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# Geological History of the Great Altai: Implications for Mineral Exploration

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**Abstract:** The Great Altai region, located at the boundary of Russia, Mongolia, China, and Kazakhstan, belongs to the system of the Central Asian Orogenic Belt. It has undergone a long complex geological and metallogenic history. Extremely rich resources of base, precious, and rare metals (Fe, Cu, Pb, Zn, Ag, Au, Li, Cs, Ta, Nb, REE, etc.) maintain developed mining and metallurgical industry, especially in East Kazakhstan, which is the key metallogenic province. The East Kazakhstan province comprises the Rudny Altai, Kalba-Narym, West-Kalba, and Zharma-Saur metallogenic belts, each having its typical mineralization profiles and deposits. The reconstructed geodynamic and metallogenic history of the Great Altai province, along with the revealed relationships between tectonic settings and mineralization patterns, allowed us to formulate a number of geodynamic, structural, lithostratigraphic, magmatic, mineralogical, and geochemical criteria for exploration and appraisal of mineral potential in Eastern Kazakhstan. Geodynamic criteria are based on the origin of different mineralization types in certain geodynamic settings during the Late Paleozoic–Early Mesozoic orogenic cycle. Structural criteria mean that the location of base-metal deposits in Rudny Altai, gold deposits in the West Kalba belt, rare and base metals in the Kalba-Narym and Zharma-Saur zones is controlled by faults of different sizes. Lithostratigraphic criteria consist of the relation of orebodies with certain types of sedimentary or volcanic-sedimentary rocks. Magmatic criteria are due to the relation between mineralization types and igneous lithologies. Mineralogical and geochemical criteria include typical minerals and elements that can serve as tracers of mineralization. The joint use of all these criteria will open new avenues in prospecting and exploration at a more advanced level.

**Keywords:** tectonic setting; mineral deposit; base metals; gold; rare metals; exploration criteria; Great Altai; Central Asian Orogenic Belt; Eastern Kazakhstan

## 1. Introduction

The Kazakhstan portion of Great Altai belongs to the Central Asian Orogenic Belt. It has undergone a long complex geological and metallogenic history, which led to the formation of extremely rich deposits of base, precious, and rare metals (Fe, Cu, Pb, Zn, Ag, Au, Li, Cs, Ta, Nb, REE, etc.) that have maintained large-scale mining and metallurgical industry. However, many mined ore fields have been depleting, and new discoveries are required for the region's development. The problem is especially urgent for the area of Rudny Altai that hosts many large sulfide deposits with more than 10% contents of Cu + Zn + Pb (Orlovka, Ridder-Sokolny, Maleevsk, Artemiev, etc.) which are being exhausted rapidly. The growing demand for rare metals and rare earths in world markets calls for resuming rare-metal production from the Kalba-Narym metallogenic belt, where the operation of large pegmatitic deposits has been tied up. Furthermore, it is important to discover more gold deposits of different types in order to enhance the gold potential of East Kazakhstan.

The experience of predicting the location of mineral deposits, which often fails the field checks in Kazakhstan and elsewhere in the world, means that the key factors of ore formation and distribution remain poorly understood. Proceeding from the idea that metallogeny is closely related with the geological evolution, the universal approach to mineral prospects can be developed by investigating the history and evolution trends of ore-forming systems.

The key scientific question is to link specific types of deposits to certain stages of the geodynamic development of the region, and to determinate the metallogenic specificity of different tectonic settings.

The aim of this study is to synthesize the available geological and metallogenic data and geochemical and mineralogical evidence from the Great Altai region, with implications for workable exploration criteria.

## 2. Geological Structures and Metallogenic Zones of the Great Altai

The Great Altai territory (Figure 1) occupies the central part of the Zaysan orogenic system which formed in the Late Paleozoic between the Early Paleozoic orogenic structures of Siberia in the northeast and Kazakhstan in the northwest, in the present frame of reference ([1–8], etc.). The Great Altai structures crop out mainly in the East Kazakhstan and Russian Altai areas but are buried under the sedimentary cover of the West Siberian Plate north of the Semipalatinsk latitude. The orogenic system spreads southeastward into the territory of China, where it meets the extension of the Late Paleozoic–Early Mesozoic Junggar orogenic structures, and then accretes the South-Mongolian arc-shaped orogenic system that encircles the Early Paleozoic orogens of Mongolia in the south.

The Great Altai region is made up of NW geological structures and encompasses the Irtysh, Rudny Altai, Kalba-Narym, West Kalba, and Zharma-Saur parallel fault-bounded zones that differ in origin, tectonic setting, deep structure, and metallogeny:

(1) Middle Late Paleozoic Rudny-Altai zone that formed on the Siberian active margin as a result of the subduction of Ob-Zaisan oceanic plate [9–11];

(2) Late Paleozoic Irtysh shear zone of high-pressure metamorphism, with large strike-slip faults related to accretionary and collisional processes [12–14];

(3) Late Devonian–Early Carboniferous Kalba-Narym zone corresponding to a continental margin basin filled with continental clastics [15–17];

(4) West Kalba or Char zone filled with marine sediments and peridotite, oceanic basalt, chert, and limestone remnants of the Middle Paleozoic oceanic crust [18,19];

(5) Zharma-Saur zone consisting of two different fragments: a Devonian–Early Carboniferous oceanic fragment with basalts and cherts formed in island-arc and spreading settings in the northeast [18,20]; an Early Devonian area of felsic volcanism and continental deposition on the active-margin of Kazakhstan in the southwest [21].

The geological history of the Great Altai region can be reconstructed from synthesis of data on local geology and key events of volcanism and magmatism in these zones [8,22,23]. The oldest rocks within the Great Altai orogenic system formed within the Paleo-Asian ocean in Early-Middle Paleozoic time [24]. The changes in the basin size and geometry are recorded in Ordovician to Devonian mid-ocean ridge basalt-chert suites to limestone-chert and reefal limestone complexes.


**Figure 1.** Metallogenic zones of the Great Altai. Arabic numbers stand for names of mineral deposits: RS = Ridder-Sokolny; Ar = Artemiev; Bn = Bakennoye; BG = Belaya Gora; Kr = Karchiga; Br = Bakyrchik; Ak = Akzhal; V = Vasil'evka; Zh = Zhanan; VE = Verkhnee Espe; Ch = Charsk; Mu = Mukur; G = Gornostaevskoe; Ma = Maksut; Yu = Yubileinoe; Se = Sekisovka; Al = Alisher; Kv = Kvartsevoe; T = Tochka; Ak = Akhmetka; As = Ashaly; D = Delbegetey; Be = Belogorskoe; Sa = Satpaevskoe; Kl = Karaotkel. The insert shows the layout and tectonic zoning of the Great Altai territory. The terranes are separated by large regional zones: CSZ—Char shaer zone; ISZ—Irtysh shear zone; NESZ—Notrh-Eastern shear zone.

Volcanic belts in the Early-Middle Devonian Rudny Altai and Chinghiz-Tarbagatay zones mark interactions between the oceanic lithosphere and the continents of Siberia and Kazakhstan, at least in two subduction zones. The subduction possibly stopped in the Late Devonian and the ocean–continent systems underwent large-scale changes, judging by the absence of the respective volcanics from the Chinghiz-Tarbagatay zone and their limited occurrence in the Rudny-Altai zone. The latest Devonian–earliest Carboniferous events left imprint in the Irtysh shear zone and the Rudny-Altai transform margin.

In the Late Devonian–Early Carboniferous, the region was a passive continental margin where a basin formed in the place of a trench and accommodated clastic sediments shed from the denuded edge of Siberia, while marine deposition and Visean island arc volcanism occurred in the Ob-Zaysan basin. Visean volcanics found in the Zharma-Saur and, less often, Char zones record resumed subduction beneath the Kazakhstan margin and, possibly, formation of oceanic volcanic arcs.

The Serpukhovian shallow-marine clastic deposition corresponding to convergence and the related orogenic movements produced polymictic sandstones (greywacke), gravels, and siltstones, along with abundant olistostromes. The lack of Serpukhovian chert and limestone indicates that the ocean had almost closed at that time. The orogeny culminated in the latest Serpukhovian (323–320 Ma), with rapid thrusting, folding, and clastic deposition. The event is marked by a structural unconformity between Early and Late Carboniferous sediments, while the Middle Carboniferous rocks mostly occur as continental molasse with conglomerate and gravel basal beds. Thus, the rock complexes of the region record the sequence of events: subduction → convergence and ocean closure → cessation of marine deposition → orogeny with related faulting and folding followed by molasse deposition, which thickened up the sedimentary section, → rifting and orogen collapse [23,25,26].

The Middle Carboniferous clastic deposition was interrupted by lava flows and deposition of tuff in a continental setting. The post-collisional Early Permian magmatism was especially extensive and produced 300 to 270 Ma compositionally diverse basalt-andesite volcanic suites, gabbro-picritic hypabyssal and gabbro-monzonite-granite and plagiogranite intrusions, dolerite and lamprophyre dikes, and granodiorite-granite and granite-leucogranite batholiths [16,17,19,27–33].

The complex geological history of the region controlled its metallogeny (Figure 1) and led to the formation of four parallel NW metallogenic belts: (1) Rudny Altai base-metal belt (Fe, Mn, Cu, Pb, Zn, and Au), (2) Kalba-Narym rare-metal belt (Ta, Nb, Be, Li, Cs, Sn, and W), (3) West Kalba gold belt (Au, Ag), and (4) Zharma-Saur belt of precious, base-metal and rare-earth mineralization (Cr, Ni, Cu, Co, Au, Mo, W, Ti, and REEs)

Rudny Altai is the key base-metal province of Kazakhstan which stores major massive sulfide deposits of (Cu, Pb, Zn, Au, etc.) mined by the Kazzink and Kazakhmys corporations. The Kalba-Narym belt accommodates pegmatitic (Bakennoye, Belaya Gora, etc.) and albitite-greisen Sn-Ta (Karasu) deposits of rare metals, as well as widespread greisen-quartz and quartz Sn-W vein deposits (Cherdoyak, Palattsy, Kaindy, etc.). Of special interest are Li-bearing albite-spodumene pegmatites (Akhmetkino) and rare-metal granites (Novo-Akhmirovo, etc.). The West Kalba belt stores gold mineralization with quartz, beresite, black shale sulfide, and other deposits (Kuludzhun, Zherek, Bakyrchik, etc.) of economic value. The Zharma-Saur belt hosts diverse mineralization: magmatic Cu-Ni (Maksut), porphyry Cu (Aktogay, Shor), quartz Au (Akzhal), sulfide Au (Suzdal), epimagmatic rare-earth (Upper Espe), and other deposits. Recent studies have provided updates to the formation patterns of massive sulfide mineralization with base, rare, and precious metals in different tectonic settings, which can be used to choose best exploration strategies.

