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Geodynamics of the Shu-Ile ore zone: integration of geophysical, geochemical and cosmogeological methods

A.B. Baibatsha[1], M.K. Kembayev[1*], S.E. Rais[1], W. Yan[2], A.K. Amantayev[1], Y.T. Biyakyshev[1]

[1]*Satbayev University, Almaty, Kazakhstan*

[2]*University of Houston, Texas, USA*

**Corresponding author:* *m.kembayev@satbayev.university*

Abstract. The article presents the results of a comprehensive study of the Shu-Ile metallogenic zone using modern geophysical, geochemical methods and technologies of remote sensing of the Earth. The purpose of the study was to establish patterns of ore deposits within the zone based on new geodynamic approaches and the integration of multidisciplinary geological data. The relevance of the work is determined by the need to create sound predictive models of mineral deposits, including gold, polymetals and related elements, in conditions of a complicated geological situation and the exhaustion of lightly explored resources. During the research, data from gravimetry, magnetic surveying, electromagnetic sensing and remote sensing data, as well as geochemical characteristics of ore-bearing formations, were analyzed. These data were compared with the results of field observations, stratigraphic and tectonic constructions. A comprehensive analysis made it possible to identify zones of active interaction between the mantle and the earth's crust, manifested in the form of deep faults, subvertical conductive structures and tectonically weakened zones that play a key role in the formation of ore nodes. Based on a set of geophysical and geochemical features, a new approach to forecasting gold-sulfide and polymetallic mineralization is proposed. It involves modeling deep structures and assessing the degree of their influence on the surface manifestations of ore mineralization. The results obtained are of great practical importance: They can be used to optimize exploration activities, increase the efficiency of drilling programs, and minimize financial costs. The proposed methodology can be successfully applied in other metallogenic provinces of Central Asia, which emphasizes the versatility and practical significance of the work performed.

Keywords: *geodynamics, geophysical anomalies, ore-forming fluids, cosmogeological mapping, mantle plumes.*

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1. Introduction

The Shu-Ile ore zone in South Kazakhstan is one of the key geological structures in the region due to its rich ore resources. Deposits of gold (Akbakai ore field), copper, uranium and other minerals have been found in this zone, making it an important target for geological research and exploration. Traditional models of plume-tectonics, widely used to study geotectonics and geodynamics, are not always able to explain the peculiar geological structure of the area, including the mosaic of the lithosphere and the diversity of tectonic structures.

In recent decades, the concept of plume tectonics, which links geodynamic processes with upward convective flows of the mantle (mantle plumes), has become increasingly popular [1-6]. This model represents an alternative view on the formation of tectonic structures and ore zones. It assumes that mantle plumes play a key role in the uplift of matter from the Earth's depths, enriching the crust with metals and creating conditions for mineralization. In the case of the Shu-Ile zone, plume tectonics helps explain the presence of ring structures, deep fault zones, and the associated magmatism and ore deposits.

Studies and analysis of the geological structure and geodynamics of the Shu-Ile ore zone from the position of plume-tectonics showed its practical significance for predicting new promising areas. For this purpose, we used an integrated approach, including geological mapping, geophysical studies and remote sensing. A review of the literature data was carried out, which emphasizes the importance of works on the study of geodynamics from a new position and adaptation of the plume-tectonic model of Kazakhstan to assess the influence of plumes on the formation of mineral provinces.

1.1. Geological and tectonic context

The Shu-Ile ore zone is located within Southern Kazakhstan, which can be considered as an element of the Central Asian orogenic belt. This belt was formed as a result of a long geological evolution starting from the Neoproterozoic, which continued into the Paleozoic and ended in the Mesozoic-Cenozoic [7]. The zone is characterized by a complex system of faults, the development of magmatism and sedimentary basins, reflecting its multistage development.

a.baibatsha@satbayev.university; m.kembayev@satbayev.university; s.rais@stud.satbayev.university; wyan3@uh.edu; abylay.amantayev99@gmail.com; Biyakyshev.Y@stud.satbayev.university
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1.2. Historical overview of studies

Geological studies of the Shu-Ile Zone began in the third half of the twentieth century, when ideas about the formation of its mineral potential were established. In the 1980s, the fundamental series of works «Geology of the Shu-Ile region» was published, where the main tectonic elements of the zone were described [8]. However, this very valuable series of works was based on the ideas of the outdated paradigm and it needs to be interpreted on the basis of new theoretical ideas, which are confirmed in the practice of geological works. Modern studies have shifted the focus of geodynamics of the region to plume-tectonic concepts. The new model shows that the territory of Kazakhstan during the Paleozoic was affected by an active mantle plume, which influenced geotectonics and mineral formation [9].

