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On the use of remote sensing data to study the geological structure and forecast mineral resources of the Shu-Ile suture

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Abstract

Purpose. This article focuses on analyzing the geodynamic processes that underline the formation of the Shu-Ile ore zone. The study is based on the principles of plume tectonics, which have gained widespread recognition in the geological community in recent decades.

Methods. The article considers the main aspects of the plume-tectonic concept, including the mechanisms of mantle material flows and their impact on regional geological processes. Special attention is paid to analyzing tectonic and magmatic events associated with forming the Shu-Ile ore zone within plume-tectonic mechanisms.

Findings. The study highlights the critical role of mantle plumes in influencing the geodynamic evolution of the Shu-Ile ore zone. Geochemical and geophysical evidence reveals the composition and characteristics of magmatic rocks, demonstrated a direct link between mantle plume processes and ore potential in the region. The findings underscore how mantle-derived material flows have significantly contributed to the formation of geological structures and mineral resources.

Originality. The study results offer a new perspective on the geological history of the Shu-Ile ore zone, emphasizing the significance of plume tectonics as a critical factor in the geodynamic processes involved in ore deposit formation.

Practical implications. This research is practical for geological studies and forecasting promising ore deposits in this region. It may serve as a basis for further research on plume tectonics and its influence on forming geological structures and mineral resources.

Keywords: *plume tectonics, geotectonics, geodynamics, geophysical studies, remote geological mapping, suture, ore formation*

1. Introduction

1.1. Problem statement

The Shu-Ile ore zone represents an essential target for geological research and mineral exploration. This region is notable for its diverse ore deposits, which have attracted the attention of scientists for decades due to their unique aspects of geodynamics and geotectonics (Fig. 1). Over recent decades, the development of new research methods and expanding theoretical frameworks in geology have highlighted plume tectonics as a critical concept in understanding the processes underlying the formation of geological structures. As a framework for interpreting geological processes related to convective mantle flows into the Earth's crust, plume tectonics offers new perspectives for analyzing the formation of ore zones and for mineral deposit forecasting.

Research on geodynamic processes and their analysis reveals that the unique geotectonics and formation of the Shu-Ile ore zone can be explained based on the principles of plume tectonics.

Figure 1. An overview map of Kazakhstan: 1 – Shu-Ile ore belt

Analyzing mantle flows and their influence on the formation of regional tectonic structures enables new insights into the region's geological history, revealing factors influencing ore deposit formation.

This work attempts to integrate modern theoretical perspectives with geological and geophysical data on the re-

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gion's geodynamics through the lens of plume tectonics. Such integration may illuminate the mechanisms underlying the formation of the Shu-Ile ore zone, providing a foundation for new practical recommendations in geological exploration and establishing scientific grounds for predicting new deposits.

The late 20th century is a breakthrough in understanding Earth's deep interior, driven by well-organized research initiatives, including deep geophysical investigations, ultradeep continental and ocean drilling, and space-based Earth studies. New data on the deep structure of the continental crust and upper mantle were gathered through comprehensive studies in the international geotraverse system. Some of these geotraverses cross Kazakhstan's territory, and based on this data, lithospheric models up to depths of 100-200 km have been developed in the republic, revealing a heterogeneous block structure in the upper mantle. At depths around 200 km, the electrical resistance of mantle material sharply decreases, which is presumed to be associated with the uplift of the asthenospheric layer's roof. In some cases, crustal structures extend into the upper mantle. In the zones of geosutures, the asthenosphere rises to levels of 80-100 km, with asthenoliths penetrating above the Mohorovičić discontinuity into the Earth's crust [1]-[4].

1.2. Brief overview of the tectonic model of Kazakhstan

Neither the geosynclinal paradigm nor the mechanically applied plate tectonics have found adequate support in field practice to explain Kazakhstan's unique geological structure. In this context, Prof. A.B. Baibatsha proposed [5]-[11] a new model of the geological structure and geodynamic development of Kazakhstan based on the principles of plume tectonics.

Currently, the tectonic structure of Kazakhstan is often described as follows: "*...the territory of Kazakhstan encompasses the western part of the Ural-Mongolian fold belt, positioned in the transition from the sub-latitudinal Mongolian-Tien Shan structures to the sub-meridional Ural-West Siberian structures. The Ural-Mongolian belt was formed by destroying the epi-Riphean platform in the Vendian (570-600 Ma)*". However, an analysis of recent data on the paleogeology of the planet and Kazakhstan suggests that neither the Urals nor Mongolia and thus the Ural-Mongolian belt, existed at this time. Kazakhstan existed independently, without clear connections to these structures or continents [12].

According to current data, Kazakhstan, as the continent "Kazakhstania" [13] existed autonomously from the Neoproterozoic until the complete formation of the supercontinent Pangea II in the Permian (~250 Ma). Kazakhstania developed without direct influence from neighboring continents and had unique geodynamic conditions. The separation of the "Kazakhstania" continent was facilitated by the fragmentation of the Rodinia supercontinent and lithospheric subcrustal movements (Fig. 2) [14]. According to modern geophysical data [8], the intrusion of a mantle plume and its penetration of the upper mantle and asthenosphere into the lithosphere led to a localized uplift and the formation of a nucleus in the shape of a ring structure – the precursor to the continent "Kazakhstania" [15]-[20]. This plume branch was active in Kazakhstania from the breakup of Rodinia through the Paleozoic, forming a nucleus with a diameter of approximately 2.5-3.0 thousand km.

Today, around 50 superplumes of various origins and mechanisms have been identified, which were active in the geological past, and some continue to function, such as those beneath the Hawaiian Islands with their erupting volcanoes [10].

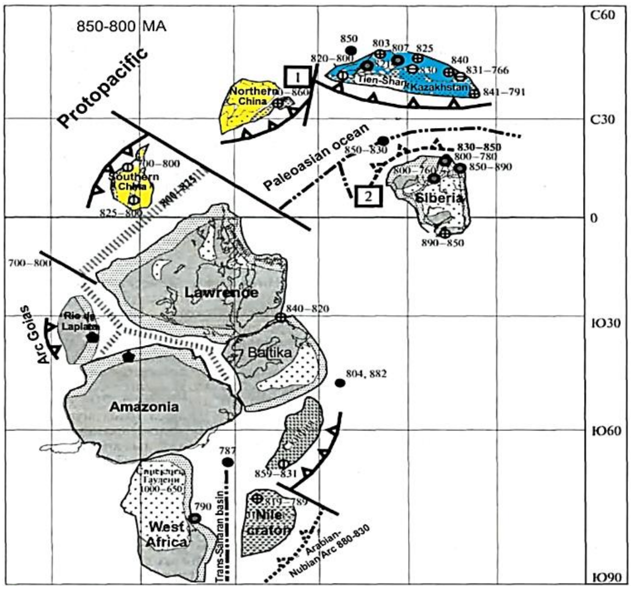


Figure 2. Paleogeodynamic reconstruction of Rodinia for the period 850-800 Ma (adapted from Kheraskova et al., 2010 [14])

American and Japanese scientists have studied and identified superplumes using advanced equipment and technologies (Fig. 3).

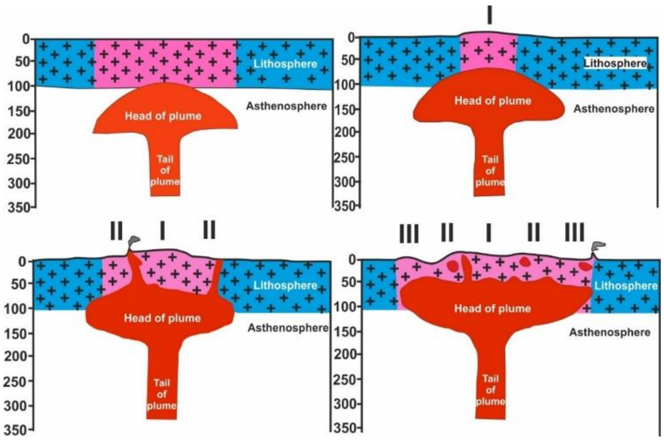


Figure 3. Model-schematic of plume intrusion into the lithosphere (adapted from Bin He et al., 2003 [21]) and stages of ring geosuture formation in Kazakhstan (adapted from A.B. Baibatsha [11])

The planet's internal pulsations triggered vertical movements in the nucleus, forming concentric ring structures. The foundation of these ring structures consisted of materials from the asthenosphere and lower mantle, compressed as a relatively rigid core into the lithosphere. This established continent, "Kazakhstania" developed under the direct influence of this foundation. Under the pressure of the mantle plume, the relatively rigid lithosphere underwent brittle deformation, forming chaotic faults, fractures, and mosaic structures. The continent exhibited primarily horizontal rotational and vertical oscillatory movements.

As the continent rotated on its axis, intense friction and pressure occurred between the ring geosutures. In these geosutures, which extend down to the mantle, local zones of compression (convergence) or extension (divergence) formed based on the direction of vertical oscillatory movements, with block widths ranging from tens to 100 km. Molten mantle material penetrated the lithosphere through these weakened zones, sometimes reaching the Earth's surface. Vertical oscillatory movements affected individual ring geosuture zones and the spaces between the ring structures. During uneven oscillations, when one edge of the continent or individual ring structures subsided while the other rose, conditions of sea or land formed accordingly. Narrow seaways often extended into geosuture zones, creating an island arc structure with varied relief. The high-stress thermodynamic environment resulted in dense faults in the consolidated rigid ring structures [22]-[24].

Since the Neoproterozoic, the continent surrounding continents have influenced Kazakhstania. During the Paleozoic, the continent's margins were bordered by ancient oceans between converging continents: the Paleo-Asian Ocean (adjacent to Siberia), the Paleo-Ural Ocean (adjacent to Eastern Europe), and the Paleo-Tethys (between Cathaysia and Tarim). Sedimentary rock accumulation, along with associated mineral resources, occurred in the submerged areas of geosuture zones. The movement of geosutures (concentric intracrustal deep faults) intensified under the pressure of drifting neighboring continents, and individual stressed blocks in the form of terranes or blocks experienced additional autonomous shifts [25].

