Mining of Mineral Deposits
Volume 18 (2024), Issue 3, 63-81

https://doi.org/10.33271/mining18.03.063

Features of the continental volcanic-plutonic belts of the Junggar-Balkhash fold system

Eleonora Seitmuratova [1], Shen Ping [2], Refat Baratov [1], Diyas Dautbekov [1], Moldir Mashrapova [1*], Nurgali Shadiyev [1], Yalkunzhan Arshamov [3]

[1] *Institute of Geological Sciences named after K.I. Satbayev, Almaty, Kazakhstan*
[2] *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*
[3] *Satbayev University, Almaty, Kazakhstan*

**Corresponding author: e-mail moldir.mashrapova@gmail.com*

Abstract

Purpose. The study aims to investigate the formation composition and structural-formation zoning of the Late Paleozoic continental volcanic and volcano-sedimentary formations of the Junggar-Balkhash fold system (JBFS). It also seeks to define the geological-geophysical characteristics and metallogenic specialization of the volcanic-plutonic belts (VPB) in the region.

Methods. The research utilizes data from detailed mapping and analysis of Late Paleozoic magmatites in JBFS over the past 10-40 years. Structural-formation zoning of the region was performed from an actualistic perspective, along with the formation typification of stratified and intrusive ore formations. The study of metallogenic specialization was conducted considering modern geophysical research methods.

Findings. Two main volcanic-plutonic belts have been identified: the Carboniferous marginal-continental Tasty-Kusak-Kotyryasan-Altunemel Belt and the Carboniferous-Permian intracontinental Balkhash-Ili Belt, which together cover about 80% of the JBFS territory. The geological-geophysical characteristics and metallogenic specialization of these belts have been defined. In particular, the findings highlight significant prospects for epithermal gold-silver and copper-porphyry mineralization.

Originality. For the first time, a structural-formation zoning of JBFS has been conducted, and the typification of volcanic-Plutonic Belts has been substantiated. Additionally, their metallogenic specialization has been determined, revealing patterns of localization for epithermal gold-silver and copper-porphyry deposits.

Practical implications. The study's results are of great importance for exploration geology, contributing to the improved efficiency of searching for ore deposits in the region, particularly epithermal gold-silver and copper-porphyry targets.

Keywords: *volcanic structures, structural-formation zoning, volcanic-plutonic belts, zoning, gold, copper, Junggar-Balkhash fold system*

1. Introduction

Kazakhstan, with its vast territory rich in diverse natural resources, is one of the leading centers of the mining industry in Central Asia. The country's abundant mineral deposits, including copper, gold, silver, uranium, and many other metals, make it a key player in the global raw materials market [1]-[3]. The geological diversity of the region provides unique opportunities for the exploration and development of mineral deposits, which, in turn, plays a crucial role in Kazakhstan's economic development [4], [5].

Geological research in Kazakhstan has been conducted for many decades, and its results have significantly impacted the development of the country's industry, energy sector, and agriculture. The development of new mineral deposits and the rational use of already known ones are essential aspects of the state policy aimed at the sustainable development of the economy [6]-[8]. Moreover, these studies contribute to attracting foreign investment in the mining sector, which is a vital factor for further economic growth [9].

Monitoring the earth's surface is essential for ensuring the safety and efficiency of mining operations, as well as minimizing environmental impact. During the extraction of subsoil resources, displacements of the earth's surface can occur, which may lead to significant structural and environmental challenges. Regular monitoring allows for the early detection of these movements, helping to prevent hazardous events such as land subsidence and damage to infrastructure [10]-[15].

Of particular importance for Kazakhstan is the study of paleovolcanism and the associated ore-forming processes. These studies not only reveal new prospects for the exploration and development of deposits but also contribute to a better understanding of the region's geological history [16]. In this context, special attention is drawn to the Junggar-Balkhash fold system (JBFS), located in southeastern Kazakhstan.

Received: 3 June 2024. Accepted: 11 September 2024. Available online: 30 September 2024

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

This region, part of the Central Asian Orogenic Belt, represents a complex nappe-fold area with a rich geological history and significant potential for mining activities [17].

The study of the geology of the Junggar-Balkhash fold system (JBFS) holds great significance for Kazakhstan's national economy [18]. The discovery and development of new mineral deposits, such as copper-porphyry and epithermal gold-silver deposits, have a direct impact on the growth of the mining industry, increasing production volumes and export deliveries [19], [20]. This, in turn, contributes to strengthening economic stability and improving the standard of living for the population. The development of the mining sector also plays a crucial role in job creation, infrastructure development, and increasing tax revenues to the state budget. In this context, the relevance of studying the processes of paleovolcanism in the JBFS becomes especially evident. The results of such studies can significantly expand scientific knowledge about the geological history of the region and provide new opportunities for the industrial development of its natural resources [21], [22].

Active research into the processes of paleovolcanism, which began in the last century, has clearly demonstrated the relationship between volcanism and ore formation. Consequently, regions with extensive manifestations of volcanogenic and volcano-sedimentary rocks have attracted the close attention of geologists from various countries [23], [24].

Among such regions is the extensive territory of the Junggar-Balkhash fold system (JBFS), which occupies a significant area in the southeastern part of Kazakhstan [25]. In the Late Paleozoic, this region was part of the Central Asian Orogenic Belt, representing a complex nappe-fold area of different ages, where the Hercynian Junggar-Balkhash, Zaysan, and Ural fold systems formed. These are separated by the Caledonian Kokchetav-North Tien Shan and Shyngystau-Tarbagatay fold systems, each possessing its own tectonic zoning (Fig. 1).

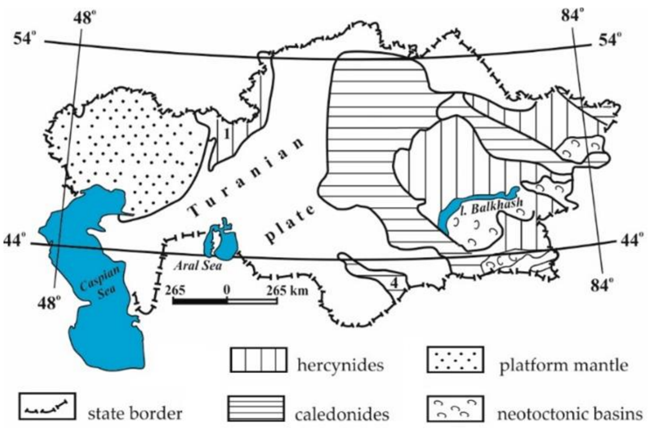


Figure 1. Position of the Junggar-Balkhash fold system (JBFS) among the fold systems of the Kazakhstan segment of the Central Asian folded megabelt [26]-[28]

This Figure 1 shows the location of the Junggar-Balkhash fold system (JBFS) in relation to the fold systems within the Kazakhstan segment of the Central Asian Orogenic Belt. The Central Asian Orogenic Belt is a major tectonic structure that includes multiple fold belts formed during the Paleozoic and is known for its complex geology and significant mineral resources.

More than 70% of the JBFS area is composed of Late Paleozoic continental volcanogenic and volcano-sedimentary formations. Given that JBFS is a major ore-producing region of Kazakhstan, its geological studies have been actively conducted by geologists from various scientific schools and generations of the former Soviet Union, and naming all the contributors would be impossible as it would result in an extensive bibliographic directory. Despite numerous studies on the Late Paleozoic continental volcanogenic and volcano-sedimentary deposits of the JBFS, many geological and metallogenic issues remain unresolved, most of which pertain to the stratigraphy of these sequences. The inconsistency of stratigraphic research results when using different methods is clearly visible in Table 1.

The decades-long problem of subdivision, correlation, and dating of these practically "silent sequences", which include continental volcanogenic formations, remains contentious. This is primarily due to their extreme paucity of organic remains and the limited amount of radiological data available, resulting from the small volume of isotopic studies. The subdivision options for these deposits have been particularly controversial when some geologists used only the biostratigraphic method. At the same time, the main method for subdividing continental volcanogenic sequences should be the lithological-facies approach.

Thus, the Junggar-Balkhash fold system (JBFS) represents one of the key geological structures of Kazakhstan, characterized by a complex geological structure and significant potential for the discovery and development of mineral resources. As part of the Central Asian Orogenic Belt, the JBFS is distinguished by a variety of tectonic processes that occurred throughout the Paleozoic, leading to the formation of numerous volcanogenic and volcano-sedimentary complexes. These complexes are essential for understanding the geodynamic evolution of the region and studying the patterns of mineral deposit localization. Despite significant progress in studying the JBFS, important issues related to the detailed stratigraphy, correlation, and dating of volcanogenic formations remain unresolved. This is due to the complexity of stratigraphic subdivision and the limited availability of isotopic data, necessitating further research and the development of new methodological approaches.

The approval of a regional stratigraphic scheme at the Republican Stratigraphic Conferences in 1971 and 1986, which adopted the "Stratigraphic Scheme of the Carboniferous and Permian of the JBFS" based primarily on the biostratigraphic method, created a situation where geologists in the region, who do not recognize this scheme, have been mapping and compiling geological maps based on completely different principles. As a result, the geological maps currently used by specialists in geological research are inconsistent with each other. Naturally, this inconsistency does not facilitate the successful resolution of metallogenic problems.

This situation prompted the authors to conduct a series of comprehensive studies in recent decades on the continental Late Paleozoic volcanogenic and volcano-sedimentary formations throughout the JBFS. Considering that during this period, no geologists in Kazakhstan, other than the authors of this article, have been conducting targeted studies of the geology and metallogeny of continental volcanogenic and volcano-sedimentary formations of the Late Paleozoic in the JBFS, it was decided to present the results of our research and several problematic and controversial issues regarding continental volcanogenic formations for discussion at the level of the international geological community.

Table 1. Correlation of the most debated schemes for the subdivision and dating of continental volcanic deposits of the Late Paleozoic JBFS*

Names of volcanic structures, stratigraphic units (suites, thickness numbers), or specific formations identified within these structures according to the formational principle (from top to bottom)	State geological maps		Geological map of the Central Kazakhstan series, scale 1:500000 (1981)	Geological exploration work – 50 and 200 (1975-1990)	Thematic studies of the 1960-1990	Results of work on the Balkhash segment by Lyapichev, G.F., Seitmuratova, E.Yu., and others (1971-1998)
	1:50000	1:200000				
Karabasan volcanic structure (VS)	Reshko M.Ya., 1970	Bedrov G.I., 1960	Koshkin V.Ya., 1980	Belyaev O.E., 1990	Lyalin Yu.I., 1967	Seitmuratova E.Yu., 1990
3 – Keregetas rhyodacite-dacite	C_{2-3} kg flora	C_{2-3} kg flora	flora	C_2 kg flora	C_{2-3} kg	C_2 kg flora
2 – Kalmakemel andesite	C_2 kl	C_2 kl	P_1 čb	C_{1-2} kl	C_2 kl	C_{1-2} kl
1 – Karkaralinsk volcano-sedimentary, andesibasalt-dacite-rhyolite	C_1 kr	C_1 kr		C_1 kr	C_1 kr	C_1 kr
Tungatar volcanic structure (VS) M-43-103	Malakhov V.S., 1962	Rybaltovskiy E.V., 1960	Koshkin V.Ya., 1981	Mazur M.A., 1987	–	Seitmuratova E.Yu., 1990
3 – Keregetas rhyolite-rhyodacite tuff-ignimbrite	C_2 kg	Absolute age – 318-320 Ma C_2 kg	P_2 šn	C_2 kg flora	–	C_2 kg flora
2 – Kalmakemel andesite-andesidacite						C_{1-2} kl
1 – Karkaralinsk volcano-sedimentary, andesibasalt-dacite-rhyolite	C_1 kr	C_1 kr		C_1 kr	–	C_1 kr
Karasuran volcanic-tectonic structure (VTS) M-43-117	Kurchavov A. M., 1965	Bespalov V.F., 1958	Koshkin V.Ya., 1981	Bezuglykh I.V., 1986	Kurchavov A.M., 1984	Seitmuratova E.Yu., 1984-1992
6 – Shangeldai trachydacite-rhyolite ignimbrite-tuff-ignispumite	P_1 kz	P_1 kz	P_1 čb flora	P_1 kz	P_1 kz flora	P_1 šn flora
5 – Dostar andesidacite-dacite	C_{2-3} arch	C_{2-3} arch				P_1 ds
4 – Koskyzyl volcano-sedimentary, rhyodacite-rhyolite				C_{2-3} kld flora	C_{2-3} kld	C_{2-3} ks flora, fauna
3 – Keregetas rhyolite-rhyodacite tuff-ignimbrite	C_2 kg	C_2 kg		C_2 kg	C_2 kg	C_2 kg
2 – Kalmakemel trachyandesite-andesibasalt-andesite	C_{1-2} kl	C_{1-2} kl		C_{1-2} kl	C_{1-2} kl	C_{1-2} kl
1 – Karkaralinsk – volcano-sedimentary, dacite-rhyodacite-rhyolite	C_1 kr	C_1 kr		C_1 kr flora	C_1 kr	C_1 kr
Sarygulzhan structure M-43-104	Isaev N.M., 1968	Bespalov V.F., 1956	Koshkin V.Ya., 1981	Kostenko A.K., 1987	Kurchavov A.M., 1984	Seitmuratova E.Yu., 1984-1992
3 – Keregetas rhyodacite-rhyolite tuff-ignimbrite	C_{2-3} kg	C_2 kl flora	C_{2-3} kg	C_2-P_1 kl flora	C_{2-3} kg	C_2 kg
2 – Kalmakemel trachy-andesite-andesibasalt-andesite	C_2 kl flora		C_{1-2} kl flora		C_2 kl flora	C_{1-2} kl flora
1 – Karkaralinsk volcano-sedimentary, conglomerate-aleurolite-sandstone with ignispumite and tuff horizons of andesi-dacite and rhyolite composition	C_1 kr flora	C_1 kr flora	C_1 kr		C_1 kr flora	C_1 kr flora
Symbyl structure	Popov V.S., 1962	Gaek O.M., 1964	Koshkin V.Ya., 1981	Tevelev A.V., 1983	Glukhan I.V., 1987	Seitmuratova E.Yu., 1991, 1992, 1995
3 – volcano-sedimentary rhyolite	D_3 fm flora	D_3 fm	P_2 mt	P_{1-2} kir	C_3-P_1 kl flora	C_{2-3} ks flora
2 – trachyandesibasalt-trachyandesite-andesite	D_{2-3}	D_{2-3} gk_2		P_2 mt	C_{1-2} kl	C_{1-2} kl
1 – volcano-sedimentary rhyolite	C_1 kr	D_{2-3} gk_1	C_3-P_1 kld	P_{1-2} kir	C_1 kr	C_1 kr

*The age indices of formations (suites) are given according to the old subdivision scheme of the Carboniferous and Permian

Note:

1. Names and indices of Late Paleozoic suites and subsuites:

arch – Arkharlin	gn – Zhantausk	kld – Koldar	kz_1 – Lower Kyzylkiin	šn – Shangeldai
čb – Chubaraygyr	it – Itbai	kr – Karkaralinsk	kzd – Kyzyladyr	tm – Temirzhal
ds – Dastar	kg – Keregetas	ks – Kusak	mt – Maitas	ts – Taskorin
dž – Dzhangeldin	kir – Karayrek	kz – Kyzylkiin	sl – Sulushokin	žn – Zhan
gk – Zhaksykon	kl – Kalmakemel	kz_2 + kr – Upper Kyzylkiin-Karmys		

2. kz_1 (Itbai) and kz_2 + kr are new stratigraphic units derived from the volumes of previously approved suites using the formational method and do not have new names.

