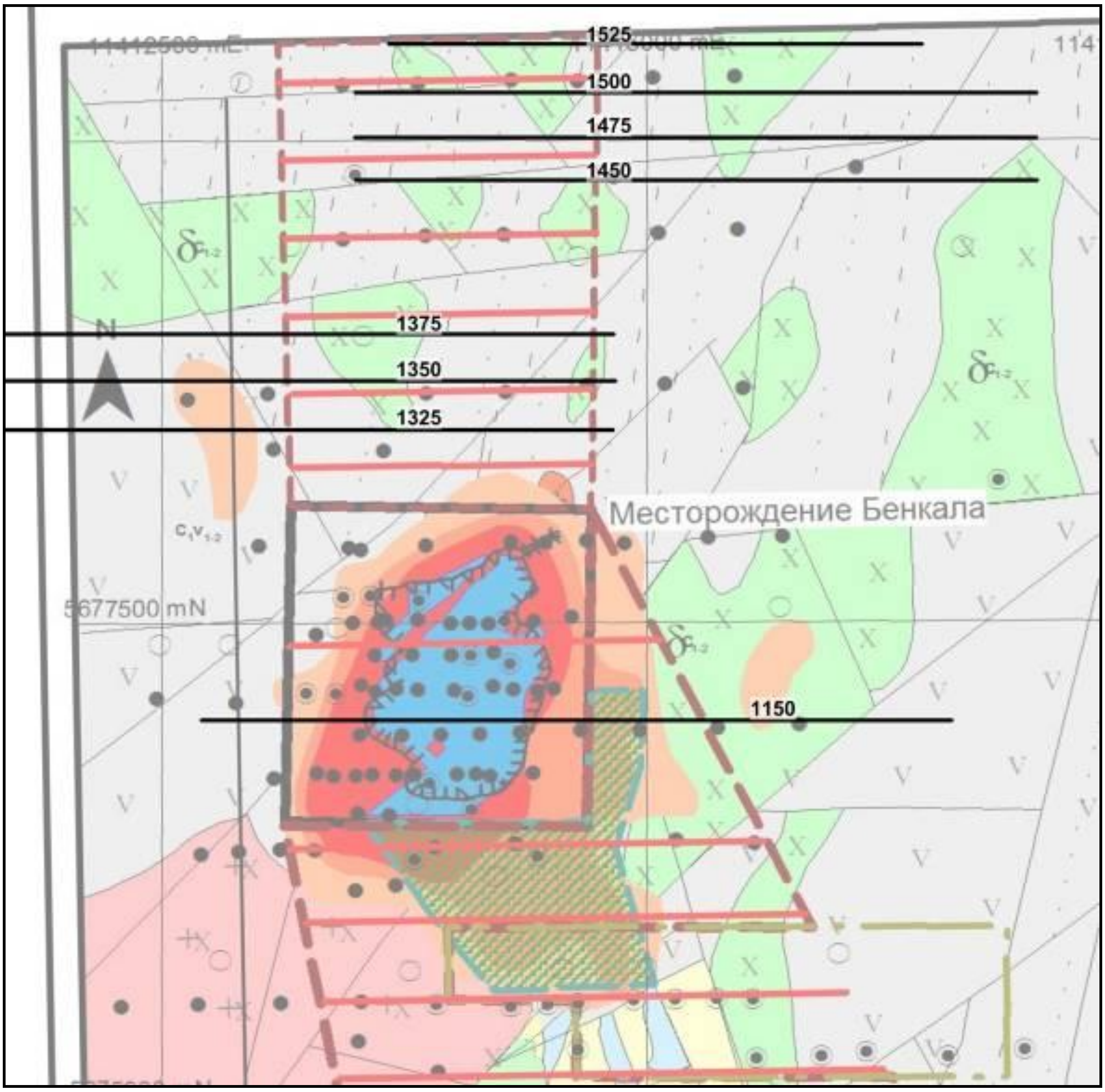


Figure 27 – The position of the northern ERT profiles on the geological map.

Most clearly, the lower water-bearing horizon appears on the resistivity models: “... The fractured waters of the foundation are confined to the upper part of the folded foundation (to a depth of 100-150 m.), Where the fracture is most developed. The most watery areas for the development of karst limestones and zones of deep faults. The flow rate of wells reaches 0.3-7 l / s. The waters are fresh and salty. Increased mineralization is observed in the areas of development of clay of the weathering crust, Chegan suite and Neogene. At the field, water salinity reaches 7-10g / l ... "

Mineralization of 7-10 g / l is quite high. The resistance of the electrolyte with this mineralization will be about 1 Ohm · m, depending on the composition of the salts. Even with insignificant porosity, we can obtain resistivity of rocks in tens, first hundreds of Ohm · m. We obtain such a subhorizontal layer as a result of inversion in the depth range 100–270 m (the position of the lower boundary may not be exact). In the western part of profiles 1450–1525, this conducting horizon decreases in thickness, up to complete degradation (Fig. 3). Where the aquifer is missing a high-resistance section: 1000-10000 Ohm. The high-resistance block, which manifests itself in sections of the resistivity in the range of pc 800-1800, can also be associated with silicification of rocks.

Another important result of the inversion of ρк is the manifestation of the subvertical conducting zone in the center of the profiles. The manifestation of the conducting zone is enhanced on the southern profiles - 14575 and 1450 (pc 2600-2800 and 2400-2800, respectively). The conductor goes to great depths, the position of the lower edge is not installed. This may be a tectonically weakened subvertical zone in the foundation along which porphyry bodies were introduced. Low resistances are probably associated with increased fracturing and watering of the zone.

The main anomaly of the induced polarization is confined to this conducting structure. Moreover, the maximum VP values are recorded on the northernmost profile - 1525, but an increase in the depth of the anomaly is observed on profile 1475. The main anomaly of the induced polarization is fixed in the central part of the ET profiles, and is most pronounced on the profiles 1525 and 1500 on the pc 2000-2800 and 2400-2800, respectively. The position of the upper edge of the anomaly is 120-150m. When moving south, the area of high airspace sinks to 300-350 m on profile 1450. As it can be seen on the North side of the profiles we have a water horizon and it gets lost when profiles are near to the South side. Conductive subvertical zone gets lower and lower as we get near to the South profiles. It is shown that, also anomaly of polarization is also getting down and down as profiles reach to the South side of the deposit.

The anomaly is promising for the detection of sulfide mineralization, since: 1) it manifests itself in the VP field on several profiles; 2) has a high intensity> 8%; 3) has a deep supply channel. The recommended position of the exploratory well is profile 1525, pc 2200 or profile 1500, pc 2400. The depth of the well is at least 200 m.

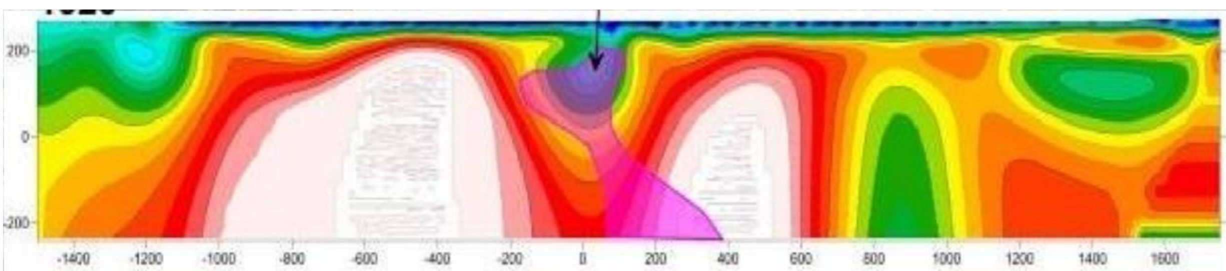


Figure 28. The results of resistance electrical inversion.

As its shown in figure 28, here is the results of 2D resistance inversion and there is a pink anomaly which is superimposed on the resistance inversion. The pink anomaly is the anomaly of polarization.

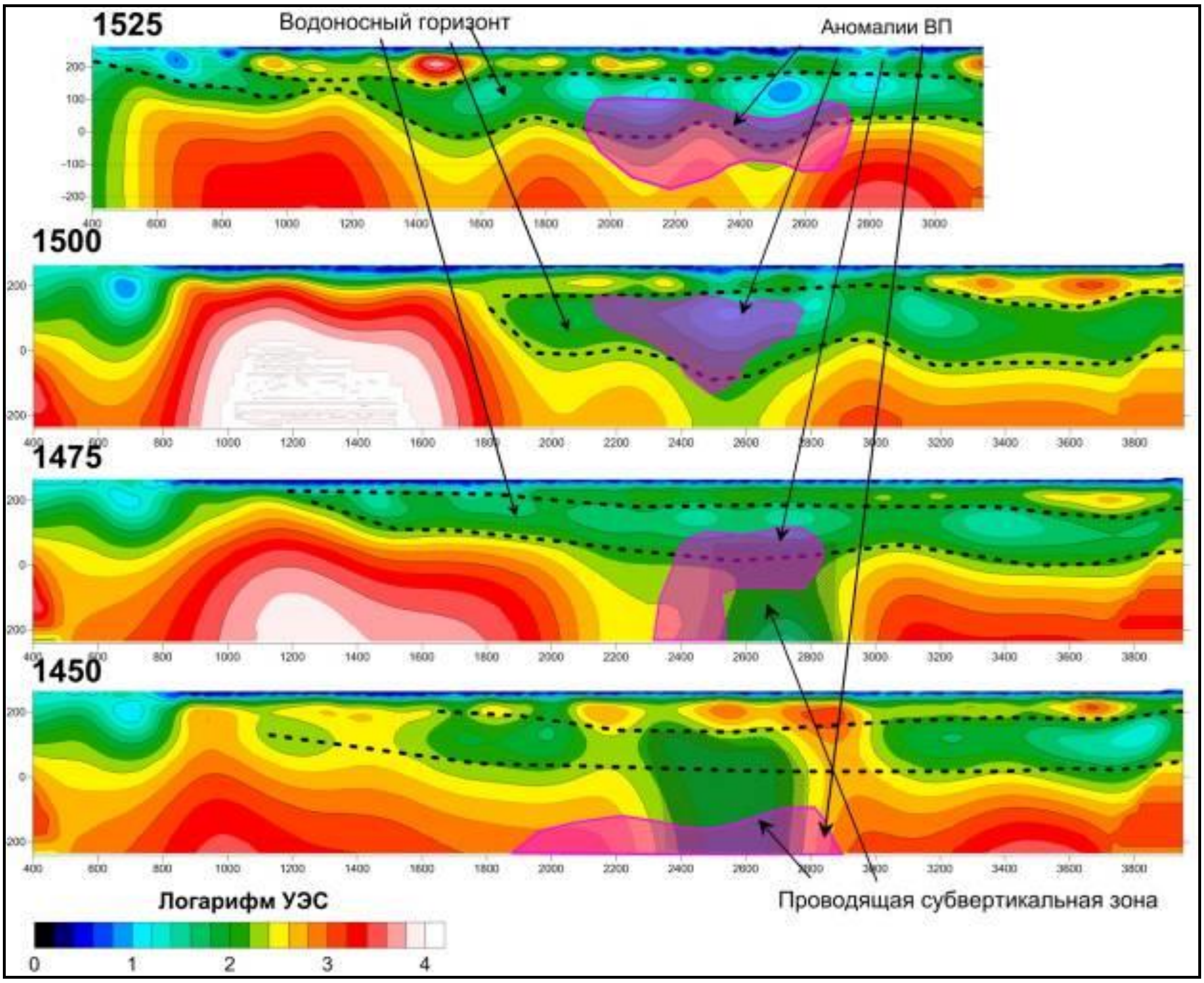


Figure 29 – Profiles 1450-1525. Resistivity models based on the results of 2D inversion.

On the resistivity models, pronounced subhorizontal interfaces appear that are not related to the lithological composition of the rocks. In our opinion, these boundaries may correspond to groundwater horizons, since three main aquifers are distinguished in the deposit area: Quaternary, Oligocene and fractured waters of folded basement rocks. Most clearly, the lower water-bearing horizon (depths of 100-270 m.) Appears on the resistivity models, where the fracturing is most developed. Increased mineralization is observed in the areas of development of clay of the weathering crust, Chegan suite and Neogene.

In the western part of profiles 1450–1525, this conducting horizon decreases in thickness, up to complete degradation (Fig. 3). Where the aquifer is missing a high-resistance section: 1000-10000 Ohm. The high-resistance block, which manifests itself in sections of the resistivity in the range of pc 800-1800, can also be associated with silicification of rocks.

Manifestation of a subvertical conducting zone in the center of the profiles. The manifestation of the conducting zone is enhanced on the southern profiles - 14575 and 1450 (pc 2600-2800 and 2400-2800, respectively). The conductor goes to great depths, the position of the lower edge is not installed. This may be a tectonically weakened subvertical zone in the foundation along which porphyry bodies were introduced. Low resistances are probably associated with increased fracturing and watering of the zone.