## 3. Materials and Methods

This study was performed with reference to a wealth of geological survey, prospecting, and exploration reports, as well as published evidence from different years, from the Great Altai territory. New data on magmatism, metamorphism, and metallogeny were collected in the course of field trips to main ore districts of the region.

The processes of intrusive and extrusive magmatism, deposition, and related ore formation were studied on fresh rocks sampled in ore-bearing igneous and volcano-sedimentary complexes within the main metallogenic areas of the region. Data on major- and trace-element contents in more than 500 samples were used to compile classification and discrimination diagrams.

Ore formation patterns and mineralogy were studied in samples of metasomatic and ore bodies from deposits of different types, as well as in monofractions of metallic and gangue minerals (native gold, pyrite, arsenopyrite, wolframite, cassiterite, tantalite, spodumene, quartz, albite, muskovite, lepidolite, and others). Mineralogical analyses were performed at VERITAS Laboratory of the D. Serikbaev East Kazakhstan Technical University (Ust'-Kamenogorsk, Kazakhstan), at the Analytical Center of the V. Sobolev Institute of Geology and Mineralogy (Novosibirsk, Russia), and at the University of Akita (Akita, Japan). The chemical compositions of rocks and minerals (about 450 analyses) were determined, respectively, by mass spectrometry with inductively coupled plasma (ICP-MS) on an Agilent 7500cx (Agilent Technologies, Santa Clara, CA, USA) spectrometer and by electron probe microanalysis (EMPA), under standard operation conditions, on a Cameca MS-46 analyzer (Cameca, Gennevilliers, France) that allowed detection and precise measurements of 73 elements (Au, Ag, Pt, Cd, In, Ir, Y, Cd, REE, U, etc.). Scanning electron microscopy and energy dispersive spectrometry (SEM-EDS), with a Jeol-100C microscope with a Kevex-Ray detector and a Jeol ISM-6390 LV microscope (JEOL, Tokyo, Japan) was applied to more than 1000 thin and polished sections. An Oxford INCA Energy system was used to study fluid inclusions, as well as micrometer inclusions of metallic and gangue minerals, and to analyze impurity elements (Au, Ag, Pt, In, etc.). The age of intrusions was constrained from published data of isotope geochronology.

The analytical work allowed us to relate gold and rare-metal mineralization to magmatism and subsequent metasomatism. The results have confirmed that ore formation occurred in several stages.

## 4. Largest Mineral Deposits

The activity at each stage in the geodynamic history of the region produced its specific type of mineralization. Below we give a brief synopsis of the structure, age, and genesis of most typical mineral deposits in the four metallogenic belts reported in previous publications, with respective references.

### *4.1. Rudny-Altai Metallogenic Belt*

The Rudny-Altai metallogenic belt (Figure 2) bordered by the NW Irtysh-Markakol and Beloretsk-Markakol shear zones is the major area of volcanic massive sulfide (VMS) base metal and gold mineralization in Kazakhstan, which provides up to 55–60% of Kazakhstan's annual gold production. The Rudny-Altai belt accommodates several large fields and deposits in three main ore districts: Ridder-Sokolny, Tishinsky, and Novo-Leninogorsk, etc., in the Leninogorsk districts; Maleevsk, Zyryanovsk, Grekhov, etc., in the Zyryanovsk district; Orlovka, Artemiev, Nikolaevsk, etc., in the Irtysh district [34–36].

VMS deposits and their Devonian ($D_1$e-$D_3$fm) basalt-andesite-rhyolite volcanic and porphyry hosts make up a single ore-magmatic system [35,36]. The metallogenic history of the area included several stages and produced mineralization at different stratigraphic levels, spanning 1000–1500 m in depth and 374–390 Ma in age (Table 1) [37–40].

**Table 1.** Geochronology and stratigraphic levels of VMS mineralization in Rudny Altai.

| Stage | Age, Ma | Method, Shcherba, 2000 | Mineralization | Deposits |
|---|---|---|---|---|
| Emsian | 394-390 | U-Pb | Fe (Mn, Pb, Zn) | Kholzun, Pnevsky |
| Emsian-Eifelian | 390-387 | U-Pb | Zn, Pb (Cu, Au, Ag) | Ridder-Sokolny, Tishinsky |
| Eifelian | 385-380 | U-Pb | Cu, Zn, Pb | Orlovka, Maleevsk |
| Givetian | 378-374 | U-Pb | Cu, Zn (Pb, Au) | Nikolaevsk, Artemiev |

Ore formation apparently occurred in submarine conditions, under thermodynamic disequilibrium [41,42], due to inputs of fluids that carried metals (Fe, Cu, Pb, Zn, Au, Ag, etc.) and dissolved gases ($CO_2$, $N_2$, $H_2S$, S, Cl, F, H, $H_2O$). The mineralization was of stratiform or metasomatic hydrothermal origin [34,42–44] controlled by the host lithology and by the contents of carbon and lime in the rocks.

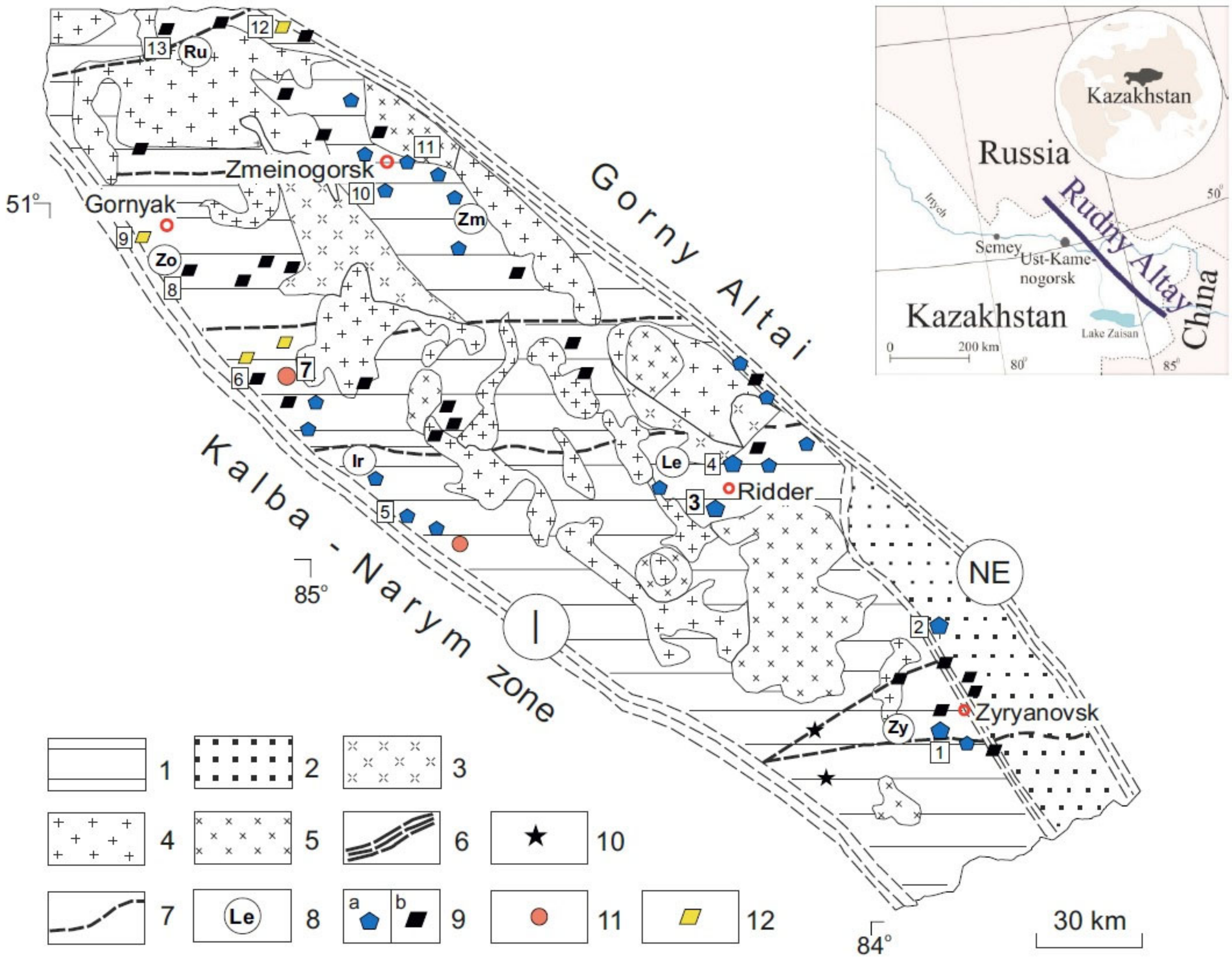


**Figure 2.** Local geology of Rudny Altai, after Gaskov [36]. 1 = Middle-Upper Devonian island-arc volcano-sedimentary rocks of Rudny Altai; 2 = Belaya Uba-Maymyr back-arc basin; 3 = Pre-Eifelian (D2) complex of diorite, quartz diorite, granodiorite, and plagiogranite; 4 = Middle Devonian (D2) Zmeinogorsk complex of granodiorite, diorite, plagiogranite, and adamellite; 5 = Middle Devonian (D2) Kalba complex of porphyritic biotite and biotite-hornblende granites; 6 = border faults between orogenic systems: Irtysh (Irt) and North-East (NE) shear zones; 7 = cross faults; 8 = ore districts; 9–12 = mineral deposits: 9 = VMS deposits with sulfide-base metal (a) and base metal (b), 10 = Pb-Zn deposits, 11 = Cu deposits, 12 = Au and base metal deposits. Numbers in squares are individual deposits in ore districts: Zyryanovsk (1) and Maleevsk (2) deposits in Zyryanovsk (Zy) district, with; Ridder = Sokolny (3) and Novy Leninogorsk deposits (4) in Leninogorsk (Le) district; Irtysh (5), Nikolaevsk (6), and Artemiev (7) deposits in Irtysh (Ir) district; Zolotukhino (8) and Orlovka (9) deposits in Zolotushino (Zo) district; Zmeinogorsk (10) and Korbalikha (11) deposits in Zmeinogorsk (Zm) district; Talaya (12) and Rubtsovsk (13) deposits in Rubtsovsk (Ru) district.