2. Materials and methods

To achieve the research objectives, data collected over more than 40 years of geological and geophysical research (1980-2020) were used. The primary focus was on the study of Late Paleozoic continental volcanogenic and volcano-sedimentary formations of the Junggar-Balkhash fold system (JBFS). These studies included both fieldwork and a comprehensive analysis of the collected data, providing an in-depth understanding of the region's geological structure.

The research paid special attention to detailed mapping and analysis of magmatic rocks in the JBFS. Work was carried out at more than a hundred reference and stratotype sections, enabling the creation of a complete picture of the region's geological structure (Fig. 2). The volcanic and volcano-tectonic structures of the JBFS are grouped into extensive belts that differ in structure and duration of development.

Figure 2. Schematic layout of typical and reference sections of Late Paleozoic volcanic structures of the Junggar-Balkhash fold system [29], [30]

Previously, these structures were united under the single Balkhash-Ili volcanic-plutonic belt (B-I VPB). However, these belts have different geological and geophysical characteristics, allowing them to be distinguished as separate structures.

Areas with a wide distribution of volcanogenic formations in modern geostructures are defined as volcanic-plutonic belts of active continental margins.

The methodological basis of the study included a comprehensive formational method, which allows for the analysis of patterns in the distribution of ore deposits and the study of geological formations in the context of their association with specific tectonic regimes. This method was chosen due to its versatility and ability to integrate various types of data (geological, geophysical, geochemical) to create a holistic picture of the development of geological structures.

Fieldwork included detailed geological mapping, during which the main volcanogenic and volcano-sedimentary complexes were described and classified. These data helped to identify the structural features of the volcanic and volcano-tectonic belts, determine their stratigraphic position, and establish their lithological composition. The analysis of the obtained data showed that the JBFS consists of several large volcanic-plutonic belts, each with distinct geological characteristics.

To study such intriguing crustal structures as the volcanic-plutonic belts (VPBs) of Kazakhstan and to identify patterns of spatial-temporal and paragenetic relationships between geological and ore formations, the authors employed the only objective and comprehensive formational method or the method of structural-material complexes [29]-[33]. According to A.D. Shcheglov, this method is "the most productive method for understanding the patterns of deposit distribution in the Earth's crust, analyzing geological formations, and, on this basis, determining their association with specific tectonic regimes".

The relevance of the mentioned methodology is determined by the fact that during the transition from the old paradigm to new geodynamic concepts, geologists can accurately operate with the only real constant – the composition of rocks and their paragenetic associations, i.e., formations. The universality of the concept of "formation" is defined by its ability to provide information about the conditions of its formation based on its material composition. It has been identified that magmatic formations often serve as more sensitive indicators of geodynamic processes than sedimentary formations. This is natural since magmatism is a primary reflection of the Earth's endogenous regimes, which determine the manifestation of geodynamic processes, unlike the secondary nature of exogenous sedimentary processes.

In this regard, areas of widespread volcanic and plutonic formations, which are identified as volcanic-plutonic belts, appear to be the most attractive megastructures for conducting formational studies.

In addition to field studies, data from magnetometry, gravimetry, seismic surveys, and magnetotelluric sounding were used. These methods helped refine the internal structure and boundaries of the Late Paleozoic volcanic complexes, identify deep faults controlling the localization of ore formations, and determine the structural features of the volcanic-plutonic belts.

The obtained data were compared with the results of previous studies, allowing for the structural-formational zoning of the JBFS. The analysis established that the volcanic-plutonic belts of the region have different geological and geophysical characteristics, indicating a complex geodynamic history of the JBFS.

Thus, the applied comprehensive approach, which includes detailed mapping, formational analysis, and the use of geophysical methods, made it possible to identify two main volcanic-plutonic belts in the JBFS territory: the Carboniferous marginal-continental and the Carboniferous-Permian intraplate belts. These belts differ in their geological characteristics and play a key role in understanding the geodynamic evolution of the region and the distribution of ore deposits.

3. Results and discussion

3.1. Characteristic features of continental Volcanic-Plutonic Belts

The term "volcanic belt" (VB) has been widely used in contemporary geological literature in the post-Soviet space for a long time. This term was used rather freely and lacked a precise definition. It was only after the studies of the 1960s, which focused on the volcanic belts of the Central Asian Fold Belt, such as the Okhotsk-Chukotka, Chatkal-Kurama, Central Kazakhstan, and others [34], that these structures started attracting increasing attention. Today, all researchers acknowledge the widespread development of volcanic belts.

Given the diversity of VB types associated with different geodynamic settings of their formation, there are numerous conflicting definitions and classifications of VBs in modern literature. Nevertheless, most definitions tend to align with V.E. Khain's definition [35], which suggests that "a volcanic belt represents an extensive (hundreds, sometimes thousands of kilometers) and relatively narrow (tens, sometimes hundreds of kilometers) geological structure, whose formation spanned one or several stages of development and was accompanied by intense volcanic and associated plutonic activity". Therefore, practically all VBs are simultaneously volcanic-plutonic belts (VPBs). However, the quantitative proportions of volcanic and plutonic products in different types of belts vary significantly. Generally, under acidic magmatism conditions, the role of intrusive formations increases.

Continental-type volcanic belts primarily form in terrestrial continental environments; they are superimposed formations that typically develop on a consolidated rigid substrate, often independent of the geological structures of the substrate. It is believed that the formation of continental VPBs occurred following significant orogenic movements on the continent, in zones of junction between continental blocks and oceanic (or transitional) types.

The formation of continental belts of various types is closely linked to the activation of tectonic activity, particularly intense in intracontinental VPBs, which develop on a more mature continental crust than marginal-continental belts. This leads to the rejuvenation and formation of new large zones of fault disturbances and intensive intrusive activity, usually represented by stock-like, linearly elongated fissure subvolcanic and hypabyssal intrusions of various compositions, often comagmatic with volcanogenic complexes.

The discussed types of VPBs are characterized by a clear superposition on substrate structures; extensive development of continental volcanogenic and volcano-sedimentary formations of various compositions, manifesting in different proportions in marginal and intracontinental VPBs, especially in the early stages of their development; and the predominant development of magmatogenic volcanic-plutonic and volcano-tectonic ring structures in intracontinental VPBs.

Examples of volcanic regions with similar cross-sectional structures include the Chatkal-Kurama region, Central Chukotka, Kamchatka, the Kuril Islands, the Indonesian Archipelago, and the Mongolian sector of the Central Asian Orogenic Megabelt [29], [30], [35], [36].

A synthesis of current concepts regarding various types of VBs allows us to justifiably typify the continental VPBs identified in Kazakhstan, focusing on a number of their key distinguishing features.

3.2. Continental VPBs of the Late Paleozoic Junggar-Balkhash fold system of Kazakhstan

The vast area of intensive late Paleozoic magmatism has been studied for many years by numerous geologists from the former Soviet Union, as mentioned earlier. Most of them adhered to the view that the late Paleozoic magmatic formations constituted a single continental Balkhash-Ili VPB. At the same time, other geologists, including S.P. Samygin, G.R. Bekzhanov, L.I. Serikov, V.N. Lyubetsky, G.F. Lyapichev, E.Yu. Seitmuratova, and others [28], [37]-[42], suggested that the extreme heterogeneity of the transverse structure of the VPB allows it to be divided into several belts.

For instance, in the explanatory note to the "Tectonic Map of Eastern Kazakhstan, scale 1:2500000" [30], the area of volcanites directly adjacent to the boundary of the Junggar-Balkhash paleobasin is identified as a complexly structured VB (late Carboniferous – middle Carboniferous) (Fig. 3). It is clearly depicted on the aforementioned map and is classified by S.G. Samygin as a marginal-continental belt. Alongside it, the authors of the note identify a second late Paleozoic VPB, whose formation, during the orogenic stage, took place entirely on the continent (Fig. 3). This map fragment illustrates the geological structure and tectonic features of Eastern Kazakhstan, showing the distribution of volcanic-plutonic belts and their respective geological formations. The first belt is associated with the final stages of continental crust formation, while the second belt represents the intracontinental volcanic-plutonic activities during the Carboniferous-Permian period.

Moreover, in the work by V.Ya. Koshkin, 1974 [43], it is stated that "The volcanic belt, named the Balkhash-Ili Belt", unites several belts of different ages which, despite their differences, are connected by a specific system of deep faults. The VBs are as follows: Famennian; Visean-Namurian; Middle-Late Carboniferous; Permian.

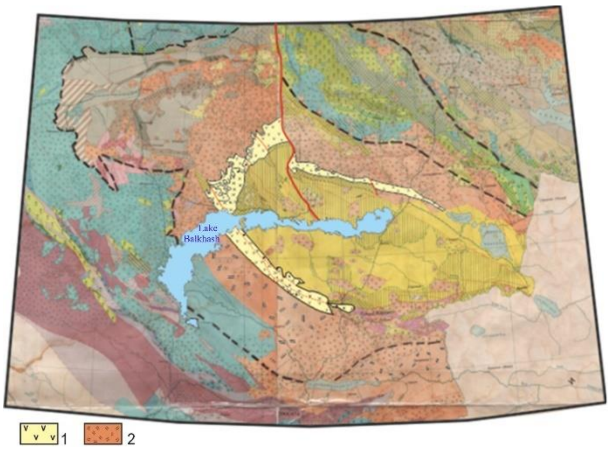


Figure 3. Fragment of the Tectonic Map of Eastern Kazakhstan, scale 1:2500000 (Chief Editor – academician A.V. Peyve) [30]: 1 – marginal-continental Carboniferous Tasty-Kusak-Kotyrasan-Altinemel Volcanic-Plutonic Belt (areas of continental crust formation, final stage, C_{1v}-$C_{2\text{-}3}$ according to A.V. Peyve); 2 – intracontinental Carboniferous-Permian Balkhash-Ili Volcanic-Plutonic Belt (continental stage, C_{2m}-P_1 according to A.V. Peyve)

In the work of Lyubetsky and Lyubetskayas [28], based on the deep structure of the region, the authors identify three extensive VPBs in the Pribalkhash region: the Ili-Balkhash-Saryemel Belt, the Ortasu-Tokrao-Aktogai Belt, and the Pribalkhash-Ili Belt. The provided examples, which could be further expanded, indicate that the typification of territories with extensive late Paleozoic magmatism manifestation in the JBFS can be multi-variant.

According to the studies [29], [38]-[42], [44], two late Paleozoic VPBs are identified in the JBFS – the Carboniferous marginal-continental and the Carboniferous-Permian intracontinental VPBs.

This conclusion is based on research conducted by the authors from 1981 to 2020, focusing on the formation method, which revealed differences in the vertical formation series of the two zones in the JBFS, previously combined into a single Balkhash-Ili volcanic-plutonic belt (VPB). These studies also allowed, for the first time, structural-formational zoning of the region from an actualistic perspective (Fig. 4).

When zoning the JBFS, it becomes evident how the two identified continental volcanic-plutonic belts are separated by deep faults and clearly demarcated as independent structures.

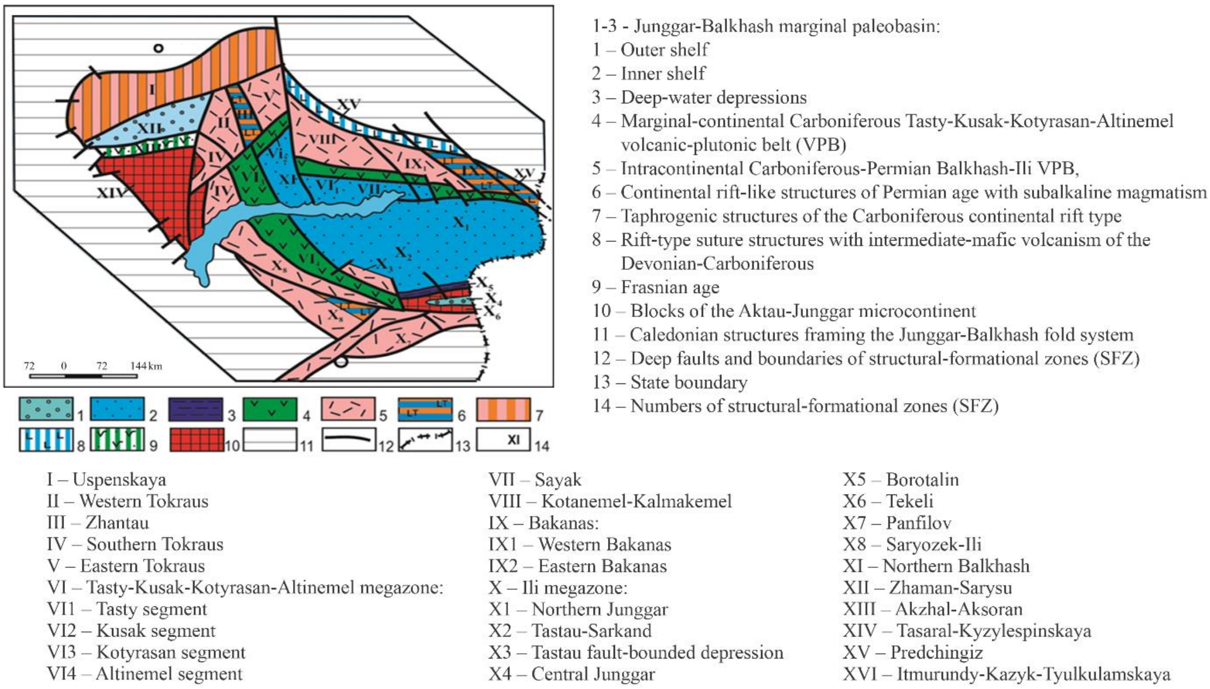


Figure 4. Structural-formational zoning scheme of the Junggar-Balkhash fold system [31], [44]

These structures differ in various geological, structural-tectonic, geophysical, and petrochemical characteristics of the Late Paleozoic volcanic and volcano-sedimentary formations of these belts, which, in many respects, coincide with the modern VPBs. This allows for their classification as continental marginal-continental and intracontinental VPBs.

Despite the fact that both the marginal-continental Tasty-Kusak-Kotyrasan-Altynemel VPB and the Carboniferous-Permian intracontinental Balkhash-Ili VPB exhibit a cyclic nature of volcanism, characterized by alternating intermediate-basic and acidic volcanic rocks, which is manifested in these VPBs at all stages of their development, they differ in a number of features. This is what led to their distinction from the previously defined single Balkhash-Ili VPB.

