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Spatial Distribution and Formation Conditions of Au-Bearing Porphyry Cu–Mo Deposits in the Northeast of Russia

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Abstract—By analogy with other metallogenic belts of the Circum-Pacific ring, the metallogenic belts in the Northeast of Russia are promising for discovery of large and superlarge porphyry-type Au–Cu–Mo deposits. The spatial distribution of these deposits is controlled by intrusive domes in Middle Paleozoic, Late Jurassic–Early Cretaceous, and Late Cretaceous volcanic belts. New data on formation conditions and sources of ore matter are presented in this paper with respect to the deposits of the Baim and Koni–P'yagina ore districts of the Oloi and Uda–Murgal metallogenic belts. Some aspects of a geological and genetic model of the porphyry copper ore–magmatic system are discussed.

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INTRODUCTION

The forecasting, exploration, and evaluation of porphyry Cu–Mo deposits in volcanic belts in the Northeast of Russia is one of the most important current lines of research aimed at expansion of mineral resources of not only copper and molybdenum but also gold, silver, and platinum group and some other rare metals.

According to the modern concept, the largest metallogenic belts in the inner zone of the Circum-Pacific belt in northeastern Asia are controlled by accretionary and postaccretionary tectonic units superimposed on island-arc and oceanic terranes (*Geodynamics*…, 2006). Massive sulfide deposits of various types related to "green tuffs" were formed in these terranes, whereas porphyry copper deposits, which are basic for several ore districts with epithermal gold–silver and base-metal mineralization (Sidorov, 1987), were originated at the stage of accretion. Sillitoe (1993) and Hedenquist and Loewenstern (1994) also supposed that epithermal gold–silver, base-metal, and gold–sulfide (Carlin-type) deposits are formed within the porphyry copper ore–magmatic system.

The study of present-day sulfide ore formation in spreading zones has shown that sulfides precipitate owing to mixing of hydrothermal fluids with seawater and led to an understanding of the nature of massive sulfide copper deposits in island arcs (Kovalev et al., 1993; Herbert and Constantine, 1991). However, sources of ore matter and the genetic model of the porphyry copper ore–magmatic system have remained debatable.

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Under the current economic conditions of northeastern Russia, most of the known porphyry Cu–Mo deposits and occurrences are not promising for economic development. However, the metallogenic belts and zones where these deposits are located are extremely important in forecasting of potentially economic high-grade epithermal gold–silver deposits.

At different times, we have studied the metallogenic belts and ore districts considered below. The most recent results of thermobarogeochemical studies were obtained only in 2005. In preparing this paper, we pursued the following goals: (i) to consider the current state of the problem and to summarize the previously obtained results, (ii) to outline the geodynamic settings favorable for formation of porphyry-type Au-bearing Cu–Mo deposits in the Northeast of Russia and the main trends in their spatial distribution, (iii) to review the geology of typical deposits and the ore composition therein, (iv) to study ore formation conditions in a comparative aspect, and (v) to clarify the relationships between epithermal Au–Ag and porphyry Cu–Mo ores in the common ore-forming system.

GENERAL OUTLINE OF PORPHYRY-TYPE DEPOSITS

Porphyry-type deposits are the main worldwide source of Cu and Mo; Au, Ag, and platinum group and some other rare metals are recovered from this ore as by-products. Porphyry deposits are accompanied by

Table 1. Some Au-bearing porphyry copper deposits of the Pacific ore belt, after Cooke et al. (2005)

Deposit	Location	Ore reserves, Mt	Gold reserves, t	Average grade		Age, Ma
				Au, g/t	Cu, %	
Grasberg	Papua New Guinea	2480	2604	1.05	1.13	3
Bingham	United States	3228	1603	0.5	0.88	38.8
Lepanto Far	Philippines	685	973	1.42	0.8	1.5
Cerro Casale	Chile	1285	900	0.7	0.35	13.5
Panguna	Papua New Guinea	1415	799	0.57	0.46	3.5
Batu Hijau	Indonesia	1644	572	0.35	0.53	3.7
Minas Conga	Peru	641	566	0.79	0.30	20
Ok Tedi	Papua New Guinea	700	446	0.64	0.64	1.2
El Teniente	Chile	11845	437	0.035	0.63	4.8
Escondida	″	2262	430	0.19	1.15	38
Bajo de Alumberta	Argentina	551	369	0.67	0.52	8
Frieda River	Papua New Guinea	1103	354	0.32	0.61	14
Pebble Copper	Alaska	1000	340	0.34	0.30	90
Tampakan	Philippines	1400	336	0.24	0.55	3.3
Atlas	″	1380	331	0.24	0.50	61
Chuquicamata	Chile	12066	301	0.04	0.55	33.6
Sipalay	Philippines	884	301	0.34	0.50	60

numerous base-metal, gold–silver, and antimony–mercury satellite deposits and placers and are important for the economic development of Chile, Peru, Uzbekistan, Kazakhstan, Mongolia, Armenia, Serbia, Macedonia, Bulgaria, Romania, and partly Mexico and Greece. Large and superlarge deposits of this type were recently found in Iran, Afghanistan, Pakistan, China, Mongolia, North and South America, Indonesia, the Philippines, Papua New Guinea, and Russia; these deposits also will be involved in economic development.

Porphyry deposits provide approximately 20% of the gold and silver produced in the United States. Large porphyry copper deposits with average grades of 2 g/t Ag and 0.4 g/t Au are located in Arizona; their hypothetical resources are estimated at 80 Mt Cu. The Bingham ore district in Utah ranks first in mining copper and second in mining molybdenum. In 1890–1971, the Bingham porphyry copper deposit yielded about 31 kt Ag and 300 t Au, including 800 t Ag at a grade of 2 g/t in 1970 alone. As much as 4 kt Ag and 55 t Au were produced over the same period from base-metal ore of this district (Konstantinov et al., 2003).

According to Krivtsov et al. (1986), porphyry deposits are classified by Ag grades into (i) Mo deposits virtually devoid of Ag, (ii) Mo–Cu deposits with <1 g/t Ag, (iii) Cu–Mo deposits with <1 to a few grams per ton Ag, and (iv) Ag–Cu deposits that commonly contain a few tens of grams per ton Ag. Although the Ag grade of porphyry copper ore is extremely low (no higher than 5–6 g/t, on average, and commonly 0.3–3.0 g/t), the bulk of silver produced is considerable owing to the enormous mass of ore involved in processing. Associated veins with high Ag and Au grades are often regarded as independent noble metal deposits.

In terms of Cu, Mo, Au, and Ag reserves, porphyry deposits are referred to as large and superlarge (100–1000 Mt of ore or more) with low and medium grades: 0.3–1.5% Cu, 0.001–0.05% Mo, 0.03–1.0 g/t Au, and 1–6 g/t Ag (Table 1).

The deposits vary from Precambrian to Quaternary in age; Mesozoic and Cenozoic deposits are predominant; the latter prevail in the Pacific ore belt (Table 1).

The classic porphyry copper provinces were formed in geodynamic settings of continental volcanic belts and volcanic island arcs.

The most important characteristics of porphyry systems (Cooke et al., 2005; Kerrich et al., 2000; Krivtsov, 2001) are as follows:

(1) Occurrence of ore-bearing minor porphyry intrusions (<2 km in diameter) composed of calc-alkaline and potassic, moderately alkaline rocks. The ore is also hosted in volcanic, sedimentary, and other country rocks. Coeval andesitic and dacitic volcanics are common for island arcs, while potassic, moderately alkaline rocks are typical of the continental setting.

(2) Hypabyssal depth of ore formation (1–4 km).

(3) Porphyritic texture of ore-bearing intrusions, where phenocrysts of feldspar, quartz, and dark-colored minerals are incorporated into a fine-grained groundmass.

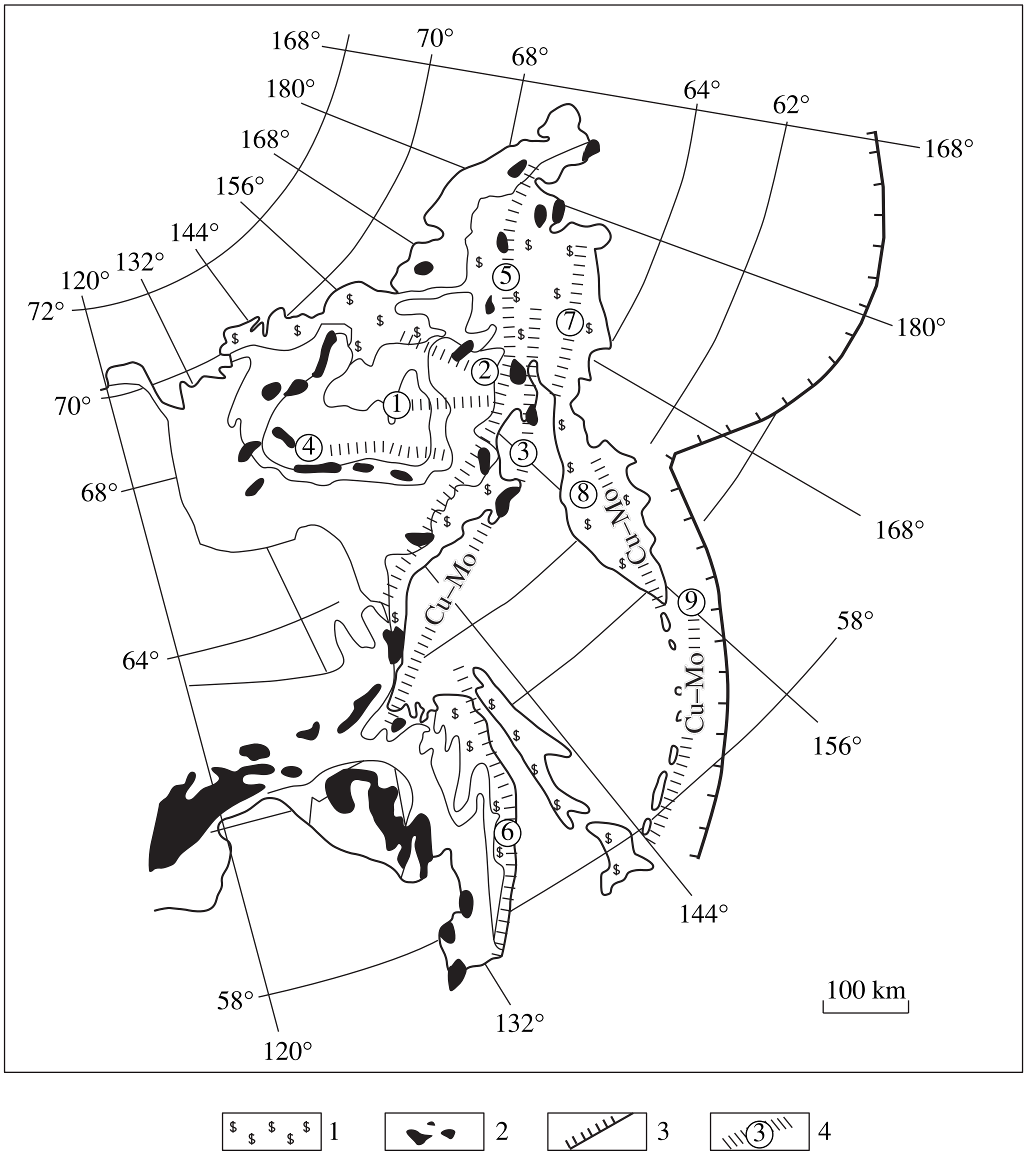

Fig. 1. Porphyry Cu–Mo metallogenic belts in the marginal-sea province of northeastern Asia. (1) Areas of volcanic rocks; (2) plutonic rocks; (3) deepwater trench; (4) porphyry Cu–Mo metallogenic belts (numerals in circles): (1) Kedon, (2) Oloi, (3) Uda–Murgal, (4) Yasachnaya River, (5) Okhotsk–Chukotka, (6) East Sikhote-Alin, (7) Koryak, (8) Central Kamchatka, (9) Kuril.

(4) Numerous intrusive phases may be pre-, syn-, and postore; late diatremes are typical of the West Pacific deposits.

(5) Progressive evolution of a steep ore-bearing stockwork from the early, short, and irregularly arranged veins and veinlets closely related to emplacement of intrusions via transitional veins lying in one plane to the late through veins and breccia bodies related to regional and local stress fields.

(6) Extensive development of metasomatic alteration and ore mineralization controlled by fractures in porphyry intrusions and country rocks.

(7) Several stages of hydrothermal alteration that develop progressively from early potassic and propylitic alteration to phyllic (sericitic) and intermediate and advanced argillic alteration.

(8) Sulfides and oxides vary from bornite and magnetite in the early mineral assemblages to transitional chalcopyrite and pyrite to late pyrite and hematite, pyrite and enargite, and pyrite and bornite.

(9) Cu–Au (Mo, Ag) is the major (economic) assemblage of metals; the Pb–Zn (Ba, Mn) assemblage also may be of economic importance; Mo is typical of central portions of continental deposits and marginal parts of island-arc deposits. Gold is visible and submicroscopic and also occurs as electrum.

(10) The early metasomatic rocks and related copper mineralization are generated by magma-derived

Table 2. Metallogenic belts with porphyry Cu–Mo and epithermal Au–Ag deposits in the East of Russia

No.	Belt	Age		Geodynamic setting	Mineral resources	Deposits and occurrences	
		index	Ma			porphyry Cu–Mo	epithermal Au–Ag
1	Kedon	D_3–C_1	416–318	Marginal continental volcanic belt	Au, Ag, Fe, Pb, Cu, Zn, In	Tabor, Shchel'ninsky, Svetkin Klyuch	Kubaka, Birkachan, Ol'cha, Zet
2	Oloi	J_3–K_1	146–100	Volcanic island arc	Au, Ag, Hg, Pb, Cu, Mo, Zn, In	Peschanka, Nakhodka, Dal'ny, Innakh	Klen, Alisa, Vesenny, Smeshlivy, Verny
3	Uda–Murgal	K_1	136–100	″	Au, Ag, Hg, Pb, Cu, Mo, Zn, In	Lora, Pryamoi, Ikrimut, Viking, Osenny	Irgunei, Dzhul'etta, Nyavlenga, Sergeevsky
4	Yasachnaya River	J_2–K_1	175–136	″	Au, Ag, Pb, Cu, Zn, In	Datsitovy, Gaisky, Nevidimka	Kunarevsky, Shiroky, Urul'tun
5	Okhotsk–Chukotka	K_2	100–70	Marginal continental volcanic belt	Au, Ag, Sn, Hg, Pb, Cu, Zn, Mo, Sb	Shurykan, Gagachi, Krasny Gory, Ol'khovka, Vecherny, Orliny	Dukat, Lunny, Kupol, Karamken, Valunisty, Sopka Rudnaya, Dvoinoi, Khakandzha
6	East Sikhote Alin	K_2–Pg_1	100–55	″	Au, Ag, Sn, Hg, Pb, Cu, Zn, B	Nochnoi, Moninsky, Sukhoi, Lazorevsky	Mnogovershinny, Belaya Gora, Maisky, Soyuzny
7	Koryak	Pg	55–23	″	Au, Ag, Sn, Hg, Pb, Cu, Zn, W	Kuibiveem, Lalankytap, Rzhav'e	Ametistovy, Ivolga, Orlovka, Sprut
8	Central Kamchatka	N_1	23–5	″	Au, Ag, Hg, Pb, Cu, Zn, In	Krasny Gory, Malakhitovy, Kirganik	Aginsky, Baran'evsky, Ozernovsky
9	Kuril	N_2–Q	5–0	Volcanic island arc	Au, Ag, Hg, Pb, Cu, Zn, In	Shumshu, Karginsky	Praslovsky, Riftovy, Kupol (Urup)

Note: Metallogenic belt numbers correspond to Fig. 1.

hydrothermal fluids with a salinity of 30–60 wt % NaCl equiv at a temperature of >600 to 400°C. The fluids responsible for the formation of the late metasomatic alteration and ore mineralization contain a meteoric component; they are less saline (<15 wt % NaCl equiv) and low-temperature (400–200°C). The host intrusions serve as a source of heat.