The main anomaly of the induced polarization is fixed in the central part of the ET profiles, and is most pronounced on the profiles 1525 and 1500 on the pc 2000-2800 and 2400-2800, respectively. The position of the upper edge of the anomaly is 120-150m. When moving south, the area of high airspace sinks to 300-350 m on profile 1450.

The anomaly is promising for the detection of sulfide mineralization, since: 1) it manifests itself in the VP field on several profiles; 2) has a high intensity> 8%; 3) has a deep supply channel.

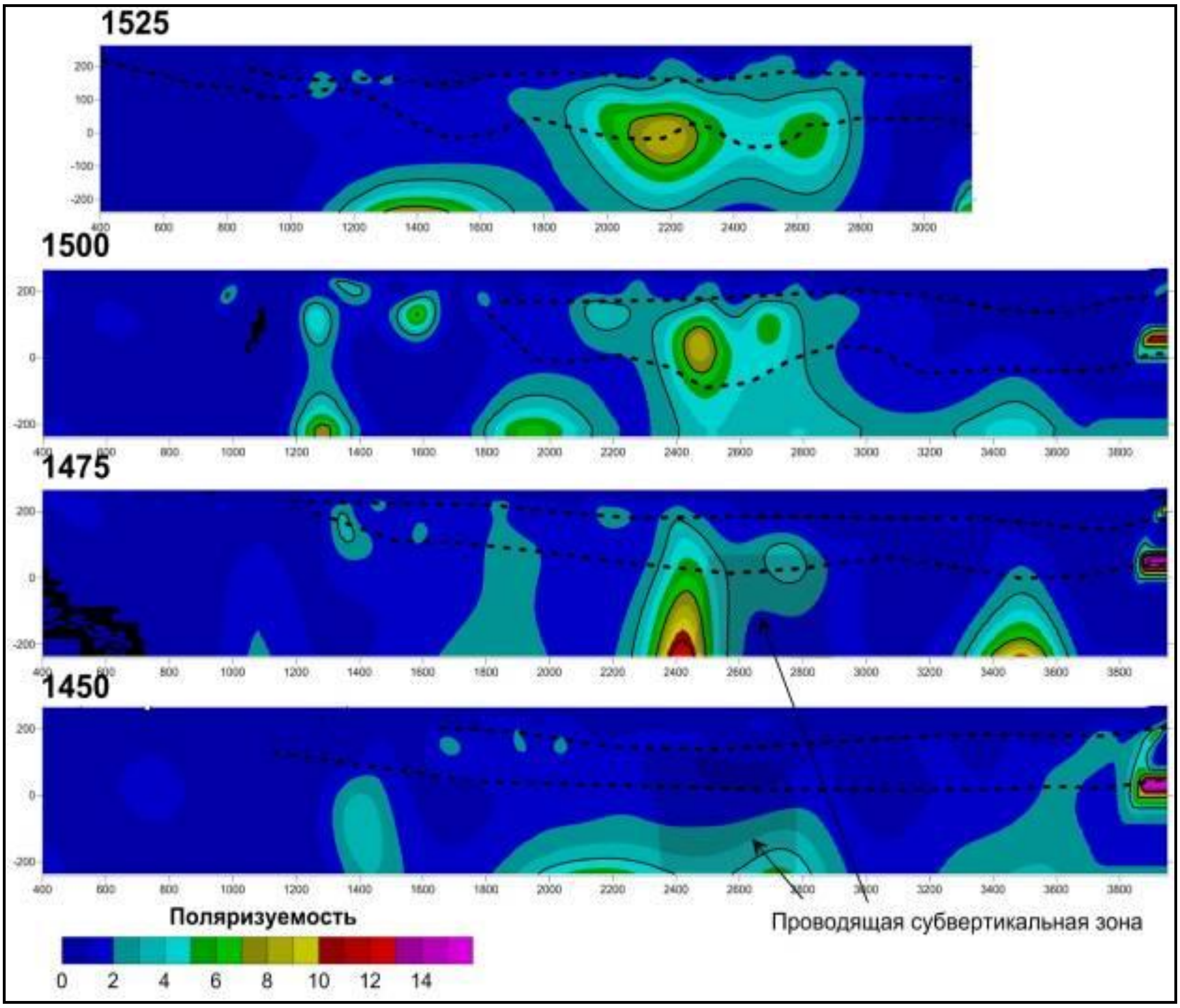


Figure 30 – Profiles 1450-1525. Polarizability Models Based on the Results of 2D Inversion.

1325-1375

Profiles 1325–1375 are located northwest of the Benkala field. In the central part of the profiles, a negative magnetic field anomaly is observed, similar in magnitude to the northern Benkala field anomaly (Figure 31). The entire western part of Electrical resistivity tomography profiles is located outside the areal measurements of IP-MG.

The section is high-resistance, resistances exceed 104 Ohm · m. In the area of the PC -400 - +200, a zone of low resistances is fixed in the near-surface part of the section. This conductor corresponds to the zone of increased polarizability of the rocks, which is a horizontal horizon with a width of about 500 m and a thickness of about 100 m (Fig. 32). The polarizability values within the anomalous region are approximately the same as on profiles 1525 and 1500, and reach 8–9%. The eastern edge of the selected zone is visible on the apparent polarizability map according to the MG data (Fig. 33).

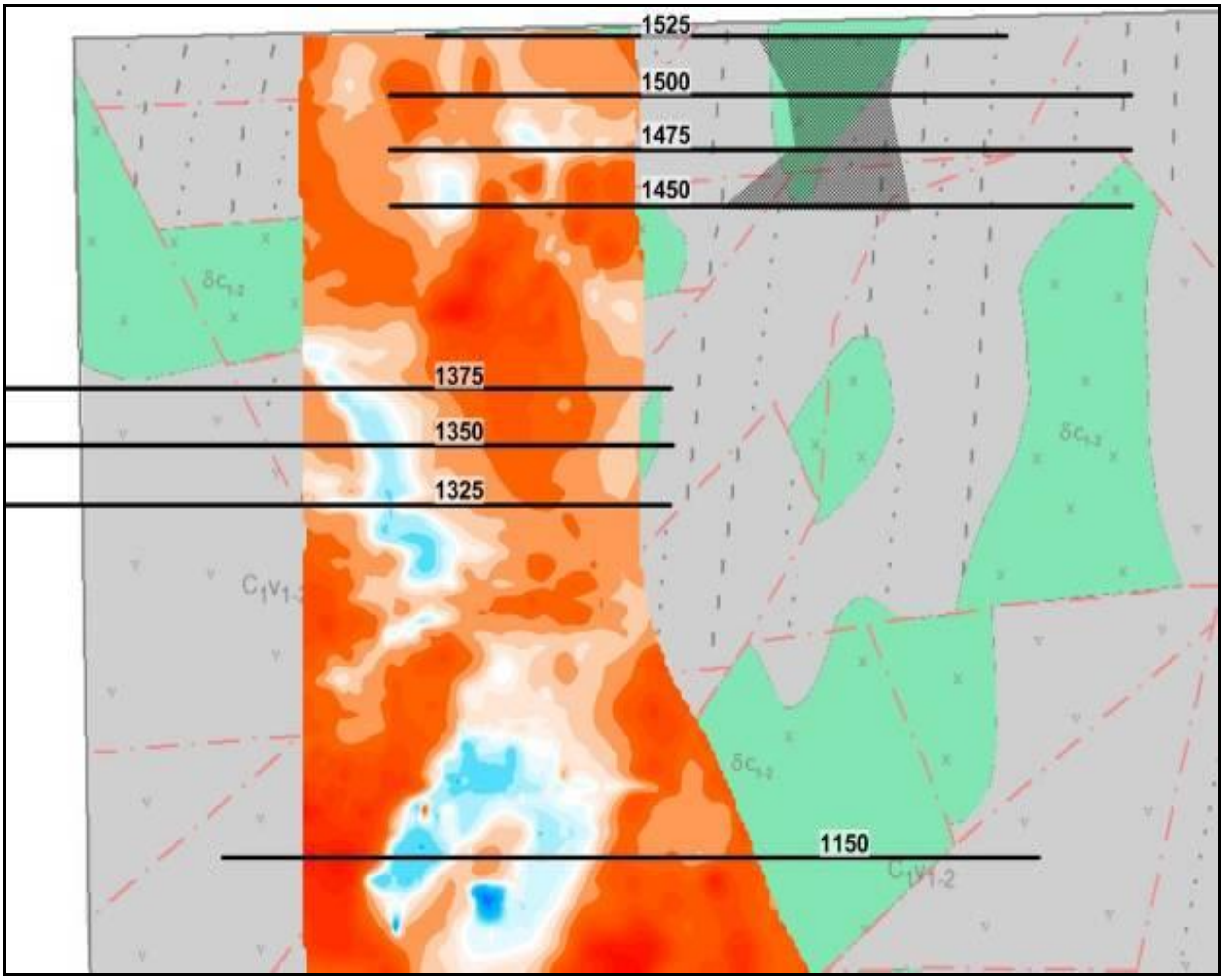


Figure 31 – The Benkala deposit area. Map of abnormal magnetic field.

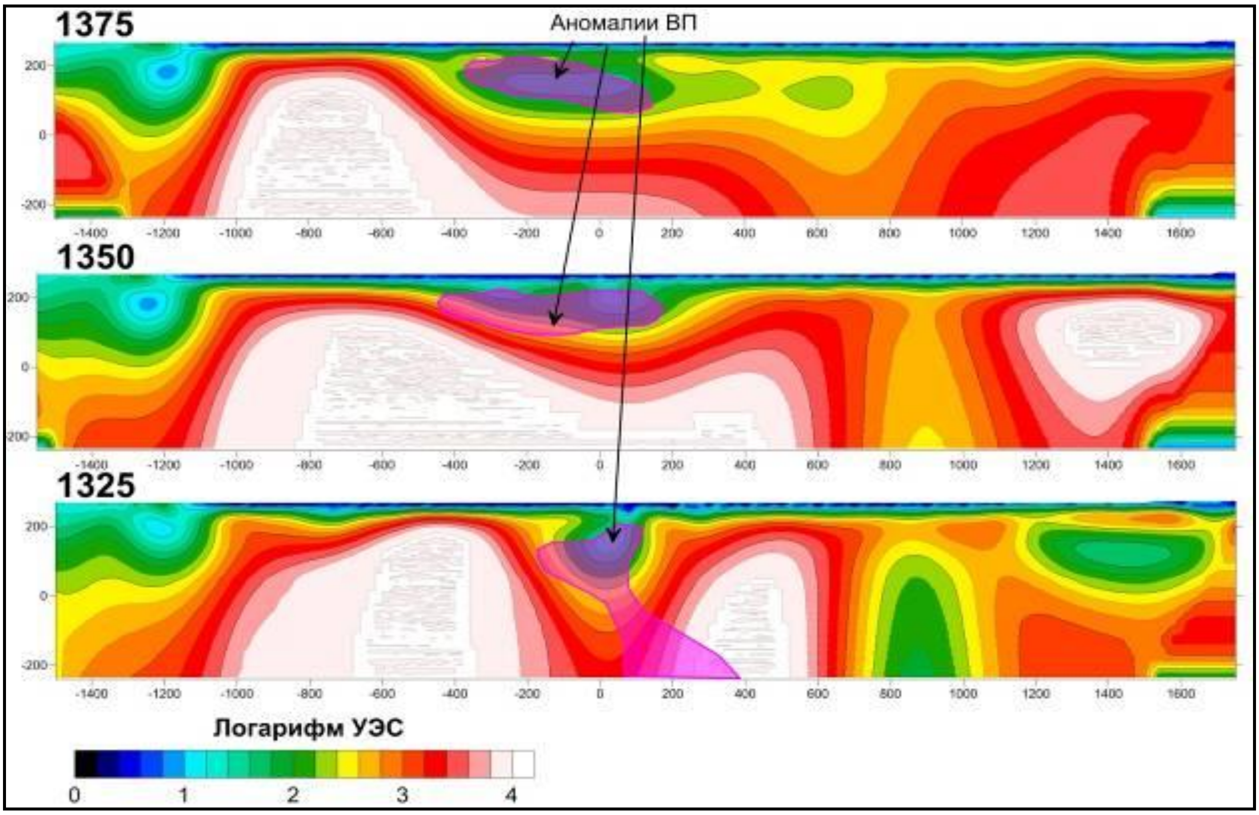


Figure 32 – Profiles 1325-1375. Resistivity models based on the results of 2D inv.