1.3. Tectonic Features

The Shu-Ile zone includes several key structures:

– The Shu-Ile suture is a zone of deep faulting and crushing that has experienced vertical displacements. Along the faults, the fragmented blocks, depending on their inclination directions and vertical displacement amplitude, experienced compression and decompression, respectively, which led to local changes in the material composition of the geologic structures of this zone.

– The ring structures testify to the progressive influence of the mantle plume into the lithosphere during the Paleozoic, which is accompanied by active manifestations of magmatism and metasomatism [10].

– Deep faults served as channels for the uplift of mantle matter and its derivatives controlling ore mineralization [11].

As field geological studies show, these features of geodynamics of this zone are well connected with the provisions of the plume-tectonic concept and localization of ore mineralizations.

2. Materials and methods

The geological analysis of the Shu-Ile ore zone employed a comprehensive suite of methods to investigate both near-surface and deep-seated processes, integrating field observations, laboratory analyses, geophysical surveys, and remote sensing technologies. The methodology was designed to elucidate the complex geodynamic processes governing the formation of the Shu-Ile metallogenic zone, with a focus on plume-tectonic mechanisms. The study area, located within the early Caledonian zone of Kazakhstan and intersecting the Jalaiyr-Naiman geosuture, necessitated a multi-scale and multi-source data integration approach to delineate crustal structures and assess their metallogenic potential. The following methods were employed, building upon and extending previous research frameworks, including those outlined by Baibatsha et al. [3].

2.1 Geologic mapping

Geologic mapping formed the cornerstone of field-based investigations, involving systematic collection of data on the rocks composing tectonic structures, their age, composition, and spatial distribution. Fieldwork included detailed documentation of metamorphic, sedimentary, and magmatic complexes, with samples collected for petrographic and mineralogical analysis. These samples were examined in their natural occurrences and under laboratory conditions using optical microscopy to characterize mineral assemblages and textural relationships. The resulting data facilitated the construction of detailed geologic maps and cross-sections, providing a robust foundation for interpreting the structural and lithological framework of the Shu-Ile zone. Mapping efforts focused on identifying key tectonic features, such as the Shu-Ile suture, ring structures, and deep faults, which are critical for understanding ore localization.

2.2. Geophysical studies

Geophysical methods were employed to probe the subsurface structure of the Shu-Ile ore zone, complementing surface geological observations. These methods included gravimetry, magnetometry, and seismic profiling, each targeting specific aspects of the lithospheric architecture.

2.2.1. Gravimetry

Gravimetric surveys analyzed residual gravity anomalies to identify zones of increased or decreased density, which are indicative of subsurface lithological variations and structural discontinuities. Data were collected through ground-based measurements and supplemented by aerial surveys, processed using specialized software to generate anomaly maps. These maps revealed positive anomalies associated with ultramafic intrusions and negative anomalies corresponding to sedimentary basins, providing insights into the distribution of dense and less dense geological bodies.

2.2.2. Magnetometry

Magnetometric studies focused on mapping magnetic field variations to delineate buried intrusions and tectonic faults. High-resolution aerial surveys and ground measurements were conducted, with data processed to produce magnetic anomaly maps. These maps highlighted linear and isometric magnetic anomalies, reflecting the presence of magnetized bodies such as basic-ultrabasic formations and granitic intrusions. The Kypshakbay Allochthon, for example, was mapped with high-intensity linear magnetic anomalies exceeding +1000 nT, indicative of its ultramafic composition.