The differentiation of the Carboniferous marginal-continental Tasty-Kusak-Kotyrasan-Altynemel belt from the previously defined Balkhash-Ili VPB was due to new geological data obtained by the authors in the process of conducting a series of geological and metallogenic studies in the JBFS over the past decades [32], [37], [38]-[42].

Among the most important of these works are the detailed study and correlation of around a hundred stratotype and reference sections of Late Paleozoic deposits, which dominate the geological structure of the JBFS (Fig. 4). This zoning scheme provides a comprehensive overview of the structural-formational divisions within the Junggar-Balkhash fold system, highlighting the various geological formations, magmatic activities, and tectonic structures that characterize the region. Each zone is numbered and described based on its geological characteristics and formation history.

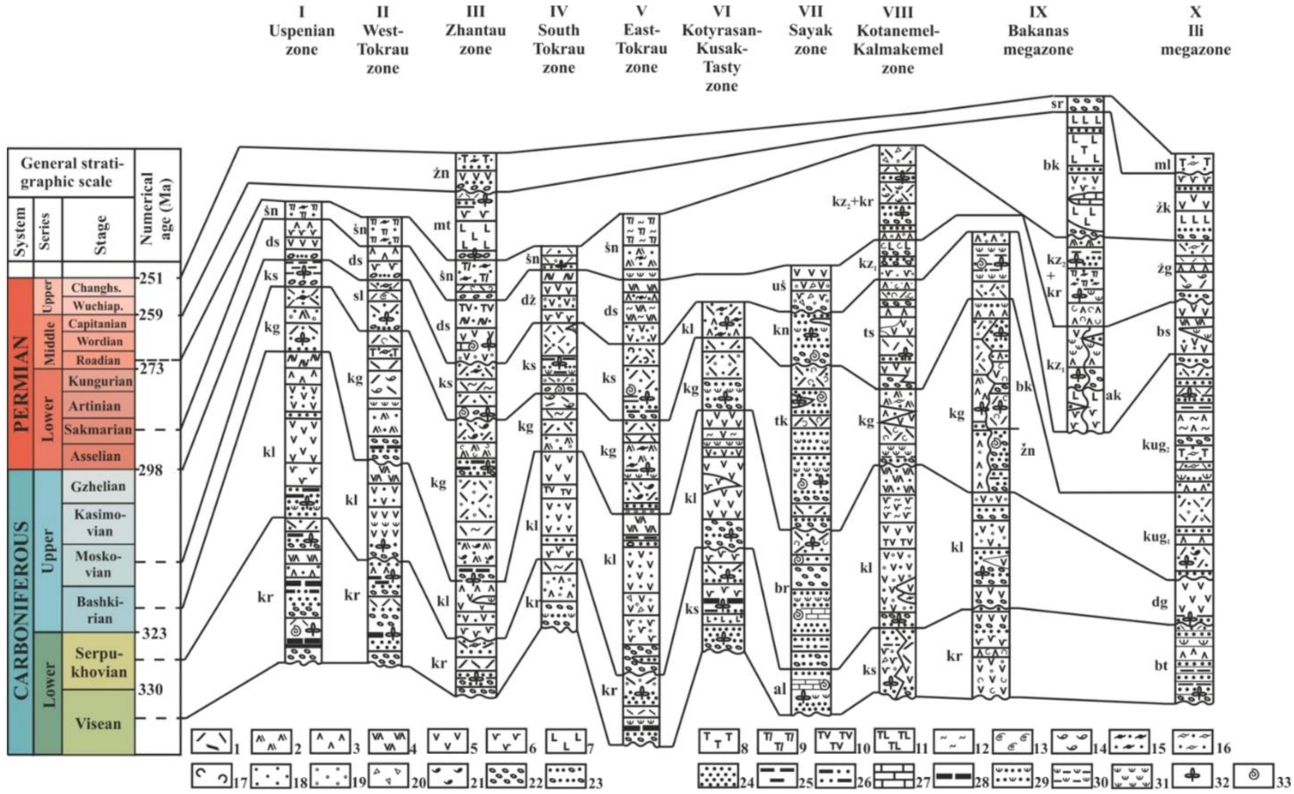
The new geological maps compiled during this process [32], [40] allowed for the first-time formation-based typification of all stratified, intrusive, and ore formations. The analysis of the patterns of specific geological formations and their associations in the region, as well as the chronological sequence of their formation, indicated several vertical series of formations characterizing certain blocks of the Earth's crust – terrains of the studied region.

Following [30], [32], [44], the authors identified these areas as structural-formational zones (SFZ). Thus, based on the outlined natural lateral-vertical series of formations, which are direct indicators of the paleoenvironments of their formation, the authors made the first attempt to conduct structural-formational zoning of the region from actualistic perspectives on a material basis (Fig. 4).

As seen in Figure 4, the following types of paleostructures are distinguished in the region: the Junggar-Balkhash marginal paleobasin (Sayak SFZ); the marginal-continental Carbonife-rous volcanic belt with elements of island-arc regimes in some parts (Tasty-Kusak-Kotyrasan-Altynemel); the Balkhash-Ili Carboniferous-Permian intracontinental VPB, in which structures of continental rift types – Zhaman-Sarysu and Akzhal-Aksoran SFZ – formed in the final stages of its development (P_2-P_3), which are peripheral zones of the Junggar-Balkhash marginal sea; and the ancient continental massif – Tasara-Kyzylespin SFZ, which is a fragment of the northeastern margin of the Aktau-Zhungar microcontinental paleomassif.

Thus, the geological structure of the JBFS, according to the identified structural-formational zones related to various paleostructures, is quite complex. For all the identified large paleostructures, there is a distinct vertical series of structural-material complexes, which are mostly divided by various types of unconformities. Thus, for the identified marginal-continental and intracontinental VPBs, the compiled vertical series of Late Paleozoic volcanic and volcano-sedimentary deposits (Fig. 5) clearly show their non-identity.

The delineation of the studied volcanic belts based on geological data is also corroborated by geophysical materials, which are available in substantial volumes due to numerous comprehensive geophysical studies (magnetic, gravity, seismic exploration, magnetotelluric sounding).



Formation Indices:
- ak – Akshokin
- al – Alabiin
- bk – Bakalin
- bkn – Bakanas
- br – Burultas
- bs – Beskainar
- bt – Batpak
- dg – Degerez
- ds – Dostar
- dž – Jangeldin
- kg – Keregetas
- kl – Kalmakemel
- ko – Koldar
- kn – Kungisayak
- kr – Karkaralinsk suite
- ks – Kusak
- kos – Koskyzyl
- kug_1 – Lower Kugalin
- kug_2 – Upper Kugalin
- kz_1 – Lower Kyzylkiin
- kz_2+kr – Upper Kyzylkiin-Karmys
- ml – Malaisar
- mt – Maitas
- sl – Sulushokin
- šn – Shanghelbay
- sr – Seyrektau
- tk – Tastykuduk
- ts – Taskor
- uš – Koldar
- žg – Zhalgyzagash
- žk – Zheldykoryn
- žn – Zhan
- žn – Znamensk

1-11 – Lavas:
- 1 – Rhyolites
- 2 – Rhyodacites
- 3 – Dacites
- 4 – Andesidacites
- 5 – Andesites
- 6 – Andesibasalts
- 7 – Basalts
- 8 – Trachytes
- 9 – Trachyandesites
- 10 – Trachyandesites
- 11 – Trachybasalts
- 12 – Fluidal lavas
- 13 – Spheroloidal lavas
- 14 – Automagmatic breccias
- 15 – Ignimbrites
- 16 – Ignispumites

17-21 – Tuffs:
- 17 – Ash tuffs
- 18 – Crystalloclastic tuffs
- 19 – Lithoclastic tuffs
- 20 – Agglomerate tuffs
- 21 – Welded tuffs

22-31 – Sedimentary and volcanogenic-sedimentary rocks:
- 22 – Conglomerates
- 23 – Gravelites
- 24 – Sandstones
- 25 – Aleurolites
- 26 – Aleurosandstones
- 27 – Limestones
- 28 – Coals
- 29 – Tuffsandstones
- 30 – Tuffaleurolites
- 31 – Tuffites
- 32 – Flora
- 33 – Fauna

Figure 5. Correlation scheme of Late Paleozoic deposits of the Junggar-Balkhash fold system [31]

These studies provide a detailed characterization of the subsurface structure of the Junggar-Balkhash fold system (Figs. 6, 7). These geophysical investigations have been crucial in supporting the geological data by providing additional insights into the deep structural features of the region. The data from these studies help in understanding the spatial distribution and the depth of geological formations, as well as identifying the presence of faults and other significant structural elements.

The interpretation of magnetometric and gravimetric data has allowed for a refinement in the boundaries of the Late Paleozoic terrestrial volcanic complexes, their thicknesses, and internal structures. In addition to their varying structural-tectonic settings, the described volcanic belts differ in terms of the areas of Late Paleozoic volcanic rock distribution, the thicknesses of the sections, the duration of Late Paleozoic volcanic activity, and, accordingly, the different associations of volcanic and volcano-sedimentary formations. For instance, the volume of volcanic products in the Tasty-Kusak-Kotyrasan-Altunemel marginal volcanic belt exceeds 75.3 thousnd cubic kilometers, while in the Balkhash-Ili intracontinental volcanic belt, it exceeds 277.5 thousand cubic kilometres (Table 2).

At the same time, an analysis of the Late Paleozoic volcanic activity in these belts, based on the volumes of volcanic products at various and identical chronostratigraphic levels, reveals not only differing evolutions of their volcanoes but also some common developmental patterns. Among these, the multi-rhythmic alternation of mafic and felsic rock types should be particularly noted, indicating that the Late Paleozoic volcanic megacycle can be divided into a series of elementary cycles, represented by specific andesitoid and rhyolitoid volcanic formations. This polycyclicity in the evolution of volcanic activity in the VPBs reflects a well-known global pattern of volcanic processes on a regional scale [35], [40], [42].

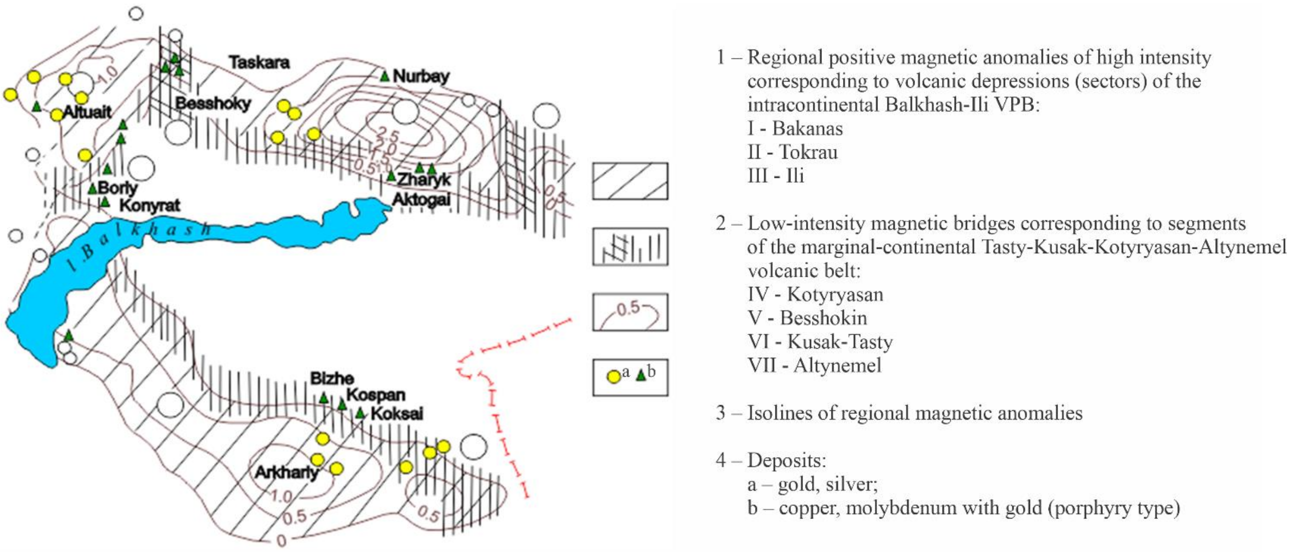


Figure 6. Regional magnetic anomalies of the Late Paleozoic Volcanic-Plutonic Belts of the Junggar-Balkhash fold system [37]

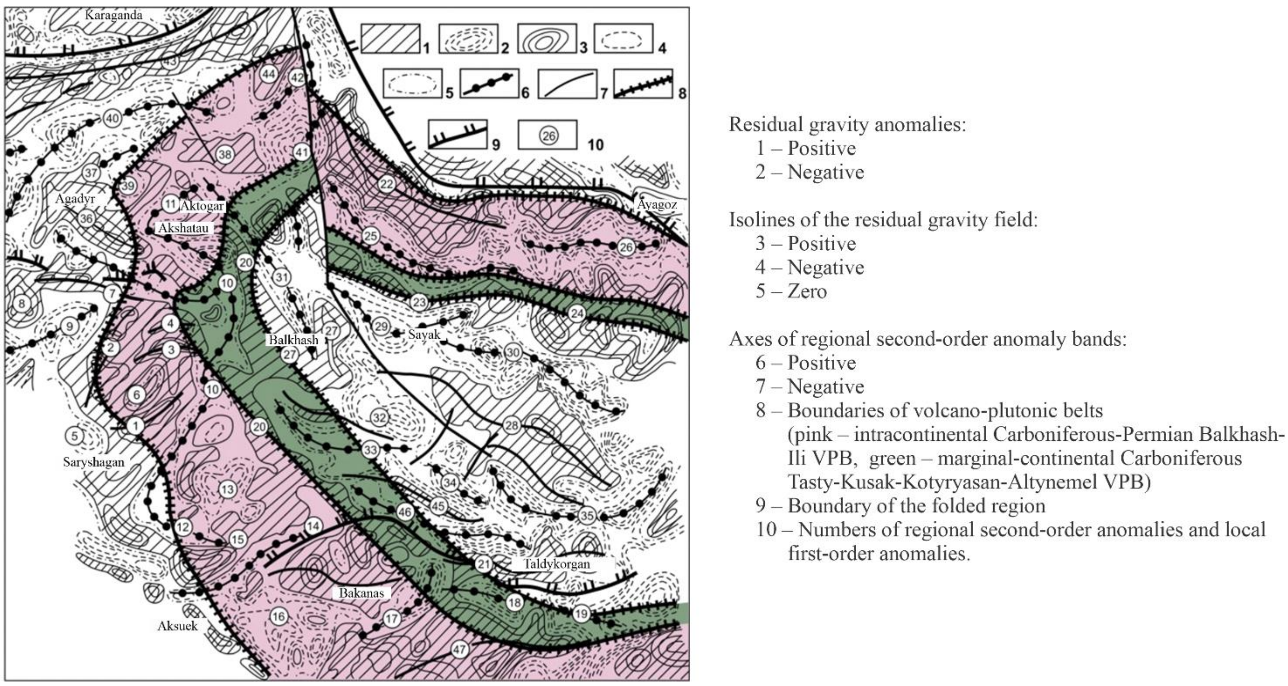


Figure 7. Schematic map of residual gravity anomalies of the Junggar-Balkhash fold system [28]

