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GEOLOGY

The Epithermal Gold–Silver Mineralization in Volcanic Belts of Northeast Asia

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Gold–silver mineralization in Northeast Asia is controlled by volcanic belts of different ages that are superimposed on cratonic, passive continental-margin, island-arc, and oceanic terranes (Fig. 1, table). According to the concept of accretion tectonics, the study region represented a dynamically evolving active continental margin in the Mesozoic–Cenozoic. This is reflected in eight NW- to SW-oriented successions of postaccretionary volcanic belts. Among them, the following six volcanic belts were developing parallel to the present-day position of the Kuril–Kamchatka deep-water trench (Fig. 1): Late Jurassic–Early Cretaceous Uda–Murgal (UMVB), Late Cretaceous–Paleogene Okhotsk–Chukot (OCVB), Late Cretaceous–Paleogene East Sikhote-Alin (ESVB), Eocene–Oligocene Koryak–West Kamchatka (KWKVB), Oligocene–Quaternary Central Kamchatka (CKVB), and Pliocene–Quaternary East Kamchatka (EKVB). The Uyanda–Yasachen (UYaVB) and Oloi (OVB) were developing parallel to the northern continental margin in the Jurassic (Fig. 2). The successive rejuvenation of volcanic belts since the Early Cretaceous corresponded to the shift of the volcanic arc–trench system toward the Pacific Ocean. In addition to the volcanic belts mentioned above, the preaccretionary Late Paleozoic Kedon marginal volcanic belt (KVB) is also known in the Omolon cratonic terrane.

All volcanic belts and auxiliary perivolcanic zones of tectonomagmatic activation in the study region are united into one of the world's largest metallogenic provinces with polychronous and compositionally diverse volcanoplutonic mineralization (Fig. 1, table). This fact provides new insight into regularities in the spatial distribution of the epithermal gold–silver mineralization and causes of variations in its mineral types in the volcanic belts mentioned above.

The *Kedon marginal volcanic belt* formed on the continental crust in the Middle Paleozoic during a period of 30–35 Ma. At present, structures of this volcanic belt are retained as fragments in the Omolon massif. The belt is composed of subaerial red-colored volcanic rocks of the differentiated series coupled with compositionally similar subvolcanic and hypabyssal intrusions. In terms of chemical composition, the volcanic rocks belong to the calc-alkaline and moderately alkaline series. The belt is characterized by the absence of large batholith-shaped intrusions and the considerable predominance of felsic volcanic rocks. It is likely that the Kedon volcanic belt is a fragment (400 × 80–130 km) of a large Circum-Siberian continental-margin belt [1]. Epithermal volcanic mineralization in the Kedon volcanic belt is represented by two types. Gold mineralization (Au/Ag = 1 : 1–1 : 5) is developed in the Kubaka, Birkachan, and Elochka deposits. The gold–silver mineralization (Au/Ag = 1 : 10–1 : 50) is developed in the Yunyi and Ol'cha deposits. The Kedon volcanic belt is characterized by the absence of silver and tin deposits that are typical of the Okhotsk–Chukot volcanogenic belt. At the same time, Ag-rich (Ag 100n g/t) mineralization is developed in jasperoids beneath volcanic rocks and in carbonate sequences in tectonomagmatic activation zones branching off from the Kedon volcanic belt. The Kubaka and Birkachan deposits are characterized by a low content of sulfides (<0.1 and 0.1–0.5%, respectively) and scanty mineral composition. This feature is typical of regenerated deposits. The ores are mainly composed of gold, electrum, and pyrite. The predominance of pyrite and hematite in the ores suggests that the mineralization in the volcanic belt can be assigned to the ore complex of Precambrian auriferous ferruginous quartzites and amphibolites that are widespread in the basement of the Kedon volcanic belt. In particular, augengneisses and diaphtorites from Precambrian cataclastic rocks of the Koargychan Ridge include amphibolites and magnetite quartz with hema-