2.2.3. Seismic reflection profiling

Deep seismic sounding was applied to examine subhorizontal tectonic flow zones and their connections to crustal anisotropy and slip surfaces. Seismic reflection profiling, using the reflection wave method (RWM), captured intracrustal tectonic stratification, identifying subhorizontal and gently inclined flow zones within the crust. These zones, detected at depths of 10-15 km, divide the crust into upper and lower parts, with notable discontinuities along the boundary between the Early Precambrian basement and the Paleozoic cover. Steep suture zones, while not directly imaged by RWM, were inferred from surface outcrops and correlated with geophysical data, revealing their extension into the mantle. The Kendyktas profile, reaching depths of up to 50 km, underscored the central role of southwest-dipping structures in the Shu-Ile ore belt's crustal architecture.

2.3. Remote sensing

Remote sensing techniques utilized satellite imagery from Landsat ETM+ and ASTER to identify tectonic structures and ore-controlling factors. Image processing was performed using ERDAS IMAGINE and ArcGIS, enabling the detection of over 1800 linear structures, 119 ring structures, and numerous areal intrusive bodies [12]. The spectral characteristics of Landsat ETM+ (15-60 m resolution, with four visible, two near-infrared, and one thermal band) and ASTER (15-90 m resolution, with four visible, six near-infrared, and five thermal bands) provided high-fidelity data for structural mapping.

Digital elevation models (DEMs) based on SRTM (90 m resolution) and ASTER GDEM (25 m resolution) were integrated to enhance topographic and structural interpretations.

Cosmogeological mapping, a key component of remote sensing, involved the interpretation of satellite imagery to produce cosmostructural maps at a 1:200000 scale. These maps identified linear, ring, and arc structures, as well as areal bodies, across two structural levels of different ages. Over 3000 linear structures were identified, with geological interpretations provided for more than 1800, including fault disruptions, layering elements, acidic dykes, and geological boundaries. Faults were classified as primary (northwest-trending with significant right-lateral displacements), significant (subparallel with smaller displacements), and secondary (shorter, sub-vertical structures). Ring structures, totaling 119, ranged in diameter from 1.5 to 190 km and were categorized as metamorphogenic, magmatogenic (plutonogenic and hypabyssal), and tectonogenic, reflecting their diverse endogenous origins. Areal bodies, comprising over 450 magmatic rock bodies, included ultramafic and acidic intrusions, with their orientations and thermal alteration halos providing clues to their emplacement mechanisms.

2.4. Structural-geological mapping

Structural-geological mapping integrated surface geological data with satellite imagery analysis to classify tectonic units. Major structural elements, such as the Jalaiyr-Naiman megasynclinorium and Bolattau meganticlinorium, were delineated, reflecting first-rank tectonic features. This method combined field observations of outcrops with remote sensing data to map fault systems, fold structures, and intrusive bodies. The identification of layering elements and fault-associated cleavage highlighted folding structures, while acidic dykes were spectrally correlated with minor intrusions. This approach ensured a comprehensive understanding of the tectonic framework, particularly the role of northwest-oriented shear zones in controlling mineralization.

2.5. Stratigraphic correlation and petrological sampling

Stratigraphic correlation involved the study of sub-intrusive and intrusive sequences through fieldwork and laboratory analysis. SHRIMP zircon dating was applied to pinpoint key magmatic events in the Neoproterozoic and Paleozoic, providing temporal constraints on tectonic and mineralization processes. Petrological sampling focused on characterizing the mineralogical and petrographic properties of ore-bearing formations, with samples analyzed for their geochemical signatures to infer ore-forming processes.

2.6. Paleogeodynamic reconstruction

Paleogeodynamic reconstruction identified ancient rift zones, back-arc basins, and volcanic arcs instrumental in ore genesis. The study emphasized Ediacaran to Early Carboniferous tectonic regimes, reconstructing the geodynamic settings that facilitated mantle plume activity and crustal mineralization. This method integrated stratigraphic, geophysical, and remote sensing data to model the evolution of the Shu-Ile zone within the broader context of the Kazakh paleocontinent.

2.7. Interpretation of ophiolite complexes

The Shu-Balkhash ophiolite complex was evaluated for its metallogenic implications, with a focus on ophiolitic nappes and thrust sheets. Their structural evolution and mineral potential were assessed through field mapping and geophysical data, highlighting their role as conduits for ore-bearing fluids.

