ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 409A, No. 6, pp. 859–863. © Pleiades Publishing, Inc., 2006.
Original Russian Text © A.A. Sidorov, I.N. Tomson, N.E. Savva, A.V. Volkov, V.Yu. Prokof'ev, E.E. Kolova, 2006, published in Doklady Akademii Nauk, 2006, Vol. 409, No. 4, pp. 504–509.

GEOLOGY

Relation between Porphyry Deposits and Their Vein Satellites

Corresponding Member of the RAS A. A. Sidorov, Corresponding Member of the RAS I. N. Tomson, N. E. Savva, A. V. Volkov, V. Yu. Prokof'ev, and E. E. Kolova

Received March 14, 2006

DOI: 10.1134/S1028334X06060043

Porphyry copper, molybdenum, tin, tin–silver, gold–rare metal and other deposits are commonly accompanied by nonporphyry ore formations that are frequently similar to the entire porphyry group. They are represented by sulfide–quartz (base metal), gold–sulfide–quartz, epithermal gold–silver, antimony, and mercury deposits of vein and stringer–disseminated ores (Table 1). The detailed study of such satellite deposits revealed that they have mineralogical–geochemical links with the basic porphyry ores. However, the porphyry and nonporphyry deposits seem to be of the same type in some places because of similar physicochemical constraints of vein formation [1, 2]. Moreover, these apparently monochronous series of porphyry vein deposits inherited the evolution pattern of older ore-bearing zones in particular regions. This fact was first marked by R. Hutchinson, R. Hodder, and V.S. Popov who suggested that some deposits in Rudnyi Altai (Sugatov, Novo-Nikolaev, and Bukhtarma), the southern Urals, Armenia, and Spain (the Sierra Colorado sector of the Rio Tinto ore field) do not belong to the porphyry copper class, because they are closely associated with massive sulfide deposits and the accompanying sodic magmatic rocks [3]. According to Savva [4], diorite intrusives in porphyry copper deposits of the northern Okhotsk region incorporate xenoliths of propylitized basalts with massive sulfide mineralization (up to 60% bornite and chalcopyrite). Based on the study of the composition of xenoliths and structural–metallogenic reconstructions, Savva suggested that copper deposits of the northern Okhotsk region are genetically related to massive sulfide deposits of island-arc volcanosedimentary complexes that occur at the basement of the inner zone of the Late Mesozoic Okhotsk–Chukot volcanic belt. Based on the study of Late Mesozoic porphyry tin–silver deposits of the Russian Northeast, we concluded that porphyry and vein satellite ores genetically related to silver–sulfide deposits in Paleozoic black shales also inherited the evolution pattern of older deposits [2].

Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia; e-mail: alexandr@igem.ru

Porphyry gold mineralization is developed in both copper and tin ore districts. In particular, this type of mineralization is widespread in the Oloi island-arc terrane (Chukotka). For example, gold mineralization was recently discovered in the Koni–P'yagin segment (Fig. 1) of the Uda–Murgal island-arc terrane (the northern Okhotsk region [4]).

In the Oloi terrane, the Asket, Yakor, and Irunei ore occurrences are closely associated with the Mo- and Cu-bearing monzonitoid intrusives. Such ore occurrences are characterized by large scales of mineralization. The intrusives are accompanied by numerous fields of propylitized volcanosedimentary rocks that incorporate abundant quartz and quartz–carbonate veins with the gold–silver–base metal mineralization [6]. The Asket ore occurrence is represented by a stockwork with quartz–sulfide patches and veinlets that contain dissemination of pyrite, chalcopyrite, molybdenite, magnetite, ilmenite, sphalerite, arsenopyrite, pyrrhotite, and native gold. With respect to several specific features, the Asket ore occurrence resembles the Baim porphyry copper deposit and its nonporphyry satellite (Vesennee gold–silver deposit). Therefore, the Asket ore occurrence can be assigned to both porphyry gold and porphyry gold–copper types.

The Yakor ore occurrence is confined to a stock of Cretaceous syenite–diorite porphyries. Orebodies are located in nearly meridional silicification and ankeritization zones that include patches, veinlets, and veins of fine-grained quartz with the gold, arsenopyrite, pyrite, chalcopyrite, antimonite, native arsenic, and realgar–orpiment mineralization. The Yakor ore occurrence is closely associated with preporphyry zones of auriferous sulfidization in sedimentary sequences that could serve as a source of ore material during the formation of intrusions and the subsequent hydrothermal activity.

