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Improving a geophysical method to determine the boundaries of ore-bearing rocks considering certain tectonic disturbances

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Abstract

Purpose is to improve a geophysical method of determining the boundaries of ore-bearing rocks and tectonic disturbances under complex mining and geological conditions while developing 3D geological models.

Methods. 3D geological models of natural objects were developed on the basis of complex structural, geological-geophysical, and lithological facies analysis with the wide use of modern 3D seismic exploration technologies taking into consideration the parameters for prediction and selection of optimal factors for ore deposit development.

Findings. The scientifically substantiated result is represented by the increased reliability and efficiency of seismic exploration for singling out the ore horizons and ore bodies as well as tectonic disturbances at different depths by specifying geological structures of the prospective areas and sites under study.

Originality. Basing on the carried out studies, methods of the development of 3D geological models to study depth geological inhomogeneities of the ore-bearing complexes under complex mining and geological conditions were improved.

Practical implications. The obtained results of 3D modelling of geological media basing on the applied 3D seismic exploration will help increase a confidence factor of scientifically substantiated prediction of ore deposits, provide optimal development of complex ore objects, reduce risks, and increase economic efficiency of solid deposit development under complex mining and geological conditions.

Keywords: *geophysics, seismic exploration, geological model, ore deposit, tectonics, geomechanics*

1. Introduction

Every year the number of people on the Earth is growing, and there will be such a problem as a lack of raw materials [1], [2]. Consequently, the development will involve the deposits located under complex mining and geological conditions and occurring at great depths. Here, large complications are expected associated with the geomechanical situation, resulting not only in large-scale deformation processes but also considerable financial losses for mining enterprises, and what is most sad, in human losses [3]-[6].

To assess the rock mass state, a stage of designing the development of mineral deposits occurring at great depths should involve geophysical research methods in order to select an optimal design solution for the development of deposits occurring at great depths [6], [8]. Then, to make management decisions on levelling the technological production for elimination of environmental impacts, it is necessary to simulate geomechanical processes based on the data obtained from geophysical surveys, thereby ensuring safe mining of a mineral deposit in an open, underground, and combined way without any financial losses [9], [10]. During the deposit development, the geomechanical processes taking place in the rock mass as a result of technogenic impact of mining, along with instrumental geodetic studies, must also be investigated using aerospace and geophysical methods, since instrumental geodetic methods give only quantitative estimates of displacements that have already occurred, but their initial origin can be controlled by geophysical methods [11].

When combining aerospace surveys, geophysical methods with geodetic monitoring based on the use of global navigation systems GNSS, laser scanners, robotic electronic total stations, digital levelling instruments, and involving the obtained data, it is possible to model geotechnical processes of the natural and technogenic rock mass state to ensure industrial safety during the subsoil development and cover economic, social, and environmental aspects [12]-[15]. In terms of an economic aspect, a timely forecast for an unfavourable geomechanical situation will save the company's financial resources [16]-[19]. A social aspect means prevention of major deformations, which saves the lives of staff dealing with mineral extraction at great depths and accompanying diseases [20]-[24]. Elimination of the mining enterprise

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waste for developing a method for fractured rock mass strengthening helps improve the environmental situation within the land allotment area (environmental aspect) [25], [26].

Numerous geomechanical and geodynamic studies are being carried out regularly at different mining sites in Kazakhstan using the latest methods and technologies [27]. However, it is impossible to avoid completely some technogenic disasters [28]. Therefore, the government of Kazakhstan pays close attention to this issue and allocates funds for scientific research in this area, which objects are mining facilities. In their essence, those are field natural laboratories where you can study, explore, and analyze the relationship of geomechanical and geodynamic processes using modern geophysical, geological, geodetic, and space methods [29]-[31].

Up to now, most of the ore regions of Kazakhstan have been studied quite well from the surface, and the fund of shallow and easily developed deposits is practically depleted. The task is to search for deposits at the depths of 1000-1500 meters. When solving such problems, direct methods of prospecting (drilling) will be replaced by the indirect ones based on the construction of volumetric geological models of ore objects, taking into account tectonic disturbances, due to the increased labour intensity and drilling costs [32]-[34].

Currently, the methods of electrical prospecting, magnetometry, and gravimetry are most widely used within the ore regions. Electrical prospecting methods are still the leading ones at the ore objects. When searching for mineralization under the cover of loose formations, this method is most effective for shallow depths (up to 250-400 m) [35]. Gravitational and magnetic methods are used for the operations related to structural depth mapping; they do not solve the problems of a detailed study of ore control complexes and ore objects [36], [37].

Therefore, it became necessary to determine the possibility of using high-density wide-azimuth 3D seismic exploration for structural mapping of ore prospective areas and detailed study of deep-occurring ore-bearing complexes. Advent of the cutting-edge devices for recording and excitation of elastic oscillations for seismic exploration works, high-resolution 3D seismic exploration, powerful capabilities of processing and interpretational complexes can ensure obtaining the required high-quality material for ore geology [38]. That can prove the efficiency of seismic exploration while solving following geological problems: studies of structural and tectonic formation of ore areas; singling out and specification of the ore control structures; identification and depth mapping of the ore control fractures; volumetric mapping of intrusions; determining spatial position of the ore-bearing zones inside the intrusive ones etc. [39], [40].

Ore seismic exploration is classified as a wide-range method used both in regional studies and while solving multi-scale problems of structural control of ore deposits in geological environments being more complex than the ones studied by traditional seismic exploration during oil prospecting [41]-[44].

For a long time, seismic exploration, being the richest in its capacities and the most informative geophysical method, seemed to be unaffordable while searching for and exploring ore deposits [46][44]. The success of a seismic method for exploring oil and gas deposits as well as difficulties of studying deep-seated and hidden ore deposits by other geophysical methods, and the reduced cost compared to drilling, have changed radically its place in the complex of ore geophysics methods in recent years and have shown the need to develop special technologies for using 3D seismic exploration at all stages of solid mineral exploration [46]-[48].