(1) Stratiform volcanic-sedimentary hydrothermal deposits formed on the bottom of a basin among Devonian lavas and pyroclastics (Ridder-Sokolny, Nikitino, Upper Uba, etc.) massives. Rhythmic ore layers deposited from sulfuric, ferric, and carbonate fluids mixed with seawater (>100 °C, 100–600 bar), while disseminated ore formed synchronously in limy-siliceous and organic sediments.

(2) Metasomatic hydrothermal deposits result from alteration of volcanic-sedimentary rocks and subvolcanic porphyry flushed by migrating metal-laden fluids. They are mainly economic massive ore beds or veined-disseminated ores: Maleevsk, Orlovka, Tishinsky,

etc., which occur among abundant subvolcanic intrusions and thick hydrothermally altered rocks with geochemical anomalies (Bi, Te, Au, Ag, Sb, etc.) and complex compositions of rich ores, with high concentrations of Cu + Pb + Zn and impurities.

Ridder-Sokolny VMS deposit in the Leninogorsk ore district (Figure 2) is located at the intersection of the North-East shear zone with W–E faults. The mineralization occurs at the Emsian stratigraphic level (Table 1) in Middle Devonian volcanic-sedimentary rocks, among subvolcanic and felsic volcanic rocks affected by quartz-sericite-chlorite, quartz-sericite, and quartz-barite metasomatism (Figure 3).

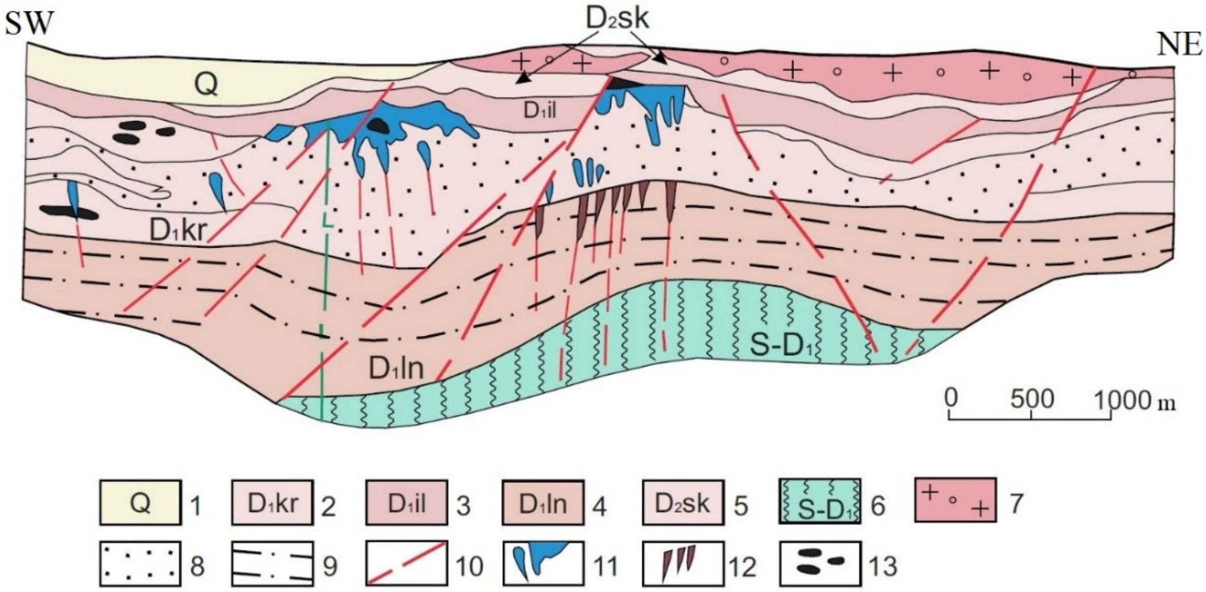


**Figure 3.** Cross section of southwestern Ridder-Sokolny deposit. 1 = quaternary sediments; 2–5 = volcanic-sedimentary formations: $D_1$kr Kryukov Fm. siliceous and calcareous-siliceous silty sand (2), $D_1$il Ilyinka Fm. medium tuff and tuffite (3), $D_1$ln Leninogorsk Fm. felsic lava and lava breccia (4), Sokolny Fm. carbonaceous-argillaceous-calcareous siltstone; 6 = Early Paleozoic schists; 7 = Middle Devonian granitoids; 8–13 = metasomatic rocks: sericitized microquartzte (8), micro-quartzite (9), small gold-sulfide-quartz veins (10), orebodies (11), pyroclastic breccias (12), sericitized shale (13).

The mineralization is multistage and polygenetic, with massive, patchy, or disseminated ores ([42,45,46], etc.) occurring as gold-rich sulfide-quartz veins in the upper level and Cu-Zn- and Cu-bearing veins at the lower level. Main metallic minerals are pyrite, galena, sphalerite, and gold (Figure 4).

The ores contain on average 1.12 wt% Zn, 0.45 wt% Pb, 0.47 wt% Cu, 14.38 ppm Ag, and 1.5 ppm Au, as well as impurities of 30 ppm Bi, 32 ppm Cd, 1. ppm Se, 130 ppm Te, 280 ppm Sb, 500 ppm As, 3 ppm In, Hg, etc. Main metallic minerals are sphalerite, galena, pyrite, chalcopyrite, gold, silver minerals, and less abundant arsenopyrite, calaverite, haematite, marcazste, native silver, native bismuth, barite, etc. The most frequent metals are Au, Ag, Te, Bi, Se, W, and Ta (Figure 4a,e,f).

Native gold occurs as inclusions in sulfide minerals or in later quartz veins and stockworks [41]. The gold resources approach the amount in the Gai Cu-Zn deposit in the Urals [40].

The large Artemiev deposit is located in the Irtysh ore district (Figure 2) and consists of VMS Cu-Zn ores [34], in Middle-Upper Devonian ($D_2$e-$D_3$fm$_1$) volcanic-sedimentary rocks crosscut by large felsic and mafic subvolcanic intrusions, as well as by plagiogranite-porphyry, dolerite, and andesite-dacite porphyry dikes (Figure 5).

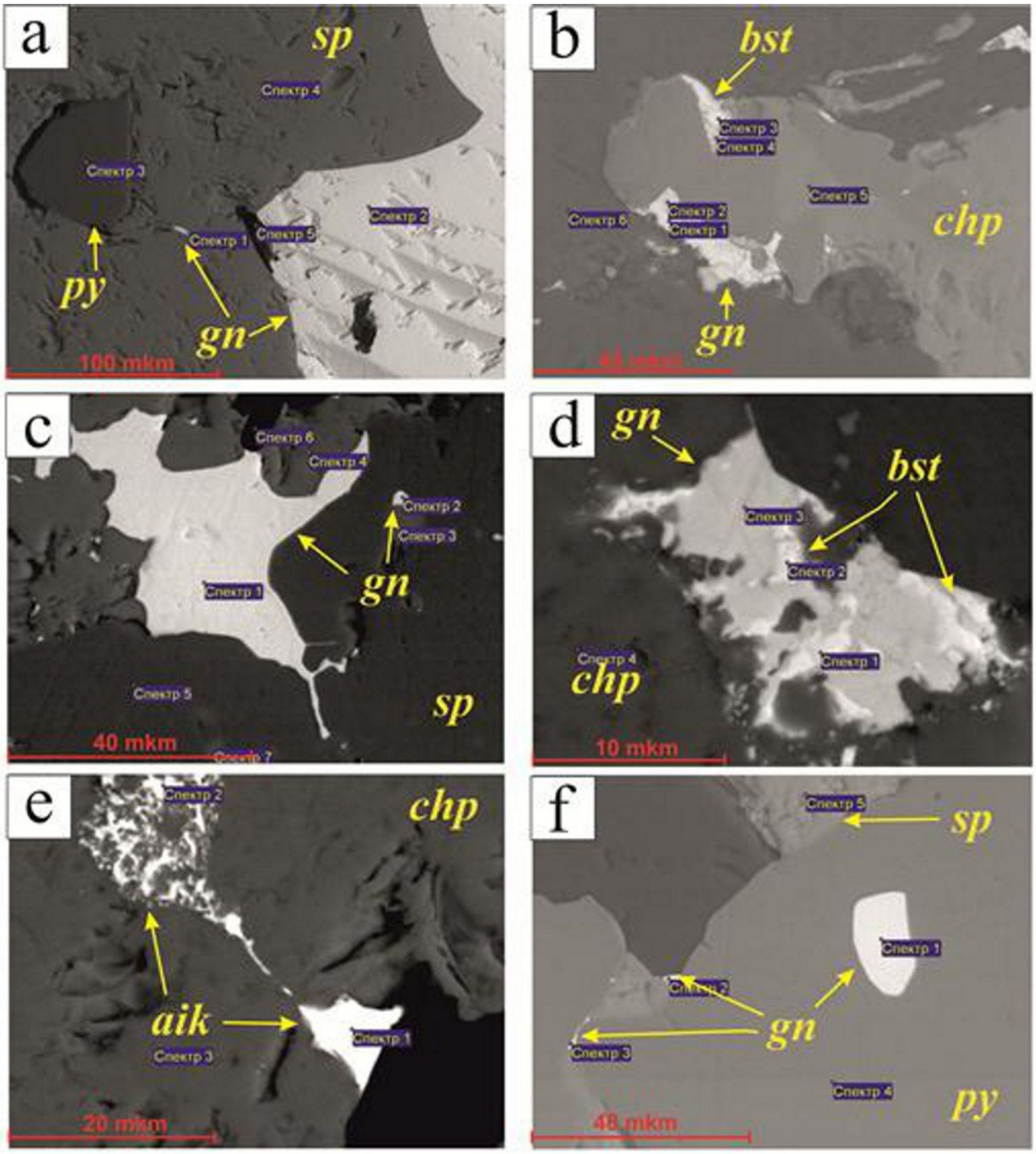


**Figure 4.** Mineralogy and mineral microinclusions in the ores of typical Rudny Altai deposits, after [47]. (**a**) Typical assemblage of galena and pyrite (py), Ridder–Sokolny deposit; (**b**) aggregates of galena (gn) and bismuthite (bst) with chalcopyrite (chp), Artemiev deposit; (**c**) galena microcrystal in sphalerite (sp), Artemiev deposit; (**d**) galena microinclusion, with bismuthite and Ta, W impurity, Artemiev deposit; (**e**) aikinite (aik) strings in chalcopyrite, Ridder–Sokolny deposit; (**f**) galena (gn) microinclusion in pyrite, Ridder–Sokolny deposit.