Table 2. Comparison of volcanic activity manifestations in the Late Paleozoic VPBs of the Junggar-Balkhash fold system [31]

Main areas of Late Paleozoic volcanism occurrence				Carboniferous-Permian Balkhash-Ili intracontinental volcano-plutonic belt			Carboniferous Tasty-Kusak-Kotyrasan-Altinemel peripheral-continental VPB		
Volcanic cycles of the Late Paleozoic	Subcycles	Age of suites	Structural-formational zones (SFZ) and megazones*	I. Uspenskaya, II. Western Tokraus, III. Zhanta-uskaya, IV. Southern Tokraus, V. Eastern Tokraus, VIII. Kotanemel, IX. Bakanas, X. Ili			Tasty-Kusak-Kotyrasan-Altinemel, VI	Area of suite distribu-tion, S (sq. km)	Volume of suites (cu. km)
			Suites / Thickness of suites min-max	Thickness of suites (average statistical and sum of averages, m)	Area of suite distri-bution, S (sq. km)	Volume of suites (cu. km)			
IV P_2wrp-P_3chn	Acidic	P_3chn	Seyriktauskaya (sr), Zhanskaya (žn), Malaisarynskaya (ml)	av.$_{-3}$-318 Σ cp.-955	15429	14734695			
	Intermediate-basic	P_2wrp	Maitasskaya (mt), Bakalinskaya (bk), Zheldykorynskaya (žk)	av.$_{-3}$-649 Σ av.-1946	18162	35343252			
III P_1^1as-P_2rd	Acidic	P_1^2-P_2 kun-rd	Shangeldaiskaya (šn), Upper Kyzylkiinsk-Karmyskaya (kz2+kr), Zhalgyzagashskaya (žg)	av.$_{-8}$-594 Σ av.-4750	82242	390649500			
	Intermediate-basic	P_1^1as-art	Dostarskaya (ds), Dzhangeldinskaya (dž), Ushmolinskaya (uš), Lower Kyzylkiinskaya (kz1), Beskaynarskaya (bs)	av.$_{-8}$-388 Σ av.-3102	92385	286578270			
II C_1s_2-C_2gz	Acidic	C_2m_2-C_3gž	Koskyzylskaya (ks), Koldarskaya (kl), Kungisayakskaya (kn), Taskorinskaya (ts), Upper Kugalinskaya (kug1)	av.$_{-8}$-474 Σ av.-3795	69399	263369205	330-750 av.$_{-6}$-535	14523	7769805
		C_2b_2-m_1	Keregetasskaya (kg), Tastykudukskaya (tk), Bakanasskaya (bk), Lower Kugalinskaya (kug1), Znamenskaya (zn)	av.$_{-10}$-647 Σ av.-6475	67319	435890525	100-1500 av.$_{-11}$-659	26902	17728418
	Intermediate-basic	C_1s_2-C_2b_1	Kalmakemelskaya (kr), Burultasskaya (br), Degerezskaya (dg)	av.$_{-8}$-771 Σ av.-6166	67043	413387138	120-2800 av.$_{-15}$-791	29225	23116920
I C_1v_2-s_1	Contrasting and sequentially differentiated	C_1v_2-s_1	Karkaralinskaya (kr), Kusakskaya (ksk), Alabiinskaya (al), Batpakskaya (bt)	av.$_{-8}$-854 Σ av.-6835	56191	384065485	120-2000 av.$_{-13}$-845	30000	2535000
Total thickness (based on average values) of volcanics in the belt				34024			2740		
Thickness of basic and intermediate volcanics in the belt				13606.25			1086.75		
Thickness of acidic volcanics in the belt				17417.75			1653.25		
Volume of basic composition volcanics in the belt						2416333937			24004170
Volume of acidic composition volcanics in the belt						8165058009			27145978
Total volume of volcanics in the belt						10581391947			51150148

3.3. Carboniferous marginal-continental Tasty-Kusak-Kotyrosan-Altunemel Volcanic Belt

The Tasty-Kusak-Kotyrosan-Altunemel Volcanic Belt (TKKAB), distinguished from the previously known Balkhash-Ili Volcanic Belt (B-I VB), extends over 1000 km with a width ranging from 15-20 km, and up to 30-50 km in places (Figs. 4, 6, 7). It is situated at the boundary of the Junggar-Balkhash marginal paleobasin and the edge of the Kazakhstan microcontinent, resting on transitional-type crust. Its stratigraphy is characterized by the continuous buildup of formation complexes from the initial stage of the belt's formation with the complexes of the actual volcanic belt, i.e., more recent formations. The clear boundary position of the belt leaves little room for debate regarding its classification as a modern marginal-continental volcanic belt.

Similar to the Far Eastern volcanic belts [36], a crucial feature of the described belt is its strict association with regional normal and reverse fault zones, which typically exhibit extensive development in the transition zone from continent to ocean. Although these deep fault zones are unlikely to be directly comparable to Benioff zones, their "depth" is confirmed by geophysical data. This suggests that they may reach mantle portions of the tectonosphere, thereby fostering intense volcanic and intrusive magmatic processes, and ultimately leading to the formation of the marginal-continental Tasty-Kusak-Kotyrosan-Altunemel Volcanic Belt. The marginal-continental setting of the described volcanic belt is characterized by a significant amount of sedimentary deposits, in addition to volcanic and volcaniclastic deposits in the initial complex of the volcanic belt (Kusak Formation), indicating coastal-marine conditions of their formation (Fig. 8).

The described volcanic belt, as noted above, is clearly delineated in geophysical fields (Figs. 6, 7). It corresponds to a regional arcuate anomaly, characterized on its inner side by anomalous segments with reduced intensity (Fig. 6). These segments consistently separate the belt and the JBFS structures with negative magnetic anomaly values. This transitional structural-formational zone corresponds to the Carboniferous marginal-continental Tasty-Kusak-Kotyrosan-Altunemel Volcanic Belt [29], [31], [44].

The marginal-continental Tasty-Kusak-Kotyrosan-Altunemel Volcanic Belt, previously considered part of the frontal zone of the Balkhash-Ili Volcanic Belt, inherits sedimentary, volcaniclastic, and volcanic complexes from the Late Devonian to Early Carboniferous (Fig. 8). Despite the presumed complex foundation structure of the marginal-continental belt, a single vertical formation sequence is mapped for all its segments: Tasty, Kusak, Kotyrosan, and Altunemel.

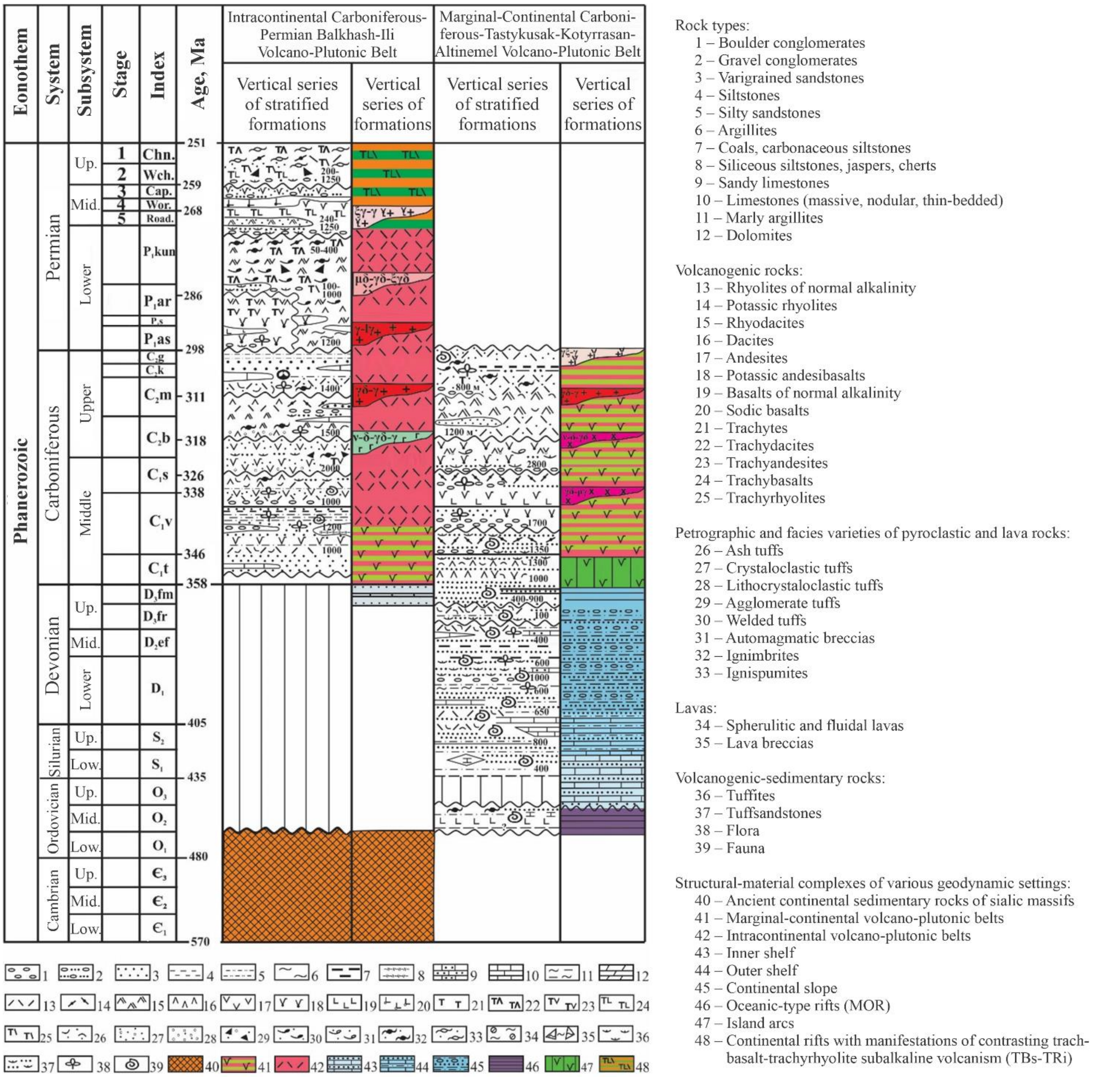


Figure 8. Structural and compositional complexes of Late Paleozoic Volcanic Belts and their formation conditions [31]

In the foundation of the volcanic belt, large tectonic plates, covers, and olistostromes of basaltic and jasperoid rocks (Itmurundin – O_1^2, Kazyk – O_2^2, and Tyuretay – O_3^2 formations) are identified among siliceous aleurites, tuffites, and siliceous-clastic rocks. These are associated with tectonized ultramafites from the Itmurundin intrusive complex (Pz_1it), comprising serpentinite, peridotite, pyroxenite, gabbro, and plagiogranite. Ultramafites, basaltoids, and jasperoids belong to the ophiolitic triad, characteristic of oceanic crust composition. According to petrochemical data, the andesite and afire basalts of the ophiolitic formation are classified as tholeiites, subalkaline, and alkaline types of basaltoids. The belt foundation is further developed by a significant flysch S-D series, forming in the geodynamic setting of a marginal sea and the Famen-Early Carboniferous marine terrigenous-carbonate deposits of the inner shelf. Of particular interest is the marine terrigenous-volcaniclastic association C_1t-v_1, whose volcanics, corresponding to the leuco-basalt-andesite-dacite-plagiophyre formation with an Na-type alkalinity, allow for the reconstruction of an island-arc geodynamic setting for this stage of the volcanic belt's development [30], [45].

The most recent (C_1v_{1-2}) formations at the base of the belt (Kemelbek, Zhabyk, Early Batpak suites) are tuffogenic-carbonate-argillaceous-terrigeneous deposits [27], [34], [39], [44] formed in marine, coastal-marine, or lagoonal environments. The vertical sequence of the Tasty-Kusak-Kotyrosan-Altyn-Emel VPB is completed by formations corresponding to the geodynamic setting of the edge-continental VPB. These include Early Carboniferous (C_1v_2-s_1) contrasting basalt-andesite-basalt-rhyodacite-rhyolite Na alkaline formations with frequent layers of terrigenous and carbonaceous-siliceous rocks (Kusak suite), and the progressively differentiated andesite-basalt-andesite-dacite-rhyolite Na, K-Na alkaline formation (Batpak suite), where the volcanic rocks include basalts and andesites close to tholeiitic types from island arc fronts in the first case, and rhyolites in the second case.

Early Carboniferous volcanic formations are closely associated with the widely expressed Early Carboniferous gabbro-diorite-tonalite-granodiorite-plagiogranite intrusive formation (Balkhash, Muzbel, Altyn-Emel complexes C_1). At the final stage of the formation of the edge-continental belt, another significant cycle of volcanism is noted, represented by a basalt-andesite formation (C_1) with Na, K-Na, and K alkalinity, including numerous transitional rocks such as trachyandesites, dacites, and andesitic dacites (Kalmak-Emel, Degerez suites C_1s_2-C_2b_1), dacite-rhyodacite-rhyolite (C_2b_2-m_1) K-Na and K alkalinity (Keregetas, Lower Kugalin suites), and rhyodacite-rhyolite ($C_2^2m_2$-gz) with a wide range of alkalinity and many layers of aleurolites, carbonaceous rocks, sandstones, tuffaceous sandstones, and tuffs (Koskysyl, Koldar, Upper Kugalin suites C_2m_2-gz ks). The vertical series of the belt is further complemented by intrusive komagmatic complexes: a progressively differentiated gabbro-diorite-granodiorite-granitic formation predominantly K-Na alkalinity (Topar complex C_2^1), adamellite-granite K-Na, less frequently Na or K alkalinity (Kaldyrmin complex C_2^2), and granite-leucogranite formations K and K-Na alkalinity with predominance of normal, and less frequently, subalkaline granites (Akchatau complex P_1^1). The consistently maintained soda-type alkalinity in the volcanic rocks of the Kusak suite (C_1v_2-$s_1$ks) (Fig. 8) may also indicate the immaturity of the continental crust at the base of the belt and, likely, its transitional type.

3.4. Carboniferous-Permian ontracontinental Balkhash-Ili Volcanic Belt

Intracontinental (intra-continental) volcanic belts are entirely located on continental crust along the margins of fold belts of various ages [31]. As independent structural settings, they were identified by U.R. Mitchell and Garson [46]. A typical example of an intracontinental volcanic belt is the Mongolo-Okhotsk type zones.