A seismic method began to be used for studying structural and tectonic features of folded regions, the morphology and conditions of occurrence of ore-bearing intrusions, for analyzing a structure of ore fields and deposits to the depth necessary for geological exploration [49]. It helps detect and trace to the depth certain tectonic disturbances, which often play an important role in the formation of ore deposits. Seismic exploration allows specifying the contours of ore-bearing intrusions, determining the positions of their apical parts, and tracing the contact side surfaces and lower edges. This increases the efficiency of prospecting for contact-metasomatic, skarn, stockwork and other deposits [50]-[52].

At first, seismic exploration was used in ore areas in the modification of refracted waves (MRW). However, now a seismic reflection method (SRM) has taken the leading position. While applying this method, seismic exploration has proved to be effective in studying gently dipping boundaries of sedimentary and metamorphic complexes, complex structures of effusive-sedimentary complexes, morphology and internal structure of intrusions, mapping to significant depths of faults, overthrusts, and large tectonic zones [53], [54].

A great contribution to the development of seismic exploration over the years was made by the employees of the AUIEF (All-Union Institute of Exploration Geophysics), being the curator and expert of the USSR Ministry of Geology in all types of ore seismic exploration, coordinating research and production work. Methodical studies of AUIEF were carried out in 15 main metallogenic provinces of Russia and CIS countries: Karelian-Kola region, Central regions, Belomorie, Ural, Norilsk, Western Yakutia, North-East, Primorye, Caucasus, Kazakhstan, Uzbekistan while searching for iron, nickel, polymetals, copper, bauxite, diamonds, gold, apatite, etc. [55]-[59].

Ore seismic exploration was classified as a wide-range method used both in regional studies of the earth’s crust and while solving multi-scale problems of structural control of ore deposits in geological environments that are immeasurably more complex than those studied by traditional seismics. The objects of study of ore seismic exploration are a variety of geological structures: intrusive formations, structural folded elements, near-contact zones, overthrust-thrust zones, faults, kimberlite pipes, weathering crusts, etc. The studies were carried out dealing with sectional localization of geological inhomogeneities: ore bodies, zones of increased rock fracturing [60], [61].

In terms of tectonics (Fig. 1), the field is located within the area of conjugation of Ayakkagyl brachyanticline and Zhezkazgan syncline; it is limited by the northern branch of Terekta fault from the south. Minor folds were found within the ore field from west to east: Itauz syncline in the form of a narrow strip stretches in the meridional direction from the north-western tip of Zhezkazgan syncline, which apices plunge onto the south.

All the structures are elongated meridionally and north-eastwardly; their apices plunge towards Zhezkazgan synclinal. In their turn, the minor fold structures are complicated on the wings by smaller folds and stepline flexures. The latter are especially developed near large disrupted disturbances, complicating the edge parts of the major folds.

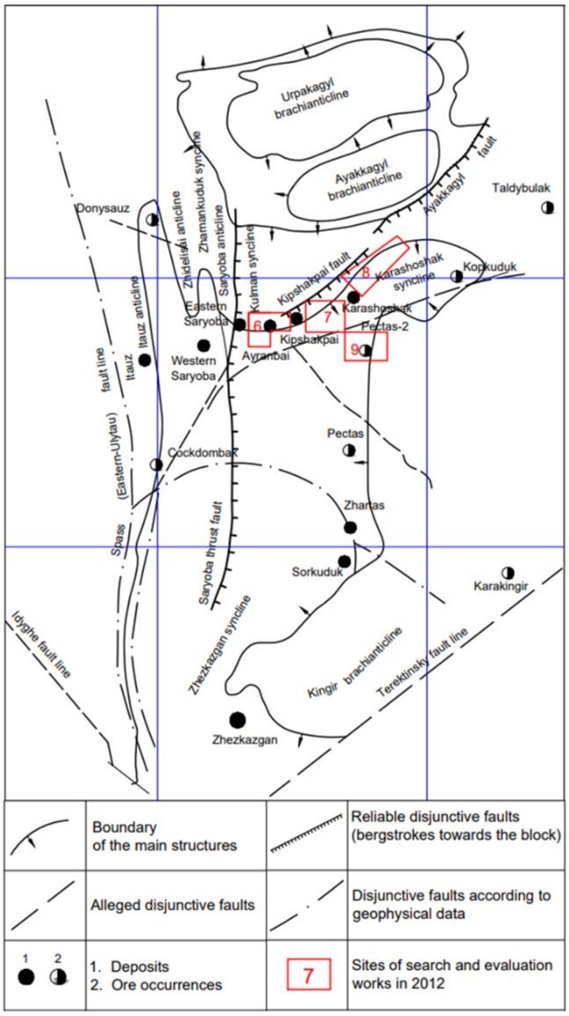


Figure 1. Scheme of a tectonic structure of Zhilandin ore field [62]

Ayakkagyl thrust is traced from the eastern edge of the mount of Ayakkagyl to the south-west up to Karashoshak deposit. Within the southern flank, the fault is accompanied by its feathering series of minor disturbances.

Kipshakpai fault is the western continuation of Ayakkagyl thrust; it is traced from the northern part of the eastern flank of Kipshakpai deposit through the southern end of Ayranbai ore occurrence up to the southern boundaries of Saryoba deposit. Saryoba upthrow-shift represents a large zone of fault of the overthrust-shift nature. To the west from Itauz synclinal, there is Western Saryoba anticline, Western Saryoba syncline, and Eastern Saryoba syncline. Further, there is wide Kulman syncline complicated by the meridional stepline flexures. In the west, Kulman syncline transforms into Kipshakpai elevation with very low reversals. Next, there is Karashoshak syncline, Kopkuduk syncline, and Taldybulak syncline. All the mentioned large faults are accompanied by minor feathering faults being not very long and having small shift amplitude [62].