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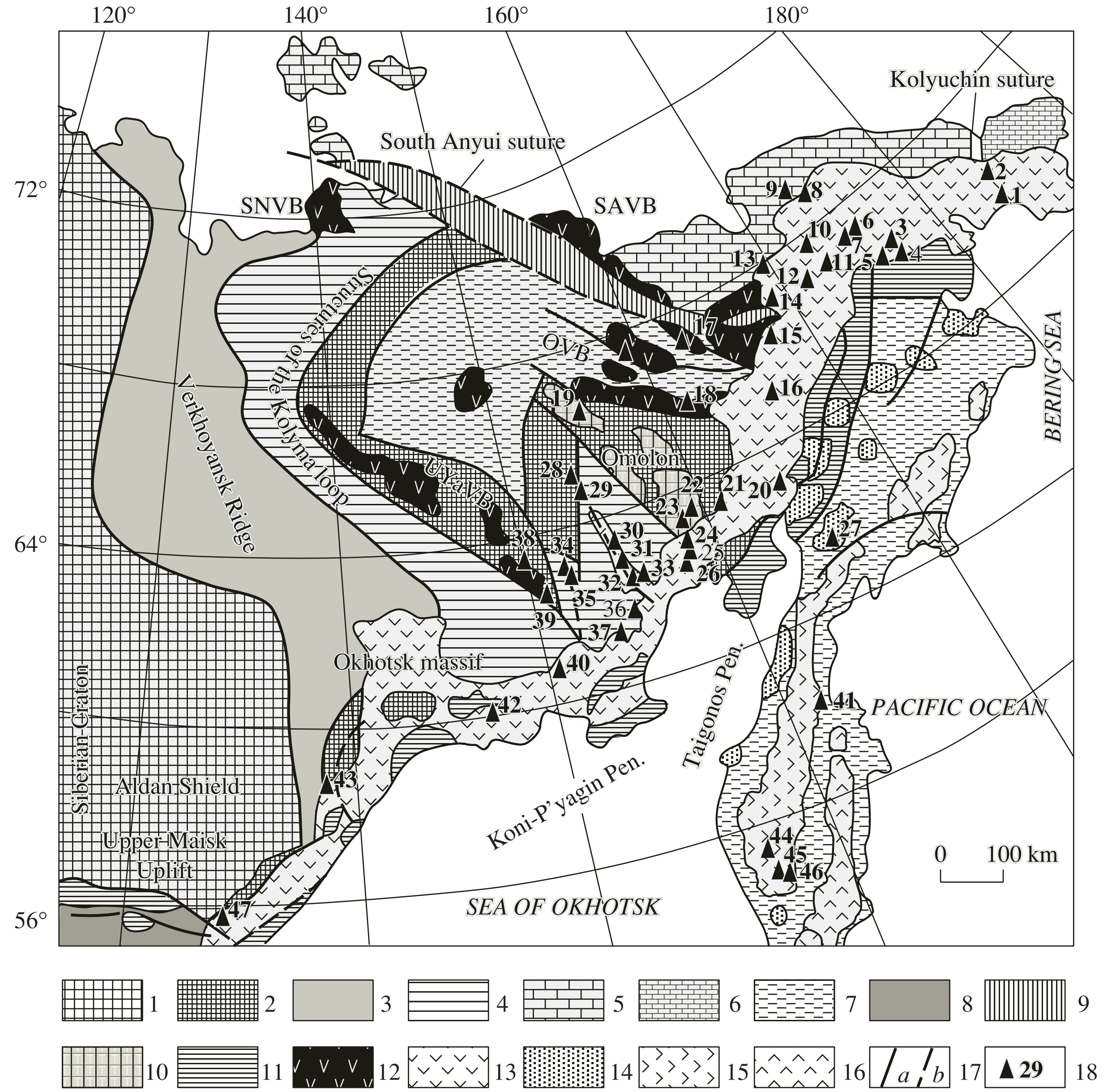