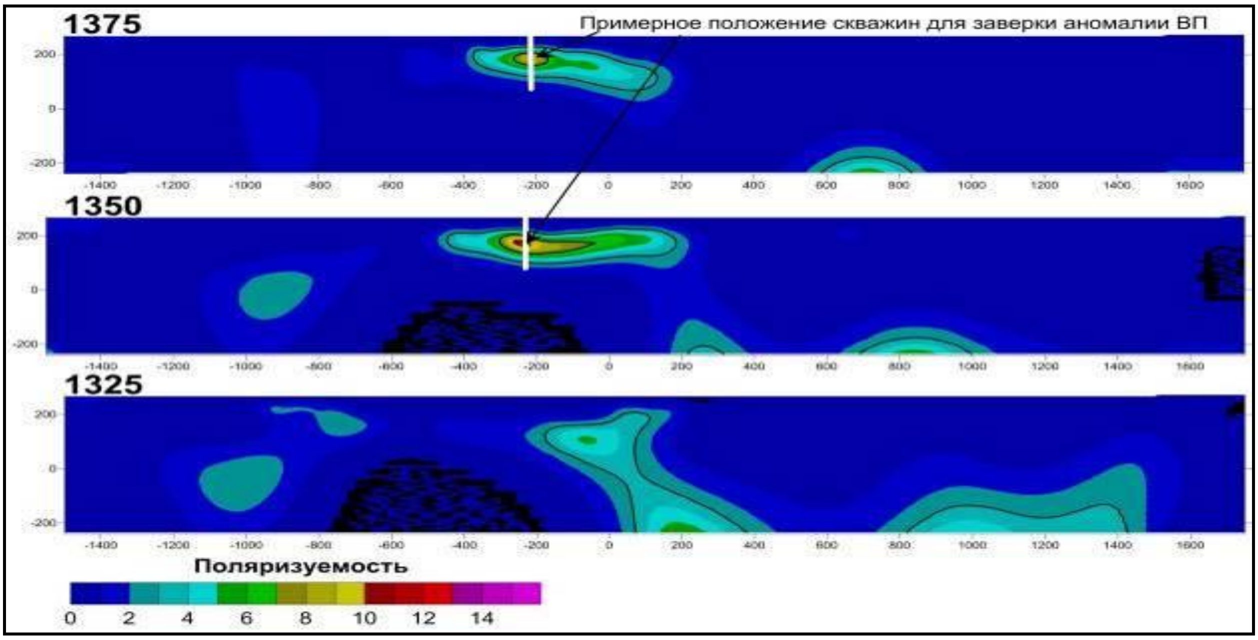


Figure 33 – Profiles 1450-1525. Polarizability Models Based on the Results of 2D Inversion.

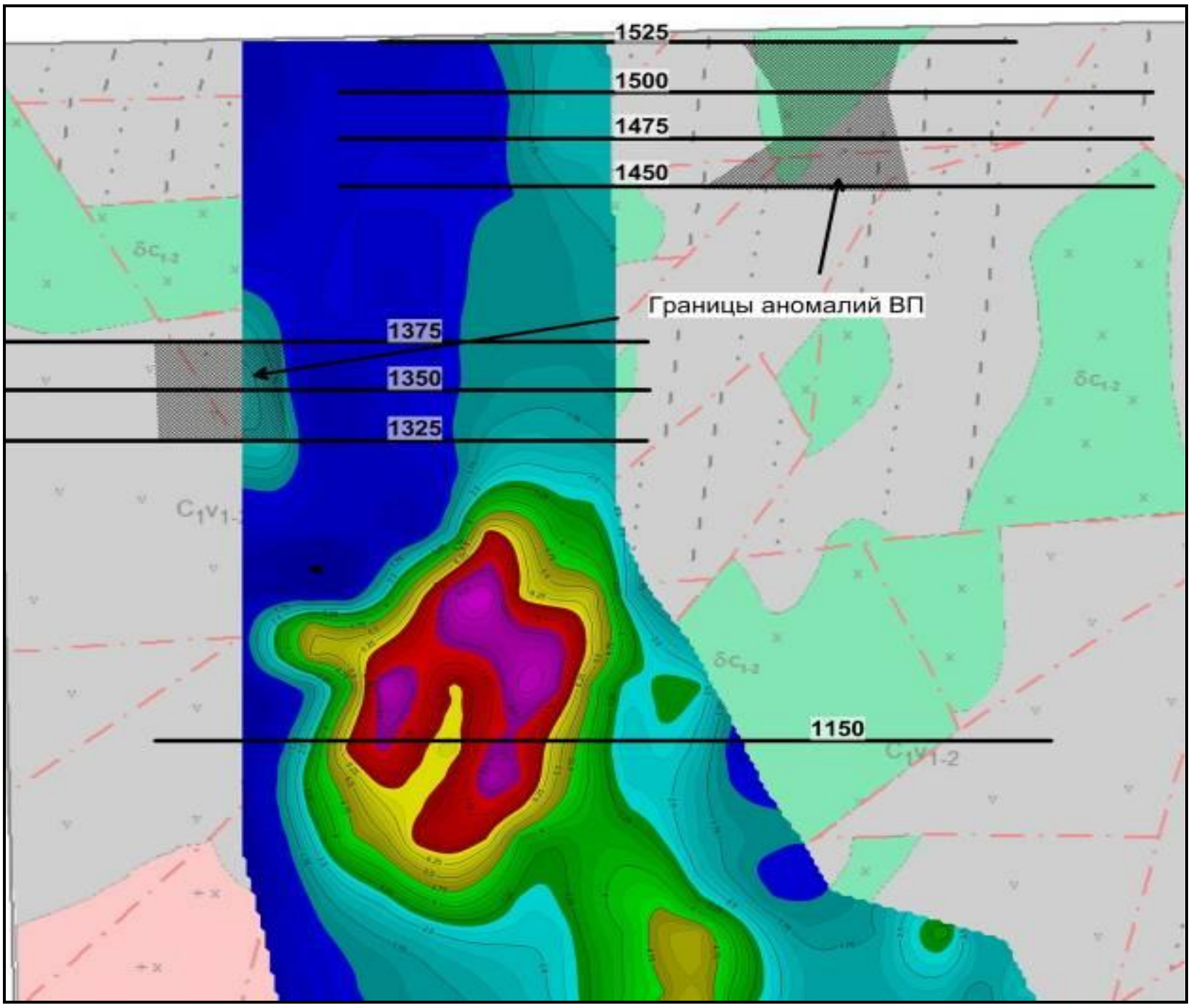


Figure 34 – The Benkala deposit area. Map of apparent polarizability based on MG data.

5.2 Benkala deposit

Profile 1150 crossed the Benkala field, which is manifested in physical fields by high apparent polarizability (9%), lower apparent resistance (ρк = 50-80 Ohm · m) (Fig. 35) and negative values of the anomalous magnetic field dTa = -200 - - 50 nT (Fig. 32).

Based on the results of electrotomography over the Benkala area, the distribution of parameters of apparent polarizabilities (IP) and apparent resistances (Rk) was calculated and areal maps Rk and IP were constructed.

The most intense anomaly in the VP field (up to 10%) was recorded in the northern part of the site, which spatially coincides with the Benkala porphyry copper ore deposit. Currently, the field is being actively developed by the open pit method (quarry). Higher polarizability values correspond to lower (less than 80 Ohm) resistance values. The metal factor was also calculated, and its abnormal zones correspond to its sharp increase. This parameter characterizes anomalous objects with high polarizability and low resistivity. According to a priori data, this zone corresponds to a sharp decrease in the magnetic field.

The above-mentioned characteristic features of copper-porphyry mineralization are precisely recorded in the southern part of the site on profiles (125-375, Zone 8), where electrical exploration revealed a drop-shaped VP anomaly with an intensity of up to 10%. Zone No. 8 spatially coincides with the previously discovered South Benkala field. Vertex Holding is currently producing iron ore (quarry) in Zone 4. Zones No. 4-7 and No. 9.10 are promising for the presence of ore occurrences of various types of metals.

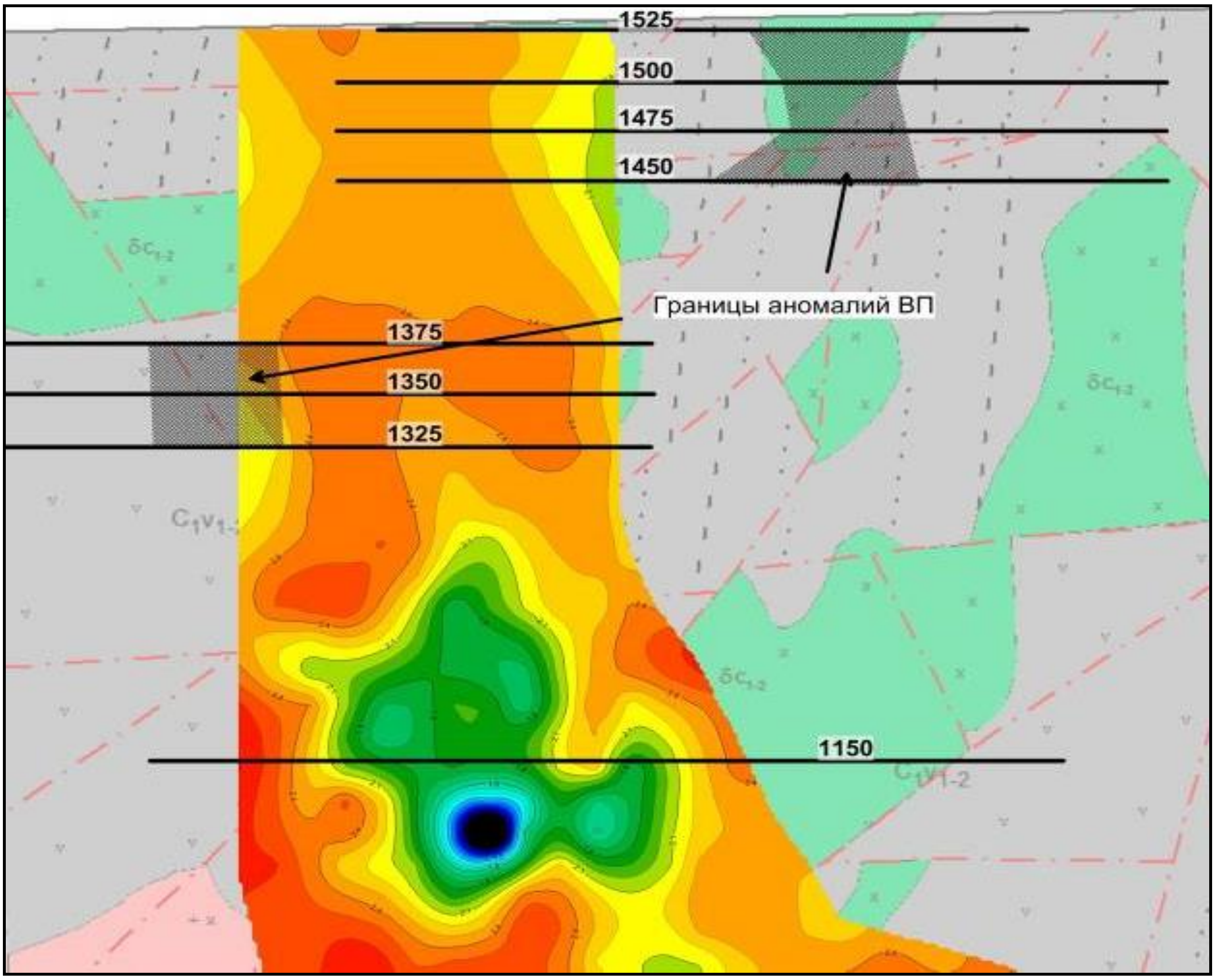


Figure 35 – The Benkala deposit area. Map of apparent resistance according to MG.

A subhorizontal conducting region associated with the hydrogeological regime appears in the sections of the electrical resistivity in the field area. The ρ values in some places fall below 10 Ohm · m. In the area of PC 1800-200, a subvertical region of increased conductivity is recorded in the UES section, which, as can be seen from the geological map, corresponds to a tectonic disturbance of the northwest strike (Fig. 36). More informative is the polarizability model. In the section η, we observe a horseshoe-shaped anomalous region typical of many porphyry copper deposits. The maximum polarizability values are fixed in the central part of the selected region, in the immediate vicinity of the surface. In the west and in the east, polarized rocks (presumably sulfide mineralization zones) are submerged to depths greater than 500 m. Bottom edges are not installed here.

