

Article

Methodology and Results of Detailed 3D Seismic Exploration in the Zhezkazgan Ore District

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Abstract: This article presents the results obtained from a high-resolution wide-azimuthal 3D seismic reflection method used for the prediction and detailed exploration of complex ore targets in the Zhezkazgan ore district of Central Kazakhstan. We demonstrate the ability of modern seismic data processing and interpretation systems to identify underground mine objects associated with stratiform copper sandstones and improve geological models. The 3D seismic imaging tools, along with the implementation of a modern seismic processing sequence, allow for the clarification of geological structures in the studied area. The target stratigraphic horizons, large faults, and microtectonic disturbances (small faults and cracks) are clearly delineated in the seismic volumes. The use of seismic attribute analyses on geological data is tested to identify ore horizons and deposits with volumetric predictions of copper mineralization. Recommendations for further exploration drilling were developed, and five new wells were drilled. Copper mineralization was confirmed in all recommended wells. We carried out a marketing review in Kazakhstan and uncovered an increased interest among subsoil use companies in 3D seismic exploration technology to investigate existing mining objects of different genetic types. These results demonstrate the expediency of 3D seismic exploration aimed at identifying ore targets.



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Keywords: 3D seismic reflection; data processing and interpretation; attributes; stratigraphic horizons; copper sandstones; ore body

1. Introduction

As the most comprehensive and informative method for geophysical investigations, seismic exploration has long been considered an expensive method for ore deposit prospecting and exploration. However, the success of seismic exploration in relation to the prospecting and exploration of complex oil and gas deposits, as well as the challenges of studying deep and hidden ore deposits through the use of conventional geophysical methods, has radically changed the role of seismic exploration in the context of ore geophysical methods [1–5].

In a composite medium represented by intensively dislocated sequences of effusive–sedimentary and igneous rocks in folded zones, seismic exploration is mainly used for regional studies and mid-scale geological mapping. At the same time, seismic exploration has rarely been used to delineate promising ore-bearing areas and ore targets for exploration drilling [6–9].

In the past, due to hardware and software limitations, the 2D single-fold reflection seismic method has traditionally been used to explore geological sections in ore mining areas. Seismic reflections have been shown to poorly delineate geological boundaries

in the shallowest part of a section (down to 500–800 m depths). The spatial–genetic relationship between ore localization on the one hand and the rocks of a certain lithological composition, magmatic bodies, tectonic zones, etc., on the other has been established in numerous ore-bearing regions. Therefore, the seismic exploration method is most often used to study the structural tectonic composition of the folds and the morphology and prerequisites of the occurrence of ore-bearing intrusions. The study of the composition of ore-hosting deposits is conducted to a depth established by the exploration assignments with a scale not exceeding 1:50,000 as a rule [10,11]. Since the modern seismic reflection method of Common Depth Point (CDP) for seismic exploration became widely used at mining sites, seismic exploration has proven to be effective at studying both the gently sloping boundaries of sedimentary and metamorphic sequences and the complex structures of effusive–sedimentary horizons, the morphology and internal composition of intrusions, and the mapping to significant depths of faults, thrusts, and large tectonic zones. Seismic exploration both clarifies the delineation of the intrusions and determines the position of their apical parts, as well as tracing the contact lateral surfaces and the lower edges. This improves the efficiency of prospecting for contact metasomatic, skarn, stockwork, and other deposits [12,13].

The capability to address more complicated and higher-level assignments such as verifications and 3D assessments of either direct ore control factors or ore deposits at practically developed depths has become possible with the introduction of 3D seismic exploration methods. High-resolution seismic reflection and 3D seismic modeling with identification of zones of elastic property alterations (amplitude, frequency, velocity characteristics, etc.) can locate deposits at depths of 3000 m and more [14,15]. To solve the abovementioned tasks, direct methods of prospecting (drilling) should be substituted with indirect methods based on composite geological modeling of ore targets which rely on the extensive use of state-of-the-art systems for seismic data processing and interpretation. At the same time, the cost of prospecting and exploration efforts will be drastically reduced [16–18].

To date, new and continuously improving techniques for seismic data processing and interpretation have been developed, bringing in new opportunities for the accumulation of useful events and for the achievement of effective noise attenuation in complex geological target investigations [19–21]. A wide range of analysis, interpretation, and well-logging methods are currently used for efficient oil and gas exploration. However, mining-related seismic explorations are also extremely relevant given the nuances of occurrence of deep ore targets [22,23].

According to the authors of [24,25], the most crucial objectives of ore seismic exploration are as follows:

- The improvement of methods for field and borehole seismic observations;
- The establishment of dedicated systems for the digital processing and interpretation of seismic data to address ore geology issues;
- The adaptation of numerous currently available technologies for the interpretation of composite wave fields using task-oriented geodata systems for ore horizon modeling and spatial tracking [26,27].

Taking into account the abovementioned points, the objective of this study is to perform sophisticated geological and geophysical modeling with extensive use of seismic exploration data in experimental areas of the Zhezkazgan ore region. The following stages were followed:

- Obtaining high-resolution time and depth migration seismic data in the time and buildup velocity models using a combination of modern procedures for digital processing of seismic events;

- Creating a seismic model that delineates zones of alteration in elastic properties (amplitude, frequency, etc.) associated with geological heterogeneity and the zones of mineralization of copper sandstones;
- Conducting structural and dynamic interpretations of seismic data and creating a seismogeological model of copper mineralization in Zhezkazgan, including structural mapping of hidden promising ore areas, seismic facies analysis, delineation of ore-bearing rocks and the boundaries of ore deposits, and identification of ore-controlling tectonic faults associated with mineralization of the zones of decompression, crushing, and fracturing;
- Developing additional geophysical criteria and factors for identification and localization of copper mineralization and ore bodies of copper sandstones in Zhezkazgan for future planning and management of mining of raw minerals.

2. Materials and Methods

2.1. Benchmarking Data Specifications

Three-dimensional seismic exploration has been carried out at local explored areas of the Zhilandy group of deposits in the Zhezkazgan copper ore region. This region includes the Zhezkazgan deposit, a deposit with exceptional reserve size, and a large number of small copper deposits of the Zhilandy group (Itauz, Saryoba, Kipshakpai, Karashoshak, and Zhartas, etc.) formed within the periphery of the Zhezkazgan syncline [28,29] (Figure 1).