2.8. Data integration

The synthesis of geological, geophysical, and cosmogeological data enabled the construction of a three-dimensional geodynamic model of the Shu-Ile zone. This model integrated seismic profiles, gravity and magnetic anomaly maps, cosmostructural maps, and field observations to elucidate the interplay between mantle plume activity, crustal fault systems, and mineralization processes. The model highlighted the role of deep faults and ring structures as channels for mantle-derived melts, providing a predictive framework for identifying prospective ore deposits.

The methodology is built upon previous research on the Shu-Ile suture, extending earlier methods with additional material adapted from Baibatsha et al. (2024). By combining multi-scale data acquisition and advanced processing techniques, this study establishes a robust framework for understanding the geodynamic and metallogenic evolution of the Shu-Ile ore zone, with implications for regional mineral exploration.

3. Results and discussion

3.1. Geological structure

Analysis of available and obtained data has shown that the Shu-Ile zone is characterized by a mosaic structure with alternation of sedimentary basins, intrusions and tectonic blocks. Ring structures formed in the Neoproterozoic indicate the impact of the mantle plume accompanied by magmatic manifestation, and linear faults of the ring structure of northwest strike control the localization of ore formations.

3.2. Geophysical anomalies

Gravity and magnetic data revealed:

– Positive anomalies associated with ultramafic intrusions (Figure 1) [13,14];

– Negative anomalies corresponding to sedimentary basins (Figure 2) [15].

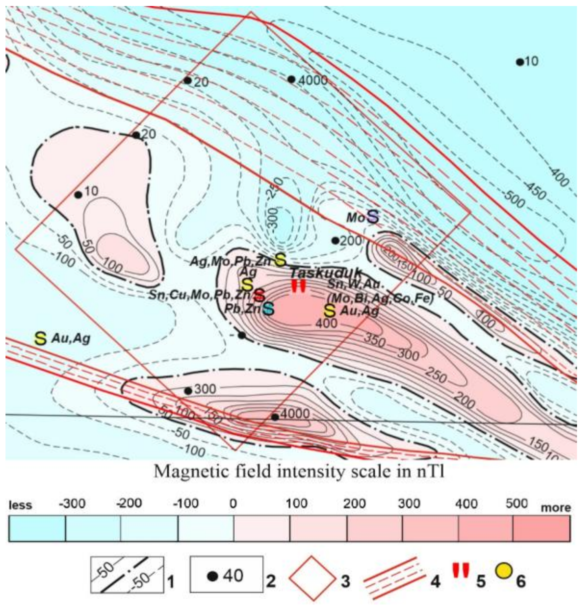

Figure 1. Residual anomalies map of the Ashyktas gold ore field: 1 - granitic (granite massifs are shown on the map of residual anomalies Δg: 1 – Mungli massif; 2 – Yergebulak massif deposits and occurrences of gold-secondary-quartzite type (in brackets – numbers on the maps): a - Ashyktas (4); b – Western Ashyktas (3); Eastern Ashyktas (5); 3 – small deposits and occurrences of gold-sulfide-quartz vein type: Ashyktas Zhilny (2), Kostakyr (6), Shubar (7), Khrustalnoye (8); 4 – Ashyktas gold ore field

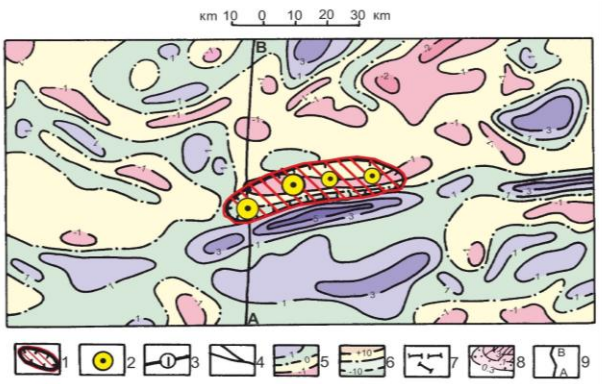

Figure 2. Scheme of the regional magnetic field of the Akbakai ore district: 1 – Kengir-Akbakai ore district; 2 – gold-sulfide-quartz deposits of Akbakai type (1 – large Akbakai, 2 – medium Svetinskoye, 3 – small Kengir, 4 – small Olimpiyskoye); 3 – deep faults separating structural-metallogenic zones; 4 – other faults; 5 – magnetic field isolines; 6 – isolines of residual gravity anomalies; 7 – reflecting sites according to seismic data; 8 – isolines of specific arsenic ore-bearing capacity (t/m/km²); 9 – line of geological-geophysical section

3.3. Remote sensing

Space images have identified key structures (Figures 3-5) including shear zones and intrusions associated with the Akbakai and Ashiktas deposits [16].