The Irunei gold–silver occurrence is located at the southeastern continuation of the Oloi island-arc terrane

Table 1. Variability series of basic porphyry formations

Ore formation series	Porphyry copper (Buchim, Peschanka)	Porphyry copper–molybdenum	Porphyry molybdenum (Climax)	Greisen rare metal (Primorye)
	Sulfide-bearing breccia (Vesennee)	Skarn sulfide–base metal	Skarn molybdenum (Tyrnyauz)	Cassiterite–quartz (Tigrinoe)
	Gold–rare metal (Rzhavyi)	Gold–quartz vein	Gold–silver (Soyuznoe)	Cassiterite–sulfide (Shcherbakov)
	Gold–silver (Plavlennitsa)	Gold–silver (Kochebulak)	Antimony–mercury	Gold–rare metal
	Carlin-type disseminated sulfide (Alshar)	Antimony–mercury		Gold–silver
	Mercury			Antimony

Note: Typical deposits are given in parentheses.

overlain by volcanic sequences of the postaccretionary Okhotsk–Chukot volcanogenic belt. The Irunei gold–silver occurrence is confined to a magmatogenic dome within the nearly meridional Anadyr deep suture. The dome is outlined by stocks and dikes of diorites, granodiorite porphyries, subvolcanic andesites, dacites, and rhyolites. The overlying sequence includes Lower and Upper Cretaceous volcanic rocks of contrasting (acid and basic) compositions. The ore-bearing adular–hydromica metasomatite zones and fields contain adular–quartz and adular–quartz–carbonate veins, veinlets, and patches with dissemination of electrum, silver sulfosalts and selenides, galena, sphalerite, and chalcopyrite. Dissemination of arsenopyrite, molybdenite, cinnabar, and realgar is less common. In terms of the structural setting, composition of magmatic rocks, and mineral composition of ores, the Irunei ore occurrence can be assigned to the porphyry copper (molybdenum) series that represents upper (nonporphyry) horizons of the porphyry gold deposit.

The geological setting of the Koni–P'yagin segment (Fig. 1) is characterized by the presence of the Srednyaya magmatogenic dome in the central part of the Koni–P'yagin Peninsula. The marginal (northeastern) part of the dome incorporates the Lora porphyry copper–molybdenum deposit accompanied by the Pryamoe deposit located at a distance of 9 km. Tourmaline–muscovite greisens developed at some distance from these deposits host gold–arsenic–bismuth occurrences (Yuzhnyi sector, Ryzhik, and Guron gold–