(11) The topology of the subducted plate controls ore mineralization in the overriding island arc. The subduction-related deformational setting gives rise to thickening of the crust, block uplifts, and faulting and fracturing favorable for development of ore mineralization.

SPATIAL DISTRIBUTION OF PORPHYRY-TYPE DEPOSITS IN THE NORTHEAST OF RUSSIA

The promising porphyry Cu–Mo deposits and occurrences in the Northeast of Russia make up metallogenic belts of various ages (Fig. 1; Table 2). More than 110 porphyry copper–molybdenum deposits and occurrences are shown in the metallogenic map of the Northeast of Russia (*Explanatory Notes*…, 1986).

The specific metallogenic features of these belts are caused by tectono-magmatic reactivation in the transitional zone from ocean to continent and, in particular, are related to the formation of the Late Cretaceous marginal continental Okhotsk–Chukotka volcanic–plutonic belt (OChVB), which is superimposed on Triassic and Jurassic island-arc and cratonic complexes that were formed above seismofocal (paleosubduction) zones that plunge down to a depth of 600–700 km. At present, the low-amplitude thrusting of perioceanic blocks under continents has been established rather reliably (Peskov and Migovich, 1980; Belousov, 1982; Vasil'ev, 1982; Umitbaev, 1986).

The Kedon Metallogenic Belt

The Kedon metallogenic belt coincides with the Middle Paleozoic volcanic belt of the same name in the Omolon Cratonic Terrane (Fig. 1; Table 2). Volcanic rocks of the Kedon belt overlap the Archean–Paleoproterozoic basement and its Phanerozoic sedimentary cover. The belt, 40000 km^2 in total area, is composed of subaerial volcanic flows of the Devonian–Lower Carboniferous Kedon Group and coeval subvolcanic and extrusive bodies. Three volcanic fields—Kedon, Rassoshino, and Tokur-Yuryakh—extend from southeast to northwest (Egorov and Goryachev, 2001). The total thickness of volcanic flows in the largest Kedon field reaches 1500–2000 m in the central part of this field and is reduced to 500–1200 m at its margins. The Rb–Sr age

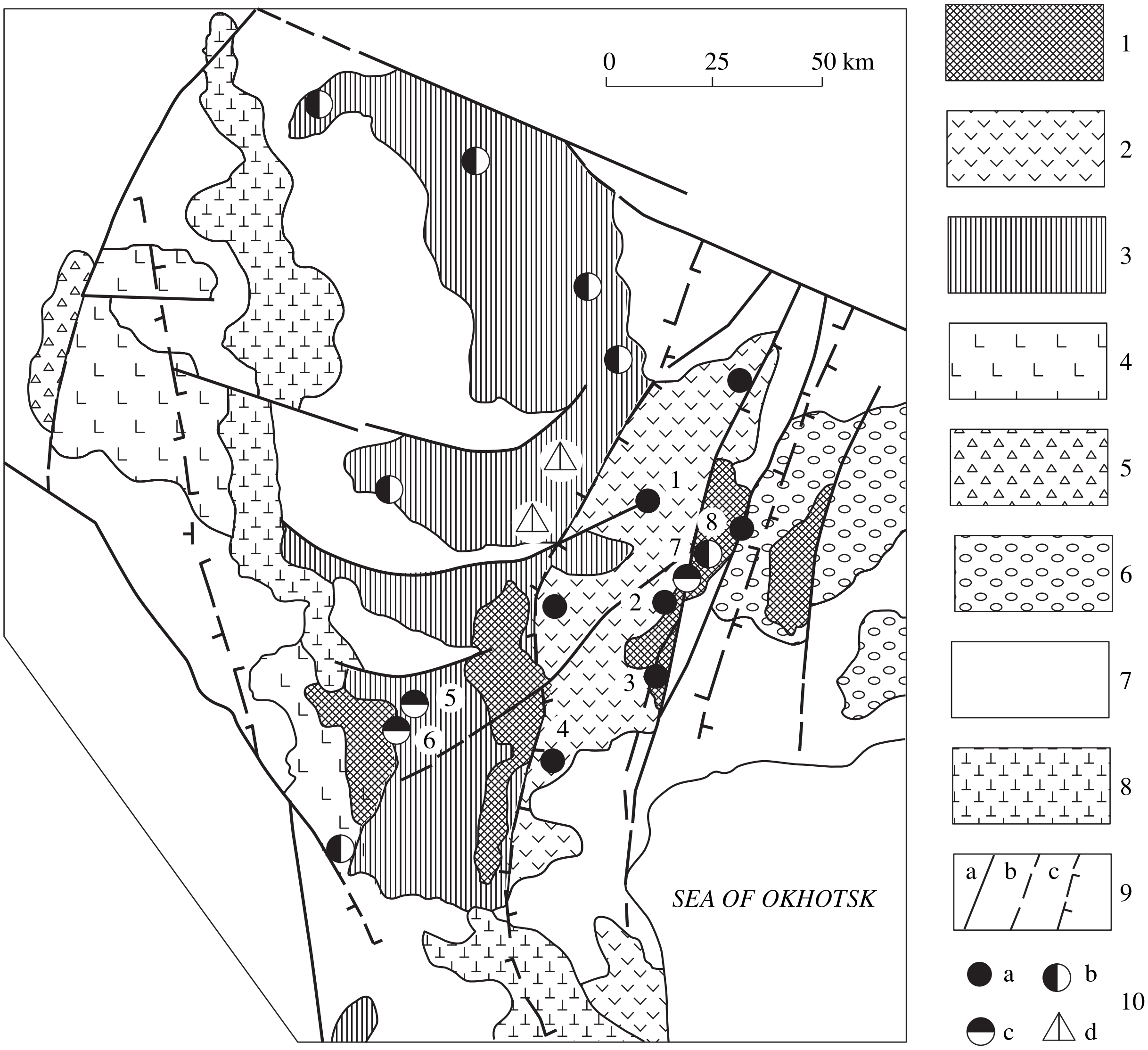

Fig. 2. Metallogenic demarcation of the southern Omolon Massif. (1) Inliers of the Precambrian crystalline basement; (2–4) Kedon lithotectonic zone: (2) Amandykan subzone, (3) Kedon–Omolon subzone, (4) Abkit subzone; (5–8) Aulandzha lithotectonic zone: (5) volcanogenic molasse, (6) molasse and cherty sequences, (7) Upper Carboniferous terrigenous and carbonate sequences, (8) Late Cretaceous andesites; (9) faults: (a) bounding the massif, (b) dividing the massif into blocks, (c) bounding metallogenic zones; (10) epithermal Au–Ag deposits (a) and occurrences (b), porphyry Cu–Mo occurrences (c), jasperoid Au occurrences (d). Deposits and occurrences (numerals in the figure): (1) Birkachan, (2) Kubaka, (3) Dubl, (4) Yelochka, (5) Vecherny, (6) Khrustal'ny, (7) Tabor, (8) Orliny.

of volcanic rocks belonging to the Kedon Complex is 334–377 Ma; relatively rare findings of Givetian brachiopods; Givetian, Famennian, and Early Carboniferous conodonts; and Early Carboniferous plant remains have been noted (Egorov and Sherstobitov, 2000).

The ore mineralization of the marginal continental volcanic–plutonic belt was formed in the Omolon Terrane during the Middle Paleozoic stage. Lateral zoning is expressed in localization of porphyry copper deposits in the east, epithermal gold–silver deposits in the transitional zone, and Au-bearing jasperoids in the west (Fig. 2).

The porphyry Cu–Mo deposits occur in the eastern part of the Omolon Cratonic Terrane and are controlled by the Upper Omolon Fault (Fig. 2). The ore mineralization is related to the intrusions of the Bulun Complex and most often located in contact zones of Middle Paleozoic granitoid plutons and subvolcanic rhyolitic intrusions enriched in potassium. Intrusive rocks of the Bulun Complex comprise quartz diorite, granodiorite, quartz monzonite, granosyenite, granite, and alkali granite and have a porphyritic appearance.

The best studied *Tabor occurrence* is confined to the eastern contact of the Orliny pluton with Archean metamorphic rocks (Fig. 2). Granodiorite of this pluton and country rocks are intruded by dikes and stocks of quartz diorite porphyry of the Bulun Complex. Numerous basic and intermediate dikes and small stocks of Cretaceous (?) age were mapped in the ore field. The disseminated ore mineralization is hosted in epidote–chlorite propylites that replace granodiorite of the Orliny pluton and quartz diorite porphyry of the Bulun Complex. A near-meridional zone of intense sulfide mineralization extends in the central part of the ore field for 3200 m, having a width of 500 m. Cappings that bear azurite and malachite are noted within this zone as segments up to 200 m wide. Trench samples from the mineralized zone yielded 0.7% Cu and 0.015% Mo. The highest contents—1% Cu and 0.5% Mo—were established in separate quartz veins with visible molybdenite. In addition to Cu and Mo, >0.1 g/t Au and 1–4 g/t Ag were detected. It is highly probable that the Orliny Au–Ag occurrence, found to the north of the Tabor occurrence (Fig. 2), is a constituent of the common porphyry system.

The Shchel'ninsky and Ledyanoi ore fields, with the same mineralization as at the Tabor occurrence, are also localized in the Upper Omolon Fault Zone. The occurrence of porphyry copper ore is expected at deep levels of the Dubl Au–Ag occurrence (Egorov, 2001) (Fig. 2).

It should be noted that Late Cretaceous porphyry Mo–Cu occurrences (Vecherny, Khrustal'ny, etc.; Fig. 2) related to the evolution of the OChVB are widespread in the South Omolon district (Pak, 2004; *Geodynamics*…, 2006).

The Oloi Metallogenic Belt

The Oloi metallogenic belt is controlled by an Early Cretaceous island arc system situated between the South Anyui and Omolon terranes. Most of it is now located at the interfluve of the Oloi and Greater Anyui rivers, extending in the northwestern direction for 400 km at a width of 200 km in the central segment (Figs. 1, 3). Numerous porphyry Cu–Mo and epithermal Au–Ag deposits (Fig. 3; Table 2) are related to the island-arc magmatism (*Geodynamics*…, 2006). Cu–Mo stockworks are localized largely in stocks and minor intrusions of the gabbro–monzonite–syenite association, while epithermal Au–Ag veins develop at their periphery.

The geological age of ore mineralization is estimated at the terminal Late Jurassic (Gulevich and Titov, 1975). K–Ar estimates indicate an Early Cretaceous age of some ore-bearing syenite intrusions; ore mineralization is also known in Lower Cretaceous sedimentary rocks (Gorodinsky et al., 1978). It cannot be ruled out that this mineralization was remobilized in the Late Cretaceous during evolution of the postaccretionary volcanic–plutonic belt.

Widespread magnetite and occurrence of Co and Pt minerals are typomorphic attributes of ore mineralization in the Oloi metallogenic belt (Shpikerman, 1998), probably, due to the effect of oceanic blocks as a basement and fragments of Precambrian rocks including jaspilites at the periphery of the Omolon Terrane. In the southeastern segment of the belt, the ore fields make up a chain that extends along the near-meridional Baim Fault as a metallogenic zone of the same name (Fig. 3). In the northwestern segment of the island-arc system, the best studied porphyry copper and epithermal gold–silver deposits are located in the Innakh and Topolevo–Krichal'sky ore districts (Fig. 3).

The Innakh district is related to one of the basement uplifts within the Oloi volcanic belt (Goryachev and Polovinkin, 1979). The ore occurrences are localized near the contacts of the Kamen Takmyka multiphase gabbro–monzonite–syenite pluton and near its northern satellites. The best studied ore occurrence, Dal'ny, is a stockwork of quartz, carbonate–quartz, and quartz–sulfide veinlets with copper–molybdenum and base-metal mineralization and gold (Gorodinsky et al., 1978). The Topolevo–Krichal'sky district resembles the Innakh district. In addition to porphyry copper occurrences, several epithermal gold–silver deposits and occurrences (Klen, Alisa, etc.) are known here. They are located in the uplifted block composed of Triassic volcanosedimentary rocks of the Khetachan Terrane near and within small syenite and syenite porphyry stocks of the Yegdegkych Complex.

The Baim metallogenic zone extends in the near-meridional direction for 80 km at a width of 6–18 km (Fig. 3) and comprises numerous Au- and Ag-bearing porphyry copper, porphyry copper–molybdenum, and epithermal Au–Ag deposits and occurrences (Table 3).

The central and northern segments of the Baim zone coincide with the southeastern block of the Kur'ya Trough of the Late Jurassic–Early Cretaceous Oloi volcanic belt. The ore mineralization is related to the gabbro–monzonite–syenite association. The porphyry copper occurrences of the Erguveem ore district in the southern segment of the Baim zone are hosted in the igneous rocks of the Anadyr sector of the outer zone of the Cretaceous OChVB (Rozhdestvensky et al., 1976; Volchkov et al., 1982).

The Cu–Mo–Au–Ag stockworks of the Peschanka and Nakhodka deposits are related to monzonite–syenite plutons located in the eastern part of the Baim zone (Figs. 3, 4). Placers of very fine gold and PGM are associated with these deposits. Numerous sulfide–quartz and quartz–carbonate epithermal veins with Au–Ag mineralization (the Vesenny deposit, the Verny and Smeshlivy occurrences) are hosted in the Upper Jurassic rocks in the western segment of the Baim zone.