Deep-seated magmatic foci developed in the most stressed regions of the continent – within the mobile geosutures. Through these channels, mantle materials ascended into the upper layers of the Earth's crust. Crustal and near-surface magmas were generated under intense thermodynamic conditions in active and reactivated geological blocks. Volcanic structures formed, and lava erupted in areas of extension. The movements within the geosutures and the enclosed blocks had vertical and horizontal orientations.

The continent's edges experienced compression or decompression, leading to corresponding geodynamic processes. Within the continent "Kazakhia," various tectonic movements exhibited classical lithospheric plate tectonics processes, such as spreading (divergence), collision (convergence), and subduction (overthrust-subduction interactions). These movements combined with strike-slip displacements caused by the adjacent, rotating continents.

Thus, structures previously identified as microcontinents by some authors are instead ring structures and tectonic blocks (terranes) of a unified nucleus. According to modern tectonic zoning [14], three concentric geosutural rings can be distinguished within the continent "Kazakhia" (Fig. 4).

– inner ring-geosuture (diameter 600-900 km) – consists of the Junggar-Balkhash and Shu-Ile tectonic systems, bound by corresponding geosutural zones;

– middle ring-geosuture (diameter ~1200-2000 km) – comprises the North Tien Shan-Kendyk-Tas-Shu-Sarysu-Central Kazakhstan-Kokshetau-Chingiz-Tarbagatai tectonic system, bordered by the Fergana-Karatau-Karsakpai-Central Kazakhstan-Chingiz-Tarbagatai geosuture zone;

– outer ring-geosuture (diameter ~2500-3000 km) – includes the Middle Tien Shan-Nuratau-Aral-Turgai-North Kazakhstan-Altai-Zaisan tectonic system, bounded by the Pamir-East Ustyurt-Mugodzhary-North Kazakhstan-Altai geosuture zone.

Located in the western part of Kazakhstan, the nucleus spans a width of approximately 500-600 km (Karaku-Ustyurt-Pre-Caspian-Ural tectonic system), representing a plate that attached from the Mediterranean region during the Mesozoic [6].

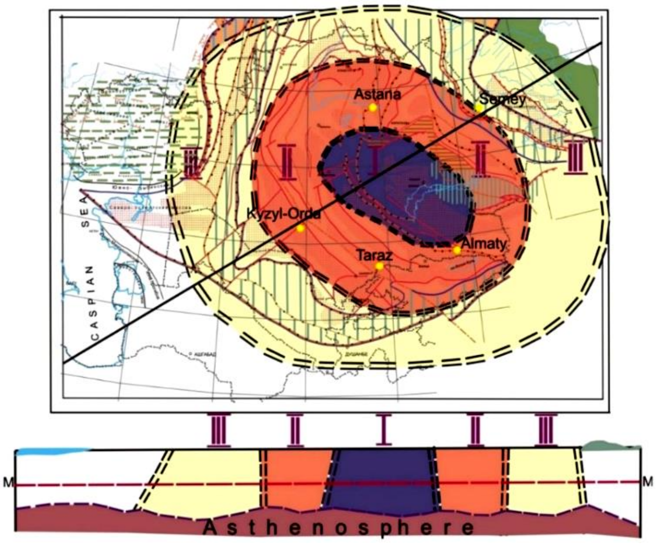


Figure 4. Schematic structure of the continent "Kazakhia": I – inner ring; II – middle ring; III – outer ring (based on the tectonic zoning map of Kazakhstan's Paleozoic by [11])

The most active areas of "Kazakhia" are the geosutural zones, which are fragmented by fault disruptions and have direct connections to the mantle. Magma formed in these active regions, introducing primary intrusions into the crust, which was composed of mantle materials. As these intrusions ascended into the crust, they assimilated with its materials. Subsidence within geosutural zones led to the formation of marine straits and basins, where submarine volcanic eruptions and oceanic crust with typical ophiolitic rock complexes occurred. Deep fractures and fracture zones served as channels for mantle-derived melts containing ore-bearing fluids to reach the upper crust. Typical marine conditions, i.e., "oceanic" settings, were created in submerged areas.

The ring structures represented a tectonic zone with active volcanoes, predominantly ultramafic intrusions, sedimentation basins, and arc-shaped denudation islands.

Formerly (before the Devonian-Carboniferous periods) regular in form, these ring structures and their bordering geosutures began changing configurations with the formation of Pangaea II. The active eastern part of "Kazakhia" started experiencing significant pressure from the mega continent "Siberia". Upon direct collision with it, the convex edges of the ring structures straightened and even bent inward. During the formation of a transpressional-collisional zone between "Kazakhia" and "Siberia", the outer edges of the ring structures in this region were subsumed and obliterated.

Final adjustments to the configuration of the continent "Kazakhia" occurred in the Mesozoic-Cenozoic era when drifting micro- and microcontinents joined from the south, southeast, and southwest, merging with "Eurasia". In the more passive northwestern and northern parts of Kazakhia, a connection with the Russian Platform (the Pre-Caspian tectonic depression) and the West Siberian Plate developed.

In Kazakhstan's modern geological structure, the inner and middle ring structures are relatively well-preserved. The inner ring has become elongated in the northwest direction, with its northwestern edge straightened and, in places, even concave. Due to the collision of the Indo-Tarim-Afghan-Iranian lithospheric plates and the formation of a collisional zone on the southern and southeastern sides, the outer and middle rings converged toward the inner ring. The deformed northeastern edge can be traced along the Altai compression zone [26]. The outer ring has also become compressed and folded into mountain belt structures from the south and southeast. In the north, it connects with the Ural mountain belt and the West Siberian Plate, while in the northwest, it is truncated by a transpressional-collisional zone with Siberia.

Before the formation of Pangaea II (Devonian-Permian), the continent of "Kazakhia" developed autonomously, evolving independently and in isolation. Its structure primarily formed internal and intercontinental zones (along the borders with neighboring continents), characterized by collision and junction zones (including overthrust and underthrust faults). Variations in the dip angles of the geosutures and contrasting vertical movements of deep faults, geosutural zones, and individual tectonic blocks drove this evolution. In divergent zones (or regions of local spreading), geosutures developed restricted rifts through which magma ascended, leading to lava outflows. Inundation of these zones resulted in the formation of ophiolites with typical marine (oceanic) rock complexes. Mantle materials, such as ultrabasites and basites, penetrated rifts and zones of decompression, sometimes reaching the crust and serving as sources of mineral deposits. Ore-bearing solutions derived from the mantle also ascended along divergent faults and fracture zones, penetrating the upper crustal layers. These weakened, open geocultural zones favored the upward movement and relatively free intrusion of asthenolites into the crust. Paleozoic-age ophiolitic zones in Kazakhstan, often mistakenly identified as relics of oceanic crust, are found in such sutures. Since Kazakhstan was under constant compression, it lacked large regional rift structures.

Convergence zones (collision or compression zones) emerged due to the movement of steep faults within the ring structures, resulting in interaction and collision among geological blocks and sectors. The collision took various forms, including mountain-building processes and sliding and thrusting. Interactions among large lithospheric blocks in Kazakhia created high thermodynamic stress. In areas experiencing thermal influence from the nearby asthenosphere, endothermic reactions between the crust and mantle emissions produced significant magmatic chambers of granitoid composition.

Collisions among rigid plates and blocks led to the fracturing of their edges, forming olistostromes – "chaotic complexes" of coarse-clastic rock with diverse petrographic composition and genesis. These olistostromes consist of fragments of various sizes and shapes. In sedimentary basins, olistostromes transition quickly into typical stratified sedimentary rocks as they move further from block margins. Due to their mode of formation, olistostromes (tectonic and gravitational) accumulate at the frontal zones of consolidated regions (thrusts and overthrusts).

The alteration of Kazakhia's circular tectonic structures is attributed to distorting their initial arrangement through the shifting and collision of once-neighbouring, now-coalesced continents and internal structural blocks. The formation of extensive fault zones cutting diagonally across the circular structures also contributed to this distortion. The final collisional stage in the Mesozoic-Cenozoic period played a key role, forming what is now called the Ural-Kazakh-Mongolian Belt. Significant right-lateral strike-slip faults developed during this phase with 150-200 km displacements or more. These displacements distorted the shape and altered the size of the ring structures in the continent's southern, southwestern, and southeastern regions. The eastern Irtysh-Altai region was also significantly modified.

This proposed geodynamic model of Kazakhstan's development explains the localization of active sedimentation zones, the occurrence of intrusive and effusive magmatism, the metamorphism of geological formations, the formation of ophiolitic zones and olistostromes, and the positioning of productive and prospective metallogenic zones, as well as regions with significant and unique mineral deposits [27]-[29] (Fig. 5).

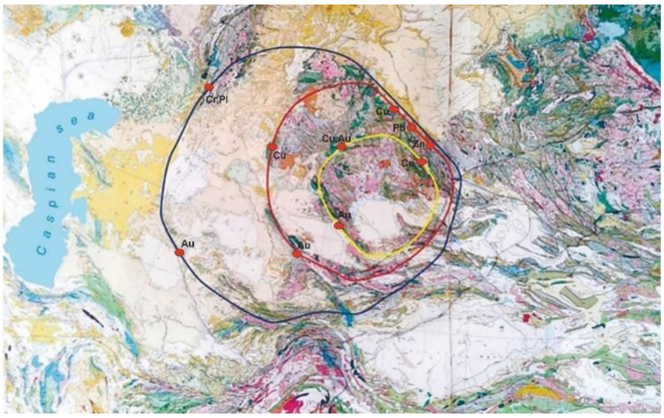


Figure 5. Location of metallogenic zones with significant mineral deposits [5]

These structures were laid down in the early stages of the territory's evolution, ultimately forming the Ural-Kazakh-Mongolian Belt in the Mesozoic-Cenozoic. During the Cenozoic era, continuous lineaments emerged, some diagonally bisecting the circular structures.

