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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
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АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

Х А Б А Р Л А Р Ы

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН»

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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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Kazakh National Research Technical University named after K.I. Satpayev,
Kazakhstan, Almaty.
E-mail: auyesbek99@mail.ru

GEOLOGICAL-GEOPHYSICAL CRITERIA OF THE JEZKAZGAN ORE DISTRICT IN CENTRAL KAZAKHSTAN

Abetov A.E. — Doctor of Sciences in Geology and Mineralogy. Corresponding Member of the National Academy of Sciences of the Republic of Kazakhstan. Professor of the Department of Geophysics and Seismology. Institute of Geology and Oil and Gas Business named after K. Turyssov, Satbayev University. Almaty, Kazakhstan
E-mail: abetov.auez@mail.ru, https://orcid.org/0000–0002–1866–7677;
Auyesbek A.A — Master's student at the Kazakh National Technical Research University named after K.I. Satpayev. Institute named after K. Turyssov, Department of "Geophysics and Seismology". Almaty. Kazakhstan
E-mail: auyesbek99@mail.ru, https://orcid.org/0009-0000-5376-0706.

Abstract. Stratigraphy, lithology, and structure of explored copper deposits and ore occurrences in the Zhezkazgan ore areas have been studied. The zonation of copper mineral distribution is confirmed in this region, where the endogenic nature of the ore is confirmed by specific elements, high temperatures of ore-forming solutions, and the absence of post-ore metamorphism. The uniqueness of the Zhezkazgan copper deposit is evident in the enormous vertical thickness of ore mineralization over a relatively small area and at shallow depths, with a tabular form associated with magmatic rocks of basic and ultrabasic compositions. The significant involvement of tectonic displacements, effusive, and intrusive magmatism in the formation of ore-bearing horizons, various structural elements, faults, and fracture systems, which served as conduits and localizers for ore mineralization, has been substantiated. There is observable correlation of isolines of positive residual gravity anomalies with the structural plan within the Zhezkazgan copper deposit and beyond. Zoning of the deposit has been performed based on the intensity of gravity anomalies Δg_a, depth of occurrence, and stratigraphic range of ore-hosting horizons. A forecast has been made regarding the possibility of identifying new ore deposits. The following characteristic combination of criteria defining copper mineralization in the Zhezkazgan ore field has been identified: a system of high-gradient and intensive maxima of geomagnetic field anomalies, concentration of rare earthquake epicenters at depths up to 20 km, and moderate amplitude of recent crustal movements. Linearly elongated relative maxima and minima of the regional gravity field transform, excess density masses along the intracrustal transform, extremely high values of heat flow density, temperatures at depths of 10 km and 30 km, and protrusions on the Moho and granulite-basaltic layer surfaces correlated with basic and ultrabasic rocks within the consolidated crust. Morphology and orientation of geophysical field anomalies align with the orientation and manifestation of disjunctive tectonics, where deep heat mass transfer processes are allowed along the planes of deep faults.

Keywords: cupriferous-sandstones, lithological-structural control, gravitational and magnetic fields, mineralization zoning, ore-bearing horizons

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Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Қазақстан, Алматы.
E-mail: auyesbek99@mail.ru

ОРТАЛЫҚ ҚАЗАҚСТАНДАҒЫ ЖЕЗҚАЗҒАН КЕНДІ АУДАНЫНЫҢ ГЕОЛОГИЯЛЫҚ-ГЕОФИЗИКАЛЫҚ КРИТЕРИЯЛАРЫ

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E-mail: abetov.auez@mail.ru, https://orcid.org/0000-0002-1866-7677;
Әуесбек А.А. — Қ.И.Сәтбаев атындағы қазақ Ұлттық техникалық зерттеу университетінің магистранты. Қ. Тұрысов атындағы институт, “Геофизика және сейсмология” кафедрасы, Алматы, Қазақстан
E-mail: auyesbek99@mail.ru, https://orcid.org/0009-0000-5376-0706.

Аннотация. Мыстың барланған кен орындары мен кен орындарының стратиграфиясы, литологиясы мен құрылымы, Жезқазған кен аймағындағы мыс кенінің пайдалы қазбаларының таралу аймақтылығы, бұл жерде рудалардың эндогендік табиғаты ерекше элементтер жиынтығымен, жоғары температурамен расталады. кен түзетін ерітінділердің құрамы және кенден кейінгі метаморфизмнің жоқтығы зерттелді. Жезқазған мыс кен орнының бірегейлігі салыстырмалы түрде шағын аумақта және таяз тереңдікте кенді минералданудың орасан зор вертикальды қалыңдығынан, оның қаңылтыр тәрізді пішінінде және негізгі және ультра негізді құрамды магмалық жыныстармен байланысында көрінеді. Кенді минералданудың өткізгіш және локализаторы қызметін атқарған тектоникалық дислокациялардың, эффузивті және интрузивті магматизмнің рудалы горизонттардың, әртүрлі ретті құрылымдардың, жарылымдар мен жарықшақтық жүйелердің қалыптасуына үлкен қатысуы дәлелденген. Гравитациялық өрістің оң қалдық аномалияларының изосызықтары Жезқазған мыс кен орнының өзінде және одан тыс жерлерде құрылымдық жоспармен корреляцияланғаны байқалады. Бұл кен орны аномалиялардың қарқындылығы Δg_a, пайда болу тереңдігі және кенді горизонттардың стратиграфиялық диапазоны негізінде аудандастырылған. Жаңа кен орындарын анықтау мүмкіндігі туралы болжам берілген. Жезқазған кен орнындағы мыс минералдануын сипаттайтын критерийлердің келесідей сипатты үйлесімі анықталды: геомагниттік өріс ауытқуларының жоғары градиентті және қарқынды максимумдарының жүйесі, 20 км-ге дейінгі тереңдіктегі сирек жер сілкінісі ошақтарының шоғырлануы және соңғы кездегі орташа амплитудасы. жер қыртысының қозғалыстары, аймақтық түрлендіргіш гравитациялық өрістің сызықты ұзартылған салыстырмалы максимумдары мен минимумдары, қыртысы ішілік түрлендіргіш бойындағы артық тығыздық массалары, жылу ағынының тығыздығының өте жоғары мәндері, 10 км және 30 км тереңдік учаскесіндегі температуралар, беттер бойындағы шығыңқы жерлер. Мохо және гранулитті-мафикалық қабат, шоғырланған жер қыртысындағы негізгі және ультра негізді жыныстармен корреляцияланады. Геофизикалық өріс аномалияларының