Geography of the ore regions developed by the seismic exploration has widened; in this context, a reflection wave method is still a leading one. One of such regions is Zhilandin group of cupriferous sandstones. It is located in the northern part of Zhezkazgan ore field and includes the deposits of Eastern and Western Saryoba, Itauz, Kipshakpai, Karashoshak, and a series of ore occurrences (Ayranbai, Pectas and others), belonging to the cupriferous sandstone type found all over the world and being genetic analogues of the deposits of Zhezkazgan ore field. Outside the countries, those are the deposits of Kabul sulphur and ore field (Ainak, Darband, Tagkhar, Javkhar and others) and the deposits of Northern Rhodesia in Africa (Chambishi, Chibuluma, Mufulira, Roan Antelope and others) [50].

Recently, seismic exploration has been re-equipped technologically with modern digital stations with wide implementation of explosive sources of excitation of elastic oscillations. 3D seismic exploration is one of them; it will help determine the boundaries of ore-bearing rocks and tectonic disturbances under complex mining and geological conditions at the considerable depths down to 1000 m. That will improve greatly the quality of geological and surveying operations [60], [38].

Thus, the purpose of the paper is to improve a geophysical method of determining the ore-bearing boundaries and tectonic disturbances under complex mining and geological conditions while developing 3D geological models. To reach the goal, it is necessary to carry out a series of studies for substantiation of the seismic exploration reliability and efficiency in terms of the singled out ore horizons and ore bodies as well as tectonic disturbances at different depths by specifying a geological structure of the analyzed prospective areas and sites.

2. Materials and methods

The proposed method of determining the boundaries of ore-bearing rocks considering tectonic disturbances is as follows. Stage one includes field 3D seismic exploration works within the local prospective sites. Basing on the analysis of geological structure of the areas under analysis, velocity characteristics, and technical and technological conditions of the progress of field works, a design of a monitoring system is developed aimed at ensuring the substantiated parameters of excitation and recording of usable reflections with the increased level of high-frequency component of elastic oscillations. Seismic exploration involving a 3D method is expedient to perform involving the areal data collection systems. While displacing active arrangement towards the recording line as well as towards the direction perpendicular to those recording lines, seismic information within the considered area of operations is received [63].

The upper part of a section is studied to define the propagation velocities of elastic waves within the upper parts to select the most favourable conditions of oscillation excitement, determine statistic corrections in terms of inhomogeneous upper part of the section, and exclude its influence on the in-depth wave field [64].

To study the upper part of the section, a refraction wave method and/or micro-seismogram log and/or microseismic torpedoing of shallow wells are applied.

Oscillations are excited with the help of explosions (explosive changes or line of detonating chords) or non-explosive sources. An optimal variant of excitement is selected according to the conditions and tasks basing on the practice of previous operations; it is clarified after the wave field analysis during the experimental works.

While recording the oscillations, grouping of seismic receivers is used. Parameters of the grouping of seismic receivers are selected depending on the wave field characteristics to provide optimal suppression of regular interferences and minimum distortion of useful signals.

According to the results of seismic exploration data processing, seismic cubes of time and depth migration before the wave seismic field stacking are obtained, and high-quality seismic models are developed, which make it possible to represent in detail an overall geological structure, specify local inhomogeneous target objects, correlate adequately the reflections, and identify anomalies related to the ore bodies.

A stage of making volumetric seismological models involves interpretation of seismic data, including two stages: structural analysis and dynamic interpretation.

Structural analysis means:

– correlation of target reflecting horizons;

– structural building (structural maps) within the target intervals and developing the thickness maps (isopachytes) between the target reflecting horizons;

– complex analysis and interpretation of the seismic data and materials of geophysical studies of wells and drilling.

Seismic data are interpreted with the help of specialized software as follows:

1. An interpretation project is developed; the formed database is downloaded into the special software. The resulting data of the processing of 3D seismic data of PSTM (prestack time migration) are downloaded.

2. Data on the velocity medium characteristic (velocities of seismic wave propagation throughout the area and depth) are downloaded. The data are the basis to estimate positions of the boundaries dividing the main geological thicknesses; preliminary referencing of a seismic wave field is made to emphasize the main reflecting horizons.

3. Stratified and support horizons are traced.

4. Faults and fractures are observed. Fractures are singled out in terms of disruption of seismic events within the vertical time sections, horizontal time slices, and by the cube of tectonic disturbances obtained from the coherence attribute.

5. The PSTM cube is downloaded, and correlations of the horizons in a depth domain are clarified.

6. A structural model is developed according to the PSTM data.

7. A final structural model (structural maps with singling out of the outlines of geological bodies) is made.

Dynamic interpretation is performed to predict and highlight the prospective areas and zones of the development of ore deposits. Dynamic analysis of a wave field for tracking tectonic disturbances and identifying wave-field anomalies related to the ore deposits involves basic known traditional software packages: Coherence Cube, Acoustic (Seismic) Inversion, Seismic Facial Analysis etc.

At a stage of geological interpretation of seismic data from the CDPM-3D (common depth point method) survey cube, the seismic profiles are singled out; the profiles coincide with the coordinates of geological sections developed according to the results of exploration drilling. The reflecting boundaries are referred to the stratigraphic complexes, their lithological inhomogeneity along the lateral and depth in terms of each geological profile taking into account changes in the velocities obtained while processing the seismic data.

As a result of correlation and integration of time sections with the actual geological data obtained after drilling, a three-dimensional model is developed to trace horizons; among the horizons, seismic sections (inlines and crosslines) are selected (with the spacing of, for instance, 10 m) as well as the profiles through any points throughout a seismic data cube. All target reflecting horizons, nature of their changes, separate rock blocks, basic tectonic disturbances etc. are represented in terms of the time and depth sections.

The ore object outlines are singled out structurally basing on a depth-velocity model (changes in the velocity of elastic wave propagation laterally and vertically) with the emphasis on the zones of wave field changes (amplitude, frequency etc.) according to the sign of bodies, being lensoid in section, associated to the flexures found along the ore-bearing horizons.