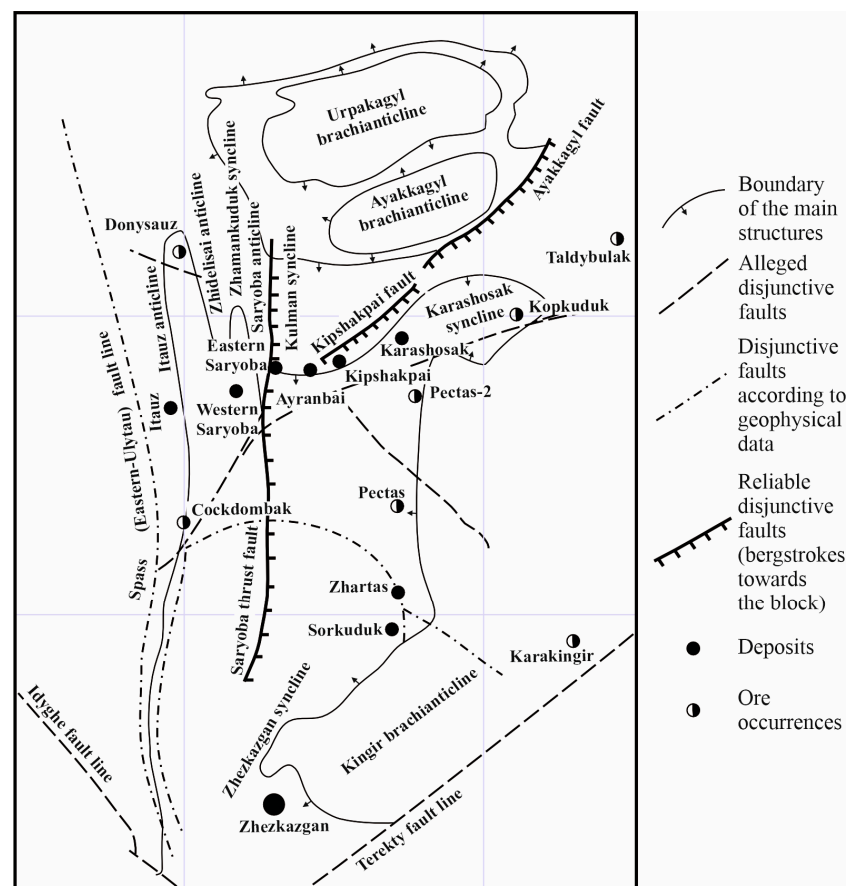


Figure 1. Layout of the deposits and ore manifestation of the Zhezkazgan region.

The geological cross section of the sequences in Zhezkazgan ore district starts with Lower Devonian sediments; volcanic rocks of heterogenous composition interbedded with red sandstones. The terrigenous and carbonate deposits are updip; red sandstones and

conglomerates of Mid Devonian, silicified limestones, sandstones, and marls of the Low–Mid Carboniferous. The total thickness of these sediments is 1500 m. The productive Zhezkazgan suite of the Mid–Upper Carboniferous with a thickness of approx. 700 m is conformably bedded. The cross section of this suite comprises rhythmically alternating gray and red sandstones and siltstones with subordinate interlayers of conglomerates. The Zhezkazgan suite is overlapped by raspberry-red sandstones, argillites, limestones, and Lower Permian marls. In some places, the Paleozoic deposits are covered by the sediments of variegated, weakly cemented sandstones, clays, sands, and pebbles of the Paleogene and Neogene (Figure 2).

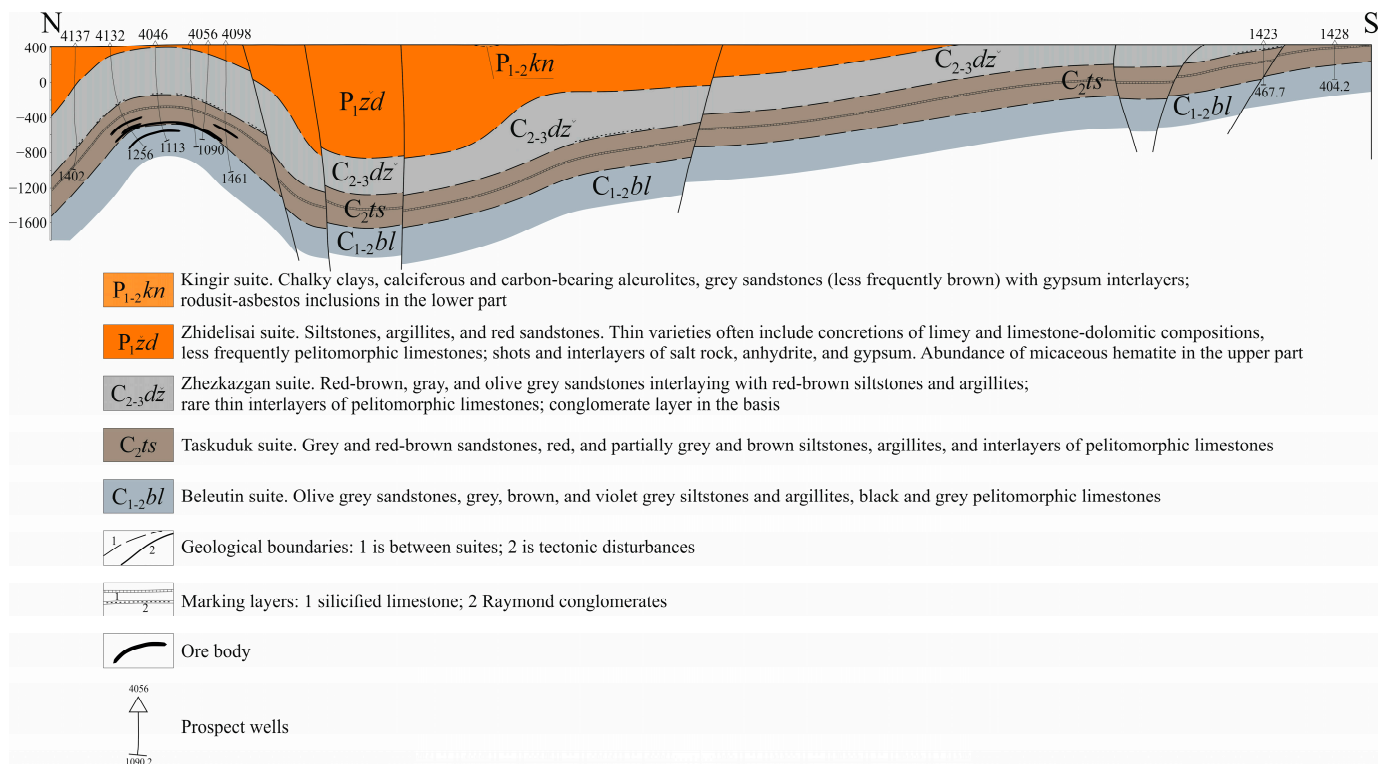


Figure 2. Schematic geological sections of the Zhezkazgan ore region (based on Zhezkazgan Geological Expedition findings).

The geological structure of the area is complicated by a sequence of tectonic faults. The largest is the Central Saryoba outburst-shear, which is located between the Western and Eastern Saryoba deposits. The small faults have been mapped in the field [30].

The deposits of the Zhilandinskaya group are spatially confined to the sediments of the upper member of the Beleuty /Lower–Middle Carboniferous layers of the Beleuty suite (C1sbl2 III) and the lower part of the Taskuduk suite (C2ts). Three horizons of ore-bearing sandstones have been identified in the upper member of the Beleuty layers: Kopkudusky (# 1v), Zhilandy (# 1b), intermediate horizon (# 1a), and Taskuduk ore-bearing horizon (# 1) are at the base of the Taskuduk suite. The horizons located stratigraphically updip contain almost no gray-colored rocks and are represented entirely by red-colored facies. No pay ore mineralization has been established.