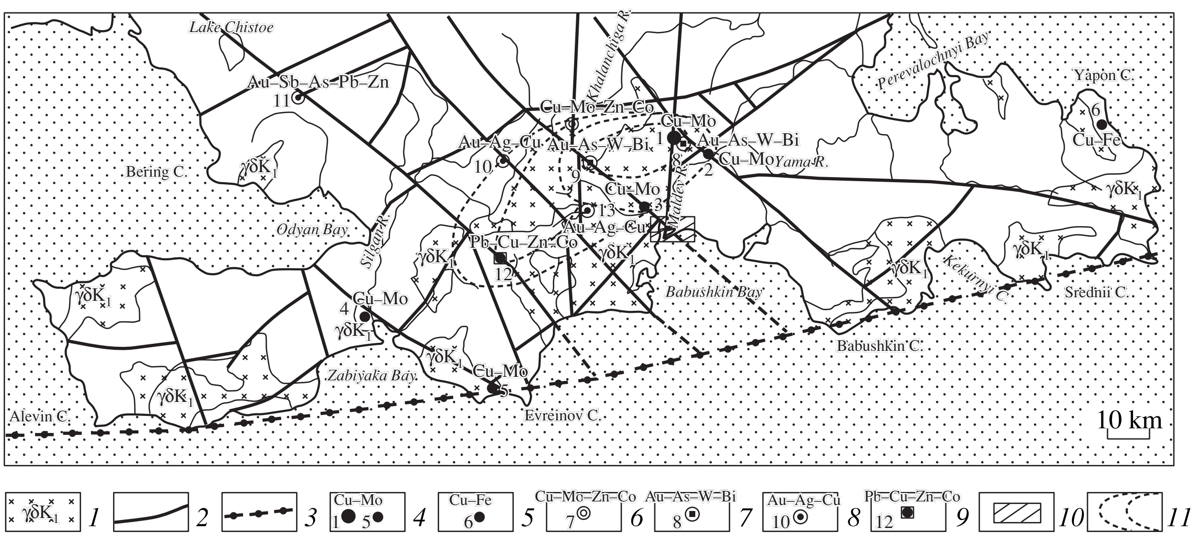

Fig. 1. Geostructural scheme of the location of gold ore occurrences in the Koni-P'yagin Peninsula. (*1*) Granodiorites ($\gamma\delta K_1$); (*2*) tectonic fractures; (*3*) Koni-P'yagin deep fault; (*4–9*) ore occurrences and their geochemical profiles: (*4*) Cu–Mo, (*5*) Cu–Fe, (*6*) Cu–Mo–Zn–Co, (*7*) Au–As–W–Bi, (*8*) Au–Ag–Cu, (*9*) Pb–Cu–Zn–Co; (*10*) auriferous placer domain; (*11*) orientation of concentric zonality. Numeral designations: (1) Lora, (2) Pryamoe, (3) Ryabinovyi, (4) Viking, (5) Ikrimun, (6) massive sulfide copper occurrence of the Yapon Cape in island-arc sediments (J_2 bt–b), (7) Tal'nik, (8) Yuzhnyi, (9) Ryzhik, (10) Krutoi, (11) Gorelyi, (12) Guron, (13) Gol'tsovyi.

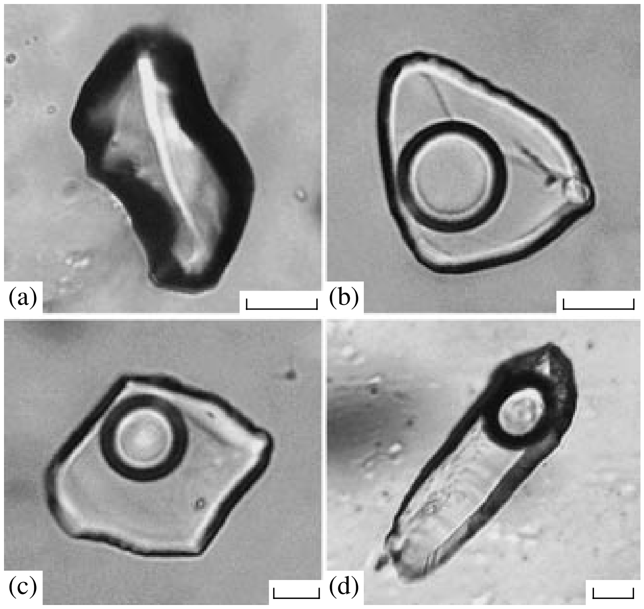

Fig. 2. Quartz-hosted fluid inclusions in ore veins of the (a, b) Yuzhnoe and (c, d) Pryamoe ore occurrences. (a) Gas-rich; (b–d) two-phase fluid. Scale bar 10 μm.

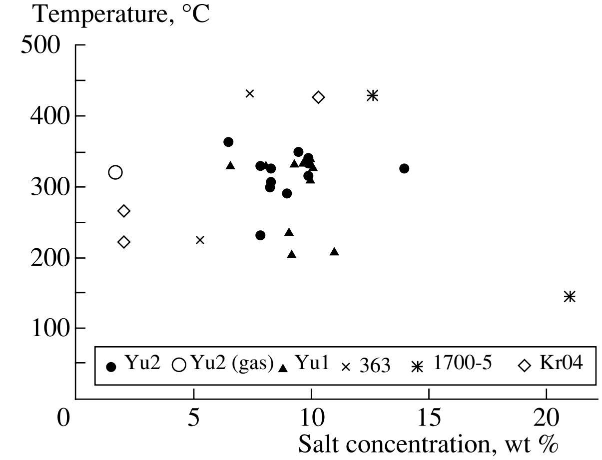

Fig. 3. Salt concentration vs. temperature relationship in ore-forming fluids in the studied deposits.

polysulfide). The periphery of the dome incorporates epithermal gold–silver occurrences (Krutoi and Gol'tsovyi sectors). The deposits and occurrences listed above are characterized by the following features: (1) the distinct spatial relation with granitoid porphyry intrusions; (2) the sequential replacement of biotite–K-feldspar metasomatites by quartz–sericite rocks (with tourmaline) and propylitic metasomatites; (3) the stringer–disseminated type of mineralization; (4) the absence of structural indicators of epithermal mineralization in ore occurrences located away from the porphyry copper–molybdenum intrusion; (5) the presence of ore mineral assemblage typical of the porphyry copper–molybdenum system (pyrite, chalcopyrite, molybdenite, and magnetite); and (6) high contents of Cu and Mo.