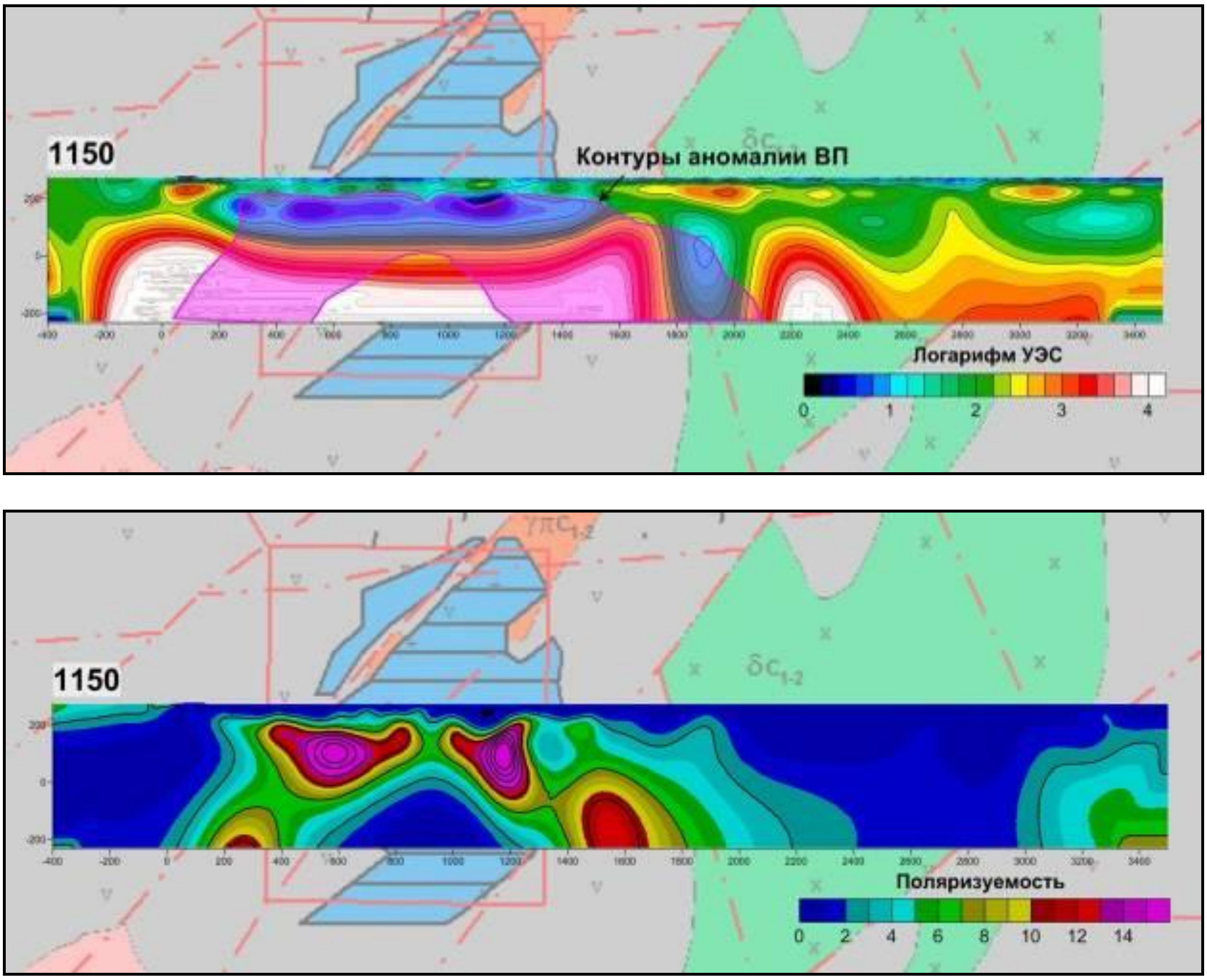


Figure 36 – Inversion results for profile 1150 (Benkala deposit). Above is the resistivity, below is the polarizability.

850 -925

The ERT method on profiles 850–925 was carried out through the areal anomaly of apparent polarizability (Fig. 41). The inversion results confirmed the presence of anomaly-forming bodies in the center of the profiles creating an anomaly on the SG maps. Presumably, there are two separate objects with increased polarizability values. The eastern body has a subvertical fall, the western body of the hollow falls to the east. The picture "crumbles" on the northern profile 925, perhaps too many iterations have been done here.

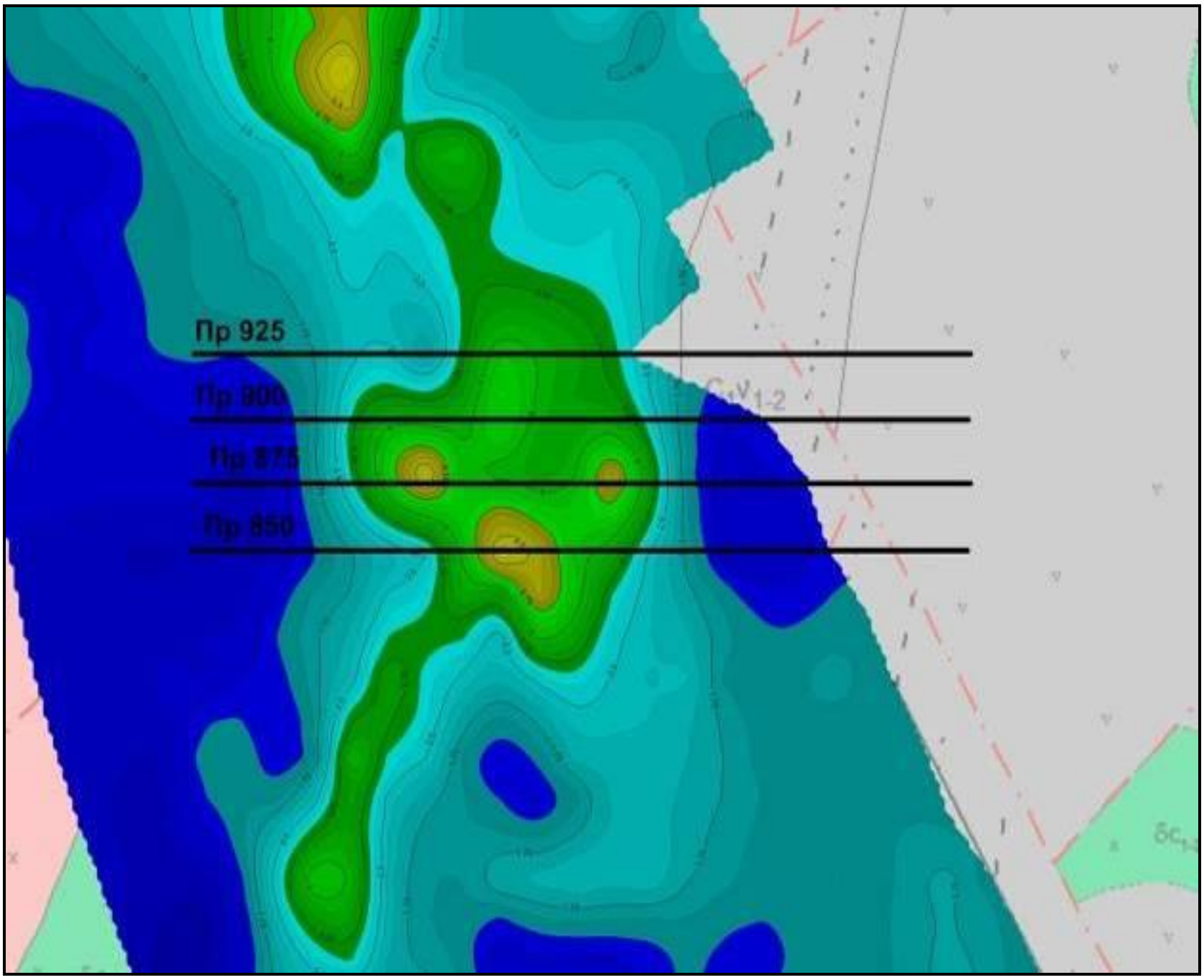


Figure 41– Map of apparent polarizability according to MG data.

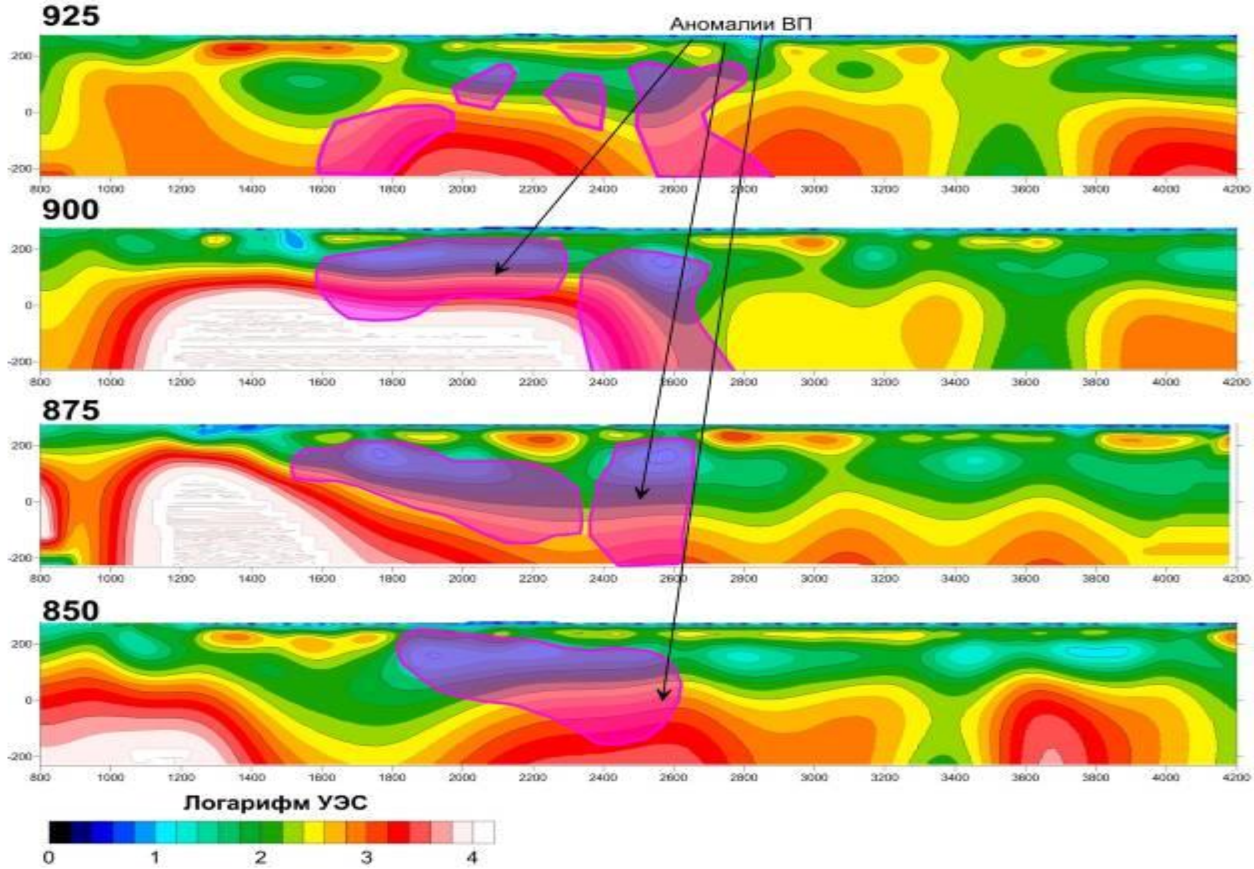


Figure 42a – Profiles 850-925. Resistivity models based on the results of 2D inversion.

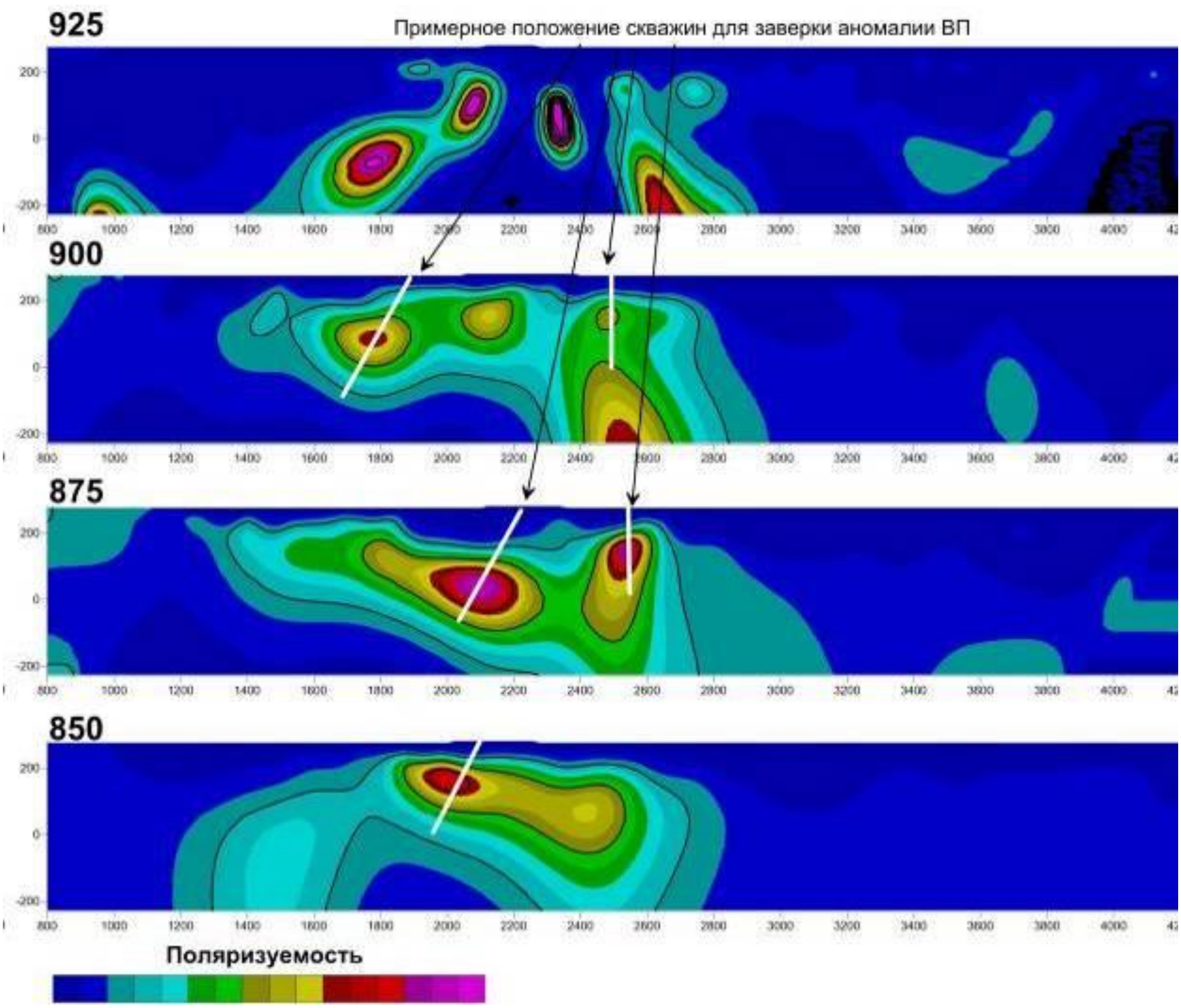


Figure 42b – Profiles 850-925. Polarizability Models Based on the Results of 2D Inversion.