The deposits and occurrences listed above are combined into a common porphyry copper series on the following grounds: (i) clearly expressed relations to the same volcanic–plutonic association; (ii) similar mineral composition and trace element assemblages in ores and minerals and occurrence of through minerals and chemical elements (Shapovalov, 1985); (iii) identical ore-forming solutions captured as fluid inclusions in

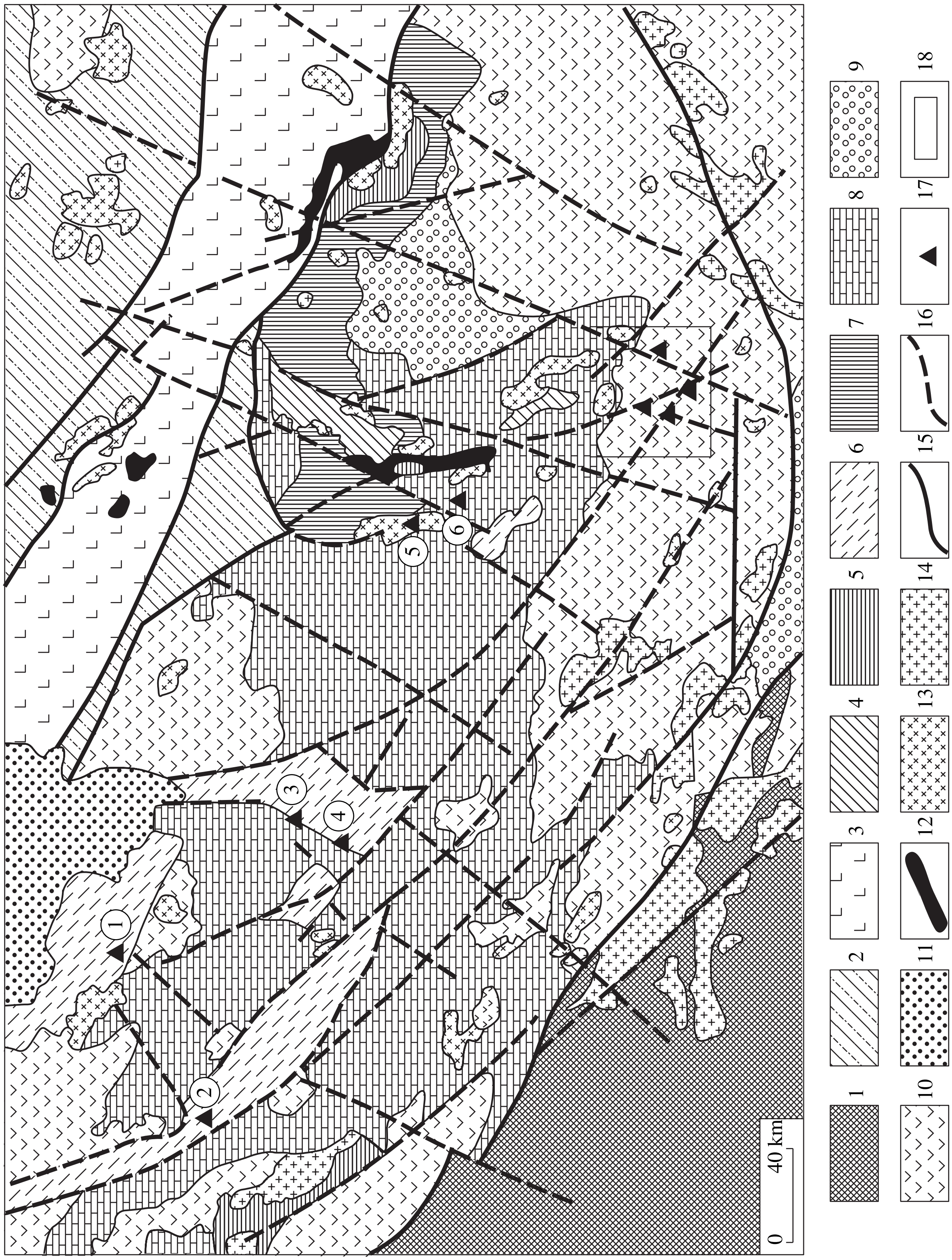
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Table 3. Porphyry Cu–Mo and Au–Ag deposits and occurrences of the Baim metallogenic zone. Compiled after results of geological exploration obtained by the Anyui Geological Exploration Expedition

No.	Deposit, occurrence	Ore district	Average grade			
			Cu, %	Mo, %	Au, g/t	Ag, g/t
1	Peschanka	Baim	0.51	0.03	0.42	1.4
2	Nakhodka	″	0.4	0.015	0.15	1.2
3	Vesenny	″	0.5	0.0004	3.6	35
4	Asket	″	0.3–1.4	0.03	0.2–11.9	0.5–30
5	Pasmurny	″	0.3–1.0	0.01	1–28.3	3–70
6	Luchik	″	0.12–0.9	0.0001–0.02	0.32	2
7	Vesenny-3	″	0.4	0.015	0.15	1.2
8	Malysh	″	0.4	0.006	0.15	6.2
9	Pryamoi	″	0.36	0.0035	0.34	2.1
10	Vesninsky	Ergyveem	0.16–2.06	0.02–0.7	0.4–7.25	1–100
11	Pryazhka-1	″	0.2–0.5	0.01–0.2	0.1–0.5	1–10
12	Pryazhka-2	″	0.34–2.79	0.03	0.01–0.1	3
13	Pryazhka-3	″	0.1–0.8	0.08–0.3	0.2	1–15
14	Sokol	″	0.5–1.0	0.01–0.2	0.2	1–10
15	Rzhavy	″	0.3	0.05	1.0	1–10

ore (Goncharov and Sidorov, 1979; Shapovalov, 1985); and (iv) similar isotopic parameters of ore lead (Shpikerman et al., 1993).

Gold of high fineness (890–950) is typical of Cu–Mo deposits and occurrences, whereas gold of low fineness (650–710) is characteristic of the Au–Ag ore mineralization. PGE were detected in ore from the Peschanka deposit (ppm): 0.012 Pt, 0.093 Pd, and 0.013 Rh. Molybdenite and chalcopyrite contain Re and Ge up to 0.001% (Shpikerman, 1998).

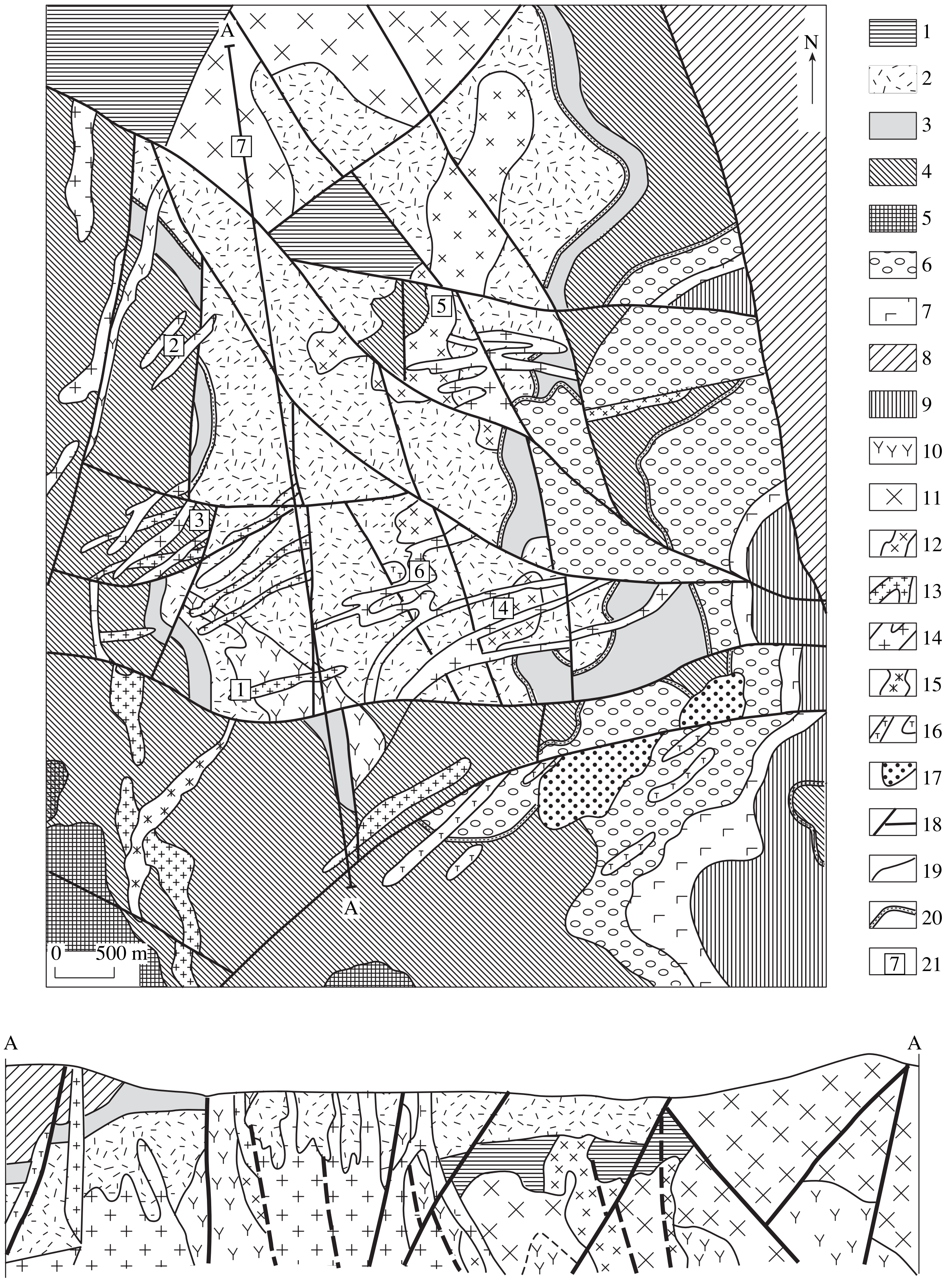
The average Cu, Mo, Au, and Ag grades and contents of some trace elements in ores from the Baim district are shown in Table 4. Gold is second in importance after copper at the Peschanka and Nakhodka deposits.

The Baim ore district is related to the southeastern prominence of the Yegdegkych gabbro–monzonite intrusion, crosscut by dike-shaped offsets of the Omchak granodiorite pluton (Shavkunov, 1973). The NW- and NE-trending ore-controlling faults are the geological boundaries of the district (Fig. 4).

The district is composed of Upper Jurassic volcanic and sedimentary rocks that make up a large anticline slightly elongated in the northeastern and nearly latitudinal directions. Rhyolitic and dacitic lavas and tuffs of the felsic sequence 400–600 m thick and basaltic andesite of the basic and lilac sequences up to 1200 m in total thickness are the most abundant; the relatively thin siltstone, sandstone, and conglomerate units have been mapped.

The volcanic and sedimentary rocks are intruded by plutonic and subvolcanic bodies subdivided into two complexes. The gabbro–syenite intrusions of the Yegdegkych Complex occur largely to the north of the Baim district; several hypabyssal bodies are known within this district. At least three intrusive phases are recognized: (1) pyroxenite (low-abundant); (2) gabbrodiorite, syenite, monzodiorite, and granosyenite; and (3) subvolcanic bodies of monzodiorite porphyry and less frequent syenite aplite and granodiorite porphyry. The U–Pb zircon age of magmatic zircons from the Yegdegkych pluton is 141.8 ± 2 Ma (Shpikerman, 1998).

Fig. 3. The Baim metallogenic zone in the context of regional tectonics, modified after Rozhdestvensky et al. (1976). (1) Precambrian and Paleozoic basement (Omolon Terrane); (2) Triassic terrigenous sequences of the Anyui Zone; (3) Upper Jurassic and Lower Cretaceous sedimentary and volcanosedimentary sequences of the Oloi Belt; (4, 5) Paleozoic sedimentary sequences of the (4) Aluchino and (5) Yarinvaam anticline uplifts; (6) Triassic sedimentary sequences of the Khetakchan Terrane; (7) Triassic sedimentary sequences of the Aluchino and Yarinvaam anticline uplifts; (8) regenerated Upper Jurassic and Lower Cretaceous sedimentary rocks; (9) Lower Cretaceous coal-bearing molasse; (10) Cretaceous volcanic rocks; (11) Quaternary loose sediments; (12) Mesozoic gabbro and diorite; (13) Mesozoic gabbro–monzonite–syenite plutonic association; (14) Mesozoic granite–granodiorite plutonic association; (15) deep boundary fault zones; (16) interblock fault zones; (17) porphyry Cu–Mo deposits (numerals in circles): (1) Dal'ny, (2) Kamen Takmyka, (3) Northeastern, (4) Kol'tsevoi, (5) Peschanka, (6) Nakhodka–Vesenny; (18) Ergunei ore district with porphyry copper occurrences.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All plutonic and subvolcanic rocks of the district are characterized by (i) an elevated sum of alkali metal oxides from 7 wt % in postmineral trachyandesite to 9.6 wt % in syenite, except for gabbro of normal alkalinity (3.4–4.5 wt % $Na_2O + K_2O$); (ii) an almost twofold prevalence of sodium over potassium; (iii) relatively low silica content; and (iv) uniform mineral composition (quartz, feldspar, pyroxene, hornblende, and biotite). According to petrochemical parameters and structural position, the rocks of the Omchak pluton may be considered as extremely evolved varieties of the Yegdegkych Complex (Gulevich, 1977).

The outlines of the Baim district as a central part of the zone bearing the same name and its internal structure are determined by the Western (Vesenninsky) and Eastern ore-controlled boundary faults, oriented in the northwestern and near-meridional directions. The oblique Baim and Nakhodka faults are accompanied by thick crush and shear zones, small zones of eruptive breccia, subvolcanic intrusions, and hydrothermal alteration (Fig. 4). The fracture zones that adjoin these faults serve as repositories of Cu–Mo stockworks. The space between ore-controlling faults affected by dynamic stresses is a severely fractured block, where the near-latitudinal and northeastern fractures are oriented perpendicularly to the ore-conducting Baim Fault. The network of these fractures hosts suites of subvolcanic granodiorite porphyry dikes and the stringer–disseminated ore mineralization.

Reactivation of the main faults at the postmineral stage resulted in division of the district into three large and nonuniformly eroded blocks: northern, central, and southern. The general structure of the Baim district resembles the tectonic wedge between the Karabulak and Kal'makyr faults controlling porphyry copper mineralization at the Dal'nee deposit in Uzbekistan (Shayakubov et al., 1980).

The general zoning of ore mineralization in the Baim district is expressed in the regular spatiotemporal change of the main ore-forming mineral assemblages and described by the following empirical series: Fe–Mo, (Cu)–Cu, (Mo)–Te, As, Sb, (Cu, Au, Ag)–Au, Ag, Zn, Pb, (As, Sb, Bi)–Fe, (Sb) (Fig. 5).

The vertical mineral and geochemical zoning of the Baim district is shown in Fig. 6. The contents of almost all ore elements decrease with depth, whereas the Cu and Mo contents increase in this direction, with the As content remaining relatively stable.

