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METALLOGENY OF THE POLYACCRETIONARY ALTAI-SAYAN OROGENIC AREA

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A general metallogenic analysis and metallogenic zoning of the Altai-Sayan orogenic area (ASOA) were carried out in terms of the modern plate tectonics and mantle geodynamics concepts. The Altai-Sayan folded area is an example of a polyaccretionary orogenic system that resulted from the long evolution of the Paleoasian ocean. The main metallogenic belts have been recognized, in which typical ore associations (model types of mineral deposits) and their ages and geodynamic settings of formation have been established. A total of 48 metallogenic belts including 450 mineral deposits of 70 model types were studied. These belts are related to four time spans (metallogeny epochs) corresponding to the cycles of geodynamic processes that led to the formation of the polyaccretionary orogenic area: Riphean-Vendian (1200–620 Ma); Vendian-Silurian (620–410 Ma); Devonian-Early Carboniferous (410–320 Ma); and Late Permian-Triassic (260–205 Ma). Study was also given to typical geodynamic settings in which ore-forming productive systems originated. It is shown that the metallogenic evolution of the ASOA was determined mainly by the multistage formation of active continental margins and island-arc systems in the Riphean-Vendian and Early (V-S) and Middle (D-C_1) Paleozoic.

At the postorogenic stage, the ASOA evolution was the most productive in the Triassic. The geodynamic and metallogenic events in this period were determined by the tectonothermal activity on the periphery of the Permo-Triassic Siberian superplume in the interblock zones of the orogenic collage, which led to serious shifts along the plate and block boundaries, the formation of near-fault troughs and grabens, appearance of rift structures, and development of anorogenic granitoid magmatism (manifested as alkali and subalkalic rare-metal granites) and alkali-basaltoid magmatism.

Transpression settings (oblique subduction) and plume magmatism are shown to have played a key role in the formation of mantle and mantle-crustal ore-forming systems. For the Middle Paleozoic and Mesozoic stages, new geochronological evidence has been obtained, and spatial and temporal correlations for the formation of the main types of mercury, gold, and rare-metal deposits have been made.

Metallogeny, terrane analysis, ore deposits, geodynamic settings

INTRODUCTION

Application of plate tectonics and mantle geodynamics concepts to the solution of the main problems of genesis and evolution of ore-forming systems and the elucidation of the factors determining their high ore potential has been of paramount importance in the theory of ore formation and metallogeny in recent time. A topical problem of research in this field is development of principles of metallogenic analysis of polyaccretionary (or polycyclic) orogenic belts with a repeated change in the geodynamic regimes of their formation. The Altai-Sayan area is a typical example of a polyaccretionary orogenic system that resulted from the long evolution of the Paleoasian ocean and subsequent within-plate processes. At the same time, this area, including the Yenisei Range, is one of the most important ore provinces in southern Siberia, with more than 450 ore deposits, including about 60 large and 20 unique accumulations.

Metallogenic analysis of areas of long multistage evolution with a repeated change in the geodynamic regimes of formation of the Earth's crust structures is based on the principles of geohistorical metallogeny. The latter include stage-by-stage study of the geodynamic settings, formation conditions, and regularities of localization of different types of mineral deposits (ore associations), ore complexes, and metallogenic associations and elucidation of the main factors responsible for the formation of highly productive ore-forming systems, metallogenic belts, and large and unique deposits.

Taking into account the great role of paleogeodynamic and paleometallogenic reconstructions based on plate tectonics and mantle geodynamics concepts in such investigations, it seems reasonable to call this line of metallogeny "geodynamical metallogeny".

Geodynamical metallogeny involves the following technical steps:

— Paleogeodynamic terrane analysis of the study area. Compilation of maps with recognition of geodynamic complexes of different types and different ages and the main Earth's crust structural elements.

— Preparation of a special deposit database. Ore-formational analysis of deposits and mineral occurrences. Construction and identification of geologo-genetic models for ore-forming systems of the main types of deposits. Collection and refinement of geochronological data on the time of deposit formation.

— Recognition of metallogenic belts related to the main time spans of geodynamic evolution (metallogeny epochs). Elucidation of the main ore-forming factors and tectonic elements controlling the metallogenic belts.

— Paleogeodynamic and paleometallogenic reconstructions of metallogenic belts for estimated time spans. Description of the geodynamic settings of formation of the main types of ore deposits, highly productive ore-forming systems, and metallogenic belts.

— Solution of prediction-metallogenic and revision problems and estimation of the possibility of discovering new ore districts and new productive types of deposits.

In the world's practice, geodynamical metallogeny began to actively develop in the middle 1980s, after a series of foreign scientific works had been published (e.g., New global tectonics, 1974) and the problem had been set up at the 24th International Geological Congress in Montreal, Canada, in 1972 and at the 4th International IAGOD Symposium in Varna, Bulgaria, in 1974. The works by Guild [1972, 1977], Zonenshain, Kuz'min, and Moralev [1976], Mitchell and Garson [1981], and Kovalev [1978] were the most prominent. By the middle 1990s, it had become evident that plate tectonics is a prevailing theory in geotectonics. An extensive literature on this problem evolved, which made a grand breakthrough in geologists' views of the regional tectonic history and formation conditions and regularities of localization of mineral deposits. But it took years for geologists to adapt for the new paradigm, check the new ideas in practice, and analyze and generalize the voluminous factual data of geological observations in particular ore provinces. Considering metallogeny in the context of new global tectonics opened wide avenues for correlation of geologic processes with the lateral geodynamics of lithosphere plates, new interpretations of the factors responsible for the formation of ore-forming systems and reconstruction of their geodynamic settings, and understanding of the nature of mantle and crustal sources of ore matter.

For the Eurasian continent, of paramount importance were the theoretical workings on the International Project "Geodynamic evolution of the Paleoasian ocean" (IGCP 238) performed by a working group supervised by R. Coleman, N.L. Dobretsov, and Xiao Xuchang [Scientific results..., 1994]. In addition, "Geodynamic map of the USSR and adjacent areas" (scale 1 : 2,500,000) appeared (1988), and results of a comprehensive research into plate tectonics of the USSR were published both in Russian and in English [Zonenshain et al., 1990]. The generalizing publications [Dobretsov and Kirdyashkin, 1998; Dobretsov et al., 2001] also played an important role in the solution of many theoretical problems of mantle geodynamics and their application to the problems of ore formation and metallogeny.

For a fundamental generalization of data on geodynamics and metallogeny of northeastern Asia and adjacent areas of the Pacific ring, two international projects ("Major mineral deposits, metallogenesis, and tectonics of the Russian Far East, Alaska, and the Canadian Cordillera" and "Mineral resources, metallogeny, and tectonics of northeast Asia") were pioneered by the Russian Academy of Sciences and the U.S. Geological Survey in 1988 and 1996. These projects were executed by geologists from Russia, the USA, Canada, Japan, South Korea, China, and Mongolia under the supervision of W. Nokleberg, L.M. Parfenov, A.I. Khanchuk, and M.I. Kuz'min. Almost all geological institutes of the Siberian and Far East Branches of the RAS were involved in the projects. The investigations were carried out on a vast area from West Siberia and eastern Kazakhstan to Pacific islands. For the entire study area, a new geodynamic terrane map (scale 1 : 5,000,000), mineral deposit maps, and metallogenic-belt maps based on age sections were compiled. A databank of these deposits was prepared, the metallogenic belts and model types of deposits were described, and paleogeodynamical and paleometallogenic reconstructions were made based on the main age sections. In the process, a research technique was developed, which was based on the new principles of geodynamic metallogeny. This was the first research of that kind in such a vast area in the world's practice. It covered regions with strongly different geodynamic histories of the Earth's crust formation: intricate terrane collages of northeastern Russia; orogenic areas of modern and ancient active continental margins of transform type; polyaccretionary orogens of the Central Asian Fold Belt; ore-bearing structures of cratons, pericratonal depressions, and ancient cratonal blocks; areas of within-plate tectonomagmatic activity, including plume magmatism, etc. The ore-formational analysis and modeling of ore-forming systems that have been intensely carried out in Russia, Canada, the USA, and other countries in recent decades served as a basis for a new metallogenic systematization of deposits, which reflects their composition, genesis, relationship with geologic processes, and type of ore-forming systems. Results of these studies were discussed at many international meetings and were presented as both printed and electronic publications by the Publishing House of the U.S. Geological Survey. In 2001, the monograph "Tectonics, geodynamics, and metallogeny of the Sakha Republic (Yakutia) area" edited by L.M. Parfenov and M.I. Kuz'min was published, which presented most of the results of investigations carried out throughout northeastern Russia. In 2005, a summarizing book on the first project was issued [Nokleberg et al., 2005]. By now, a summarizing book on the second project has been prepared. Most of it concerns with geodynamics and metallogeny of the western North Asian craton, folded structures of its framing, and theoretical questions; these studies were performed by scientists from the Institute of Geology and Mineralogy, Novosibirsk. Today, such investigations are considered extremely urgent in the world's geological practice. A similar project is now in progress under the supervision of Prof. D. Blandel, London University, in Europe ("Geodynamics and ore deposits of Europe" (GEODE)). Also, the work on the International Project "Global assessments of undiscovered nonfuel mineral resources" (GMRAP) supervised by K. Schulz, U.S. Geological Survey, began.

