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Three-dimensional geological and geophysical model of the Myutenbay gold deposit, Muruntau ore field, Uzbekistan

Akram GOIPOV[1, *], Zbigniew MAŁOLEPSZY[2], Maksud ISOKOV[1], Madumar TURUGUNALIEV[1], Shokir AKHMADOV[1], Zainiddinkhon MUSAKHONOV[1] and Asliddin ESHMURODOV[3]

[1] Ministry of Mining and Geology of the Republic of Uzbekistan, State Institution "Institute of Mineral Resources", Olimar 4, Tashkent, Uzbekistan; ORCID: 0000-0003-1720-2998 [A.G.], 0000-0003-3769-3691 [M.I.], 0009-0000-8784-537 [M.T.], 0000-0002-8983-9763 [S.A.], 0009-0004-7555-0629 [Z.M.]

[2] Polish Geological Institute – National Research Institute, Upper Silesian Branch, Królowej Jadwigi 1, 41-200 Sosnowiec Poland; ORCID: 0000-0003-4465-2038

[3] Ministry of Mining and Geology of the Republic of Uzbekistan, State Institution "Institute of Geology and Geophysics", Tashkent, Uzbekistan; ORCID: 0009-0008-3597-8443

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A three-dimensional geomagnetic model of the Myutenbay deposit has, been created in the *Geosoft Oasis Montaj* program, based on digital modelling of magnetic exploration data previously carried out at the site, and using the petrophysical characteristics of the ore-bearing rocks. A three-dimensional model of the ore bodies was created in *Micromine* software using information from boreholes obtained during the exploration stage of the deposit. The shape of the ore bodies and that of the three-dimensional magnetically disturbing objects in the geomagnetic model were established as identical. A two-dimensional geomagnetic model clearly shows the fault zone, the folded rocks of the Murun suite and the orientation of the ore bodies within the Kosmanachi ore-bearing strata. The mapped magnetic anomalies reflect zones of progressive regional metamorphism, which collectively determined the location of gold ore mineralization. Zones of correlatable magnetic maxima reflect the development of pyrite-pyrrhotite vein-disseminated mineralization, related to areas of gold-producing ore body.

Key words: deposits, gold, fault, magnetic susceptibility, density, geomagnetic model, Murun suite, Kosmanachi ore-bearing strata.

INTRODUCTION

Quantitative interpretation of geophysical data is challenging. Due to the superposition principle inherent in magnetic fields, it is almost impossible to separate the observed field into its components with a sufficient degree of reliability to enable unambiguous quantitative calculation of the effect of a specific body. In addition, all calculations are carried out with average fixed values of density and magnetization. The orientation of the magnetization vector and its magnitude are often only assumed, while the magnetic properties of the body directly depend on the content of the magnetic fraction, which is also usually unknown. These factors reduce the results of these quantitative calculations to showing a range of possible interpretations, and in no case can there be proof of the correctness of the model selected. This is illustrated by the way that for the same observed magnetic field, various researchers have proposed different, and sometimes mutually contradictory, models of the deep geological structure, when using the results of quantitative interpretation by the selection method. Aware of these limitations, in this paper we provide a qualitative interpretation on the basis of a comprehensive analysis of all available geological and geophysical information, in this comparative analysis of ore body shape using geomagnetic modelling to identify closed mineralization.

GEOLOGICAL SETTING

The territory of the Southern Tien Shan, extending through Northern China, Kyrgyzstan, Tajikistan, Uzbekistan and then to

* Corresponding author, e-mail: akram.goipov7@gmail.com
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the Urals, is one of the most important gold belts, hosting numerous super-large and large gold deposits of world class, such as the Muruntau deposit. Muruntau in the Central Kyzyl-Kum desert, with past production of ~3,000 metric tonnes (t) Au since 1967, a present annual production of ~60 t Au, and large remaining resources, is the world's largest epigenetic Au deposit (Seltmann et al., 2020). Other deposits include the Daugyztau deposit with medium reserves (Yakubchuk et al., 2002), and the Jilau deposit, which is a shear-zone, gold-bearing quartz vein deposit with total resources of ~54 million tonnes at a gold grade of 1.12 g/t, located in the Republic of Tajikistan (Cole et al., 2000). The Sawayaerdun gold deposit hosted by Carboniferous metasedimentary rocks is considered to be the largest Muruntau-type gold deposit in the Chinese Tian Shan metallogenic belt (Chen et al., 2012).

In the Republic of Uzbekistan, the territory of the Southern Tien Shan covers the western end of the Southern Tien Shan orogenic system and its boundaries include the western end of the Nurata ridge and the Central Kyzyl-Kum uplands.

The Southern Tien Shan orogenic system in general is a convex arc to the south, which in the west, outside the study area, turns sharply to the north, passing into the Ural orogenic region, with its main structural elements exhibiting clear linearity and general approximately E–W elongation (Fig. 1).

This reflects the existence of a system of deep (regional) faults dividing the orogenic series of parallel elongated blocks with characteristic features as regards stratigraphic section, tectonic/structural and magmatic style. This allowed Pyatkov et al. (1964) to identify five structural/stratigraphic subzones within the Kyzyl-Kum Desert for the first time. Subsequent study by Bukharin et al. (1985) refined and supplemented this zonation, identifying 12 structural-stratigraphic zones in the Southern Tien Shan. Structural-stratigraphic subzones were identified within each zone.

Gold ore deposits of the Kyzyl-Kum and Nurata regions of Uzbekistan (Fig. 1) are confined to the Southern Tien Shan orogenic belt. They are located in black shales (Muruntau, Myutenbay), carbonate, terrigenous and volcanic rocks (Kokpatas, Balpantau), and intrusive rocks (Zarmitan zone) (Koneev et al., 2019).

The Muruntau deposit is a giant metamorphogenic-orogenic gold deposit. It was formed through the mobilization of

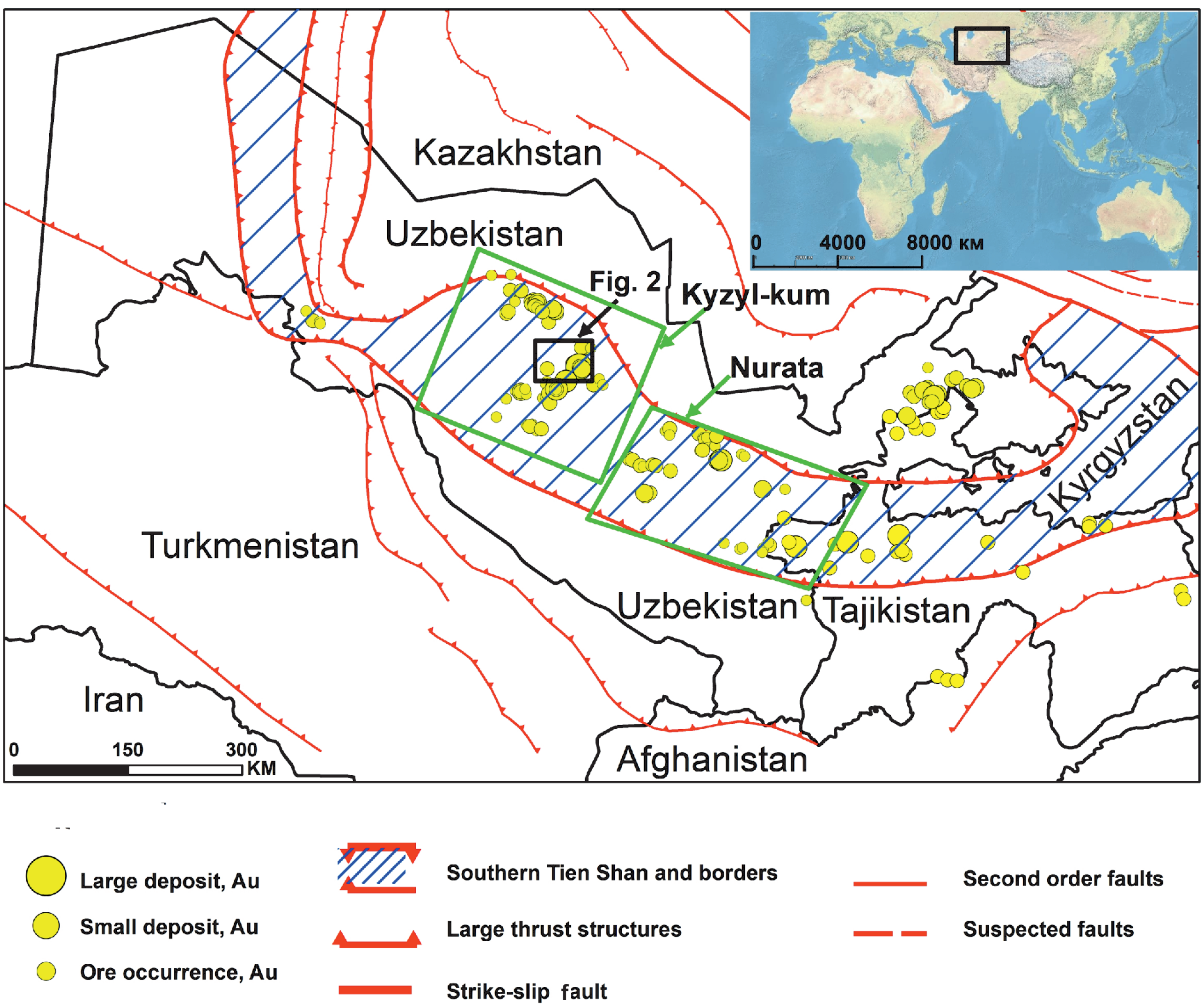

Fig. 1. Western termination of the Southern Tien Shan orogenic system hosting gold ore deposits

gold and associated elements from Cambrian black shales during the Variscan orogeny, with subsequent deposition in zones of enhanced permeability controlled by major fault structures. Its eastern extension is the Myutenbay (Myutenbai) deposit, which is currently mined as a single open-pit operation together with Muruntau. Consequently, many published articles refer only to the "Muruntau deposit", while the name "Myutenbay" is mentioned more rarely.