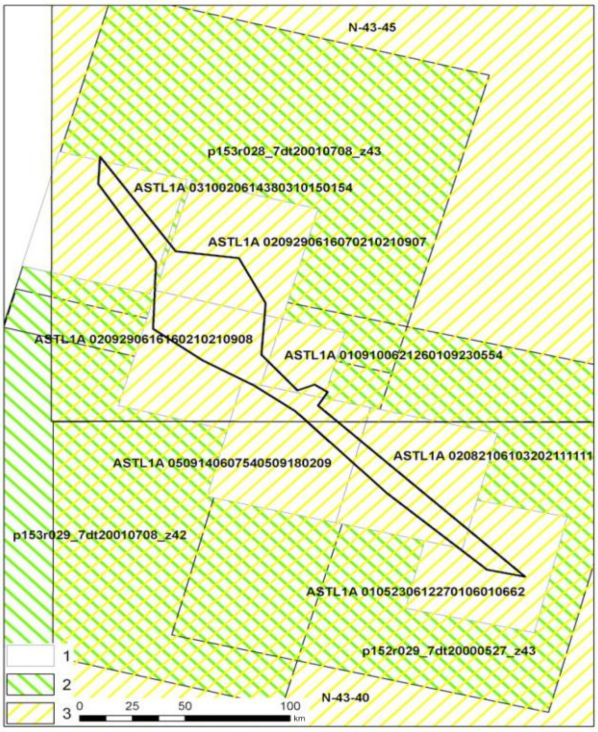

Figure 3. Scheme of coverage of the work area with space data. 1 – ASTER data; 2 – Landsat ETM+ data; 3 – mosaics based on Landsat ETM+ data

Remote sensing analysis has identified shear zones, dikes, and acidic intrusions that define key structural elements of the study area. These features show a clear spatial relationship with the Akbakai and Ashiktas deposits, underscoring their geological significance. Overall, the results demonstrate the effectiveness of satellite imagery in mapping structural and lithological controls on mineralization.

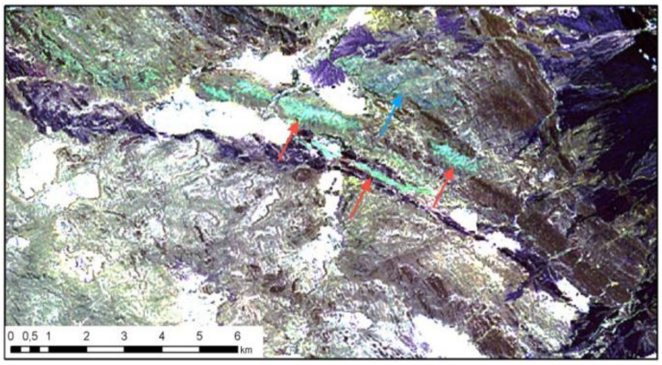

Figure 4. Dikes (shown by red arrows) and stem (shown by blue arrow) of acidic composition in Landsat ETM+ image processing materials

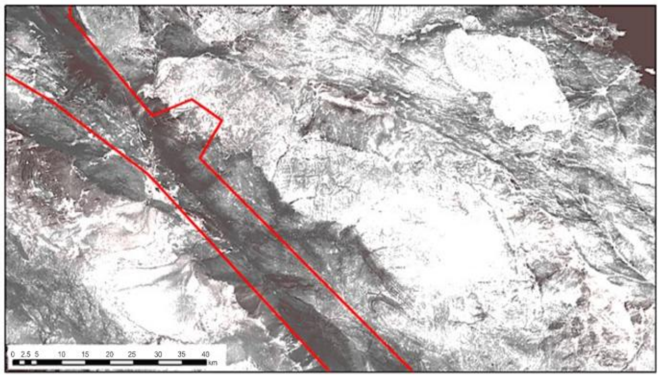

Figure 5. Bodies of sosdvig intrusions of acidic composition near the northeastern boundary of the work area in the materials of processing of Landsat ETM+ images by the «Iron oxides» method

3.4. Integration model

Synthesis of field, geological-geophysical and cosmogeological data shows that the formation of the Shu-Ile suture and its ore potential is plume-tectonic in nature. Based on the results of the studies, linear and ring structures that determine the localization and position of the area intrusive bodies in the mapped zone are clearly identified (Figure 6).