One of the topical and complicated (in terms of plate tectonics) problems of development of the metallogeny theory is metallogenic analysis of polyaccretionary orogenic belts related to the long polycyclic (Bertrand cycles) evolution of paleo-oceans [Khain, 1992]. The Altai-Sayan orogenic area, a southwestern folded framing of the North Asian craton, is a typical example of a polyaccretionary orogenic system. Metallogeny of the Altai-Sayan province as a polycyclic folded area was first generalized by V.A. Kuznetsov [1967] in the prevailed context of the fixist concept of geosyncline tectonics. The generalization was based on ore-formational analysis and methods of geohistorical metallogeny including a subsequent, stage-by-stage, study of tectonic, magmatic, and related ore-forming processes. Kuznetsov's works are of significant importance even today, when the geological paradigm has changed and application of plate tectonics and mantle geodynamics concepts to the solution of the main problems of the origin of ore-forming systems and the regularities of ore deposit localization has become one of the main lines in the ore formation and metallogeny theory.

METALLOGENY OF THE ASOA CONTINENTAL MARGINS OF DIFFERENT AGES

The Altai-Sayan orogenic area (ASOA) and corresponding metallogenic province are part of the global Central Asian orogenic belt, which resulted from the long evolution of the Paleoasian ocean and its continental margins and subsequent within-plate processes [Dobretsov, 2003; Distanov and Obolensky, 1994; Obolensky et al., 1999]. The ore formation processes in the ASOA showed a successive evolution. The early stage of metallogeny evolution (in the Early Riphean) was related to the origin of the Paleoasian ocean and destructive processes on the periphery of the Siberian craton. Later on (in the Early and Middle Paleozoic), the accretion of island arcs of different ages and formation of active continental margins took place. The margins of different ages and metallogeny reflect the successive Bertrand cycles of the Paleoasian ocean evolution. These time spans fit the generally accepted term "metallogeny epoch". Each cycle is divided into three stages: preaccretionary (subduction), accretion-collision, and postaccretionary. The postorogenic stages of metallogeny evolution were related to within-plate processes caused by the activity of the Permo-Triassic Siberian superplume, interblock shifts, and within-plate rifting accompanied by the formation of mantle and mantle-crustal ore-forming systems [Dobretsov and Vernikovsky, 2001; Borisenko et al., 2005].

Neoproterozoic (Riphean-Vendian, 1200–620 Ma) continental margin of the North Asian craton. The Neoproterozoic (R–V) continental margin of the southwestern North Asian craton formed at the early stage of the Pangea breakup and origin of the Paleoasian ocean [Khain and Bozhko, 1988; Dobretsov et al., 1995a]. The Riphean margin formation proceeded in two stages. At the early stage (R_{1-2}), in the regime of extension and divergence of continental blocks, a passive continental margin with elements of continent-marginal rifting originated. At the late stage (R_3–V), in the regime of convergence, subduction processes, and accretion, an active continental margin formed. In northern Transbaikalia and East Sayan [Dobretsov et al., 1985] as well as in the Yenisei Range and other regions [Khain et al., 1993], a Riphean ophiolite belt was revealed along the periphery of the Siberian craton (from Taimyr through Yenisei Range and East Sayan to Baikal uplift), which testifies to the existence of an active subductional continental margin in the late Riphean (convergence stage). This is evidenced from both the obducted ophiolite nappes and relics of primitive island-arc systems in the Yenisei Range (Isakovka and Predivinsk zones) and in the Baikal-Vitim zone.

Thus, the Riphean craton margin is characterized by the following specific features:

— formation of a belt of large pericratonal depressions, i.e., marginal sedimentary basins with elements of synchronous rifting and high endogenic activity (Yenisei, near-Sayan, Baikal-Patom, etc.);

— formation of a Riphean ophiolite belt along the craton periphery, weak development of island-arc systems, and transition of pericratonal depressions into back-arc basins at the subduction-accretion stage;

— at least two-stage formation of collisional granitoids: (1) during the early collision of island arcs with craton blocks (microcontinents) (R_3) and (2) at the main collision-orogeny stage (V) [Vernikovsky et al., 2003; Vernikovsky and Vernikovskaya, 2006];

— formation of a series of deep faults (mainly shifts) at the craton–orogen boundary (Priyeniseisky, Main East Sayan, etc.), which appreciably determined the nature of continent-marginal accretionary prisms, mantle-crustal magmatism, and metamorphism;

— formation of shelf complexes of essentially carbonate rocks overlying ancient cratonal terranes at the postaccretionary stage (V), in which some types of sedimentary deposits are localized.

One of the global early events in the geodynamic and metallogenic evolution of the study area was the formation of the transregional South Siberian pericratonal metallogenic belt [Distanov and Obolensky, 1994; Ponomarev et al., 1996]. A system of marginal structures of the Siberian Platform, including a belt of pericratonal depressions, aulacogens, rifts, and marginal and transform faults forming the block structure of the basement, was recognized and described as a typical element of the ancient platform by Pavlovsky [1959] and Kosygin and Luchitsky [1964] and has been comprehensively studied up to now. Special study was given to the petroleum potential of these structures [Surkov et al., 1996; Basharin et al., 1996]. The formation of marginal craton structures at the early stage of opening of the Paleoasian ocean in the Middle Riphean gave rise to a series of highly productive metallogenic belts and ore districts. The formation of continental margin was related to the wide occurrence of mantle plume processes and rift crushing of Pangea in the Riphean [Surkov et al., 1991]. At the divergence stage of this period, a series of actively subsided pericratonal depressions with high endogenic and submarine hydrothermal activities formed along the craton periphery. This was not a typical passive continental margin as was earlier treated in many tectonic reconstructions. Such marginal subsidences with thick beds of terrigenous-carbonate turbidites and local manifestations of rift and interblock volcanism should be obviously referred to as highly productive metallogenic basins with high endogenic activity and the so-called synchronous rifting [Shcheglov, 1997] and be considered a specific class of seas formed in the regime of active rifting. All this led to the formation of large stratiform deposits of Pb, Zn, Fe, and Mn and enrichment of black-shale strata with Au and other elements. Subsequent accretion processes resulted in a regional ore-bearing ophiolite belt [Khain et al., 1993] and a series of commercial metamorphogene-hydrothermal deposits of Au, Sb, etc.

The largest and highly productive metallogenic pericratonal depressions in the southern Siberian Platform — Yenisei and Baikal-Patom — are of specific structure. They formed at triple rift junctions. Opposite to these depressions, there are blocks of large microcontinents — Upper-Keta–Khakassian (in the Yenisei part of the West Siberian Plate) and Barguzin-Vitim (in the North Baikal region) — that were separated from the platform and then again accreted to it in the Late Riphean-Vendian. Island-arc systems are scarce (Isakovka allochthone, Predivinsk zone, and relict blocks in the East Sayan accretionary collage).

Two subsequent stages of evolution of the Riphean sedimentary basin of the Yenisei Range were established: Early-Middle Riphean Sukhoi Pit (1450–1100±50 Ma), corresponding to the divergence (rift) stage of the margin evolution, and Middle-Late Riphean Tungusik (1100–850±50 Ma), corresponding to the convergence (island-arc) stage [Neklyudov, 1995]. Mantle volcanism at the first stage produced primary Au, Sb, and W ores [Berger and Neklyudov, 1991]. The Tungusik basin evolved on the Sukhoi Pit basin and combined elements of trough zones and island arcs with manifestation of differentiated mantle-crustal volcanism. This is a basin where most of pyrite, pyrite-polymetallic, and Pb-Zn deposits of the Yenisei Range as well as Fe-Mn deposits are localized. Gold and W-Au-Sb deposits (Verkhny Enashimo, Uderei, and Razdol'ny ore clusters) form a well-defined N-S-striking ore belt east of the Central uplift (anticlinorium), along its junction with the Angara-Pit synclinorium. Recent models imply that most of large Au and Au-Sb deposits of the Yenisei Range are of multistage polygenic sedimentary-metamorphogene-hydrothermal genesis [Li and Shokhina, 1978; Genkin et al., 1994; Neklyudov, 1995].