морфологиясы мен ориентациясы дизъюнктивтік тектониканың көріну бағыты мен сипатына сәйкес келеді, мұнда терең жарықтар жазықтығында терең жылу және масса алмасу процестеріне жол беріледі.

Түйін сөздер: мысты-құмтас, литологиялық-құрылымдық бақылау, гравитациялық өріс, минералдануды аудандастыру, кен горизонттары.

© А.Е. Абетов, А.А. Ауесбек*, 2024
Казахский национальный технический университет им. К.И. Сатпаева, Казахстан, Алматы.
E-mail: auyesbek99@mail.ru

ГЕОЛОГО-ГЕОФИЗИЧЕСКИЕ КРИТЕРИИ ЖЕЗКАЗГАНСКОГО РУДНОГО РАЙОНА В ЦЕНТРАЛЬНОМ КАЗАХСТАНЕ

Абетов А.Е. — доктор геолого-минералогических наук, член-корреспондент Национальной академии наук Республики Казахстан, профессор кафедры геофизики и сейсмологии Института геологии и нефтегазового дела им. К. Турысова, Университет Сатбаева, Алматы, Казахстан
E-mail: abetov.auez@mail.ru, https://orcid.org/0000-0002-1866-7677;
Ауесбек А. — студент магистратуры Казахского национального исследовательского технического университета имени К.И. Сатпаева, Институт имени К. Турысова, кафедра «Геофизики и сейсмологии», Алматы, Казахстан
E-mail: auyesbek99@mail.ru, https://orcid.org/0009-0000-5376-0706.

Аннотация. Изучены стратиграфия, литология и структура разведанных месторождений и рудопроявлений меди, зональность размещения минералов медных руд в Жезказганском рудном районе, в котором эндогенная природа руд подтверждается набором специфических элементов, высокой температурой рудообразующих растворов и отсутствием пострудного метаморфизма. Уникальность Жезказганского месторождения меди проявляется в огромной вертикальной мощности рудной минерализации на сравнительно небольшой площади и на малых глубинах, пластообразной форме и приуроченности к магматическим породам основного и ультраосновного составов. Обосновано большое участие тектонических дислокаций, эффузивного и интрузивного магматизма в формировании рудоносных горизонтов, разнопорядковых структур, разломов и систем трещиноватости, служивших проводниками и локализаторами рудной минерализации. Наблюдается коррелируемость изолиний положительных остаточных аномалий гравитационного поля со структурным планом на самом Жезказганском месторождении меди и за его пределами. Выполнено районирование данного месторождение по интенсивности аномалий Δg_a, глубине залегания и стратиграфическом диапазоне рудовмещающих горизонтов. Дан прогноз о возможности выявления новых рудных залежей. Выявлено следующее характерное сочетание критериев, характеризующих медное оруденение в Жезказганском рудном поле: система высокоградиентных и интенсивных максимумов аномалий геомагнитного поля, концентрация редких очагов землетрясений на глубинах до 20 км и умеренная амплитуда новейших движений земной коры, линейно-вытянутые относительные максимумы и минимумы региональной трансформанты гравитационного поля, избыток плотностных масс по внутрикоровой трансформанте, экстремально высокие значения плотности теплового потока, температур на срезе

глубин 10км и 30 км, выступы по поверхностям Мохо и гранулит-базитового слоя, коррелирующие с основными и ультраосновными породами в составе консолидированное коры. Морфология и ориентация аномалий геофизических полей согласуется с ориентацией и характером проявления дизъюнктивной тектоники, где по плоскостям глубинных разломов допускается процессы глубинного тепломассопереноса.

Ключевые слова: медистые-песчаники, *литолого-структурный контроль*, гравитационное и магнитное поле, зональность оруденения, рудоносные горизонты

Introduction

Central Kazakhstan is a unique metallogenic province in Kazakhstan, hosting significant copper deposits (up to 36.3 %). The geological structure and localization of copper ores in the Zhezkazgan ore region have been extensively studied by researchers such as I.S. Yagovkin, K.I. Satpaev, T.A. Satpaeva, N.G. Kassin, M.P. Rusakov, G.L. Padalka, N.G. Razumovsky, T.I. Preobrazhensky, V.I. Shtifanov, S.Sh. Seyfullina, Sh.E. Esenova, L.V. Kopyatkevich, G.D. Mladentsev, L.F. Narkelyun, N.B. Golodnova, N.N. Nuralin, and others.

Significant contributions to the study of the geological structure of the Zhezkazgan ore field were made by employees of geophysical expeditions of the Kazakh Geophysical Trust and geological departments under the general guidance of M.D. Morozov, A.P. Gavel, V.N. Ivanov, V.V. Brodov, G.R. Bekzhanov, A.F. Igoshin, and others.

Materials from regional geophysical studies in Central Kazakhstan (including the Zhezkazgan ore region) have been summarized in works by M.D. Morozov, V.V. Brodov, G.R. Bekzhanov, R.A. Eydlin, O.D. Ivanov, B.I. Zhurbitsky, A.L. Kolik, V.I. Goldschmidt, M.V. Kuminova, A.V. Stroitelev, I.P. Benevolensky, B.R. Yumanov, Kazanli, F.S. Moiseenko, I.I. Kronidov, A.S. Kumpan, and others (Daukeev et.al., 2002: 216).