According to Kempe et al. (2016), the Muruntau gold deposit formed through a multi-stage process involving metamorphism, magmatism, and hydrothermal activity. The mineralization is linked not to magmatic input, but to high-temperature fluid-rock interaction, producing gold-bearing stockworks and metasomatites. Geochemical data indicate mixed mantle, crustal, and meteoric fluid sources, with brecciation processes possibly enhancing ore concentration. Unresolved problems include the timing of events and the role of brecciation in the ore genesis. Complementing this, Savchuk et al., (2018) emphasized the morphological features of the main ore body and highlighted successive deformation cycles (Caledonian, Variscan, and Cimmerian). He proposed a morphogenetic classification of ore bodies and argued for a subduction–hydrothermal model of ore formation. Together, these studies underline the importance of both tectonic evolution and fluid processes in shaping the unique Muruntau metallogenic system. Recent studies provide new insights into the structural and genetic framework of the Muruntau gold deposit. The Muruntau deposit is considered a product of polygenetic, multistage ore formation (Kotov and Plotinskaya, 2022). Mineralogical analysis and zoning of metasomatites (beresites, listvenites) revealed a complex ore composition (native gold, tellurides, sulphosalts) and demonstrated the inadequacy of single-factor genetic models (magmatic, metamorphic). The main mineralization is shown to be associated with the beresite and listvenite stages of metasomatism. These findings indicate a prolonged history of deposit formation involving heterogeneous sources of matter and fluids. Soloviev et al. (2023) identified three zircon age groups from the Sardara (Sharykty) granitoids: ~322, ~302, and ~289 Ma. The older ages correspond to the subduction stage, while the younger ages reflect post-collisional magmatism. The similarity with the ages reported from Muruntau indicates a common deep magmatic source and a long-term evolution from subduction to post-collisional settings. According to Mukhin et al. (2023), the Muruntau megaterrane is composed of repeatedly metamorphosed Proterozoic–Lower Paleozoic volcano-sedimentary rocks, overlain by Upper Paleozoic carbonates and Lower Carboniferous flysch-olistostromes. Four major deformation stages (D1–D4) were identified, including Early Paleozoic thrusting and Late Carboniferous orogeny, with folds, anticlines, and thrust zones playing a key role in controlling mineralization.

The Myutenbay gold deposit is situated in the southeastern part of the Tamdytau Mountains, within the eastern part of the Muruntau ore field (Fig. 2) of the Zarafshan-Alai structural-stratigraphic zone, Kyzyl-Kum segment, Southern Tien Shan. The Tamdytau Mountains or uplift consists of two merged anticlines: North Tamdytau and South Tamdytau. The uplift extends from the south-west to the north-east. To the north and west, the Tamdytau uplift is bordered by the Dzhamankum trough, which has a triangular shape in plan. It is filled with Upper Cretaceous, Paleogene and Neogene deposits with a total thickness of 800 m.

According to the geodynamic zoning scheme (Bukharin et al., 1985), the geotectonic position of the Kyzyl-Kum Desert is in the western part of the South Tien Shan fold system, the Kyzyl-Kum segment, with parts of all the structural-stratigraphic zones (SSZs): North Bukantau, South Bukantau, Turkestan-Alai, Zarafshan-Turkestan, Zarafshan-Alai. In the Tamdytau Mountains from the north are the South Bukantau, western parts of the Turkestan-Alai and Zarafshan-Alai SSZs (Fig. 2).

The South Bukantau zone can be interpreted as a basement uplift (median massif) within the Lower Paleozoic structure, representing an exposure of the pre-Paleozoic basement within the collisional framework, confined to the suture zone between the Turkestan-Alai and North Bukantau structural units. It is characterized by a distribution of gold-bearing metamorphic units. This zone is diverse in its expression of granitoid magma-

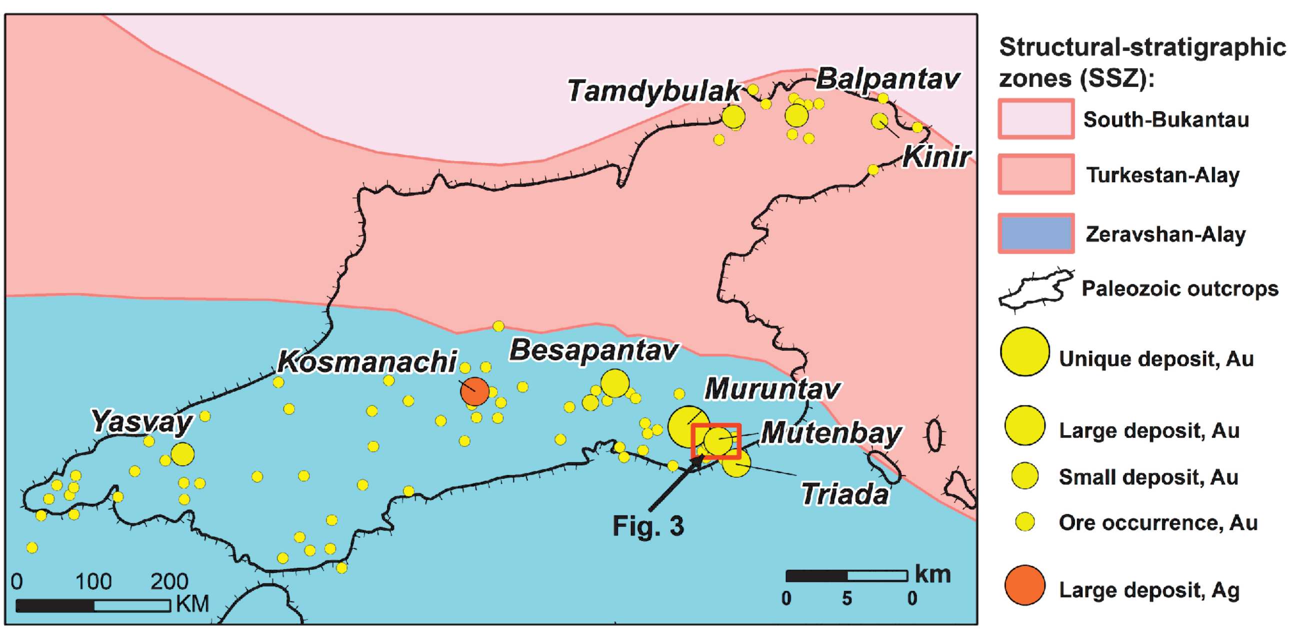

Fig. 2. Structural stratigraphic zoning and location of ore bodies in the Tamdytau Mountains

tism (granites, granodiorites) and the acompanying granitoids of the lyakovo series. The metallogenic appearance of the zone and its prospects are determined by a wide distribution of industrial gold-bearing capacity (Kokpatas and Okzhetpes deposits). The Turkestan-Alai zone, as traced with an average width of ~60 km from the South Bukantau zone, is characterized by a weakly differentiated and predominantly negative magnetic field, within which elongated intense magnetic anomalies, as a rule, coincide with the local and gravity maxima. The units of the Lower-Middle Paleozoic are of the same type as those of the North Bukantau zone. And, the terrigenous strata of the Upper Paleozoic are much thinner (up to 3000 m), with frequent internal discordances. Within the zone, bodies of gabbro-peridotite, gabbroid, plagiogranite, tanalite, quartz monzonite and leucogranite are recorded. The Zarafshan-Turkestan zone, up to 90 km wide, is characterized by carbonate-terrigenous formations (PZ_1) in the east (up to 6300 m) and volcanogenic-carbonate-siliceous-terrigenous strata in the west (4500 m), mainly terrigenous (up to 5000 m) formations (S1), a carbonate succession (D-C_2m_1) (3500 m) and terrigenous, coarse clastic strata at the top (up to 2000 m) (C_2m-P_1). The entire section is characterized by strong variability in the thickness of coeval strata and frequent unconformities. The S_1w_2-C_2m_1 deposits, previously considered to be confined to synsedimentary troughs, commonly comprise parts of an allochthonous tectonic cover on the D-C_2 rocks. Carbonate deposits of D_1 everywhere unconformably overlie different parts of O_2-S_1 (Bukharin et al., 1985). Modern interpretations of the geological/structural history of the regional succession are shown in Figure 3.

In general, the Zarafshan-Turkestan zone is characterized by intense late Caledonian folding, accompanied by faulting, which marks the transition between two major collisional stages: the Caledonian (Silurian–Devonian) and the Variscan (Carboniferous–Permian). Pre-Devonian structures are represented by large elliptical uplifts of brachyanticlinal type, elongated along the boundaries of the zone and complicated by smaller folds. These features are important in the framework of the metallogenic zoning (Golovanov, 2003); all large gold and uranium deposits are limited to the Zarafshan-Turkestan metallogenic zone (Tamdytau uplands). It represents a block–fault tectonic framework, bounded to the west and east by regional oblique fault systems, and is characterized by the widespread development of large brachiform folds, the predominance of terrigenous sedimentary formations, and long-lived, reactivated fault tectonics.