All known Pb and Zn deposits are localized in the polymetallic belt of the Yenisei Range in the trough zone of the Tungusik basin, west of the Central uplift (Bol'shoi Pit synclinorium). This zone has preserved the Sukhoi Pit extension and downwarping regime and is characterized by stagnant sedimentation and local volcanic activity of metaliparite-andesite-basalt association [Ponomarev and Zabirov, 1988]. Most of polymetallic deposits are confined to the southern, most subsided part of the synclinorium (Angara ore district), where mainly hydrothermal-sedimentary pyrite-pyrrhotite-sphalerite-galena ores occur concordantly with the host terrigenous-carbonate rocks (Gorevskoe and other deposits) as well as veinlet-disseminated galena-sphalerite ores in chemogenic and algal limestones and dolomites (Moryanikhinskoe, Merkurikhinskoe, Krutoe, etc.). Formation of ore-forming systems of the unique Gorevskoe Pb-Zn deposit [Kuznetsov et al., 1990] seems to have been related to the conjugation of interblock deep faults of NW strike with the cross structure of the interplate Irkineeva fault, which gave rise to the Irkineeva-Vanavara aulacogen.

In general, the marginal platform structures are characterized by a belt metallogenic zoning and temporal trend of metallogenic processes depending on the change of geodynamic settings [Geology and metallogeny..., 1985]. Lateral zoning is the most distinct in the Yenisei Range (from west to east): near-Yenisei zone — Fe, Cr, Mn, Cu, and Zn mineralization; Vorogovka-Angara zone — Pb and Zn; Central — Au, Sb, and W; Angara-Pit — Fe. At the collision stage of formation of the Yenisei Range structures, the Late Riphean granites and alkali metasomatites hosted W, Mo, Be, Nb, and REE ores of the Tatarsk-Tyrada metallogenic belt.

Along the southwestern periphery of the North Asian craton, endogenic processes were considerably affected by the formation of deep faults (mainly shifts) (Priyeniseisky, Main East Sayan, etc.), along which Ti-Fe deposits are localized in Late Riphean gabbroids of the Lysansk and Near-Sayan metallogenic belts as well as the Beloziminskoe Ta-Nb-REE-carbonatite deposit.

The Neoproterozoic (Riphean-Vendian) stage of evolution of the Paleoasian ocean and marginal structures of the North Asian craton in the ASOA was characterized by the following geodynamic settings of formation of highly productive metallogenic belts (Table 1):

1 — continent-marginal pericratonal subsidences, rifts, and aulacogens with a high endogenic activity;

2 — accretionary prisms with fragments of complexes of oceanic crust, island arcs, back-arc basins, and epicratonal rift troughs;

3 — cratonal metamorphic terranes (including intrablock graben subterranes);

4 — continent-marginal shear zones with accretionary wedges (transform craton margins);

5 — continent-marginal belts of collisional granitoids;

6 — overlying carbonate complexes of continental slopes on the craton and microcontinent margins;

7 — residual marginal terrigenous basins.

Early Paleozoic (Vendian-Silurian, 620–410 Ma) active continental margin of the Siberian paleocontinent. The Early Paleozoic stage of evolution of the Central Asian mobile belt played the greatest role in the formation of the Earth's crust in the Altai-Sayan orogenic area. In the Late Vendian-Early Cambrian, after the completion of the Baikalian orogeny, a new stage of tectonic evolution of the Paleoasian ocean, equivalent to the Bertrand cycle, began [Khain, 1992; Khain and Seslavinsky, 1991]. It was expressed as a new pulse of the ocean opening, formation of Early Paleozoic active continental margin, and subsequent accretion-collision processes. The geodynamic evolution of the southwestern Siberian paleocontinent (in the modern frame of reference) in this period was characterized by the following events:

— wide development of island-arc systems, subduction-accretion zones, and continent-marginal magmatic arcs, whose position was much determined by the boundaries of ancient blocks and microcontinents;

— formation of regional transpression shear structures at the collision stage, which controlled the areas of mantle-crustal magmatism of ore-bearing gabbro-granitoid series breaking through volcanosedimentary and turbidite deposits;

— appearance of postcollisional (anorogenic) granite-leucogranite and subalkalic rare-metal granite intrusions along the shear boundaries of ancient blocks.

The settings in which highly productive ore-forming systems and metallogenic belts formed at that time were controlled by the wide development of volcanic island arcs, subduction-accretion zones, and continent-marginal magmatic belts. Island-arc complexes, including magmatic arcs and deposits of fore-arc and back-arc basins, occupy large areas in the modern ASOA structure. Vendian-Cambrian island-arc complexes formed within the Kuznetsk-Tuva island-arc system, which had originated after the accretion of Precambrian microcontinents to the Siberian craton [Berzin and Kungurtsev, 1996]. The system fragments in the modern ASOA structure are observed in northwestern Mongolia, Gorny Altai, Salair, Kuznetsk Alatau, Tuva, and West Sayan. Because of the subsequent horizontal movements, island-arc fragments lost their primary lateral connections with neighboring structures, which hampers the identification of their structure and evolution. The island-arc complexes are of two ages: Vendian-Early

Table 1

Geodynamic Settings of Formation of the ASOA Metallogenic Belts and Marginal Structures of the Western Periphery of the North Asian Craton in the Neoproterozoic (Riphean-Vendian, 1200–620 Ma)

Ore associations	Deposits
Continent-marginal pericratonal subsidences, rifts, and aulacogens	
Metallogenic belts: Central Yenisei (CY), Vorogovka-Angara (VA), and Angara-Pit (AP)	
Au, in black shales	**Olimpiadinskoe**, Enashiminskoe
Au-quartz metamorphogene-hydrothermal	**Sovetskoe**, El'dorado
Au-Sb metamorphogene-hydrothermal	Udereiskoe, Razdol'ninskoe
Pb-Zn hydrothermal-sedimentary (SEDEX type)	**Gorevskoe**
Pb-Zn stratiform, carbonate-hosted	Moryanikhinskoe
Fe hematite sedimentary	**Ishimbinskoe**, **Udorongovskoe**, **Nizhneangarskoe**
Fe skarn	**Enashiminskoe 2**, **Polkan Gora**
Accretionary prisms with fragments of complexes of oceanic crust, island arcs, back-arc basins, and epicratonal rift troughs	
Metallogenic belts: Isakovka (IS) and Bokson-Kitoi (BK)	
Zn-Pb-Cu pyrite-polymetallic volcanogenic hydrothermal (VHMS)	Khariuzikhinskoe
Mn volcanosedimentary (and weathering crust)	**Porozhinskoe**, Mokhovoe
Fe, in ferruginous quartzites (BIF)	Isakovskoe
Au, in black shales	**Zun-Kholba**
Au-sulfide-quartz vein	Ondol'toi
Porphyry Au	Tainskoe
Nepheline magmatic	Botogol'skoe
Bauxite sedimentary	Boksonskoe
Chrysotile-asbestos, in serpentinites	Il'chirskoe
Metamorphic craton terranes (including graben subterranes)	
Metallogenic belts: Kan (KN) and Near-Sayan (NS)	
Au-sulfide-quartz vein	Kuzeevskoe, Bogunaevskoe
Li-Sn-Be pegmatite	Barginskoe
Mo-W-Be greisen	Kanskoe
REE(±Ta, Nb, Fe) carbonatite	**Beloziminskoe**
Ti-Fe magmatic, in gabbroids	Zhidoiskoe
Diamond-bearing kimberlites	Onotskoe
Talc-magnesite metasomatic	Ingashinskoe
Continent-marginal shear zones with accretionary wedges (transform craton margins)	
Metallogenic belts: Lysansk (LS)	
Ti-Fe magmatic, in gabbroids	**Lysanskoe**, Kedranskoe
Continent-marginal belts of collisional granitoids	
Metallogenic belts: Tatarsk-Tyrada (TT)	
Li-Sn-Be pegmatite	Enashiminskoe 1
Mo-W-Be greisen	Olen'ya Gora
W-Mo skarn	Il'inskoe
Ta-Nb-REE, in alkali metasomatites	**Tatarskoe**
Overlying carbonate complexes of continental slopes on craton and microcontinent margins	
Metallogenic belts: Mras (MR) and Bellyk (BE)	
Phosphorite sedimentary	Belkinskoe, Tamalykskoe, Seibinskoe
Phosphorite, in weathering crusts	Telekskoe
Barite sedimentary	**Martyukhinskoe, Sorminskoe, Tolcheinskoe**
Residual marginal terrigenous-carbonate basins	
Metallogenic belts: Igarka (IG) and Bedoba (BD)	
Cupriferous sandstones	**Graviiskoe**, Sukharinskoe, Kurishskoe, Bedobinskoe

Note. Bold-typed are large and unique deposits.

Cambrian and Early-Late Cambrian. They bear volcanogenic pyrite-polymetallic deposits (Ulugo ore belt, Kyzyl-Tashtyg deposit [Kuzebny et al., 2001]), volcanosedimentary and skarn Fe-ore deposits (West Sayan, Gornaya Shoria, Kuznetsk Alatau), and volcanosedimentary Mn deposits (Durnovskoe, Salair Ridge; Usinskoe and Mazul'skoe, Kuznetsk Alatau). The Khemchik-Kurtushiba ophiolite belt in Tuva bears large chrysotile-asbestos deposits (Aktovrak, Sayanskoe).