5.3 South Benkala 0-550

The largest volume of ERT measurements was performed in the southern part of the area of work, in the area of the Benkala South ore occurrence (Fig. 37). Ore occurrence is characterized by an area intense anomaly of apparent polarizability> 10% (Fig. 38), a zone of reduced values ρк <100 Ohm · m (Fig. 39) and a reduced background of the magnetic field (Fig. 40). According to the values of the parameters ρк and ηк, the anomaly is similar to the Northern Benkala deposit.

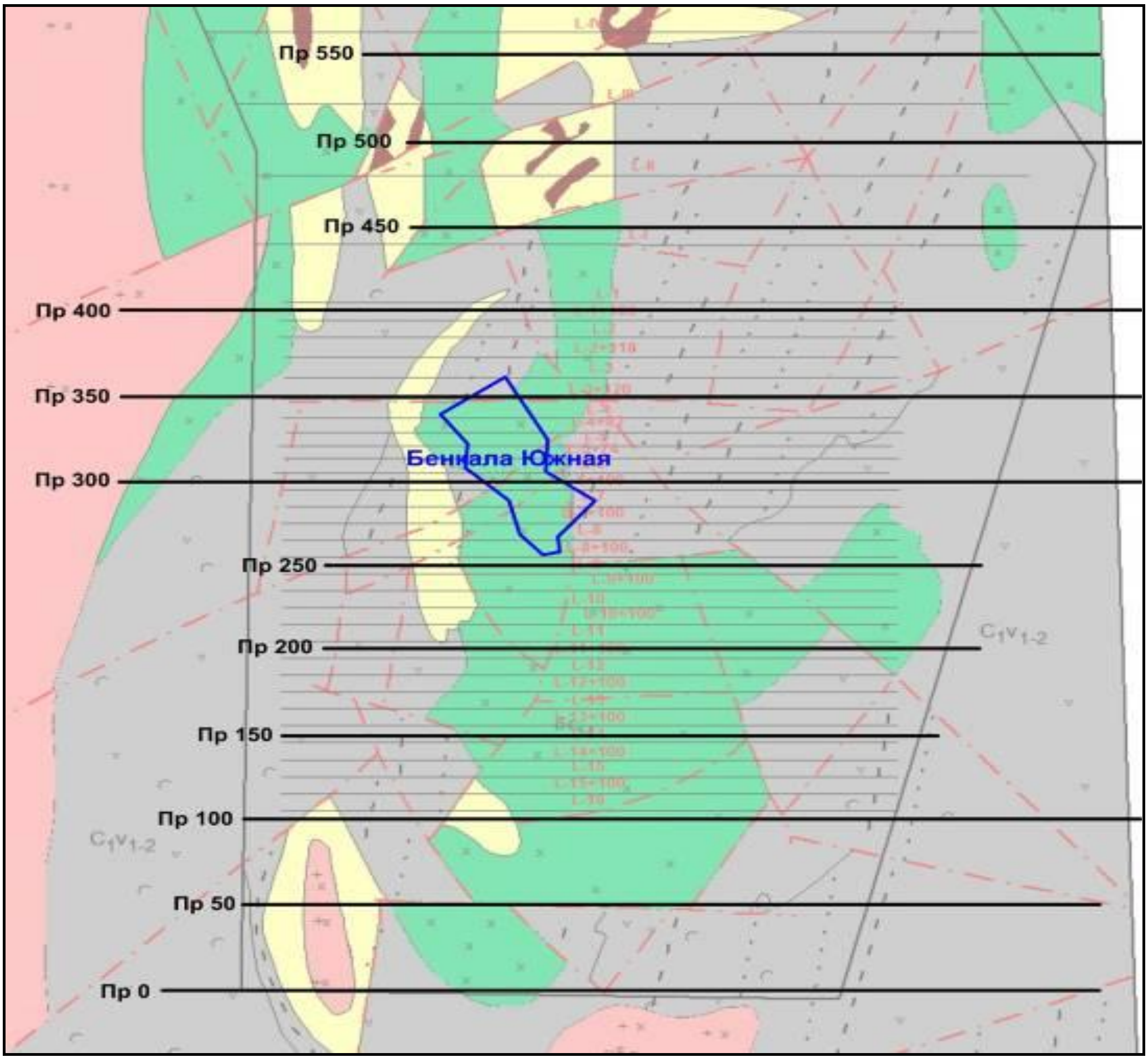


Figure 37– The position of ERT profiles in the Benkala South section.

At geoelectric sections, the ore occurrence region of Benkala Yuzhnaya is marked by an intense anomaly of resistivity. The minimum values of resistivity are recorded on profiles 250 and 300 - less than 10 Ohm. It seems to us that here the anomaly of resistivity is made up of the influence of groundwater and sulfide mineralization of porphyry bodies. As a result, there is no such clear horizontal layering on geoelectric models as on northern profiles, although subhorizontal boundaries are present. Contours of anomalies in resistivity (in blue) are plotted on a geological map.

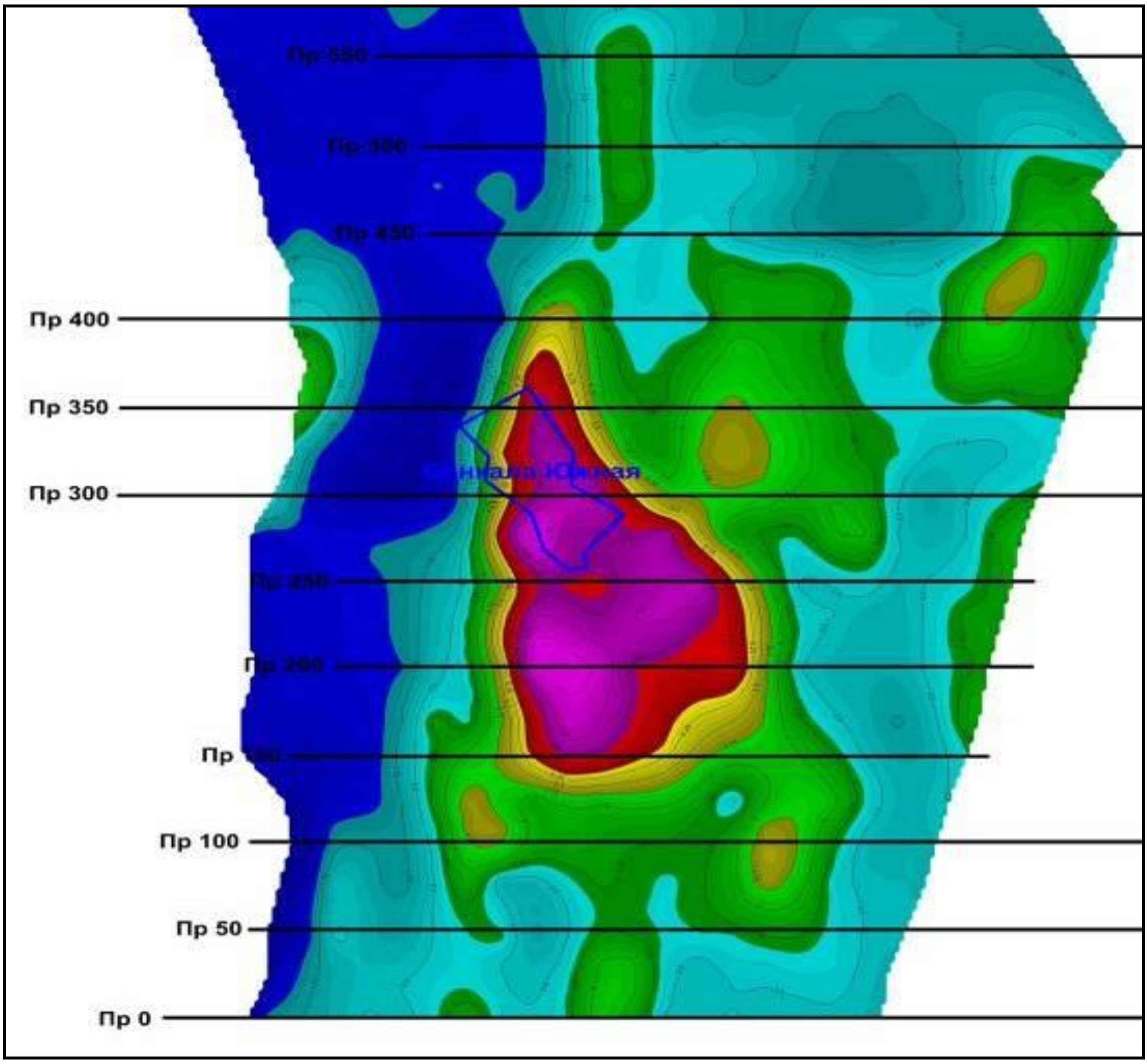


Figure 38 – The southern part of the site. Map of apparent polarizability according to MG data.

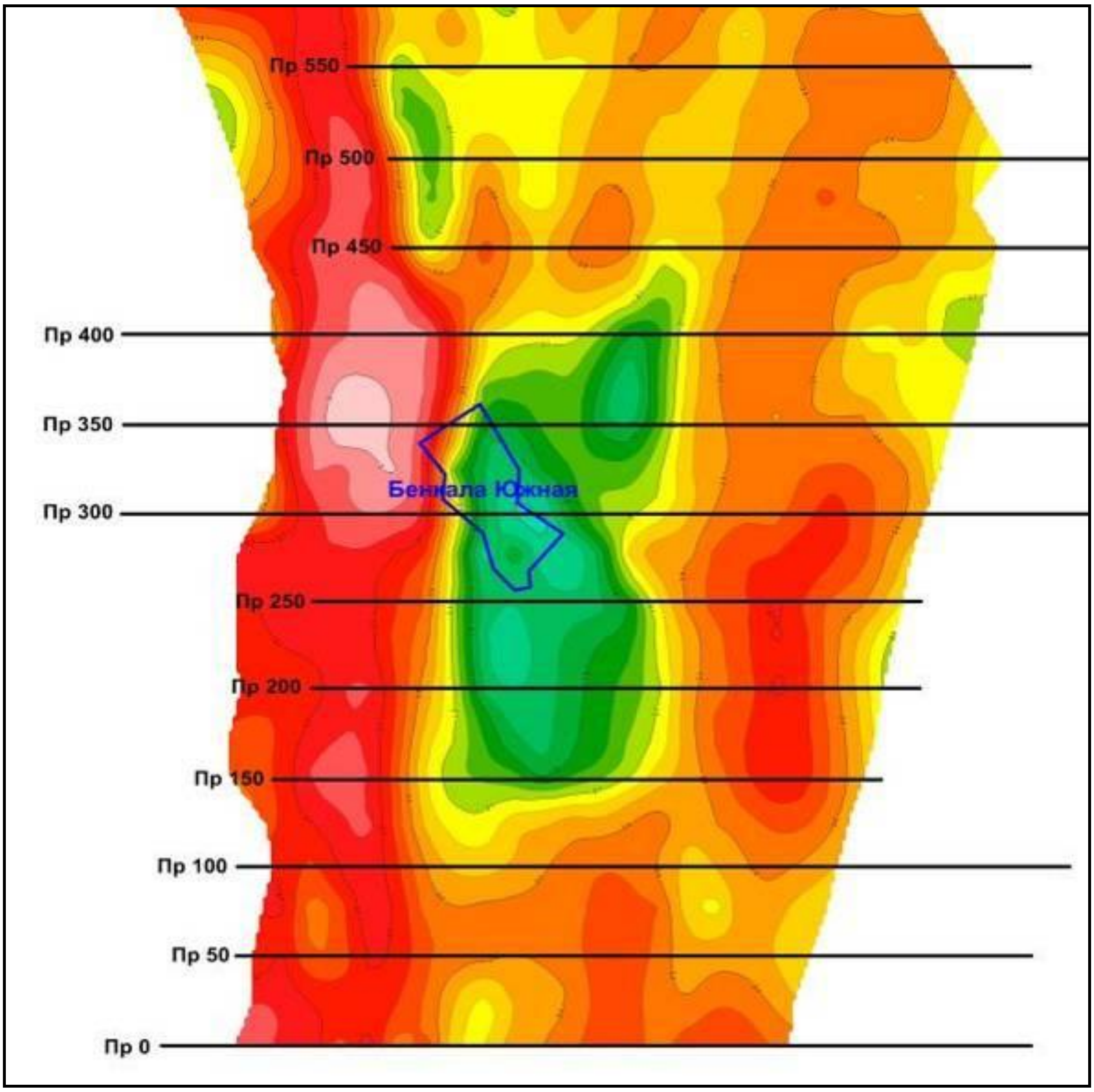


Figure 39 – The southern part of the site. Map of apparent resistance according to MG.