Fig. 1. Volcanic belts and gold–silver deposits in Northeast Eurasia. Tectonic scheme is modified after [12]. (*1*) Siberian Craton; (*2*) large blocks with continental crust of the Siberian Craton; (*3, 4*) passive margin of the Siberian Craton (Verkhoyansk Complex): (*3*) Paleozoic–Mesozoic rocks; (*4*) Mesozoic rocks; (*5*) folded cover of the Chukot continent; (*6*) East Chukot–S'yuard (Eskimos) block; (*7*) Koryak–Kamchatka accretion belt; (*8*) Mongol–Okhotsk foldbelt; (*9*) Late Mesozoic collision sutures; (*10*) Kedon continental-margin volcanic belt (Late Paleozoic); (*11, 12*) Late Jurassic–Early Cretaceous suprasubduction rocks: (*11*) Uda–Murgal island-arc system, (*12*) Uyanda–Yasachen (UYaVB), Oloi (OVB), Svyatoi Nos (SNVB), and South Anyui (SAVB) volcanic belts; (*13*) Okhotsk–Chukot continental-margin volcanic belt (Late Mesozoic); (*14–16*) Cenozoic volcanic belts: (*14*) Koryak–West Kamchatka (Eocene–Oligocene), (*15*) Central Kamchatka (Oligocene–Quaternary), (*16*) East Kamchatka (Pliocene–Quaternary); (*17*) large faults: (*a*) boundaries of blocks, (*b*) zones of tectonomagmatic activation; (*18*) epithermal gold–silver deposits: (1) Pepenveem, (2) Korrida, (3) Valunistoe, (4) Tenkerei, (5) Zhil'noe, (6) Televeem, (7) Proval'nye Ozera, (8) Sopka Rudnaya, (9) Promezhutochnoe, (10) Enmyvaam, (11) Arykvaam, (12) Kaenmyvaam, (13) Dvoinoi, (14) Kupol, (15) Gornostaevyi, (16) Irgunei, (17) Klen, (18) Vesennii, (19) Ol'cha, (20) Sergeev, (21) Kegali, (22) Birkachan, (23) Kubaka, (24–26) Evenki group: (24) Oroch, (25) Irbychan, (26) Sopka Kvartsevaya, (27) Ametist, (28) Rogovik, (29) Gromada, (30) Lunnoe, (31) Arylakh, (32) Dukat, (33) Gol'tsovyi, (34) Pechal'noe, (35) Vetvistyi, (36) Dzhul'eta, (37) Nyavlenga, (38) Kunarev, (39) Shirokoe, (40) Karamken, (41) Ozernov, (42) Burgagylkan, (43) Khakanzha, (44) Aginsk, (45) Baran'ev, (46) Ogancha, (47) Avlayakan.

titized quartz. A lump sample of the quartz is enriched in Au (40.1 g/t) and Ag (306 g/t). In the magnetite quartzite, the Au and Ag contents are 2.4 and 30 g/t, respectively. The concentration of Au in sulfidized Precambrian amphibolites, gneisses, and migmatites of the Abkit Uplift has been reported in several works. Based on the geological setting and mineral assemblages, ore occurrences in the Kedon volcanic belt can be assigned

Volcanic belts and epithermal gold–silver deposits in Northeast Asia

Volcanic belt	Age		Geodynamic setting	Mineral resources	Au–Ag deposits and occurrences
	index	Ma			
Kedon	D_3–C_1	416–318	Continental margin	Au, Ag, Fe, Pb, Cu, Zn, In	Kubaka, Birkachan, Ol'cha, Yunyi, Zet, and others
Oloi	J_3–K_1	146–100	Island arc	Au, Ag, Hg, Pb, Cu, Mo, Zn, In	Klen, Alisa, Vesennii, Smeshlivoe, Vernoe, and others
Uda–Murgal	K_1	136–100	Island arc	Au, Ag, Hg, Pb, Cu, Mo, Zn, In	Irgunei, Dzhul'eta, Sergeev, and others
Uyanda–Yasachen	J_2–K_1	175–136	Island arc	Au, Ag, Pb, Cu, Zn, In	Kunarev, Shirokoe, Urul'ta, and others
Okhotsk–Chukot	K_2	100–70	Continental margin	Au, Ag, Sn, Hg, Pb, Cu, Zn, Mo, Sb	Dukat, Lunnoe, Kupol, Nyavlenga, Karamken, Valunistyi, Sopka Rudnaya, Dvoinoi, Khakandzha, and others
East Sikhote-Alin	K_2–₽$_1$	100–55	The same	Au, Ag, Sn, Hg, Pb, Cu, Zn, B	Mnogovershinnoe, Belaya Gora, Maisk, Soyuznoe, and others
West Kamchatka–Koryak	₽$_1$	55–23	The same	Au, Ag, Sn, Hg, Pb, Cu, Zn, W	Ametist, Ivol'ga, Orlovka, Sprut, and others
Central Kamchatka	N_1	23–5	The same	Au, Ag, Hg, Pb, Cu, Zn, In	Aginsk, Baran'ev, Ozernov, and others
East Kamchatka	N_2–Q	5–0	The same	Au, Ag, Hg, Pb, Cu, Zn, In	Kumroch and others

Note: Positions of volcanic belts are shown in Fig. 1.

to the Kalgoorlie-type mineralization in the West Australian Shield [2].