The most productive are the Taskuduk and Zhilandy horizons, composed of layers of gray fine-grained sandstones interbedded with gray and less often red siltstones, intraformational conglomerates, and brown sandstones. Sharp facies transitions are quite often observed. There are 2–4 layers of medium-grained dark gray sandstones and conglomerates with a high content of organic matter that are often observed in the section of the ore-bearing horizons.

The internal structure of the deposit is determined by its confinement to a sequence of transverse and box folds, flexures, and faults of a north-northeast trend. The flexures and faults are accompanied by zones of crushing and brecciation. The tectonic breccias are cemented by quartz, barite, and calcite. The ore bodies inside the layers of gray sandstones are of various shapes (isometric, lenticular, and ribbon-like). The boundaries between the ore bodies and barren sandstones are both gradual and sharp [31–33]. The ground mass of ore components was deposited in the first phase and formed disseminated ores. The same minerals had been deposited in the second phase; however, mineralization was concentrated in the veins and cracks. The deposits have a clear vertical zoning, with clearly distinguished zones of oxidation, secondary sulfide enrichment, and primary sulfide ores [34].

A review and analysis of a previously conducted seismic exploration performed by field crews of Zhezkazgangeologiya JSC within the Zhezkazgan syncline and border areas has shown that seismogeological conditions of the study area are favorable for detailed seismic exploration. The Zhezkazgan Depression contains certain common features with marginal trough-type structures and, in particular, with an oil-bearing Pre-Ural Depression in terms of its structural position, basement immersion depth, tectonics, and composition. The distinctive signs of oil and gas potential in the form of hydrocarbon gas manifestations and accumulations of droplet-liquid oil have been established within the depression.

The target reference horizons linked to the base of carbonate sediments of the Lower Carboniferous (R^{III}), the bottom of Mid-Viséan sediments (R^{II}), the base of the Taskuduk suite (R^I), and the base of salt-bearing Permian (R^I) have been traced within the Zhezkazgan depression based on reflection of seismic sections obtained in different years. The faults of various orders have been confidently traced within the area by identifying areas with gaps in horizon correlation, vertical displacement of the same boundaries and the presence of diffracted waves.

The velocity characteristics of the rocks of the entire section are presented as follows, based on available historical seismic data: The uppermost part of the section is represented by a very loose low velocity layer (LVL). Its thickness varies from 2–3 m to 25–35 m. The velocity in the LVL fluctuates between 500 and 1700 m/s. Stratigraphically, the low velocity layer corresponds to Quaternary system sediments. A layer of variegated clays of the Cenozoic age with a thickness of 20–60 m is traced below the LVL. The values of formation velocity are 1500–2400 m/s. The formation velocities of the weathering crust of various rocks vary between 2200 and 2700 m/s.

The Low Carboniferous sediments are characterized by large velocity differentiation (from 3500 to 6500 m/s). The Tournaisian formations are noted for increased velocity values of 5000–6000 m/s due to silicified limestone beds. The velocities of the Viséan sediments vary within 4000–6000 m/s with maximum velocity values apparently corresponding to the distribution zones of dense limestones, dolomites, and anhydrites. The red-colored terrigenous strata of the Upper–Middle Carboniferous are characterized by velocities of 4000–5500 m/s. An overwhelming majority of the Zhezkazgan suite has a velocity of 4700–5000 m/s. According to seismic well logging data for Yu-29, the formation velocity is 4600 m/s, and for Yu-24—4500–4650 m/s. The Permian sediments have quite different velocities in various parts of the basin. The red-colored formations of the Zhidelisay suite and the light marls, sandstones, and argillites of the lower parts of the Kingir suite have a velocity of 2600 to 4000 m/s (wells Yu-29, Yu-2). The halogen formations widespread in the Zhidelisay and lower parts of the Kingir suites are characterized by a significant range of velocities, fluctuating between 3500 to 5000 m/s (well Yu-29). The upper part of the Kingir suite (dark marls, limestones, sandstones) has higher velocities in relation to the underlying red-colored deposits equal to 5000–5500 m/s (wells Yu-30, Yu-17, etc.).

An overall velocity model has been developed demonstrating a sharp increase in the velocities in the upper part of the cross section up to 5600 m/s. The sharpest velocity boundaries are those at the base of loose sediments, the base of Upper Tournaisian rocks, the top of Upper Famennian limestones substages, and separate horizons within Famennian production pay. The mode of occurrence of various strata is the essential factor for the reflected waves method. The heterogeneity of the upper part of the cross section (from 100–150 to 1000 m/s) and the resulting significant horizontal velocity gradients is an unfavorable factor impacting the accuracy of velocity determination. The causes of such heterogeneities may be different; in particular, the heterogeneities developed due to a drastic difference in the velocity of Permian sediments and their specific occurrence. To a certain extent the nature of alteration of efficient velocities corresponds to the nature of alteration in boundary velocities along the top of Paleozoic sediments.

2.2. Methodology

The methodology for 3D reflection of seismic exploration at ore deposits in Kazakhstan was tested and evaluated using the Pektas, Donyzauz, and Western Saryoba areas of the Zhilandy ore deposit of the Zhezkazgan ore region. A fairly substantial volume of seismic data has been accumulated here within recent decades, with various methods and modifications (DSS (Deep Seismic Sounding), CRM (Correlation Refraction Method), RSS (Reflection Seismic Survey), ECWM (Earthquake Converted-Wave Method), CDP (Common Depth Point)) in both profile and aerial options being applied [35–38].

The following geological and structural features of the experimental sites are favorable seismogeological factors for the detailed study of ore horizons:

1. The main ore-bearing horizon is the Taskuduk horizon of the Taskuduk suite; it is the most saturated with pay ore mineralization. The next most saturated is the Zhilandy horizon, which is on the sediments of the Beleuty layers of the Low Carboniferous (C1sbl). The cross section of ore-bearing strata is distinguished by fine medium-grained sandstones, Raymund and intraformational conglomerates, gravelites, siltstones, and silty sandstones;
2. The pay ores were identified in gray sandstones with layers of limestones with fauna. The Taskuduk horizon of the suite is represented by a pack of gray fine-grained sandstones interbedded with frequently picking gray, less frequently red, siltstones, gray intraformational conglomerates, and brown sandstones. The Zhilandy horizon of the Beleuty layers has a geological section similar to Taskuduk;
3. There are numerous small cracks (ranging from thread-like to 1–2 cm) filled with calcite and disseminated ore minerals in the Taskuduk and Zhilandy horizons. The pay ore mineralization in the areas of significant development of thread-like cracks has a vein-disseminated character;
4. The ores in these horizons have the following properties:
 - Ore mineralization tends to be in medium- and coarse-grained sandstones of gray and dark gray color (often enriched with carbonized organics), mainly on calcareous cement;
 - Barren layers are usually represented by plastic siltstones and fine-grained sandstones, characterized by a weak degree of crushing;
 - The confinement of ground mass of ores to gray-colored medium-grained sandstones is substantiated by its fragility and high porosity;
5. Structural control of mineralization is clearly expressed: more intense mineralization is confined to the zones of rock fragmentation on the flanks of the folds and to the zones of flat sloping intra- and inter-layer faults.