Table 4. Average grade of major and associated elements in ores at deposits of the Baim district, after Shpikerman (1998)

Element	Deposit		
	Peschanka	Nakhodka	Vesenny
%			
Cu	0.51	0.4	0.5
Mo	0.002	0.004	0.0004
g/t			
Au	0.45	0.15	3.6
Ag	1.5	1.2	35
Bi	5.0	4.0	<1.0
Sn	1.8	3.9	<1.0
Cu/Mo	300	125	1250
Cu/Au	13500	33500	200
Ag/Au	3.4	8	10

Thus, the Cu–Mo and Au–Ag ore mineralization in this district reveals a characteristic mineralogical and geochemical zoning and other attributes typical of the inner and outer zones of the porphyry copper ore–magmatic system.

Since the Peschanka (Anyui) deposit has been described in previous publications (Volchkov et al., 1982; Migachev et al., 1984; Shpikerman, 1998), we consider in this paper less well known ore objects from the southern part of the Baim district, where eight occurrences located within a relatively small area (~30 km^2) are distinguished from one another in geology and ore mineralization (Fig. 4). Most of them are in immediate contact with one another, making up complicate mineral complexes (Shavkunov, 1973).

The Nakhodka ore field comprises Au-bearing porphyry copper occurrences of the northern block spatially related to intrusions of the Yegdegkych Complex, which serve as sources of placers of high-fineness gold. The Vesenninsky Au–Ag deposit in the central block is related to dikes of the Omchak Complex and feeds placers of low-fineness gold.

The Au-bearing Nakhodka porphyry Cu–Mo deposit was discovered in 1971 by L.D. Shkol'ny and explored in

Fig. 4. Geological sketch map of the Baim ore district. Compiled by V.S. Shapovalov after data reported by B.N. Shavkunov and L.D. Shkol'ny. (1–6) Upper Jurassic volcanic and sedimentary rocks: (1) conglomerate, andesite, siltstone, and sandstone; (2) dacite, rhyolite, tuff, and ignimbrite; (3) siltstone, gravelstone, sandstone, and conglomerate; (4) andesite, basaltic andesite, and tuffs of the same composition; (5) andesite (lava and tuff) and ash tuff units; (6) tuffaceous gravelstone and conglomerate of mixed composition; (7) Lower Cretaceous terrigenous rocks; (8) Upper Jurassic volcanic and sedimentary rocks; (9) Triassic flyschoid sequences; (10–17) plutonic and subvolcanic rocks, including the Yegdegkych Complex: (10) gabbro; (11) monzonite, syenite, monzodiorite, and granosyenite; (12) monzodiorite porphyry; (13, 14) Omchak Complex: (13) porphyritic diorite, (14) granodiorite porphyry; (15–17) postmineral complex: (15) quartz albitophyre, (16) trachyandesite, (17) quartz diorite; (18) master faults; (19) stratigraphic and intrusive contacts; (20) unconformable contacts; (21) ore occurrences (numerals in boxes): (1–4) epithermal Au–Ag, (5–7) porphyry Cu–Mo.

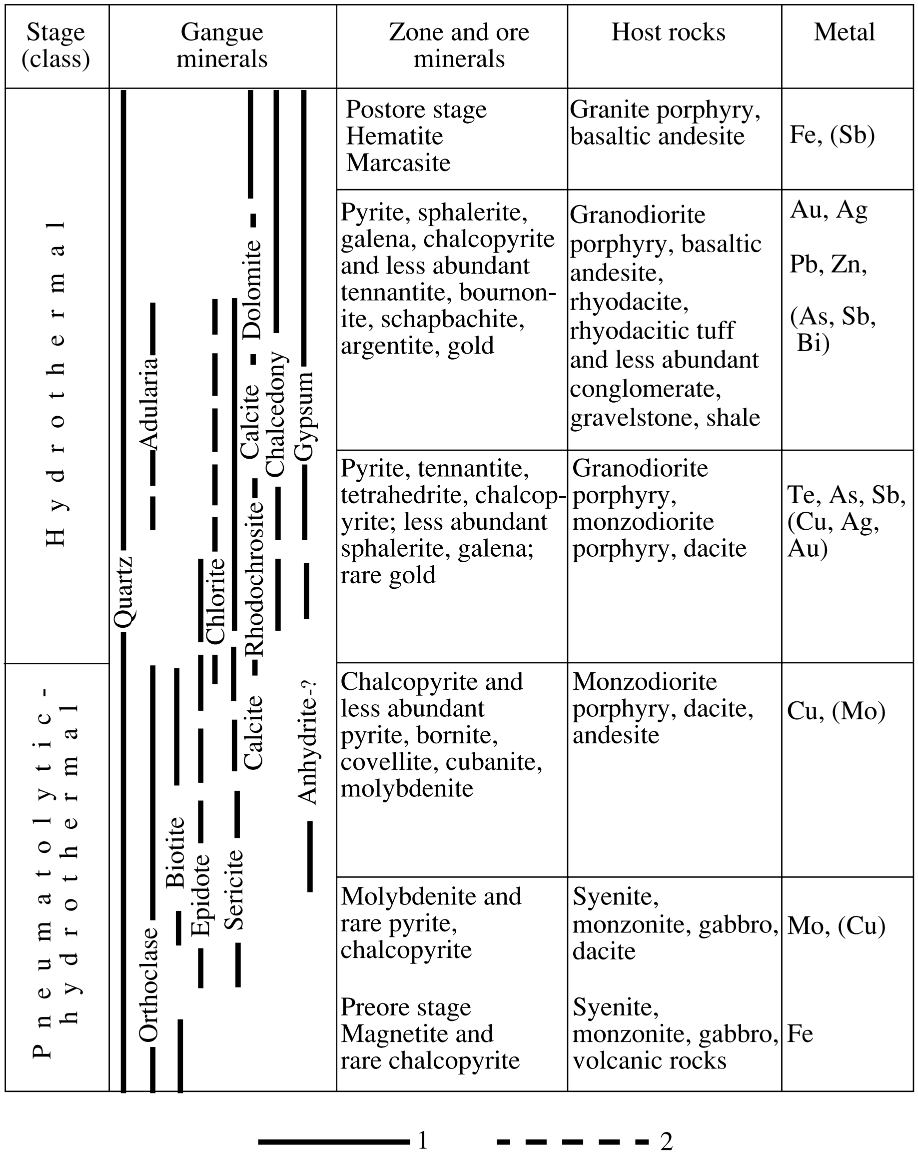

Fig. 5. Primary zoning of ore mineralization in the Baim district. Abundance of (1) major and (2) subordinate gangue minerals.

1972 by I.P. Klyushkin. The subsequent study of this deposit was conducted by M.E. Gorodninsky, V.V. Gulevich, G.I. Sokirkin, V.I. Goncharov, A.A. Sidorov, Yu.P. Rozhdestvensky, Yu.I. Edovin, V.P. Shapovalov, and others. The Nakhodka deposit combines four areas: Second and Third Vesenny, Nakhodka, and Malysh.

Four stockworks more than 4 km^2 in total area extend down to 300 m or deeper; the average grades are 0.4% Cu, 0.015% Mo, and 0.15 g/t Au. These parameters allow us classify this object as a large deposit.

The Nakhodka deposit is located in the NW-trending zone of a positive magnetic anomaly combined with geochemical halos of Cu (0.01–0.05%) and Mo (0.005–0.010%) (Shavkunov, 1973). Volcanics of the felsic sequence, tuffaceous sedimentary rocks of the lower terrigenous sequence, and numerous monzodiorite intrusions are exposed here (Fig. 7). The porphyritic texture of intrusive rocks indicates that they have been eroded insignificantly.

The stockworks, isometric and slightly elongated in the northwestern direction, are dense networks of quartz–sulfide veinlets oriented in the northwestern and northeastern directions. The length of veinlets varies from a few decimeters to 1–2 m, being sporadically longer, and their thickness, from fractions of a millimeter to 2–3 mm, rarely reaching 1–2 cm. The host rocks are replaced with biotite, potassium feldspar, quartz, and sericite and impregnated with chalcopyrite, pyrite, and molybdenite. The substantially copper ore (the Second and Third Vesenny areas) and molybdenum ore (the Malysh and, partly, the Nakhodka area) markedly differ from one another in the character of ore mineralization and its localization.

The copper ore is composed of quartz–chalcopyrite veinlets and sulfide impregnation hosted in monzodiorite porphyry and partly in felsic volcanics. Eruptive and tectonic breccia crop out locally near tectonic zones. The primary chalcopyrite ore is exposed at the present-day denudation level. A thin (~20 m) zone of secondary sulfide enrichment with bornite and chalcocite occurs locally. Supergene mineralization is widespread, but the oxidation zone develops only near the Earth's surface. Gold and silver in this ore type are related only to chalcopyrite and, to a lesser extent, pyrite.

The Mo ore is confined to sporadic, short and curved lenticular veins up to 20–30 cm thick composed of gray or bluish gray quartz with abundant, finely dispersed and less frequently fine scaly molybdenite disseminations. These veins are accompanied by zones of anastomosing veinlets. The zones of molybdenite–quartz veins are relatively small. The host syenite porphyry and monzonite, as well as felsic volcanics, are affected by potassic alteration and bleached.

The Vesenny Au–Ag deposit is situated 15 km south of the Peschanka deposit at the southwestern flank of the Nakhodka ore field (Fig. 4) and separated from this field by a normal fault. Volcanic and sedimentary rocks are exposed over an area of 1 km^2 and cut by numerous dikes (diorite, dacite, and granodiorite porphyry) of the Omchak Complex.

The Au–Ag mineralization is hosted largely in felsic volcanics and penetrates into the overlying andesite along granodiorite porphyry dikes. Orebodies are mineralized crush zones, where the host rocks are severely affected by quartz–sericite alteration and silicified.

The main ore zone is controlled by a body of eruptive breccia elongated in the northeastern direction along the contact with porphyritic diorite. The orebody thickness in its northeastern and central parts reaches 53.6 m. The Au grade varies from 0 to 68.2 g/t (3.6 g/t, on average) and the Ag grade, from 0 to 277.4 g/t (35 g/t, on average). The amount of sulfides ranges from 2–5 to 20%. The ore mineralization is finely disseminated, stringer–disseminated, and related to pockets. Galena and sphalerite are the major minerals; pyrite, chalcopyrite, tennantite, magnetite, and molybdenite are inferior in abundance. Marcasite, cubanite, freibergite, bournonite, electrum, argentite, and native silver occur in insignificant amounts. Quartz and rhodochrosite, along with subordinate amethyst, calcite, chalcedony, sericite, chlorite, adularia, barite, and apatite, are gangue minerals. Supergene minerals comprise covellite, malachite, azurite, psilomelane, hematite, lepidocrocite, and iron hydroxides. Native gold as dusty grains is extremely rare. Most gold is incorporated as an isomorphic admixture into pyrite and other sulfides. Silver occurs as its own minerals (native silver, argentite, and bournonite) and as an isomorphic admixture in fahlore, galena, and partly in pyrite. The average

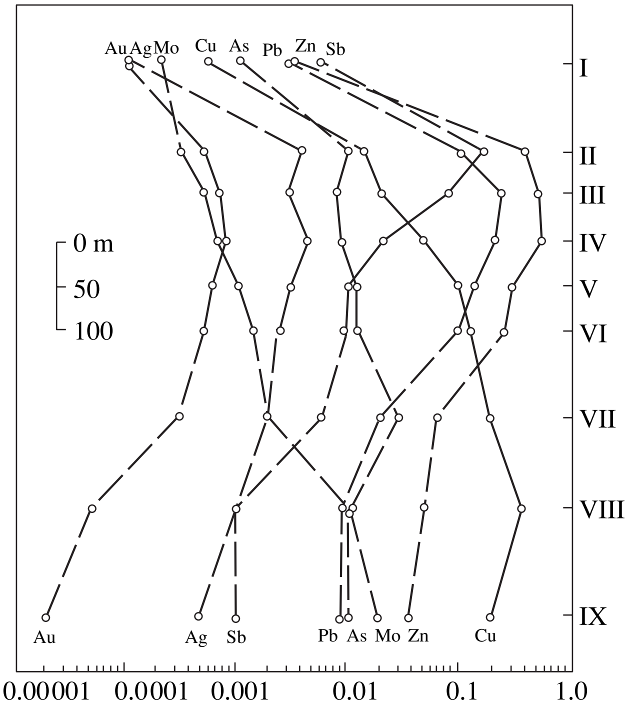

Fig. 6. Variation of major element contents with depth. (I–IX) Mineral assemblages: (I) hematite–quartz (Vesnushka area), (II–VI) galena–sphalerite–carbonate–quartz (Vesenny area), (VII) fahlore–quartz (Nakhodka–Evrika area), (VIII) chalcopyrite–quartz (the Second Vesenny area), (IX) molybdenite–quartz (Malysh area).

Au/Ag ratio is 1/9. According to the preliminary evaluation, the stockwork ore mineralization over an area of 0.5 km^2, traced to a depth of 200 m, corresponds to the class of large deposits.

In addition to the aforementioned deposits, the Baim metallogenic zone includes a great number of promising ore occurrences (Table 3). A new large mining and metallurgical center for production of Cu, Mo, Pb, Zn, and noble metals could be developed in this part of the Chukchi Peninsula in the near future.