The *Uyanda–Yasachen volcanic belt*, which was mainly formed in the Late Jurassic–Neocomian, is a NW-oriented series of conjugated grabens. The structures of this belt are superimposed on continental uplifts (Kolyma and Omulev) and adjacent parts of synclinoriums (In'yali–Debin and Sugoi). The Ilin–Tas zone is mainly composed of basaltic rocks, whereas the Darpir zone consists of intermediate and felsic volcanic rocks. In the first case, sediments were accumulated in marine conditions. In the second case, the initial subaqueous sedimentation gave way to the subaerial setting at the final stage. Volcanic rocks make up separate extended fields or intrusive-domal clusters and depressions. The metallogeny of this volcanic belt is appreciably less studied relative to the other belts mentioned above. The Ilin–Tas (inner) zone of the belt is characterized by the copper porphyry mineralization associated with high-alkaline (sodic) basalts [3]. The metallogeny of the Darpir (outer) zone is much more diverse. The major silver–base metal mineralization is accompanied by subordinate cassiterite–silicate, silver–antimony, antimony–mercury, and gold–silver occurrences. Metallogenic specialization of the Uyanda–Yasachen volcanic belt can be related to the development of carbonate-rich stratiform copper and base metal deposits in the Paleozoic basement [3]. In general, the outer zone of the Uyanda–Yasachen belt is characterized by the presence of silver mineralization. The antimonite mineralization is also widespread. Faults zones developed as auxiliary elements of the Uyanda–Yasachen belt in the western Verkhoyansk region incorporate large epithermal silver–base metal deposits (Prognoz and Mangazei) and numerous gold–silver occurrences of the N'yutakam district [4].

The *Oloi volcanic belt* is controlled by the Early Cretaceous island-arc system sandwiched between the South Anyui and Omolon terranes (Fig. 1). The NW-oriented Oloi belt extends over more than 600 km and reaches the Svyatoi Nos Cape [5]. Its width is as great as 200 km in the central sector. Numerous porphyry Cu–Mo and epithermal gold–silver deposits in this belt are related to magmatism of the paleoisland arc. The Cu–Mo stockworks are confined to stocks and small massifs of the gabbro–monzonite–syenite series, while the epithermal gold–silver veins are developed along the periphery of these intrusive bodies. Based on the geological setting and isotope data, the mineralization is attributed to the terminal Late Jurassic [3]. The Oloi belt is characterized by an abundance of sulfides, hematite, and minerals of Co and Pt [2], probably owing to the ophiolitic composition of the substrate and the presence of fragments of the Precambrian crust with ferruginous quartzites. According to [3, 6], the porphyry Cu–Mo and epithermal gold–silver deposits and occurrences in the Oloi belt can be united into a single ore-formation series based on the following features: (1) distinct paragenesis with a single volcanotectonic depression; (2) similarity and legacy of the mineral composition and trace elements in ores and minerals (presence of the same ore minerals and elements in all assemblages); (3) identical compositions of mineral-forming solutions in the ore-hosted fluid inclusions; and (4) similar isotopic characteristics of the ore lead [3].