Mineralization occurs as seven 10–300-m-wide and 12-m-thick lens-shaped orebodies arranged in a 1000 m long chain at the boundary between the two different formations. The ores show prominent vertical zonation (top to bottom) of barite-base metal, pyrite-base metal, Cu-Zn, and Cu-sulfide zones with the respective assemblages of (i) Pb-Zn minerals and minor amounts of barite, Au, Ag, Cd, Hf, Sb, As, Te, etc., in the hanging wall and (ii) Cu-Bi- pyrite in the footwall of the orebodies.

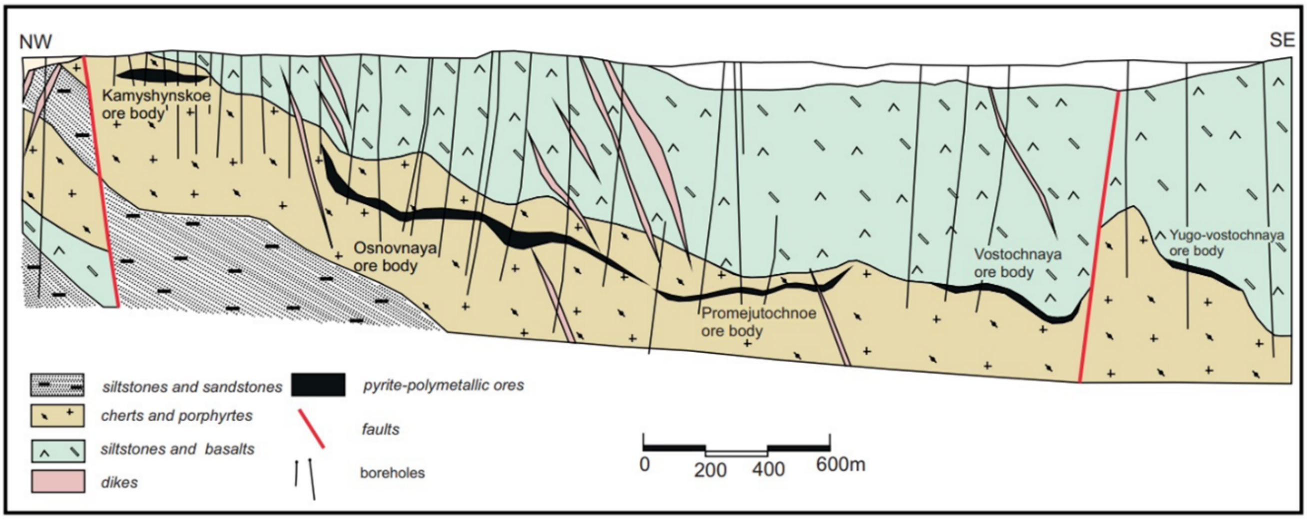


**Figure 5.** Cross section of the northeastern part of Artemiev deposit [34,47].

The ores contain on average 2.1 wt% Pb, 8.15 wt% Zn, 2.23 wt% Cu, 129 ppm Ag, and 1.52 ppm Au, as well as impurity elements of 80 ppm Bi, 420 ppm Cd, 39 ppm Se, 10 ppm Te, 850 ppm Sb, and 400 ppm As. The metallic minerals are chalcopyrite, sphalerite, galena, pyrite, fahlite, gold, silver minerals, As pyrite, Ag and Bi tellurides, barite, etc. (Figure 4).

### *4.2. Kalba-Narym Metallogenic Belt*

The Kalba-Narym rare-metal belt of Great Altai is located between the Irtysh shear zone and the West Kalba belt. The Kalba-Narym belt is composed of multi-phase granitoids of the Kalba and Monastery complexes making large fields at intersections of the NW Kalba-Narym, Terekta, and other faults with N-S and NE faults that were the principal magma conduits [16,17].

The rare metal pegmatitic Yubileinoye deposit (Figure 6) within the Asubulak ore field is a typical case of rare-metal mineralization in the Kalba-Narym belt [48]. It is related to multiphase granitoids of the Kalba complex, with its orebodies along the margins of phase I medium-coarse grained biotite granite intrusions. Rhythmic vertical zoning of pegmatite veins and Ta, Nb, Be, Li, Cs, Sn, and W ores records pulse-like inputs of pegmatitic ore-forming fluids [49]. The deposit, 8–10 by 2–3 km in size, extending in the W–E direction, is controlled by a W–E fault within the Tastyube granite intrusion of the Kalba complex. The Kalba granites, the predominant lithology in the area, are of two phases: medium to coarse-grained porphyritic biotite granites (phase I) and strongly muscovitized two-mica medium-grained granites (phase II). Ores occur as microcline-albite and albite-spodumene pegmatite veins in the phase I granites (Figure 6). The spodumene assemblage is especially rich in Ta, Nb, Be, Li, Rb, and Cs rare metals [50].

The ores have highly diverse mineralogy and chemistry. The mineralogy consists of albite and microcline feldspars, vein minerals of quartz, muscovite, beryl, spodumene, and metallic phases of tantalite-columbite, pollucite, and cassiterite, along with quite widespread tourmaline, apatite, garnet, gilbertite, sulfides (arsenopyrite and pyrite), microlite, calcite, and amblygonite. Molybdenite and petalite are of rarer occurrence, while epidote, titanite, chlorite, biotite, hornblende, pyrochlore, wolframite, monacite, scheelite, and ilmenite are scarce. The main metals are Ta, Sn, Li, Rb, and Cs.

Pollucite pegmatites (Figure 7) bear microinclusions of manganotantalite and cassiterite coexisting with pollucite, as well as fluid inclusions of microlite (with 6.52 wt% W), scheelite, chalcopyrite, cuprite, galena, and metallic tin.

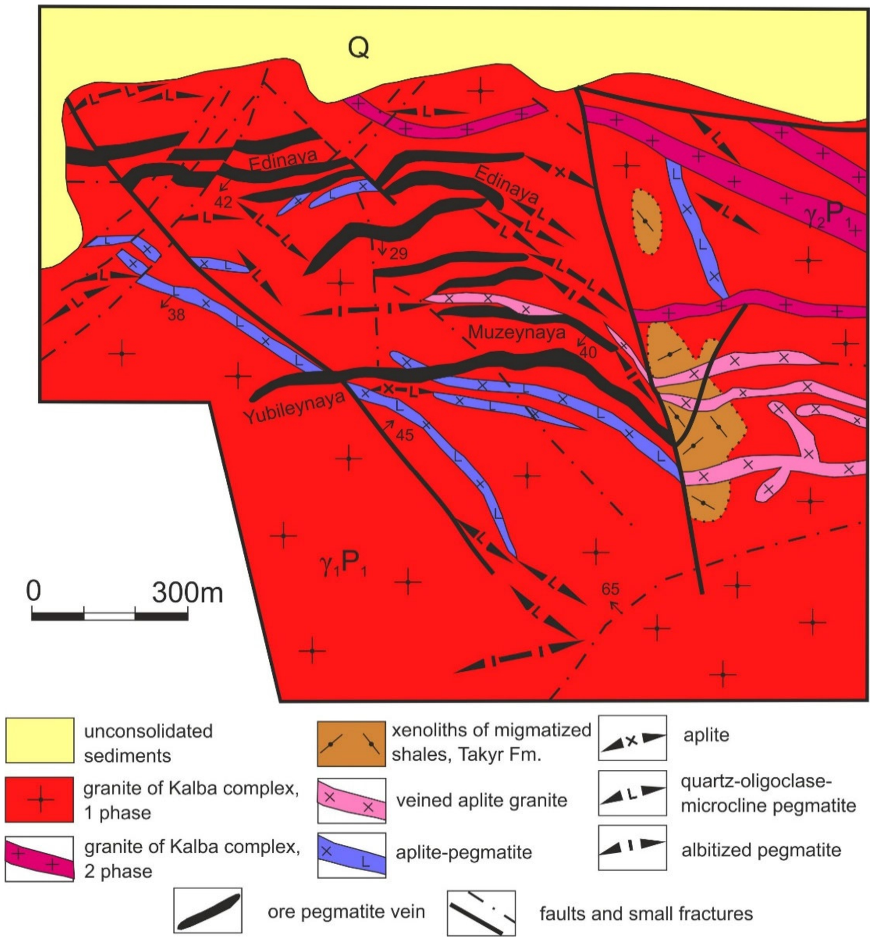


**Figure 6.** Geological sketch of the Yubileynoye pegmatite deposit (map view), after unpublished data of V.A. Filippov.