Conducting structural and metallogenic analysis into the folding of the region is advisable where large deposits have been discovered. This approach provides valuable information when conducting exploration work to identify zones of gold mineralization in closed areas of varying depths.

Similar geological and ore formations of different geological ages differ significantly in both their distribution and the scale of their ore content. In 1973, detailed exploration was conducted within the eastern part of the Muruntau ore field, and in 1977, the State Reserves Commission approved a complete change to the descriptive phrase for the Myutenbai deposit (Kasavchenko and Achkasova, 1972). A report on the calculation of reserves for the Myutenbay deposit was submitted in mid-October 1979. The reported reserves amounted to 124,000 t of gold. Currently, only the upper part of the deposit is being mined, while investigations of its deeper horizons are ongoing. The last comprehensive exploration of the deeper levels was conducted by Mikkonen between 1988 and 1998.

Industrial mineralization of the Myutenbay deposit is localized in the deposits of the Kosmanachi ore Formation, which are the main ore-bearing strata for the ore field (Fig. 4).

Within the deposit, 5 ore deposits of different sizes have been identified and delineated to a depth of 1400 m. Of these, 3 deposits are relatively large, the rest are medium and small. The conditions of occurrence of ore bodies and their morphologies are almost completely subordinate to the spatial distribution, scale of quartz-vein and related vein silicification zones.

The metasomatic factor is an important feature of mineralization. All gold ore deposits with relatively low but stable gold contents are confined to areas of development of phlogopite-potassium feldspar-quartz metasomatites.

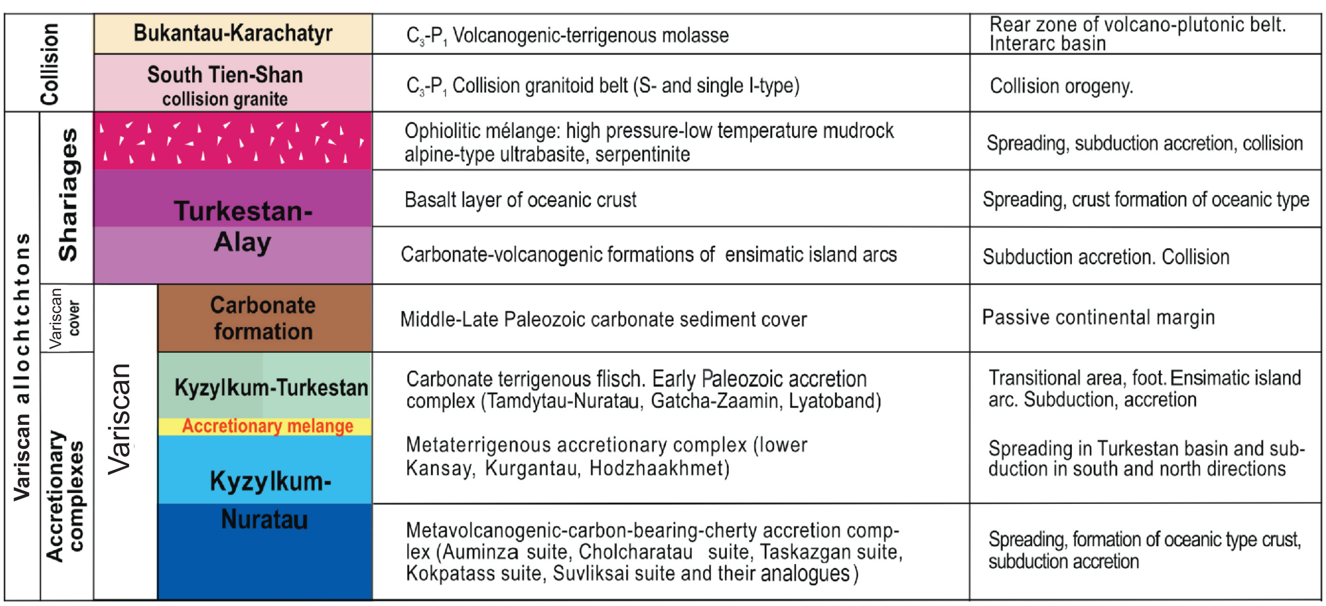

Fig. 3. Geodynamic assemblages of the folded basement of the Alay microcontinent, South Tien Shan (Turamuratov and Mirkamalov, 2016)

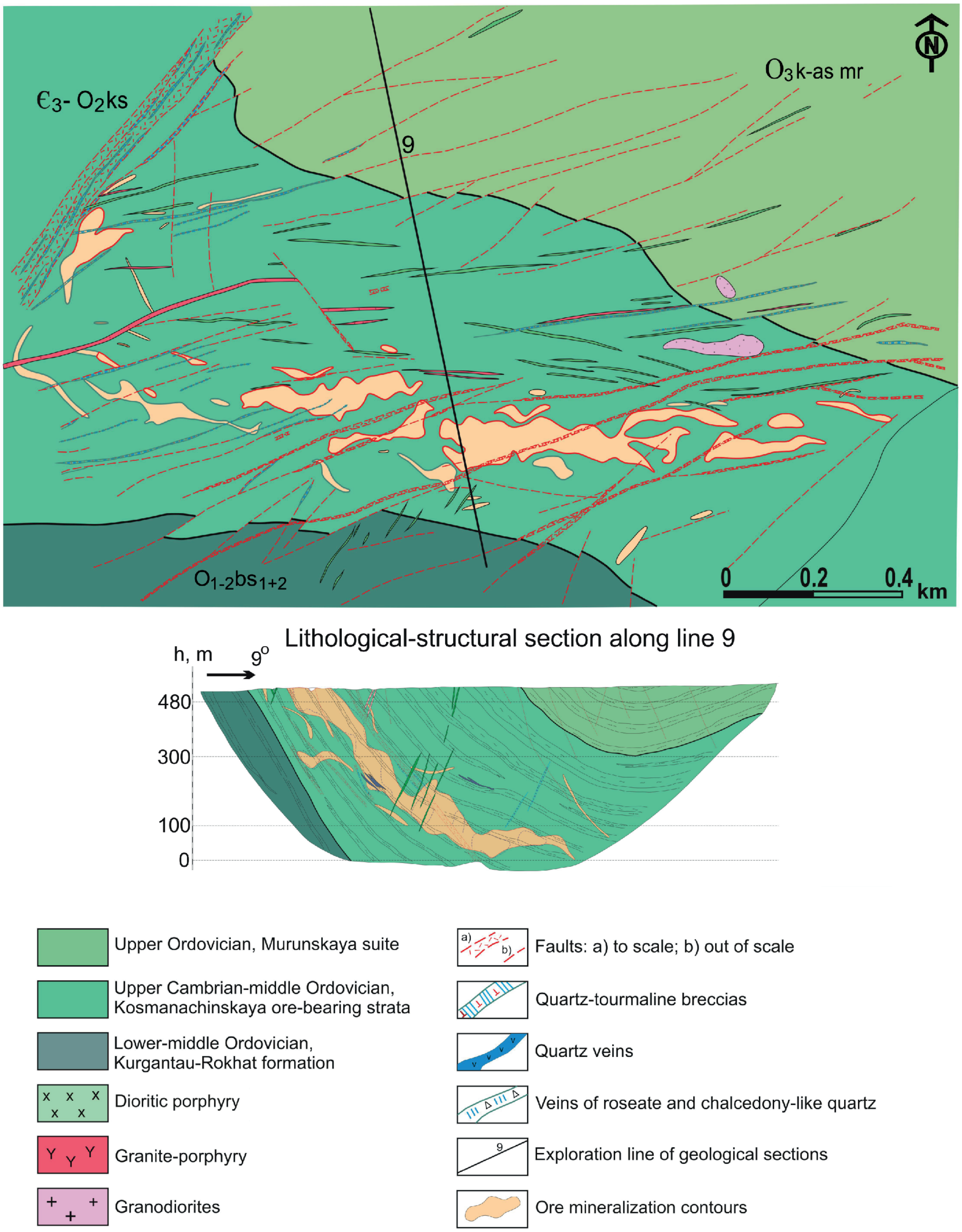

Fig. 4. Schematic geological map of the Myutenbay gold ore deposit (Mikkonen, 1998)

The host metaterrigenous rocks are represented by a unit of alternating metasandstones, metasiltstones, and metapelites. Metasandstones and metapelites are subordinate in distribution compared to metasiltstones, which make up 60–80% of the metaterrigenous rocks. Within the ore-bearing zones, silty and sandy rock varieties act as the most favourable environment for ore localization (Fig. 3).

There are two mineral assemblages productive for gold at the deposit: quartz-potassium feldspar and quartz-sulphide.

The sulphide content of the Myutenbay deposit is comparable to that of other deposits of the Muruntau ore field, and does not exceed 2%.

According to the geological and industrial type of ore, the Myutenbay deposit is gold-quartz (Mirkamalov et al., 2010). The gold is free, and its material composition is similar to that of the Muruntau deposit (Shayakubov, 1998).

The Myutenbay deposit is structurally confined to the southern wing of the Variscan syncline, located in sandy-shale strata of the Lower Besapan subsuite (now called the Kosmanachi ore-bearing strata). In the Muruntau ore field, during mineralization, the folding of the Besapan Formation and the sinistral adjustment in the Sangruntau-Tamdytau shear zone were caused by two simultaneous events:

– activation of the sinistral Muruntau-Daugyztau shear zone, which developed at an angle of almost 90° to the previous shear zone,
– intrusion of granitoid plutons. These structural events also led to a refocusing of the hydrothermal fluid flow into new permeability zones (Drew et al., 1996).