Copper deposits explored in copper-bearing sandstones play a leading role in mining volumes. In 2006, out of the total copper production in Kazakhstan (442.6 thousand tons), the share of copper from the Zhezkazgan group of deposits amounted to 200.7 thousand tons (45.3 %). Specifically, the volume of extracted ore reached 24.194 million tons with an average copper content of 0.83 %, and the majority is attributed to Zhezkazgan – 19.827 million tons of ore with an average copper content of 0.91 %.

At the Zhezkazgan ore region, explored copper deposits and manifestations are concentrated in the terrigenous sediments of the Middle and Upper Carboniferous and in the terrigenous and carbonate formations of the Upper Devonian and Lower Carboniferous (Satbayev, 1967: 279; Satbayev, 1968: 312).

In these sediments, the Zhezkazgan, Western Saryoba, Kipshakbay, Karashoshak, Itauz, Taskura deposits and the Zhaman-Aibat deposits have been explored (Figure 1).

The copper-polymetallic bodies in the Uytas deposit (Uytas, Berdiken, Koshkumabay areas) are associated with the carbonate sequence of the Upper Devonian-Lower Carboniferous. In coeval conglomerates and sandstones, copper mineralization occurrences are identified in the Altynkazgan, Karadin, Terecty, Baytleu areas, where they are localized within gray gravelites, sandstones, and conglomerates, often associated with quartz-barite veins (Abdulin, 1981).

The conducted research is based on diverse and multi-scale studies carried out by different authors, organizations, and in different years.

The integration of this extensive dataset for the Zhezkazgan ore field required the utilization of information on stratigraphy, lithology, deep tectonics, seismicity, distribution of regional, zonal, and local anomalies of gravity, geomagnetic, and thermal fields, latest movements of the Earth's crust, as well as associated anomalous heterogeneities of the Earth's crust and their role in the ore formation process (Nusipov et.al., 2007).

Based on the results of a systematic analysis of geological-geophysical data using modern software, a distinctive combination of geological-geophysical criteria characterizing only copper mineralization in the Zhezkazgan ore field has been identified.

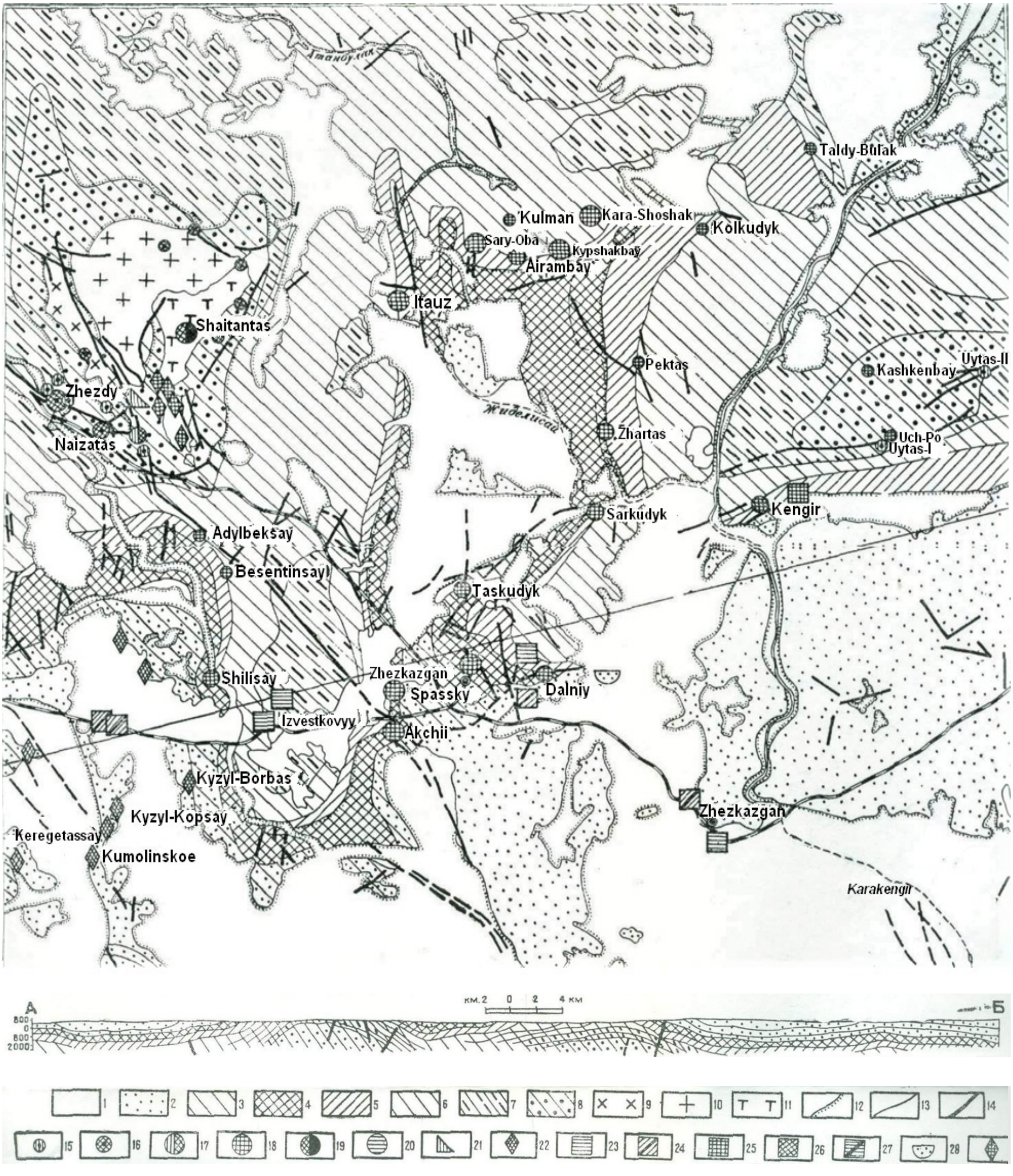

Figure 1 – Geological map of the Zhezkazgan ore region (according to F.V. Bespalov).