The Uda–Murgal Metallogenic Belt

The Uda–Murgal metallogenic belt is related to the inner zone of the OChVB and is controlled by the continent margin and the boundaries of the paleoisland arc that bears the same name (Parfenov, 1984; Savva, 2005). The island-arc rocks are traced now near the left bank of the Uda River, on the Koni–P'yagina and Taigonos peninsulas, and in the basins of the Penzhina and Anadyr rivers (Fig. 1). The island arc is composed of tholeiitic basalts and basaltic andesites, including lavas, tuffs, tuffaceous breccias and siltstones; felsic rocks amount to 4%. The total thickness of this sequence varies from 3 to 7 km. Calc-alkaline volcanics are prevalent (the total $Na_2O + K_2O$ sum is about 4 wt %); greenstone alteration is typical. The volcanic and sedi-

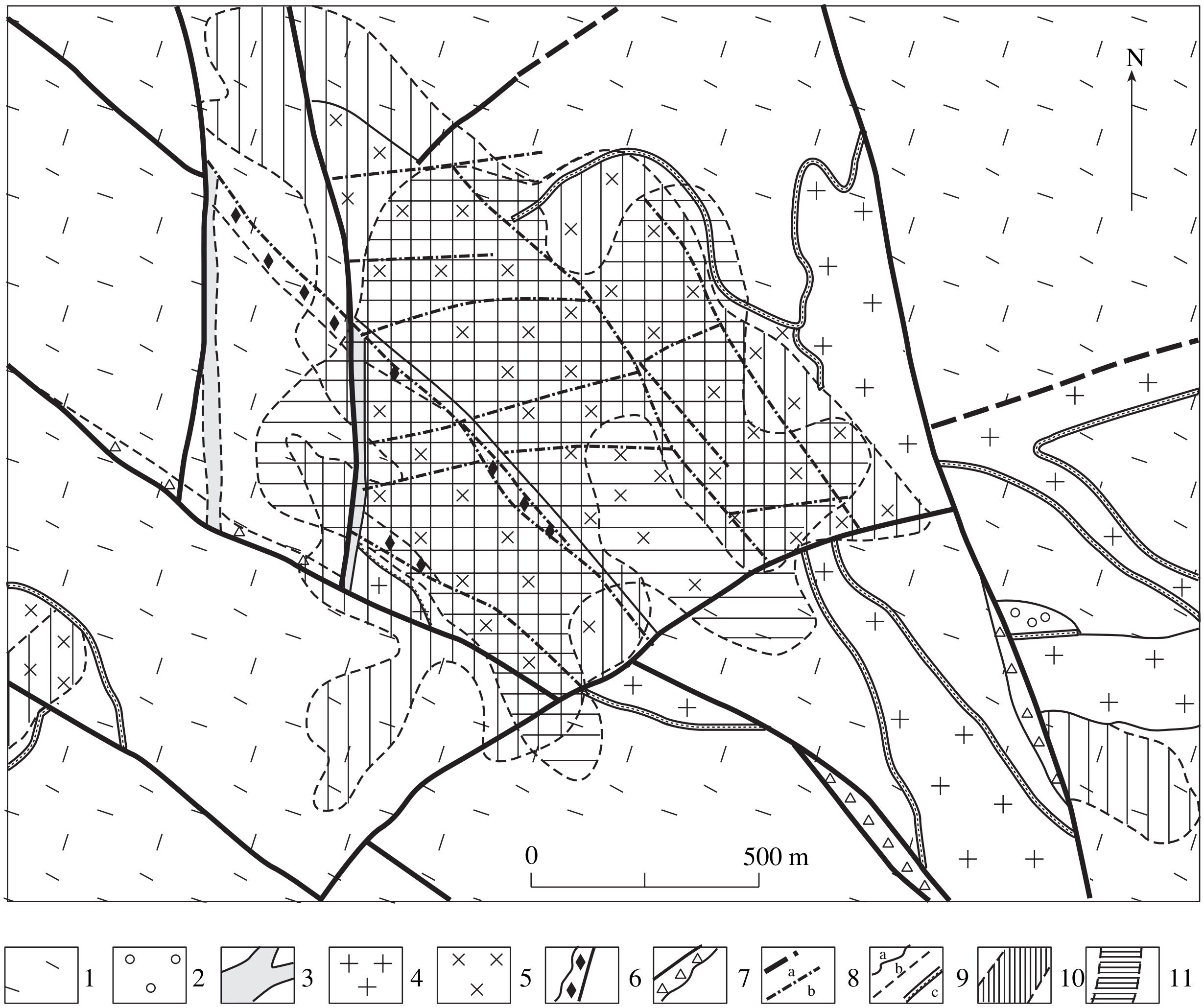

Fig. 7. Geological sketch map of the Nakhodka ore field. Compiled by V.S. Shapovalov after data reported by B.N. Shavkunov and G.I. Sokirkin. (1) Sequence of felsic volcanics (rhyodacitic tuffs); (2) lower terrigenous sequence (siltstone, sandstone, gravelstone); (3) basalt and porphyritic diorite dikes; (4) granodiorite porphyry of the Cretaceous Omchak Complex; (5) monzodiorite porphyry of the Late Jurassic Yegdegkych Complex; (6) eruptive breccia; (7) crush and mylonite zones; (8) master faults (a) and splays (b); (9) stratigraphic and intrusive contacts: (a) mapped, (b) inferred, (c) accompanied by contact metamorphism; (10, 11) stringer–disseminated Cu–Mo ore: (10) mainly copper, (11) mainly molybdenum.

mentary rocks were deposited on an uplift bordered by marine troughs like the Greater Kuril Islands (Parfenov, 1984).

The large area of porphyry Cu–Mo deposits coincides with the frontal zone of the OChVB, superimposed on the terrigenous–volcanic complex of the marginal continental arc, which is highly deformed and locally thrust over the continent. The porphyry-type Cu–Mo ore mineralization is related to the magmatic uplifts in the Chelomdzha–Yama and Anadyr deep fault zones, which mark a gravitational step that serves as a boundary between the frontal and back zones of the volcanic belt.

The Magadan district, which extends for 500 km along the coast of the Sea of Okhotsk, has been studied better than others. The deposits and occurrences known here (Osenny, Oksa, Usa, Viking, Lora, Etandzha, Ikrimun, etc.) are localized within multiphase plutons that belong to the Early Cretaceous gabbro–tonalite–plagiogranite (sodic) association with a low initial Sr isotope ratio and to the subordinate Late Cretaceous gabbro–granodiorite–granite association (Kotlyar et al., 2001). As a rule, the ore fields are conformable to the contours of ring magmatic structures 7–12 km in diameter. The stringer–disseminated and vein–stockwork mineralization is associated with porphyry complexes (Skibin, 1982; Savva, 2005). The Cu mineralization gives way to Mo–Cu and, farther, to Mo ore, often with W, toward the continent, and this lateral zoning is correlated with the increase in the thickness of the granitic layer and enrichment of ore-bearing igneous complexes in leucogranites and granite porphyries. Numerous Au occurrences are also related to granitoids (Vetvisty,

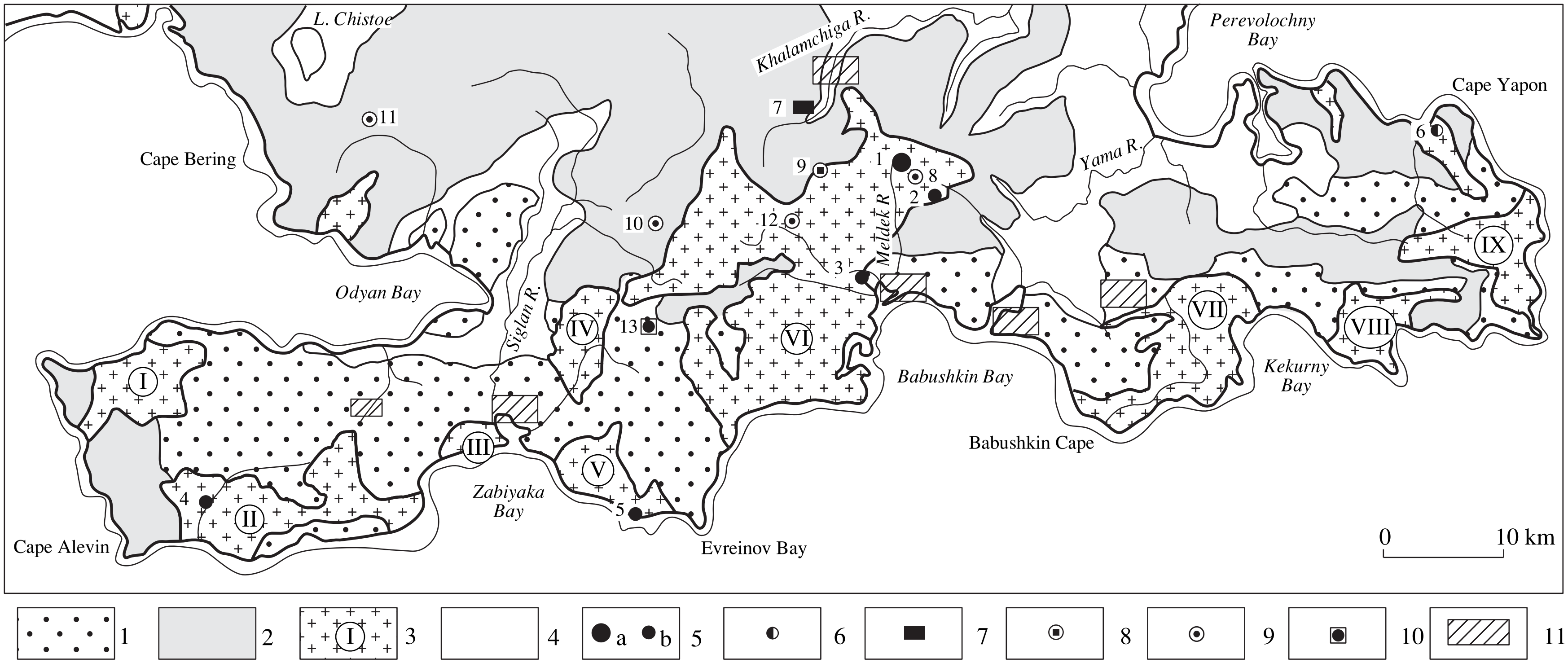

Fig. 8. Geological sketch map of the Koni–P'yagina Peninsula. Compiled by N.E. Savva after data reported by V.G. Korol'kov. (1) Triassic and Jurassic sedimentary and volcanic complexes; (2) Early Cretaceous volcanic complexes; (3) granitoid plutons; (4) Neogene–Quaternary loose sediments; (5–10) deposits (a) and ore occurrences (b): (5) Cu–Mo, (6) Cu–Fe, (7) Cu–Mo–Zn–Co, (8) Au–As–W–Bi, (9) Au–Ag–Cu, (10) Pb–Cu–Zn–Co; (11) area of gold placers. Granitoid plutons (Roman numerals in map): (I) Northwestern, (II) Antarinsky, (III) Cape Kiras, (IV) Argaskich, (V) Pavlovich Cape, (VI) Srednensky, (VII) P''yagina, (VIII) Nakat, (IX) Kekurny; ore deposits and occurrences (Arabic numerals in map): (1) Lora, (2) Pryamoi, (3) Ryabinovy, (4) Antarinsky, (5) Viking, (6) Yapon, (7) Tal'nikovy, (8) Yuzhny, (9) Ryzhik, (10) Krutoi, (11) Gorely, (12) Gol'tsovy, (13) Guron.

Table 5. Gold occurrences on the Koni–P'yagina Peninsula

Type	Occurrence	Geochemical assemblage	Position of ore mineralization relative to intrusions	Grade
Epithermal Au–Ag	Krutoi	Au-Ag-Cu-Se	Above intrusion	2.0–28 g/t Au (up to 580 g/t); 17.0–266.8 g/t Ag (up to 2600 g/t)
	Gorely	Au-Ag-Sb-As-Pb-Zn	Near intrusion	2.0–13 g/t Au; 0.5–4.0 g/t Ag
Au-granitoid related	Ryzhik	Au-As-W-Bi	Contact zone of intrusion	0.2–30 g/t Au (3–4 g/t, on average); 3–10 g/t Ag (up to 105 g/t); up to 550 ppm Bi
	Southern area	Au-As-W-Bi	Contact zone of intrusion	0.3–2.5 g/t Au, 1.8–2.6 g/t Ag, 13.0–15.5 ppm Bi, 0.12% As
Gold–sulfide	Guron	Pb-Cu-Zn-Co	Near intrusion	0.02–97.6 g/t Au, up to 4.1 g/t Ag, 1–20% pyrite
Porphyry Cu–Mo	Lora, Pryamoi, Viking	Cu-Mo-W	Within intrusion	0.2–1.0 g/t Au, up to 3 g/t Ag
Laterite	Tal'nikovy, Balochny, Buochakh	Cu-Mo-Zn-Co	Weathered intrusive rocks	Up to 1 g/t Au, up to 1 g/t Ag, shows of gold in heavy concentrate
Placer	In the framework of the Nakkhatandzha Basin	Zircon and magnetite are predominant in heavy concentrate	Polygenetic primary sources	1–10 g/m^3 Au

Teutedzhak, Berezovy, Sentyabr'sky, etc.). The epithermal Au–Ag vein deposits (Dzhul'etta, Nyavlenga, etc.) are spatially associated with porphyry-type deposits. The ore at these deposits is stably enriched in silver.

The porphyry Cu–Mo and Au–Ag occurrences on the Koni–P'yagina Peninsula. The relations of the Late Mesozoic granitoid magmatism to the Benioff zone are confirmed by the lateral ore zoning, which is expressed in the most complete form on the Koni–P'yagina Peninsula. The copper mineralization hosted in basic volcanics is prevalent in the areas located close to the Okhotsk–South Taigonos Suture. The area of this mineralization is strictly limited by the Koni–P'yagina Suture. The porphyry Cu–Mo occurrences (Lora, Viking, Ikrimun, Pryamoi, and Ryabinovy) related to granitoids are localized within and to the north of this fault zone (Fig. 8). According to Umitbaev (1986), the Koni–P'yagina Fault is traced along the southern coast of the peninsula for 200 km and the width of the fault zone is 20–25 km. The fault dissects Upper Triassic, Jurassic, and Lower Cretaceous terrigenous and volcanic sequences and controls large plutons of Early Cretaceous granitoids, gabbro and diorite stocks, and subvolcanic intrusions of various compositions. The southern extension of this fault is hidden beneath the water of the Sea of Okhotsk and is marked by intense magnetic anomalies of near-latitudinal orientation.

The following sequence of magmatic events and related ore mineralization may be outlined on the basis of isotopic geochronology (Kotlyar et al., 2001): a first stage dated at 104 Ma (greisenization and autometasomatism of the Srednensky pluton; formation of pyrite impregnation in country rocks near contacts with intrusions); a second stage 97–92 Ma in age (emplacement of diorite and formation of eruptive breccia); the main stage of formation of Cu–Mo and associated Au–Ag mineralization; and a final stage 86–76 Ma in age (emplacement of dikes and partial redistribution of previously formed ore). This long history is caused by the origination and further evolution of the multistage Srednensky pluton.

The Lora porphyry Cu–Mo deposit is situated on the Koni–P'yagina Peninsula 18–20 km to the north of Babushkin Bay (Fig. 8) and occupies an area of 10 km^2. The deposit was discovered and partly explored by Tal'nichny Expedition in 1982–1986 (Yu.Yu. Vorob'ev and F.N. Vasetsky). The ore mineralization is localized in the most uplifted northern part of the Srednensky pluton, known as the Meldek intrusive dome, in the inner zone of the Uda–Murgal arc (Fig. 8). The ore field is composed of Early Cretaceous medium-to-coarse-grained hornblende–biotite granodiorite and tonalite. These rocks make up the framework of the younger stocklike porphyry intrusions, including granodiorite, quartz diorite, and diorite porphyries. The highest grade part of the ore field, with ore pockets and disseminations, is related to stocks of quartz diorite. Quartz–sulfide, quartz–chlorite–sulfide, and sulfide veinlets and ore impregnation also occur in the country rocks. According to preliminary data, the metal grades in ore vary within wide ranges: 0.07–0.6% Cu in granodiorite and >1% (0.5%, on average) in diorite; 0.007–0.05% Mo (0.025%, on average); 0.3–7 g/t Ag (2.1 g/t, on average); and 0.1–1.0 g/t Au (0.2 g/t, on average). At present, the deposit has been evaluated as a medium-size object.