At the collision stage, regional dextral strike-slip faults formed, which controlled the areas of mantle-crustal magmatism of ore-bearing gabbro-granitoid series breaking through volcanosedimentary and turbidite deposits [Berzin, 2003]. The fault structures bear large gold-sulfide-quartz and gold-skarn deposits of Kuznetsk Alatau and eastern Tuva. Gold-skarn (Natal'evskoe, Lebedskoe, etc.) and gold-sulfide-quartz (Tsentral'noe, Berikul', Komsomol'skoe, Kommunar, and Saralinskoe) deposits are confined to granitoids of the Martaiga and Lebed' complexes (€–O); Fe-skarn deposits of the Tel'bes ore district, to granitoids of the Tel'bes complex (O_2–S_1); and Cu-Mo-skarn, scheelite-skarn, and magnetite-skarn deposits, to the Ulen'tuim alkali-granitoid complex (O_2–S_1) [Kuznetsov et al., 1971; Alabin and Kalinin, 1999].

At that time, Ti-Fe deposits formed in gabbroids in strike-slip zones on the transform craton margin in East Sayan (Iya belt). Along the western boundary of the Sangilen block of the Tuva-Mongolian microcontinent, the Tastyg metallogenic belt with a large deposit of REE-Li pegmatites originated. Its formation is related to intrusions of Silurian anorogenic granite-leucogranite pegmatite complex on the transform microcontinent margin. The coexistence of mantle and mantle-crustal ore-forming systems is a typical feature of transpression (collision-strike-slip) geodynamic settings.

In the Early Paleozoic (V–S) period of formation of the Earth's crust structures on the western margin of the Siberian paleocontinent, the most favorable geodynamic settings for the origin of highly productive ore-forming systems were (Fig. 1, Table 2):

— island arcs and back-arc basins;

— accretionary wedges with fragments of oceanic crust, island arcs, and back-arc basins;

— continent-marginal strike-slip zones with accretionary wedges (transform craton margins);

— collisional gabbro-granitoid plutonic belts superposed on volcanosedimentary and turbidite strata of the continental margin;

— postcollisional (anorogenic) granite-leucogranites and subalkalic granites.

Metallogeny of the Middle Paleozoic active continental margin of the Siberian paleocontinent (D–C_1, 410–320 Ma). The Hercynian metallogeny epoch was one of the most significant periods in the evolution of ore formation processes in the ASOA. In the Middle Paleozoic (D–C_1, 410–320 Ma), the active southwestern margin of the Siberian paleocontinent formed. Endogenic magma and ore formation processes covered a vast area from Rudny Altai to Siberian Platform periphery. This Hercynian continental margin is characterized by:

— formation on the heterogeneous basement of an Early Paleozoic fold-block system;

— oblique transpressional occurrence of subduction-accretion processes, which resulted in widespread strike-slip faults [Buslov et al., 2000, 2003];

— wide fields of development of rear rift basins (Minusa, Kuznetsk, Tuva, etc.) and framing volcanoplutonic belts with ore mineralization.

According to paleogeodynamical reconstructions [Yolkin et al., 1994], the Middle Paleozoic Irtysh-Zaisan ocean basin was inherited from the Ordovician and Silurian. The Hercynian continental margin was best expressed in structures of Rudny Altai and Gorny Altai. In the Middle Paleozoic, the Rudny Altai area was a Cordillera-type ensialic volcanic island arc evolving on the basement of the Ordovician-Silurian passive continental margin [Rotarash et al., 1982]. The continent-marginal volcanic belt of Gorny Altai, separated from Rudny Altai by the Belaya Uba-Maimyr zone of the back-arc trough and by the Northeastern crush zone, formed on the sialic block of the Altai-Mongolian microcontinent.

The Rudny Altai and Gorny Altai structures show a distinct metallogenic zoning as a result of different geodynamic settings of origin of endogenic ore-forming systems. Volcanics of the neighboring Rudny Altai and Gorny Altai blocks are petrochemically zonal and differ in metallogeny [Gas'kov et al., 1999]. The Rudny Altai structures are made up of calc-alkalic volcanics of contrasting basalt-rhyolite association characterized by antidromous evolution and predominance of acid rocks. These rocks bear pyrite-polymetallic and barite-polymetallic (with Au and Ag) deposits of the Rudny Altai metallogenic belt. Study of deposits and ore fields in northwestern Rudny Altai confirmed their localization at the centers of volcanic activity of contrasting basalt-rhyolite association of antidromous evolution. Polymetallic deposits accumulated mainly in submarine shallow volcanic shelf following the model of subsea-floor ore deposition through metasomatism and filling of interlayer fluid fracturing cavities within weakly lithified sediments in zone of boiling-up of ascending hot fluids [Distanov and Gas'kov, 1999]. The antidromous evolution of volcanism reflected on the composition of the accompanying mineralization. Early