1- Quaternary and Tertiary systems (alluvial, eluvial, proluvial sediments); 2- Permian system, Kengir suite (marls, limestones, sandstones, aleurolites, salts); 3- Permian system, Jidelisay suite (argillites, aleurolites, sandstones); 4- Middle and Upper Carboniferous, Zhezkazgan suite (sandstones, aleurolites, argillites, conglomerates); 5- Middle Carboniferous, Taskuduk suite (sandstones, aleurolites, argillites, chert); 6- Lower Carboniferous, Viséan substage (sandstones, aleurolites, limestones); 7- Lower Carboniferous, Tournaisian substage (limestones, marls, shell rock, dolomites with silica concretions); 8- Devonian system (limestones, dolomites, sandstones, conglomerates, andesitic porphyrites, quartz porphyries, quartz albite porphyries and their tuffs); 9- Archean deposits (mica-plagioclase schists, quartz-plagioclase schists, quartzites); 10- Devonian biotite granites; 11- Devonian granodiorites and syenite-diorites; 12- Boundary of unconformable deposition; 13- Boundary of normal stratigraphic contact; 14- Fault disruptions; Mineral deposits and occurrences: 15- Iron, 16- Manganese, 17- Iron-manganese, 18- Copper, 19- Nickel and cobalt, 20- Lead, 21- Mountain crystal, 22- Amphibole asbestos, 23- Limestone, 24- Building sand, 25- Brick clays, 26- Clay gypsum, 27- Marls, 28- Rock salt, 29- Chrysotile asbestos.

Materials and research methods

The factors controlling the distribution of copper mineralization became the focus of the research, and the results are reflected in this article.

Lithological and structural control of copper mineralization. A unique feature of the Zhezkazgan copper deposit is the multilayered nature of the ore with the localization of industrial ore bodies only in the layers of medium- to coarse-grained sandstones and conglomerates of the Middle-Upper Carboniferous (Abdulin, 1981).

On the central part of the deposit, the ore-bearing sequence is divided into two suites: the lower Tasquduk and the upper Zhezkazgan, separated by layers of Raimund conglomerates.

The ore-bearing sequence comprises 22 layers of gray sandstones, of which 19 are ore-bearing, hosting 27 ore deposits.

Areas with equal proportions of thickness between gray and red sandstones, with sustained thickness and extent, are most favorable for locating industrial ore bodies (Smelov et.al., 1983: 145–157; Yesenov, 1968).

Tectonic control. The Zhezkazgan ore region is geologically distinguished within the areas of Early Caledonian consolidation, characterized by complex tectonic zoning and widespread magmatic rocks (Korobkin, 2011: 71–77).

Throughout the Paleozoic and partially in the Mesozoic-Cenozoic, this region experienced longitudinal and transverse shift displacements, thrust movements, progressively complicating the initial structural plans.

Volcanic formations and intrusive magmatism have a significant presence in this area. Key milestones in the manifestation of the latter include the Cambrian period (layered peridotite-gabbro-norite and alkaline-ultramafic complexes) and the end of the Ordovician to the beginning of the Silurian (large masses of granites, granodiorites, and diorites) (Korobkin, 2011; Malchenko et.al., 2002).

The endogenic nature of the Zhezkazgan depression's ores is indicated by the presence of trace elements (Re, Ni, Co, Os, Ag), while the absence of post-ore metamorphism and the high temperature of ore-forming solutions are indicated by the presence of chalcopyrite-bornite-digenite solid solutions and cubic modification of chalcopyrite, known as putoranite. This allows for the assumption of intrusive control over copper mineralization (Bekzhanov et.al., 2000: 396).

The ore-bearing sequence in the Zhezkazgan copper deposit forms complex anticlinal and synclinal structures. The major commercial reserves of copper and polymetallic ores are localized on the anticlinal uplifts and flexures of the first order, such as the Kengir and Zhilandin ones (Bekzhanov et.al., 2000; Miroshnichenko et.al., 2002).

The southeastern boundary of the ore field is limited by the Terektin fault, and the western boundary is characterized by a system of large meridional Ulutau faults with a significant extent (up to 800 km) and a width of about 150 km.

According to N.N. Nuralin (1976), regional faults formed during the creation of large block structures of the first order. Subsequently, during the next stage of tectonic activity, folds of the second-third order, layer zones of shifts, stratification, and fracture breaks developed under the conditions of lateral compression of rocks and the influence of tangential forces acting from the southeast to the northwest.

The process of ore deposition is believed to be associated with the formation of folds of the second order and related breaks. The final stage is associated with the formation of post-ore movements, such as strike-slip and throw-slip movements of sublatitudinal direction (Miroshnichenko et.al., 2002: 271).

It is essential to emphasize that the main part of copper reserves (up to 75 %) is concentrated in the dome structures and flexural inflections, while the remaining 25 % is found in synclinoria of the second order (Yesenov, 1968).

The Pokrovsky, Krestovsky, and Annensky ore-bearing domes were identified in the Zhezkazgan copper deposit. In cross-section, they are characterized by a chest shape (Figure 2). The domes axes are elongated in a northeast direction and plunge to the southwest. Ore mineralization is traced for several kilometers on each of them in the form of arcuate zones.

Local folding is accompanied by the development of synchronous and cross-cutting fractures, as well as intra- and inter-layer zones of fracturing, which served as conductors and localizers of ore mineralization (Satbayev, 1968; Smelov et.al., 1983). Fracturing reached its maximum development in areas with the distribution of brittle, less plastic sandstones and conglomerates. In such areas, ore deposition occurred from hydrothermal solutions due to a sharp drop in pressure and temperature.