While interpreting seismic information, one should control and, if necessary, correct a pulse shape attracting the data of vertical seismic profiling and/or the mathematical seismic modelling data.

The second stage involve development of a digital database basing on generalization, analysis, and preparation of all the available geological and geophysical information within the areas and their edging territory including the drilling results, kern studies, geophysical well studies, detailed field geophysical studies etc.

The third stage means modelling a wave field of the object under analysis applying modern processing and interpretational complexes to develop volumetric seismological models in the form of 3D data on the parameters of seismic signals (x, y, z, f) and identify the boundaries of spatial location of the ore-bearing rocks [39].

The final stage involves singling out and outlining the ore bodies and tectonic disturbances on the basis of geostatic and geoseismic modelling as well as complex analysis of all geological and geophysical information.

The abovementioned method was used while interpreting geological and physical data with the application of three-dimensional seismic exploration to identify ore control horizons, faults, and fractures to trace them in space and develop a model of ore deposits, tectonic disturbances within the cupriferous sandstone deposit Saryoba in Central Kazakhstan.

The development of 3D geological models of ore bodies included: field 3D seismic exploration within the site (Fig. 2), analysis of the initial geological and geophysical materials and formation of databases of geological and geophysical information, interpretation of seismic data, complex analysis of geological and geophysical information, geostatic analysis, and development of seismological models of ore fields.

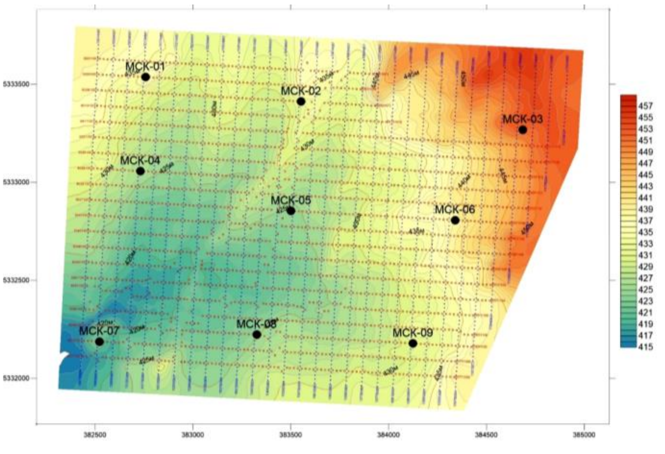


Figure 2. Scheme of the arrangement of micro-seismogram log wells within the site of Western Sarybora

Following data were used to create the database with further development of geological and geophysical models basing on the cube obtained after processing field seismic data:

– results of regional geological and geophysical studies;

– results of detailed geological studies, drilling;

– results of geochemical studies;

– field geophysical studies: magnetic exploration, gravitational exploration, electric exploration;

– data of 3D seismic exploration.

The geological and geophysical models were developed taking into consideration geological data obtained during different years while field studying [65]. Geological interpretation of seismic data was performed involving the “Geographix Discovery” (Halliburton) software and additional modules of calculation of dynamic attributes. The main purpose of the methodology is to design adequate exploration wells to identify ore-bearing horizons and tectonic disturbances at deep depths; in this context, the following should be used:

– structural maps of productive levels singled out in terms of seismic exploration data as a result of interpretation of CDPM-3D seismic materials;

– results of determining the regularities for distributing a valuable component within the considered site carried out by a geostatic method and a method of geological blocks;

– geostatic analysis of the geological and geophysical data;

– analysis of the distribution of the most porous sandstones within the areas of abnormally high open fracturing.

3. Results and discussion

Interpretation of seismic data means their use considering the apriori information and according to the target task to determine a model of geological environment being in compliance with the processing results. The key content of the interpretation process involves computational, logical, and heuristic operations with the interpreted wave field and its attributes as well as matching the seismic and apriori information.

There are following basic stages of interpretation:

– correlation (tracing) of the main reflecting horizons;

– tracing of discontinuous disturbances (faults and fractures);

– developing the maps of isochrones and structural maps in terms of the highlighted horizons;

– calculation of dynamic attributes (coherence cubes, mean-square amplitudes, inversions etc.) along the singled out horizons. Dynamic attributes make it possible to make conclusions concerning lithology and facial changes within the zone of interest.

During the interpretation process, two mutually interdependent approaches are combined:

– geophysical one meaning the determination of structural models and seismographic parameters of the environment according to the seismic data;

– geological one meaning predictions of lithological and petrographic, genetic, and other geological characteristics of the environment according to the seismic materials.

The notion of interpretation includes also representation of the results and evaluation of their reliability and accuracy.

As a result of structural developments and dynamic interpretation of the seismic data, a structural model, i.e. structural maps and outlines of geological bodies, was developed (Fig. 3).

Peaking of the faults and fractures was performed in terms of failures of seismic events within the vertical and horizontal time sections (slices) as well as within the cube of tectonic disturbances obtained from the coherence attribute. Further, productive horizons were traced within the inline and crossline network profiles with the spacing of 100×100 m; dynamic parameters were analyzed for detailed study of the section lithology.

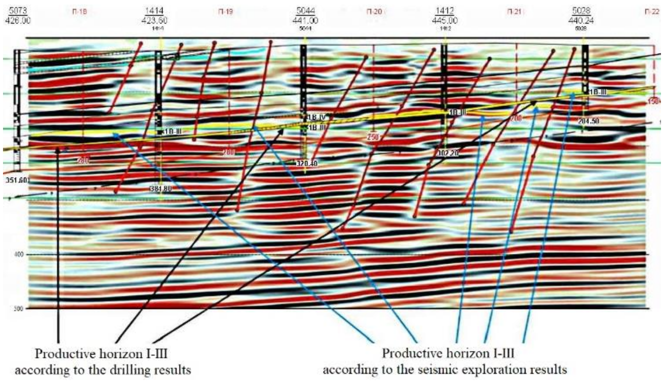


Figure 3. Correlation of the horizons within a stratigraphic interval (time prognosis within the profile XXXII)

While correlating the sections, quality is controlled including the development of 3D model of the traced horizons. During the data correlation, a reflecting boundary was selected in the time domain; the boundary was being traced clearly within the period of 180-130 ms taken conventionally as 1B-III horizon that controls the occurrence of cupriferous sandstone. Above the horizon, a body, being lensoid in section, is traced near the well 5044; the body is identified as horizon 1B-IV.