Kazakhstan's ring structure is also reflected in physical fields, primarily in the gravity field. The block structure of Kazakhstan's crust is indicated by extensive, linear strips of closely spaced isoanomalies (high-gradient areas) in the Δg gravity field. Here, zones of deep faults are highlighted, dividing Kazakhstan's crust into several mega-blocks and blocks. Based on geophysical data, some faults penetrate the entire crustal thickness and reach the upper mantle [8].

The proposed new model of Kazakhstan's geodynamic evolution, grounded in plume tectonics, offers a theoretical foundation for understanding the region's unique geotectonics and predicting the locations of mineral deposits.

2. Materials and methods

The area under study belongs to the early Caledonian zone of Kazakhstan, which forms a geosutural belt east of the Kokchetav-North Tian Shan zone of Precambrian geological blocks. This region intersects the Zhalaiyr-Naiman geosuture zone and the Bolattau anticlinorium, extending from the Shuk Precambrian block in the east.

Commonly used terms, such as the "Zhalaiyr-Naiman Synclinorium" and "Bolattau Anticlinorium", do not represent actual tectonic structures but have become customary symbols. Using traditional terms and geological structure names can lead to difficulties and inconsistencies, especially when combining morphostructural and geo-historical terminology. It is also challenging to delineate major morphostructural tectonic elements due to the distinct two-tiered structural makeup of the Caledonian formations in the Shu-Ili belt, which include an initial tectonically active layer and a newly formed Hercynian layer. While the primary tectonic structures are early Paleozoic in origin, the "anticlinorium" and "synclinorium" designations apply more to Devonian volcanic-tectonic synform structures and the Lower Paleozoic layers separating them. Nevertheless, to maintain continuity in geologic-geographic and structural-tectonic classification, we use the synclinorium and anticlinorium divisions, with the prefix "mega-" for first-rank structures. Accordingly, we simplify the natural tectonic structure by identifying the Zhalaiyr-Naiman megasynclinorium and Bolattau meganticlinorium (Fig. 6).

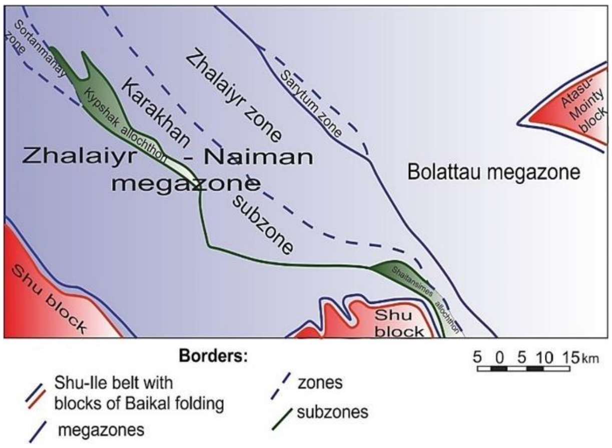


Figure 6. Tectonic zoning scheme of the northern part of the Shu-Ile belt [1]

Comprehensive long-term studies have been conducted within the Republic of Kazakhstan to investigate the deep structure of Kazakhstan's lithosphere and its relationship to metallogeny. These studies have been consolidated in the fundamental work "Deep Structure and Mineral Resources of Kazakhstan" (2002). The research primarily focused on the structure and composition of the deep subsurface, mainly below the M-boundary, concluding a link between metallogeny and processes in the upper and lower mantle. Patterns in the distribution of ore provinces are considered about an extensive mantle plume, deep faults, and mantle-level material flow zones. In comparison, less attention was paid to the internal structure of the Earth's crust against the backdrop of these global-scale phenomena [30]-[32].

Our objectives were more specific. We aimed to develop an understanding of the crustal roots and boundaries of the tectonic units observed at the surface to gather data on their formation history. Actual information on this topic can be inferred from the structural characteristics of the Earth's crust obtained through the seismic reflection method, complemented by gravimetry and magnetometry data. These reveal certain regularities in crustal structure, primarily identifying tectonic stratification within the crust. The concentrated reflection zones are interpreted as areas of increased anisotropy in physical properties and concentrations of slip surfaces caused by tectonic rock flow. This interpretation is further supported by the outcrops of inclined flow zones on the surface, where signs of intense cleavage flow and dynamometamorphism in the rocks, usually called compression zones or high-grade suture facies, can be observed. The reflection wave method (RWM) data reveal only subhorizontal and gently inclined tectonic flow zones, while steep suture zones are beyond their scope. However, these steep zones are well mapped on the surface, while the subhorizontal zones can only be detected in steep topography. Therefore, in areas with even relief, such as the Kazakh uplands, the reflection wave method remains the only practical approach to reveal tectonic layering [33].

Two primary levels of subhorizontal tectonic flow zones have been identified within Kazakhstan's crust. The upper level lies within the crust and divides it into an upper and lower part, while the lower level follows the M-boundary [34]. Seismic profiles from the region provide information to only 10-15 km depth, thus capturing only the intracrustal level. Furthermore, a notable discontinuity appears along the boundary between the Early Precambrian basement and the Paleozoic cover. The major inclined flow zones intersect subhorizontal displacements and are traced into the mantle (based on data from other regions in Kazakhstan). As mentioned, these zones surface along suture zones, representing their profound manifestations. Additionally, secondary inclined suture zones are subordinate to and constrained by the main ones. The surfacing of these zones is often associated with ophiolites and positive gravitational anomalies. These zones also exhibit suture characteristics, representing branches and bifurcations rather than the primary suture trunks [34].

A general trend of vergence in the major suture zones at depth shows that their main branches dip southwestward, with the outcrops of these branches occurring along the Sarytum Zone. Tectonic flow zones emerging at the surface in the Zhalaiyr-Naiman Suture on the Arys-Balkhash and Kendyktas profiles dip steeply (at angles exceeding 45°) to the northeast. The main branch of the Sarytum Zone truncates them. On the Zhamanai-Batkarazhal profile, the Zhalaiyr-Naiman Zone dips southwestward, while its tectonic sheets are thrust northeastward. The findings on the dominant role of the Sarytum Zone in structuring the major suture zones and the northeast vergence of its main branch seem paradoxical, as the Zhalaiyr-Naiman Suture has traditionally been considered the principal one. This perception likely arose due to the concentration of significant ophiolite complexes along this zone and their relatively minor occurrence in the Sarytum Zone. However, in the Kendyktas profile of the Shu-Ile Ore Belt's crustal structure, the wave method (RWM) data reaches depths of up to 50 km, and the central role of southwest-dipping structures is evident [35]. The abundance of ophiolites in the Zhalaiyr-Naiman Zone may be related to its lateral proximity to its mantle root. In any case, the southwestward dip of the main suture branch aligns with the overall zonation of the suture system and the continental magmatic belt. This model is further supported by a volcanic arc and back-arc basin along the edge of the Late Cambrian Zhalaiyr-Naiman Sea.

The branching of the primary suture with northeastward dips likely arose during the phase of tectonic compression, playing a vital role in the abduction of ophiolite allochthons onto the Shu-Kendyktas Block. It is worth noting that southwest vergence (northeast dips) characterizes most of the collision structures in Eastern Kazakhstan. This is likely due to the clockwise rotation of the Paleozoic continent Kazakhstania during much of its post-Ordovician Paleozoic history, corresponding to right-lateral shear in the crust.

The opposing dips of primary and secondary suture branches lead to the formation of distinctive synform structures underlain by tectonic flow zones with ophiolites. Examples include the Zhailymin Divergent Rift, the Zheltaus and Shatyrkul Blocks, and the Shalgin Thrust Sheet. Notably, these structures host the principal ore-bearing tectonic units, encompassing all major ore fields of the main suture zones: Shatyrkul, Khantau, Akbakai (Fig. 7), and Shalgin-Karaobin. Intense dislocation processes at the bases of such synforms played a crucial role in mobilizing ore material from ultrabasic and other complexes caught in the "dynamometamorphic mill".

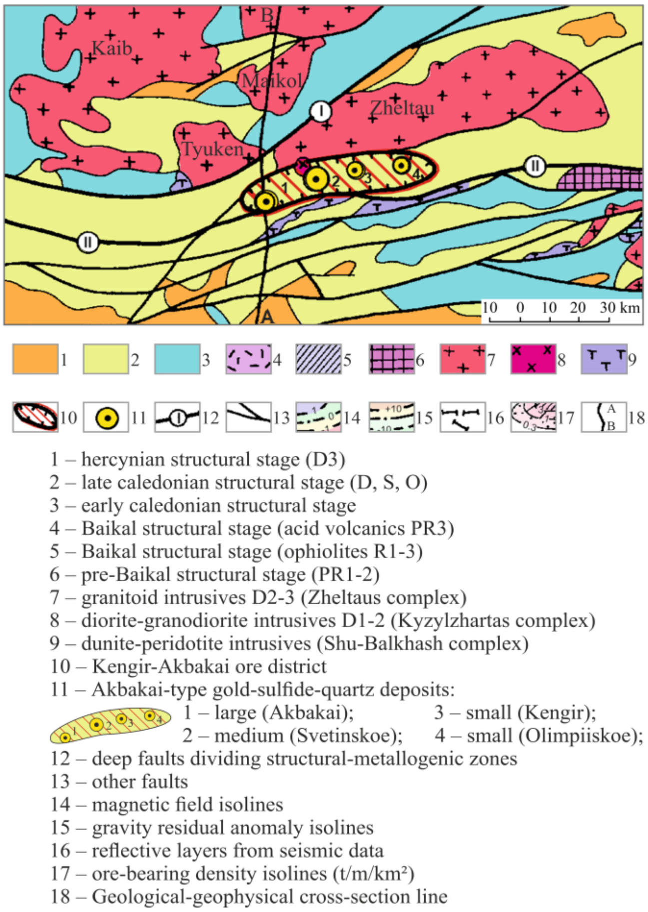


Figure 7. Geological-structural map of the Akbakai ore field

All intrusive masses are shown in the geological-geophysical sections as flat, thin bodies. They are mainly positioned along interformation detachments at the boundary between Devonian volcanics and the Lower Paleozoic or metamorphic basement, typically considered Precambrian. However, this is not universally evident, nor is it fully proven. In nearly all cases, the underlying Neoproterozoic-Paleozoic strata beneath the intrusions are reduced in thickness, indicating that the stratigraphic assignment of these sub-intrusive strata may not be reliably justified. All were delineated based on geophysical data. Meanwhile, granite-gneiss halos surround specific masses, such as the Kordai-Shatyrkul Massif, whose Precambrian or Paleozoic ages remain debated. In this context, it is plausible that the reduction in Neoproterozoic and Paleozoic strata beneath the intrusions is linked to the granitization of these layers. Consequently, the continental crust thickened during Paleozoic orogeny through silica-potassium metasomatism, stigmatization, and magma melting from intrusive strata. This process serves as a critical mobilizer of ore components from the substrate. However, while dynamometamorphism is characteristic of sutures, granitization is an interblock (possibly intracrustal) process and is only indirectly related to sutures [36], [37].