The *Uda–Murgal volcanic belt* represents the basement of the Okhotsk sector of the OCVB. This belt is controlled by the continental margin and boundaries of the Okhotsk paleoisland arc [5]. The paleoisland arc is exposed on the left bank of the Uda River, the Koni–P'yagin and Taigonos peninsulas, and basins of the Penzhina and Anadyr rivers (Fig. 1). The island arc includes basalts and basaltic andesites, their tuffs and tuffaceous breccias, and subordinate felsic rocks (no more than 4%). Rock sequences in the volcanic belt are 3 to 7 km thick. The field of epithermal Au–Ag and porphyry Cu–Mo deposits coincides with the front of the OCVB superimposed upon the terrigenous–volcanic complex of the continental-margin arc. The latter rock complex is intensely dislocated and locally overthrusted toward the continent. The stringer–disseminated and vein–stockwork mineralizations are associated with porphyry complexes [7]. The successive replacement of the Cu-rich mineralization by the Mo–Cu and Mo-rich varieties (often with W) and the Sn mineralization toward the continent correlate well with thickening of the "granite" layer and increase in the contribution of leucocratic granites and granite porphyres in the ore-bearing magmatic complexes. Ores of the epithermal gold–silver vein deposits (Dzhul'eta, Nyavlenga, and others) are characterized by progressive ore formation and high contents of Ag [8].

The *Okhotsk–Chukot volcanic belt* formed over 25 Ma (middle Albian–Cenomanian) [9] at the boundary between the continental Verkhoyansk–Chukot and Koryak–Kamchatka terranes. This belt is 3000 km long and represents an autonomous structure of the Earth's crust composed of subaerial volcanic rocks (Fig. 1). Relative to the oceanic margin, the Okhotsk–Chukot belt is divided into the inner, outer, and perivolcanic zones. The inner zone is underlain along the Okhotsk segment by the Koni–Murgal terrane (Fig. 1), which was a part of the island-arc system in the Late Paleozoic–Neocomian. This zone was transformed into the continental-margin magmatic arc at the last stage of evolution. We believe that the perivolcanic zone of the Okhotsk–Chukot belt is a region of tectonomagmatic reactivation of Mesozoic structures related to the activity of the volcanic belt. This zone extends along the outer boundary of the belt. The intricate structure of terranes of the basement and the Okhotsk–Chukot belt stimulated the diversity of epithermal deposit types. The inner zone of the belt mainly accommodates porphyry Cu–Mo deposits. The outer and perivolcanic zones include gold–silver and tin ore formations (including the tin–silver mineralization). The gold–silver subtype is more widespread in the outer zone (Karamken, Sopka Kvartsevaya, Sopka Rudnaya, Kupol, and Dvoinoi). Deposits of the silver subtype (Dukat, Lunnyi, Arylakh, and others) are confined to the volcanic rift located between the Yana–Kolyma and Omolon terranes of the Okhotsk–Chukot belt (Fig. 1).

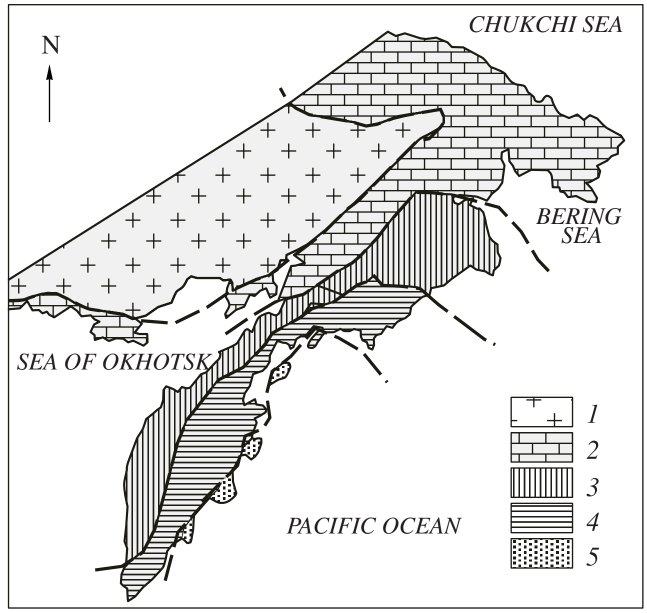

Fig. 2. Tectonic scheme of the continental margin of Northeast Eurasia in the Middle Jurassic (based on [12]). (*1*) Continental margin of Northeast Eurasia in the Middle Jurassic; (*2–5*) accreted terranes: (*2*) in the Middle Cretaceous, (*3*) in the Late Cretaceous–Paleocene, (*4*) in the Middle Eocene, (*5*) in the Middle Miocene.