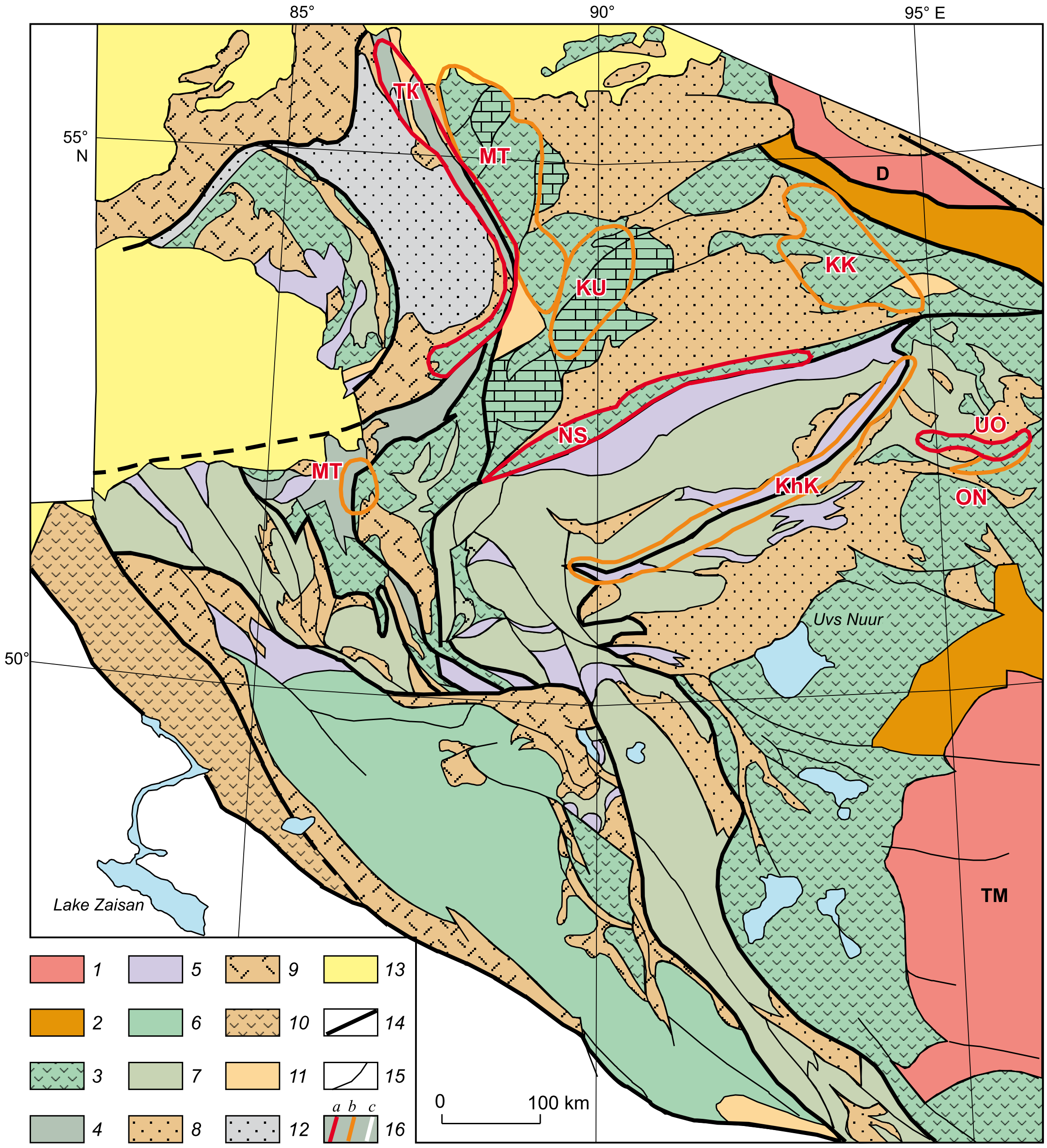

Fig. 1. Schematic occurrence of Early Paleozoic (V–S) metallogenic belts in structures of the Altai-Sayan orogenic area (structure-geodynamic map was borrowed from [Dobretsov et al., 2001]). ***1*** **— ancient blocks formed by Archean-Proterozoic metamorphic strata, Late Proterozoic accretion-island-arc complexes, and Vendian-Cambrian shelf deposits (D — Derbina block, TM — Tuva-Mongolian microcontinent);** ***2*** **— fragments of Late Proterozoic passive continental margin, composed of metamorphic and terrigenous-carbonate strata;** ***3*** **— Vendian-Cambrian volcanosedimentary island-arc complexes;** ***4*** **— fragments of oceanic underwater uplifts with Vendian-Lower Cambrian carbonate and siliceous-carbonate cover (ancient blocks and seamounts);** ***5*** **— complexes of Vendian-Cambrian accretion zones, in places, with fragments of ophiolites and high-pressure rocks;** ***6*** **— Vendian-Cambrian flyschoid strata of the Altai-Mongolian terrane (microcontinent), in places, overlain by Ordovician and Silurian strata;** ***7*** **— areas of occurrence of Late Cambrian-Ordovician-Silurian sea molasses and flyschoid and shelf deposits;** ***8*** **— Early-Middle Devonian volcanosedimentary rift complexes of rear-arc basins overlain by Middle-Late Paleozoic continental molasse in large depressions;** ***9*** **— Devonian-Early carboniferous complexes of volcanosedimentary rocks of back-arc basins and shelves, formed on active continental margin;** ***10*** **— Middle Paleozoic (Devonian-Carboniferous) Rudny Altai island arc;** ***11*** **— Permian metamorphic complexes;** ***12*** **— Late Paleozoic-Triassic molasse of Kuznetsk trough;** ***13*** **— Mesozoic-Early Cenozoic cover of the West Siberian Plate;** ***14*** **— large fault zones (shifts at the final stages of the Paleozoic evolution of the ASOA);** ***15*** **— other faults and geologic boundaries;** ***16*** **— metallogenic belts:** ***a*** **— preaccretionary,** ***b*** **— accretion-collision,** ***c*** **— postaccretionary. TK — Taidon-Kondoma; NS — North Sayan; UO — Ulugo; KhK — Khemchik-Kurtushiba; MT — Martaiga; KU — Kiyalykh-Uzen'; KK — Kizir-Kazyr; ON — Ondum.**

Table 2

Geodynamic Settings of Formation of the ASOA Metallogenic Belts in the Early Paleozoic (Vendian-Silurian, 620–410 Ma)

Ore associations	Deposits
Island arcs and back-arc basins	
Metallogenic belts: Taidon-Kondoma (TK), North Sayan (NS), and Ulugo (UO)	
Fe magnetite skarn	**Tashtagol**, **Sheregesh**, **Kazskoe**, **Ampalykskoe**, **Anzasskoe**, **Abakanskoe**
Mn volcanosedimentary	**Usinskoe**
Native copper (Lake Superior type)	Taimetskoe
Cu-Zn pyrite hydrothermal-sedimentary (Cyprus type)	Mainskoe
Zn-Pb-Cu pyrite-polymetallic volcanogenic hydrothermal (VHMS)	**Kyzyl-Tashtyg**
Accretionary wedges with fragments of oceanic crust, island arcs, and back-arc basins	
Metallogenic belts: Khemchik-Kurtushiba (KhK)	
Chrysotile-asbestos, in serpentinites	**Aktovrak**, **Sayanskoe**
Continent-marginal shear zones with accretionary wedges (transform-like craton margins)	
Metallogenic belts: Iya (I)	
Ti-Fe magmatic, in gabbroids	Verkhne-Iiskoe
Collisional gabbro-granitoid plutonic belts	
Metallogenic belts: Martaiga (MT), Kiyalykh-Uzen' (KU), Kizir-Kazyr (KK), and Ondum (ON)	
Au-sulfide-quartz beresite	Berikul', Gavrilovskoe, Saralinskoe, Kommunar
Au skarn	Sinyukhinskoe, Natal'evskoe, Ol'khovskoe, Tardan
Au-telluride-Hg	Yuzikskoe
Cu skarn	Kiyalykh-Uzen'
Fe skarn	Samson, **Tabratskoe**, Irbinskoe
W-Mo skarn	Tuim, Balyksinskoe
Mo-W-Be greisen	Turtek
Fe-oxide volcanosedimentary	Belokitatskoe
Postcollisional (anorogenic) granite-leucogranites and subalkalic granites	
Metallogenic belts: Tastyg (TG)	
Li-Sn-Be pegmatite	**Tastygskoe**, Kara-Adyr
Ta-Nb-REE, in alkali metasomatites	Aryskanskoe

manifestations of the Eifelian-Givetian essentially acid volcanism bear gold-silver-barite-polymetallic deposits (Zarechenskoe, Zmeinogorskoe, etc.), and rhyolite-dacite and basalt-andesite differentiates of the Givetian-Frasnian volcanism, widespread pyrite-polymetallic deposits (Yubileinoe, Korbalikhinskoe, Rubtsovskoe, etc.). The unique ore potential of the Rudny Altai polymetallic belt is obviously due to the specific geodynamic evolution of ensialic island-arc system on the thick accreted terrigenous-carbonate shelf deposits of the Ordovician-Silurian passive continental margin. In this respect the Rudny Altai belt is similar to the Iberian pyrite-polymetallic belt and the Bathurst ore district in the northern Appalachians.

Volcanics of the Korgon and Kholzun zones in Gorny Altai are a subalkalic basalt-andesite-rhyolite association of homodromous evolution formed in epicontinental subaerial and shallow-water settings. They bear volcanosedimentary, including skarnized, Fe and Fe-Mn deposits. In the Charysh-Inya block of Gorny Altai, a specific structure-formational zone (subterrane) with Devonian rift complexes developed in Ordovician-Silurian carbonate-terrigenous strata, gold and Ti-magnetite (in layered gabbroids) types of mineralization were found.

In the Middle Paleozoic, the Salair Range, an Early Paleozoic island-arc system, was subjected to the processes that gave rise to the Hercynian active continental margin, namely, basic magmatism (which was expressed as dike belts and small intrusions) and acid porphyry magmatism. At this stage, gold-barite-polymetallic deposits of the Salair ore field and quartz-gold mineralization formed. The mineralization was localized mainly in strike-slip zones and transverse faults [Distanov, 1977].

Devonian-Early Carboniferous rear-arc basins and framing volcanoplutonic belts widespread in the ASOA seem to be of high ore potential. Until recently, they have been regarded as intermontane depressions formed at the subplatform stage of the regional evolution. These structures are characterized by:

— formation on the fold-block basement of the ASOA Caledonides;

— wide occurrence of volcanic processes and formation of intrusive comagmatic rocks at the early rift stage of basin evolution and shallow-depth terrigenous deposits, including red-colored and carbonaceous facies, at the late stages of sedimentation;

— high alkalinity of both basic and acid volcanics, up to high-alkali rocks (nepheline dolerites, phonolites, and nephelinites), and wide spread of intrusive comagmatic rocks of volcanoplutonic complexes (from gabbronorites to alkali and biotitic granites) and alkaline rocks (theralite-syenites, urtites, nepheline syenites, etc.) [Luchitsky, 1960; Levchenko and Graizer, 1965];

— rift evolution of these basins under rear-arc dispersed spreading at the early stages of their formation and ramp deformations and their squeezing by folded structures at the accretion-collision (orogeny) stage [Mossakovsky, 1963].

The extremely intense effusive activity in the Minusa basin in the Early Devonian and Eifelian was accompanied by intrusive magmatism, both mantle and mantle-crustal. At this stage, two ore-bearing volcanoplutonic series formed: porphyry and basaltoid. The former intrusion bears abundant Cu and contact-metasomatic Fe deposits and polymetallic and rare-metal ore occurrences, and the latter, orthomagmatic deposits of Fe, Ti, P, and V, contact-metasomatic deposits of Fe, and vein hydrothermal deposits of Cu, Ni, and Co [Levchenko, 1974].

In the rear-arc setting on the periphery of the Minusa basin, the Devonian porphyry magmatism superposed on early granitoid plutons is expressed as large-scale porphyry Cu-Mo mineralization (Sorskoe, Ipchul'skoe, and Agaskyrskoe deposits). Such a long inherited evolution of ore-bearing porphyry granitoid systems is a specific feature of porphyry Cu-Mo ore clusters, determining large-scale mineralization [Distanov et al., 1998].

Of great interest are nepheline-rock massifs in Kuznetsk Alatau (Kiya-Shaltyr area) and in the Sangilen upland in southeastern Tuva (Bayan-Kol area). According to their age and petrochemistry, many researchers consider them comagmatic to alkaline rocks of rear-arc basins. The plumes of hot spots are obviously of asthenospheric upper-mantle nature and formed in the same geodynamic setting as depression structures in the hinterland of convergent subductional continental margins. The same explains the specific mantle-crustal type of metallogeny of ensialic back-arc basins [Guild, 1977].