The Carboniferous-Permian Balkhash-Ili Volcanic Belt, situated between the Carboniferous edge-continental Tasty-Kusak-Kotyrosan-Altyn-Emel Belt and the Devonian edge-continental Central Kazakhstan Volcanic Belt, extends over 1600 km with a width ranging from 80-100 km to 120-200 km (in the northern part), exhibits many features characteristic of intracontinental volcanic belts. It encircles the Carboniferous edge-continental volcanic belt internally, being displaced 40-100 km inward from the paleobasin boundary. The external or rear boundary of the Balkhash-Ili Belt is uneven on the modern erosional surface with sharp displacements along transverse deep faults of the Sokurkey-Gulshad-Birksi-Tortkul, Saryoba-Keregetas-Akshoky-Symbil, Central-Kyzylray, Central-Junggar, and other faults, which determined the manifestation of Late Paleozoic volcanism in the form of superimposed volcanic-plutonic (VPS) and volcanic-tectonic structures (VTS) on the structures of the external Caledonian framework.

The boundary between the Carboniferous-Permian intracontinental Balkhash-Ili Volcanic Belt and the Carboniferous edge-continental Tasty-Kusak-Kotyrosan-Altyn-Emel Belt is complex and coincides with a series of deep faults that are often magma-controlling. Evidence for this is the association with intrusive bodies, primarily Early Carboniferous granitoids of the Balkhash (C_1) and Muzbel (C_1) complexes and volcanic vents of the Kusak (C_1v_2-s_1) suites. Throughout the boundary, such as along the Konyrat-Borly-Shozek deep fault, Early Carboniferous intrusive bodies like Tortkul, Karateke, and Kyzyljal appear to be "strung" onto the fault. Additionally, a "Muzbel belt" of Early Carboniferous granitoids is associated with much of the bordering Muzbel Fault. The described boundary of the volcanic belt also acts as a petrochemical "barrier", as it is associated with a sharp change in magma alkalinity from sodium to normal and even potassium types (Fig. 9).

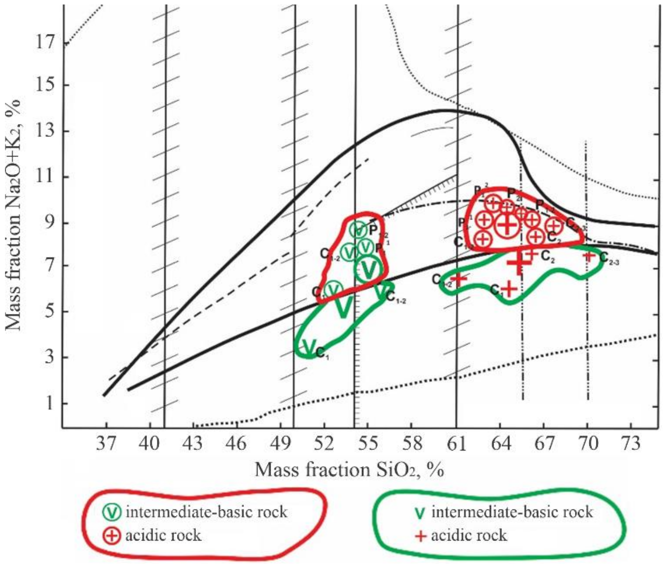


Figure 9. Position of various-aged volcanic rocks of Late Paleozoic volcanic-plutonic belts of the Junggar-Balkhash fold system on the classification scheme of igneous rocks. Coordinates SiO_2 – (Na_2O + K_2O) [29], [31]: (1) – average chemical composition of volcanic rocks of different ages in Carboniferous-Permian Intracontinental VPBs; (2) – average chemical composition of volcanic rocks of different ages in Carboniferous Marginal-Continental Tastykusak-Kotyrrasan-Altinemel VPB of JBFS

Analysis of Late Paleozoic volcanism in belts, based on the petrochemical composition of volcanic rocks at various and identical chronostratigraphic levels, reveals their individual petrochemical characteristics and formation on intracontinental, continental, and transitional crust types.

The traditional segmentation of the Carboniferous-Permian Balkhash-Ili Volcanic Belt (B-I VB) into the north-western Tokrau, northern Kotanemel-Kalmakemel, north-eastern Bakannas, and southern Junggar or Ili sectors is based on regional faults that divide it into several large sectors [27], [43]. The deep structure of these sectors varies, as confirmed by geophysical data (Figs. 6, 7).

The Balkhash-Ili Volcanic Belt is distinctly characterized by an extensive semicircular regional zone of high-intensity positive anomalies. The maximum positive values (50-100 nT) correspond to the Tokrau, Kotanemel-Kalmakemel, Bakannas, and Ili volcanic depressions, which are constituent parts (sectors) of the intracontinental Carboniferous-Permian Balkhash-Ili Volcanic Belt.

The Balkhash-Ili Volcanic Belt represents a clearly superimposed megastructure, as it covers a wide range of structurally heterogeneous deposits with significant interruptions in sediment accumulation, varying in composition, age, and geodynamic setting (Fig. 8).

In the magnetic field, the boundaries of both the intracontinental Carboniferous-Permian Balkhash-Ili Volcanic Belt and its individual volcanic depressions are clearly delineated at regional and local levels, predominantly showing positive field values (Fig. 6). Interpretation of magnetometric data also allows for clarification of the thickness of volcanic complexes and their internal structure. According to geophysical data, the thickness of volcanic rocks in the central parts of the Tokrau Depression is 2000-3000 meters, in the Bakannas Depression reaches 4000-5000 meters, and in the Ili Depression is 3000-4000 meters.

According to geophysical data [28] and [37] the base of the Tokrau Depression is characterized by granito-gneiss domes (GGD) with a granitic-metamorphic layer ranging from 1 to 5 km in thickness. Some of these domes are exposed on the surface as isolated blocks of the Aktau-Junggar sialic paleomassif, including the Tasaral-Kyzylespinsky, Aktau-Moyntinsky, and Central-Junggar domes. Gravitational anomalies also reveal a series of granito-gneiss domes, such as the Saryolen, Maitas-Konyrat, which are grouped in a long meridional band in the northern segment of the Carboniferous-Permian intracontinental B-I VB.

In the base of the Bakannas Depression, basic and metabasic complexes and individual blocks of the crust with a granitic-metamorphic layer are observed, notably the Aktogay GGD. Higher in the stratigraphy, Paleo-island-arc uplifts are recorded, with the most significant being the Koldar uplift.

In the Kalmakemel zone, gravitational anomalies of positive sign reveal island-arc uplifts, while negative anomalies indicate depressions. Based on combined gravimetric and seismic data, two island-arc volcanic uplifts are distinguished: the Kalmakemel frontal uplift and the Zhorginskoe rear uplift, separated by the Kotanemel inter-arc depression [47]. These areas host the Tasorin-Tuz and Muzbel-Tuz mineral deposits.

In the Ili volcanic depression, sialic basement domes include the Zhideli-Kuygan, Ili-Bakannas, part of the southeastern extension of the Aktau-Junggar paleocontinent, marked by isometric and irregularly oval gravity anomalies (Fig. 6). At a higher level – in the middle Paleozoic structural tier – volcanic uplifts penetrated by granodiorite plutons and isolated trough-like depressions are noted.

A significantly distinguishing feature of the Carboniferous-Permian intracontinental Balkhash-Ili VB is the compositional makeup of the geological formations involved in its structure (Figs. 3, 8).

The pre-Paleozoic formation series at the base of the B-I VB in the northwestern Tokrau and southern Ili segments is characterized by the following compositional complexes: Proterozoic (NP) slate-quartzite formation (Aikarlyn, Taskorin, Altinsyngan, Usek series). The intrusive magmatism of these rocks includes granito-gneiss plagiogranite (Uzunzhalsky, Mynshukursky) complexes. Younger (V-$Є_1$) basement deposits represent terrigenous-carbonate and carbonate formations (Bylkyldak, Baepchin, and other suites, Basagin series). The formation series of the belt is further developed by formations of the continental slope and base of the Aktau-Junggar continental massif, including terrigenous quartz-arkosic formations of the Vendian (Kenelinsk, Kopal suites), and siliciclastic-carbonate-terrigenous formations (Aksuransk, Tekeliy, Sarykum, Zhamshin, Chazhogay, Kurchiliks suites) of $Є_2$-O_1 age. Higher in the formation series of the Tokrau and Ili segments, the belt is overlain by the edge-marine stage complexes of the B-I VB base (C_1t_2-v_2) [27], [34], [40], [48].

The Carboniferous-Permian intracontinental Balkhash-Ili Volcanic Belt is primarily represented by terrigenous flysch and flysch-molasse series. Its formation culminates in the development of a volcanogenic-sedimentary andesite-basalt-carbonaceous-siliciclastic formation of C_1v_{1-2} age (Kemelbek Suite).

The composition and structure of the basement in the northern (Kotanemel-Kalmakemel) and northeastern (Bakanas) segments of the intracontinental B-I VB are almost identical to the basement of the previously described Carboniferous marginal-continent VB. Differences are noted during the Late Carboniferous when volcanic-terrigenous sediments of the Karabulak Graben appear among predominantly terrigenous and carbonate-terrigenous flysch marginal marine complexes. The volcanics, predominantly andesite-basalts and andesites of the calcareous-alkaline series with somewhat increased alkalinity, correspond to the continuously differentiated andesite-basalt-andesite-dacite-riolite formation.

The formations of the Carboniferous-Permian B-I VB, which are polycyclic and generally synchronous throughout the belt, include the following vertical formation series (Figs. 5, 8, 9). Early Carboniferous volcanogenic-sedimentary, and less frequently, volcanogenic, successively differentiated andesite-basalt-andesite-dacite-riolite formations (Karkaralinsk, Batpak suites – C_1v_2-s_1 kr, bt) vary widely from zone to zone, primarily due to the changing ratio of sedimentary to volcanogenic rocks. Among the latter, rhyolites (ignimbrites, ignispuemites, hyaloclastic and crystal-clastic tuffs) dominate, belonging to the sub-alkaline and calcareous-alkaline series with varying alkalinity types – K-Na and K (Figs. 5, 8, 9).

Subsequently, the formation series is augmented by Early-Late Carboniferous differentiated basalt-dacite-andesite, dacite-andesite formations of the andesite family with K-Na and K alkalinity (Kalmakemel, Degerez suites – C_1s_2-C_2b_1) with rare sedimentary interlayers. The co-magmatism of these volcanics includes gabbro-diorite-diorite-granodiorite-adamelite formation (multiphase Toparsky, Kokdalinsky, and Early-Koytassky complexes, C_2^1).

The Late Bashkirian-Early Moscovian stage of B-I VB development is characterized by intense acidic volcanism and localized uneven transgression of the Junggar-Balkhash marginal sea. This results in the formation of volcanogenic-sedimentary associations, with the volcanics consisting of a successively differentiated andesite-dacite-rhyolite, dacite-rhyolite formations (Keregetas, Lower-Kugalin suites – C_2b_2-$m_1$kg, kug$_1$) with K-Na alkalinity.

Alongside acidic volcanics, intrusive masses of adamellite-granitic formation with K-Na and K alkalinity (Kaldyrmin, Kumzhalsky, Koytassky complexes C_2^2) are widespread throughout the B-I VB. During the Late Carboniferous, the formation series in the majority of the SBZ belt is supplemented by volcanogenic-sedimentary associations of rocks (Koskizyl, Koldar, Upper-Kugalin suites - C_2m_2-gz, kl, ks, kug$_2$).

The volcanics in this association are mainly rhyolites and ultra-acidic rhyolites (SiO_2 up to 76-78%) with K-Na and K alkalinity (Fig. 9). Co-magmatism of the Late Carboniferous rhyolites includes normal biotite granites and leucogranites of the Akchatau, Besobin, Kyzyltas, Lepsinsk rare-metal complexes (P_1^1), corresponding to granitic-leucogranitic formation with K-Na and K types of alkalinity.

Subsequent magmatism in the B-I VB during Permian times was driven by the growth of a mantle plume, which induced rifting of the young, newly-formed Carboniferous continental crust and new stages of tectono-magmatic activation, manifested as Early-Middle Permian (P_{1-2}), Middle-Late Permian (P_{2-3}), and Late Permian (P_3) volcanic cycles.

The Asselian-Artinskian volcanic activity begins with the extrusion of sub-alkaline basic to intermediate volcanic rocks – trachybasalts, andesite-basalts, trachyandesites, andesidacites, latites, and less frequently dacites, mainly K, less frequently K-Na alkalinity, and trachitoid varieties (Jangeldin, Dostar, Lower-Kyzylkain, Akshokin, Besskainar suites, P_1^1-a-ar), corresponding to andesite, basalt-andesite-basalts, andesite-dacite-andesite formations of the sub-alkaline series (Figs. 5, 9, Table 2).

The belt also features co-magmatic volcanic monzonitoid intrusive complexes: Kokdombak, Umit, Ushtobin – P_1^2-P_2^1. The Early-Middle Permian cycle (P_1^2-P_2^1) concludes with intense acidic volcanism, which, due to its breadth and magnitude, is the principal crust-forming event for the JBFS (Fig. 5).

For the majority of the SBZ (Structural-Facial Zone) of the Carboniferous-Permian intracontinental B-I VB, the manifestation of Late Paleozoic volcanism concludes at this stage. The varying volumetric ratios of volcanic rocks within the SBZ of the B-I VB allow for the distinction of the Trachydacite-Riodacite-Rhyolite and Dacite-Rhyolite Formations (Shangeldy, Upper-Kyzylkain-Karmys, Itbay, and Zhalgyzagash suites from the Early to Late Permian (P_1-P_2^1).

Intrusive formations that are comagmatic with the Early Permian acidic volcanic rocks include granitoids of the granite-granodiorite formation (Kyzylkainar, Late-Katutaus, and Torangalyk complexes from the Late Permian, P_2).

The final (P_2^2-P_3) volcanic cycle, which completes the formation of the B-I VB, is less pronounced and is associated with marginal and transverse zones of deep faults (Zhantau, Eastern-Bakanas, Ili SBZ) formed as continental rifts in the cap of the mantle plume [29], [31], [44]. The deep nature of these rifts is confirmed by the eruptions of subalkaline basaltoids of K alkalinity, corresponding to the trachybasalt-andesibasalt-trachyandesite formation (Maytas, Bakalin, Zheldykorin suites, P_2^2-P_3^1) (Figs. 5, 9).

The formation sequences of all segments of the B-I VPB (Basaltic-Intrusive Volcanic-Plutonic Province) are capped by volcanogenic-sedimentary and volcanogenic formations of the trachyrhyolite-rhyolite and trachydacite-rhyolite series, which are predominantly K-alkaline (Zhanskaya, Seyriktauskaya, and MalaySarinskaya suites, P_3^2). The sedimentary rocks of the volcanogenic-sedimentary associations are represented by volcanomictic red-colored molasse-like formations (Figs. 5, 9). Intrusive comagmatic rocks of the last two volcanic formations – monzogabbro, monzodiorite-monzogranodiorite (Kadyrsky, Taskorinsky, Early Southern Junggarian, P_3^1), and granosyenite-potassium granite (Kyzyladyrsky, Kukentaysky, Late Southern Junggarian, P_3^2) – are scarcely manifested in the belt.