Role of mantle plumes. The data obtained from the performed studies indicate that the mantle plume, which led to the splitting of the Rodinia megacontinent and the isolation of the continent of Kazakhia in the Neoproterozoic, was active during the Paleozoic. The active plume led to the formation of ring structures and sutural zones, within which the corresponding geologic structures and geologic formations developed. Linear structures of different ranks were channels of upwelling solutions that enriched the crust with metals. Comparison of the proposed model with currently existing global analogs (the Hawaiian Plume) confirms its adequacy.

3.5. Practical significance

Plume-tectonic model of geodynamics of Kazakhstan can serve as a reliable theoretical basis explaining the formation of geological structures, and allows to predict new promising areas for mineral prospecting [17]. Ring zones of geosaturas are a system of deep faults and crushing zones. They serve as channels for the penetration of magmatic melts, create conditions for the formation of derivative magmas in the Earth's crust and their ore derivatives for the formation of ore deposits (Figure 7).

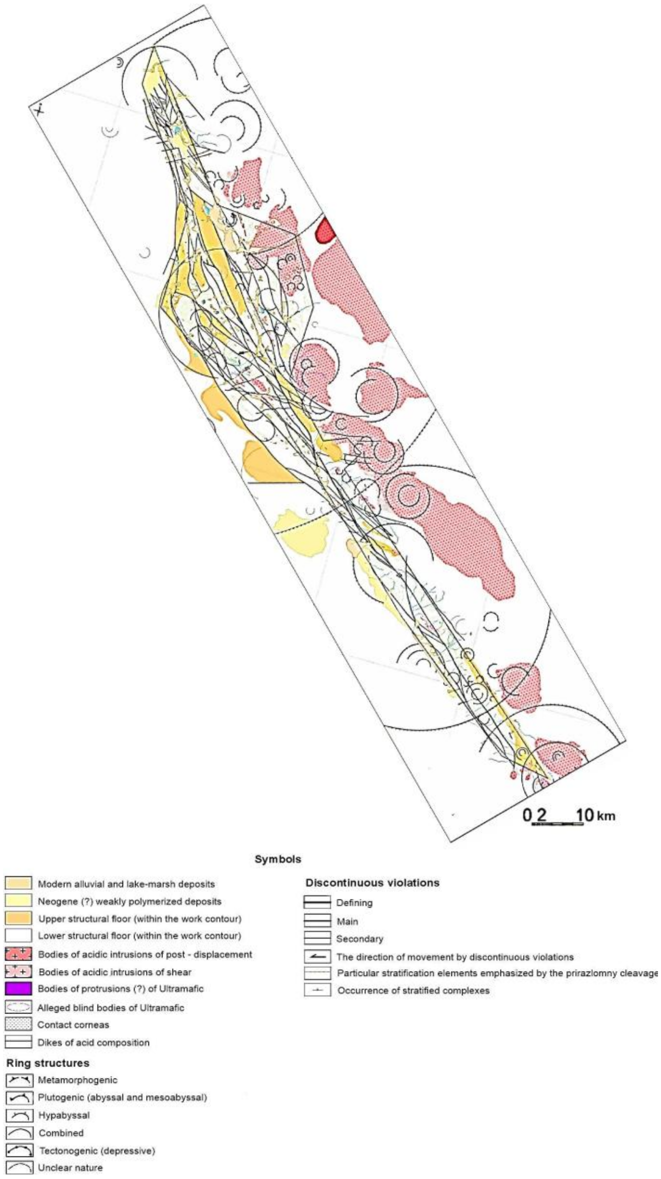

Figure 6. Spatial and structural scheme of the Jalaiyr-Naiman zone. M: 1:200 000

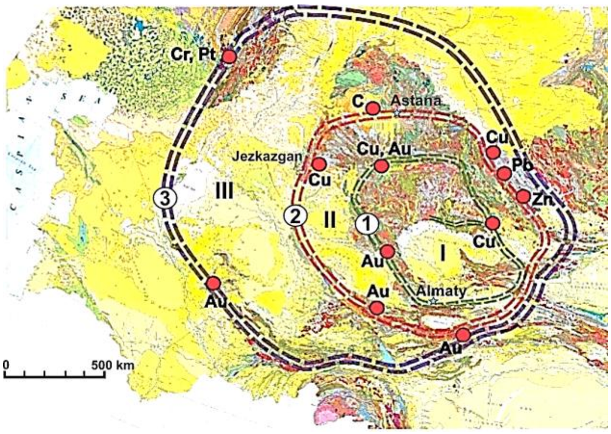

Figure 7. The location of metallogenic belts with the largest mineral deposits along geosuture zones (1, 2, 3) between ring structures (I, II, III) (by Baibatsha, 2020)

Thus, the plume-tectonic model provides both a genetic explanation of ore-bearing structures and a practical framework for guiding mineral exploration in Kazakhstan.

4. Conclusions

The study of the geological structure of the Shu-Ile ore zone in Kazakhstan based on the concept of plume-tectonics allowed us to create an adequate geological model of geodynamics to understand the complex processes that determined the geological evolution of this region. Based on the integration of geologic mapping, geophysical studies and remote sensing data, it was possible to confirm that mantle plumes played a key role in the formation of the tectonic structure and mineral