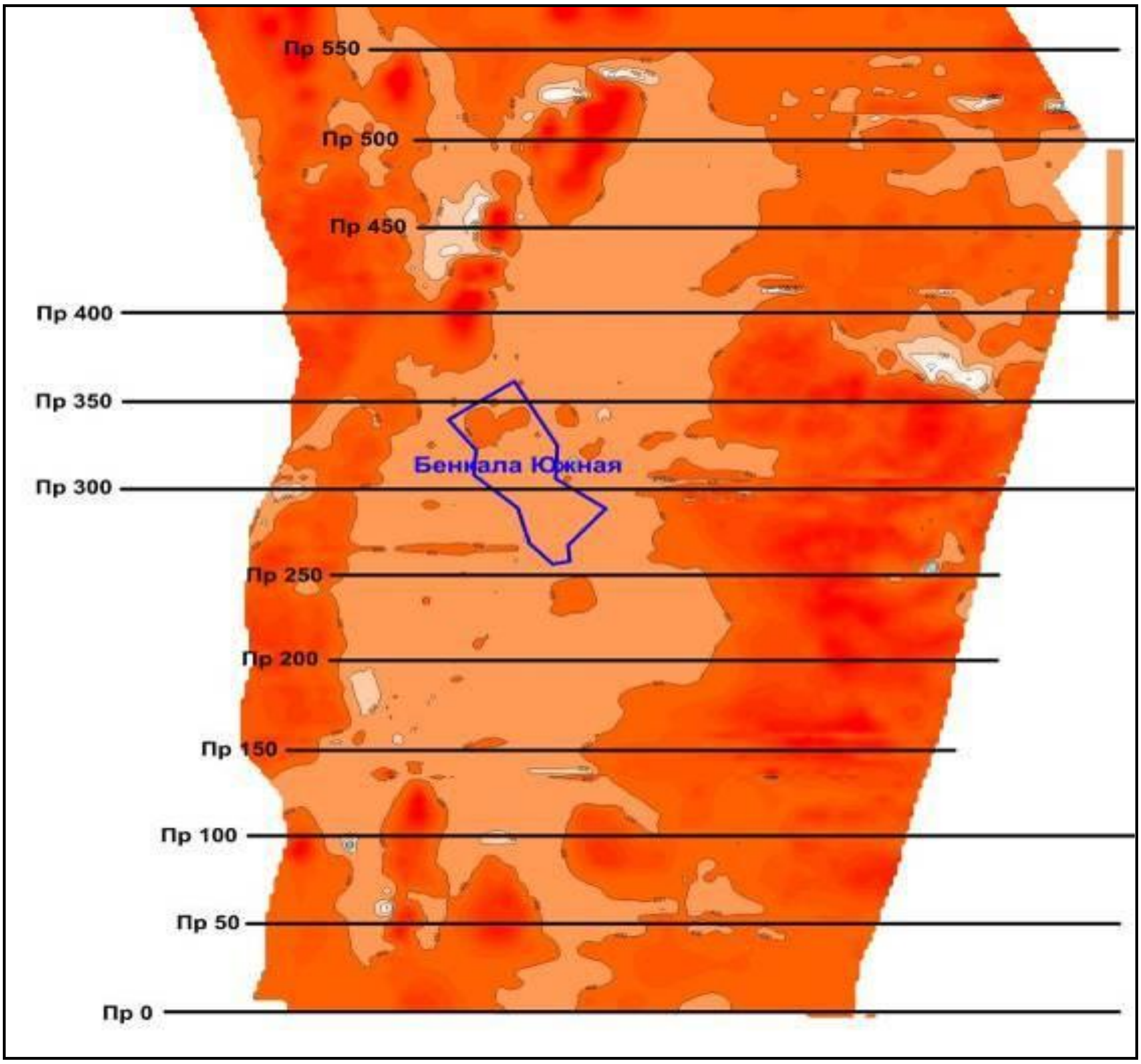


Figure 40 – The southern part of the site. Map of abnormal magnetic field.

In addition to the central anomaly associated with the South Benkala ore occurrence in geoelectric sections, it is possible to distinguish subvertical anomalies of increased conductivity, apparently associated with tectonic disturbances. One of these deep zones is located on the western edge of the most intense areal anomaly of resistivity (Fig. 41). In the southern part of the work area, on profiles 0 -150, the intensity of the central resistivity anomaly decreases. P values do not fall below 50 Ohm. Another areal anomaly of low resistances is recorded in the eastern part of profiles 350–500 (Fig. 41). The polarization models obtained from the results of 2D inversion fundamentally differ from the resistivity sections. Anomalous zones of increased polarizability of the rocks have clear boundaries and limited distribution. The maximum values of η are observed in the central part of the area, on profiles 200-350, and relate to the Benkala South ore occurrence.

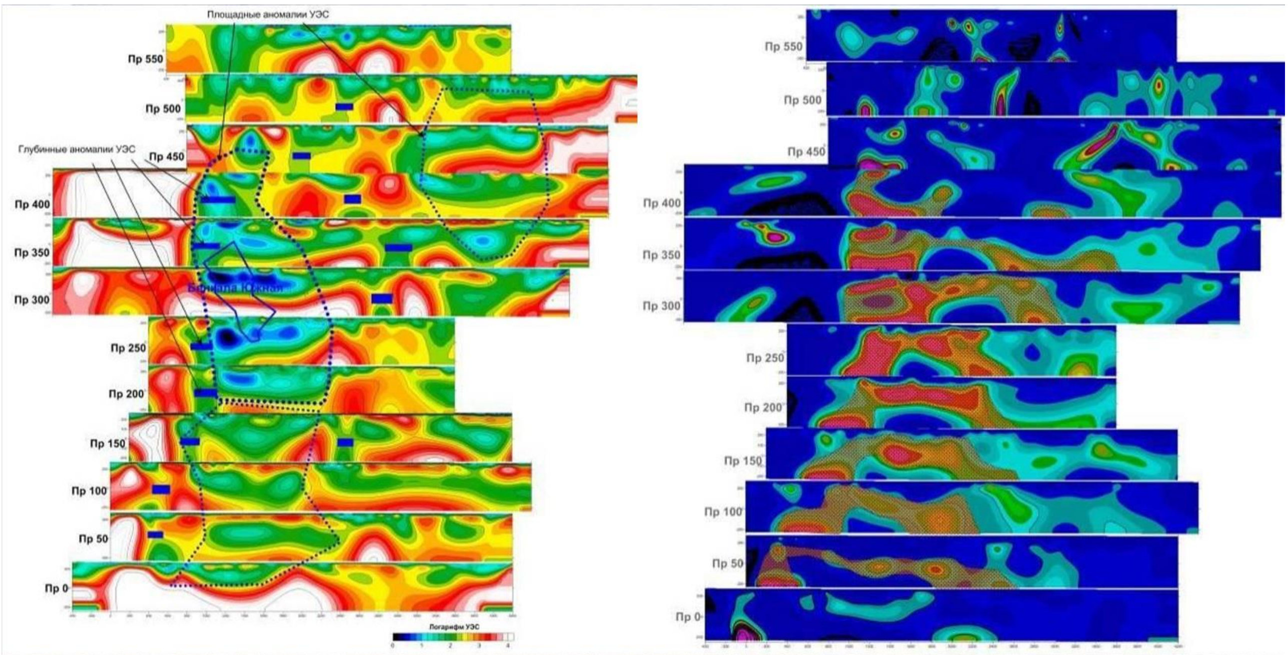


Figure 41 – Benkala South. Resistivity sections according to the results of inversion and sections of polarizability according to the results of inversion.

In terms of polarizability, several objects of different morphology and sizes can be distinguished.

1) The linear zone on the western flank of the work area. On the map (Fig. 14) is highlighted in black outline. Profiles: 0 - 450. Stretch: Northeast. Width: about 400 m. Depth: the lower edge has not been established, the anomaly goes to a depth of> 500 m. The linear structure of the anomalous region on profiles 0 - 250 suggests that it is connected either with the tectonic zone or with the technogenic object.
2) The main areal anomaly of the IP, confined to the Benkala South ore occurrence. On the map (Fig. 42), the area is highlighted in red. The form of the anomaly is arcuate (as on Benkala South), plunges to the east, in the west has a complex structure intersecting with the linear zone of IP No. 1. Profiles: 0 - 500. Width 1000-1200 m.
3) The deep low-contrast region observed east of the main anomaly of IP No. 2. Profiles: 150-350.
4) Northeastern anomalous region, highlighted by a white outline. Profiles: 300-500, maximum on profile 450, pc 3200 - 4200. Width: about 1000 m. The anomaly can be associated with sulfide mineralization around a local copper-porphyry body. Place of certification by drilling: Profile 450, pc 3400-4000.
5) A local polarized body on the western flank of profiles 300, 350, 400. The object is small in size ≈ 500 × 200 m. It is best manifested on profile 350, where the depth of the upper edge is less than 100 m.

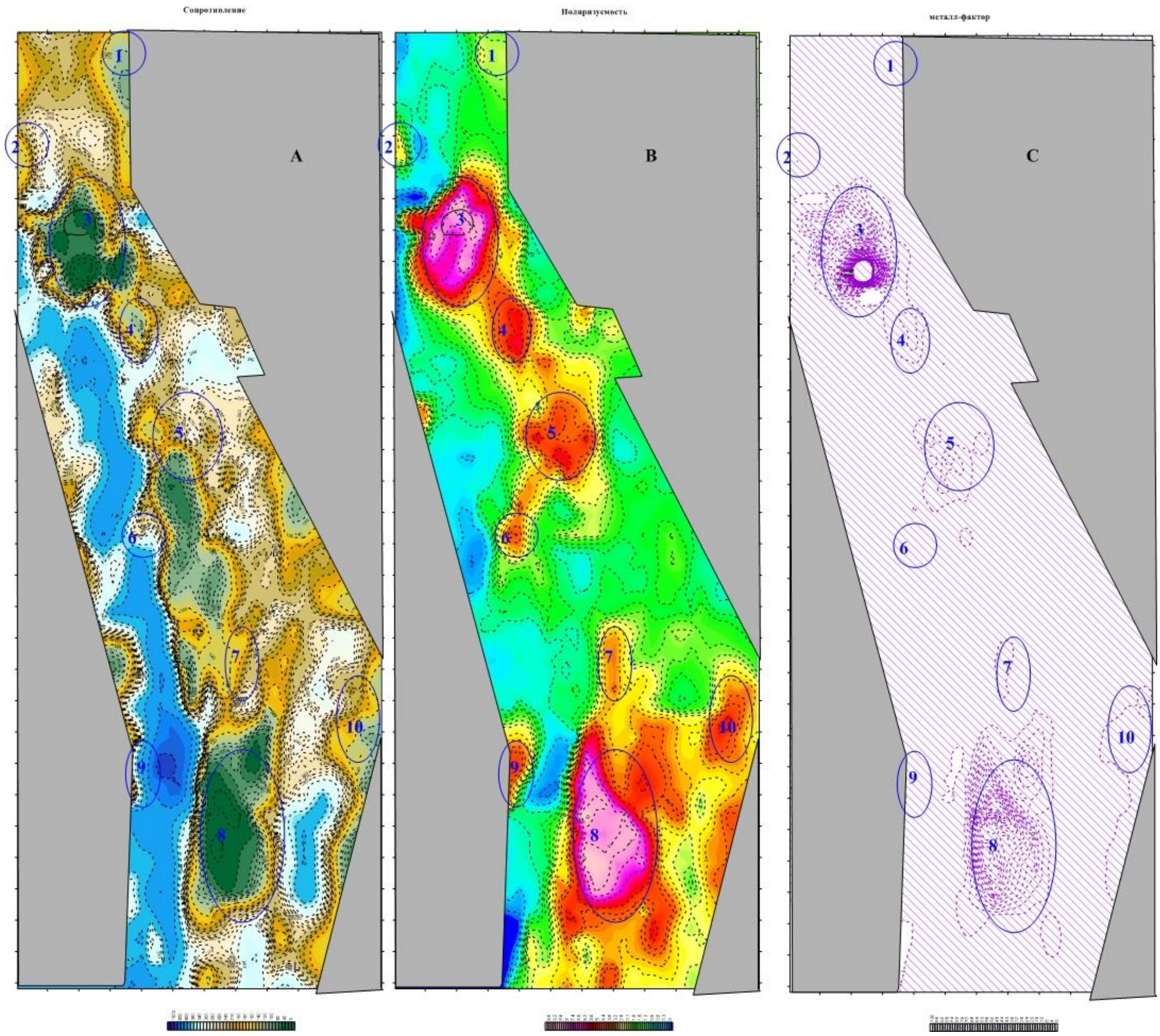


Figure 41a – Maps of apparent resistance (A), polarizability (B) and metal factor (C) according to Benkala square. Anomalous zones are marked with blue ovals in the run.