However, the final development of the B-I VPB is marked by the intensive emplacement of large plutons from the youngest leucogranite-alaskite formation of K-alkaline affinity (Kyzylraisky, Bakanassky or Kyzyltassky, Sandyktassky or Khorgossky complexes, P_3-T_1).

3.5. Metallogenic features of the late Paleozoic VPBs of the JBFS

For many decades, the metallogenic specialization of the Late Paleozoic continental volcanogenic deposits was considered to be copper-rare metal-polymetallic, as reflected in all metallogenic maps of the Junggar-Balkhash region. Accordingly, the JBFS (Junggar-Balkhash Fold System) was considered prospective only for the exploration of these named minerals [27], [28], [34]. However, thematic and industrial studies conducted by the authors over the past 10-30 years on the geology and metallogeny of the JBFS have revealed several new metallogenic aspects of the Late Paleozoic VPBs [38]-[42].

One of the most significant of these is the gold-silver-bearing potential of the JBFS, which was mentioned by A.B. Diarov (1968) and B.S. Zeilik (1968) as early as the 1960s. However, no substantial scientific or industrial efforts have been made to develop this direction in the JBFS up to the present time. This is evidenced by the almost complete absence of active gold mining enterprises in the region, with the exception of small deposits mined by prospectors at Taskora, Arkharly, Mystobe, Yenbekshi, and Sholkyzyl.

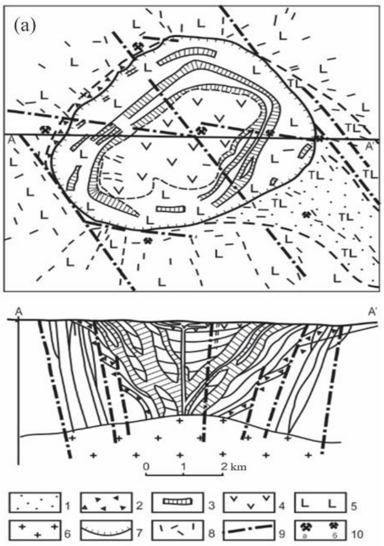
At the same time, the undoubted high gold potential of the JBFS is evidenced by the "Gold-silver map of the JBFS" at a scale of 1:500000, covering an area of 55 sheets at a scale of 1:200000. The map shows more than 2000 objects of various formation affiliations, among which epithermal deposits undoubtedly predominate. Of the occurrences marked on the map, 684 mineralization points have an Au content ranging from 0.01 to 0.1 g/t; 773 points range from 0.5 to 1.0 g/t; 577 points range from 1.0 to 5.0 g/t, and 90 points exceed 5.0 g/t [41].

Among the numerous gold-silver occurrences in the study region, the predominant geological-industrial type based on a number of ore-bearing criteria is epithermal gold-silver mineralization, which is well-studied globally and has attracted increasing interest from resource users in recent decades [45], [46], [49]-[56].

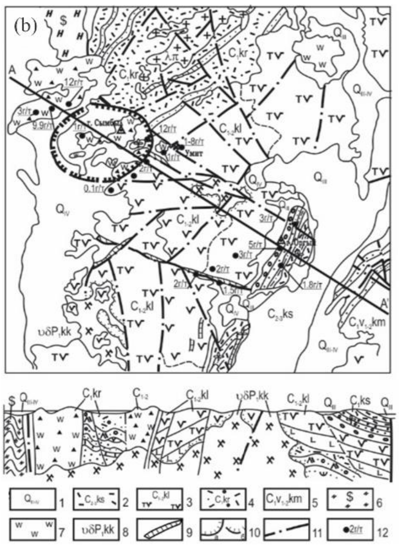
Given the reliably established pattern of gold deposit localization to volcanic-plutonic belts, the task arose to refine their metallogenic specialization. A statistical analysis of the quantitative occurrence of traditional copper, rare metal, polymetallic, and newly identified numerous gold-silver occurrences in the VPBs showed that copper-porphyry and epithermal gold-silver mineralization predominate in the region [57], [58]. While copper-porphyry mineralization in the JBFS has been intensively studied since the discovery of the large copper-porphyry deposit Medny Konurad for nearly a century, as already noted, epithermal gold-silver mineralization has been practically unexplored, despite its abundance in the JBFS.

Nevertheless, the available extensive data on the study of gold ore occurrences have demonstrated their great potential due to the discovery of a number of analogies with known large epithermal gold-silver deposits worldwide, based on various geological criteria: Vatukoula on the island of Fiji – Symbil, Southern Tokraus Tectonic Fault Zone (SFTZ); Kalgoorlie, Western Australia – Taskora, Kotanemel-Kalmakemel SFTZ; Kremnica, Slovakia - Southern Kuder, Western Tokraus SFTZ, etc. (Fig. 10).

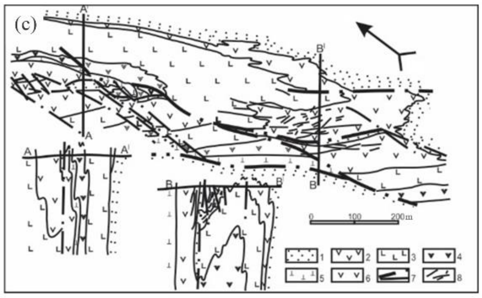
In light of the above, the region is highly favorable for the discovery of large epithermal Au-Ag deposits, which are currently among the most prioritized for gold extraction. This is due to new technologies (tank and heap leaching) that allow for the development of these deposits with an average gold content of around 1 g/t or even lower. A prime example of such an epithermal deposit within a VPB is the Round Mountain gold deposit, with approximately 300 tons of gold (Fig. 11).



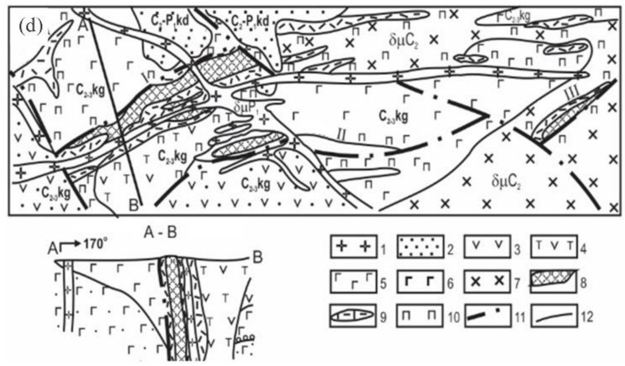
1 – Trachybasalts
2 – Intrusive agglomerates
3 – Andesitic conical deposits
4 – Biotite andesites
5 – Basalts
6 – Magmatic reservoir
7 – Caldera contour
8 – Dykes
9 – Main fracture zones
10 – Gold deposits: (a) main; (b) other



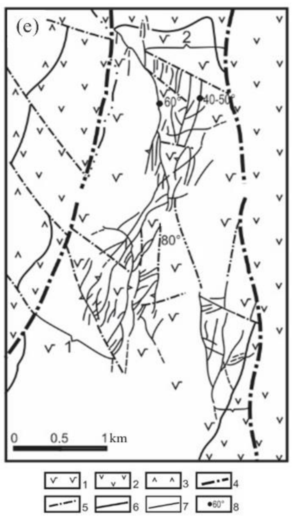
1 – Recent deposits
2 – Koskizylskaya formation (C2-3ks): pumiceous tuffs, rhyolitic ignimbrites
3 – Kalmakemelskaya formation (C1-2kl): andesibasalts, trachybasalts, andesites
4 – Karkaralinskaya formation (C1kr): rhyolites, dacites and their tuffs with layers of tuffites and sandstones
5 – Kemelbskaya formation (C1v1-2km): sandstones, limestones, aleurolites with layers of carbonaceous shales and andesibasalts
6 – Unclassified cambrian deposits: quartzites, quartz-sericite schists
7 – Secondary quartzites over rocks of the Symbil and Northern Orgyin volcanoes
8 – Intrusions of monzonites, monzodiorites of the toparsky complex (C2tp)
9 – Quartz veins
10 – Boundaries of calderas of Symbil and Northern Orgyin: (a) mapped; (b) proposed
11 – Faults
12 – Mineralization points with gold content



1 – Black flag beds
2 – Golden mile dolerites
3 – Paringa metabasalts
4 – Williamstown dolerites
5 – Devon consol metabasalts
6 – Hannan's lake serpentinites
7 – Tectonic faults: (a) major; (b) others
8 – Ore bodies



1 – Q dioritic porphyrites of the Renneperm intrusive complex
2 – Tuff conglomerates, tuff sandstones of the Koldar suite. Kergetas suite
3 – Trachyandesite tuffs
4 – Explosive breccias
5 – Andesibasaltic porphyrites. Kalmakem suite
6 – Andesidacite tuffs
7 – Subvolcanic dioritic porphyrites
8 – Hydrothermally metasomatized rocks of adular-quartz composition with native Au
9 – Quartzified rocks
10 – Propylitized rocks



1 – Pyroxene andesites (N_1^2)
2 – Young pyroxene andesites (N_1^2)
3 – Pyroxene-amphibole andesites (N_1^3-N_1^4)
4 – Ore-controlling faults
5 – Thin faults
6 – Veins of Au-Ag-polymetallic ores
7 – Weakly ore-bearing veins
8 – Strike and dip

1 – Quaternary deposits
2 – Andesitic porphyrites
3 – Granite porphyrites
4 – Monquartzites
5 – Quartz veins
6 – Shear zones and stockwork quartzification
7 – Fault dislocations

***Figure 10.** Comparison of characteristic epithermal gold-silver deposits of the world and Kazakhstan [38]: (a) geological map and cross-section of calderas of Vatukoula and the gold ore deposits located within its bounds (according to L.S. Denholm); (b) geological map and cross-section of calderas of Symbil (Northern Balkhash Area) and the location of the Umit mineral occurrence within its bounds (according to E.Y. Seitmuratova); (c) geological plan and cross-sections of the Kargurli deposit (according to R.V. Woodall); (d) schematic geological map of the Taskora deposit (according to A.B. Diyarov); (e) geological scheme of the Kremnica deposit (according to M. Bemer); (f) geological scheme of the Southern Kuder deposit (according to B.S. Zeilik)*

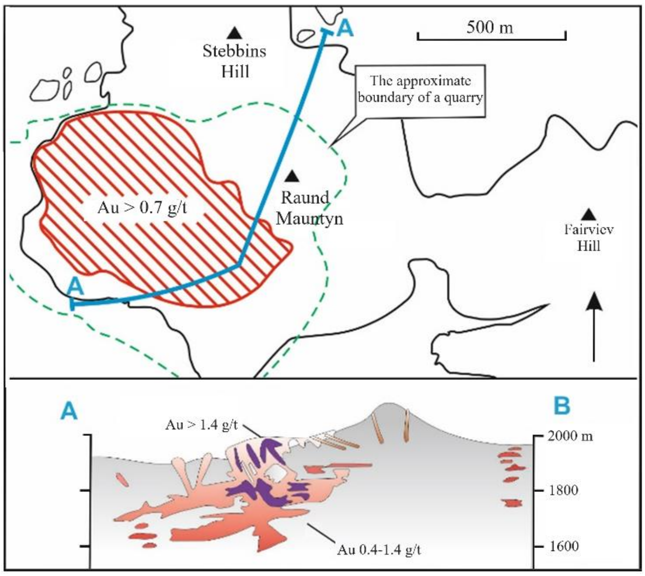


Figure 11. Schematic geological map of the Round Mountain deposit (USA) [52]

Unfortunately, large deposits of this geological-industrial type have not yet been discovered in the JBFS, whereas in the continuation of the intracontinental Balkhash-Ili VPB on the territory of China, large deposits such as Akhi (56 tons) and Koershenkola (170 tons) have been identified (Fig. 12).

Therefore, investigating the reasons for the absence of large epithermal Au-Ag deposits in the Late Paleozoic VPBs of the JBFS by further studying the most promising areas to identify objects of this ore formation appears to be highly relevant. One of the primary reasons for the ineffective search for such deposits may be the failure to consider the characteristic of their occurrence, where single large deposits coexist within the same ore district, and even within the same field, alongside numerous smaller-scale ore bodies.

A typical example of such a distribution of gold-bearing objects is the ore fields of the Tavua Polo deposits (over 90 tons), Silverton-Telluride (about 300 tons), Kivatin province, and others (Fig. 13). These large deposits are located within unified caldera-type structures alongside numerous non-commercial occurrences: 21 objects in the first case, and 37 in the second.

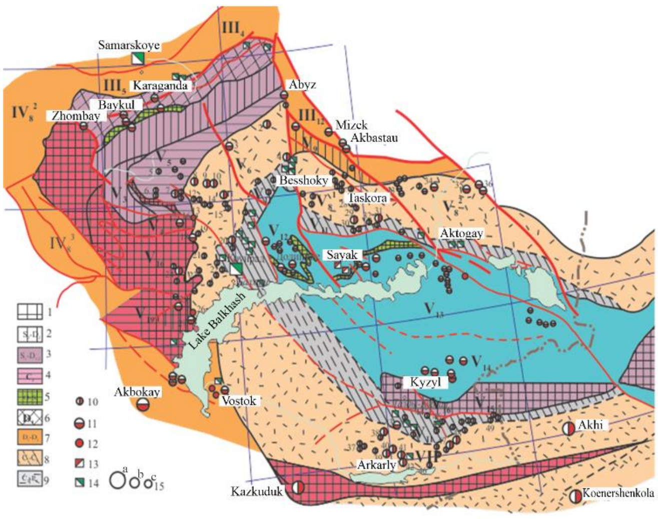
Consequently, when searching for epithermal gold deposits in the VPBs, it is necessary to evaluate the entire potentially ore-bearing area, of which there are hundreds in the JBFS. Additionally, an important consideration during area-wide exploration for Au-Ag occurrences is the possibility of reassessing them as large-volume disseminated and stockwork (veinlet-disseminated) deposits with low-grade ores [42], [49], [50], [52]. Properly evaluated in this way, the recommended gold-bearing objects could significantly enhance the portfolio of genuinely promising areas. However, the most important regional exploration criterion for epithermal gold-silver deposits in the JBFS is the clearly established higher gold potential of the intracontinental Balkhash-Ili VPB. This pattern serves as a valuable guide during exploration activities.

For many years, the primary issue in the metallogeny of the JBFS, driven by the need to provide a reliable mineral base for the Balkhash Mining and Metallurgical Combine, has been the search for copper-porphyry deposits in the region.

Global exploration practices for copper-porphyry deposits show that most of these deposits are localized within major structural elements of the Earth, such as volcanic belts [46], [51], [56], [59]-[64], and the JBFS is no exception. Among the copper occurrences in the JBFS, the majority (68%) are copper-porphyry manifestations, predominantly located within both Late Paleozoic VPBs of the JBFS (Fig. 12).