potential of the Shu-Ile suture. These processes not only formed the unique lithospheric architecture of the region but also became a determining factor in the concentration of economically significant mineral deposits, including gold, copper and uranium. This approach allows us to rethink the geological history of the region, going beyond the traditional models of plate tectonics, which are often insufficient to explain the complex structural and mineral features of the territory and are not confirmed by the practice of geological exploration.

The main tectonic elements of the Shu-Ile zone, such as ring structures, linear deep faults and tectonic flow zones, area intrusive bodies, which led to the formation of economic minerals, were identified and characterized. The resulting survey data correlated with geophysical anomalies and remote sensing data to develop a holistic model linking mantle processes to crustal mineralization processes, providing a favorable context for mineral formation in the Shu-Ile Zone and understanding the relationship between deep-seated processes and metallogeny. This approach deepens our understanding of the geological evolution of Kazakhstan and enriches the science of plume-tectonics, providing a concrete example of its successful application in a region with high tectonic and mineralogical complexity. The proposed theoretical ideas about the geodynamics of the Shu-Ile zone are of practical importance in predicting promising areas for prospecting.

Author contributions

Conceptualization: ABB, MKK; Data curation: SER, AKA; Formal analysis: ABB, MKK, SER, WY; Funding acquisition: MKK; Investigation: ABB, MKK, WY, YTB; Methodology: ABB, MKK, SER; Project administration: MKK; Resources: ABB, MKK, SER, YTB; Software: SER, AKA; Supervision: ABB; Validation: ABB, MKK; Visualization: ABB, MKK; Writing – original draft: ABB; Writing – review & editing: ABB, MKK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Шу-Іле рудалы зонасының геодинамикасы: геофизикалық, геохимиялық және космогеологиялық әдістердің интеграциясы

А.Б. Байбатша[1], М.К. Кембаев[1*], С.Е. Раис[1], В. Ян [2], А.К. Амантаев[1], Е.Т. Биякышев[1]