We carried out thermo- and cryometric investigations of fluid inclusions in quartz samples from veins of the Yuzhnoe ore occurrence and veinlets of the Pryamoe deposit (Table 2; Figs. 2, 3). Quartz grains from ore veins of the Pryamoe deposit contain primary, pseudosecondary, and secondary fluid inclusions (1–70 μm) of negative crystalline or irregular shape (Fig. 2). In some quartz samples, the fluid inclusions are associated with syngenetic gas-rich inclusions (Fig. 2a) that testify to the heterogeneous (boiling) state of a mineral-forming fluid. The two-phase (gas–liquid) inclusions in quartz (Figs. 2b–2d) homogenize into a liquid phase at 431–143°C and contain a water solution with 21.0–5.3 wt % NaCl equiv. The solution is mainly composed of sodium and magnesium chlorides (eutectics temperature ranges from –47 to –29°C). The fluid density varies from 0.50 to 0.94 g/cm^3. The gas bubble in one inclusion contains a small amount of solid carbon dioxide that melts at –59.3°C, testifying to the presence of an admixture of low-boiling gases (Fig. 2d). The gas-rich inclusions contain a similar solution (eutectics temperature –28°C) with 1.7 wt % NaCl equiv and homogenize into gas at 431–321°C. The pressure varies from 360 bar at 431°C to 110 bar at 321°C. Results presented in Table 2 and Fig. 3 demonstrate similar constraints of ore formation in gold–rare metal and porphyry copper–molybdenum deposits. They significantly differed from fluids that produced amethyst in an orebody of the epithermal Kupol gold–silver deposit (western Chukotka).

Thus, porphyry gold deposits are widespread in gold–sulfide mineralization zones in the Kolyma and Chukot terranes of the passive continental margin. They are particularly abundant in postaccretionary volcanic zones (e.g., the Okhotsk–Chukot volcanogenic belt) and less developed in zones of synaccretionary magmatism. The auriferous porphyry intrusives are confined to zones with a fine dissemination of sulfides (arsenopyrite and pyrite) in the carbonaceous–clayey and sandy sequences of the Verkhoyansk Complex. Ore deposits and occurrences are confined to stocks composed of diorites, granodiorites, biotitic granites, and adamellites. Late differentiates are represented by rhyolite, granite porphyry, and lamprophyre dikes. Geochemical fields of deposits are marked by anomalous concentrations of Au, Ag, Sn, W, As, Hg, and U. The mineralization is developed over a significant area inside the granitoid massifs, as well as in their apical portions and hornfelsized rocks and outer contact zones.

The link between porphyry gold deposits and gold–sulfide mineralization is prominent in the Maisk deposit, where ore-bearing quartz veinlets confined to porphyry dikes and hornfelses in the central part of disseminated gold–sulfide orebodies are compositionally similar to ores of porphyry gold deposits.

Table 2. Results of thermo- and cryometric investigations of quartz-hosted fluid inclusions from ore veins in the Yuzhnoe and Pryamoe deposits

Sample no.	Mineral	*n*	Temperature, °C				Salt concentration. wt % NaCl equiv	*d*, g/cm^3	Pressure, bar
			homogenization	eutectics	ice melting	CO_2 melting			
Yu-2	Quartz PS	10	364	–30	–4.0	–	6.5	0.66	–
	The same	5	350	–32	–6.2	–	9.5	0.74	–
	″	19	342	–36	–6.5	–	9.9	0.76	–
	Q (P)	9	334	–29	–6.5	–	9.9	0.78	–
	Q (PS)	3	330	–29	–5.0	–	7.9	0.75	–
	The same	4	327	–34	–5.3	–	8.3	0.76	–
	″	4	326	–38	–10.1	–	14.0	0.84	–
	″	3	308	–30	–5.3	–	8.3	0.76	–
	″**	2	321 G	–28	–1.0	–	1.7	n.d.	110
	″	3	316	–34	–6.5	–	9.9	0.80	–
	″	2	300	–32	–5.3	–	8.3	0.81	–
	″	9	291	–31	–5.8	–	9.0	0.83	–
	Q (S)	5	232	–29	–5.0	–	7.9	0.90	–
Yu-1	Quartz (P)	3	342	–42	–6.6	–	10.0	0.76	–
	Q (PS)	4	335	–35	–6.4	–	9.7	0.77	–
	Q (P)	16	334	–34	–6.1	–	9.3	0.77	–
	Q (PS)	2	331	–43	–5.2	–	8.1	0.75	–
	The same	4	331	–33	–4.1	–	6.6	0.73	–
	″	6	328	–38	–6.7	–	10.1	0.79	–
	″	3	311	–36	–6.6	–	10.0	0.81	–
	Q (P)	23	238	–38	–5.9	–	9.1	0.90	–
	Q (PS)	11	209	–38	–7.4	–	11.0	0.94	–
	The same	3	206	–39	–6.0	–	9.2	0.93	–
363	Quartz* PS	2	431	–34	–4.7	–59.3	7.5	0.50	360
	Q (PS)	3	224	–32	–3.2	–	5.3	0.88	–
1700-5	Quartz PS	3	429	–42	–8.9	–	12.7	0.64	–
	The same	2	143	–47	–18.1	–	21.0	1.08	–
Kr04-1	Amethyst (P)	11	267	–21	–1.2	–	2.1	0.78	–
Kr04-2	Q (PS)	8	222	–21	–1.2	–	2.1	0.86	–