The identification of patterns in the localization of copper-porphyry mineralization within the Late Paleozoic VPBs of the JBFS has revealed a clear specialization of the Carboniferous marginal-continental Tasty-Kusak-Kotyrasan-Altynemel VPB for this type of mineralization, where 84% of copper-porphyry occurrences are concentrated (Fig. 12). Furthermore, it has been found that all major copper-porphyry deposits, such as Konyrat, Aktogay, and Koksay, are localized within the marginal-continental Tasty-Kusak-Kotyrasan-Altynemel VPB, while smaller deposits like Altayt, Almaly, and Nurbay are found in the Carboniferous-Permian intracontinental Balkhash-Ili VPB (Fig. 12).

The conducted analysis of the distribution patterns of copper-porphyry occurrences in the JBFS reveals many similarities with the distribution of known copper-porphyry deposits in VPBs worldwide, which supports the continued high potential for discovering new large copper-porphyry deposits in the Late Paleozoic VPBs.



1 – Blocks of the precambrian basement of the Junggar-Balkhash fold system
2 – Atasu-Nura structural-formational zone (periphery of the Junggar-Balkhash marginal paleobasin)
3 – Uspen Structural-formational zone (continental rift of famennian-carboniferous age)
4 – Junggar-Balkhash marginal paleobasin (O1-2-C2)
5 – Spasskaya riftogenic zone
6 – Central Kazakhstan marginal-continental Devonian volcanic-plutonic belt (VPB)
7 – Central and rear zones
8 – Tasty-Kusak-Kotyarsan-Altynemel marginal-continental Carboniferous volcanic-plutonic belt (VPB)
9 – Balkhash-Ili intracontinental Carboniferous-Permian volcanic-plutonic belt (VPB)
10 – Gold deposits
11 – Gold-silver deposits
12 – Gold-polymetallic deposits
13 – Gold-copper deposits
14 – Copper-porphyry deposits with gold
15 – a – Large and medium-sized deposits; b – Small deposits, c – Ore occurrence

Figure 12. Schematic map of gold and copper deposits in the Devonian and Late Paleozoic continental volcanic-plutonic belts of Kazakhstan [38], [39]

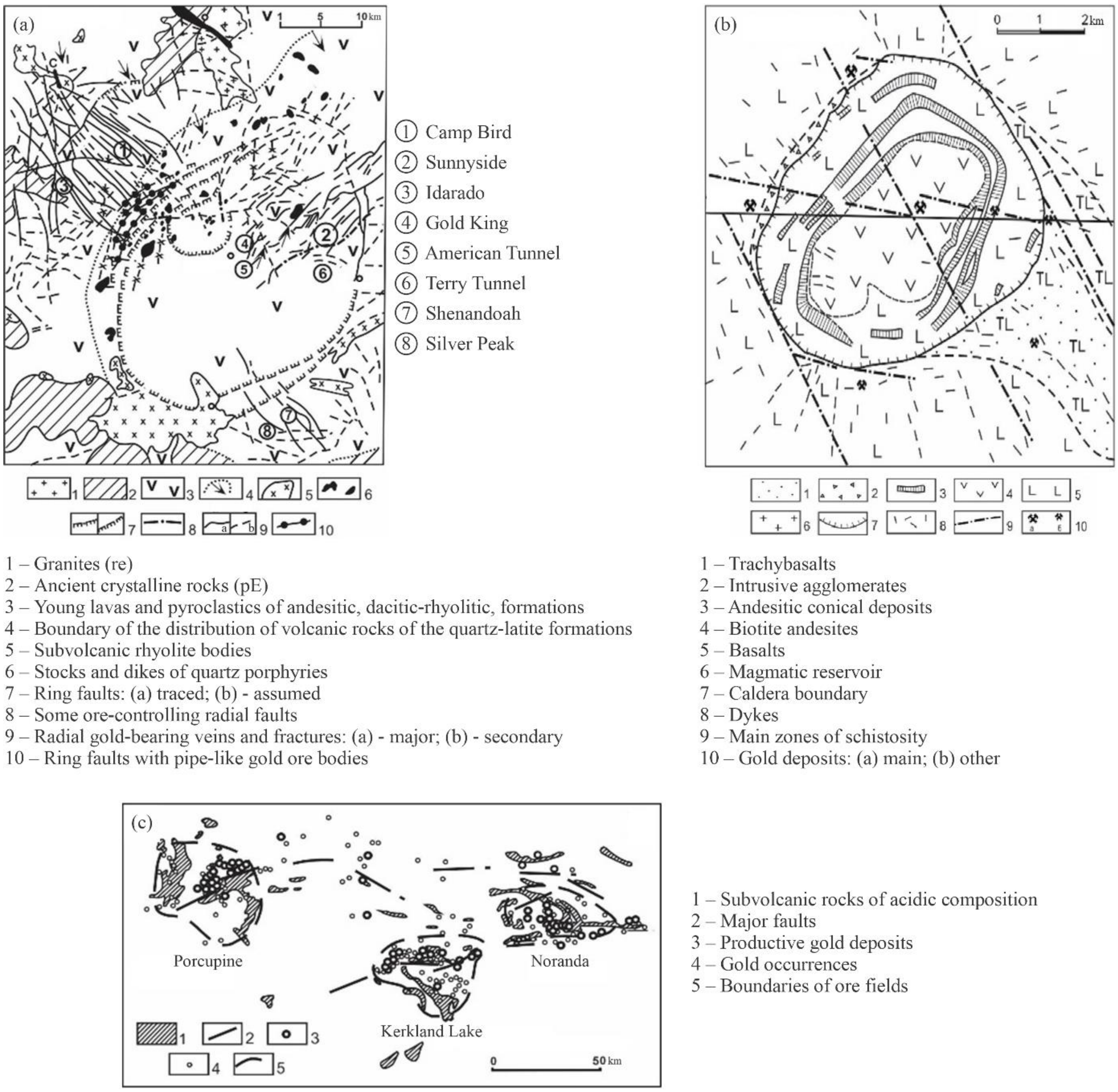


Figure 13. Uneven distribution of gold occurrences in gold-bearing fields [38], [52], [53]: (a) Silverton-Telluride ore Field; (b) Vatukoula and the distribution of gold deposits (according to L.S. Denholm); (c) distribution of gold fields in the eastern part of the Kivatin province (according to A.M. Goodwin)

Consequently, it is recommended to focus exploration efforts on the three most favorable ore districts: Balkhash, Aktogay, and Ust-Ili in the Carboniferous marginal-continental Tasty-Kusak-Kotyrasan-Altynemel VPB.

Future exploration and prospecting for copper-porphyry mineralization should be conducted in two directions. Firstly, it is necessary to continue in-depth exploration of known sites, considering the concept of multi-tiered mineralization in volcanic epithermal deposits (e.g., Nurkazgan, Grasberg, etc.). Secondly, it is crucial to resume the search for commercial copper-porphyry deposits hidden beneath loose sediments in the JBFS territories. According to deep geophysical data, these areas exhibit a geological structure similar to the benchmark Konyrat district, for example, the Pribrezhnoye area [39], [51].

4. Conclusions

The multi-stage studies of the Late Paleozoic continental volcanic and volcano-sedimentary deposits of the Junggar-Balkhash fold system (JBFS) have established that their distribution areas can confidently be classified as Volcano-Plutonic Belts (VPBs). The identified and studied VPBs of different ages, including the Carboniferous marginal-continental and Carboniferous-Permian intracontinental belts, demonstrate a long and complex geological evolution, influenced by their formation on a heterogeneous basement in various paleogeodynamic settings and under different durations of volcanic activity.

Comprehensive analysis has shown that the geological structures of the JBFS are characterized by complex architecture, heterogeneous composition, and a diversity of petrochemical features. The polymetallic specialization of the geological formations within these belts is comparable to similar structures of the Pacific Megabelt. A key feature of the Kazakhstani VPBs is their significant duration of development: from approximately 327.0 to 298.9 million years for the marginal-continental belt and from approximately 327.1 to 251.9 million years for the intracontinental belt. These time intervals reflect the prolonged volcanic activity, manifested in numerous volcano-plutonic and volcano-tectonic structures, where up to four cycles of intermediate-basic and acidic volcanism have been recorded.

The statistically proven priority of copper and gold mineralization in the Late Paleozoic VPBs of the JBFS underscores the importance of further research aimed at the exploration and development of these types of ore deposits. These mineralizations are key global sources of metals such as Cu, Au, Ag, Mo, Re, Bi, Hg, and others. The application of developed exploration criteria and geological search models, proposed by leading specialists in this field, allows for a significant increase in the efficiency of discovering new copper-porphyry and epithermal gold-silver deposits in the Late Paleozoic continental VPBs of the JBFS.

The high level of study of copper-porphyry and epithermal gold-silver occurrences in global practice, along with the many years of research experience in Kazakhstan, indicates a significant potential for discovering new deposits of these types in the JBFS, making the region an important target for further geological exploration.

Author contributions

Conceptualization: ES; Data curation: ES; Formal analysis: ES, RB, MM; Funding acquisition: ES; Investigation: ES, SP, RB, DD, NS, YA; Methodology: ES, SP; Project administration: ES; Software: RB, MM; Supervision: ES; Validation: ES, RB, DD, YA; Visualization: ES, SP; Writing – original draft: ES, SP, NS; Writing – review & editing: ES, SP, RB, DD, MM, NS, YA. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan, AP14870043 “Evaluation of industrial prospects of ore-bearing capacity of structural-formation zones of paleozoids of Kazakhstan on the basis of metallogenogram analysis”.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

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

References

[1] Dorian, J.P. (2006). Central Asia: A major emerging energy player in the 21st century. *Energy Policy*, *34*(5), 544-555. https://doi.org/10.1016/j.enpol.2005.11.009

[2] Issatayeva, F.M., Aubakirova, G.M., Maussymbayeva, A.D., Togaibayeva, L.I., Biryukov, V.V., & Vechkinzova, E. (2023). Fuel and energy complex of Kazakhstan: Geological and economic assessment of enterprises in the context of digital transformation. *Energies*, *16*(16), 6002. https://doi.org/10.3390/en16166002

[3] Togizov, K., Kenzhetaev, Z., Temirkhanova, R., Muzapparova, A., Omirgali, A., & Altaibayev, B. (2024). The influence of the physicochemical characteristics of ores on the efficiency of underground well leaching of uranium deposits in Kazakhstan. *Minerals*, *14*(4), 381. https://doi.org/10.3390/min14040381

[4] Dandan, Z., Zixin, H., Mingyi, L., Haidi, Z., & Yongwei, G. (2023). Analysis of Kazakhstan’s copper resources, development situation and investment potential. *Northwestern Geology*, *56*(1), 156-165. https://doi.org/10.12401/j.nwg.2022007

[5] Issatayeva, F.M., Rudko, G.I., & Portnov, V.S. (2019). Technical and economic substantiation of developing Kusmuryn copper deposit (Kazakhstan). *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *6*, 19-24. https://doi.org/10.29202/nvngu/2019-6/3

[6] Nurpeisova, M., Bekbassarov, Z., Kenesbayeva, A., Kartbayeva, K., & Gabitova, U. (2020). Complex evaluation of geodynamic safety in the development of hydrocarbon reserves deposits. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *1*(439), 90-98. https://doi.org/10.32014/2020.2518-170X.11

[7] Kuandykov, T.A., Karmanov, T.D., Kuldeyev, E.I., Yelemessov, K.K., & Kaliev, B.Z. (2022). New technology of uncover the ore horizon by the method of in-situ leaching for uranium mining. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Science*, *3*(453), 142-154. https://doi.org/10.32014/2022.2518-170x.186

[8] Kenzhetaev, Z.S., Kuandykov, T.A., Togizov, K.S., Abdraimova, M.R., & Nurbekova, M.A. (2022). Selection of rational parameters for opening and drilling of technological wells underground uranium leaching. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *3*(453), 115-127. https://doi.org/10.32014/2022.2518-170x.184

[9] Zainal, P., Zhakupova, S., & Iztayeva, A. (2019). Analysis of inflow the direct foreign investments in priority sector the economy of Kazakhstan. *Farabi Journal of Social Sciences*, *5*(1), 54-63. https://doi.org/10.26577/CAJSH-2019-1-s7

[10] Togizov, K., Issayeva, L., Muratkhanov, D., Kurmangazhina, M., Swęd, M., & Duczmal-Czernikiewicz, A. (2023). Rare earth elements in the Shok-Karagay ore fields (Syrymbet ore district, Northern Kazakhstan) and visualisation of the deposits using the Geography Information System. *Minerals*, *13*(11), 1458. https://doi.org/10.3390/min13111458

[11] Kyrgizbayeva, G., Nurpeisov, M., & Sarybayev, O. (2015). The monitoring of earth surface displacements during the subsoil development. *New Developments in Mining Engineering: Theoretical and Practical Solutions of Mineral Resources Mining*, 161-167. https://doi.org/10.1201/b19901-30

[12] Oliinyk, T., Yefimenko, S., Abdrakhmanova, Z., Kan, A., & Issatayeva, F. (2020). Online ore monitoring using EDXRF method on process conveyor belts at Kazakhmys Corporation LLC operations. *E3S Web of Conferences*, *166*, 02010, https://doi.org/10.1051/e3sconf/202016602010

[13] Nurpeissova, M., Bekbassarov, S., Bek, A., Kyrgizbaeva, G., Turisbekov, S., & Ormanbekova, A. (2017). The geodetic monitoring of the engineering structures stability conditions. *Journal of Engineering and Applied Sciences*, *12*(11), 9151-9163. https://doi.org/10.3923/jeasci.2017.9151.9163

[14] Yousufi, A., Ahmadi, H., Bekbotayeva, A., Arshamov, Y., Baisalova, A., Omarova, G., & Pekkan, E. (2023). Integration of remote sensing and field data in ophiolite investigations: A case study of Logar ophiolite complex, SE Afghanistan. *Minerals*, *13*(2), 234. https://doi.org/10.3390/min13020234

[15] Rysbekov, K.B., Kyrgizbayeva, D.M., Miletenko, N.A., & Kuandykov, T.A. (2024). Integrated monitoring of the area of Zhilandy deposits. *Eurasian Mining*, *41*(1), 3-6. https://doi.org/10.17580/em.2024.01.01

[16] Baibatsha, A.B., Bekbotayev, A.T., & Bekbotayeva, A.A. (2013). Ore-bearing strata lithology of the Zhezkazgan copper sandstones deposit. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, *1*, 135-140. https://doi.org/10.5593/SGEM2013/BA1.V1/S01.019

[17] Kröner, A., Hegner, E., Lehmann, B., Heinhorst, J., Wingate, M.T.D., Liu, D.Y., & Ermelov, P. (2008). Palaeozoic arc magmatism in the Central Asian Orogenic Belt of Kazakhstan: SHRIMP zircon ages and whole-rock Nd isotopic systematics. *Journal of Asian Earth Sciences*, *32*(2-4), 118-130. https://doi.org/10.1016/j.jseaes.2007.10.013

[18] Seitmuratova, E., Arshamov, Y., Bekbotayeva, A., Baratov, R., & Dautbekov, D. (2016). Priority metallogenic aspects of late paleozioc volcanic-plutonic belts of Zhongar-Balkhash fold system. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, *1*, 511-518. https://doi.org/10.5593/sgem2016/b11/s01.064

[19] Nurpeisova, M.B., Sarybaiev, O.A., & Kurmanbaiev, O.S. (2016). Study of regularity of geomechanical processes development while developing deposits by the combined way. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *4*, 30-36.