The *Koryak–West Kamchatka volcanic belt* extends along the western coast of the Kamchatka Peninsula and walls of the Penzhina depression (Fig. 1). The composition of volcanic rocks varies from basalts to rhyolites. The volcanic sequence is 3500 m thick. The northern Oligocene part of the belt within the Koryak Highland is characterized by reduced thickness and more felsic composition. Eocene volcanic rocks make up a virtually continuous cover extending over the western coast and can be interpreted as an island arc, because the volcanic sequence includes shallow-water sedimentary facies [10]. The southern part of the Koryak–West Kamchatka belt incorporates the Okynchevayam gold–silver occurrence, small mercury occurrences, and cassiterite placers. The northern part includes the Ichigin–Uineivayam ore district with the large Ametist deposit and numerous gold–silver and tin occurrences associated with paleovolcanic edifices of the andesite–dacite–rhyolite formation.

The Paleogene *Central Kamchatka volcanic belt* is controlled by the Main Kamchatka deep fault zone over nearly 1800 km (Fig. 1). This belt represents the largest orogenic structure in Kamchatka. In contrast to the volcanic belts described above, the Central Kamchatka belt is dominated by andesites and basaltic andesites. This feature reflects the presence of a mafic basement in the belt and governs the metallogenic specialization of the Central Kamchatka belt: absence of tin and silver occurrences; abundance of near-surface telluride mineralization of the gold–silver formation. The Central Kamchatka belt incorporates the greatest number of economic gold–silver deposits that are united into the North Kamchatka, Ogancha–Kozyrev (Central Kamchatka), and South Kamchatka ore districts. In addition, the Central Kamchatka belt includes numerous mercury and gold–mercury occurrences. Alunite–sulfur ores are associated with secondary quartzites.

The *East Kamchatka volcanic belt* adjoins the present-day Kuril–Kamchatka trench and extends parallel to the southeastern coast of Kamchatka from its southernmost end to the Aleut island-arc section (Fig. 1). The belt was initiated in the Pliocene. Active volcanism is continuing to this day. Metallogeny of the East Kamchatka belt is poorly studied. This belt incorporates the Kumroch gold–silver deposit. The process of gold–silver mineralization is continuing now in the East Kamchatka belt, e.g., in the interior of the Uzon Caldera [10].

In addition to the volcanic belts mentioned above, some tectonomagmatic zones branching off from volcanic depressions of the OCVB also incorporate the epithermal gold–silver deposits. In the Khurchan–Orotukan zone, the epithermal Pechal'noe (Au–Ag) and Vetvistoe (Ag–base metal) deposits occur in Jurassic terrigenous sequences beneath remnants of Late Cretaceous volcanic rocks. Gold–silver deposits in tectonomagmatic reactivation zones and the large Hishikari deposit (Japan) are characterized by similar formation conditions [11].

Figure 1 shows that volcanic belts of different ages are juxtaposed in some districts. For example, a significant part of the Okhotsk–Chukot belt overlaps the Uda–Murgal belt. Volcanic depressions of the former belt and auxiliary tectonomagmatic activation zones are also superimposed upon the Kedon volcanic belt. These districts include several multistage gold–silver deposits (Dzhul'eta, Nyavlenga, and others). The Kubaka and Birkachan deposits include Paleozoic and Mesozoic gold–silver mineralizations. However, the metallogeny of the majority of such ore districts is poorly studied.

Even the brief overview of volcanic belts in Northeast Asia presented in this communication shows that the mineralogy of the epithermal gold–silver deposits in these belts depends on the metallogeny and composition of rocks in structures of the basement and, probably, the Precambrian basement. The porphyry Cu–Mo and massive sulfide ore districts, as well as regional zones of disseminated sulfides, include deposits of gold–silver and silver subtypes. Basic–ultrabasic rock complexes host deposits of the gold–silver–telluride subtype; ferruginous quartzites incorporate deposits of the gold subtype; and tin ore districts include the gold–silver deposits [4].

The volcanic belts and zones described in the present paper are poorly studied. Therefore, not only small and medium bonanza deposits, but also large epithermal gold–silver deposits may be discovered in Northeast Russia. The potential of the epithermal stockwork mineralization, which can be developed by the method of open pit mining and heap leaching, deserves the organization of special prospecting and research works in the study region.

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