A detailed 3D seismic exploration has been carried out at approved locations of known deposits of copper sandstones in order to study the features of seismic events and obtain detailed data on the structural and stratigraphic composition of ore-hosting strata, identify kinematic and dynamic parameters of wave field characteristic of ore horizons and ore bodies associated with textural and structural heterogeneities, and verify significant copper targets and create an objective model of ore horizons.

The specific features of the composition and structure of ore deposits that make them different from many other sulfide deposits are crucial for substantiation and approval of prospecting methods at Zhezkazgan-type deposits. These ores are dominated by a triad of copper sulfides—chalcocite, chalcopyrite, and bornite—and pyrite is almost untraceable. As a result, many electrical methods that are often successfully used for prospecting for pyrite and porphyry deposits are ineffective for copper sandstones. In this case, the localization of copper sandstones (in the form of formations or band deposits) within permeable horizons is crucial. The copper concentrations without any delineation sharply decrease to Clarke values in overlying and underlying deposits (usually much less permeable).

A full-scale 3D seismic survey was carried out at Pektas, Donyzauz, and Western Sayoba. An example of the seismic survey in Saryoba is shown in Figure 3. The shot-receiver layout was designed based on the analysis of the area's geological composition, velocity properties, and technical and technological conditions for field operations. The experimental methodology allowed us to substantiate acquisition parameters focused on the target horizons with an increased level of high-frequency components of the seismic record. A cableless SCOUT seismic recorder system was used to perform seismic exploration with the 3D source–receiver layout. To calculate seismic datum statics and investigate Low Velocity Layer (LVL) parameters, the uphole survey was carried out with the uphole regular grid being implemented on every area of study (Figure 3).

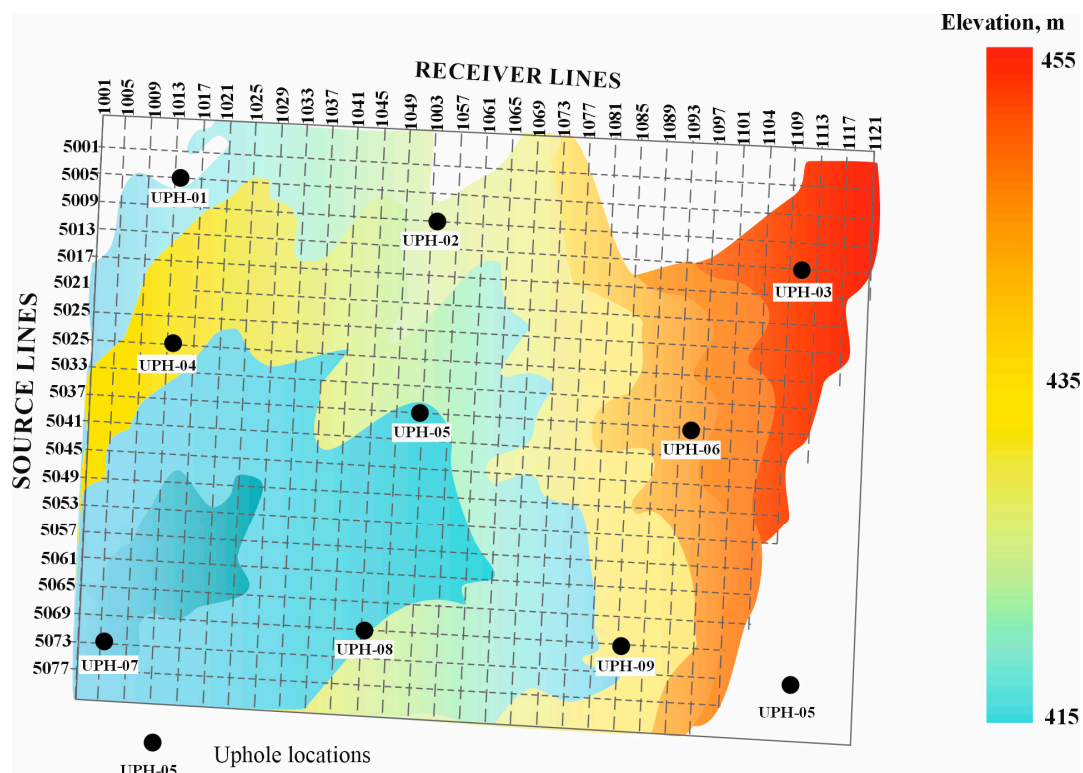


Figure 3. Saryoba area. Elevation map and layout of seismic acquisition survey.

The 3D survey geophysical pattern tests and survey design were assessed using MESA Core 10.4 software, taking into account the real geological situation and onsite infrastructure.

High-quality field seismic data were acquired due to: prompt adjustment of real receiving points (RPs) and shot points (SPs) depending on surface conditions; offsets of compensation SPs; calculation of theoretical fold and bin attributes; download of theoretical, approved and laid, drilled and worked-out RPs and SPs into Field Geo Data Base software (version 2) and build-up of performance progress maps; regular development and verification of final SPS files for office processing and delivery to a stationary computing center for further data processing.

The processing of seismic data acquired at Pektas, Donyzauz, and Western Sayoba was performed using SeisSpace (Halliburton) software, version 5000.8.2.4. The processing sequence and parameters for each area were selected and optimized using a wide range of modules. Each area had a dedicated processing sequence due to the differences in acquisition patterns. The variety of mathematical procedures used during data processing ensured the development of an optimal seismic data processing sequence, allowing us to preserve kinematic and dynamic features of the wave field for further identification and tracking of target horizons; ensure reliable structural buildups; process and link the data recorded using VSP methods; achieve high resolution and accuracy of detailed buildups; and increase the reliability of structural buildups of deep target horizons due to maximum exclusion of interference from overlying geological targets [39].

The time and depth data volumes were produced for each area, along with velocity models delivered from velocity analysis during processing.

There were two interdependent approaches used during interpretation:

- Geophysical approach—determination of structural models and seismogeological parameters based on seismic data;
- Geological approach—prediction of lithological-petrophysical, genetic, and other geological properties based on seismic and drilling data.

The first approach involved mathematical seismic modeling, using calculation of wave fields for theoretical models displaying features of the geological section (Figure 4). This allowed us to obtain a seismic and geologic justification for kinematic and dynamic features of seismic waves; apply seismic attributes to justify geological targets; establish correlation between seismic waves and boundaries of the geological section (“stratigraphic matching”); and select optimal parameters for certain interpretation procedures: inversion, wavelet processing, stratigraphic deconvolution, etc.

The geological interpretation of seismic data was carried out using GeoGraphix Discovery 2019.4 software and additional modules for dynamic attributes calculation. Benchmarking data interpretation was carried out in two stages: structural modeling and seismic attribute analysis.

Pre-stack time migration (PSTM) and pre-stack depth migration (PSDM) data were used as the basis for structural interpretation. The PSTM and PSDM data cubes were used to correlate horizons in time and depth and build isochrone and structural maps (Figure 5). The averaged time–depth dependence obtained from the pre-stack time migration velocity model was used to convert isochrone maps into structural maps (Table 1).