The ore-bearing zone is relatively narrow, up to 300 m. The ore bodies are subconformable with the schistosity and oriented in the north-west direction. The southern wing of the syncline is characterized by a synclinal dip to the north-east. In the ore zone, the dip angles of the schistosity are 60–70° (angle of incidence); with a depth at the horizon of +300 m, they flatten out to 35–50°. The hinge of the syncline dips to the east at an angle of 30°. The flattening of the schistosity creates favourable conditions for the gold mineralization. In the structure of the Myutenbay deposit, faults of various orientations are of great importance. The zone of the Southern fault to the north-east of the Myutenbay deposit acquires an approximately E–W orientation, dividing into a bundle of diverging branches of subvertical occurrence. Seams with a thickness of a few metres are made of crushed host rocks, friction-formed clay and quartz veins (Golovanov, 2001).

The northeastern faults are the most widely developed in the deposit. These are normal structures trending at an azimuth of 70°, dipping northwest within the Southern Fault zone at angles of 70–75°. Closer to the Southern Fault zone, they bend and acquire an approximately E–W strike. The faults are filled with brecciated rocks and friction-formed clays. Quartz veins are rare, with thicknesses ranging from 0.5 m to several metres (Golovanov, 2001; Mirkamalov et al., 2010).

METHODOLOGY

One of the key stages in interpreting the aeromagnetic data was determining whether the anomalies recorded during geological exploration correspond to specific lithotypes or distinct geological objects (Senchina and Mingaleva, 2022). For this study, we used previously collected aeromagnetic data, taking into account the current topography of the deposits as well as anthropogenic modifications that may have affected them, in order to carry out magnetic surveying.

To achieve the study's objectives, a comprehensive workflow system was implemented, encompassing stages of data collection, digitization, analysis, and integrated 3D modelling of geological and geophysical data. All processing was performed using specialized software packages.

DIGITIZATION AND CONSTRUCTION OF THE DEPOSIT'S STRUCTURAL FRAMEWORK

The initial stage involved the creation of a digital structural-lithological model of the deposit. For this purpose, archival materials from geological surveying were digitized, including geological maps at scales of 1:10,000 and 1:2,000, exploration profiles, and assay data. Digitization and the construction of surfaces for geological boundaries, fault zones, and structural elements were performed using the *Micromine* software package. The outcome of this stage was a three-dimensional block model of the geological structure, which served as the structural framework for subsequent interpretive modelling.

CORRELATION AND STATISTICAL ANALYSIS OF PETROPHYSICAL PROPERTIES

The next stage involved a detailed analysis of the petrophysical characteristics of the ores and host rocks. A representative dataset was compiled from laboratory measurements of density, magnetic susceptibility, and spontaneous polarization. Statistical processing, including the calculation of descriptive statistics (mean, variance, median), and the construction of scatter plot matrices, was performed using *Statistica*. Correlation analysis helped identify robust relationships between various physical properties and gold grade, which is essential for the verification of geophysical models.

PROCESSING OF AEROMAGNETIC DATA AND 3D INVERSION

A crucial stage of the research was the processing and interpretation of aeromagnetic survey data. Raw data underwent standard processing procedures in the *Geosoft Oasis Montaj* environment, which included correction for terrain effects, reduction to the pole, and filtering to isolate anomalies of different wavelengths. For quantitative interpretation and construction of a three-dimensional model of the rock mass's magnetic susceptibility, a volume inversion method (3D inversion) was applied using the *Voxi* module. The structural framework created in stage 3.1 was used as a constraint for the inversion, enabling the generation of a geologically realistic model of the spatial distribution of magnetic properties, which are directly related to mineralization and metasomatic zones.

INTEGRATED 3D MODELLING

The final stage involved the integration of results from all previous studies into a unified three-dimensional model. The geological block model (Micromine), enriched with the results of statistical (*Statistica*) and geophysical (*Geosoft Oasis Montaj, Voxi*) analysis, allowed for comprehensive interpretation and refinement of the location of ore-controlling structures and prospective target zones.

Based on exploration materials reported by Mikkonen (1998), a three-dimensional model of the ore bodies of the Myutenbay deposit was constructed (Fig. 5).

The deposit also contains ~E–W trending and north-west striking faults, with fault planes dipping steeply (60–70°) to the north. The zone thickness is up to 0.5 m. The length is a few hundred metres. Faults of this direction are blocked by north-east-trending faults. Dykes of diorite porphyrite, both metasomatically altered and fresh, are located along them. Quartz-tourmaline breccias tend to zones of E–W orientation.

The Muruntau syenodiorite-granophyre dyke complex (P_2–T_1 m) is developed in South Tamdytau. Within the research area, the dykes are grouped into Dzhamantau-Myutenbay narrow, ~E–W-trending belts. The dykes were studied by Podkopaev (1965) and Sher (1972). The most distinct and extensive (length up to 60 km, width up to 2 km) is the central belt. The northern (10 x 2 km) and southern (20 x 2.5 km) belts are less distinct and developed in part. The central belt in the eastern part has the shape of a flattened oval with a width of ~1 km. The Dzhamantau-Myutenbay dyke belt is confined to the core part of the the Myutenbay anticline formed in the Late Paleozoic, and its northern and southern wings show a pattern of placement of dykes of different compositions, expressed in the location of acidic dykes mainly in the eastern part of the area, among the deposits of the Besapan suite, where they form closed, often en echelon-like clusters along the periphery of the oval. To the west, they are replaced by dykes of medium-basic composition.

The dykes of the Muruntau complex are distinguished by increased contents of lead, tin, molybdenum and bismuth, and are enriched in gold in places. The metamorphism of the Muruntau complex dykes may be a result of the thermal effects of post-thrust granitoid magmatism (Tulyaganov et al., 1984).

Materials in the ore-bearing wells MS-2 and MS-3 indicate that the ore intervals are composed of the same feldspar-quartz metasomatites that are noted at the Myutenbay deposit.

Specifically, we aim to establish whether the shape of the three-dimensional magnetically disturbing bodies corresponds to the shapes of the ore bodies.

Sulphide mineralization zones, which commonly bear gold ore mineralization, are distinguished by anomalies of increased and high polarizability. In the zones of pyrite-pyrrhotite (FeS_2 –$Fe_{1-x}S$).

Mineralization, both positive (e.g., Muruntau, Myutenbay deposits) and negative magnetic anomalies (e.g., Besapantau, Kokpatas gold deposits, Vysokovoltnoye “High Voltage” gold-silver, Kosmanachi silver deposits) occur, depending on the magnetic properties of pyrrhotite. This characteristic allows us to establish the relationship between pyrrhotite ($Fe_{1-x}S$) mineralization and ore zones.

In our study, the term polarizability refers to chargeability as measured by the Induced Polarisation (IP) method, which is sensitive to the presence of disseminated sulphides such as pyrite and pyrrhotite. These sulphide minerals are also the main sources of magnetic anomalies, because pyrrhotite, in particular, can have variable magnetic properties, producing both positive and negative anomalies. Thus, IP anomalies of high chargeability and magnetic anomalies may coincide spatially, but they reflect different physical properties: electrical polarizability *versus* magnetic susceptibility.

Tables 1 and 2 show the physical properties of the ore-bearing rocks of the Myutenbay deposit, which are compiled from the archival materials of the Petrophysical Party of the Kyzyl-Kum geological exploration expedition.

RESULTS

In the *Statistica* software, the petrophysical characteristics of the rocks of the Myutenbay deposit were analysed using the pair and partial correlation method. The results of the statistical

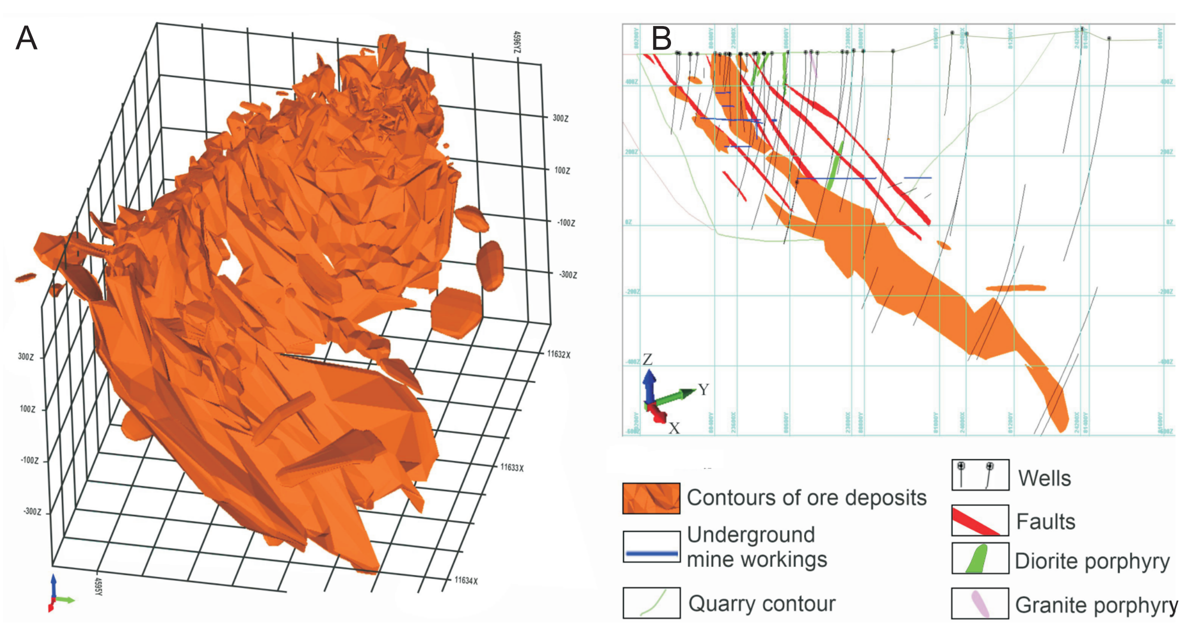

Fig. 5. Results of modelling of the Myutenbay gold deposit

A – framework of the ore deposit, 3D section; **B** – structure of the ore deposit, 2D section