We have recognized the following most ore-productive geodynamic settings and metallogenic belts during the evolution of the Middle Paleozoic active continental margin (Fig. 2, Table 3):

— island arcs and back-arc basins with volcanogenic pyrite-polymetallic deposits (Rudny Altai belt);

— volcanoplutonic belts of active continental margins with volcanosedimentary Fe and Fe-Mn, magmatic Ti-Fe(+V), Fe-skarn, and polymetallic hydrothermal-metasomatic deposits (Korgon-Kholzun, Salair, and Teya belts);

— rear-arc rift depressions and framing volcanoplutonic belts with porphyry Cu-Mo, greisen W-Mo-Be, metasomatic Pb-Zn-Ag, epithermal Au-Ag and Au-Hg, and barite and fluorite vein deposits and Ta-Nb-REE mineralization in alkali metasomatites (Sora, Chapsordag, Agul, and Kizhi-Khem belts);

— alkaline-magmatism areas of occurrence of hot spots with magmatic nepheline deposits (Bayan-Kol and Kiya-Shaltyr belts);

— strike-slip zones of transform continental margins with rare-metal Sn-W mineralization (Teletskoe-Bashkaus-Kharkhira zone) and with gabbro-granite series with gold mineralization and layered gabbroid intrusions with Ti-Fe mineralization (North Altai gold-ore belt);

— continent-marginal terrigenous-carbonate basins with sedimentary bauxite deposits (Berd'-Maya belt).

In that period, crust-mantle volcanogenic hydrothermal, granitoid and porphyry (with combined sources of ore matter), orthomagmatic basaltoid, and essentially mantle alkaline systems were the main endogenic ore-forming systems.

Late Paleozoic-Early Mesozoic stage of within-plate tectonothermal activity (P_2–T, 260–205 Ma). Metallogeny of this period was determined mainly by the development of trap and associated alkaline-ultrabasic and granitoid magmatism, which was related to the activity of the Permian-Triassic Siberian superplume in the Siberian Platform and framing folded areas [Dobretsov, 2003]. Granitoids coeval with the plume, which were produced in areas with thick lithosphere and crust as a result of preceding collision processes, are of *A*-type [Borisenko et al., 2006a]. In the northwest of the North Asian craton, where plume magmatism was the most

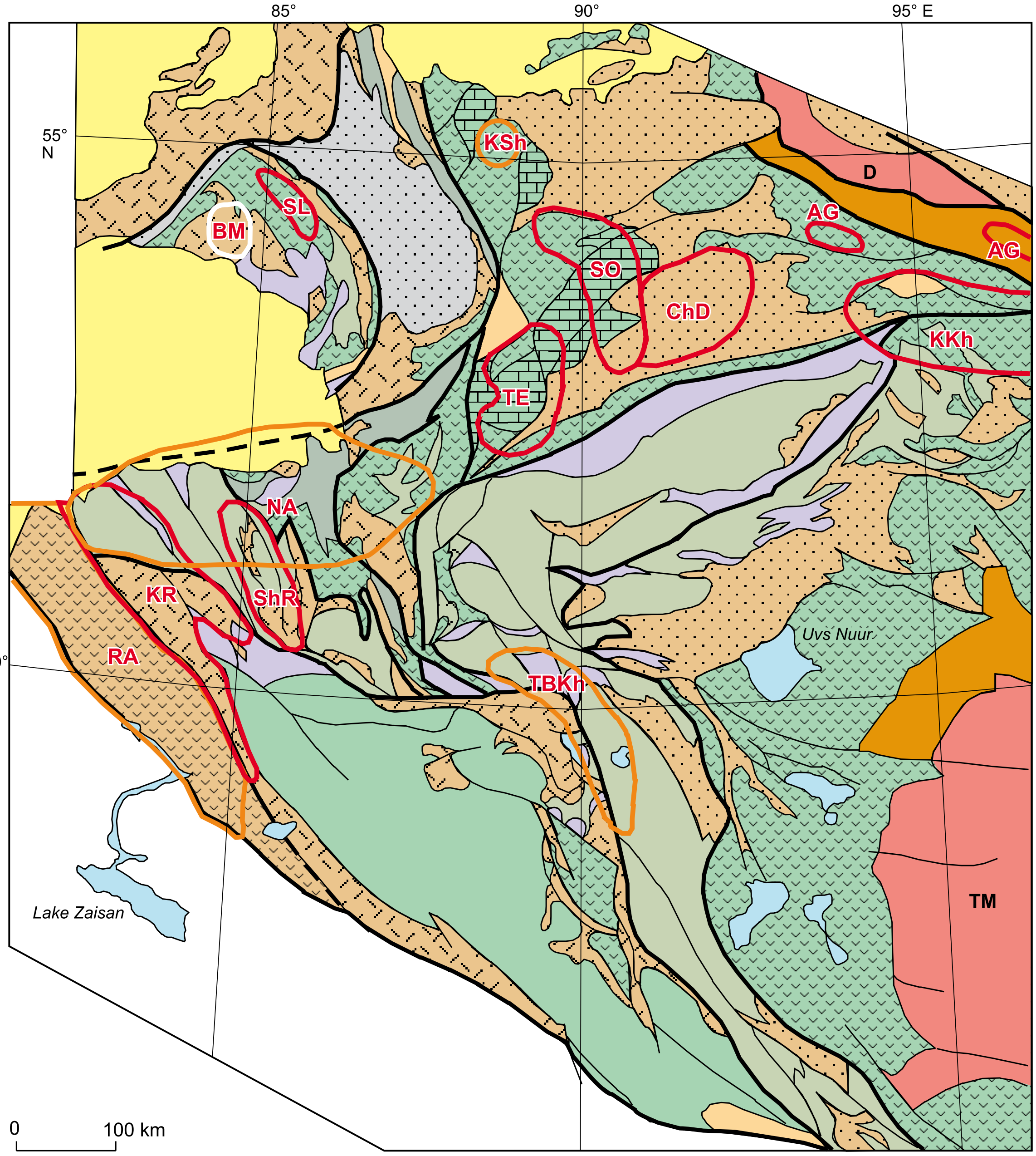

Fig. 2. Schematic occurrence of Middle Paleozoic (D–C_1) metallogenic belts in structures of the Altai-Sayan orogenic area (structure-geodynamic map was borrowed from [Dobretsov et al., 2001]). Metallogenic belts: RA — Rudny Altai; ShR — Shirgaita; KR — Korgon-Kholzun; SL — Salair; TE — Teya; SO — Sora; ChD — Chapsordag; AG — Agul; KKh — Kizhi-Khem; KSh — Kiya-Shaltyr; NA — North Altai; TBKh — Teletskoe-Bashkaus-Kharkhira; BM — Berd'-Maya. Other designations follow Fig. 1.

intense, there are Cu-Ni-PGE sulfide magmatic, native-copper, Iceland spar, Fe skarn-hydrothermal (Angara-Ilim type), graphite metamorphic, Fe-Ti (±Ta, Nb, P)-carbonatite, REE (±Ta, Nb, Fe)-carbonatite, and phlogopite-carbonatite deposits related to trap and alkali-ultrabasic magmatism. In the Noril'sk metallogenic belt and in the Taimyr region, *A*-type granitoids bear porphyry Cu-Mo, greisen and skarn W-Mo, and polymetallic types of mineralization.

The most ore-productive period of this stage of the ASOA evolution was the Triassic. Its geodynamic and metallogenic events were determined by:

Table 3

Geodynamic Settings of Formation of the ASOA Metallogenic Belts in the Middle Paleozoic ($D–C_1$, 410–320 Ma)