As a result of correlation and referencing the time sections to the actual geological data obtained as a result of drilling, 3D models of the traced horizons have been developed, among which one can select seismic sections (inlines and crosslines) with 10 m spacing as well as profiles through any points throughout the seismic data cube. All target reflecting horizons, their nature of change, separate rock blocks, basic tectonic disturbances etc. are shown on the time and depth sections (Fig. 4).

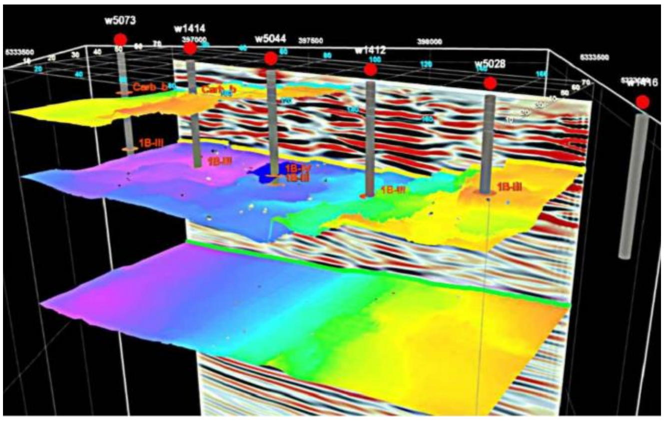
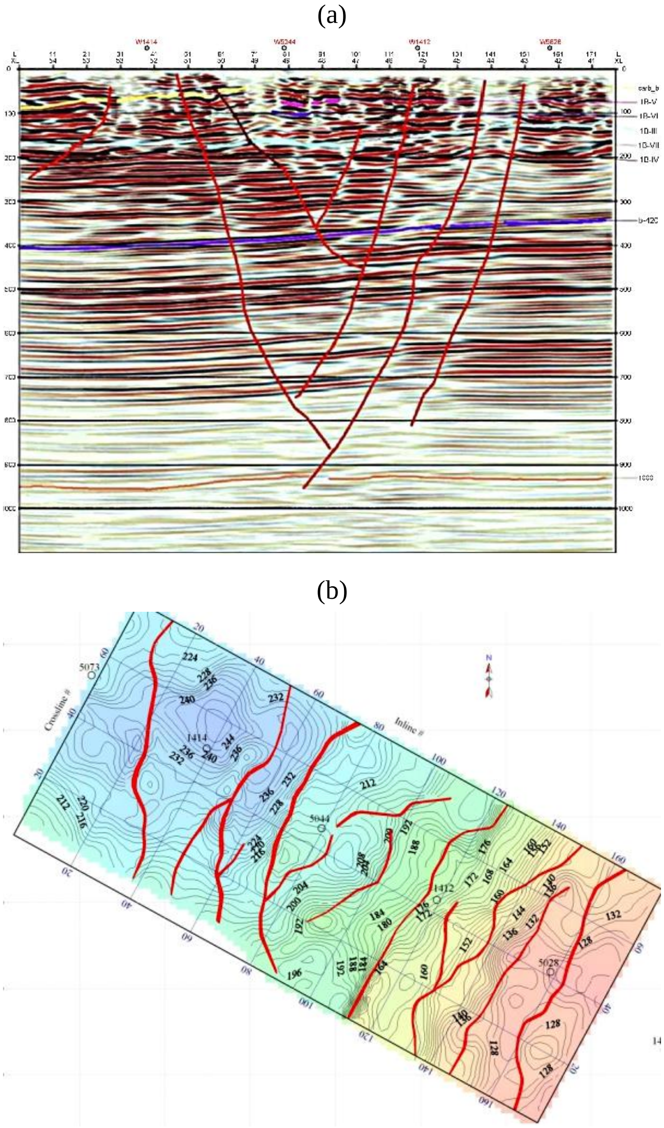


Figure 4. Volumetric image of the model of the developed reflecting surfaces

Due to the lack of borehole geophysical information, seismic horizons were referred basing on the drilling results and velocity analysis taken from the reports on previous-year seismic operations.

While developing a depth seismic section, depth referencing of the horizons was performed basing on a depth-velocity model obtained at the stage of pre-stack depth migration. Within the upper section part, in terms of 0.5-6.0 m thickness of ore-bearing horizons, such an approach makes it possible to identify only the interval of 20-25 m thick in the wave field; the ore-bearing horizons is within that interval. Moreover, the error of stratigraphic referencing to the upper part can reach tens of metres and more than 1000 m at the depth.

Within the sites of Zhilandin group of deposits, the CDPM-3D seismic materials were interpreted, isochrone maps and structural maps in terms of reflecting horizons C2pk (roof of cherts), 1B-IV, 1B-III (ore-bearing greenish-grey sandstones within the Upper Beleutin layers) and C1nbl1 (roof of the Lower Beleutin layers) at a scale of 1:5000 were constructed. Microtectonic disturbances (minor faults and fractures) were singled out in terms of seismic sections (Fig. 5).


(a)

(b)

Figure 5. Interpretation of seismic data: (a) depth seismic; (b) surface

After completing the pre-stack depth migration, a depth cube was obtained, in terms of which separate correlation of the traced horizons was carried out.