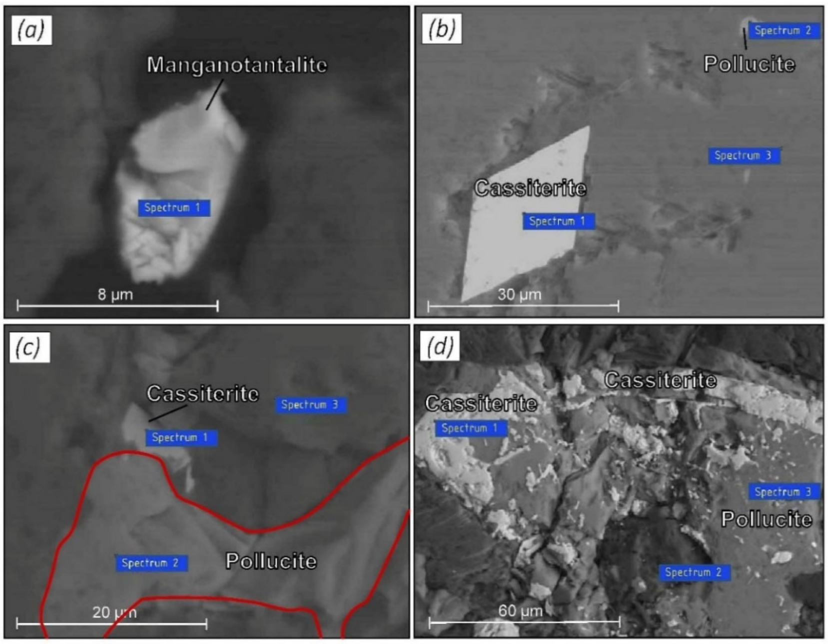


**Figure 7.** Mineral microinclusions in pollucite pegmatites: manganotantalite (**a**), cassiterite (**b**), pollucite and cassiterite (**c**), and cassiterite strings in pollucite (**d**).

The abundances of trace element and precious metals in the Yubileynoye rare-metal and related minerals are, respectively, 54 ppm La, 99 ppm Ce, 12 ppm Pr, 42 ppm Nd, 2 ppm Sm, 1.4 ppm Yb, and 2.2 ppm Gd, with 0.2–0.7 ppm Au and 0.6–1.8 ppm Ag. Tantalite-columbite samples contain as much as >50 ppm Au, 15.4 ppm Ag, 69.9 ppm Pt, 12.2 ppm Ir, 1243 ppm U, etc.

The main types of rare-metal pegmatites formed in a granite-pegmatite system by pulse-like cyclic fluid inputs (Figure 8) through open or restricted conduits [51,52]. New isotope dating gave similar Ar-Ar biotite, muscovite, and lepidolite ages of 291 to 286 Ma for the Kalba phase I granites and related mineralization [16,48].

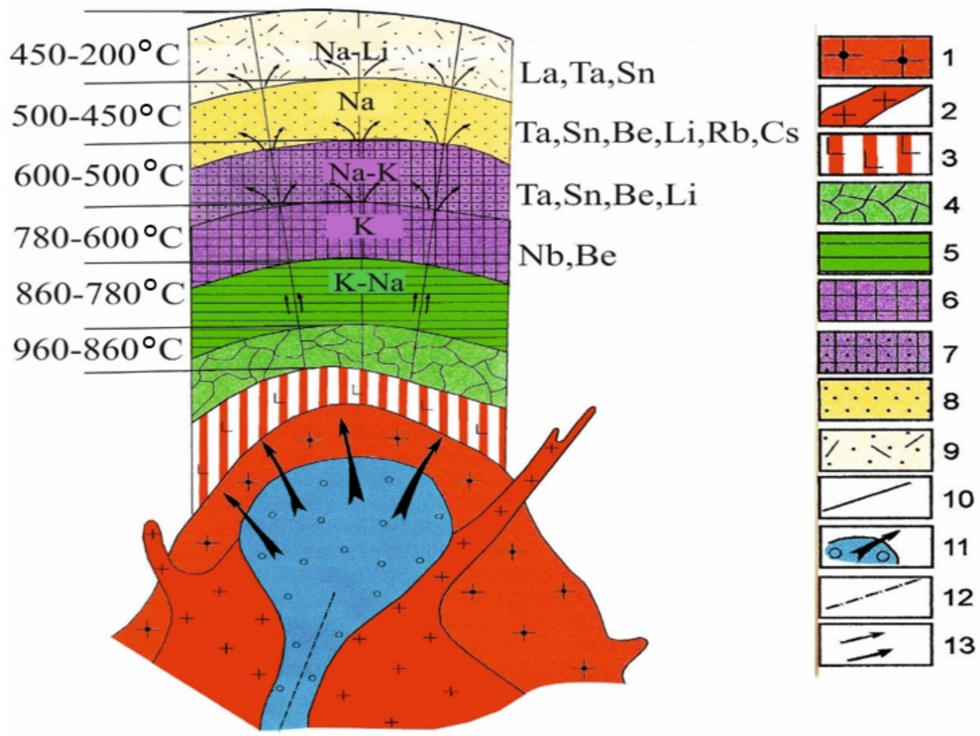


**Figure 8.** Formation model of Kalba rare-metal pegmatites. 1 = medium-coarse-grained biotite granites (phase I); 2 = fine- and medium-grained muscovite (phase II); 3 = aplite, aplitic granite; 4 = graphic pegmatite, 5 = oligoclase-microcline gangue pegmatite, 6 = microcline pegmatites (with beryl and columbite); 7 = microcline-albite pegmatite with tantalite, cassiterite, beryl, and spodumene; 8 = albitic pegmatite; 9 = albite-spodumene; 10 = fracture; 11 = direction of fluid flow; 12 = fault magma conduit; 13 = flow of ore-bearing melts [53].

The Kalba pegmatites contain indicator elements of Li, Rb, Cs, F, B, Ta, Be, and Sn, and a number of minerals typical of rare-metal pegmatitic mineralization, which make the Kalba ores similar to other pegmatite deposits worldwide [54–56]: albite, cleavelandite, muscovite, lepidolite, fluorapatite, spodumene, pollucite, color tourmaline, cassiterite, tantalite, microlite, etc.

### *4.3. West Kala Metallogenic Belt*

The West Kalba belt (Figure 9) is the key zone of gold mineralization in the region, with more than 40 gold deposits [57]. The largest sulfide-black shale gold deposits (Bakyrchik, Bolshevik, Gluboky Log, etc.) are located along NW and W–E transcrustal faults, while gently dipping mineralization zones and band- or lens-shaped orebodies of hydrothermally altered black shales with strings and patches of metasomatic quartz and abundant disseminated Au pyrite and arsenopyrite follow pinnate faults [58–61].

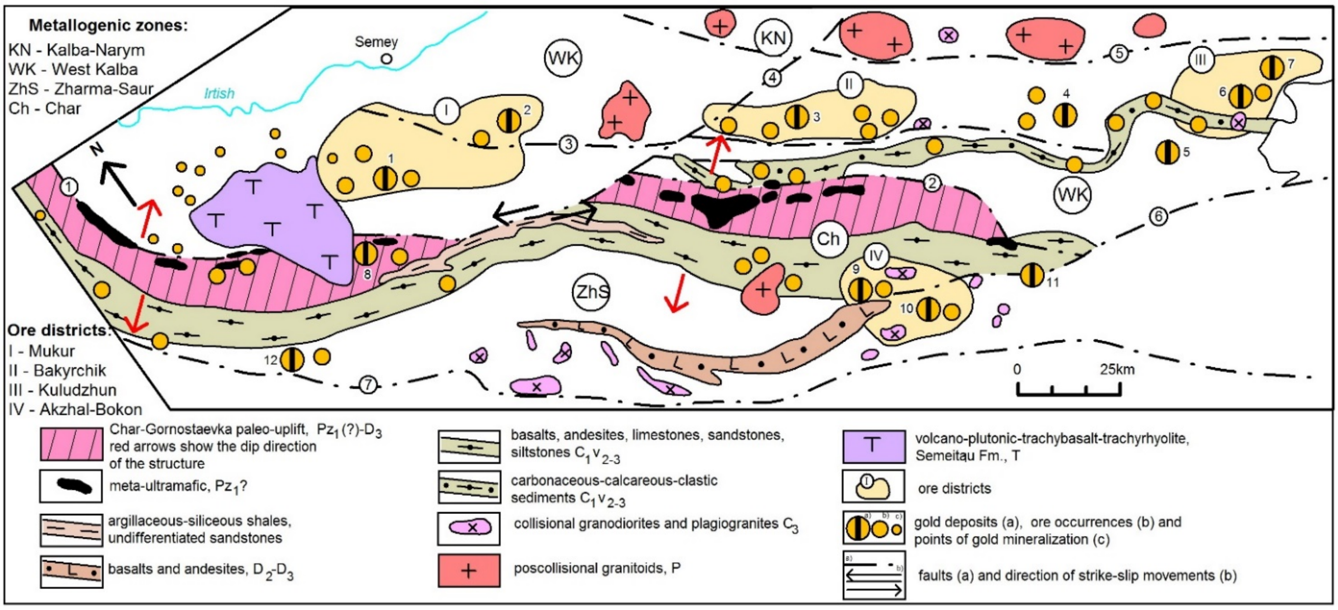


**Figure 9.** Gold deposits in the West Kalba and Zharma-Saur belts. Numbers in circles stand for names of faults: 1 = Gornostaevka; 2 = Char; 3 = West Kalba; 4 = Znamensky; 5 = Terekta; 6 = Sardzhal; 7 = Baiguzin-Bulak. Arabic numbers stand for names of deposits: 1 = Zherek; 2 = Kedey; 3 = Bakyrchik; 4 = Sentash; 5 = Jumba; 6 = Kuludzhun; 7 = Layly; 8 = Suzdal; 9 = Akzhal; 10 = Boko; 11 = Ashaly; 12 = Zhanan.

Bakyrchik, the largest gold field in the West Kalba gold belt (Figure 10), comprises the Bakyrchik, Gluboky Log, Bolshevik, Promezhutochnoye, Kholodny Klyuch, Chalobay, and Sarbas deposits. Gold-bearing (up to 0.10–0.150 ppm Au) black shales, along with syngenetic gold-pyrite mineralization, occur among continental clastics of the $C_3$ black shale Bakyrchik Fm.