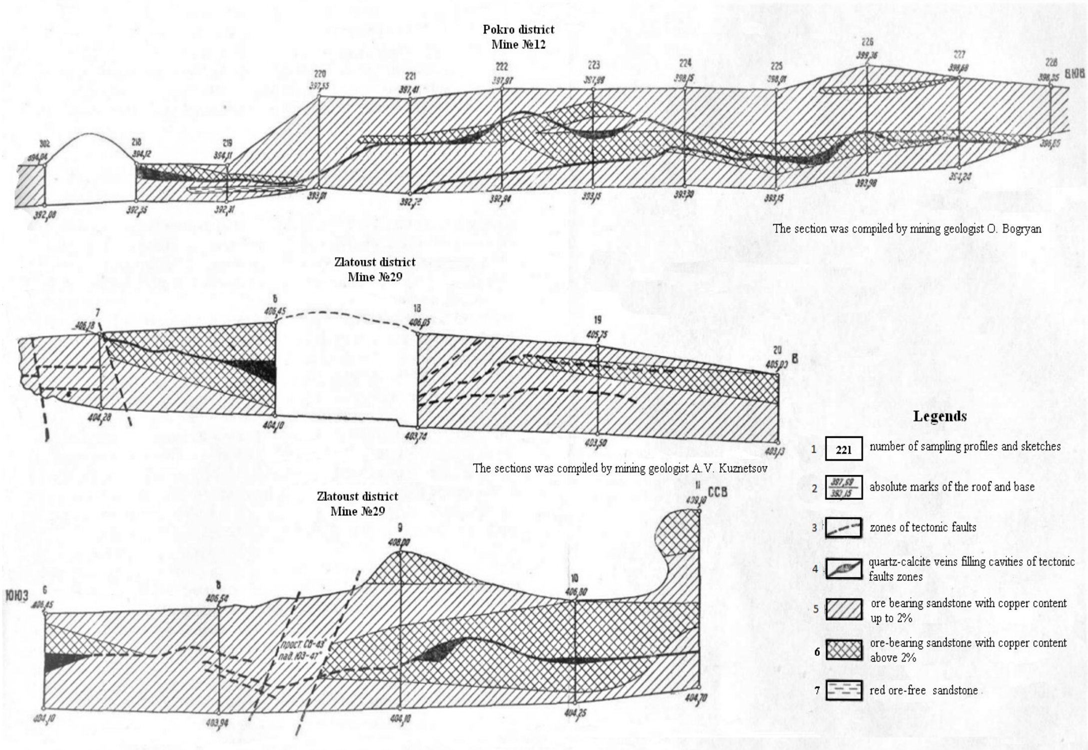

Figure 2 – Jezkazgan. Tectonics of ore deposits based on secondary development data (modified from Kuznetsov A.)

Zonation of ore mineralization. In the copper deposit of Zhezkazgan, a consistent pattern in the composition of ore deposits has been established as investigated by T.A. Satpaeva. The central part of this deposits typically exhibit enrichment in copper, characterized by the presence of chalcosine and bornite. Moving towards the periphery, these give way to chalcopyrite, galenite, and sphalerite. Beyond the ore bodies, iron sulfides, such as pyrite, marcasite, and occasionally arsenopyrite, are prevalent.

The entire deposit is categorized into four groups - lower, middle, intermediate and upper (Satpaeva et.al., 1986: 59–65). The lower group comprises the first and second ore horizons, dominated by chalcosine and galena ores.

Ascending through the geological stratigraphy, the middle group encompasses the ore bodies of the third and fifth horizons, demonstrating an expanded development area. Aligned in a northwest direction in conjunction with the deposits of the lower group, they collectively form the most extensive ore zones.

A notable feature is the substantial vertical thickness of ore mineralization observed in Central Jezkazgan, spanning an interval from -50 to -450 meters in absolute elevation, yet covering a relatively small area of 30 square kilometers.

The formation of the Zhezkazgan copper deposit occurred at a shallow depth, specifically within 600-1800 meters from the dome part of the volcano-plutonic structure. Reconstruction results indicate that its elevation above the contemporary Earth's surface did not surpass 1100 meters (Abdulin, 1981; Lyubetseva et.al., 2009).

The occurrence conditions and morphology of ore bodies are characterized by significant variability. In the northern part of the deposit, ore bodies exhibit a tabular form and are continuously traced by delve and boreholes to depths of up to 550 meters. They are oriented in a southeast azimuth (120–130°) and form a joint ore zone, comprising closely situated tabular bodies that are associated with magmatic rocks of both primary and ultrabasic compositions.

On the northwest flank of the deposit, mineralization is represented by steeply dipping bodies towards the southwest (60–80 °). With increasing depth, there is a flattening of the ore bodies (Lyubetseva et.al., 2009).

The extension of the zone then sharply changes to a sub-meridional direction, and ore bodies are traced further in a southern direction for an additional 300 meters.

Residual Gravity Field Anomalies. At the Zhezkazgan copper deposit, geophysical features of copper mineralization were extensively utilized in the initial stages of exploration from 1926 to 1932. The first gravimetric studies were conducted during the period 1929–1932. The results of gravity measurements were used to solve problems of regional geology and tectonic zonation.

During this period, electric exploration methods such as equipotential – line, induction, intensity, and natural sources were carried out in order to directly search for copper ores.

Due to the good electrical conductivity of ores with high copper contents, electrical anomalies were created, the verification of which by drilling indicates the high efficiency of the work carried out. Out of 24 verified anomalies, industrial ores were identified within the contours of 13 anomalies, two had deposits with disseminated mineralization, three contained oxidized ores, and only six anomalies turned out to be barren. Thus, within the contours of 75 % of the verified anomalies, ore deposits were identified.