Ore associations	Deposits
Island arcs and back-arc basins	
Metallogenic belts: Rudny Altai (RA) and Shirgaita (ShR)	
Zn-Pb-Cu pyrite-polymetallic volcanogenic hydrothermal (VHMS)	**Korbalikhinskoe**, Rubtsovskoe, Stepnoe, Talovskoe, Zarechenskoe
Pb-Zn hydrothermal-sedimentary (SEDEX)	Shirgaitinskoe
Au-sulfide-quartz beresite	Sekisovskoe (eastern Kazakhstan)
Volcanoplutonic belts of active continental margins	
Metallogenic belts: Korgon-Kholzun (KR), Salair (SL), and Teya (TE)	
Fe-oxide volcanosedimentary	**Kholzunskoe**, Kalgutinskoe, Chilanskoe
Fe-magnetite skarn	**Inskoe**, **Beloretskoe**, Teiskoe, Izykhgol'skoe, Abagasskoe
Ti-Fe magmatic, in gabbroids	**Kharlovskoe**, **Patynskoe**, **Kul'-Taiga**
Polymetallic Pb-Zn-Ag metasomatic, in carbonate strata	Ust'-Chagyrskoe
Barite-polymetallic Pb-Zn-Ag hydrothermal-metasomatic, in aluminosilicate strata	**Salairskoe**
Pyrite-polymetallic Cu-Zn-Pb volcanogenic hydrothermal (VHMS)	Urskoe
Porphyry Cu-Au	Kamenushinskoe
Au-quartz vein	Salairskoe ore field
Rear-arc rift depressions and accompanying volcanoplutonic belts	
Metallogenic belts: Sora (SO), Chapsordag (ChD), Agul (AG), and Kizhi-Khem (KKh)	
Porphyry Mo	**Sorskoe**, **Ipchul'skoe**, **Agaskyrskoe**
Porphyry Cu-Mo	**Agul'skoe**, Dzhetskoe, Aksugskoe
Mo-W-Be greisen	Raduga, Kazyrskoe
Polymetallic Pb-Zn-Ag metasomatic, in carbonate strata	Karasugskoe, Igr-Gol
Pb-Zn skarn	Yuliya Svintsovaya
Ag-Sb vein	Tibikskoe
Fluorite hydrothermal	Zhurskoe
Barite hydrothermal	Chapsordag, Taptan-Turazy
Native copper (Lake Superior type)	Voroshilovskoe, Koksinskoe
Cupriferous sandstones	Tustuzhul'skoe, Pechishchenskoe
Alkaline magmatism in hot spots	
Metallogenic belts: Kiya-Shaltyr (KSh) and Bayan-Kol (BK)	
Nepheline magmatic	**Bayan-Kol'skoe**, **Toskul'skoe**, **Kiya-Shaltyrskoe**, **Goryachegorskoe**
Shear zones of transform continental margins accompanied by collisional granitoid, porphyry, and basic magmatism	
Metallogenic belts: North Altai (NA) and Teletskoe-Bashkaus-Kharkhira (TBKh)	
Au-Cu skarn	Karaminskoe, Topol'ninskoe, Choiskoe
Au-sulfide-quartz	Bashchelakskoe
Porphyry Cu-Mo-(Au)	Kul'bich
Sn-W greisen	Yustydskoe, Balyktinskoe, Turgen (Mongolia)
Cu-Co-W hydrothermal	Karakul'skoe
Continent-marginal terrigenous-carbonate basins	
Metallogenic belts: Berd'-Maya (BM)	
Bauxite sedimentary	Berdsko-Maiskoe, Obukhovskoe

— tectonothermal activity on the periphery of the Permian-Triassic Siberian superplume in interblock zones of orogenic collage (granite-leucogranite and subalkalic rare-metal complexes);

— within-plate rifting, interblock strike-slip and thrust faults accompanied by basaltoid and alkali-basaltoid magmatism.

Intense strike-slip motions along large faults were favored by the formation of conjugate local pull-apart structures and large regional thrust structures [Berzin and Kungurtsev, 1996; Dobretsov et al., 1995b] controlling the localization of anorogenic granitoid complexes and dike basite and alkali-basite belts. This period was characterized by the production of rare-metal mineralization — formation of greisen Mo-W and Sn-W and epithermal Au-Hg deposits in Gorny Altai, Tuva, and the Tom'-Kolyvan' folded zone; Ta-Nb-Ti deposits in alkali metasomatites and pegmatites in Tuva and Gorny Altai; and porphyry Cu-Mo mineralization in northern and central Mongolia. Judging from ^{40}Ar-^{39}Ar dating, As-Ni-Co, Ag-Sb, Hg, and Au-Hg mineralization was produced in the west of the ASOA, which was controlled by Triassic rift-strike-slip structures. In this metallogenic epoch, the most considerable ore-bearing structures formed, such as the Kuznetsk-Alatau Hg belt, Delyun-Yustyd Ag-Sb zone, Tuva Hg belt, and Khovu-Aksy Ni-Co ore cluster.

In southern Gorny Altai, there are the Kalguty ore cluster with W-Mo-Be greisen stockwork and quartz-vein deposits in anorogenic granites and the Ulug-Tanzek metallogenic belt with Sn-W greisen and Ta-Nb-REE deposits in alkali metasomatites.

In recent time, U-Pb, Rb-Sr, and ^{40}Ar-^{39}Ar ages have been obtained for many granitoid plutons in the study region. They give an insight into the temporal correlation of rare-metal mineralization with granites and evidence its polychronous formation. The mineralization was related to granitoid magmatism of different geodynamic settings — collision and within-plate rifting associated with strike-slip faulting.

We obtained additional dates for Mo-W-Be mineralization of the Kalguty belt [Borisenko et al., 2004, 2006a]: The ^{40}Ar-^{39}Ar age of granite-porphyry is 218±1 Ma, and that of ongonite, kalgutite, and granite-porphyry dikes, 202.4±0.8–204±7.8 Ma; the Re-Os age of molybdenite from greisenized granite-porphyry from "molybdenum stock" is 220±1 Ma, and that of molybdenite from quartz-molybdenite-wolframite vein, 218±1 and 208.7±1.9 Ma. Thus, the Re-Os and ^{40}Ar-^{39}Ar ages agree with each other. Obviously, the Kalguty granite massif is older than 200 Ma; with regard to the ages of its two complexes, it is dated at 225–230 Ma. This time span agrees with the Rb-Sr age of 228±5.4 Ma corresponding to the Late Triassic in the Geochronological Scale. The Chindagatuiskoe (southern Altai) and Ulanul'skoe (western Mongolia) Mo-W deposits fall in the same age interval. The ^{40}Ar-^{39}Ar age of granite-porphyry of the Ulanula massif is estimated at 215±3.6 Ma.

Thrust structures associated with alkali-basaltoid dike complexes bear Sb-Hg and Hg deposits of carbonate-cinnabar-listwaenite and barite-cinnabar types, and crush zones, Ag-Sb vein epithermal deposits. The ^{40}Ar-^{39}Ar age of the Altai Hg mineralization is 234.4±1.3 Ma (Kok-Uzek deposit) and 231±1.3 Ma (Tyute deposit), and that of the Chazadyrskoe Hg deposit in Tuva is 227±16.3 Ma [Borisenko et al., 2006b].

We have recognized two types of metallogenic belts that formed at the postorogenic stage of the ASOA evolution (Fig. 3, Table 4):

— metallogenic belts related to within-plate anorogenic granitoid magmatism;

— metallogenic belts related to within-plate rifting and strike-slip-thrust structures with basaltoid and alkali-basaltoid magmatism.

EVOLUTION OF ORE FORMATION PROCESSES DURING THE GEODYNAMIC DEVELOPMENT OF THE ASOA

The continental margins of the Altai-Sayan polyaccretionary area, which formed during the long evolution of the Paleoasian ocean, have had several episodes of mineralization characterized by a certain trend of evolution.

Formation of the Riphean continental margin was related to the wide development of mantle plume processes and rift crushing of the Pangea supercontinent. At this stage, actively subsiding pericratonal depressions with high endogenic and underwater hydrothermal activities formed along the craton periphery. This gave rise to large stratiform deposits of nonferrous metals, Fe, and Mn and syngenetic enrichment of black-shale strata with Au and other elements. Subsequent accretion processes resulted in a regional ore-bearing ophiolite belt and commercial metamorphogene-hydrothermal deposits (Au, Au-Sb, etc.).

The Early Paleozoic (V–S) continental margin manifested itself as numerous volcanic island arcs and continent-marginal volcanoplutonic and strike-slip-collision gabbro-granitoid belts. Ancient craton blocks (micro-continents) played an important role in the regional geodynamics of that period. Various deposits (Ti-Fe magmatic, Fe skarn, Au skarn, Au-sulfide-quartz hydrothermal, volcanogenic pyrite-polymetallic, and chrysotile-asbestos) formed on the margin.