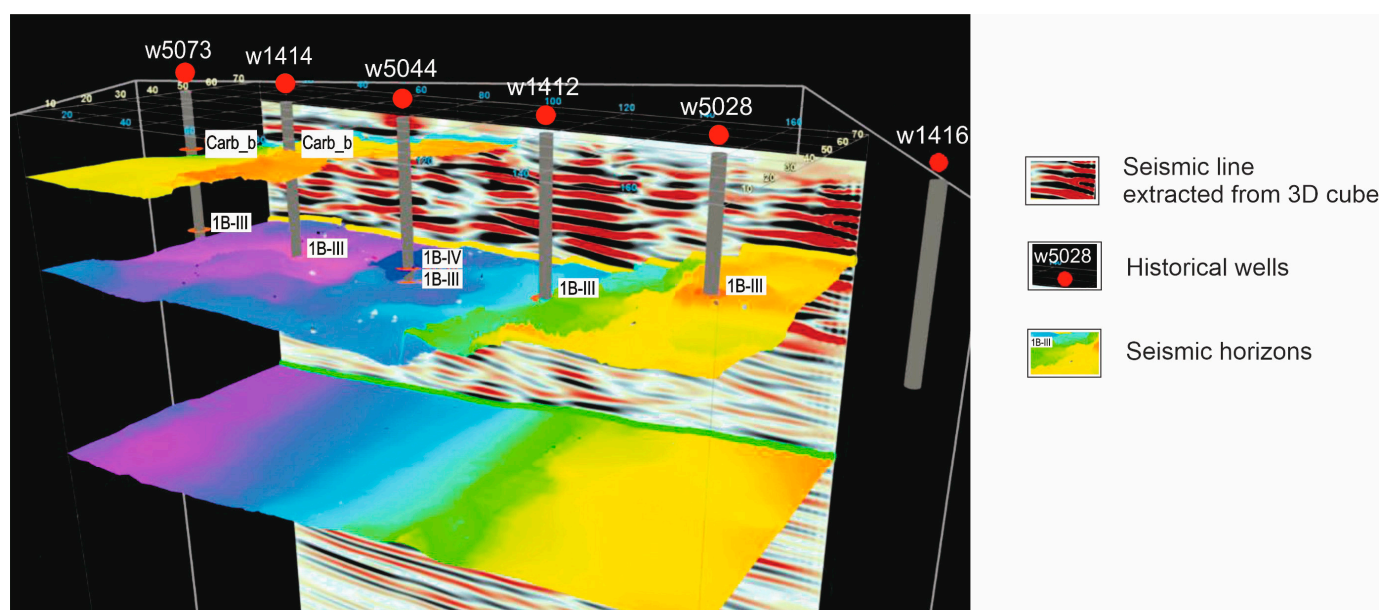


Figure 4. Pektas area. Three-dimensional image of model of buildup reflective boundaries.

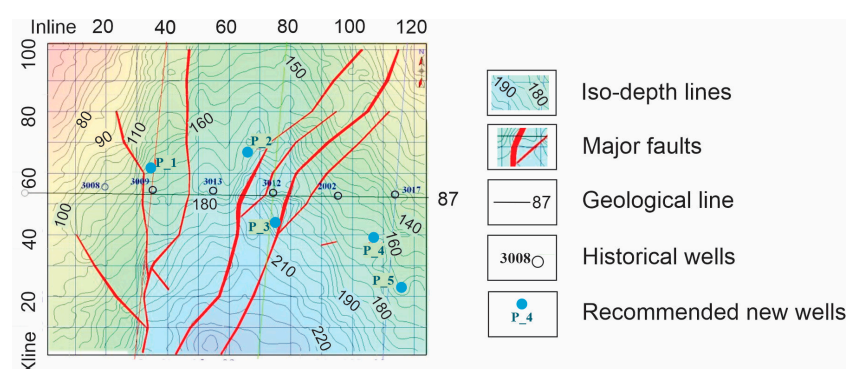


Figure 5. Donyzauz area. Kopkuduk ore pay horizon structural map.

Table 1. Time–depth dependence based on processing data.

Vertical Depth	Two-Way Time	Well ID	Vertical Depth	Two-Way Time	Well ID	Vertical Depth	Two-Way Time	Well ID
0	0	3009	0	0	3012	0	0	3017
60	41	3009	132	69	3012	151	64	3017
76.2	53	3009	161.6	85	3012	200	131	3017
175	157	3009	232	183	3012	289	170	3017
265	211	3009	322	228	3012	556	302	3017
743	348	3009	1149	459	3012	1625	584	3017
1440	494	3009	2052	701	3012	2196	739	3017
2277	698	3009	5996	1990	3012	6030	1994	3017
5720	1889	3009	9770	3000	3012	9776	3000	3017
9780	3000	3009			3012			

The attribute interpretation included amplitude attributes characterizing variability of lithology; statistical attributes responsible for variability of bed thickness; and attributes defined by wavelet analysis showing lithofacies alterations. Figure 6 shows examples of some amplitude attributes—“sweetness” (wavelet amplitude variations), coherence (tectonics), and seismic facies attributes (wavelet shape variations) for the studied areas. Every particular attribute provided valuable additional information for modeling.