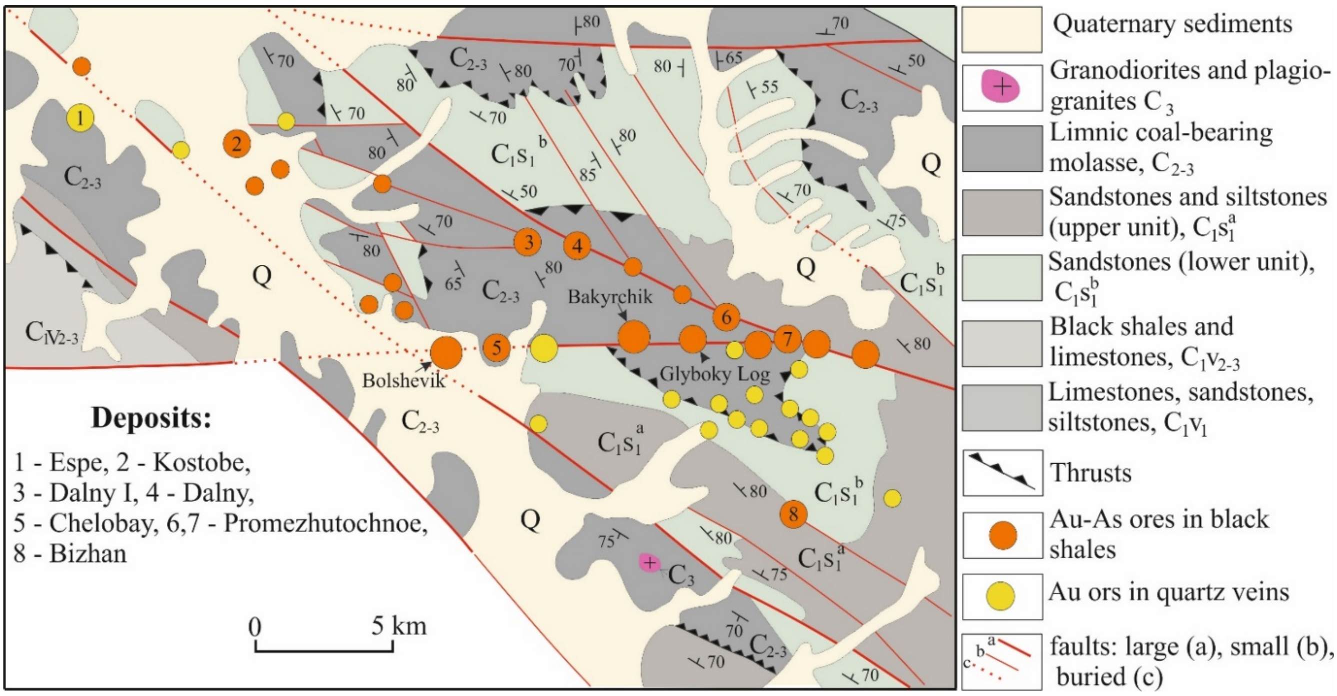


**Figure 10.** Location map of deposits in the Bakyrchik ore field (using unpublished data of V.I. Tikhonenko).

The Bakyrchik orebodies, with 9.4 ppm average grades, have been sampled to depths of 1000–1500 m and imaged by geophysical methods down to 3000 m. The band- or lens-shaped orebodies arranged in concordant zones are localized along large faults or at their intersections with the W-E Kyzyl shear zone [58].

The rocks show linear metasomatic zoning, with carbonatization and chloritization in the outer zones and listwanitization, beresitiziation, and albitization in the inner zones (Figure 11). The mineralization zones bear several mineral assemblages (listed from smaller to greater abundance): melnikovite-pyrite-pyrrhotite-marcasite; gold-quartz-carbonate-chalcopyrite with scheelite; gold-base metals-quartz; quartz-carbonate-antimonite-tetrahedrite; and gold-pyrite-arsenopyrite. Arsenopyrite (3.0 to 15.0 vol%) and pyrite (1.5 to 22.0 vol%) occur, respectively, as prismatic, acicular, or columnar and as cubic or dodecahedral grains. They contain up to tens or less often hundreds of ppm Au and 5 ppm Ag. The ores bear up to 1.5 wt% Cu and hundredth fractions of wt% Sn, Mo, W, and Bi [57,62–64].

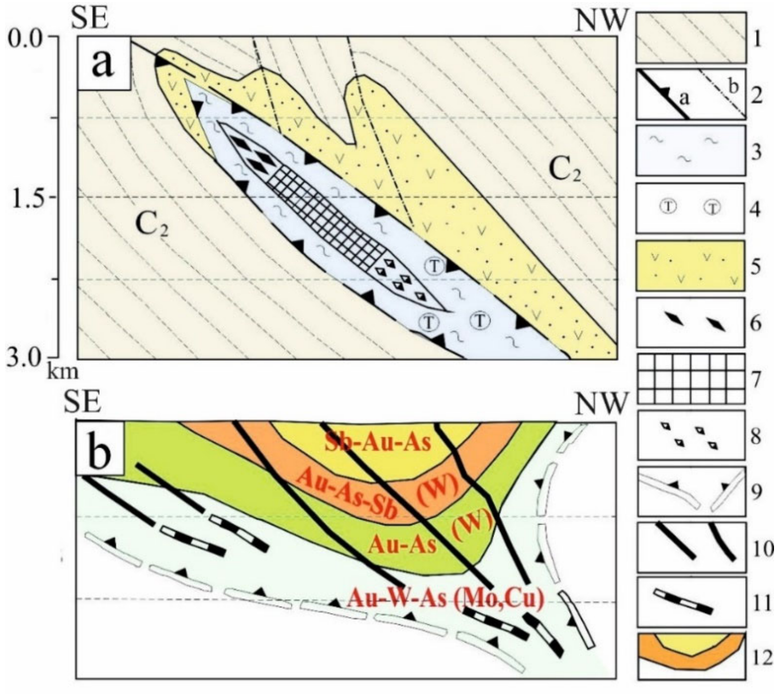


**Figure 11.** Metasomatic (**a**) and geochemical (**b**) zoning of the Bakyrchik ore field [58]. 1 = coal-bearing sediments; 2 = shear zones: thrusts (**a**) and other faults (**b**); 3–7 = sericite (3), tourmaline (4), chlorite-albite (5), carbon-kaolinite-sercite (6), and carbon-sericite (7) metasomatism, 8 = sericite-phlogopite-carbonate; 9 = contour of the ore field in the projection on the vertical plane; 10–11 = established (10) and proposed (11) centerlines of ore deposits; 12 = geochemical zones.

The Bakyrchik deposit is similar to the known Mureuntau, Kumtor, and other giant black-shale gold deposits [57,65]. All gold deposits in the Bakyrchik field are rich in tungsten and other rare-earth metals due to late quartz-carbonate-scheelite-chalcopyrite Au-Mo mineralization (redeposited ores). Wolframite in the Kumtor ores varies from 0 to 30.4 vol%, and calcium wolframite contains 20–300 ppm Sc, 500–1000 ppm La, 30,000 Sr, 10 to 1000 ppm Mo, 100 to 6000 Y, and 400 ppm Yb. The Muruntau scheelite contains 100 to 6000 ppm Y, 250 ppm Nd, 190 to 350 Ce, 2 to 130 ppm Eu, 400 to 1100 ppm Sr, 0.5 to 4.0 Lu, and 20 to 90 ppm Sm. Gold and rare-metal relations in the Bakyrchik field have been insufficiently studied but the ores are known [66] to bear rare metals and REEs (W, Mo, Sn, Y, Ce, Ga, In, Ta, Yb, Er, La, PGE, etc.). Scheelite concentrate is a potential source of W, REEs, Mo, and Bi. Most of gold is found at the middle and upper levels of the Bakyrchik deposit, while tungsten increases with depth (Figure 11).

### 4.4. Zharma-Saur Metallogenic Belt

The belt is located at the junction of the Early Paleozoic Kazakhstan (continental) and Late Paleozoic–Early Mesozoic Zaysan (oceanic) structures. It hosts diverse mineralization of gold, Cu-Ni, porphyry Cu, rare metals, and rare earths.

The Verkhnee Espe deposit (Figure 12) belongs to the Akbiik-Akzhailau batholith belt of the Zharma-Saur zone with rare-metal-REE mineralization. Rare metals occur in the northern apical part of the Akzhailau granite intrusion among exposed alkaline riebeckite granites of the Keregetas-Espe complex [53].