Table 6. Porphyry Cu–Mo metallogenic zones of the Okhotsk–Chukotka belt. Compiled after results of prospecting obtained by the Sevvostgeologiya Territorial Geological Survey

Metallogenic zone	Occurrence	Mineralization type	Contents
Korkodon–Nayakhan	Orliny, Aksu	Porphyry Mo–Cu	0.05–0.1% Cu, 0.07% Mo
South Omolon	Vecherny, Khrustal'ny, Dubl-Yuzhny, Gruntovy	″	0.01–0.05% Cu, 0.07% Mo, 0.04–0.2 g/t Au, 1–10 g/t Ag
Okhotsk	Chelasin	Porphyry Cu	0.5–1.0% Cu, 0.5–10 g/t Au, >10 g/t Ag
Viliga	Piritovy	″	0.46% Cu, 0.01–0.05% Mo
″	Oktava	Porphyry Mo–Cu	0.05–0.1% Cu, 0.08% Mo
Tanyurer	Krasny Gory, Tyl'pygyrgyn, Krasny, Chekogytgynal	Porphyry Cu	0.5–1.0% Cu, 0.2–1.0 g/t Au, 1–10 g/t Ag
Chaun	Shurykan, Pykarnayan	Porphyry Mo–Cu	0.01–0.05% Cu, 0.01–0.2% Mo, 0.2–0.5 g/t Au, 1–10 g/t Ag
Ol'khovka	Ol'khovka, Probny	Porphyry Cu	0.5–1.0% Cu
Maivel'mai	Maivel'mai, Granatovy	Porphyry Mo–Cu	0.05–0.1% Cu, 0.1% Mo
Provideniya Bay	Gagachi, Khed, Chechekuyum	Porphyry Mo–Cu	0.1–0.7% Cu, 0.01% Mo, 0.2–1.0 g/t Au, 1–10 g/t Ag

Unlike the Lora deposit, the Pryamoi prospect (Fig. 8), which occupies a lower hypsometric position, reveals an ore-bearing porphyry core with high-grade copper mineralization; explosion (rather than eruptive as at the Lora deposit) breccia occurs at this prospect. The copper ores at the Viking and Ikrimun deposits (Fig. 8) on the Okhotsk coast are still higher grade.

The Viking deposit is located in the core of an intrusive dome composed of Early Cretaceous tonalite and plagiogranite with xenoliths of Middle Jurassic rocks incorporated therein. Numerous younger granitoid porphyry intrusions are exposed at the dome margins. Sulfide, sulfide–quartz, and sulfide–feldspar–quartz veins and veinlets and zones of ore disseminations are hosted in hydrothermally altered Early Cretaceous tonalite and porphyritic quartz monzonite, making up a stockwork traced for many hundreds of meters along the strike and for 450–500 m in the vertical direction in coastal cliffs. The stockwork is oriented parallel to the contact of the porphyry intrusion. The inner zone of metasomatic alteration is marked by lenticular orthoclase segregations, while quartz–sericite and epidote–chlorite metasomatic rocks are characteristic of the outer zones. Pyrite, chalcopyrite, molybdenite, arsenopyrite, goethite, chalcocite, and covellite are the major ore minerals; the gangue minerals include quartz, orthoclase, chlorite, biotite, muscovite, and zeolites. The ore contains 1.0–39.0% Cu, 0.15–20.0% Mo, 185 g/t Ag, and up to 0.4 g/t Au; Bi, Se, Te, Re, and W have been detected in the ore.

Numerous gold occurrences that were found on the Koni–P'yagina Peninsula as a result of prospecting carried out in 1998–2004 (Table 5) turned out to be related to some extent to porphyry Cu–Mo systems, although they started to form before the emplacement of porphyry intrusions. These occurrences are not large, but could be mined together with spatially related porphyry deposits.

The Okhotsk–Chukotka Metallogenic Belt

The Okhotsk–Chukotka metallogenic belt, which comprises numerous volcanogenic deposits, extends for more than 3500 km along the eastern margin of the Asian continent and coincides with the Late Cretaceous–Paleogene volcanic–plutonic belt of the same name and its perivolcanic zone (*Explanatory Notes*…, 1986; Umitbaev, 1986; Nokleberg et al., 2005). The following types of ore mineralization are known in this belt: porphyry Cu–Mo deposits; epithermal Au–Ag veins; gold–sulfide impregnations; gold mineralization related to granitoids; Sn- and Ag-bearing base-metal mineralization of vein, skarn, and porphyry types; and Hg- and Sb-bearing veins. The belt consists of several metallogenic zones; porphyry Cu–Mo deposits are known in some of these zones (Table 6). However, in most zones, no works aimed at prospecting for porphyry-type ore have been conducted.

GENETIC FEATURES OF ORE MINERALIZATION IN THE BAIM AND KONI–P'YAGINA ORE DISTRICTS

In the *Baim ore district*, the evolution of the Late Jurassic–Cretaceous volcanic–plutonic complex embraced several tectono-magmatic stages (phases) and was accompanied by emplacement of porphyry stocks and dikes, tectonic deformation, explosion phenomena, characteristic postmagmatic alteration of rocks, and formation of Au–Ag and Cu–Mo ore mineralization (Shapovalov, 1994).

The formation of K-feldspar–magnetite–quartz metasomatic alteration immediately predated the Cu–Mo mineralization. The chronological relationships and character of this mineralization, including newly formed biotite and scapolite, allow us to suggest that

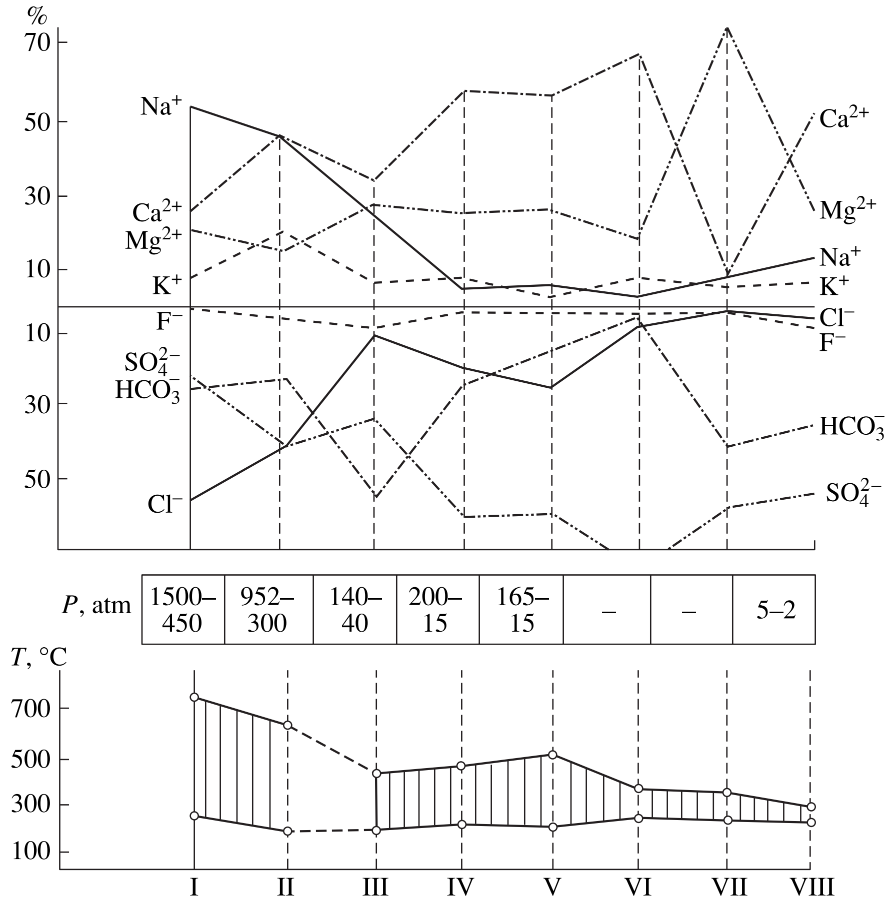

Fig. 9. Variation of temperature, pressure, and composition of mineral-forming solutions in the process of ore deposition. Stages of ore formation: (I) molybdenite–quartz, (II) chalcopyrite–quartz, (III) fahlore–quartz, (IV) base-metal–quartz, (V) galena–sphalerite–carbonate–quartz, (VI) columnar quartz (postore), (VII) dolomite, (VIII) hematite–quartz.

the premineral metasomatic rocks were formed from substantially gas solutions with a predominance of Na, K, Fe, Cl, and CO_2 at a temperature of 700°C or higher. Such a temperature of potassic alteration has been established at many other porphyry Mo–Cu deposits (Berzina and Sotnikov, 1968; Piznyur, 1980). The premineral complex resides in local areas of the parental Late Jurassic gabbro–syenite intrusion and along the faults in its outer contact zone.

The contraction fractures that arose in the cooled apical portion of the intrusion could not release the gas pressure, which gave rise to explosions, as well as rejuvenation of older and formation of new fractures. The mixing of gas solutions with vadose water enriched in alkali chlorides led to the formation of highly concentrated pneumatolytic–hydrothermal solutions responsible for the formation of molybdenite–quartz veins at a high temperature (700°C or higher) and a pressure of more than 150 MPa, which was maintained during the next stage, when chalcopyrite–quartz stockworks were formed in monzodiorite porphyry. Such high values of the thermodynamic parameters and the heterogeneous aggregate state of mineral-forming solutions were probably caused by ore formation that followed crystallization of magmatic melt without an appreciable break. Irrespective of the depth of the ore-generating source, the release of ore-bearing solutions (initially substantially gaseous), the formation of hydrothermal solutions, their transport, and ore deposition were tightly compressed in time. Similar thermobarogeochemical characteristics were obtained for granitoid-related gold deposits in the Northeast of Russia (Shapovalov and Savva, 1979).

The next, gold–silver stage was predated by intense tectonic rearrangement expressed in development of the northeastern and near-latitudinal crush zones and emplacement of the Late Jurassic–Early Cretaceous dike suite consisting of granodiorite and diorite porphyries. Veins of the fahlore–quartz assemblage occupied a transitional spatiotemporal position between two ore types. The productive base-metal–quartz and galena–sphalerite–carbonate–quartz assemblages were formed within a temperature range of 380–120°C from slightly mineralized (up to 15–18%) sulfate–bicarbonate–calcium–magnesium solutions at a shallow depth and a low pressure (20–0.5 MPa). The hydrothermal process

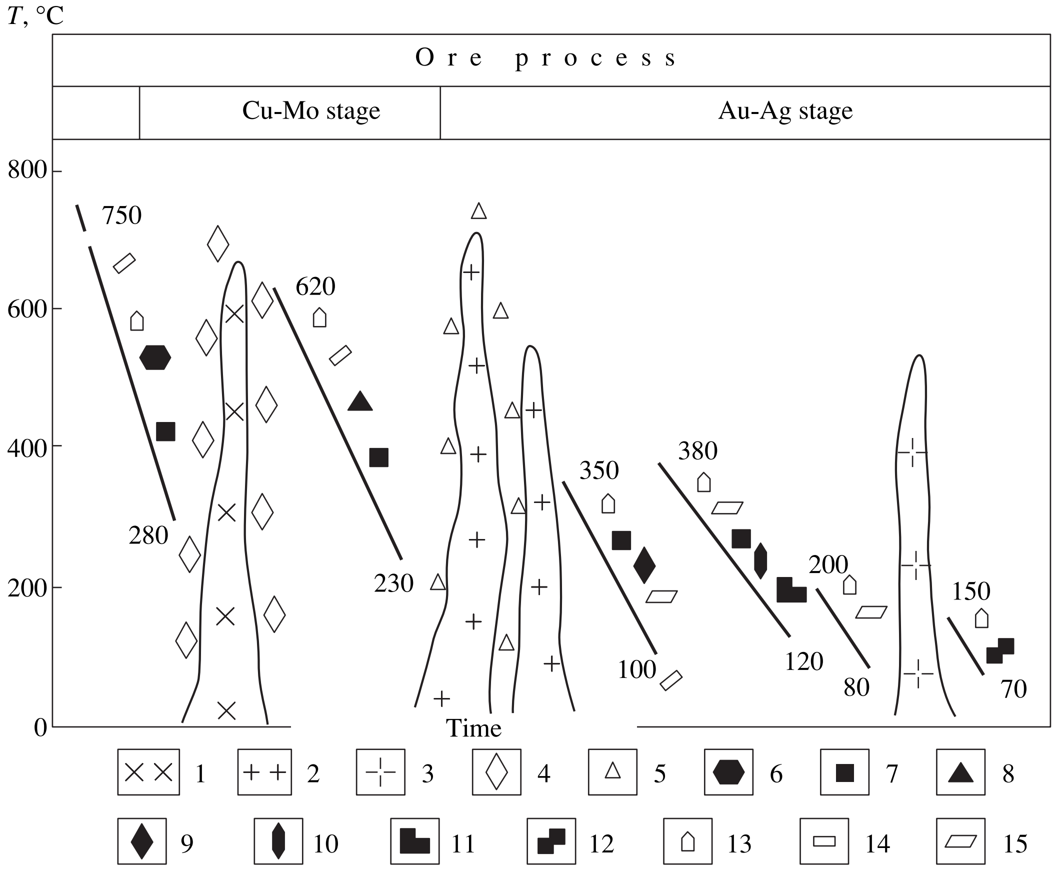

Fig. 10. Intramineral magmatism and sequence of ore formation in the Baim district. (1) Late Jurassic–Early Cretaceous monzodiorite porphyry and aplite; (2) Early Cretaceous granodiorite porphyry and porphyritic diorite; (3) Cretaceous granite porphyry; (4) eruptive and explosion breccias; (5) tectonic breccia; (6) molybdenite; (7) pyrite; (8) chalcopyrite; (9) fahlore; (10) sphalerite; (11) galena; (12) magnetite and hematite; (13) quartz; (14) orthoclase; (15) rhodochrosite, calcite, and dolomite.

was completed with formation of low-temperature (<150°C), almost barren hematite-bearing quartz veins after emplacement of the late generation of Cretaceous subvolcanic intrusions composed of quartz porphyry and quartz albitophyre.

A progressive (with certain inversions) decrease in temperature and pressure accompanied by a contrasting compositional change in solutions (Fig. 9) is the common tendency in the evolution of multistage (pulsatory) pneumatolytic–hydrothermal mineral formation at a shallow depth.

The particular stages of ore formation were closely related to the respective magmatic phases (Fig. 10).

The Srednensky magmatic dome in the central part of the *Koni–P'yagina ore district* determines its geological structure (Fig. 8). The Lora porphyry Cu–Mo deposit is situated in the northeastern marginal part of this dome; the Pryamoi prospect is located 9 km away from this deposit; Au–As–Bi occurrences hosted in tourmaline–muscovite greisen (Yuzhny, Ryzhik, and the Guron Au-polysulfide prospect) were found at a distance from the latter. The periphery of the dome is marked by epithermal Au–Ag occurrences (Krutoi, Gol'tsovy).