Table 1

Physical properties of ore-bearing rocks of the Myutenbay deposit (samples from the mine horizon)

Rocks	Density (σ average) [g/cm^3]	Magnetic susceptibility 10^{-5} SI units (æ average)	Polarizability (η average) [%]
Silicified sandstones and siltstones	2.70	49	7.1
Silicified carbonaceous shales	2.70	30	14.0
Silicified siltstones with sulphides	2.73	30	8.9
Silicified shales with sulphides	2.74	35	10.3
Carbonaceous shales with sulphides	2.72	37	19.3
Sandstones. siltstones and shales	2.72	38	9.7
Vein quartz	2.65	6	2.3
Quartz metasomatites	2.66	57	3.7
Vein quartz with sulphides	2.71	5	7.4
Quartz metasomatites with sulphides	2.71	56	8.7
In total for the deposit	2.70	47	8.1

Table 2

Physical properties of rocks of the Myutenbay gold deposit (by wells) (compiled using materials of Artemenko and Zhalilov, 1972)

Rocks	Density (σ average) [g/cm^3]	Magnetic susceptibility, 10^{-5} SI units (æ average)	Polarizability (η average) [%]
Ore-bearing rocks			
Sandstones and siltstones	2.69	9	10.8
Mica-feldspar-quartz shales	2.71	10	21.4
Mica-feldspar-carbonaceous shales	2.72	15	23
Ore-bearing rocks in general	2.70	11	14.8
Zones of hydrothermal alteration near ore			
Siltstones and sandstones, siltstones	2.69	10	10.6
Shales, mica-feldspar-quartz, siltstones	2.70	21	13.4
Shales, mica-feldspar-carbonaceous, siltstones	2.71	16	12.6
Siltstones	2.70	12	11.2
Sulphidized sandstones and siltstones	2.71	15	21.0
Shales, mica-feldspar-quartz, sulphidized	2.74	24	21.5
Shales, mica-feldspar-carbonaceous, sulphidized	2.73	19	29.0
Sulphidized rocks, on average	2.72	17	23.3
Ore zone			
Sandstones and siltstones bearing gold-sulphide mineralization	2.69	14	15
Mica-quartz schists bearing gold-sulphide mineralization	2.73	16	23
Mica-carbonaceous schists bearing gold-sulphide mineralization	2.75	16	29
Ore quartz	2.65	4	5
Ore zone as a whole	2.70	12	15.9
Deposit as a whole	2.70	13	16.7

analysis for polarizability and density of ore-bearing rocks show a strong positive correlation ($r = 0.81$), suggesting a close petrophysical relationship between these two parameters. Analysis of pair and partial correlations for polarizability and density of ore-bearing rocks shows a correlation coefficient of $r = 0.97$ (Fig. 6), and for the ore zone shows an ideal ratio of the correlation coefficient of $r = 0.99$ (Fig. 7).

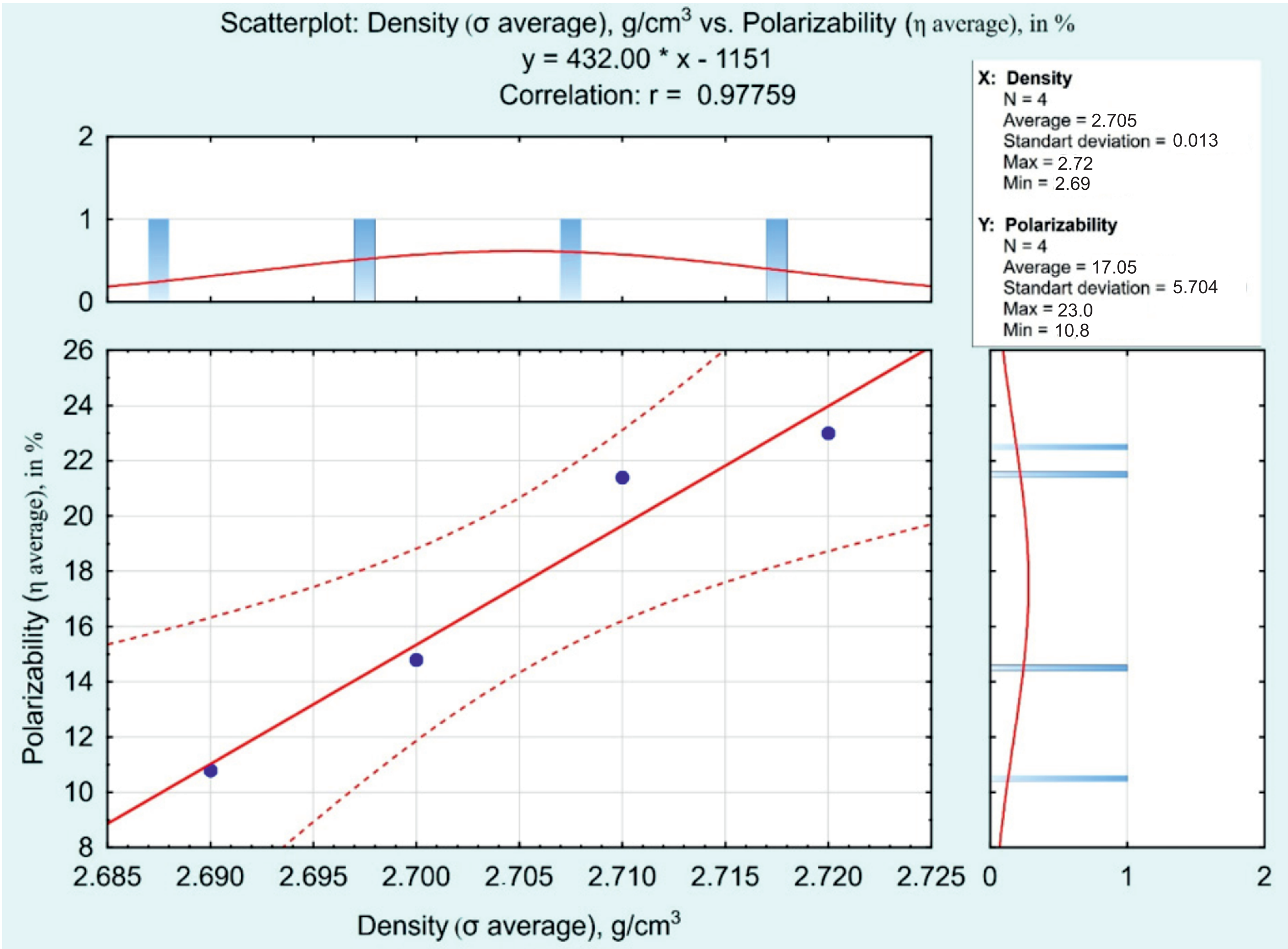

Fig. 6. Pairwise and partial correlations of hydrothermal alteration near ore (polarizability–density)

The results of pair and partial correlations for polarizability, density, and magnetic susceptibility of rocks from the Myutenbay deposit showed that the strength of correlation increases as hydrothermal alteration zones are nearer the ore-bearing rocks and transition into the ore zone. These results indicate the existence of a strong statistical relationship between the petrophysical parameters, which will further serve when conducting exploration work of their analytical presentation and assessment of the accuracy of determining the desired parameters using these petrophysical links.

The magnetic properties of ore and near-ore metasomatites of gold-producing mineralization of the Muruntau type are directly dependent on the content of pyrrhotite, specifically its monoclinic variety, and can be either magnetic or practically non-magnetic.

According to the observations of Kremenetsky (1990) based on borehole SG-10, pyrrhotite is stable within the chlorite-muscovite-biotite subfacies of metamorphism, whereas pyrite is stable within the chlorite-sericite subfacies. Regionally metamorphosed rocks are overprinted by locally altered rocks, the formation of which is attributed to metasomatic processes. The principal gold anomalies of the ore field are spatially associated with distinct types of metasomatites, the study of which, at the Muruntau and Myutenbay deposits, has been the focus of numerous investigations. These observations highlight the critical role of pyrite-pyrrhotite stability fields as redox-sensitive indicators, directly linking the metamorphic and metasomatic evolution of the host rocks to ore-controlling processes and gold mineralization.

The presence of sulphide mineralization in the rock strata increases their density by 0.04 g/cm^3.

To model the geomagnetic field, a map of the anomalous magnetic field ΔTa at a scale of 1:25,000 was used, obtained as a result of airborne geophysical studies with the Makfar-II station (1988), which made it possible to significantly supplement the available geological and geophysical characteristics of the study area.

The magnetic field of the territory under consideration is sharply differentiated and is extremely heterogeneous in terms of the degree of tension by local anomalies, their frequency and intensity.