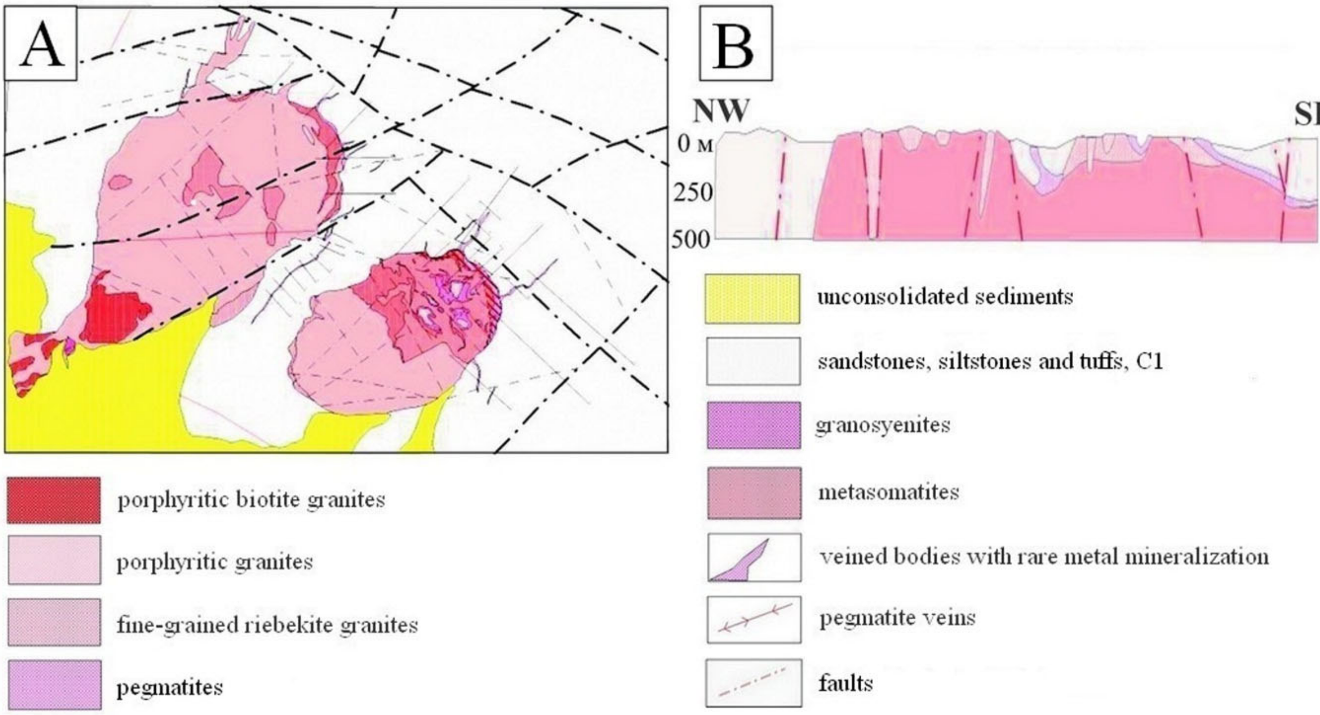


**Figure 12.** Geological map (**A**) and cross section (**B**) of the Verkhnee Espe deposit [67].

Abundant alkaline granites in the area were metasomatized at the postmagmatic stage, together with the country rocks. Metasomatic reactions provided Li, Rb, Y, Nb, Zr, and REE inputs into the rocks [68]. Mineral layers or veins are mainly localized along low-angle intrusion margins [69]. Main metallic minerals are zircon, pyrochlore, gagarinite, thorite, etc., as well as less abundant cassiterite, columbite, phenacite, gadolinite, etc. The contents of rare metals increase upward from the intrusion center.

Relatively high concentrations of Nb, U, and Ta are found in 0.1 mm pyrochlore grains (Figure 13). Nb and Ta most often occur in riebeckite, aegirine, astrophylite, thorite, zircon, and ilmenorutile [70,71], while REEs are found in gagarinite and less often in monacite, tengerite, bastnaesite, xenotyme, yttrofluorite, and cenosite. The contents of trace and rare-earth elements reach 1132 ppm Th, 580 ppm U, 791 ppm Ce, 571 ppm Nd, 403 ppm Sm, 639 ppm Gd, 490 ppm Dy, 506 ppm Er, 158 ppm Pr, 201 ppm Tb, 231 ppm La, 16.3 ppm Eu, 111 ppm Tm, 43 ppm Lu, and 11690 ppm Y.

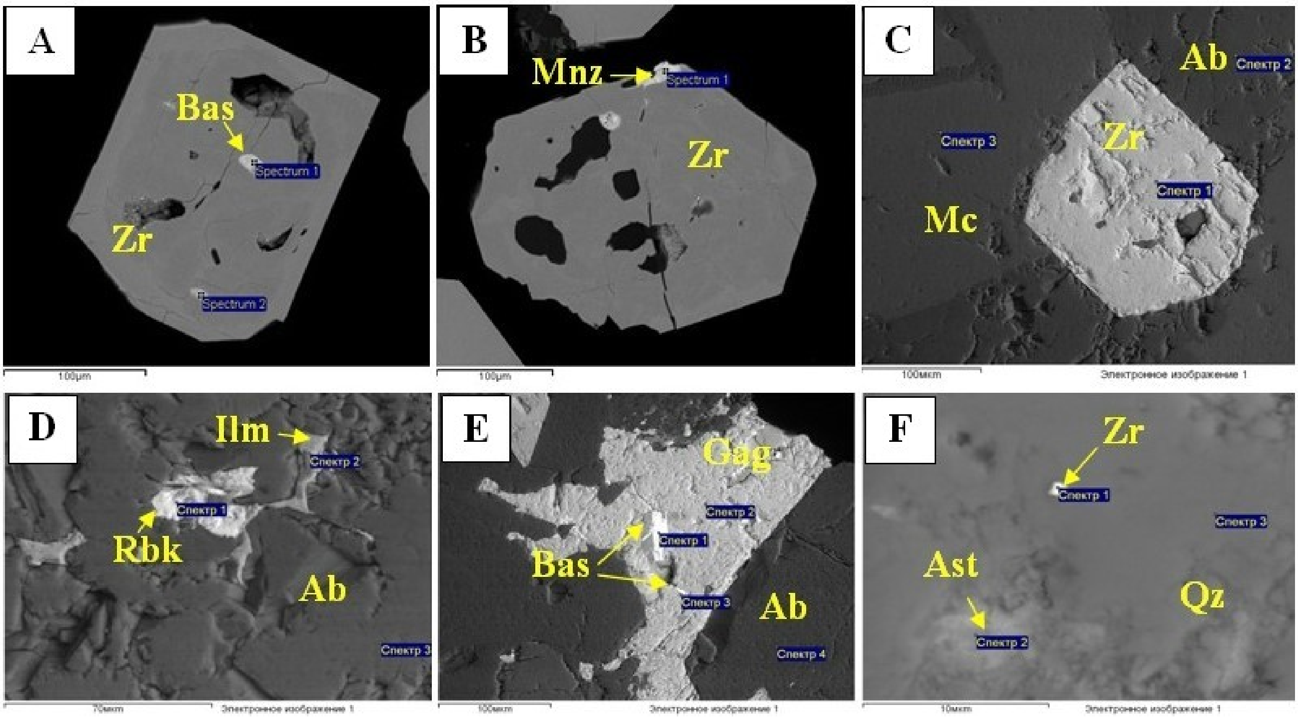


**Figure 13.** Microinclusions of REE minerals in the Espe granites, Verkhnee Espe rare-element deposit. Scanning electron microscope images (JSM 6390LV), analyst A. Sadibekov. (**A**) Bastnaesite microinclusions in zircon; (**B**) monazite inclusions in zircon; (**C**) zircon grain at contact with albite and microcline; (**D**) riebekite and ilmenite inclusions in albite; (**E**) gagarinite in albite and bastnaesite in gagarinite; (**F**) astrophyllite microinclusions in quartz, with gold in astrophyllite.

## 5. Discussion

Synthesis and analysis of the geological and mineralization data from the Great Altai region open new perspectives on the evolution of major metallogenic structures as a basis for exploration criteria, especially in poorly investigated and buried areas. The mineralization processes, with formation of base, rare, and precious metals and other types of mineral deposits, developed in different tectonic settings in the course of its long history (Table 2) [27,30,48–50,52,61,63,67,72–80].

**Table 2.** Geodynamic settings and mineralization types in different areas of Great Altai.

| Orogeny | Geodynamic Settings | Rudny Altai | Kalba-Narym | West Kalba | Zharma-Saur |
|---|---|---|---|---|---|
| Early Paleozoic | Oceanic (O-S) | Copper sulfide (Cu, Fe, S) Karchiga deposit [73] | | Cr, Ni, Co in ultramafics Char deposit [72] | |
| Late Paleozoic–Early Mesozoic | Subduction ($D_1$-$C_1$) | VMS Cu, Zn, Pb, Au, Ag Ridder–Sokolnoye, Artemiev deposit (this study) | | | |
| | Collisional ($C_1$-$C_2$) | No magmatic events | | | |
| | Late Collisional ($C_2$) | Au, Ag, Te in granodiorites and granites Sekisovka deposit [61,63] | Cu, Ni in peridotites and gabbro Alisher deposit [30] | Au, As, Ag in plagiogranites and granodiorites Bakyrchik deposit (this study) | Au in dacites and granodiorites Vasil'evka deposit [74] |
| | Postcollisional ($P_1$) Postcollisional ($P_2$-$T_1$) | | Ta, Nb, Be, Li, Cs in granites and pegmatites Bakennoe, Yubileinoye, Belaya Gora, Kvartsevoye deposits Li, Cs pegmatites Tochka, Akhmetka deposits [48–50,52,77] | Au, As in monzodiorites and granites Akzhal, Achaly deposits [76] Sn, Be in granites and leucogranites Delbegetey deposit [67] | Cu, Ni, PGE in gabbro and picrite Maksut [27,75] Ta, Nb, Zr in alkaline granites Verkhnee Espe deposit (this study) |

**Table 2.** *Cont.*

| Orogeny | Geodynamic Settings | Rudny Altai | Kalba-Narym | West Kalba | Zharma-Saur |
|---|---|---|---|---|---|
| Middle-Late Mesozoic | Intracontinental ($K_2$-$Pg_2$) | | | Ti, Zr in kaolinite weathering profiles Satpayev, Karaotkel deposits [78,79] Ni, Co in nontronite weathering profiles Belogorskoye deposit [72,80] | Au in kaolinite-sericite weathering profiles Zhanan deposit [74] |

During the Early Paleozoic orogenic cycle, the Great Altai territory was occupied by the Zaysan oceanic basin, a part of the Paleo-Asian ocean ([1,3–5], etc.), which shrank and closed as a result of accretionary-collisional events. The remnants of oceanic crust survived as fault blocks and lenses of Ordovician metamorphic ultramafic and mafic igneous rocks, as well as seafloor basalts, cherts, and hemipelagic sediments known as the Char ophiolite belt along the axis of the West Kalba zone [18,24,81]. The Char belt hosts preserved small deposits and occurrences of Cr, Ni, Co, and Cu related to ultramafic magmatism in a spreading setting [72]. Metamorphic rocks that represent oceanic fragments appear also in the Kurchum-Kaldzhir block of the southeastern Great Altai (Figure 1). Amphibolites and amphibolite schists host chalcopyrite and pyrrhotite mineralization (Karchiga and Kogoday VMS deposits) [73]. The Karchiga deposit is comparable to the Besshi VMS deposit [82] according to its geological setting and predominant copper mineralization.

The Late Paleozoic–Early Mesozoic orogenic cycle encompassed accretionary-collisional events associated with the Siberia-Kazakhstan convergence, closure of the Zaysan ocean, and formation of the Great Altai orogenic belt [1,22,23,25,26]. The geological and metallogenic structures of this period formed during successive subduction, collisional, and postcollisional events.