3. Paleogeodynamic reconstructions

Based on SHRIMP data, the oldest basement strata of the studied part of the Kazakh paleocontinent date back to 3491 Ma. However, we need more knowledge about them, as this age is represented by only a single zircon grain core found in diorites from the Anyrakhay Mountains. The early Precambrian strata consist of amphibolite-gneiss and migmatite-gneiss complexes dating to approximately 1800 Ma. These are overlain by a carbonate-quartzite-shale cover of a Meso-Neoproterozoic shallow-water complex belonging to the Shu-Kendyktas and Atasu-Junggar blocks (terranes). SHRIMP data indicate that zircon grains in the tectonic blocks retain records of the formation and breakup of the supercontinent Rodinia [38]. After its breakup, both blocks belonged to the northeastern part of Paleogondwana. Both blocks contain porphyroins and granites from a Neoproterozoic marginal-suture volcano-plutonic belt, dated to 965-1200 Ma, indicating their proximity to each other within Paleogondwana along an active continental margin [39]. In the late Neoproterozoic, around 700-725 Ma, overlying volcanic rocks formed, representing the Neoproterozoic complex of the Kendyktas, Zheltau, and Shu regions, delineating a system of deep faults along the suture zone [40], [41].

3.1. Ediacaran-Early Cambrian

The opening of the suture zones ultimately led to the formation of oceanic crust, the fragmentation of the continent, and the emergence of an archipelago of island blocks separated by marine basins. The block terranes in the study area are represented by the Shu-Kendyktas, Atasu-Junggar, and Zheltau blocks, while the Zhalaiyr-Naiman and Sarytum basins represent the marine basins. Evidence for the formation of seas is provided by the Shu-Balkhash ophiolite complex, aged 513-559 Ma, along with olistoliths of mid-ocean ridge basalts and ophiolites from the Katnak complex, dated to 590 Ma.

3.2. Middle-Late Cambrian

The existence of the Zhalaiyr-Naiman Sea during this time is confirmed by the discovery of Late Cambrian conodonts in jasper olistoliths within the tectonic mélange of the Zhalaiyr-Naiman suture [42]. This sea featured a passive margin along the Shu-Kendyktas block, represented by a carbonaceous-carbonate-siliceous-terrigenous complex of the Middle-Upper Cambrian age. This margin was partly land, from which clastic material was periodically eroded and transported into the basin's sediments. The existence of the Sarytum Sea is supported by a condensed Upper Cambrian-Middle Ordovician section discovered by L.E. Popov, found within a tectonic cover related to the Sarytum suture zone in an olistolith of chert [43]. The condition of the Zheltau terrane remains unknown, as deposits from this time are absent. The Atasu-Junggar block was covered by a shallow sea that hosted carbonate banks.

3.3. Late Cambrian

The initiation of subduction in the Zhalaiyr-Naiman Sea beneath the Shu-Kendyktas block triggered the formation of a simatic volcanic arc. This block is represented by an island-arc basalt complex and a back-arc basin, whose formation is indicated by a complex of parallel dikes and volcaniclastic sediments overlain by Late Cambrian jaspers, which in turn overlie the passive-margin deposits of the Shu-Kendyktas block. At this time, a complex with submarine landslide deformations and fragments of subduction oceanic crust also began to form. The source of clastic material for the back-arc basin sediments was located behind it, within the Shu-Kendyktas block. The state of the Zheltau block during this period is still being determined, as no Late Cambrian sediments are present, though they may have been eroded later. The Sarytum marine basin existed, where condensed abyssal cherts were deposited. The Atasu-Junggar block was likely a low-lying landmass, as no sediments of this age or signs of significant erosion are present.

3.4. End of Late Cambrian-Tremadocian

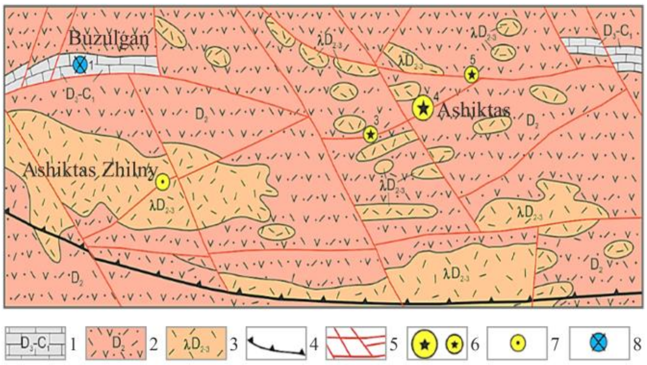
Tectonic activation led to the convergence of the Zheltau and Shu-Kendyktas blocks, resulting in the contraction of the Zhalaiyr-Naiman marine basin and forming a residual basin in its place. The subduction process involved the volcanic arc and the Sulusai back-arc basin, leading to a deep depression that includes fragments of marine basalts, cherts, basalts, and volcanogenic-sedimentary layers of the Cambrian age. This basin gradually transitions into a flysch-olistostrome formation, created in the residual basin due to the tectonic nappes' movement. The collision between the Zheltau and Shu-Kendyktas blocks caused the formation of the nappes. The earliest nappes, composed of the deepest eclogite-bearing dynamometamorphic schists, are found within the Zheltau terrane (Anyrakhai Mountains).

Subsequent nappe movements were directed towards the Shu-Kendyktas terrane, involving margin deposits, ophiolitic fragments, and island-arc complexes. This tectonic activity caused a vergence shift in the Zhalaiyr-Naiman suture. The Zheltau terrane experienced an uplift, eroding previously overlying sediments and exposing Precambrian layers and deep horizons of eclogite-bearing dynamo metamorphic schists, forming an informal structure beneath it with suture branches. Around this time, the synform of the Zhaiylmin Trough, containing an ophiolite complex, likely formed. Structures originally subducted beneath the volcanic arc and later beneath the Shu-Kendyktas block were overthrust and partially reoriented towards this terrane. This reorientation is evident in the deep geological-geophysical profile of Aris-Balkhash. The Shatyrkul tectonic nappe probably formed during this period.

In the northwest, these processes were less intense. The closure of the Zhalaiyr-Naiman basin did not result in significant uplift of the Kypshakbai terrane, nor did it lead to sediment erosion or thrusting onto the Shu-Kendyktas block. The Zhalaiyr-Naiman suture maintained its original subduction beneath this block [44], [45]. Nappes from this zone were thrust over the Kypshakbai and North Betpak-Dala blocks-terranes (Fig. 8).

3.5. End of Tremadocian-Floian-Dapingian

As a result of the convergence between the Shu-Kendyktas and Zheltau blocks, the subduction zone shifted to the margin of the Sarytum Sea, where a new island arc suture system formed. This system consisted of a double island arc, an interarc basin, and a back-arc basin along deep faults of the geosuture. Evidence for the existence of an outer simatic arc includes the petrochemical characteristics of some basalts previously attributed to the ophiolite complex. The tectonic mélange in the Sarytum zone likely began forming in this volcanic arc zone. The lower part of the Early-Middle Ordovician complex, filled with large fragments of deepwater jaspers and basalts, also belongs here.



1 – limestone (Meister formation)
2 – andesite-dacite-rhyolite volcanogenic-terrigenous (Taszharghan and Ogiztau formations)
3 – subvolcanic bodies of acidic composition (quartz porphyries, felsite- and granite-porphyries)
4 – regional fault with northwest strike (SWboundary of the Akshagat-Kenkazgan gold-bearing zone)
5 – second- and third-order faults
6 – deposits and occurrences of gold-secondary quartzite type
7 – small deposits and occurrences of gold-sulfide-quartz vein type
8 – lead and zinc occurrences in Buzulgan within mineralized limestones of D3-C1

Figure 8. Geological structure of the Ashiktas deposit

The deposits of the interarc basin are represented by a volcanogenic-sedimentary sequence containing Floian conodonts, previously associated with the Zhalgyz Formation but incompatible with its ophiolite interpretation.

The inner sialic arc overlays the edge of the Zheltau terrane, where a typically island-arc Floian volcanic complex is in situ. The volcanic products of this arc are represented by the Balgogin Formation, which consists of basalts, andesites, and tuffs of andesitic and rhyolitic composition, tuff sandstones, and sedimentary rocks containing Floian fauna. A plagiogranite-granodiorite complex of the Middle Ordovician age represents the intrusive facies of island arc magmatism. Back-arc basin deposits, separated from the suture, are found on the southeastern edge of the Kypshakbai block (terrane), in the Sarybulak block of the Shu-Sarysu terrane, and the Kordai tectonic nappe.