In terms of pre-stack time migration cube, correlation of the traced horizons C2zl (roof of Zlatoust horizon), 1 (roof of Taskuduk horizon), 1-b (roof of Zhilandin horizon), and 1-c (roof of Kopkuduk horizon) as well as across two deep horizons called conditionally C1v and C1t was performed within the area of Zhilandin group of deposits. After completing the pre-stack time migration, a depth cube was obtained, in terms of which separate correlation of the traces horizons 1 (roof of Taskuduk horizon), 1-I, 1-IIb and 1-III, (ore deposit, non-commercial lead ore), 1-b (roof of Zhilandin horizon), and 1-c (roof of Kopkuduk horizon) was performed. Besides, according to the depth migration data in a seismic wave field the flexures became apparent, in terms of which three bodies, being lensoid in section, were outlined near the well within the intervals with ore-bearing; the bodies were called conditionally Object-I, Object-II, and Object-III (Fig. 6).

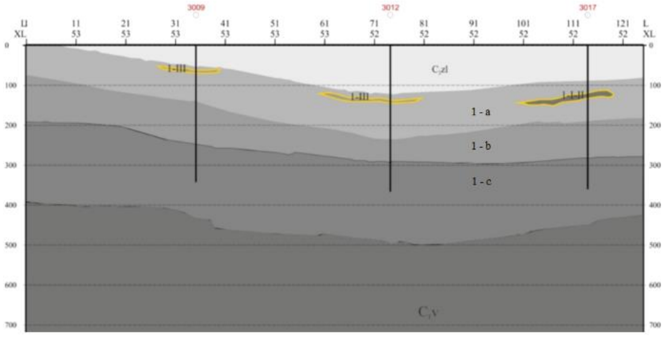


Figure 6. Interpretation of the seismic data in terms of geological profile

Within one site of Zhilandin deposit, the interpretation has helped construct isochrone maps and structural maps in respect of 4 horizons: 3 (floor of Pokrovsk horizon), 2 (floor of Zlatoust horizon), 1 (floor of Taskuduk horizon), 1c (ore deposit of Upper Beleutin deposits formations) at a scale of 1:5000 (Fig. 7). Seismic sections clearly demonstrate microtectonic disturbances (minor faults and fractures); however, due to large volume of those fractures and loss of image informativeness on the seismic sections, only basic (large) faults are represented on the sections and structural maps.

A stage of dynamic interpretation involved testing the methodology within the conditionally singled out ore horizons and deposits 1, 1a, 1b, and 1c, characterized by the manifestation of ore grade mineralization. Seismic facies classification was performed according to the wave shape for the first (1) ore horizon within the interval of seam 1-II (3 m above horizon I).

Analysis and classification of seismic facies with the adjusted attribute analysis of a wave field make it possible to study a wave field structure in more detail and identify seismic anomalies, which are possible related to a geological factor of the section under consideration.

There are three approaches in the sphere of seismic facies analysis:

– classification by the pulse shape within the specified trace window;

– classification of a set of maps or slices by horizons as well as proportional slices;

– volumetric classification.

The facies analysis methodology is based on the neural network operation; it is applied for the wavelet shape and use an interval approach. The seismic trace windows are taken from the interval selected by a geophysicist. Applying the neural network algorithm, seismic traces within this interval are analyzed according to the wavelet shape; that is the basis to develop a model consisting of a set of synthetic traces determined by the corresponding colour and representing the availability of different wavelet shapes inside the preset interval of study. Then, each trace from the initial seismic data cube within the interval is compared with the synthetic traces, and, basing on the minimum correlation between them, defined with certain colour corresponding to the model traces.

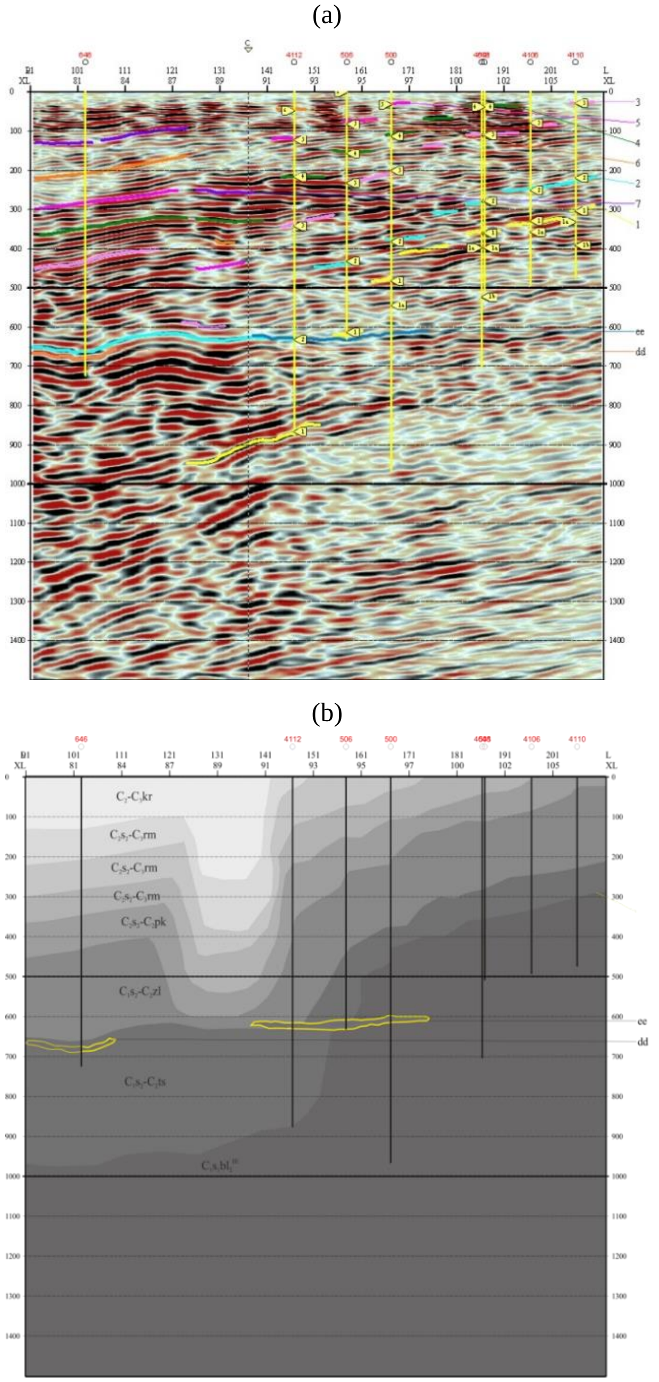


Figure 7. Section fragments: (a) depth seismic; (b) geological section in terms of seismic data throughout the geological profile