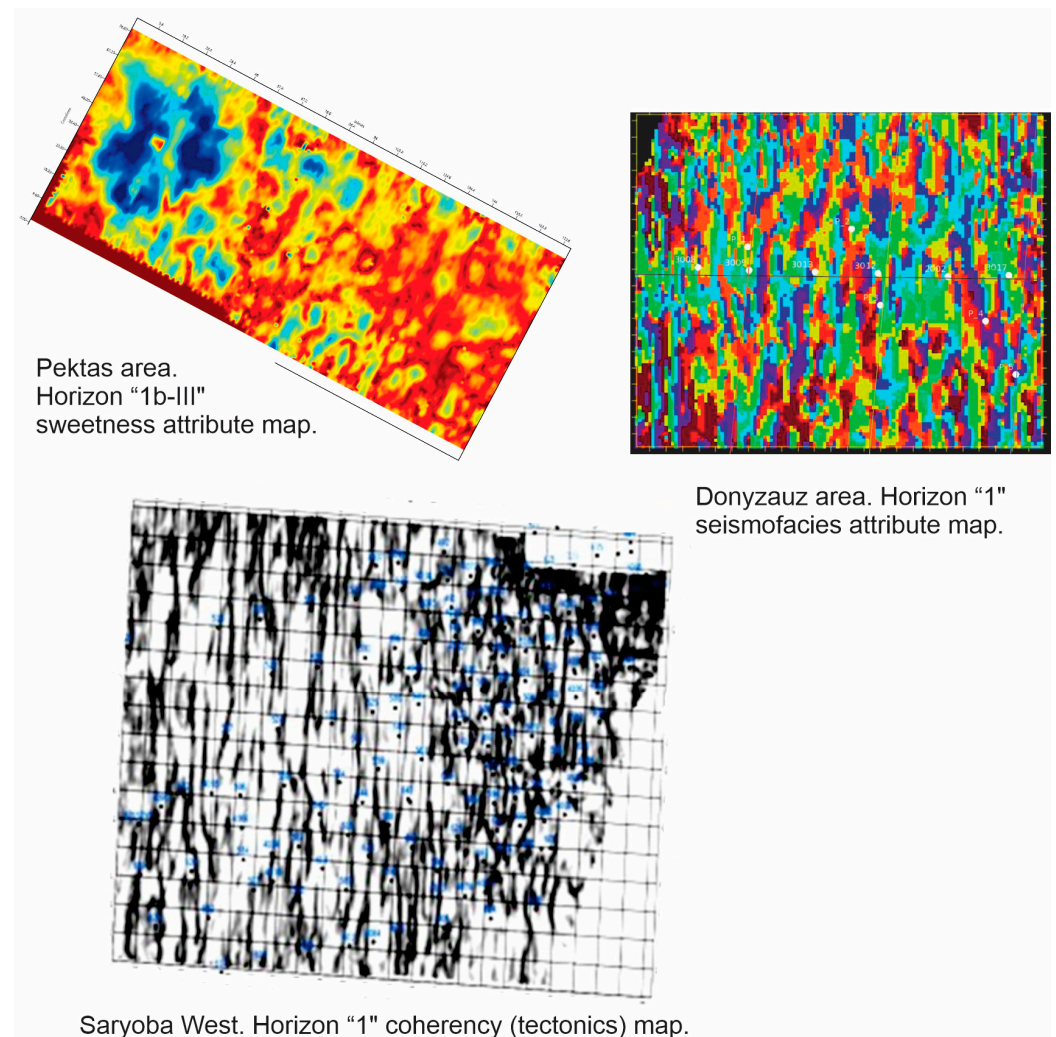


Figure 6. Examples of attribute analysis maps. Explanation is given in the text.

The structural modeling and attribute interpretation resulted in the following:

- Structural modeling (structural maps and contours of geological bodies) for experimental areas;
- Picking of faults and cracks along the discontinuities of synphase axes on vertical and horizontal time slices, as well as along the cube of tectonic faults derived from coherence attributes;
- Production horizons were traced along inline and crossline seismic lines with a 100×100 m grid;
- The dynamic parameters for detailed study of the lithology of the section were analyzed.

3. Results

In general, the seismic data clearly outline the composite structure of geological boundaries across the entire area of each section, especially in the upper inter-well section which cannot be assessed using well drilling data.

The seismic wave field within the target interval at 0–200 ms is characterized by the composite nature of the reflections, apparently due to the shortcomings of the field data acquisition technique (the reflection events are discontinuous; the correlation of reflecting boundaries is complicated by interference between different seismic waves), which, un-

fortunately, could not be attenuated during seismic data processing, thus excluding the possibility of definite correlation of the reflectors in this time interval.

The seismic wave field of the reflection complex at the values exceeding 180–200 ms differs sharply from the wave pattern associated with upper sediments. The reflecting boundaries were well traced and the wave pattern is represented by a sequence of reflections showing conformable occurrence at depths greater than 300 m. The presence of reflections on time sections is completely determined by the behavior of reflecting boundaries, characterized by dynamic expression and traceability within the entire study area. To a lesser extent, the poor quality of seismic data is associated with dipping events which do not exceed 10–12° within the study area, as well as with the heterogeneity of velocity properties of the upper part of the section studied during the uphole survey.

Analysis of the wave field of the time migration cube by target horizons showed a good correlation between amplitudes and geological data. Comparing the geological map of the Pektas site and slices of the time-migrated data volume (PSTM), it was found that linear forms of amplitude anomalies of seismic exploration coincided with submeridional geological sediments (Figure 7).

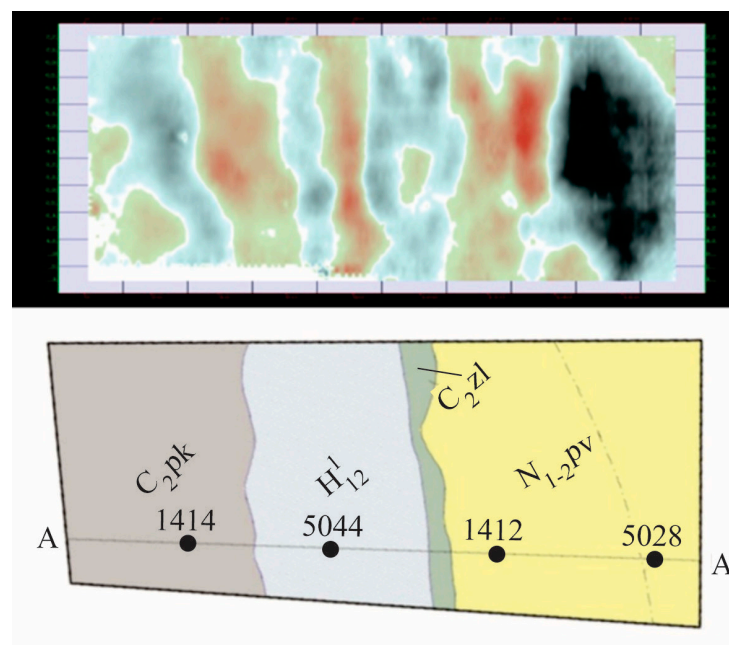


Figure 7. Pektas area. Comparison of PSTM time slice and geologic map.

The seismic lines coinciding with coordinates of geological sections together with existing well information were extracted from the seismic data. The reflectors and geological boundaries were included based on the changes in lithology of the boreholes marked on seismic lines and velocity laws obtained during data processing.

Depth seismic data were obtained at the Donyzauz site after pre-stack depth migration (PSDM) and were used for separate correlation of the outlined horizons 1 (top of Taskuduk horizon), 1-I, 1-II, and 1-III (ore deposit, cut-off grade lead ores), 1-b (top of Zhilandy horizon), and 1-v (top of Kopkuduk horizon).

Moreover, according to the depth migration data, the flexures that occurred in the seismic wave field were used for delineation of three lens-shaped targets in cross section in the vicinity of the boreholes and in the intervals of ore occurrence. The targets were conventionally named Target-I, Target-II, and Target-III (Figure 8).

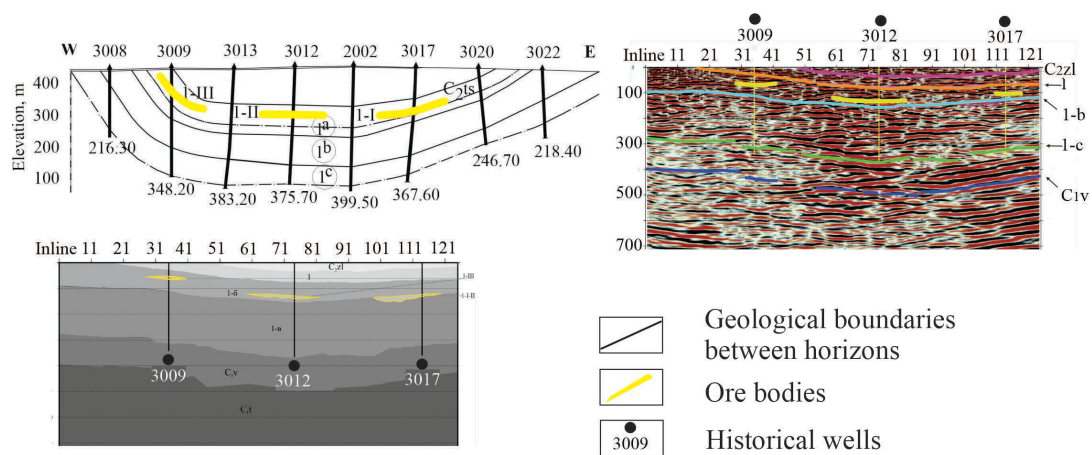


Figure 8. Donyzauz area. Interpretation of seismic data along seismic line 87.