The main elements determining the morphology of the magnetic field in the south-west of the area are large maxima ΔTa (Fig. 8).

In the magnetic field map (ΔTa) within the ore field, a positive anomaly was revealed, which, in our opinion, is related to metamorphic zones formed as a result of the contact action of an intrusion of average composition.

The geological nature of the local anomalies that are spatially confined to the granitoid massifs is associated with the

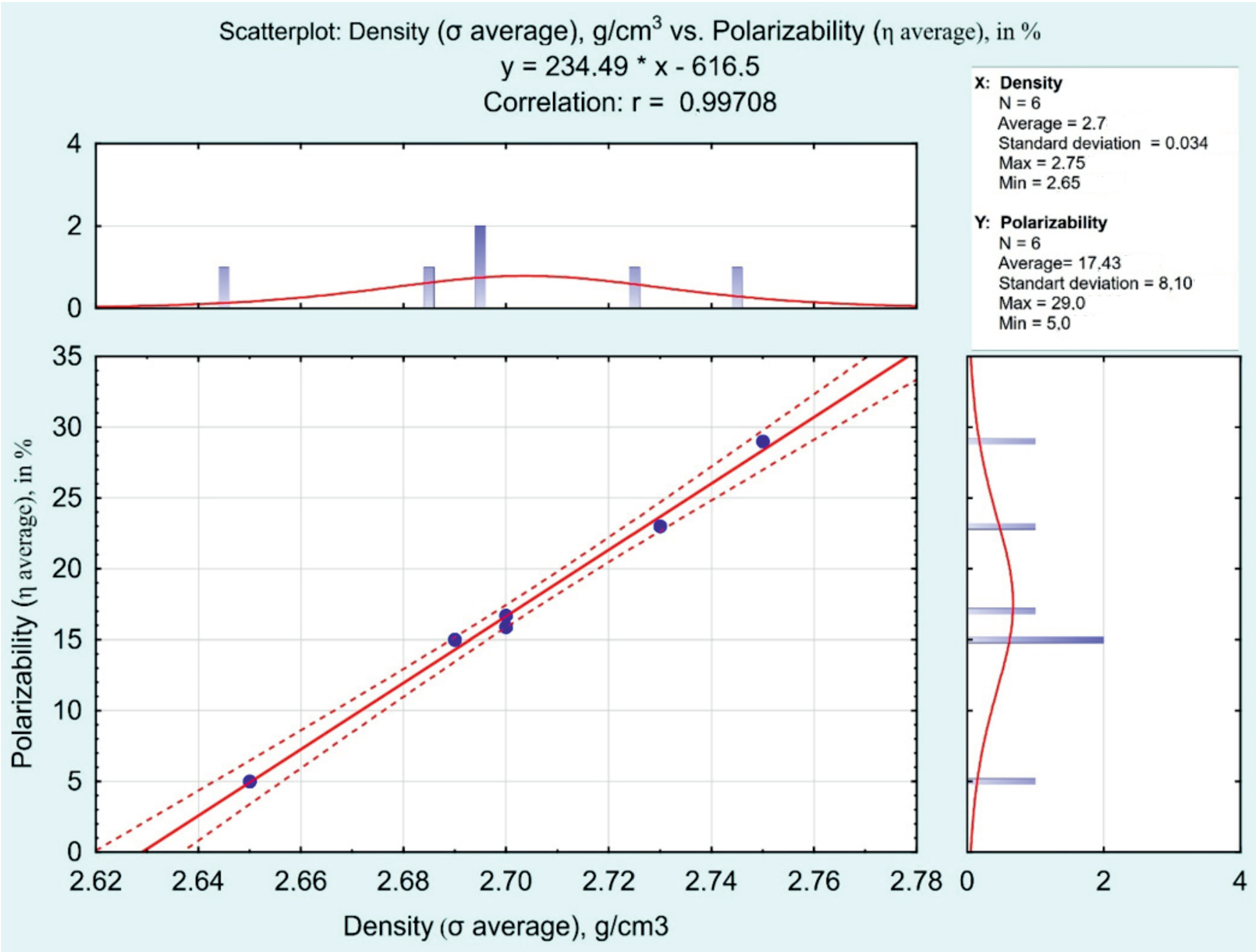

Fig. 7. Pairwise and partial correlations of ore zone (polarizability–density)

morphology of their roof. In other cases, it is assumed that the minima are associated with an increase in the thickness of the terrigenous rocks of the Taskazgan-Besapan complex, or with areas of rock decompression; the maxima are associated with the approach to the surface of the pre-Mesozoic basement of the metabasic part of the section of the Lower Taskazgan subsuite.

The northern part of the area is characterized by a mosaic field and in the regional plan is the eastern part of the extensive ~E–W-trending South Tamdytau positive magnetic anomaly, complicated by high- and medium-frequency components of different signs.

To create a geomagnetic model of the Myutenbay deposit, archival cartographic materials were used, Fedotkin (1988) used an aeromagnetic survey. Linear isonomalies were tied to the coordinate system and digitized in ArcGIS-10.8 programs as linear spatial objects (*shp file). Next, this view was converted to point objects using the Line to Point function. This contains X, Y coordinates and values in nano Tesla (nT). To isolate and visualize the geometry of the magnetic source body, a 3D model of the anomalous magnetic field was computed using the *Voxi* module in *Geosoft Oasis Montaj*. The resulting model, enhanced through frequency-domain filtering, delineates the spatial configuration of the magnetically disturbing object (Fig. 9).

The three-dimensional model of the magnetically excited objects of the Myutenbay deposit was constructed using the physical property data of rocks obtained from boreholes (Tables 1 and 2). In particular, the values of magnetic susceptibility were taken into account for different lithological types and alteration zones, including ore-bearing rocks, hydrothermal alteration zones adjacent to the ore, and the ore zone itself. These data indicate that the magnetic susceptibility of the modelled objects reflects the distribution of ore-related lithologies and their transformation by hydrothermal processes. Accordingly, the magnetically excited bodies in the 3D model correspond to the zones with elevated or contrasting susceptibility values, which are spatially associated with ore-bearing rocks and their alteration halos. This ensures that the model is not only consistent with measured petrophysical parameters but also highlights the geophysical signatures of the ore system

Using the *Geosoft Oasis Montaj* programs, a geomagnetic model was built and compared against geological sections at a scale of 1:2000, which were compiled based on drilling data (Fig. 10A).

In terms of lithological composition, the Lower Ordovician Kurgantau Suite (O_1kr) and the Kosmanachi ore-bearing strata ($\in_3$-O_2 ks) contain siliceous rocks, whereas the Rokhat Suite (O_{1-2} rh) and the Murun Suite (O_3mr) are completely devoid of them. A similar conclusion can be drawn with respect to volca-

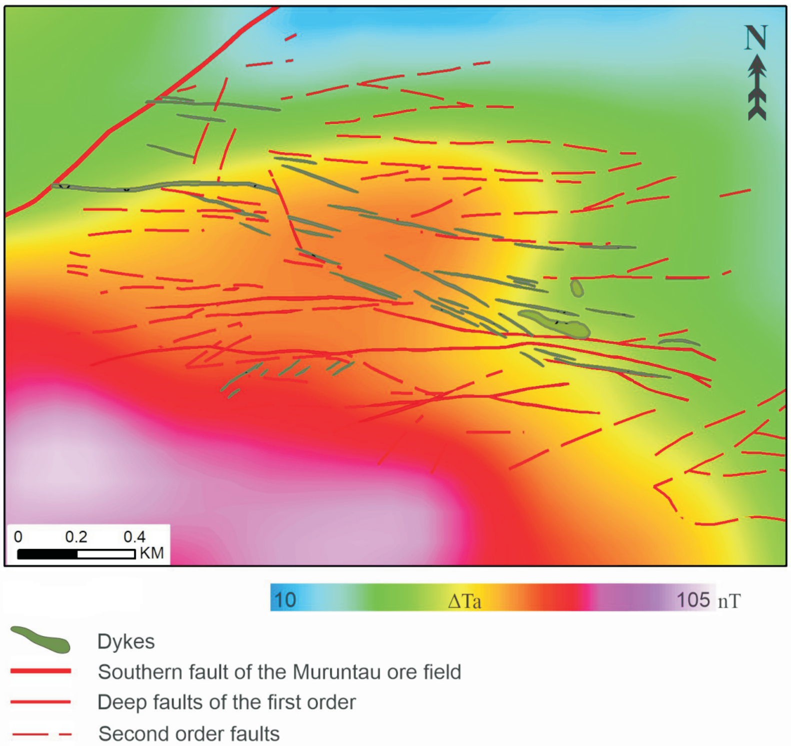

Fig. 8. Map of the anomalous magnetic field (ΔTa) of the territory of the Myutenbay deposit

nic products. The highest carbonaceous content and sulphide saturation (based on the pyrite balance) are characteristic of the Kosmanachi ore-bearing strata, whereas these features are least developed in the Kurgantau Suite. The Kosmanachi ore-bearing strata represent the most pelitic, finely layered, and facies-variable part of the succession, and, consequently, the most heterogeneous in terms of physical-mechanical properties and response to tectonic stress. Owing to the presence of thick interbeds of plastic carbonaceous metapelites, this unit is also the most prone to the development of subconcordant tectonic dislocations.

The next step is to compare the results of geomagnetic modelling with geological sections. The models created in this way represent the block structure of the deposit as the underlying Taskazgan and overlying Kosmanachi ore-bearing strata, with step-like gradients delineating the fault zone (Fig. 10B).