By analogy on the territory of the Benkala deposit, criteria were identified for identifying areas promising for copper-porphyry mineralization:

Rk	reduced values to140 Омм
Ip	increased values from 3%
Magnet field dT	a sharp decrease in the magnetic field to 600 nT
Metal-factor	Increased values

Based on the results of electrotomography over the Benkala area, the distribution of parameters of apparent polarizabilities (IP) and apparent resistances (Rk) was calculated and areal maps Rk and IP were constructed. The most intense anomaly in the VP field (up to 10%) was recorded in the northern part of the site, which spatially coincides with the Benkala porphyry copper ore deposit. Currently, the field is being actively developed by the open pit method (quarry). Higher polarizability values correspond to lower (less than 80 Ohm) resistance values. The metal factor was also calculated, and its abnormal zones correspond to its sharp increase. This parameter characterizes anomalous objects with high polarizability and low resistivity. According to a priori data, this zone corresponds to a sharp decrease in the magnetic field.

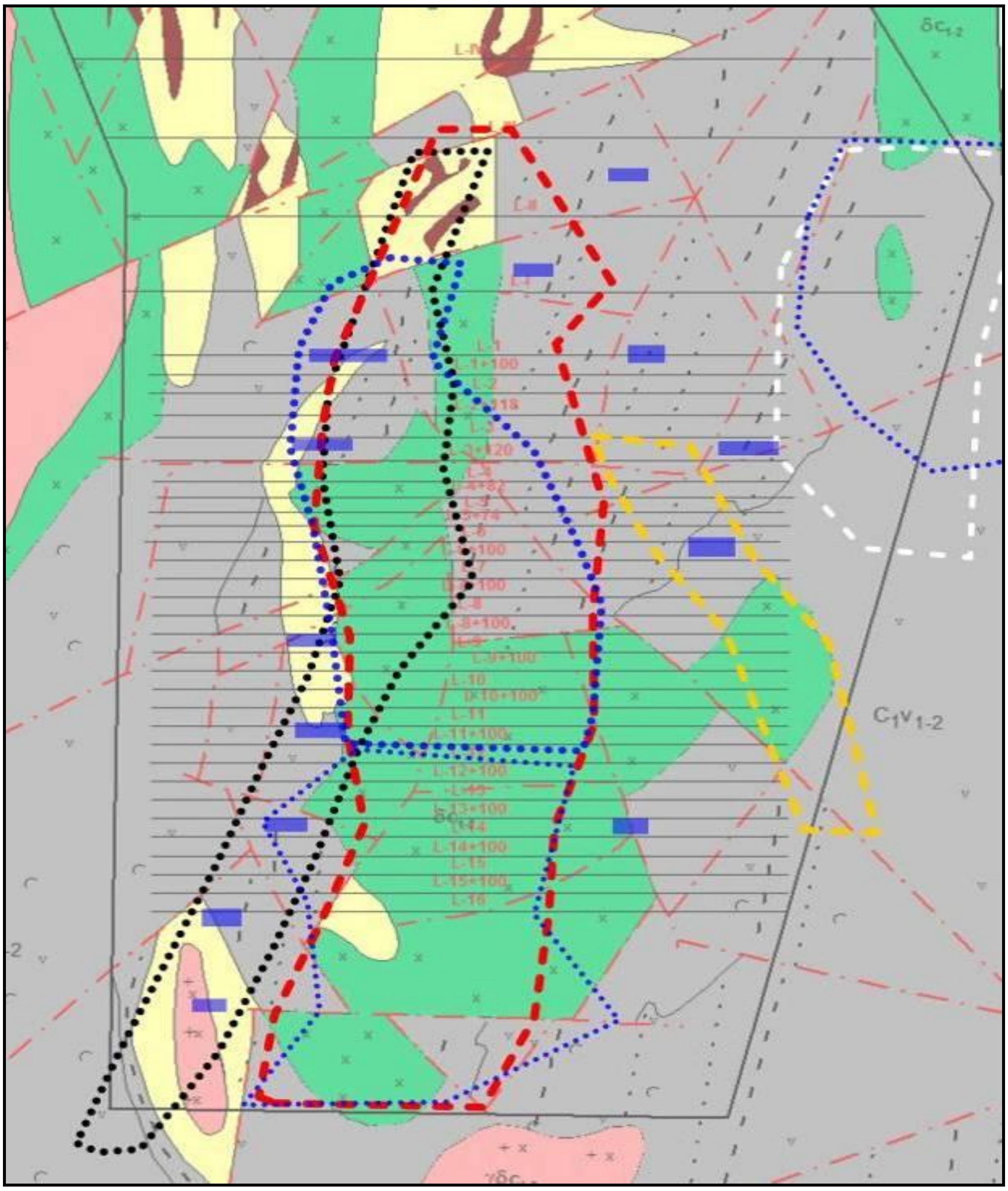


Figure 43 – The contours of the anomalous zones by the level of resistivity and induced polarization against the background of the geological map.

The above-mentioned characteristic features of copper-porphyry mineralization are precisely recorded in the southern part of the site on profiles (125-375, Zone 8), where an electrical anomaly of an airspace with an intensity of up to 10% was found to be drop-shaped by electrical prospecting. Zone No. 8 spatially coincides with the previously discovered South Benkala field. Vertex Holding is currently producing iron ore (quarry) in Zone 4. Zones No. 4-7 and No. 9.10 are promising for the presence of ore occurrences of various types of metals.

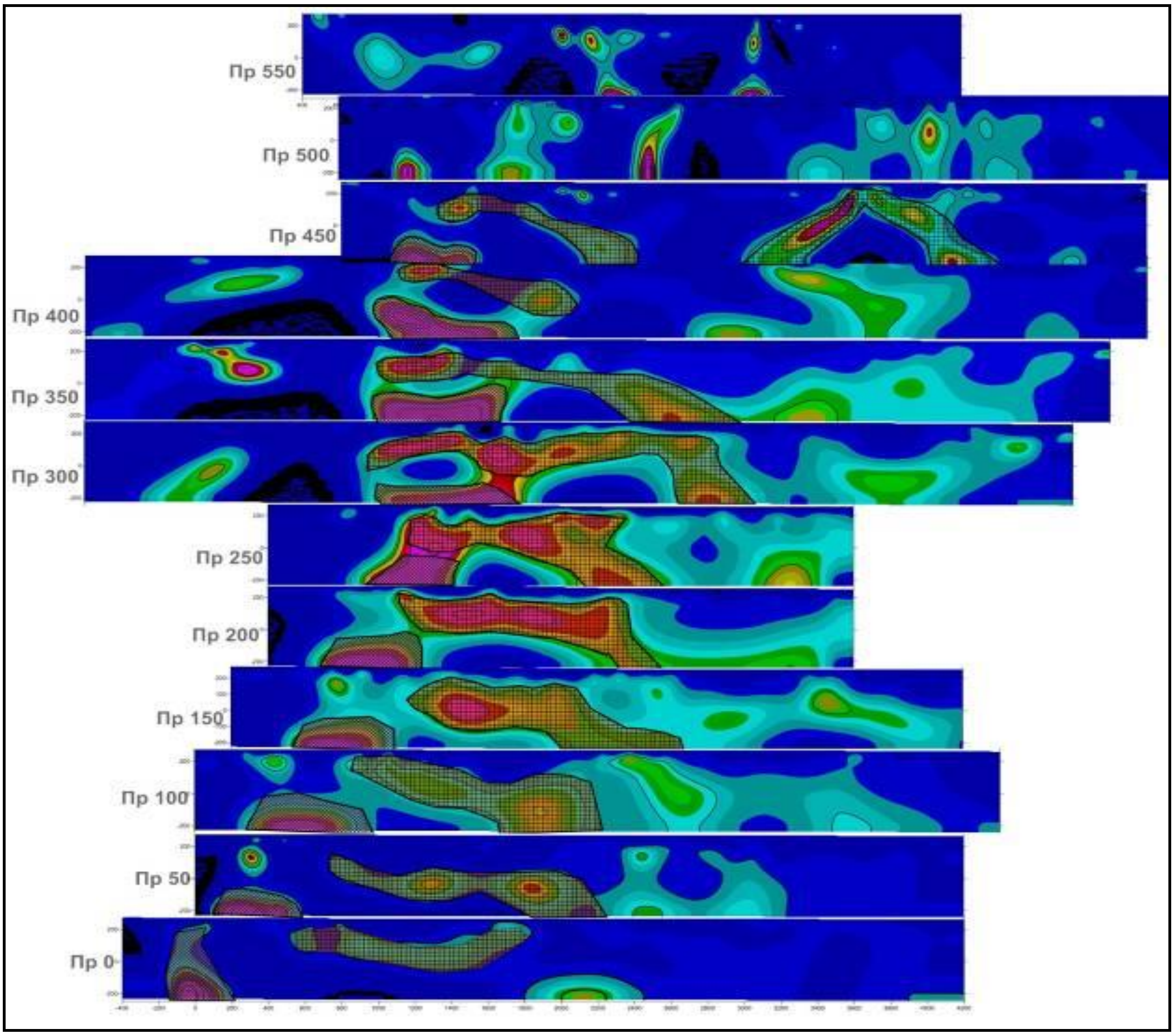


Figure 44 – Areas of intense induced polarization in the center of the site are separated.

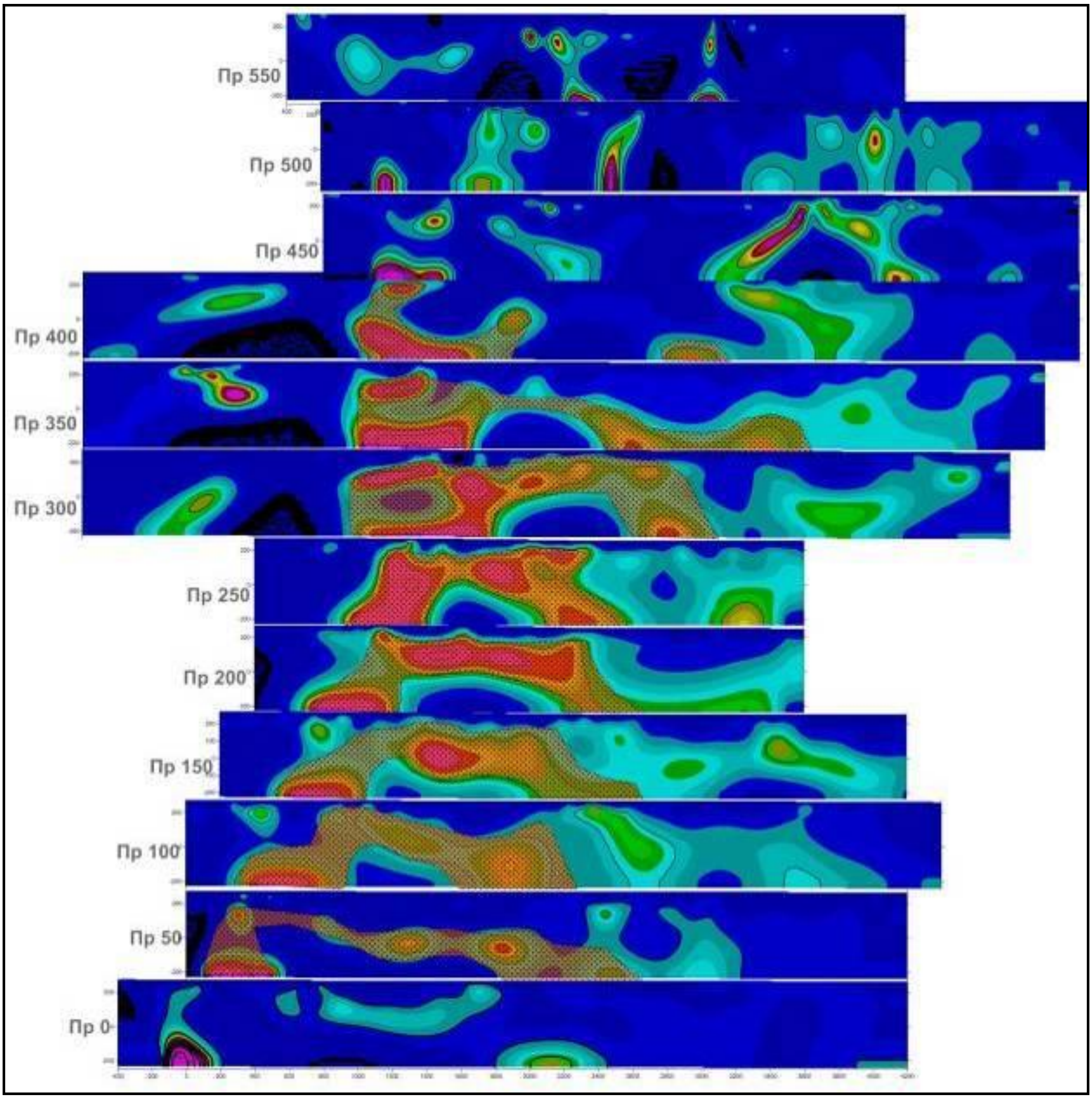


Figure 45 – Polarizing regions are part of a single porphyry system.