The approach means changing wavelet shape caused by alternating lithology by the spatial distribution of seismic facies within the preset interval of study. A final map of seismic facies shows the changes in terms of wavelet shape that depends on varying physical parameters of the section (velocity, density, and thickness of the seams).

A technique of seismic facies analysis involving PCD (principle of componential analysis) was applied to improve the quality of a seismic facies map for the target time interval. The essence of the method is as follows. Seismic samplings from the initial data volume are projected into the multidimensional cross-plot. The main axis of data distribution is determined from the obtained data cloud. The samplings are projected onto this axis and distributed according to their amount and changeability. The components containing excessive information and noise are usually deleted from the newly generated 3D volume; they are not used during the further process of classification.

The sections of a seismic facies cube (Fig. 7) show that blue colour of seismic facies corresponds to seam (deposit) 1-II marked as 1top – 1bot. At the points where seam thickness is about 10 m and more, seismic facies are traced rather steadily. At the points of disturbances as well as due to inhomogeneity of seismic data, traceability is violated with the observed mixing of seismic facies.

The obtained seismic facies cube (Fig. 8) was used as the additional source of information while tracing the deposit within an inter-well space. Distribution of the seismic facies classes over the area determines the domains being the most appropriate for new drilling points.

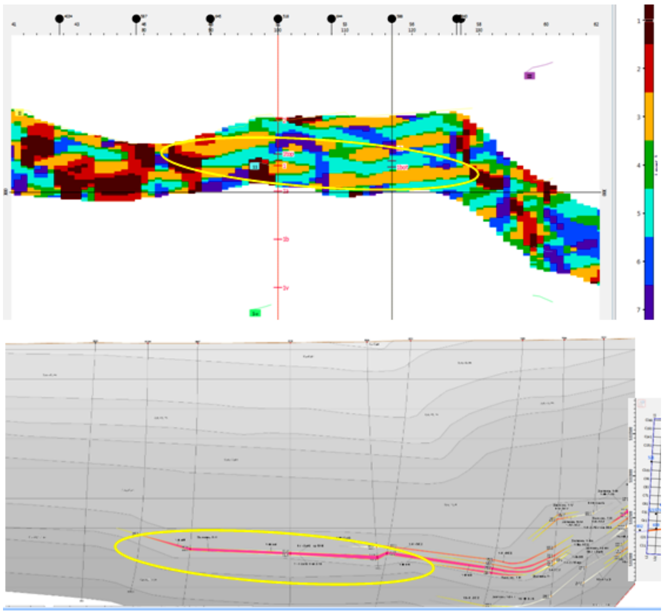


Figure 8. Section on the geographical profile from the seismic facies cube

A technique for identifying ore objects on the basis of high-resolution 3D seismic exploration is as follows:

– relying on the analysis of geological structure of the considered sites, velocity characteristics, and technical and technological conditions of field operations, a design of the field observation system is developed; that is aimed at ensuring the substantiated parameters of excitation and recording of usable reflections with the increased levels of a high-frequency component of elastic oscillations;

– 3D field seismic exploration is carried out within the prospective sites;

– seismic exploration data are used to get seismic cubes of pre-stack time and depth migration of reflections of a wave seismic field, and structural models of the considered depth area are developed;

– digital database of the available geological and geophysical information concerning the prospective sites and their edging territories is created;

– wave field of the studied volume is modeled in the form of 3D data, and boundaries of spatial location of the ore-bearing rocks are specified;

– basing on the structural interpretation of seismic data, geological objects are outlined;

– relying on the dynamic interpretation of seismic data, predictions are made, and prospective sites and zones of the development of ore-bearing deposits are singled out;

– in terms of complex analysis of the geological and geophysical information, geostatic and geoseismic models of the considered object are constructed;

– relying on the analysis of geostatic and geoseismic models of the object under analysis, zones of peculiar features of seismic signals, connected with the spatial position of the mineralization areas, are identified, and ore bodies are outlined.

Relying on the proposed method of ore object specification basing on high-resolution 3D seismic exploration, it is proposed to sink the designed prospecting wells to clarify geological structure and define ore-bearing horizons within one of the sites of Zhilandin group of cupriferous sandstone deposits (Fig. 9).

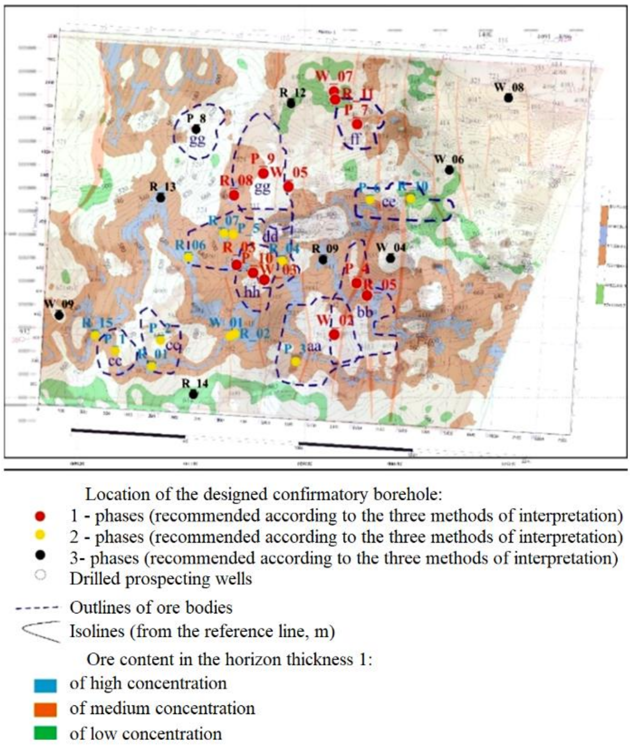


Figure 9. Map of prospective sites with high (grey) and low (light) ore concentration in the thickness of the site of Zhilandin group of cupriferous sandstone deposits