The direct task of magnetic exploration is to determine the parameters of the magnetic field based on the known characteristics of magnetic masses: shape, size, depth, magnetization angle and magnetic susceptibility (Bogoslovsky et al., 2018).

The magnetic properties of geological formations of the Taskazgan and Besapan suites are determined by the level of superimposed progressive regional metamorphism. Magnetically active rocks, regardless of their composition and stratigraphic affiliation, geological formations in the muscovite-biotite zone, contain syngenetic vein-disseminated pyrite-pyrrhotite and pyrrhotite mineralization. Their magnetic susceptibility varies widely from 0 to $27 \cdot 10^{-5}$ SI units. The wide range of changes in magnetic properties is due to the presence of pyrrhotite of two types: highly magnetic – monoclinic syngony and non-magnetic – hexagonal syngony. The magnetic susceptibility of the rocks is determined by the content of monoclinic pyrrhotite. The remaining metamorphic zones are practically non-magnetic. Their magnetic susceptibility fluctuates in the range of $2–35 \cdot 10^{-5}$ SI units.

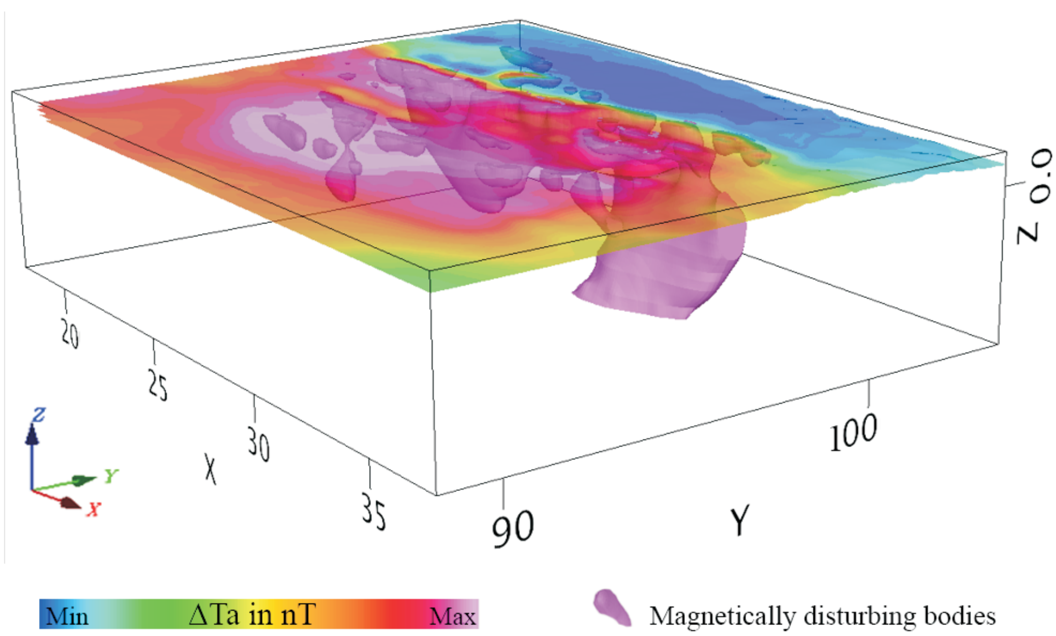

Fig. 9. Three-dimensional model of magnetically excited objects of the Myutenbay deposit

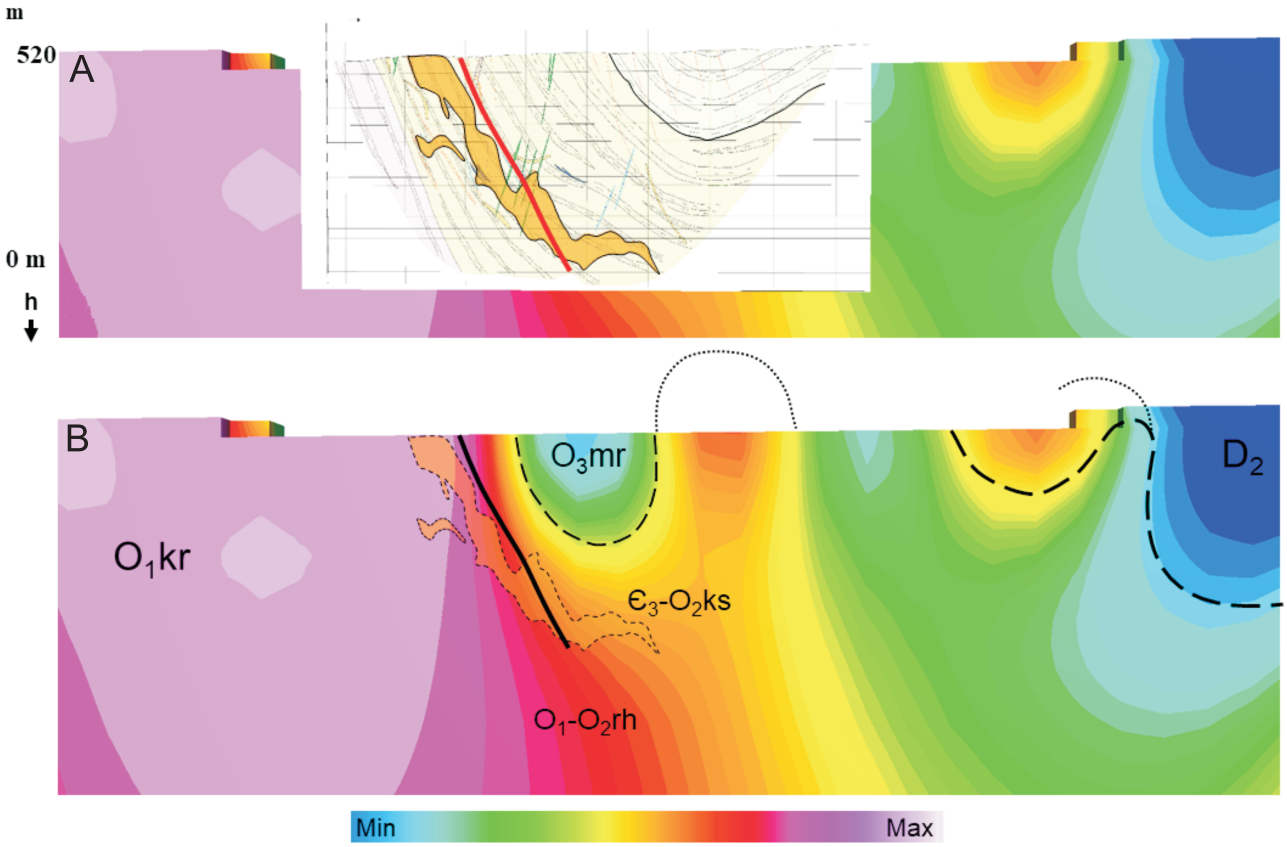

Fig. 10. Comparison of the lithological and structural section of the Myutenbay deposit along exploration line no. 9 (A) with the results of geomagnetic modelling (B)

O_1kr – Lower Ordovician Kurgantau suite; O_{1-2} rh – Rokhat suite; $\in_3$–O_2ks – Kosmanachi ore-bearing strata ($\in_3$-O_2ks); O_3mr – Murun suite; D_2 – Middle Devonian, carbonate rocks; the directions of the section are shown with black lines in the geomagnetic model in Figure 9

The geological nature of the magnetic field anomaly is associated with the metavolcanic rocks of the lower Taskazgan, as well as with areas of contact-metasomatic changes in the supra-intrusive zones.

The geomagnetic model constructed for the Myutenbay deposit reveals a large-scale fold structure, which we interpret as a manifestation of the regional syn-metamorphic thrust zone. The geometry of this fold, displaying characteristics of both synclines and anticlines, aligns with the structural style documented by Mukhin et al. (2023) for the region, particularly with the recumbent folds in the north Dzhurgantau antiform.

A distinctive feature of the ore field, with no parallel at such scale among other Kyzyl-Kum deposits, is the presence of several ~E–W-trending shear zones. These zones are composed of rocks deformed to varying degrees, up to phyllonites, as well as intensely metasomatized carbonaceous sequences intruded by dykes. This highlights the deep-seated nature of these structural zones. We note also the location of the ore field within the peripheral part of the thermodome (Dzhurgantau) ancient basement structure, as well as the ore-controlling role of the carbonate screen. Another significant factor is the long duration of the ore-metasomatic process, which developed within carbonaceous terrigenous rocks. These rocks have been commonly considered to by geochemically distinctive with respect to gold.

Thus, the geophysical model (Fig. 10) reflects the distribution of physical parameters and identifies anomalies associated with potentially ore-bearing zones, thereby enabling the delineation of areas with increased prospectivity. At the same time, the structural scheme (Fig. 11), compiled on the basis of geological observations, specifies the nature of these anomalies and demonstrates their relationship with the Dzhurgantau-Taskazgan anticlinal node, where crystalline schists are exposed in the cores and meta-basalts and marbles occur on the flanks. The comparison of both models shows that the ore-controlling factors are not only anomalies of the physical fields but also deep-seated fold structures that form tectonic traps for mineralization. This corroborates the reliability of the interpretation obtained and significantly increases the robustness of predictive-prospecting constructions, providing a more substantiated basis for geological exploration planning.