The deposits and occurrences listed above are characterized by (i) distinct spatial relations with porphyry granitoid intrusions; (ii) lateral metasomatic zoning: potassic (biotite–K-feldspar) ⟶ phyllic (quartz–sericite with tourmaline) ⟶ propylitic alteration; (iii) stringer–disseminated ore; (iv) the absence of textural indications of epithermal ore mineralization in ore occurrences associated with a Cu–Mo-bearing porphyry intrusion; (v) major ore minerals—pyrite, chalcopyrite, molybdenite, and magnetite—typical of the porphyry Cu–Mo system; and (vi) elevated Cu and Mo grades.

The results of thermo- and cryometric study of fluid inclusions in quartz from veins at the Yuzhny occurrence and veinlets at the Pryamoi prospect are presented in Table 7 and Figs. 11 and 12. Primary, pseudosecondary, and secondary two-phase (gas–liquid) inclusions 1–70 μm in size were found in ore-bearing quartz veins; the inclusions have the shape of a negative crystal or are irregular in outline (Fig. 11). In some quartz samples, the gas–liquid inclusions are associated

Table 7. Results of thermo- and cryometric studies of fluid inclusions in quartz from ore veins at the Yuzhny, Pryamoi, and Kupol prospects and deposits

Sample	Mineral, inclusion type	n	T_{hom}, °C	T_{eut}, °C	$T_{ice\ melt}$, °C	$T_{melt CO_2}$, °C	C_{salt}, wt % NaCl equiv	d, g/cm^3	P, bar
Yu-2	Quartz, P	9	334	–29	–6.5	–	9.9	0.78	–
	″ *PS	2	321, gas	–28	–1.0	–	1.7	nd	110
	″ PS	63	364–291	–(38–30)	–(10.1–4.0)	–	14.0–6.5	0.84–0.66	–
	″ S	5	232	–29	–5.0	–	7.9	0.90	–
Yu-1	Quartz, P	19	342–334	–(42–34)	–(6.6–6.1)	–	10.0–9.3	0.77–0.76	–
	″ PS	19	335–311	–(43–33)	–(6.7–4.1)	–	10.1–6.6	0.81–0.73	–
	″ S	37	238–206	–(39–38)	–(7.4–5.9)	–	11.0–9.1	0.94–0.90	–
363	Quartz, *PS	2	431	–34	–4.7	–59.3	7.5	0.50	360
	″ S	3	224	–32	–3.2	–	5.3	0.88	–
1700-5	Quartz, PS	3	429	–42	–8.9	–	12.7	0.64	–
	″ S	2	143	–47	–18.1	–	21.0	1.08	–
Kr04-1	Amethyst, P	11	267	–21	–1.2	–	2.1	0.78	–
Kr04-2	Amethyst, PS	8	222	–21	–1.2	–	2.1	0.86	–

Note: Samples: Yuzhny prospect: Yu-1 and Yu-2; Pryamoi deposit: 363, 1700-5; Kupol deposit: Kr04-1, -2; * heterogeneous fluid (boiling); genetic type of inclusions: (P) primary, (PS) pseudosecondary, (S) secondary; n is the number of measurements; d is the density.

with substantially gaseous inclusions (Fig. 11a), testifying to the heterogeneous state (boiling) of mineral-forming fluid. The two phase gas–liquid inclusions in quartz (Figs. 11b–11d) are homogenized into the liquid phase at 431–143°C and contain an aqueous solution with a salinity of 21.0–5.3 wt % NaCl equiv; Na and Mg chlorides are prevalent in the solution (the eutectic temperature is –(47–29)°C). The fluid density ranges from 0.50 to 0.94 g/cm^3. A small amount of carbon dioxide was frozen in a gas bubble of one inclusion and thawed at –59.3°C, indicating a certain admixture of low-boiling gases (Fig. 11d). The substantially gaseous inclusions contain a similar solution (the eutectic temperature is –28°C, with a salt concentration of 1.7 wt % NaCl equiv) and are homogenized at 431–321°C into the gas phase. The pressure varied from 360 bars at 431°C to 110 bars at 321°C.

The data of Table 7 plotted on a diagram (Fig. 12) demonstrate similar conditions of ore formation at granitoid-related Au and porphyry Cu–Mo deposits of the Koni–P'yagina district and identical fluid compositions differing from that determined for amethyst at the epithermal Kupol Au–Ag deposit in the western Chukchi Peninsula.

Table 8. Ore minerals of xenoliths in the Ryabinovy area

Major	Subordinate	Rare
Bornite	Magnetite	Cubanite
Chalcopyrite	Pyrite	Arsenopyrite
Chalcocite (neodigenite)	Sphalerite	Pyrrhotite
		Covellite
		Djurleite
		Betekhtinite

The formation of the aforementioned deposits in the Baim and Koni–P'yagina ore districts was related to the porphyry copper system of island arcs and marginal continental belts.

The age of porphyry copper mineralization commonly corresponds to the age of ore-bearing igneous complexes (Krivtsov et al., 1986). The porphyry copper occurrences found in metallogenic belts of the Northeast of Russia were formed from the Middle Paleozoic to the Quaternary (Fig. 1; Table 2). Porphyry copper deposits of different ages are known from the Baim metallogenic zone of the Oloi Belt and from the Kedon metallogenic belt. Late Jurassic deposits are located in the north within the Oloi volcanic belt, while Late Cretaceous deposits occur at the southern flank of the OChVB (Fig. 3).

In the Kedon volcanic belt (Fig. 2), Middle Paleozoic occurrences (Tabor, etc.) are combined with Late Cretaceous deposits (Vecherny, etc.). The porphyry copper deposits of the OChVB are related to Late Cretaceous granitoids over the entire extent of this belt. Superposition of porphyry copper deposits of various ages is known in the Andean and North American metallogenic belts (Krivtsov et al., 1986). Such a superposition testifies to the inherited character of porphyry copper mineralization and to the probable participation of transitional crustal sources in ore formation. This

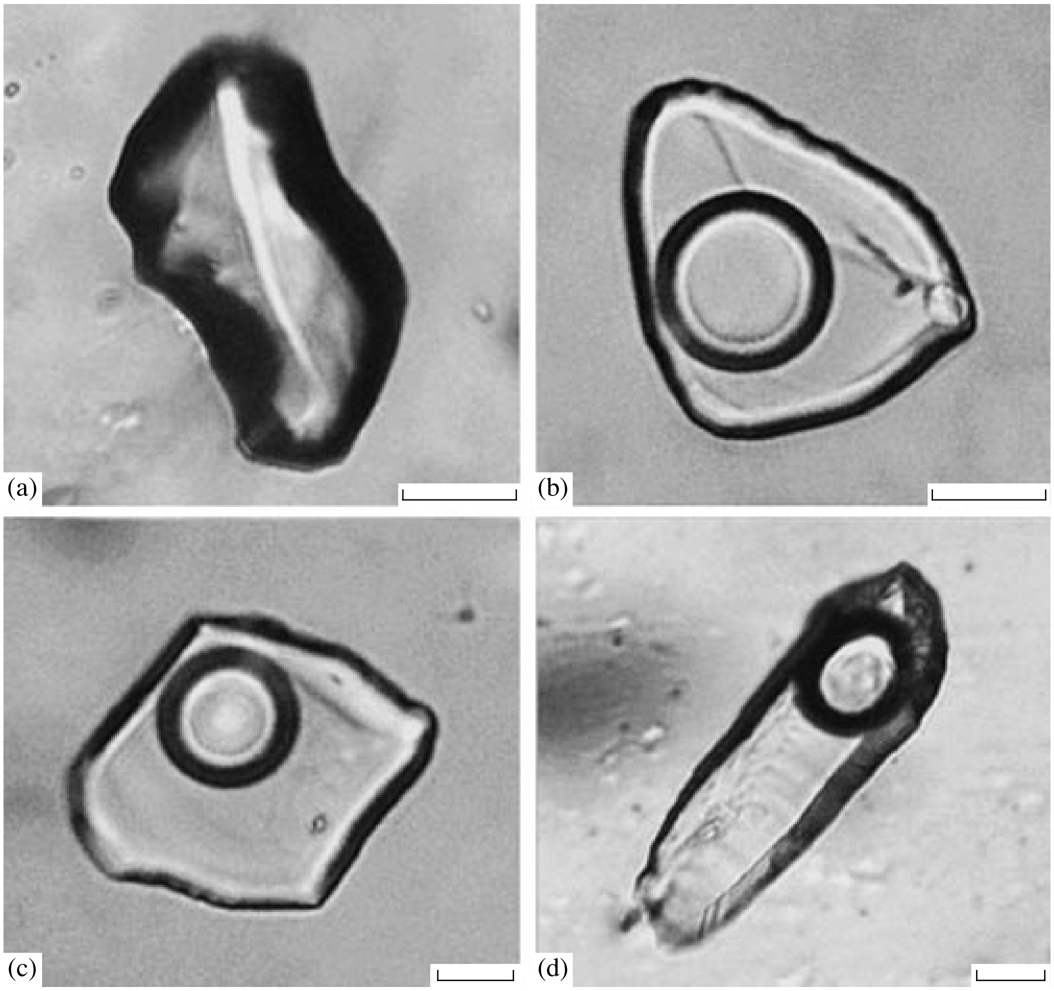

Fig. 11. Fluid inclusions in quartz from ore veins at the (a, b) Yuzny and (c, d) Pryamoi prospects. (a) Mainly gaseous, (b–d) two-phase. Scale bar 10 μm.

suggestion is supported by the results obtained from the study of Koni–P'yagina ore district.

A number of copper occurrences in the coastal part of the Koni–P'yagina Peninsula are hosted in Jurassic island-arc volcanic and sedimentary complexes. The Serdtse Kamennoe (Stony Heart) occurrence in basalt of the Poperechensky Sequence, the Khrustal'ny Creek occurrence in basalt of the Labirint Sequence, the Cape Vykhodnoi occurrence in siltstone of the Oldyan Formation (a stratiform body 4 m thick), occurrences hosted in sedimentary rocks of the Beregovsky Formation in coastal cliffs of Babushkin Bay, and the occurrence of Cape Yapon (sulfides in Middle Jurassic basalt and basaltic andesite with <0.2% Cu) may be mentioned in this respect (Fig. 8). There are some indications that massive sulfide ore occurrences are hosted in these sequences. It cannot be ruled out that Cu-bearing basalts or copper massive sulfide lodes hosted in Triassic and Jurassic island-arc complexes served as sources of Cretaceous porphyry copper deposits.

Xenoliths of rocks from island-arc complexes were found by S.A. Shubin in diorites of the Srednensky pluton approximately 15 km to the south of the Lora por-

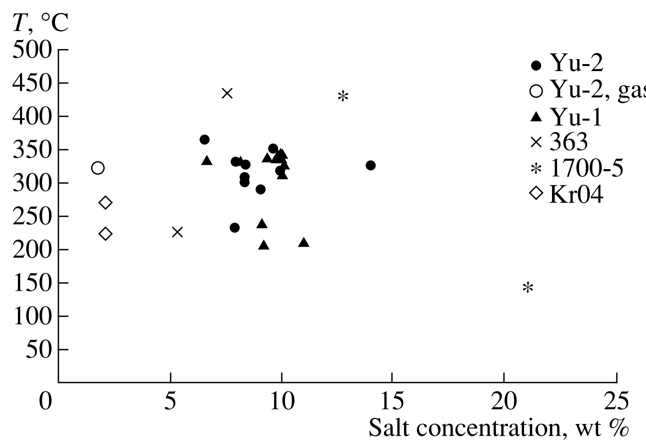

Fig. 12. Salt concentration in ore-forming fluid versus temperature. Sample numbers correspond to Table 7.

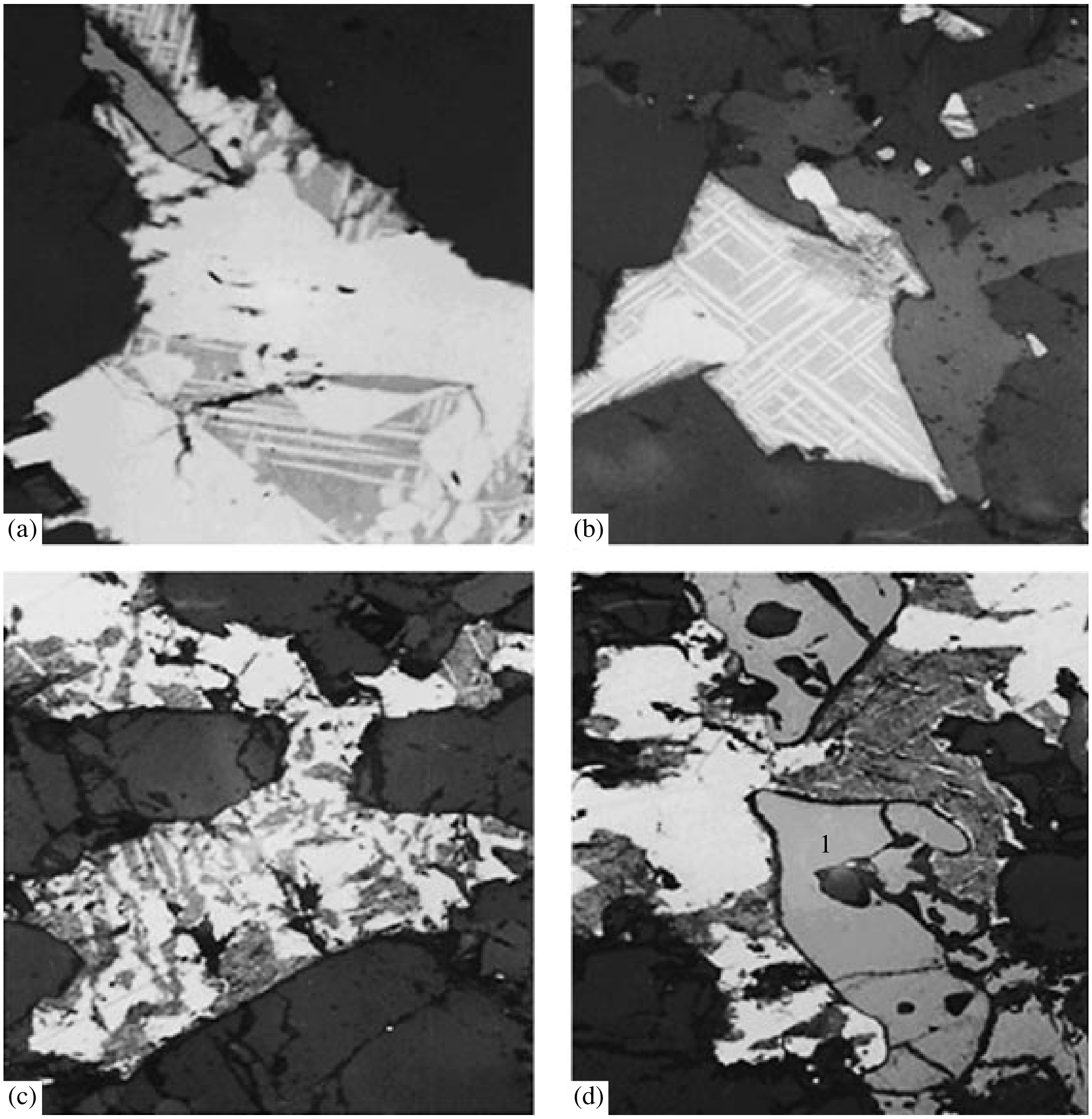

Fig. 13. Ore mineralization in xenoliths from the Ryabinovy area. Polished sections, magn. 120. (a, b) Exsolution structure of bornite in chalcopyrite; (c) intergrowth of bornite, chalcopyrite, and chalcocite; (d) the same in intergrowth with magnetite (1).

phyry Cu–Mo deposit. These xenoliths, which contained dense and abundant (up to 50%) bornite and chalcopyrite impregnations, have been studied in detail by Savva (2003). The xenoliths are angular fragments of severely altered basalts and fine clastic tuffs 10–15 cm in size with welded shells (1–3 cm) of diorite. The altered volcanics contain 30–60% sulfides. The banded texture of the xenoliths is emphasized by the contact metamorphism, variable degree of replacement with hydromica, and arrangement of lenticular sulfide segregations. Particular sulfide lenses are up to 3 cm long and as thick as 3 mm. Most xenoliths reveal uniformly distributed ore grains 0.1–2.0 mm in size that fill interstices between rock-forming minerals (Fig. 13). The minerals identified in the xenoliths are listed in Table 8.