However, in subsequent years, geophysical study has been suspended, and in the further exploration of the Jezkazgan copper deposit, geophysical methods were not used. This can be attributed to the successful geological results obtained from drilled exploration wells. As a result, the final nature of the gravity anomaly has not been conclusively established until now.

The correlation of gravity anomalies with copper mineralization is evident over a significant part of the Zhezkazgan deposit, including ore zones such as Pokro-North, Zlatoust, Pokro-Southwest, Krestovsky, and Akchii-Spassky. In the central part of this deposit, the maximum values of residual gravity anomalies (+2.75 +3.25 mGal) are observed, elongated in a northeast direction and associated with the Pokrovsky dome (Figure 3).

An exception is the Annensky area, where oxidized ores with low density predominate, and intense negative minima Δg_a are extended.

In the apical dome, the eighth and ninth ore-bearing horizons stand out, characterized by relative maxima of positive residual gravity anomalies.

For the western part of the deposit, there is a gradual decrease in the intensity of residual gravity anomalies with the descent of the ore-hosting thickness and its overlying by the Lower Permian sediments of the Zhideleysay Formation. The behavior of isolines of the residual gravity anomalies correlate entirely with the general distribution of rocks (Figure 3).

The boundaries of the deposit in this area are demarcated by the +1.0 mGal isoline. Beyond the deposit, despite the proximity to the ground surface of the ore-bearing horizons of the Zhezkazgan and Taskuduk suites, the intensity of residual anomalies decreases to +0.25 to +0.5 mGal and less (Figure 3).

On the southwest and southeast peripheries of the deposit, both positive and negative isolines appear. The reliability of their correlation becomes less certain with the structural plan of ore-bearing horizons.

For the northern and northeastern parts of the deposit, the boundary of copper ore extension is accompanied by a more elevated gravitational field, the amplitude of which varies within the range of +1.25 to + 1.75 mGal, decreasing to +0.8 mGal in some areas (Figure 3).

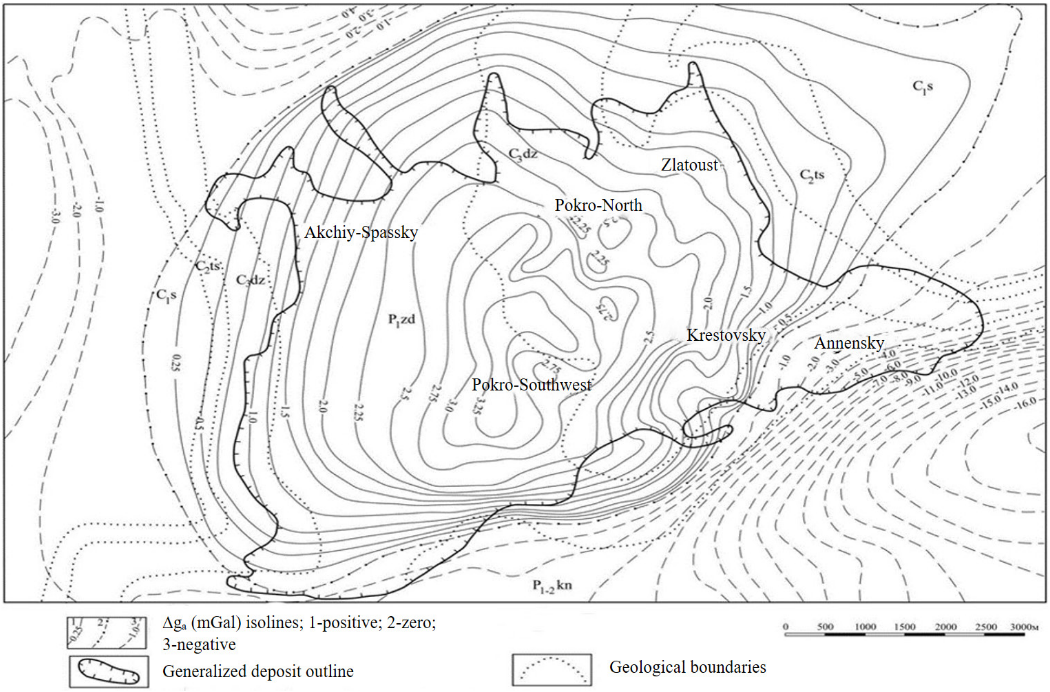

Figure 3 – Map of the residual gravity field of the Zhezkazgan deposit (modified from Suleimenov, Kogai, et al., 1983).

The contour of positive anomalies Δg_a exhibits scalloped edges. In some areas, these can be traced beyond the Zhezkazgan deposit, extending up to 2.0–2.5 km. The displacement of residual anomalies of the gravitational field beyond the boundaries of the explored contours of the deposit involves the identification of new ore deposits, taking into account the lack of knowledge to a depth by exploratory drilling.

In the western part of the deposit, the bottom of the ore-bearing deposits of the Taskuduk horizon corresponds to anomalies Δg_a values with an amplitude of 0.25–0.45 mGal, while for the northeastern part of the deposit, elevated values ranging from 0.4–0.8 mGal are characteristic.

This implies the presence of subsurface objects with increased density, such as deposits from the Visianian and Serpukhovian stages of the Lower Carboniferous with a density of no less than 2.70–2.72 g/cm³, potentially hosting copper-polymetallic deposits, associated with lower stratigraphic horizons of the Famennian and Frasnian stages of the

Upper Devonian (Satpayev, 1968).

Thus, based on gravimetric survey data, undiscovered ore deposits may exist in the northern part of the Zhezkazgan deposit, localized at great depths compared to the southern and southeastern flanks.

According to drilling data, ore deposits drilled on the southeastern flank of the deposit are shallow and associated with the Zhezkazgan suite. The boundaries of ore occurrence in this part of the deposit are accompanied by the highest residual gravity gradient values, ranging from 0.2 to 0.4 mGal per 100 m, whereas for the southwestern part, it is lower, around 0.1 mGal per 100 m (Figure 3).