The proposed methods concerning 3D seismic exploration of a deposit has improved the quality of the developed geological model of the deposit. First of all, the quality depends on the adequacy of the initial data and correctness of a structural model of the analyzed site developed on the geological and geophysical materials as well as on the analysis of distribution of the most porous sandstone interlayers within the areas of abnormally high open fissility with the resulting high ore concentration in the enclosing thickness. It also will help design exploratory wells for the considered prospective ore objects with high confidence; that will reduce the percentage of drilled “empty” wells.

Further, following technologies are planned to be used to assess a geomechanical state of the rock mass along with geophysical studies:

– 3D modelling (basing on unmanned vehicles, ground laser scanning, and GIS) – from the process of geological and geophysical operations to the determination of a geotechnical state of the rock mass for safe deposit development under complex mining and geological conditions;

– IT-technologies involving GNSS technologies of mining and surveying operations, monitoring of the rock mass state.

While defining the area for laying a geodynamic field, it is supposed to use the results of geological surveyance deaing with determining the ore-bearing levels based on the 3D seismic exploration.

Thus, the paper estimates the possibility of applying modern processing and interpretational complexes in terms of ore objects to obtain high-quality materials and shows the efficiency of ore seismic exploration while solving certain tasks of the analysis of structural and tectonic formation of ore fields as well as singling out and clarifying the ore control structures in the sedimentary and effusive-sedimentary folded rock complexes. Moreover, a method of detection and depth mapping of ore control faults and volumetric mapping of intrusions is represented. Spatial position of the ore-bearing intra-intrusive zones is determined; differentiated intrusions are localized, and their morphology is studied.

4. Conclusions

Development of a rational complex of geological and geophysical studies and 3D modelling during the deposit prospecting and exploitation determines the scientific and practical efficiency of the deposit development under complex mining and geological conditions.

Attention should be paid to the formation of the database of geological and geophysical information (field studies, generalization and analysis of the previous materials), development and use of a rational complex of geological and geophysical studies, and geological modelling for searching for, prospecting, and development of ore deposits.

The obtained 3D seismic image along with the applied modern 3D procedures of digital processing and interpretation of seismic signals has helped clarify a geological structure of the target objects of the research.

According to the results of recording, processing, and interpretation of the seismic exploration data and involving the extensive use of modern seismic recording and processing systems accompanied by the results of exploratory drilling, the experimental fields of the deposit of Zhilandin group have been analyzed to single out spatial position of the ore-bearing levels within Upper Beleutin and certain layers of Taskuduk suite of the lower series of carboniferous system. Structural maps and attribute maps have been analyzed considering the previous-year drilling results; recommendations have been given as for the location of exploratory wells.

3D modelling of geological media involving 3D seismic exploration helps increase a confidence factor of scientifically substantiated prediction of ore deposits, provide optimal development of complex ore objects, reduce risks, and increase economic efficiency of the solid deposit development under complex mining and geological conditions. In general, 3D seismic exploration will allow improving sustainability of mining and processing as well as other industries of the Republic of Kazakhstan; it will also help strengthen a social and economic factor of the development of little towns of Kazakhstan.

The research has made it possible to obtain the data concerning the position and morphology of reflecting surfaces of stratigraphic horizons at the stratiform ore occurrences. That also has helped determine special and genetic connection between the ore localization and the rocks of certain lithological composition in the effusive-sedimentary and igneous complexes with different geological and structural framework.

Minor-amplitude folded and tectonic disturbances of the zone of crushing and fissility have been identified; structural mapping of the ore prospective areas and fractural tectonics of the deep-seated ore-bearing complexes (down to the depth of 0.8-1 km) have been represented.

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Удосконалення геофізичного способу визначення меж рудовмісних порід з урахуванням тектонічних порушень

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Мета. Удосконалення геофізичного способу визначення меж рудовмісних порід та тектонічних порушень у складних гірничо-геологічних умовах при побудові 3D геологічних моделей.

Методика. Створення тривимірних геологічних моделей природних об'єктів здійснювалося на основі комплексного структурного, геолого-геофізичного та літолого-фаціального аналізів із широким використанням сучасних технологій 3D сейсморозвідки з урахуванням обґрунтування параметрів прогнозування й вибору оптимальних параметрів розробки рудних покладів.

Результати. Науково-обґрунтованим результатом є підвищення достовірності та ефективності сейсморозвідки для виділення рудних горизонтів і рудних тіл, а також тектонічних порушень на різних глибинах за рахунок уточнення геологічної будови досліджуваних перспективних площ і ділянок.

Наукова новизна. На підставі проведення досліджень удосконалено методику побудови 3D геологічних моделей для дослідження глибинних геологічних неоднорідностей рудовмісних комплексів у складних гірничо-геологічних умовах.

Практична значимість. Отримані результати 3D моделювання геологічних середовищ на основі застосування 3D сейсморозвідки дозволять збільшити коефіцієнт достовірності науково-обґрунтованого прогнозування рудних покладів, забезпечать оптимальну розробку складно побудованих рудних об'єктів, а також знизять ризики та збільшать економічну ефективність освоєння родовищ твердих корисних копалин.

Ключові слова: *геофізика, сейсморозвідка, геологічна модель, рудний поклад, тектоніка, геомеханіка*