The mineralized xenoliths contain more Fe, Cr, and Cu than the ore at porphyry-type deposits (Table 9). The Cu contents determined with AAS are much higher than those in granodiorites and higher by an order of magnitude than those in ore-bearing diorite of the porphyry system; the Ag contents are also elevated (Table 10). The positive correlation between Cu and Cr in porphyry-type ore indicates that this ore is related to deep sources. The ore mineral assemblages and geochemical signatures of the xenoliths suggest that granodiorites could have captured fragments of copper massive sulfide ore formed in an island-arc setting.

The studied xenoliths do not show the character of the primary copper massive sulfide ore in full because of thermal metamorphism and partial granitization of xenoliths. Nevertheless, they clearly indicate that high-grade volcanic-hosted massive ore actually occurs in island-arc complexes.

Table 9. Grades of ore at the Lora and Pryamoi porphyry Cu–Mo deposits and the Ryabinovy area

Element	Grade, ppm (average of ten determinations)		
	Lora (ore)	Pryamoi (ore)	Ryabinovy (ore xenoliths)
Pb	32.2	35.6	18.6
Cr	43.4	45.0	125.2
W	14.3	8.3	0.8
Fe	6.5%	4.7%	17.6%
Bi	10.9	12.5	4.5
Mo	150.3	11.1	3.8
Sn	8.9	6.8	12.5
Cu	575.3	1577.1	10812.0
Ag	1.01	0.92	3.5
Zn	89.5	121.4	152.1
Ni	7.2	8.9	12.3
B	180.0	61.1	38.7
Sb	4.7	8.4	1.7

Note: The analyses were performed using express emission spectrometry at the Northeast Interdisciplinary Research Institute, Far East Division, Russian Academy of Sciences.

DISCUSSION

The Cu–Mo porphyry systems of the Koni–P'yagina district of the Uda–Murgal metallogenic belt were formed in a crust of transitional type in the course of active interaction of Early Cretaceous igneous complexes with Triassic and Jurassic island-arc rocks. The massive sulfide lodes hosted in island-arc complexes in the basement of younger volcanic and plutonic belts were sources of copper, as can be clearly seen from relationships of tonalites with the Triassic–Jurassic sequences of basalts and basaltic andesites in the coastal cliffs of the northern Okhotsk region. Numerous xenoliths of basaltic rocks that contain as much as 50% sulfides (bornite, chalcocite, and chalcopyrite) are especially striking in this respect. The porphyry copper ore occurring nearby contains up to 37% Cu (Viking prospect).

The geochemical specialization of porphyry copper ore also indicates its cognation with basalts; in particular, copper reveals the closest correlation to chrome. The gain of molybdenum most likely was related to felsic volcanic and granitoid plutonic complexes. Indeed, porphyry molybdenum deposits devoid of Cu (Oksa, Osenny) appear at a distance from island arcs and backarc faults limit the occurrence of copper mineralization.

Early magnetite is abundant at the deposits of the Oloi metallogenic belt. Furthermore, quartz–hematite veins were formed at the late hydrothermal stage in the Baim ore district (Shapovalov, 1994). V.G. Kaminsky suggested that magnetite at the Peschanka deposit is a product of crystallization of the Yegdegkych pluton. Goryachev and Polovinkin (1979) explained the occurrence of magnetite in the Innakh ore field by autometasomatic alteration that accompanied crystallization of magmatic melt. In our opinion, magnetite and hematite could have been formed as a result of remobilization and redeposition of iron from jaspilites that occur in the basement of the Oloi–Berezovsky paleoceanic arc. This

Table 10. Au, Ag, and Cu contents (ppm) in ore from the Lora porphyry Cu–Mo deposit and ore xenoliths from the Ryabinovy area

Sample/trench	Material	Au	Ag	Cu
	Lora deposit			
240/t-12	Metasomatically altered diorite with pyrite pockets up to 1.5 cm in size and coarse flakes of molybdenite	0.041	3.06	367.7
252/t-4	Tourmaline–quartz–muscovite greisen	–	1.02	10.2
261a/t-5	Fine-grained diorite with chalcopyrite pockets up to 2–30 mm in size; up to 5% sulfides	0.064	2.41	11044.2
266/t-6	Granodiorite with pyrite and chalcopyrite disseminations; up to 3% sulfides	0.016	4.52	7831.3
345/t-1	Porphyritic diorite with pyrite and chalcopyrite disseminations	0.011	3.57	764.5
347/t-1	Quartz–tourmaline–muscovite greisen	0.012	4.21	115.8
t-20/3	Slightly altered diorite	0.005	0.022	65.8
	Ryabinovy area			
1286/7	Xenoliths with copper mineralization (bornite + chalcopyrite)	0.010	7.30	34414.9
1286/10	Xenoliths with copper mineralization (bornite + chalcopyrite)	0.004	2.52	3625.4
1286/6	″	0.003	2.61	4814.4
1286/7	″	0.128	10.83	41338.6

Note: Analyses were performed using atomic absorption spectroscopy (AAS) at the Northeast Interdisciplinary Research Institute, Far East Division, Russian Academy of Sciences; analyst T.V. Kryachko.

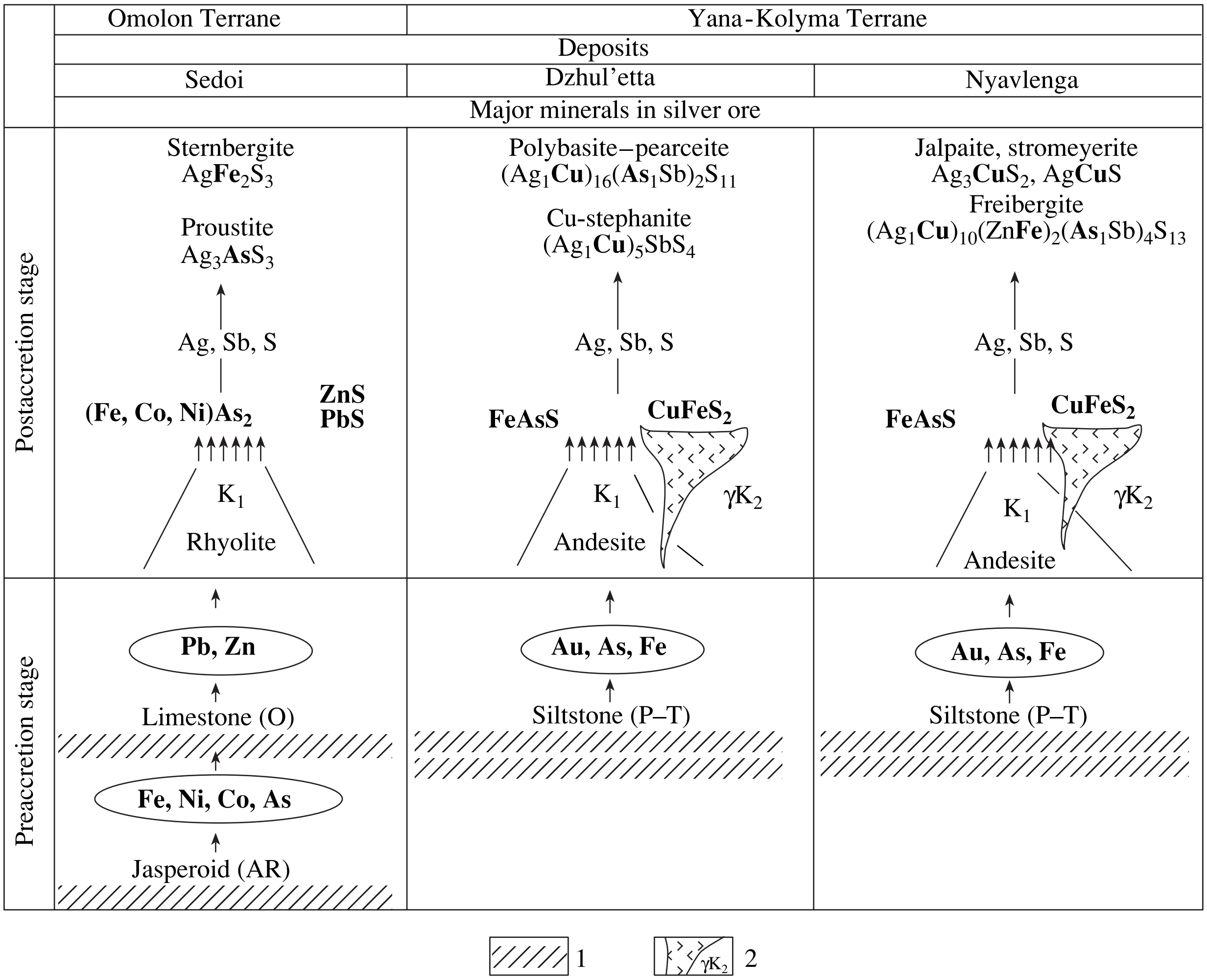

Fig. 14. Mobilization and redistribution of material in rocks lying at the base of volcanic structures. (1) Sedimentary country rocks; (2) Late Cretaceous granitoids.

suggestion is supported by widespread jaspilites and magnetite skarn bodies in the Precambrian metamorphic sequences of the Omolon Cratonic Terrane adjacent to the arc (*Geology*…, 1983). Blocks of Precambrian rocks may have been incorporated into the basement of this arc due to their displacement in the process of accretionary thrusting.

According to Shcheglov (1980), the basement of regions that underwent reactivation affects the character of regional metallogeny; the basement of particular zones and districts exerts an influence upon the geochemical and mineral types of ore deposits (Umitbaev, 1986). The evolution of an ore system and formation of an entire series of mineral deposits implies multiple redistribution of materials, so that newly formed minerals inherit and retain in their composition information on the preceding stages. In addition to the isotopic composition of ore minerals (Sidorov and Volkov, 2004), the speciation and chemical composition of ore minerals at epithermal Au–Ag deposits should be regarded as important evidence (Tomson et al., 2003).

The well-known Dzhul'etta epithermal Au–Ag deposit may be cited as an example. This deposit is localized at the junction of three metallogenic units: the Omsukchan zone with a Sn, Ag, Fe, Pb, and Zn geochemical profile; the Yana–Kolyma Au–Ag–As metallogenic province; and the Uda–Murgal porphyry copper metallogenic belt. Their influence was imprinted on the mineralogical and geochemical specialization of the postaccretionary ore at the Dzhul'etta deposit, first of all, in the productive mineral assemblages: (i) electrum–fahlore, (ii) polybasite–pearceite (Pb, Zn, Fe, Au, Ag, Cu, As, Sb), and (iii) küstelite–acanthite (Au, Ag, Se). In terms of mineral species, this effect was expressed in development of arsenic and copper mineral phases (Fig. 14): polybasite (up to 2.5% As), pearceite (up to 10.5% Cu), and acanthite (up to 4% Cu and 3.4% As). The high sulfide content in ore at the Dzhul'etta deposit is comparable with that at the Omsukchan deposits (Dukat, etc.).

The second example concerns the Nyavlenga multistage epithermal Au–Ag deposit, situated 40 km west of the Dzhul'etta deposit. Upper Jurassic preaccretionary rocks of the Yana–Kolyma metallogenic province serve as the basement of the volcanic edifice that hosts the Nyavlenga deposit. These rocks are characterized by elevated contents of Au, As, Pb, and Zn. The gain of these components from the basement is reflected in a high As content of freibergite; high total sulfide contents, including galena and sphalerite; and development of the late quartz–arsenopyrite assemblage. The effect of the Uda–Murgal belt on the ore mineralization at the Nyavlenga deposit is expressed in the intramineral granitoid injections specialized for Cu and Mo and in the abundance of molybdenite, as well as Cu–Ag sulfides (stromeyerite, jalpaite, and mckinstryite), in the Au–Ag ore (Fig. 14).

In the Omolon Cratonic Terrane, Paleoproterozoic jaspilites enriched in Fe, Co, and Ni, as well as Neoproterozoic–Lower Paleozoic carbonate rocks with dispersed Pb and Zn, exerted an influence on the composition of epithermal ores. These rocks were accreted in the Middle Paleozoic (the Kedon Group of volcanic rocks) and in the Mesozoic along the Konginsky Fault. The epithermal Au–Ag and Ag-bearing base-metal deposits are localized in the young volcanic structures. Furthermore, it was established that the model isotopic age of lead in galena from the Mesozoic deposit corresponds to the age of the basement: the Ordovician at the Sedoi occurrence and the Neoproterozoic in the Pravaya Vizual'naya area (Shpikerman et al., 1993). The concentrations of Co and Ni in loellingite of the productive assemblage reach 1.4 and 3.2 wt %, respectively. Sternbergite and argentopyrite are predominant as Ag mineral species (Fig. 14).

The examples cited above demonstrate that, in contrast to the Baim zone, the epithermal Au–Ag mineralization in the OChVB, to a certain extent, is isolated in time from the porphyry copper–molybdenum mineralization. Thus, the crustal sources of ore matter likely were different. A similar inference was made on the basis of Re–Os dating of porphyry copper and epithermal gold ore at the Grasberg deposit in Indonesia. It is suggested that gold at this giant deposit was derived from sedimentary rather than from igneous rocks (Mathur et al., 2000).

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