3.6. Darriwilian-Sandbian

At the boundary between the Middle and Late Ordovician, nappe formation continued due to the closure of the back-arc basin. During this time, the Kordai and Sekseuldalin tectonic nappes likely formed. There was a significant convergence between the Zheltau and Shu-Kendyktas blocks, reconfiguring the island arc system. The active island arc volcanism zone shifted into the Shu-Kendyktas terrane, accompanied by intensive granodiorite-granite intrusive magmatism. Thus, the island arc took on characteristics of a continental-margin volcanic-plutonic belt. According to the classical model, this reconfiguration is associated with the flattening of the suture zone due to the uplift of the continental margin.

In front of the volcanic arc, a broad Anderken forearc basin (terrace) formed, filled with shallow-water carbonate-terrigenous sediments. These sediments overlapped the eroded Balgogin Early Middle Ordovician volcanic arc. In the foreland of the island arc system, a block represented by the tectonic mélange of the Sarytum zone continued to form within the Sarytum basin.

3.7. Katian-Early Silurian

In the mid-late Ordovician, convergence within the suture zone brought the Atasu-Junggar microcontinent closer to the Zheltau-Shu-Kendyktas blocks, initiating the closure of the Sarytum marine basin. This resulted in a residual basin filled with molasse sediments, with olistostromes formed by tectonically active nappes playing a role. The nappes of this phase consist of thrust sheets of the Early-Middle Ordovician siliceous complex from the foot of the passive suture margin, along with fragments of oceanic basalts, though in smaller quantities. These nappes were primarily thrust over the Atasu-Junggar terrane.

By the end of this phase, a sizeable orogenic uplift formed, encompassing nearly the entire internal geosuture of the Kazakhstania paleocontinent. This marked the culmination of the structural formation of the central suture zone. All subsequent processes can be considered superimposed, contributing only minor complexity to its structure. In the Silurian, signs of localized divergence appeared amidst the uplift, leading to the formation of local rifts, such as the Mynaral Rift.

3.8. Early-Middle Devonian

With the closure of marine basins in the main suture zones, active tectonic processes, including crustal subsidence, shifted toward the periphery of the Junggar-Balkhash Sea and the Atasu-Junggar block. This shift led to the development of a Devonian volcanic-plutonic belt, with the northeastern part of the study area lying in the belt's central zone. Here, volcanic-plutonic activity was intense, featuring numerous magma sources, a diversity of volcanic and plutonic facies, and the formation of complex volcanic-tectonic structures.

The rhythm of volcanism and plutonism was driven by periodic fluctuations in the levels of active magmatism within the lithosphere above the suture in the volcanic-plutonic belt. Pre-existing nappe-fold structures in the main suture zones played a significant role in localizing magmatic bodies, linking auriferous intrusions with suture zones and terranes of the primary sutures.

The belt's back-arc zone was located southeast, with its boundary with the central zone running along the Sarytum zone in the south and the Zhalaiyr-Naiman zone in the northwest. Distinct volcanic centers like the Karasai and Kurmanshytin centers were in this back-arc zone. Volcanic-plutonic processes within these centers followed a rhythmic pattern similar to the belt's central zone. The centers are characterized by ring structures, discernible in satellite imagery and mapped by the shape of geological bodies, and ring faultslcanic centers in the back-arc zone, volcanic-sedimentary sequences with relatively simple epizonal fold-fault structures were widespread.

3.9. Frasnian

The geodynamic events of the Frasnian were influenced by processes occurring along the edge of the Junggar-Balkhash Sea. During this time, the northwestern portion of the Junggar-Balkhash basin closed, which coincided with the emplacement of Late Devonian compressional-palingenetic granites within the Devonian volcanic belt. This granitic complex is prominent within the Atasu-Junggar and Zheltau terranes. At this stage, the entire area experienced a phase of continental orogenic uplift, with divergent activity resuming only at the end, marked by renewed extension in the Mynaral local rift and other minor structures of this type.

Compressional orogenesis was accompanied by deformations primarily associated with large-scale fault movements, with the most notable suture-related deformations occurring along major strike-slip fault zones. The origins of the Zhalaiyr-Naiman strike-slip fault likely date back to Late Ordovician compression, as evidenced by the associated depressions of this age, many of which exhibit rhomboid shapes typical of pull-apart basins. Large-scale right-lateral strike-slip displacements during the Late Devonian are suggested by the development of cleavage in Devonian volcanic sequences within these fault zones [46], [47].

3.10. Famennian-Early Carboniferous

Famennian rifting in the suture zone followed Frasnian compression in much the same way that Silurian rifting succeeded Late Ordovician compression. This was likely a natural response to previous uplift and compression, manifesting as subsidence and extension. This tectogenesis was accompanied by weak but distinctive alkaline volcanism, represented mainly by tuffs with only rare lava flows. Small volumes of hydrothermal deposits are also characteristic in tectonically active basins.

The regional structures controlling Famennian-Late Carboniferous processes consist mainly of northwest-striking faults, typically normal and oblique-slip faults, concentrated in the northeastern part of the region. Among these is the well-defined Mynaral Rift, a suture inherited from the Silurian. Distinct local pull-apart basins can be identified within more extensive northwest-trending rift zones. Northeast-striking faults are present in the southeast and northwest, possibly influencing divergent structures. For instance, the Zhaiylminsky Rift lies at the intersection of the Mynaral fault system and the Uspensky fault zone. This intersection may contribute to the rift's notable ore-bearing potential.

The southeastern intersection between the Mineral structure's fault system and the northeast-striking faults of Southern Junggaria is obscured by younger sediments in the Ile Valley. Southeast of this intersection, Famennian-Early Carboniferous sequences consist of volcanic rocks from the Pribalkhash-Ile volcanic belt. Carboniferous strata within the Pribalkhash-Ile volcanic belt of the Besmoinak block are displaced southwestward by several hundred kilometers. This suggests that the Mynaral Rift may continue beneath the sediments of the Shu Valley and into western Prissykul.

The final stages of the Paleozoic in the region's southeast saw the superposition of Middle Carboniferous-Permian sequences from the Pribalkhash-Ile volcanic-plutonic belt, marking the concluding phase of plume tectonics. Additionally, compressional-palingenetic Permian leucogranite intrusions, related to the overall closure of the Junggar-Balkhash Sea, are widespread across northeastern zones.

4. Geophysical fields and their relationship to geological structure

The characteristics of the gravity and magnetic fields vary across different parts of the study area, corresponding to structural-tectonic differences. In the western part, the anomalies and anomalous zones of the gravimagnetic field have a northwest-oriented, linear structure with alternating positive and negative zones. In contrast, in the eastern part, the field characteristics are more isometric, reflecting a geological structure dominated by intrusive formations, primarily of acidic composition (granites and granodiorites). This dominance of acidic intrusions contributes to the mosaic pattern in the magnetic field and the broad, areal distribution of negative gravity anomalies. The gravity field can thus be divided into several regions corresponding to distinct tectonic structures.

The Zhalaiyr-Naiman Megasyncline and the Bolattaus Meganticline, identified based on geological data, lack a clear boundary between them in the gravity and magnetic fields. The boundary lies in the central and southeastern areas, with relatively stable negative anomalies. Only in the northwest is the boundary marked by zones with high gradients in gravity and magnetic anomalies, indicating the spatial location of the Ergenektinsky Fault Zone.

The southwestern boundary of the Zhalaiyr-Naiman Megasyncline aligns with the buried Severo-Shu Fault, which partially coincides with the Betpakdalinsky Fault along the boundary where Devonian and Carboniferous rocks are distributed. The Severo-Shu buried fault separates the Zhalaiyr-Naiman Megastructure from the Shu Anticline, composed of folded complex stones. In the study area, these rocks are represented by Lower Carboniferous terrigenous-carbonate deposits, which are almost non-magnetic and have a low density (2.54 g/cm³). The magnetic and gravity fields above them show negative values of -100 to -150 nT and -14 to -16 mGal, respectively, consistent with their petrophysical properties.

The Zhalaiyr-Naiman Megasyncline is characterized by alternating linear zones of positive and negative gravity and magnetic fields, with its structural subdivisions more distinctly defined in geophysical data. For instance, the Zhuyantobin Anticline, which includes the Kypshakbay and Shaytansimes allochthons, is generally associated with a cheerful gravity field of up to +20 mGal and predominantly positive magnetic anomalies (ΔT). Within this, narrow, northwest-trending negative magnetic anomalies are observed, representing non-magnetic volcanic-sedimentary rock units or being harmful components of ΔT anomalies over highly magnetized objects where the magnetization vector inclination reaches 65°.

In the southern part of the Zhuyantobin Anticline, the positive gravity field is interrupted by a north-northwest-trending negative anomaly (Δg) with values down to -16 to -22 mGal, associated with Lower Carboniferous deposits of minimal density that extend into the western part of the Karakoldinsky volcano-tectonic graben-syncline.

The Kypshakbay Allochthon, represented by basic-ultrabasic and basalt formations from the Ashysu suite, is mapped in the magnetic field (ΔT), with aerial surveys showing high-intensity, linear magnetic anomalies of over +1000 nT. The Shaytansimes Allochthon is marked by a less intense, narrow local magnetic anomaly of up to +300 nT.

The Bolattaus Meganticlinorium, occupying the central and northeastern parts of the territory, is primarily characterized by a calm negative gravity field with isometric anomalies Δg ranging down to -16 to -18 mGal. This negative gravity field is due to the extensive development of acidic intrusive magmatism, concentrating on the large granitoid massifs, including the Sasyrlinsky, Bolattaus, and Takyrkudyk plutons in its southern area. The latter two massifs are bordered on the southwest, west, and northwest by the Susyztaus Synclinorium, mainly composed of Lower to Middle Ordovician siliceous-terrigenous sequences. These sequences are intru-ded by more minor intrusions of intermediate and elemental composition, some of which do not reach the erosion surface and are reflected as fragmented positive magnetic fields with individual anomaly intensities reaching up to +500 nT or more.

East of the Susyztaus Synclinorium lies the Taszhargan Anticlinorium, which does not appear in gravity or magnetic fields. In the easternmost part of the Bolattaus Meganticlinorium, bounded to the east by a slightly elevated gravity field up to +2 mGal, the Yeginbulak Synclinorium is noted, comprised of Lower to Middle Ordovician siliceous-terrigenous sequences.