The subduction of the Zaysan oceanic plate beneath the active margin of Siberia in the Rudny Altai area lasted from the Early Devonian to the earliest Carboniferous. Voluminous Early-Middle Devonian volcanism led to the formation of a metallogenic belt with large shallow VMS Au, Ag, and Ba and Au-rich Cu-Zn deposits [34,35]. The mineralization was controlled by NW transcrustal faults. The Rudny Altai orebodies are of hydrothermal stratiform type, with high percentages of metallic minerals (pyrite, chalcopyrite, sphalerite, galena) and diverse compositions (Cu, Pb, Zn, Au, Ag, Cd, Se, Bi, etc.). These features make them similar to VMS-type deposits ([35,36,40], etc.).

The collisional stage of the geological and metallogenic evolution began with closure of the Zaysan ocean in the earliest Pennsylvanian and formation of the Great Altai orogenic system consisting of parallel terranes. The peak of collisional events occurred at the end of the Early Carboniferous—the beginning of the Middle Carboniferous. Intensive thrusts and folding occurred. There was no magmatism in this setting of maximum compression. The late collisional stage began in the Middle–Late Carboniferous. The collapse of the orogen began, and the regional faults arose, along which shear and extension movements occurring. The system of diagonal transcrustal faults controlled the emplacement gabbro, gabbro-diorites, granodiorites, and plagiogranites in the time interval between 315 and 305 Ma. Mineral deposits formed in all terranes [30,61,63,74], with especially rich gold mineralization hosted by granodiorite and plagiogranite small intrusions and dikes on the periphery of the Char-Gornostaevka uplift, in the regional-scale NW West Kalba gold belt.

The postcollisional stage was the time of voluminous Early Permian ultramafic-mafic and granitic magmatism [23] in a setting of general extension and strike-slip in the Great Altai territory. Ultramafic and mafic small intrusions in the Zharma-Saur belt host Cu-Ni mineralization, e.g., Maksut deposit [27,75,83]. The Akzhal and Ashaly gold deposits in the West Kalba belt occur within diorite and granodiorite small intrusions [76]. Large deposits of rare-metal (Li-Cs-Ta-Nb-Be) pegmatites in the Kalba-Narym zone formed during the emplacement of phase 1 granitic batholith [16,17,26,32]. The large-scale Early Permian magmatism that covered vast territories in the western Central Asian Orogenic Belt and extended northward into the Great Altai region was presumably maintained by the activity of a mantle plume [26,29,84–86], which formed the Tarim Large Igneous Province. Many ore deposits in the western part of the Central Asian orogenic belt were formed precisely in the Early Permian [87–89]. Their formation is explained by the activity of the Tarim LIP [77,85,89,90].

Another episode of magmatic activity in the region occurred in the earliest Triassic and was related to the activity of the Siberian superplume within the corresponding Siberian Large Igneous Province [89,91,92]. Magmatism associated with the Siberian LIP is well studied and described in many works ([92–95], etc.). Many Permian-Triassic igneous rocks are considered in association with Siberian LIP [91,96–98]. In the south the distribution area of Siberian LIP is drawn along the southern border of the West Siberian basin [92]. In recent years more and more evidence of Permian-Triassic within-plate magmatism has appeared for the southern part of the area of the Siberian LIP. In addition to the well-known trap basalts in the Kuznetsk basin [99,100], the dyke swarms of lamprophyres and subalkaline diorites, and the intrusive massifs of subalkaline monzonites and syenites are described in the Altai region [97,101,102]. Permian-Triassic intrusions of granites and leucogranites, which are accompanied by dolerite and lamprophyre dykes, are also widely distributed within the Altai and adjacent regions [91,103,104]. The southernmost manifestation of the Siberian LIP has been described on the territory of Eastern Kazakhstan. This is the Semeitau volcanic structure, for which the Early Triassic age was determined by paleontological methods, and then confirmed by $^{40}Ar/^{39}Ar$ dating [105]. Recently we obtained new data about the Early Triassic age of the rocks of the nearby Delbegetei massif.

Some previous works (in particular [106]) asserted the manifestation of Triassic and Jurassic magmatism in the territory of Eastern Kazakhstan. In recent years, many objects mentioned in that work were re-dated using modern methods (U-Pb SHRIMP-II and LA_ICP-MS on magmatic zircon grains). The results of these studies are presented in some recent works, including with participation of the authors of this article [16,17,23,26,29,32]. It was proved that all the objects of East Kazakhstan, considered in [106] as Early and Middle Triassic, are in fact of Early Permian age.

During the Middle-Late Mesozoic (Cimmerian) orogenic cycle, the Great Altai geological structures developed in a continental setting [22] and were exposed to denudation and redeposition of eroded bedrock material. Two large limnic basins appeared on the flanks of the Great Altai: Lake Zaysan in the southeast and Lake Kulunda in the north. Mineralization developed in weathering profiles upon Paleozoic bedrocks that formed in a wet and warm subtropic climate. They are a nontronite profile of weathered seprenitnized serpentinites, which hosts Belogorsk gold deposits in the West Kalba belt [72,106]; kaolinite-sericite weathering profiles in the West Kalba and Zharma-Saur areas, with Zhanan and Mukur gold deposits, respectively [22]; a kaolin profile and sand placers with Satpaev and Karaotkel Zr-Ti deposits in the West Kalba area [78,79].

Neotectonic faulting and general uplift of the Altai mountains during the Cenozoic (Alpine) orogenic cycle shaped the present surface topography in the region. Unconsolidated Cenozoic sediments host gold, ilmenite, cassiterite, tantalite, and other placer deposits of heavy metals. Most placers have been depleted, but some prospects can be expected from additional exploration for fine gold near river mouths, as well as from old buried placers in intermontane basins and valleys.

The reconstructed geodynamic and metallogenic history of the Great Altai province, along with the revealed relationships between tectonic settings and mineralization patterns, allowed us to formulate a number of geodynamic, structural, lithostratigraphic, magmatic, mineralogical, and geochemical criteria for exploration and appraisal of mineral potential in Eastern Kazakhstan.

Geodynamic criteria. Mineral deposits of different types in the Great Altai region originated in different settings during Early Paleozoic, Late Paleozoic–Early Mesozoic, and Middle-Late Mesozoic orogenic cycles. The most important economic types of base-metal mineralization formed on an active continental margin in the Rudny Altai area. Most of gold mineralization is associated with Late Carboniferous–Early Permian accretionary-collisional processes and plume-related magmatism in the Tarim Large Igneous Province. The same Tarim plume was responsible for large-scale crust melting and emplacement of granitic batholiths in the Early Permian, which led to the formation of economic rare-metal deposits.

Structural criteria. Mineral deposits are mainly controlled by fault systems of different sizes, especially NW and diagonal transcrustal faults in all zones of the region: base-metal deposits in Rudny Altai, gold deposits in the West Kalba belt, and ore-bearing granites of the Kalba and Zharma-Saur batholith belts. The postcollisional strike-slip since the Early Permian produced WE and NE tectonic zones which host gold mineralization in the West Kalba belt and rare metals in the Kalba-Narym zone.

Lithostratigraphic criteria. Orebodies are often associated with certain types of sedimentary or volcanic-sedimentary rocks. The Rudny Altai base-metal deposits occur among Devonian volcanics, while the West Kalba gold placers are found among coal-bearing molasse and greywacke.

Magmatic criteria. Different mineralization types are related to certain types of igneous bodies. Gold deposits are found near Late Carboniferous syncollisional small intrusions and granodiorite-plagiogranite dikes, almost in all gold fields. Cu-Ni mineralization occurs within Pennsylvanian peridotite-gabbro intrusions or within Early Permian picrite-gabbro small intrusions. Rare-metal pegmatite mineralization is associated with the Kalba granitoids: pegmatite veins follow intrusion margins and outpinching offshoots of phase I intrusions.

Mineralogical and geochemical criteria. Analyses of mineralogy and element contents in ores and their hosts revealed typical minerals and elements that can serve as tracers of mineralization. Namely, minerals such as magnetite, goethite, arsenopyrite, antimonite, gold and silver phases, as well as some elements in rocks (Fe, Mn, Cu, Pb, Zn, As, and Sb) are common to zones of gold-bearing sulfide mineralization. The samples we analyzed contain rare micrometer lead (alamosite, kentrolite, melanotekite, cotunnite) and nickel (bunsenite, trevorite, gersdorffite) phases and accessory cassiterite, wolframite, scheelite, and microlite. The ores bear native gold (with Ag and Pt impurities) amenable to concentration by gravity and flotation methods. Multistage rare-metal pegmatite mineralization can be predicted from the presence of mineral assemblages including cleavelandite, muscovite, lepidolite, spodumene, pollucite, tantalite, microlite, etc., and elements such as Ta, Nb, Be, Li, Cs, and Sn. Pegmatite veins bear diverse Ta minerals (columbite, tantalite-columbite, manganotantalite, ixiolite, and microlite) that accumulated rare metals late during the evolution of the pegmatite magmatic system.

## 6. Conclusions

1. Studies in the recent decades have provided updates to the VMS base metal, gold, and rare-metal mineralization patterns in the Great Altai region, which created the basis for geodynamic, structural, lithostratigraphic, magmatic, mineralogical, and geochemical criteria for exploration and appraisal of mineral resources.

2. Geodynamic criteria are based on the origin of different mineralization types in certain geodynamic settings during the Late Paleozoic–Early Mesozoic orogenic cycle.

3. Structural criteria mean that the location of base-metal deposits in Rudny Altai, gold deposits in the West Kalba belt, rare and base metals in the Kalba-Narym and Zharma-Saur zones is controlled by faults of different sizes.

4. Lithostratigraphic criteria consist of the relation of orebodies with certain types of sedimentary or volcanic-sedimentary rocks.

5. Magmatic criteria are due to the relation between mineralization types and igneous lithologies.

6. Mineralogical and geochemical criteria include typical minerals and elements that can serve as tracers of mineralization.

7. The joint use of all these criteria will open new avenues in prospecting and exploration at a more advanced level.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

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