[1]*Satbayev University, Алматы, Қазақстан*

[2]*Хьюстон университеті, Техас, АҚШ*

**Корреспонденция үшін автор: m.kembayev@satbayev.university*

Аңдатпа. Мақалада қазіргі заманғы геофизикалық, геохимиялық әдістер мен Жерді қашықтықтан зондылау технологияларын қолдана отырып, Шу-Іле металлогениялық зонасын кешенді зерттеу нәтижелері келтірілген. Зерттеудің мақсаты жаңа геодинамикалық тәсілдер мен көпсалалы геологиялық деректерді біріктіру негізінде кен нысандарын зона шегінде орналасу заңдылықтарын белгілеу болып табылды. Жұмыстың көкейтестілігі күрделі геологиялық жағдай мен біршама оңай барланған ресурстардың сарқылуы жағдайында алтын, полиметалдар мен ілеспе элементтерді қоса алғанда, пайдалы қазбалар кенорындарының негізделген болжамды модельдерін құру қажеттілігімен анықталады. Зерттеу барысында гравиметрия, магниттік түсірілім, электромагниттік зондылау және қашықтықтан зондылау деректері, сондай-ақ кен түзілімдерінің геохимиялық сипаттамалары талданды. Бұл деректер далалық геологиялық байқаулар нәтижелерімен, стратиграфиялық және тектоникалық құрылымдармен салыстырылды. Кешенді талдау мантия мен жер қыртысының белсенді өзара әрекеттесу аймақтарын бөліп көрсетуге мүмкіндік берді, олар терең ақаулар, субвертикал өткізгіш құрылымдар және тектоникалық босаңсыған зоналар түрінде білінеді, олар кен түйіндерінің қалыптасуында шешуші рөл атқарады. Геофизикалық және геохимиялық белгілердің жиынтығы негізінде алтын-сульфидті және полиметалды минералдануды болжаудың жаңа тәсілі ұсынылды. Ол терең құрылымдарды модельдеуді және олардың кенді минералдануының беткі көріністеріне әсер ету дәрежесін бағалауды қамтиды. Алынған нәтижелер маңызды қолданбалы мәнге ие: оларды геологиялық барлау жұмыстарының бағыттарын оңтайландыру, бұрғылау ұңғымалары бағдарламаларының тиімділігін арттыру және қаржылық шығындарды азайту үшін пайдалануға болады. Ұсынылған әдістемені Орталық Азияның басқа металлогениялық провинцияларында сәтті қолдануға болады, бұл орындалған жұмыстың әмбебаптығы мен практикалық маңыздылығын көрсетеді.

Негізгі сөздер: *геодинамика, геофизикалық ауытқылар, кенжасаушы флюидтер, космогеологиялық карталау, мантия плюмдері.*

Геодинамика рудной зоны Шу-Иле: интеграция геофизических, геохимических и космогеологических методов

А.Б. Байбатша[1], М.К. Кембаев[1*], С.Е. Раис[1], В. Ян [2], А.К. Амантаев[1], Е.Т. Биякышев[1]

[1]*Satbayev University, Алматы, Казахстан*

[2]*Хьюстонский университет, Техас, США*

**Автор для корреспонденции:* m.kembayev@satbayev.university

Аннотация. В статье представлены результаты комплексного изучения Шу-Иле металлогенической зоны с применением современных геофизических, геохимических методов и технологий дистанционного зондирования Земли. Цель исследования заключалась в установлении закономерностей размещения рудных объектов в пределах зоны на основе новых геодинамических подходов и интеграции многопрофильных геологических данных. Актуальность работы определяется необходимостью создания обоснованных прогнозных моделей месторождений полезных ископаемых, включая золото, полиметаллы и сопутствующие элементы, в условиях усложнённой геологической обстановки и исчерпания легкоразведанных ресурсов. В ходе исследований были проанализированы данные гравиметрии, магнитной съёмки, электромагнитных зондирований и данных дистанционного зондирования, а также геохимические характеристики рудоносных формаций. Эти данные были сопоставлены с результатами полевых наблюдений, стратиграфическими и тектоническими построениями. Комплексный анализ позволил выделить зоны активного взаимодействия мантии и земной коры, проявляющиеся в форме глубинных разломов, субвертикальных проводящих структур и тектонически ослабленных зон, которые играют ключевую роль в формировании рудных узлов. На основе совокупности геофизических и геохимических признаков предложен новый подход к прогнозированию золотосульфидной и полиметаллической минерализации. Он предполагает моделирование глубинных структур и оценку степени их влияния на поверхностные проявления рудной минерализации. Полученные результаты имеют важное прикладное значение: они могут быть использованы для оптимизации направлений геологоразведочных работ, повышения эффективности буровых программ и минимизации финансовых затрат. Предложенная методология может быть успешно применена и в других металлогенических провинциях Центральной Азии, что подчёркивает универсальность и практическую значимость выполненной работы.

Ключевые слова: *геодинамика, геофизические аномалии, рудообразующие флюиды, космогеологическое картирование, мантийные плюмы.*

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