[20] An, F., Zhu, Y., Wei, S., Zhang, H., & Zhao, L. (2022). Variation of crustal thickness in central west Junggar orogenic belt: Insight into its Late Palaeozoic tectonic evolution. *International Geology Review*, *64*(13), 1799-1816. https://doi.org/10.1080/00206814.2021.1961103

[21] Skoblenko, A.V., Degtyarev, K.E., Travin, A.V., Batanova, V.G., Skuzovatov, S.Y., Kanygina, N.A., & Ryazantsev, K.M. (2024). Two episodes of Early Palaeozoic high-pressure metamorphism in North Balkhash ophiolite zone (Central Kazakhstan, western Central Asian Orogenic Belt): Evidence for tectonic evolution of Junggar-Balkhash Ocean. *Lithos*, *482-483*, 107672. https://doi.org/10.1016/j.lithos.2024.107672

[22] Aitkazinova, S.K., Nurpeisova, M.B., Kirgizbaeva, G.M., Milev, I. (2014). Geomechanical monitoring of the massif of rocks at the combined way of development of fields. *International Multidisciplinary*

Scientific GeoConference Surveying Geology and Mining Ecology Management, *2*(2), 279-292.
[23] Duczmal-Czernikiewicz, A., Baibatsha, A., Bekbotayeva, A., Omarova, G., & Baisalova, A. (2021). Ore minerals and metal distribution in tailings of sediment-hosted stratiform copper deposits from Poland and Kazakhstan. *Minerals*, *11*(7), 752. https://doi.org/10.3390/min11070752
[24] Portnov, V S., Yurov, V.M., & Mausymbaeva, A.D. (2018). Influence of surface properties of minerals on rebellious ore disintegration. *Journal of Mining Science*, *54*, 681-689. https://doi.org/10.1134/S106273911804460
[25] Nurpeissova, M., Bitimbayev, M.Zh., Rysbekov, K.B., Derbisov, K., Turumbetov, T., & Shults, R. (2020). Geodetic substantiation of the Saryarka copper ore region. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *6*(444), 194-202. https://doi.org/10.32014/2020.2518-170X.147
[26] Abdulin, A.A. (1981). *Geologiya Kazakhstana*. Alma-Ata, Kazakhstan: Nauka, 309 s.
[27] Bespalov, V.F. (1971). *Geologicheskoe stroenie Kazakhskoy SSR*. Alma-Ata, Kazakhstan: Nedra, 382 s.
[28] Lyubetskiy, V.N., & Lyubetskaya, L.D. (1993). Podvizhnye poyasa tektonosfery Kazakhstana. *Geologiya Kazakhstana*, *1*, 1-12.
[29] Seitmuratova, E.Yu. (2011). *Pozdniy paleozoy Zhongaro-Balkhashskoy skladchatoy oblasti (Kazakhstan) (stratigrafiya, magmatizm, istoriya stanovleniya okrainy kontinenta v pozdnem paleozoe)*. Almaty, Kazakhstan: Nedra, 278 s.
[30] Peyve, A.V., & Mossakovskiy, A.L. (1982). *Tektonika Kazakhstana (Obyasnitelnaya zapiska k tektonicheskoy karte Vostochnogo Kazakhstana 1:2500000)*. Moskva, Rossiya: Nauka, 138 s.
[31] Seitmuratova, E.Yu. (2002). *Pozdnepaleozoyskie vulkanogennye i vulkanogenno-osadochnye formatsii Zhongaro-Balkhashskoy skladchatoy oblasti (stratigrafiya, geologo-petrologicheskie osobennosti)*. Almaty, Kazakhstan: Nauka, 254 s.
[32] Lyapichev, G.F., Seitmuratova, E.Yu., & Borukaeva, M.R. (1991). Pozdnepaleozoyskie vulkanogennye formatsii Dzhungaro-Balkhashskoy skladchatoy sistemy. *Magmatizm i Rudonosnost Kazakhstana*, 77-85.
[33] Shcheglov, A.D., Govorov, I.N., & Petrachenko, E.D. (1982). Osnovnye cherty tektonicheskogo razvitiya magmatizma i metallogenii vulkanicheskikh poyasov Vostoka Azii. *Vulkanologiya i Seysmologiya*, *3*, 39-58.
[34] Esenov, Sh.E., Kayupov, A.K., & Kolesnikov, V.V. (1972). *Geologiya i metallogeniya Severnogo Pribalkhashya*. Alma-Ata, Kazakhstan: Nauka, 268 s.
[35] Khain, V.E. (1970). Tektonicheskie tipy vulkanicheskikh poyasov. *Problemy Geologii i Metallogenii Vulkanicheskikh Poyasov*, *1*, 9-20.
[36] Veldyaksov, F.F., Kobylyanskiy, Yu.G., & Umitbaev, R.B. (1974). Rol fundamenta kontinentalnykh vulkanogennykh poyasov v evolyutsii vulkano-tektonicheskikh struktur (na primere Okhotsko-Chukotskogo poyasa). Evolyutsiya vulkanizma v istorii Zemli. *Trudy I Vsesoyuznogo Paleovulkanicheskogo Simpoziumy*, 284-289.
[37] Bekzhanov, G.R. (1984). *Glubinnye struktury i medno-porfirovye orudenenie Dzhungaro-Balkhashskoy skladchatoy sistemy*. Alma-Ata, Kazakhstan: Nauka, 232 s.
[38] Seitmuratova, E.Yu., & Saydasheva, F.F. (2015). *Epitermalnoe Au-Ag orudenenie mira i Kazakhstana*. Almaty, Kazakhstan: Nauka, 238 s.
[39] Seitmuratova, E.Yu., Arshamov, Ya.K., Baratov, R.T., & Dautbekov, D.O. (2016) Geologicheskie i metallogenicheskie osobennosti vulkano-plutonicheskikh poyasov Kazakhstana. *Izvestiya. Seriya Geologicheskie i Tekhnicheskie Nauki*, *3*(427), 60-87.
[40] Seitmuratova, E.Yu., Goganova, L.A., & Lyapichev, G.F. (1997). Itogi geologicheskikh i biostratigraficheskikh issledovaniy pozdnepaleozoyskikh otlozheniy Balkhashskogo segmenta zemnoy kory Kazakhstana. *Geologiya Kazakhstana*, *5*, 33-56.
[41] Seitmuratova, E.Yu. (1998). Zolotonosnost pozdnepaleozoyskikh vulkano-plutonicheskikh poyasov ZhBSO (problemy ee izucheniya i osvoeniya). *Geologiya i Razvedka Nedr Kazakhstana*, *2*, 13-24.
[42] Seitmuratova, E.Yu., Rafailovich, M.S., Diarov, A.B., & Saydasheva, F.F. (2007). K postanovke poiskov krupnoobemnykh vulkanogennykh zoloto-serebryanykh mestorozhdeniy v Kazakhstane. *Geologiya i Okhrana Nedr*, *4*, 7-27.
[43] Koshkin, V.Ya. (1974). Tektonicheskoe polozhenie Balkhash-Iliyskogo gertsinskogo poyasa. *Tektonika Uralo-Mongolskogo Skladchatogo Poyasa*, 86-92.
[44] Seitmuratova, E.Yu. (2000). *Geologicheskoe doizuchenie Kounrad-Akchatauskogo rudnogo rayona masshtaba 1:200000 territorii listov L-43-III, IV, IX, X*. Otchet. Almaty, Kazakhstan: Komitet geologii, 900 s.
[45] Struzhkov, S.F., & Konstantinov M.M. (2025). *Metallogeniya zolota i serebra Okhotsko-Chukotskogo vulkanogennogo poyasa*. Moskva, Rossiya: Nauchnyy mir, 318 s.
[46] Mitchell, A., & Garson, M. (1984). *Globalnaya tektonicheskaya pozitsiya mineralnykh mestorozhdeniy*. Moskva, Rossiya: Mir, 496 s.
[47] Lyalin, Yu.I. (1981). Vulkanizm i tektonika pozdnego paleozoya. *Problemy Tektoniki Kazakhstana*, 90-101.
[48] Koshkin, V.Ya. (1981). Stratigrafiya verkhnego paleozoya Severnogo Pribalkhashya. *Materialy po Geologii i Geofizike Vostochnogo Kazakhstana*, 11-28.
[49] Goncharov, V.I., Gomyanin, G.N., & Goryachev, N.A. (2002). Krupnoobemnye mestorozhdeniya zolota i serebra vulkanogennykh poyasov. *Doklady Akademii Nauk*, *387*(5), 678-680.
[50] Goryachev, N.A., Volkov, A.V., Sidorov, A.A., Gomyanin, G.N., Savva, N.U., & Okrugin, V.M. (2010). Au-Ag-orudenenie vulkanogennykh poyasov Severo-Vostoka Azii. *Litosfera*, *3*, 36-50.
[51] Zvezdov, V.S. (2019). Major and giant porphyry copper deposit formation environments. *Otechestvenaya Geologiya*, *5*, 16-35.
[52] Hedenquist, J.W. (1996). Epithermal gold deposits: Styles, characteristics and exploration. *The Society of Resource Geology: Resource Geology Special Publication*, *1*, 16-24.
[53] Sher, S.D. (1972). *Metallogeniya zolota: (Severnaya Amerika, Avstraliya i Okeaniya)*. Moskva, Rossiya: Nedra, 215 s.
[54] Sander, M.V., & Einaudi M.T. (1990). Epithermal deposition of gold during transition from propylite to potassic alteration at Round Mountain, Nevada. *Economic Geology*, *85*, 285-311. https://doi.org/10.2113/gsecongeo.85.2.285
[55] Sillitoe, R.H., & Lorson, R.C. (1994). Epithermal gold-silver-mercury deposits at Paradise Peak. Nevada: Ore controls, porphyry gold association, detachment faulting, and supergene oxidation. *Economic Geology*, *89*, 1228-1248. https://doi.org/10.2113/gsecongeo.89.6.1228
[56] Zhao, X.B., Xue, C.J., Seltmann, R., Andersen, J.C.Ø., & Zhang, G.Z. (2020). Volcanic-plutonic connection and associated Au-Cu mineralization of the Tulasu ore district, Western Tianshan, NW China: Implications for mineralization potential in Paleozoic arc terranes. *Geological Journal*, *55*(3), 2318-2341. https://doi.org/10.1002/gj.3750
[57] Togizov, K., & Antonenko, A. (2020). The structural tectonic position and predictive search criteria for the lead-zinc karst mineralisation (South Kazakhstan). *International Multidisciplinary Scientific GeoConference EXPO Proceedings*, 335-340. https://doi.org/10.5593/sgem2020/1.1/s01.042
[58] Yessendossova, A., Mykhailov, V., Maussymbayeva, A., Portnov, V., & Mynbaev, M. (2023). Features of the geological structure and polymetallic mineralization of the Uspensky (Central Kazakhstan) and Dalnegorsky (Far East) ore districts. *The Iraqi Geological Journal*, 44-60. https://doi.org/10.46717/igj.56.2F.3ms-2023-12-9
[59] Sidorov, A.A., Volkov, A.V., Chekhov, A.D., Savva, N.E., Alekseev, V.Yu., & Uyutnov, K.V. (2011) Vulkanogennye poyasa okrainno-morskoy litosfery Severo-Vostoka i ikh rudonosnost. *Vulkanologiya i Seysmologiya*, *6*, 21-35.
[60] Shilo, N.A. (1997). Vulkanogennye poyasa i ikh zoloto-serebryanaya mineralizatsiya. *Smirnovskiy Sbornik*, *97*, 38-74.
[61] Cook, D.R., Hollings, P., & Walshe, J.L. (2005). Giant porphyry deposits: Characteristies, distribution and tectonic controls. *Economic Geology*, *100*(5), 801-818. https://doi.org/10.2113/gsecongeo.100.5.801
[62] Singer, D.A., Berger, V.I., Menzie, W.D., & Berger, B.R. (2005). Porphyry copper deposit density. *Economic Geology*, *100*(3), 491-514. https://doi.org/10.2113/gsecongeo.100.3.491
[63] Sillitoe, R.H. (2010). Porphyry copper systems. *Economic Geology*, *105*(1), 3-41. https://doi.org/10.2113/gsecongeo.105.1.3
[64] Shen, P., Pan, H., & Seitmuratova, E. (2017). Petrogenesis of the mineralized granitoids from the Kounrad and Borly porphyry Cu deposits and the East Kounrad porphyry Mo deposit in Kazakhstan: Implication for tectonic evolution and mineralization of the western part of the Central Asian Orogenic Belt. *Lithos*, *286*, 53-74. https://doi.org/10.1016/j.lithos.2017.06.006

Особливості континентальних вулкано-плутонічних поясів Жонгаро-Балхаської складчастої системи

Е. Сейтмуратова, Ш. Пінг, Р. Баратов, Д. Даутбеков, М. Машрапова, Н. Шадієв, Я. Аршамов

Мета. Дослідження формаційного складу та структурно-формаційного районування пізньопалеозойських континентальних вулканогенних та вулканогенно-осадових утворень Жонгаро-Балхаської складчастої системи (ЖБСС). Визначення геолого-геофізичних характеристик і металогенічної спеціалізації вулкано-плутонічних поясів регіону.

Методика. Використані дані детального картування та аналізу пізньопалеозойських магматитів у ЖБСС за останні 10-40 років. Проведено структурно-формаційне районування регіону з актуалістичних позицій, а також формаційна типізація стратифікованих та інтрузивних рудних утворень. Вивчення металогенічної спеціалізації проводилося з урахуванням сучасних методів геофізичних досліджень.

Результати. Виділено два основні вулкано-плутонічні пояси: кам'яновугільний окраїно-континентальний Тасти-Кусак-Котирасан-Алтинемельський та кам'яновугільно-пермський внутрішньоконтинентальний Балхаш-Ілійський, що охоплюють близько 80% території ЖБСС. Визначено геолого-геофізичні особливості та металогенічну спеціалізацію даних поясів. Зокрема, виявлено великі перспективи епітермального золото-срібного й мідно-порфірового оруднення.

Наукова новизна. Вперше проведено структурно-формаційне районування ЖБСС та обґрунтовано типізацію вулкано-плутонічних поясів, а також визначено їхню металогенічну спеціалізацію. Виявлено закономірності локалізації епітермальних золото-срібних і мідно-порфірових родовищ.

Практична значимість. Результати дослідження мають важливе значення для пошукової геології, сприяючи підвищенню ефективності пошуку рудних родовищ у регіоні, особливо епітермальних золото-срібних та мідно-порфірових об'єктів.

Ключові слова: *вулканічні структури, структурно-формаційне районування, вулкано-плутонічні пояси, районування, золото, мідь, Жонгаро-Балхаська складчаста система*

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.