The processing of geophysical data, their qualitative and quantitative interpretation and complex analysis of geological and geophysical data, were performed mainly by traditional methods and computer processing. In addition to three-dimen-

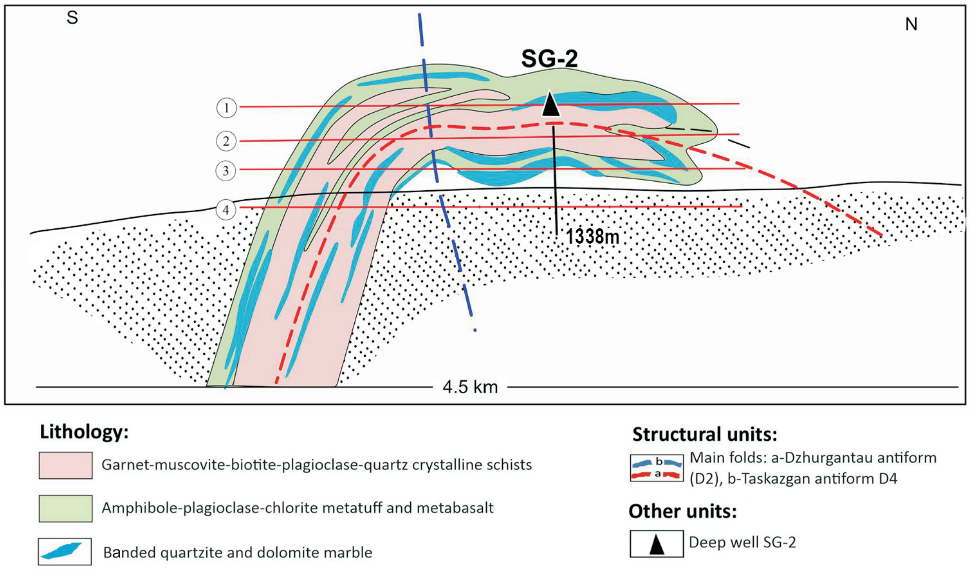

Fig. 11. Lithological cross-section of the recumbent part in the north Dzhurgantau antiform (Taskazgan area)

Based on Mukhin et al. (2023)

sional modelling, the analysis of the spatial arrangement of geological and structural elements (faults, ore bodies, dykes and magnetic field isolines) of the deposit was performed in the *PyGMI* programs (Fig. 12). The need for this analysis is the previously established fact that in central Kyzyl-Kum, as regards the formation of gold ore deposits, the mineralization is associated with significant structural, lithological and magmatic factors. To establish these factors, the elements noted above were analysed.

The Myutenbay deposit is structurally complex due to the effects of faults, mainly of ~E–W-trending and northeastern strike (Fig. 12A, B), and of folds. Together, the faults form zones of powerful shearing and brecciation. The main folded structure in the deposit is a Variscan second-order syncline, the shape of which in different parts of the deposit along its strike determines the morphology of the ore deposits.

The processing of geophysical data, their qualitative and quantitative interpretation and complex analysis were carried out mainly by traditional methods, computer processing (*ArcGIS*, *Geostatistica*, *Geosoft Oasis Montaj*, *PyGMI*) taking into account the spatial arrangement of ore zones and structures according to the frequency division of magnetic fields (Fig. 12).

A total of 34 ore deposits have been identified and explored at the deposit (Fig. 12D). Three main morphological types of deposits are distinguished: subconcordant gently sloping deposits of sheet-like, trough-like, saddle-shaped form; steeply dipping deposits in brecciated zones between large faults in the form of lens-shaped ore pillars; and subconformable deposits in areas with monoclinal occurrences of ore-bearing rocks in the form of lenses and plates (Golovanov, 2001).

Quantitative analysis of the magnetic field revealed a clear confinement of the Myutenbay deposit area to the area of increased magnetic field values. All previously identified zones of ore mineralization are spatially located within this area and are completely controlled by its distribution (Fig. 12F, G).

Statistical analysis of the spatial distribution of the orientation of geological and structural elements showed a large convergence, that in terms of the orientation of ore zones, the orientation of the dykes and the orientation of the isolines of magnetic fields are identically of E–W direction. The spatial statistical analysis shows a dominant E–W orientation, common to the ore zones, dykes, and magnetic anomalies. This trend is segmented and offset by a secondary set of NE-striking faults, which displace the ore zones relative to one another.

CONCLUSIONS

In the magnetic field, the deposits have the following characteristics:

– Devonian carbonate rocks with negative values,
– Murun suite with low values,
– Kosmanachi ore-bearing strata with average values
– The underlying Taskazgan complex with high values.

A three-dimensional model of ore bodies was created in *Micromine* software using borehole data obtained at the exploration stage of the deposit.

Despite the different scales, the geological profile and the map of the anomalous magnetic field reflect the same major geological features. These include fault zones, the synclinal form of the folded Murun Formation, and well-defined contacts between contrasting rock units.

Based on the above, the following magnetic field elements can be attributed to the search magnetic forecasting criteria.

1. Regional positive magnetic anomalies indicating dome-shaped metamorphic structures of progressive regional metamorphism, which generally delineate the location of gold ore mineralization.

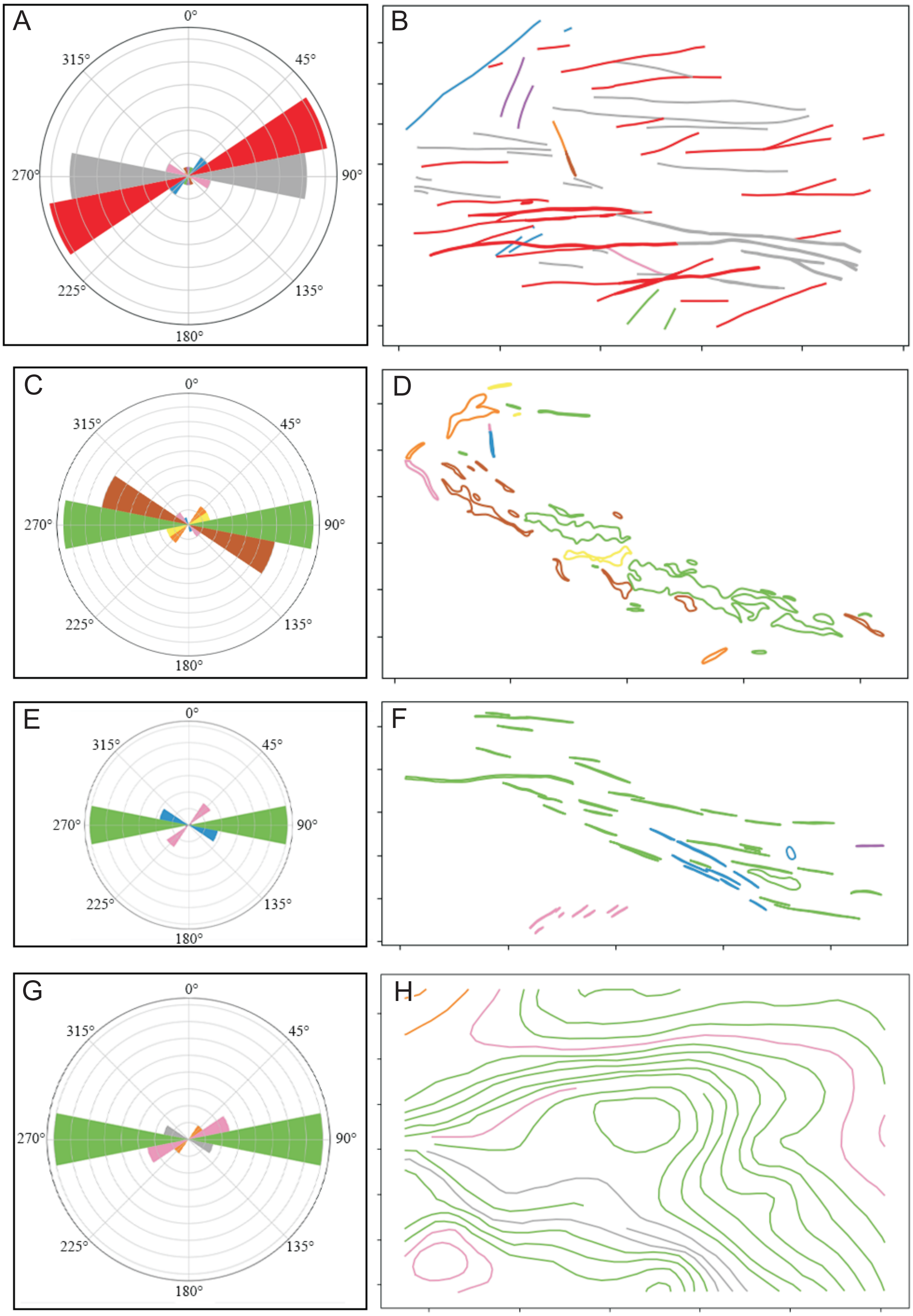

Fig. 12. Statistical distribution of orientation of geological and structural elements of the area of the Myutenbay deposit

A – rose diagram of fault zones; **B** – spatial distribution of fault zones in plan; **C** – rose diagram of orientation of ore zones; **D** – ore zones in plan; **E** – rose diagram of dykes; **F** – dykes in plan; **G** – orientation of magnetic field isolines in rose diagrams; **H** – distribution of magnetic field isolines in plan

2. Zones of correlated magnetic maxima, which are caused by the development of pyrite-pyrrhotite vein-disseminated mineralization within the areas of gold-producing ore body.

3. Intense anomalies of reverse magnetization, located within the frame of regional positive anomalies, associated with areas of pyrrhotite mineralization exhibiting polar magnetization.

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