Localized gravity anomalies Δg with intensities up to +4 mGal appear in the northeastern corner of the zone and along its southern boundary. These anomalies are likely caused by concealed Middle Devonian diorite intrusions, also recorded by slightly elevated magnetic anomalies.

Lastly, geophysical data reveals a local dioritic (granodioritic) intrusion in the southeasternmost corner. The geophysical fields above it is ambiguous. In contrast, the magnetic field features a well-defined local anomaly (ΔT) with an intensity exceeding +500 nT, the regional gravity field situates the intrusion within a gradient zone, identifiable only by a slight curvature of the Δg isoanomalies indicating an increase in the gravity field. This is observed on the composite residual anomaly map Δg of sheet L-42-XVIII at a 1:200000 scale.

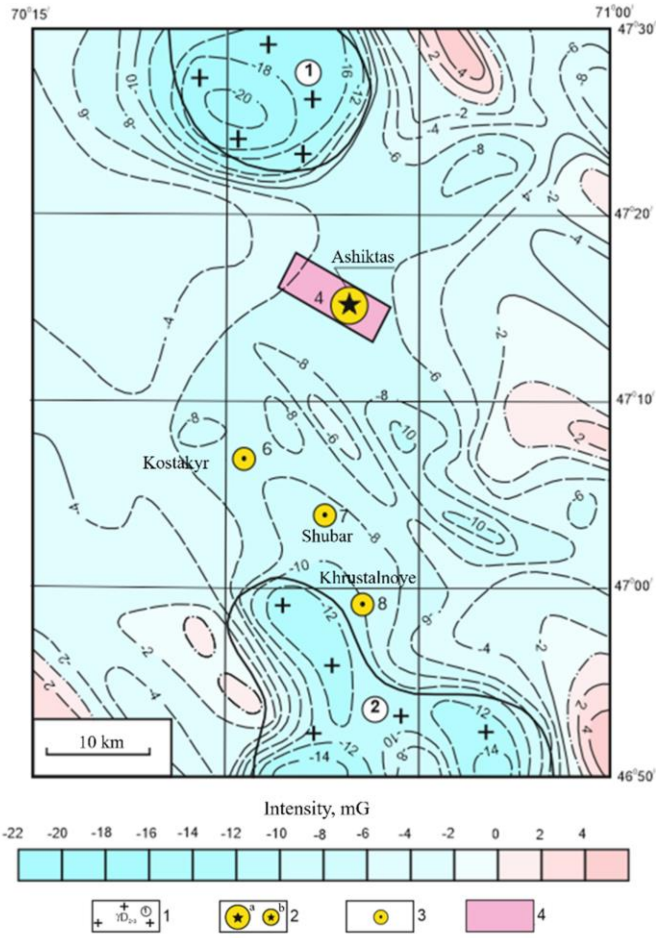
The Atasu-Mointy Block, which wedges into the eastern boundary of the Bolattaus Meganticlinorium, is marked by a relatively positive gravity anomaly in the form of a northeast-trending structural nose in the Δg isolines. This anomaly reflects the area of development of Late Neoproterozoic rock formations and a local negative isometric anomaly in Δg down to -6 mGal, as well as a negative magnetic field reaching -200 nT. This pattern is due to the acidic intrusions present in this region.

The main regional faults and fault zones trending northwest have been identified based on gravity and magnetic fields, their variation, high gradients, and shifts of linear anomalies. According to tectonic zoning data, these faults typically separate megazones, zones, and subzones, which correspond to synclinorial and anticlinal structures. The significant faults (from southwest to northeast) include the North Shusky (Betpak-Dala) Fault (Fig. 9), Zhuantobin, Syrt, Kypshakbay, Akbakai (Fig. 10), Aksor, Altynsai, and Ergenektin faults. Besides these primary faults, numerous more minor faults are also observed in the regional geophysical fields, with orientations varying from latitudinal to meridional. This is shown in the descriptions of the gravity and magnetic fields and in geological-tectonic structure maps based on geophysical data at a 1:200000 scale (Fig. 11).

5. Geological studies and cosmogeological structures

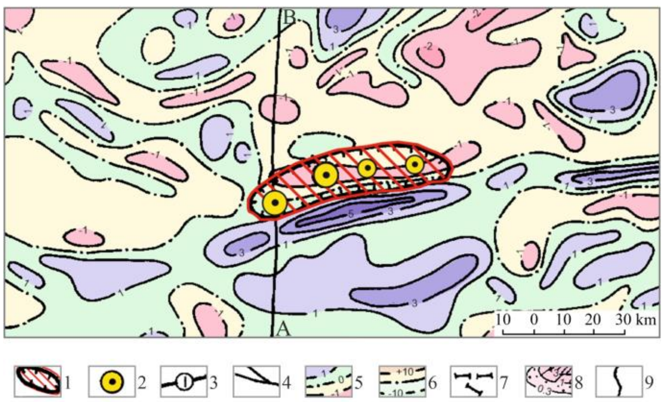
5.1. Geological development history

The Shu-Ile Belt, within which the described area is located, is an active geosuture region of early Caledonian origin. According to our concept of the development of the Paleozoic Kazakhstan Geosuture Megasystem, the Ediacaran to Middle Cambrian period corresponds to the Salairian stage; the late Cambrian and the Silurian represent the early Caledonian phase; the Middle Ordovician corresponds to the middle phase; the Late Devonian represents the late Caledonian phase; and from the end of the Frasnian onward, the Hercynian phase begins.



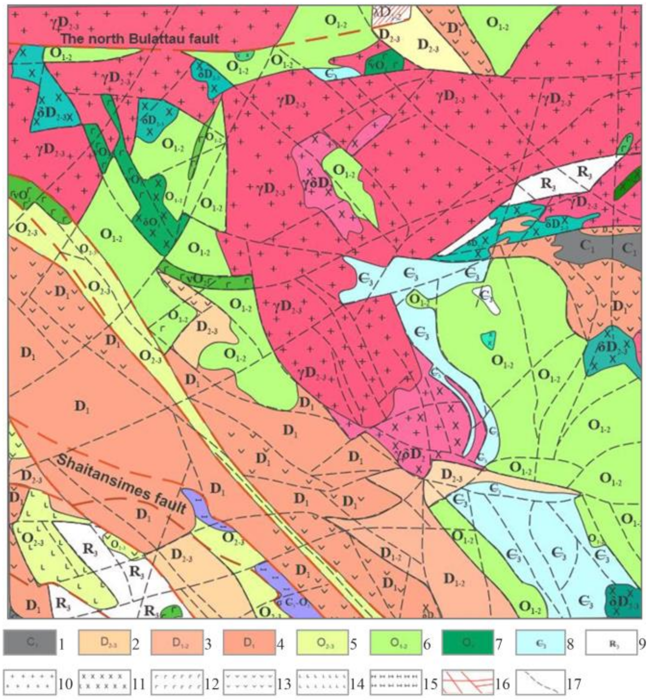
1 – granite (granite masses shown on the residual anomaly map Δ*g*):
(1) - Mungly massif; (2) - Yergabulak massif;
2 – gold-secondary quartzite type deposits and occurrences
(numbers in parentheses refer to maps):
(a) - Ashiktas (4); (b) - western Ashiktas (3); eastern Ashiktas (5);
3 – small deposits and occurrences of gold-sulfide-quartz vein type:
Ashiktas vein (2); Kostakyr (6); Shubar (7); Khrustalnoe (8);
4 – Ashiktas gold ore field

Figure 9. Map of residual anomalies of the Ashiktas gold ore field



1 – Kenjir-Akbakai ore district
2 – gold-sulfide-quartz deposits of the Akbakai type
3 – deep faults separating structural-metallogenic zones
4 – other faults
5 – magnetic field isolines
6 – isolines of residual gravity anomalies
7 – reflective platforms (based on seismic data)
8 – iso-lines of specific arsenic ore content (t/m/km²)
9 – geological-geophysical section line

Figure 10. Scheme of the regional magnetic field of the Akbakai ore district



1 – Late Carboniferous era	10 – granites
2 – Early-Middle Devonian	11 – diorites
3 – Middle-Late Devonian	12 – gabbros
4 – Late Devonian	13 – andesites
5 – Early-Middle Ordovician	14 – basalts
6 – Middle-Late Ordovician	15 – peridotites
7 – Late Ordovician	16 – second- and third-order faults
8 – Early Cambrian	17 – other faults
9 – Mesoproterozoic	

Figure 11. Geological-tectonic zoning based on geophysical data (sheet L-42-XVII) after [48]

Active tectonic processes occurred much further east of the Shu-Ili Belt in the last two phases. On the other hand, the Salairian tectonic phase occurred east of the Chingiz-Tarbagatai system. At the same time, the described area was a back-arc region, partially affected by destructive processes [49].

5.2. Cosmogeological mapping

Based on cosmogeological data interpretations, cosmostructural maps have been compiled for the Shu-Ili geosuture zone area, identifying multiple regions with potential for noble, non-ferrous, and rare metals [50]. In this zone, investigations were conducted interpreting remote sensing materials from space – satellite imagery – to produce a cosmogeological map at a 1:200000 scale [51], [52]. The source data for work on the topic “Development of a Cosmostructural Map of the Khantau-Akbakai Area, Prospective for Non-Ferrous and Precious Metals” included archival data from Landsat ETM+, ASTER satellite images, and materials from their processing [53].

The following factors justify the selection of these space systems:

1. The orbits of the Landsat and Terra satellites (on which the Aster radiometer is installed) are circular rather than elliptical. This ensures that images are captured with a consistent spatial resolution across the entire imaging area.