The image of the geological section built according to drilling data shows that the geological sediments along seismic line 87 are synclinal with a sharp increase in the angles of incidence in stratigraphic sequences at the edges of the area being studied.

However, seismic exploration data show more flat bedding for shallow horizons ($20\text{--}22^\circ$), as well as a block structure of the section with tectonic elements.

The sections (inlines—sections along receiver lines, and crosslines—sections along shot lines) show a qualitative picture of the seismic wave field used to delineate fault zones and fracturing areas [40]. Such zones can potentially be confined to hydrothermal sources (channels), which fed the ore bodies in the past. The seismic section along geological profile XXXII of the Pektas site clearly shows the presence of deep faults, which are apparently the channels of intrusion of ore solutions from deep magmatic centers to overlying layers (Figure 9).

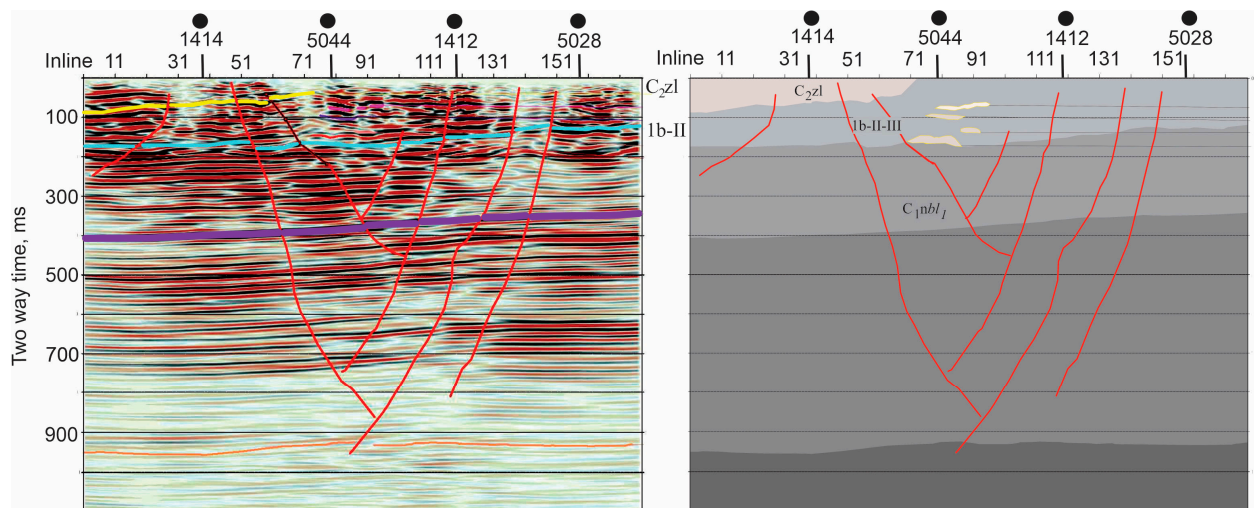
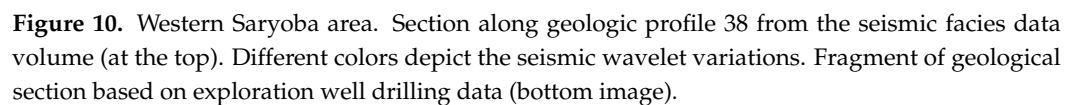


Figure 9. Pektas site. Interpretation of seismic data along profile XXXII.

The facies analysis was carried out by applying a neural network algorithm, according to seismic signal shape and using the interval approach. A seismic facies classification of wave field pending signal shape was performed at Western Saryoba site for the first (1) ore horizon within the interval of horizon I-II (3 ms above horizon I) (Figure 10).



During attribute interpretation, the seismic facies attribute allowed us to analyze the alteration of seismic wavelets along target horizons. This refers to lithofacies' composition of ore-bearing horizons and parameters of the ore bodies. Similar lenticular targets were found between existing wells and traced at the Pektas site. These targets were delineated along seismic sections in the vicinity of old borehole 5044, which drilled down to ore horizons 1B-IV, 1B-III in the Beleuty horizon of the Serpukhovian stage. Such targets were considered as structurally favorable for the concentration of copper mineralization. The stratigraphic reference is based on a depth-velocity model derived from data processing. In total, five targets were identified in Upper Beleuty systems in the vicinity of borehole 5044. According to existing drilling data, ore manifestations at horizon 1B-IV were drilled by borehole 5044 only. No targets have been verified by old neighboring boreholes 1414 and 1412, which were drilled northwest and southeast of borehole 5044, respectively. Figure 11 shows fragments of a structural map with lens-shaped ore targets highlighted. For example,

target I is located at absolute elevations of 210–215 m and is extended NW–SE with a sheet-like planning structure.

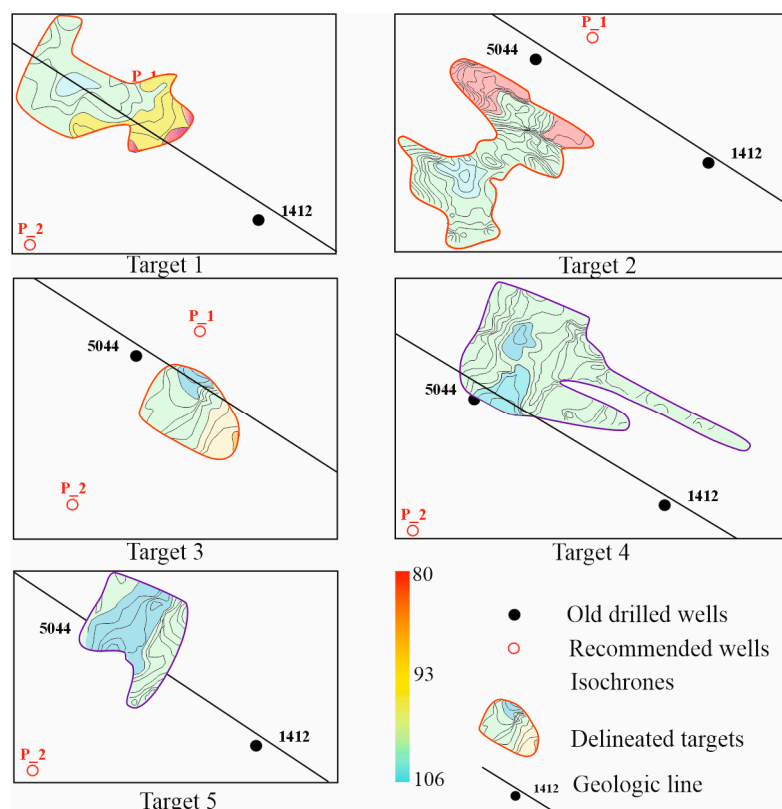


Figure 11. Pektas site. Identification of lenticular targets of ore bodies according to 3D seismic isochrones.