On corresponding opposite sides, gravity field gradients vary from 0.12 to 0.5 mGal/100 m and 0.03-0.07 mGal/100 m, aligning well with the aforementioned values anomalies Δg_a.

All of this indicates the urgent need for exploration drilling of ore-bearing horizons on the northern and northeastern flanks of the deposit, where elevated values of residual anomalies Δg_a have been identified.

Results and discussion

The nature of the gravity anomaly has not been definitively established up to the present time. The main difficulty in its interpretation lies in the diversity of sources that created the observed anomaly and the lack of information on the parameters of presumed disturbing objects. This significantly limits the possibility of conducting a comprehensive quantitative interpretation of the anomalous gravitational field.

Based on the interpretation of geophysical and geochemical data for the Zhezkazgan ore field by Suleimenov K., Kogai S., et al. (1983) predicted ore zones with excess density of 0.2 g/cm³ and 0.3 g/cm³ under known ore deposits into the lower horizons 1–3 of the Taskuduk Suite in Central Jezkazgan. These, together with the explored deposits, contribute to the observed cumulative anomaly.

However, out of the drilled 51 exploration wells with depths up to 1551 meters, only 3 wells revealed separate ore bodies with copper industrial mineralization with a thickness of no more than 3 meters. Additionally, balance sheet lead ores were identified in 4 wells, and unbalanced copper and lead ores were found in 6 wells. The remaining 38 wells were ore-free or encountered poor mineralization with copper content not exceeding 0.1–0.2 %.

Bryzgalov S. (1987–1989) attempted to explain the nature of gravity anomalies by deep sources, with a cumulative gravitational effect caused by the influence of ore deposits, dense Paleozoic rocks, and the Caledonian basement.

In the structure of the anomaly, the predominant role was assigned to undivided formations of the Cambrian-Ordovician with increased density (2.78 g/cm³), the thickness of which in the tectonic block limiting the deposit reaches 2.0–2.5 km.

However, geological data indicate that dense basement rocks have not been penetrated by drilling. For instance, according to the results of the deep well Kyzylkakskaya P-1, located 80 km south of the Zhezkazgan deposit, Cambrian-Ordovician rocks were not identified, and Devonian rocks at a depth of 2210 meters discordantly overlie ancient Proterozoic deposits represented by metamorphic schists.

Nevertheless, the study of the geological structure of the Caledonian basement indicates its specific contribution to the formation of the gravity anomaly.

In our opinion, the maxima of residual anomalies Δg_a may be associated with Ordovician intrusions of ultrabasic and basic compositions identified in the Eskulinsky dome, located 30–35 km northwest of the Zhezkazgan deposit.

To some extent, this opinion is confirmed by the data from regional geophysical studies (Zhurbitsky, 1968), according to which hidden depths of hyperbasite formations are developed to the west and south of the deposit.

Increasing the reliability of forecasting the placement of copper ore in the Zhezkazgan ore field is undoubtedly directly related to the data of deep tectonics, seismicity, the distribution of regional, zonal, and local anomalies of gravity, geomagnetic, and thermal fields, recent movements of the Earth's crust, as well as their associated anomalous heterogeneities of the Earth's crust and their role in the formation of copper deposits.

Based on a systematic analysis of the extensive set of geological-geophysical data using modern software, a combination of criteria characterizing only copper mineralization in the Zhezkazgan ore field has been identified. Among these criteria are:

1. A contrastingly expressed zone of geomagnetic field anomalies ΔT_a, elongated in the northwest direction and consisting of three maxima with increased intensity (+200 to +400 nT) and sharp gradients of change in this parameter. This anomaly zone is likely caused by hidden (uneroded) intrusions of intermediate-mafic compositions, playing a significant role in metamorphic processes (Abetov et.al., 2023).

2. Moderate amplitude of recent crustal movements (+300 to +400 meters or more), correlating with identified active faults. Anomalies of recent crustal movements are distinguished by a polygonal shape of the tectonic elements forming them (Abetov et.al., 2023).

3. The presence of linearly elongated relative maxima and minima of the regional transformant of the gravity field, extending in the meridional direction. The intensity of the latter varies widely from +25 to +40 to -55 to -155 mGal. The formation of regional decompacted objects is associated with the uplift of mantle material and its intrusion into the Earth's crust, followed by the opening of rift zones and eruptions of high-alkaline basalts (Timush, 2011: 290).

4. The intracrustal transformant of the gravity field records an excess of density masses, manifested in variously oriented, strongly dissected anomalies of positive sign with intensities ranging from +20 to +70 mGal. These anomalies correlate with the extension of deep faults and the structural plan of tectonic elements on the Earth's surface. The configuration and sizes of these anomalies vary in a complex dependent relationship on the internal structure and composition of the folded basement (Timush, 2011; Abetov et.al., 2020).

The local transformant of the gravity field with anomaly intensities of -10 to +15 mGal is characterized by anomalies of different sizes and orientations, with polygonal, elongated, and isometric shapes that not amenable to zoning and are often not controlled by faults. It reflects the high-frequency gravitational effect from local near-surface objects of the Earth's crust up to depths of 5–7 km and likely has a neotectonic origin (Timush, 2011; Abetov et.al., 2020).

5. Increased readings of heat flow density, characterized by extremely high values (50–60 mW/m², areas up to 80 mW/m²). The morphology of the anomalous heat flow area corresponds to the nature of tectonics faults, where processes of deep heat transfer are allowed along the planes of deep faults (Smirnov, 1980:150).

Anomalously high temperature values in the slices at depths of 10 km (up to 300 °C and more) and 30 km (up to 1000 °C and more), correlating with basic and ultrabasic rocks with increased thermal conductivity (up to 0.6–1.2 kJ/(kg*K)) comprising the consolidated crust. The sub-meridional and northwestward extension of the area with increased geothermal anomaly values coincides with the orientation of regional faults (Moiseenko et.al., 1983; Abetov et.al., 2019).