2. Enhanced spectral characteristics. With medium spatial resolution (15-60 m), Landsat ETM+ satellite images provide four spectral bands in the visible spectrum, two in the near-infrared, and one in the thermal range. ASTER satellite images, also at medium spatial resolution (15-90 m), offer

four spectral bands in the visible spectrum, six in the near-infrared, and five in the thermal range. Additionally, the scene size for Landsat ETM+ data is 185 by 185 km, while for ASTER, it is 60 by 60 km. No other space system provides such capabilities.

3. Over the operational life of Landsat ETM+ and ASTER programs, a vast archive of images has accumulated, repeatedly covering the entire globe. Access to these archival materials is available either free of charge or promptly for a modest fee.

4. According to regulatory documents (Requirements for Remote Bases of State Geological Maps-1000/3 and State Geological Maps-200/2), data from these two systems are recommended as baseline resources.

The digital elevation model based on SRTM data (with a spatial resolution of 90 m) was obtained from the Global Land Cover Facility (GLCF) library of space data from the University of Maryland, USA, via the website: http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp.

The digital elevation model based on ASTER data (ASTER GDEM) (spatial resolution of 25 m) was acquired from the US Geological Survey website at http://gdex.cr.usgs.gov/gdex/.

The overall project workflow under the contract included the following key stages:

– selection of space data;
– preparation and processing of space data;
– preparation of remote sensing bases;
– interpretation and development of a cosmostructural map;
– report preparation.

During the work, commercial licensed software ERDAS IMAGINE and ARCGIS were used. A complete set of remote sensing bases at overview and primary scales was prepared, a cosmostructural map of the area was developed, the main cosmo-geological ore-controlling factors were identified, and recommendations for further directions in geological exploration were provided (Fig. 12).

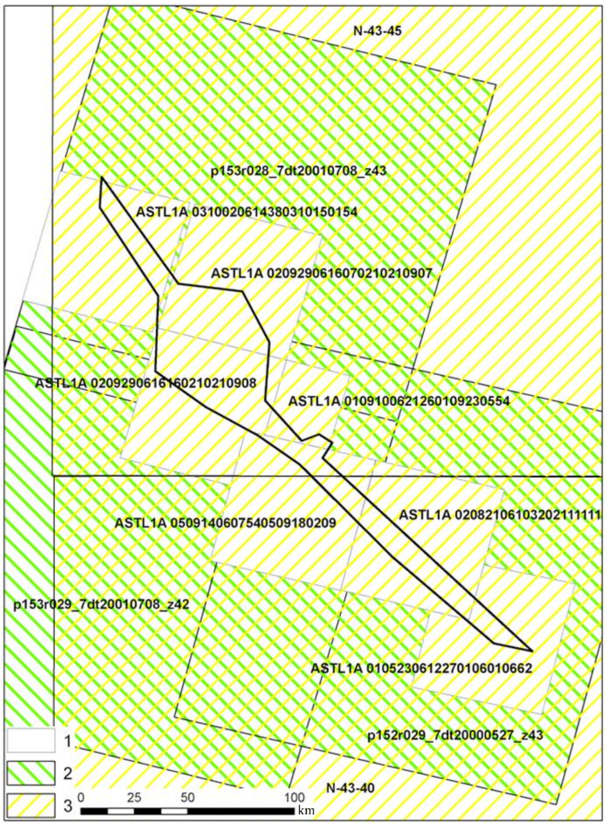


Figure 12. Map of project area coverage with space data: 1 – ASTER data; 2 – Landsat ETM+ data; 3 – mosaics of Landsat ETM+ data

5.3. Cosmo-geological structures of the area

Through processing and interpretation of all acquired remote sensing materials and digital elevation models, linear, ring, and arc structures, areal bodies, and two structural levels of different ages have been identified within the study area [54]-[56].

5.4. Linear structures

Over 3000 linear structures of various origins were identified within the study area, with geological interpretations provided for more than 1800 lineaments. The structures that received geological interpretation include fault disruptions, layering elements, acidic dykes, and geological boundaries.

The faults within the area predominantly trend northwest. These faults are conditionally classified as primary, central, and secondary. The primary faults are northwest-trending faults showing significant right-lateral displacements with amplitudes exceeding 12 km. This tectonic structure dips steeply northeast, likely flattening to sub-horizontal at depth, giving the primary fault a listric morphology. The significant faults are subparallel to the primary fault, likely with a similarly steep northeast dip near the surface but with significantly smaller displacement amplitudes-hundreds of meters. Secondary faults include the remaining auxiliary structures, which are primarily sub-vertical, shorter in length, and generally exhibit horizontal displacement amplitudes within the range of hundreds of meters. The primary and significant faults impart a lens-like wavy structure to the area.

Distinct layering elements are well-defined across the study area, clearly outlining folding structures. In our view, fault-associated and interlayer cleavage highlights many of these elements.

Acidic dykes vary in thickness, and some can only be indicated with out-of-scale linear symbols due to the working scale. Spectrally, these dykes correspond entirely to minor acidic intrusions (Fig. 13).

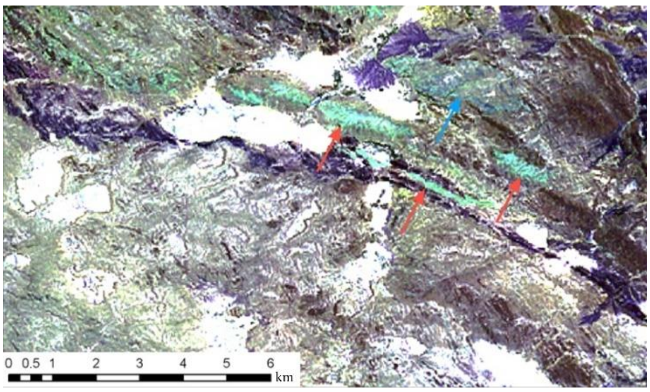


Figure 13. Acidic composition dykes (shown with red arrows) and stock (shown with blue arrow) in Landsat ETM+ image processing data

5.5. Ring structures

A total of 119 ring and arc structures have been identified and mapped. The diameters of the detected ring structures range from 1.5 to 190 km. Based on their manifestations, it can be confidently stated that all identified structures belong to geoblemes and have various endogenous origins.

Generally, ring structures with diameters greater than 120-150 km are classified as metamorphogenic. Their formation is due to processes of metamorphic granitization occurring at the Moho boundary [57]. One such structure has been mapped within the studied area. It is located in the northwestern part of the area. Its arc segments extend well beyond the boundaries of the study area, with its epicenter (centroid) falling within the influence zone of a major fault, likely marking channels for the transfer of energy and deep-seated material [57], [58].

Seventy-seven of the identified ring and arc structures are classified as magmatogenic, of which 63 are plutonogenic and 14 are hypabyssal.

Plutonogenic ring structures, associated with the formation of acidic intrusions, have radii ranging from 1 to 47 km and are located on the hanging wall of the shear zone, near the northeastern boundary of the area. The position of these ring structures suggests a genetic link between significant shear displacement and acidic intrusions.

Hypabyssal ring structures are related to the formation of stocks and dikes of acidic composition and ultramafic protrusions. The radii of these structures range from 0.8 to 5 km, and they are also predominantly located on the hanging wall of the shear structure.

Eleven tectonogenic ring and arc structures have been identified, with radii ranging from 0.8 to 13 km. Their formation is associated with subsidence in localized areas of the region. Some of the mapped ring and arc structures have complex, combined origins. For some structures, it is not possible to determine a likely genesis.

5.6. Areal bodies

Areal bodies consist of magmatic rock bodies of various compositions. Approximately 450 bodies of different compositions and emplacement forms have been identified.

Intrusive bodies of ultramafic and acidic compositions have been identified within the study area. Over 300 ultramafic bodies have been mapped. The sizes of such bodies typically do not exceed several hundred meters. Along their long axes, they are elongated parallel to the defining and major fault disruptions. The absence of thermal alteration in contact areas indicates a protusional nature of their emplacement.

More than 100 intrusive bodies of acidic composition have been identified and mapped. These bodies are narrow dikes, stocks, and batholiths, possibly gabbro-porphyry intrusions. Thermal alteration traces are observed in nearly all acidic bodies, indicating their intrusive nature. The width of hornblende halos is at most 1.7 km for batholiths and 300 m for stocks. Almost all acidic bodies are characterized by their long axes trending northwest, coinciding with the orientation of the defining and major fault disruptions (Fig. 14).

This indicates that granitoid intrusions formed during shear deformations. Another characteristic feature of the batholiths in the studied area is the near-total absence of a prototectonic crack system of the solid phase within the plutonic rocks despite longitudinal and transverse cracks. This suggests a significant degree of erosional truncation of these acidic granitoid batholiths.

However, an acidic body has been identified in close proximity to the study area's boundary, whose long axis is orthogonal to the general direction of shear (Fig. 15). This suggests a possible post-shear age for this intrusive body.