The seismic facies distribution maps were calculated for selected targets. Seismic signal variations can be interpreted as changes in lithology and presence of mineralization. Two new well locations to 600 m deep have been recommended based on the anomalies in seismic facies and the delineation of lenticular targets identified in the seismic wave field. The contours of three prospective targets were delineated in the Donyzauz area known for more complicated geology. Prospective targets were structurally delineated according to the feature of lenticular targets in the section, confined to flexures and discovered along ore-bearing horizons. In total, five exploration wells drilled to 500 m depth have been recommended along the contours of ore bodies identified in the seismic wave field (Figure 12).

The contours of eight prospective targets—aa, bb, cc, dd, ee, ff, gg, and hh—have been identified at the Western Saryoba site located within the boundaries of the deposit being mined. The targets cc and gg were identified in two spatial units in the same depth interval referring to tracked marker horizons (Figure 13). The sizes of all identified targets are summarized in Table 2.

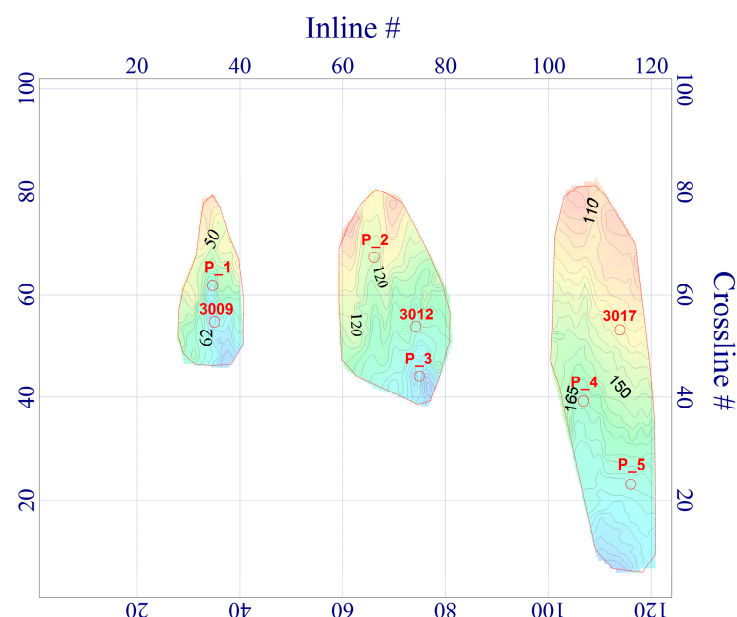


Figure 12. Donyzauz site. Structural maps of horizons of identified ore targets (depth migration data). Contour 1-III.

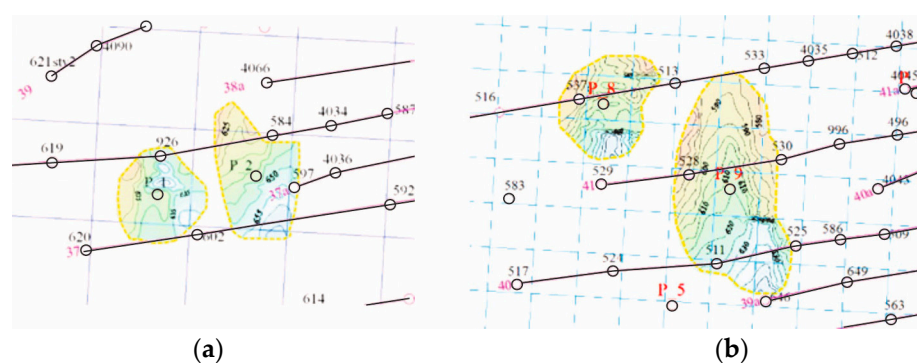


Figure 13. West Saryoba area. Examples of lenticular ore bodies identified according to seismic data: (a) target—cc; (b) target—gg. The legend is the same as for previous Figures.

Table 2. Sizes of targets identified according to seismic exploration data in Western Saryoba area.

Target	Size, sq.m.
aa	106,751.11
bb	94,421.92
cc	27,013.41
cc	35,163.47
dd	119,286.88
ee	52,929.48
ff	35,439.22
gg	38,053.36
gg	95,390.13
hh	42,191.41

It is recommended to drill ten exploration wells (P_1–P_10) to 550–820 m depth along the contours of the ore bodies identified in the seismic wave field.

4. Discussion

As a result of reflection 3D seismic data interpretation, isochron and structural maps have been compiled at a scale of 1:5000 corresponding to the base of the Pokrovsky (C2pk), Zlatoust (C2zt), and Taskuduk (C2ts) horizons. The deep-lying stratigraphic horizons of lower sections of the Carboniferous system, large faults, and micro-tectonic disturbances (small faults and cracks) are clearly distinguished by seismic sections.

The analysis of seismic data and extensive application of drilling data allowed to identify spatial extent of ore-bearing horizons in the Upper Beleuty and Taskuduk suite layers of the lower section of the Carboniferous system, where exploration drilling had been earlier performed. The top of silicified limestones (C2pk), ore-bearing greenish-gray sandstones in the Upper Beleuty layers (1B-IV, 1B-III), and the top of the Lower Beleuty layers are clearly visible as reflecting horizons in seismic wave fields (C1nbl1). Taking into account historical drilling data, the localization of target horizons and ore bodies was delineated.

The subsoil use company has drilled five verification wells at new targets out of 17 (seventeen) recommended wells and copper mineralization has been confirmed for all drilled wells.

5. Conclusions

Application of a 3D reflection seismic method with modern processing and interpretation capabilities allowed us to extend the instrumental scope used for copper sandstone mining of the Zhezkazgan area in Central Kazakhstan.

The recommendations for drilling verification wells has been issued based on the analysis of structural maps and attribute maps and taking into account the geological modeling.

At the stage of dynamic interpretation, the seismic facies attribute allowed us to analyze the alteration of the shape of seismic wavelets along target horizons linked to the lithofacies feature composition of ore-bearing horizons and parameters of ore targets.

We assessed the possibility of using high-density wide-azimuth 3D seismic exploration along with numerous methodological and technical tools, including methods of seismic data processing, to analyze the geological section. The technologies for extracting data regarding both the structural forms of the targets being studied and the fine internal heterogeneity of the rocks comprising those targets (lithological heterogeneity, filtration-capacitive properties, fluid saturation, fracturing, etc.) are extensively applied for existing domestic and international methods of field seismic data processing and interpretation.

Seismic exploration is characterized by high resolution, technological effectiveness, and an outstanding volume of data obtained. The use of modern geodata systems for precise positioning in the field, processing in time and depth domains, and geological interpretation of anomalous parts of the sections in relation to ore targets will assist identification of mineral deposits and prospective targets.

The novelty of the study is its development of a technology for customized processing and interpretation of the results of high-resolution reflection seismic methods intended for stratiform ore objects in Zhezkazgan ore region. Attribute analysis of seismic wave fields (dynamic interpretation) was implemented to outline the ore-controlling horizons and ore bodies, their spatial positions, and determination of their properties and parameters. Seismic facies analysis using neural network algorithms was used to model the litho-facial patterns and rock properties. As a result, successful recommendations for new exploration well positions were developed.

This methodology is recommended for testing ore objects of different genetic types.

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