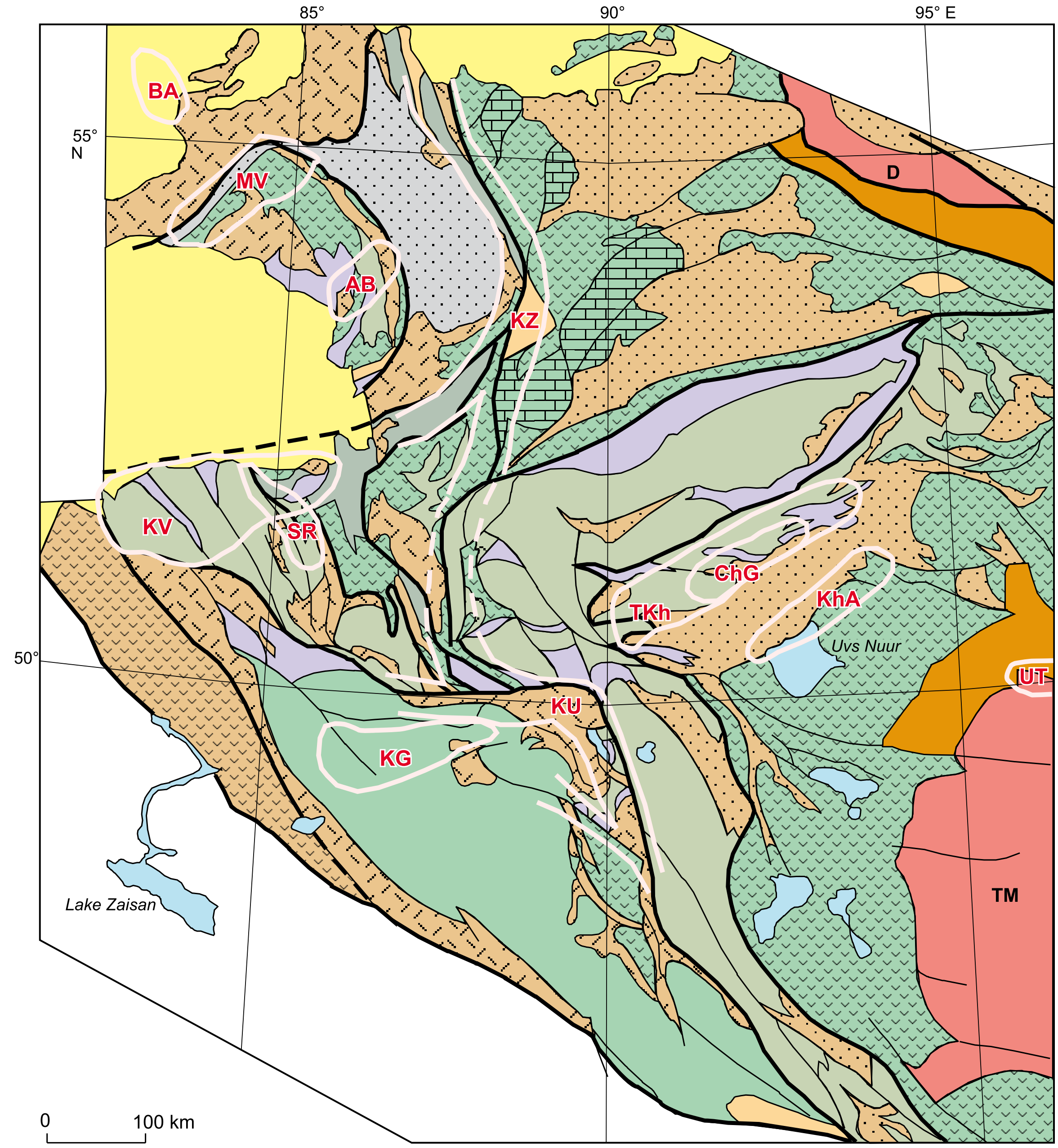

Fig. 3. Schematic occurrence of Late Paleozoic-Early Mesozoic (P_2–T) metallogenic belts in structures of the Altai-Sayan orogenic area (structure-geodynamic map was borrowed from [Dobretsov et al., 2001]). Metallogenic belts: BA — Barlak; KV — Kolyvan'; KG — Kalguty; UT — Ulug-Tanzek; TKh — Terligkhaya; ChG — Chergak; KhA — Khovu-Aksy; KU — Kurai; KZ — Kuznetsk; MV — Mavrinsk; AB — Alambai; SR — Sarasa. Other designations follow Fig. 1.

The Middle Paleozoic continental margin is a typical active margin of transform type with oblique subduction. Continent-marginal strike-slip zones and conjugate cross suprasubductional faults with extension are widespread in the region. They were important ore-controlling structures. Island-arc systems formed on the sialic basement of the previously originated (O–S) passive continental margin, which affected their high ore productivity. The block basement of preceding Caledonides abounds in rear-arc rift basins with accompanying volcanoplutonic belts. All this led to the formation of deposits of nonferrous metals, Fe, Ti, Al, Mo, W, Au, etc.

Middle Paleozoic accretion-collision processes terminated with the closure of the Paleoasian ocean and general

Table 4

Geodynamic Settings of Formation of Metallogenic Belts in the ASOA in the Permo-Triassic (260–205 Ma)

Ore associations	Deposits
Postcollisional (anorogenic) leucogranites and alkali granites	
Metallogenic belts: Barlak (BA), Kolyvan' (KV), Kalguty (KG), Ulug-Tanzek (UT), and Zashikhinsk (ZSh)	
Sn-W greisen	Kolyvanskoe II, Achitnurskoe
W-Mo-Be greisen	Kolyvanskoe I, Kalgutinskoe, Urzarsaiskoe
Be skarn	Beloretskoe
Ta-Nb-REE, in alkali metasomatites	Ulug-Tanzek, Verkhne-Kundusskoe, Zashikhinskoe
Ta-Li ongonite	**Alakhinskoe**
Within-plate rifting and interblock shear dislocations with basaltoid and alkali-basaltoid magmatism	
Metallogenic belts: Chergak (ChG), Kharadzhul' (KhD), Khovu-Aksy (KhA), Kurai (KU), Kuznetsk (KZ), Mavrinsk (MV), Terligkhai (TKh), Alambai (AB), and Sarasa (SR)	
Ni-Co-arsenide	Khovu-Aksinskoe, Chergak, Askhatiin-Gol (Co)
Sb-Hg epithermal	Aktashskoe, Pezas, Mavrinskoe, Chagan-Uzunskoe, Belo-Osipovskoe, Terligkhaiskoe
Ag-Sb sulfosalt	Askhat, Ozernoe

cratonization. Note that during the evolution of the Paleoasian ocean and the formation of the Central Asian orogenic belt, each accretion stage was preceded by divergence, stress relaxation, and local continental rifting stages, whose role in the regional metallogeny calls for further study.

Recent geochronological investigations of a great number of deposits related to the Mesozoic within-plate magmatism, interblock dislocations, and rifting have revealed the most productive metallogeny stage, P_2–T (260–205 Ma). Study of petrology, geodynamics, and zonal occurrence of Permo-Triassic within-plate plume magmatism both within the Siberian Platform and on its periphery, in orogenic belts (including the Altai-Sayan folded area), gives insight into the ore potential of the region, first of all, deposits of sulfide Cu-Ni-PGE, porphyry Cu-Mo, rare-metal Sn-W, and epithermal Au-Hg and Ag-Sb sulfosalt ore associations [Dobretsov et al., 2005; Borisenko et al., 1992, 2006a; Vladimirov et al., 2006].

CONCLUSIONS

The above data on the tectonic and metallogenic evolution of the polyaccretionary ASOA show the formation of the main types of mantle and mantle-crustal ore-forming systems (and corresponding ore associations) in particular geodynamic settings. In metallogenic analysis in terms of plate tectonics, ore-formation analysis and construction of geologo-genetic models of ore associations (model types of deposits) are of great importance for elucidating the settings of origin of ore-forming systems and factors determining their high ore potential. Recent works on geodynamics and metallogeny of the Central Asian orogenic belt have shown that many ore associations and ore complexes are indicators of particular geodynamic settings. Localization of metallogenic belts and zones is determined by their relationship with particular structure-lithologic geodynamic complexes. These works are of great importance for the theory of ore formation and metallogenic prediction, including that for new types of deposits. It would be appropriate to set the term "geodynamic metallogeny" reflecting a highly effective line of metallogenic studies in terms of plate tectonics and mantle geodynamics.

A typical feature of polyaccretionary orogenic systems is the recurrence of geodynamic settings of continental margins of different ages and corresponding ore associations. At the same time, the Earth's crust structure of the folded area became more intricate stage by stage, which determined the specific formation of some continental margins and their specific ore potential.

The most ore-productive geodynamic processes during the formation of continental margins of the ASOA were:

1. Formation of a system of marginal structures along the periphery of the North Asian craton at the divergence

and convergence stages of evolution of the Neoproterozoic continental margin (pericratonal depressions and marginal rifts with high endogenic activity).

2. Formation of ensialic island arcs (in particular, of Cordillera type) on the basement of preceding passive continental margins (Rudny Altai polymetallic belt).

3. Formation of Middle Paleozoic (Hercynian) volcanoplutonic belts and rear-arc basins on the heterogeneous basement of Early Caledonides.

Oblique subduction and strike-slip motions that gave rise to transform continental margins played an important role in the formation of highly productive mantle and mantle-crustal ore-forming systems and metallogenic belts of East Sayan, Rudny Altai, and the Salair Range. Localization of large ore clusters of active continental margins was determined by transverse suprasubduction and interblock fault zones.

At the Late Paleozoic-Early Mesozoic postorogenic stage of the ASOA evolution, the geodynamic and metallogenic events were much determined by tectonothermal activity on the periphery of the Permo-Triassic Siberian superplume. The ore formation was related to within-plate rifting, serious strike-slip motions, formation of fault troughs and grabens, and accompanying anorogenic magmatism of alkali and subalkalic rare-metal granites and dike alkali-basaltoid magmatism. In this metallogeny epoch, the main ore-bearing structures originated, such as the Kuznetsk Alatau Hg, Dellyun-Yustyd Ag-Sb, Tuva Hg, and Ubsunur–Bayan-Kol Ni-Co belts and Ulug-Tanzek Ta-Nb and Kalguty W-Mo ore clusters.

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