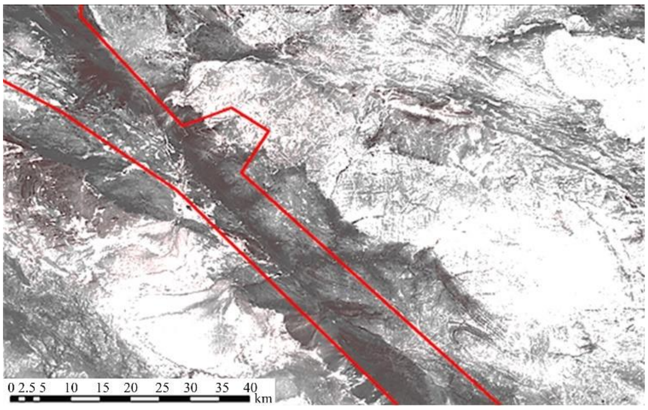


Figure 14. Acidic composition shear intrusive bodies near the northeastern boundary of the study area in Landsat ETM+ image processing data using the "Iron Oxides" method

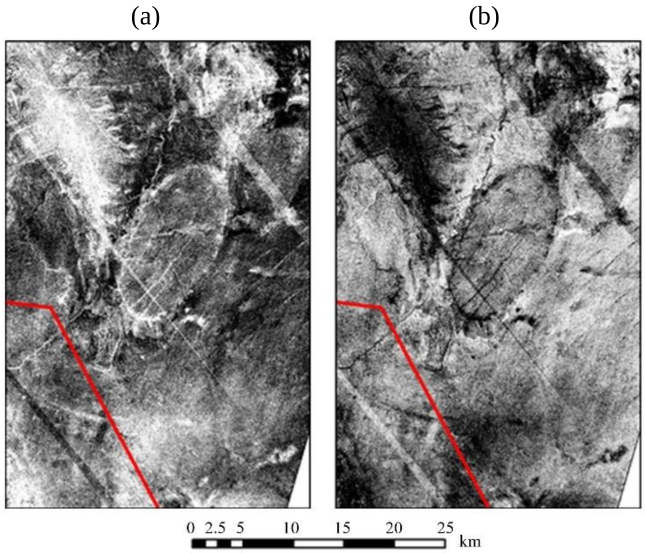


Figure 15. Late granitoid body near the northeastern boundary of the study area in ASTER image processing data. Methods of image processing: (a) hydrothermal alterations; (b) ferriferous silicates

Thus, at least two complexes of acidic intrusions of different ages are proposed within the studied area, whose metallogenic loads may vary. A zonal distribution of intrusive bodies is outlined within the hanging wall of a significant right-lateral shear displacement. Directly within the tectonic shear zones, which define the major fault disruptions, small ultramafic bodies are located, forming single lenses and lens zones extending up to 11 km with outlet widths of up to 3.0-3.5 km. This is followed by a strip up to 11.5 km wide, predominantly developed with small acidic bodies – dikes and stocks. Finally, there is a zone with the development of acidic batholiths. It is assumed that such a zonal distribution of magmatic formations may determine the zonal metallogenic load.

5.7. Prospective areas based on satellite image interpretation

Typically, identifying ore-controlling factors involves a comprehensive analysis of diverse data types for the area, such as geological, structural, geochemical, metallogenic, and other relevant data [59].

In this case, however, the report authors have only structural and limited geological information for the area. Therefore, this study identifies only structural ore-controlling factors [60]-[63]. Following the methodology outlined above, spatial-structural maps of the Zhalaiyr-Naiman (Shu-Ile) region were created, displaying the complete range of selected elements. The map showing the area's satellite data coverage is provided in Figure 16.

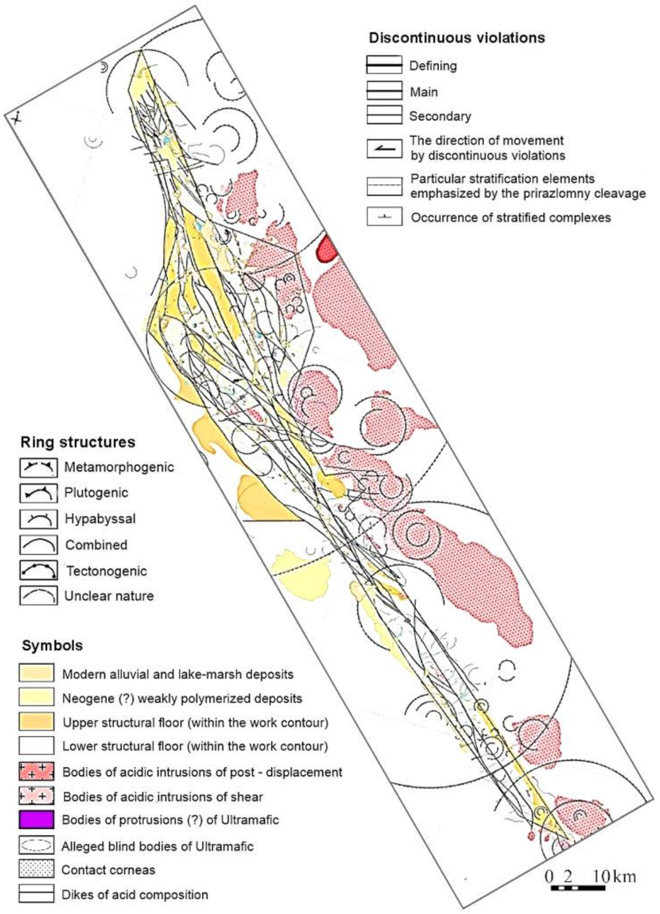


Figure 16. Space-structural scheme of the Zhalaiyr-Naiman zone; M:1:200000 [6]

The area shows potential for magmatogenic mineral resources associated with forming ultramafic and acidic igneous rock complexes. Mineral occurrences within the study area are likely to include chromites, platinum group metals, chrysotile asbestos, and gold. Furthermore, molybdenum and tin deposits may be present near the northeastern boundary of the area [64]-[67].

The identified factors controlling mineralization include:
– shear deformation zones with a northwest orientation;
– magmatogenic and combined ring structures;
– ultramafic rock bodies;
– complex and curved contacts of acidic intrusions, exhibiting signs of thermal alteration in the host rocks.

In the Shu-Ile area, structural factors identified from satellite data suggest potential for various mineral resources, particularly those associated with ultramafic and acidic igneous complexes. Critical ore-controlling structures include northwest-oriented shear zones, magmatogenic and composite ring structures, ultramafic bodies, and contacts of acidic intrusions with signs of thermal alteration in the surrounding rocks.

These features indicate favorable conditions for chromites, platinum group metals, chrysotile asbestos, gold, molybdenum, and tin mineralization, especially near the northeastern boundary of the area.

6. Conclusions

The analysis of geological structure research and geodynamic formation of the Shu-Ile ore zone from the perspective of plume tectonics broadens our understanding of this unique geological feature. The study highlights the importance of considering plume tectonics as a critical mechanism influencing this region's geotectonic formation and ore deposits. Geochemical, geophysical, and cosmogeological data analysis has revealed characteristic features of plume-tectonic processes, their impact on ore deposit formation, and the structure of geological formations within the Shu-Ile zone. Furthermore, the patterns and characteristics of plume-tectonic processes identified during this study provide new prospects for predicting and exploring ore deposits in this region and similar geological structures. Consequently, this research contributes significantly to our understanding of the geological history of the Shu-Ile ore zone. It enables the formulation of insights into its formation mechanisms, considering the influence of plume tectonics.

The Main Suture Zone is characterized by a complex and prolonged tectonic history throughout the Paleozoic, with industrial ore specialization that includes gold-uranium-rare metals and polymetals. The formation range of mineral deposits extends from the Precambrian to the Mesozoic across various geodynamic settings and ore-hosting geological complexes. The chronological and geodynamic evolution of the most representative ore types in the primary suture zones is noteworthy: Ediacaran-Cambrian (passive continental margin) – Pb, Zn, Au (mineralized sediment deposits of Buryltas); C_3–O_2 (submersion stage) – Ba (Shyganak); O_3 (early compression) – Au, Cu, Mo, Fe (Kogadyr, Shatyrkul, Khantau); D_{1-2} (submersion stage) – Au, U (Akbakai, Ashiktas, Zhidel); D_{2-3} (middle compression) – Sn, W, Au, U (Taskuduk, Botaburym, Bie); D_3fm (divergence stage of geosuture faults) – Fe, Mn (Akshagat); C_1 (fault convergence stage) – Cu, Mo, CaF_2 (Kaskyrmys, Taskainar); P_1 (late fault convergence) – W, Mo, Bi (Shalgya, Karaoba); MZ-KZ (intrasuture stage) – U, Mo, brown coal (Nizhneiles, Granitnoye).

The tectonic position of the Main Suture Zone within the regional structures of the Kazakh paleocontinent has been defined, along with its geodynamic evolution, tectonic-magmatic complexes, position within geophysical fields, and features of its deep structure.

Author contributions

Conceptualization: AB; Data curation: SR, BA; Formal analysis: YV, BA; Investigation: AB, MK, BA; Project administration: MK; Resources: AB, YV, MK, SR, BA; Software: SR; Supervision: AB; Writing – original draft: AB, MK, BA; Writing – review & editing: AB, YV. All authors have read and agreed to the published version of the manuscript.

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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.

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Використання даних дистанційного зондування для вивчення геологічної структури та прогнозування мінеральних ресурсів структури Шу-Іле

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Мета. Стаття присвячена аналізу геодинамічних процесів, покладених в основу формування рудної зони Шу-Іле. Дослідження ґрунтується на використанні положення плюм-тектоніки, яка останніми роками набула широкого визнання в геологічному співтоваристві.

Методика. Розглядаються основні аспекти плюм-тектонічної концепції, включаючи механізми внутрішніх потоків мантійних матеріалів та їх впливу на регіональні геологічні процеси. Особлива увага приділяється аналізу тектонічних та магматичних подій, що супроводжують формування рудної зони Шу-Іле, у контексті плюм-тектонічних механізмів.

Результати. Дослідження підкреслює критичну роль мантійних плюмів у впливі на геодинамічну еволюцію рудної зони Шу-Іле. Геохімічні та геофізичні дані розкривають склад та характеристики магматичних порід, демонструючи прямий зв'язок між процесами мантійних плюмів та рудним потенціалом у регіоні. Результати розкривають важливість того, як потоки матеріалу, отримані з мантії, зробили значний внесок у формування геологічних структур та мінеральних ресурсів.

Наукова новизна. Результати дослідження дозволили висунути новий погляд на геологічну історію Шу-Ілеської рудної зони, наголошуючи на значущості плюм-тектоніки як ключового фактора в геодинамічних процесах формування рудних родовищ.

Практична значимість. Дослідження має практичне значення для геологічних досліджень та прогнозу перспективних рудних родовищ у даному регіоні. Воно може бути основою для подальших досліджень у галузі плюм-тектоніки та її впливу на формування геологічних структур і корисних копалин.

Ключові слова: *плюм-тектоніка, геотектоніка, геодинаміка, геофізичні дослідження, космогеологічне картування, сутура, рудоформування*

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