Areas with increased geothermal anomaly values are characterized by linearly elongated anomalies of the geomagnetic field with a sub-meridional orientation and enhanced value the density of the consolidated crust, directly related to the different thermal conductivity of rocks constituting the consolidated crust.

6. Recorded earthquake sources, concentrating at depths of 4–21 km and localized near deep faults or fault nodes, delineating tectonic blocks with varying intensity and sign of geomagnetic field anomalies. This observation correlates with seismic activity and recent movements of the Earth's crust (Mikhaylova et.al., 2018: 146–155; Mikhaylova, 2013).

7. Highs on the top of the granulite-basalt layer (up to 15–20 km) and on the Moho surface (at depths of 40-42 km). However, while the highs on the granulite-basalt layer aligns with the orientation of deep faults and the direction of tectonic elements, structures on the Moho have complex geometric forms and are not controlled by faults. Their predominant extension is orthogonal to deep faults (Shacilov et.al., 1995; Lyubetskiy et.al., 2000; Shabalina, 2010: 128–133).

Based on the results of our study, the following rational set of geophysical works is recommended for the Zhezkazgan ore field – magnetic exploration, electrical exploration using induced polarization (IP) and transient electromagnetic (TEM) methods.

As additional research, gravity exploration and geochemical surveys could be recommended.

Magnetic exploration will provide results that can be used for geological interpretation of geophysical information: identification of rock assemblages, tectonic structures, mapping the systems of tectonic faults, and intrusive formations (endo and exocontacts).

IP and TEM methods will allow accurate and visual delineation of the copper-bearing zone, as well as tracking the main geological structures, determining their spatial position, and elements of occurrence.

Therefore, the recommended set of geophysical methods will allow to effectively solve the assigned exploration problems.

Conclusion

1. In the Zhezkazgan ore region, explored copper deposits and manifestations are concentrated in terrigenous sediments of the Middle and Upper Carboniferous, as well as in terrigenous and carbonate formations of the Upper Devonian and Lower Carboniferous. Copper reserves in this region are concentrated in the domes and flexural folds of II and III order structures.

Longitudinal and transverse-shift, overthrusting horizontal displacements, volcanic formations, and intrusive magmatism of all known types (ultramafic, mafic, intermediate, acidic, alkaline) have a significant presence.

The endogenic nature of copper ores in the Zhezkazgan region is confirmed by a set of specific impurity elements, high temperatures of ore-forming solutions, and the absence of post-ore metamorphism.

This ore region is located at the junction of regional faults, which played a crucial role in the formation of structures of different orders, faults, and fracture systems, acting as conduits and localizers of ore mineralization.

The Zhezkazgan copper deposit is characterized by a tremendous vertical thickness of ore mineralization over a relatively small area. Ore bodies formed at shallow depths have a tabular shape and are associated with magmatic rocks of mafic and ultramafic compositions.

Central parts of ore bodies are enriched in copper and composed of chalcocite and bornite, which are gradually replaced by chalcopyrite, galena, and sphalerite towards the periphery. Beyond the ore bodies, iron sulfides, represented by pyrite, marcasite, and occasionally arsenopyrite, are developed.

2. In most of the Zhezkazgan copper deposit, there is a correspondence between the isolines of positive anomalies and the structural plan of the deposit, including the extension of ore-hosting rocks. Anomalies of variable sign correspond to the marginal parts of the deposit. The correlation level here becomes less reliable.

The possibility of detecting new ore deposits is confirmed by the traceability of positive anomalies in certain areas outside the contour of the Zhezkazgan deposit.

In the western part of this deposit, weakly intensive gravity anomalies Δg_a are observed, while in the eastern part, there is an increase in the intensity of these anomalies. This can be attributed to the greater depth of copper deposits and the expansion of the stratigraphic range of productive horizons due to the inclusion of the Famennian and Frasnian stages of the Upper Devonian.

3. The nature of gravitational anomalies has not been definitively established to date due to the diversity of sources and parameters of gravimetrically disturbing objects. According to existing concepts, residual gravitational anomalies have been associated with: a) deep-seated hyperbasite formations developed to the west and south of the Zhezkazgan copper deposit (Zhurbitsky, 1968); b) ore zones with excess density beneath known ore deposits (Suleimenov et al., 1983); c) predominant role of high-density undifferentiated formations of the Cambrian-Ordovician with increased density and thickness (Bryzgalov, 1987: 89).

Through a system analysis of geological-geophysical data, we identified a combination of geological and geophysical criteria characterizing copper mineralization at the Zhezkazgan ore field. Among these criteria are:

- a distinctly expressed system of high-gradient and intensive maxima of geomagnetic field anomalies (ΔT_a), linearly elongated relative maxima and minima of the regional transformant of the gravitational field, excess density on the intracrustal transformant, extremely high values of heat flow density and temperatures at depths of 10 km and 30 km, highs on the tops of Moho and granulite-basite layer correlating with the basic and ultramafic rock compositions with increased thermal conductivity in the consolidated crust.

- the morphology and orientation of anomalies in heat flow, geothermal fluctuations, geomagnetic anomalies, and the transformant of the gravitational field correlate with the orientation and manifestation of disjunctive tectonics, allowing for processes of thermal mass transfer along the planes of deep faults.

- concentrations of earthquake sources at depths of 4–21 km and moderate amplitudes of recent movements of the Earth's crust are localized around deep faults or fault nodes that separate tectonic blocks.

Based on the results of the carried out research, it is justified to recommend the following rational set of geophysical methods at the Zhezkazgan ore field: magnetic exploration, electrical exploration using induced polarization and transient processes. As additional study, gravity exploration and geochemical surveys are recommended.

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