The regions of high polarizability values marked by us as 1 and 2 can be considered as separate objects of different nature and origin, as shown in Fig. 44. It can be assumed that this is a frame of one large porphyry field, as in Fig. 45. Both concepts fit into the picture of our models.

Based on the processing of electrical exploration measurements, a database of geoelectric parameters was created in the WLF database. The created Database is intended for further comprehensive interpretation with the use of magnetic, gravity and electrical exploration (DES and AMT) measurements. An example of building a composite map of a geophysical complex in Voxler software is shown in Figure 47.

As its seen in figure 47, on the 3D model of Resistivity and Induced Polarization superimposed 3D models of Magnet pole and Topography. This 3D model has been added into Data Mining and nowadays this model is widely used by customers.

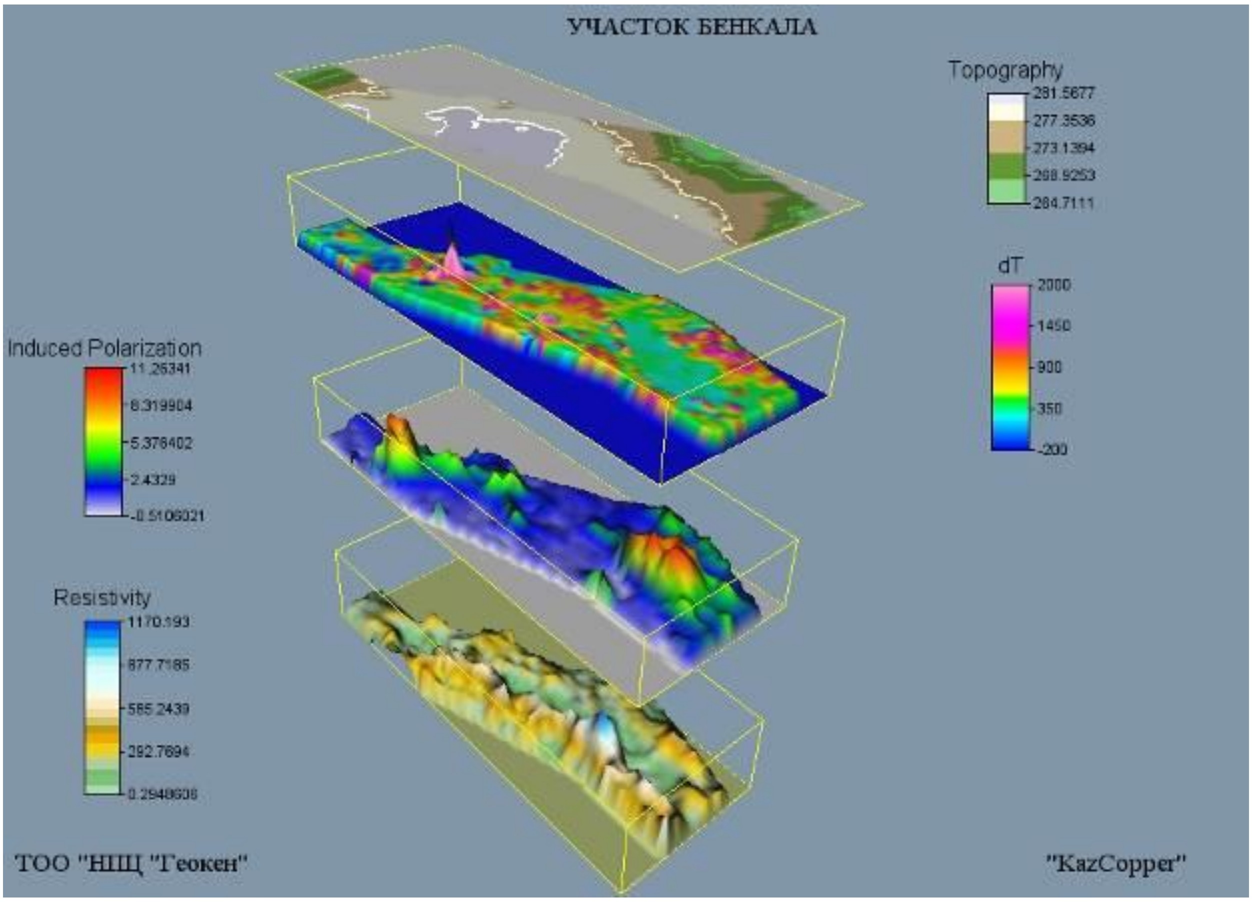


Figure 47 – The results of integrated geophysical work on Benkala area. Three-dimensional visualization in the Voxler system.

By collection all of the results of experimental and methodical work with the results of measuring work we have found the geographical location of geological objects and set the location of boreholes. Based on the results of the electrical exploration work, design wells were recommended in the areas of Benkala and South Benkala, overall there are going to be drilled 6 boreholes vertically (90 degrees) with at least 200 meters of depth (look ate the table below).

Field	Location	№ p	Number	Profile	Picket	Depth	Angle
Benkala	North	1	BN-1	1525	2200	200	90
		2	BN-2	1500	2400	200	90
South Benkala	South	1	BN-3	200	1500	**200**	**90**

		2	BN-4	250	1800	**200**	**90**
		3	BN-5	300	1700	**200**	**90**
		4	BN-6	350	1200	**200**	**90**

Table 7 – Design wells specified by the results of geophysical surveys.

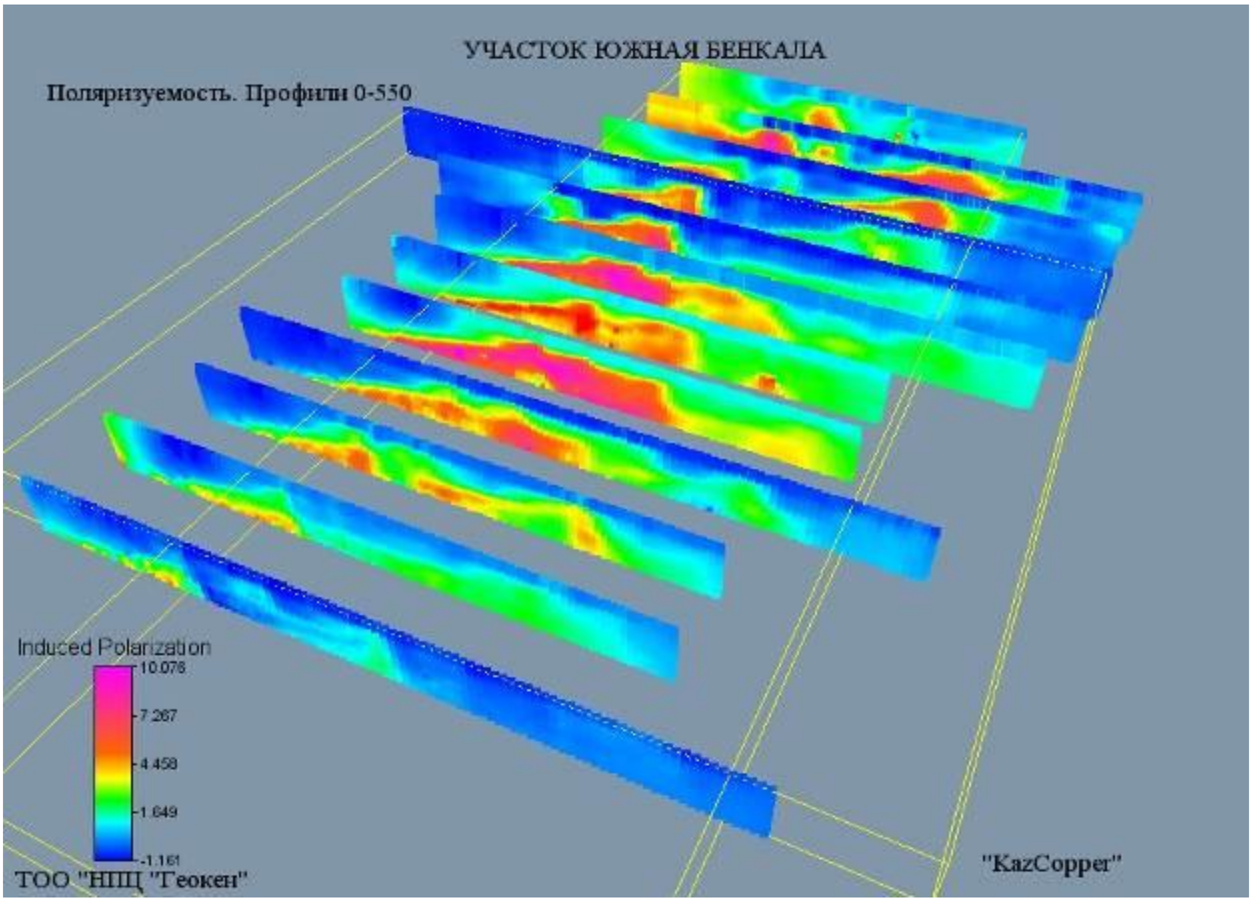


Figure 46 – Results of electrical resistivity tomography of South Benkala.

6 Work results and recommendations

The main results of the work:

1) According to the results of electrical exploration work in the area of Benkala and South Benkala, promising areas were identified.
2) Well projects were set based on the results of geophysical surveys.
3) On the basis of electrical exploration and electrical tomography, in particular, recommendations are given for further detailed exploration work
4) Made an overview of existing methods of electrotomography and selected the most optimal monitoring system in the conditions of the Benkala deposit
5) Analyzed the information content of the electrotomography data
6) Isolated of geophysical criteria for the detection of zones promising for porphyry copper mineralization
7) Made a recommendations for using ERT

Recommendations

By doing conductive field observation of the structures of the ground and measuring the resistivity and polarizability of the geological objects with all methods of electrical resistivity tomography and according to the results of 1D, 2D and 3D electrotomography, we recommend conducting electrical exploration precisely using the 2D technique, due to:

- Reasonable price
- High speed work
- A wide range of tasks

CONCLUSION

Thankfully to developments of vertical electrical sounding and induced polarization every year, electrical resistivity tomography has become the most usable method among a lot of electric survey. Electrical resistivity tomography with 2D method is one of the best method for ore bodies. However, thorugh the measuring works of 2D ERT in Benkala and South Benkala deposit we can conclude that 2D ERT can be used for identifying water horizons. All of the tasks have been solved and the location of boreholes have been set.

LIST OF REFERENCES

1 M.H. Loke, and R.D. Barker, Rapid least-squares inversion of apparent resistivity pseudo-sections using quasi-Newton method: Geophysical Prospecting, 48, 181–152, 1996.

2 Aizebeokhai AP, Olayinka AI, Singh VS (2010). Application of 2D and 3D geoelectrical resistivity imaging for engineering site investigation in a crystalline basement terrain, southwestern Nigeria. Journ. Environ. Earth Scien., DOI: 10.1007/s12665-010-0474-z, p. 1481.

3 Loke, M.H., Barker, R.D., 1996b. Practical techniques for 3D resistivity surveys and data inversion. Geophysical Prospecting 44, 499– 523.

4 Dahlin, T. 2000. Short note on electrode charge-up effects in DC resistivity data acquisition using multi-electrode arrays. Geophysical Prospecting, , 48, 181-187.

5 Bobachev A.A., Marchenko M.N., Modin I.N., Pervago E.V., Urusova A.V., Shevnin V.A. New approaches to electrical sensing of horizontally heterogeneous media. // Physics of the Earth 1995 - N 12 - p. 79-90.

6 Ritz, M., Robain, H., Pervago, E., et al. 1999. Improvement to resistivity pseudosection modelling by removal of near-surface inhomogeneity effects: application to a soil system in south Cameroon. Geophysical Prospecting 47 (2): 85-101.

7 Alumbaugh, D.L. and Newman, G.A., 2000. Image appraisal for 2-D and 3-D electromagnetic inversion. Geophysics, 65, 1455-1467.

8 Dahlin,T. and Loke, M.H., 1998. Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling, Journal of Applied Geophysics, 38, 237-249.

9 Electrical survey. Manual on electrical exploration practice for students of geophysical specialties. Edited by prof. VC. Khmelevsky, Assoc. I.N. Modina, Assoc. A.G. Yakovleva. Moscow, 2005 .-- 311 p.

10 Bobachev A.A., Gorbunov A.A., Modin I.N., Shevnin V.A. 2006, Electrotomography by the method of resistance and induced polarization. Instruments and systems for exploration geophysics. N02, 14-17.