Note: (Yu1, Yu2) Yuzhnoe occurrence; (363, 1700-5) Pryamoe deposit; (Kr04-1, Kr04-2) Kupol deposit; (*) heterogeneous fluid (boiling); genetic type of inclusions: (P) primary, (PS) pseudosecondary, (S) secondary; (*n*) number of measurements; (*d*) fluid density; (n.d.) not determined.

The porphyry gold deposits are also closely associated with the well-known Kolyma gold–quartz formation. The geochemical (including the Pb isotope characteristics) and geostructural data indicate that these deposits are spatially associated with large auriferous pyrite (pyrrhotite) zones confined to faults in sandy–clayey (black shale) sequences of the Verkhoyansk Complex. We studied some fragments of such a zone at the Degdekan deposit. Here, gold–sulfide veins in black shales are accompanied by coarse-grained pyrite patches that include microaggregates of galena, sphalerite, and gold. The auriferous pyrite grains have a quartz rim in some places. Auriferous intrusions of the early collisional (prebatholith) complex are composed of K- and Na-rich granite and granodiorite porphyries. The perivolcanic zone of the Okhotsk–Chukot volcanogenic belt also incorporates postaccretionary granitoids.

Quartz veins in intrusions are commonly similar to gold–quartz veins in dikes (dike type of the gold–quartz formation). These two types of veins show transitional varieties. For example, porphyry gold occurrences of the Basugun'in and Burkhalin ore nodes are confined to granite and granodiorite porphyry massifs at numerous ore deposits and occurrences in the central Kolyma region. Stockworks, veins, and patches of porphyry ores have the quartz–sulfide composition. The quartz–tourmaline–sulfide assemblage is less common. Ore minerals are mainly represented by arsenopyrite and löllingite. Molybdenite, native bismuth, bismuthinite, bismuth sulfotellurides, and fine-grained gold are the subordinate minerals. Relative to gold–quartz deposits, porphyry gold deposits are characterized by the following specific features: the presence of higher-temperature mineral assemblages; the beresitization of ore-hosting rocks; an extremely irregular distribution of sulfides in ores; the presence of fine dissemination of native gold, bismuth, and their tellurides in sulfides; and the presence of sulfide-free (regenerated) quartz veinlets with very pure gold flakes (fineness 900 or more).

The porphyry gold mineralization of Sn-bearing intrusives in the Okhotsk–Chukot volcanogenic belt and its perivolcanic framing is supported by the presence of Au in the Galimoe, Kinzhal, Neva, Trud, and other tin deposits of the Omsukchan (Dukat) ore district. Such gold mineralized is also developed in several other ore districts of the Kolyma and Chukot regions. Some technological samples from these deposits contain 2 g/t Au. The Au content is as high as 16 g/t in some places of the Ilintas deposit, 20 g/t in arsenopyrite samples [7], 6 g/t in the sulfide concentrate from the Galimoe deposit, and 14.3 g/t in the sulfide concentrate from the Kinzhal deposit [8]. All these deposits can be united into two conjugated ore formation series: silver (gold)–sulfide series and porphyry tin (silver) series. The first (silver–sulfide) series of the Dukat type predated the porphyry series. The superposition of porphyry mineralization on the silver–sulfide variety is indicated by the prominent rejuvenation and redeposition of sulfide ores at the Dukat deposit.

The majority of granitoid massifs in Kolyma and Chukotka are confined to intrusive domes. Moreover, many massifs were squeezed out from clayey sequences of the Verkhoyansk Complex as a result of later neotectonic movements. This is well recorded along the valleys of creeks and ravines [1]. Therefore, many hypabyssal intrusions with gold–rare metal mineralization confined to the less eroded framing are associated with epithermal gold–silver, antimony, and antimony–mercury deposits of the vein type.

However, the comparative analysis of mineralogical–geochemical associations shows that vein ores in the satellite deposits have genetic links with porphyry ores, because the porphyry deposits and their satellites in the Russian Northeast developed in zones with fine sulfidization (nanomineralization) of enclosing rocks or preporphyry massive sulfide mineralization.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project no. 04-05-64359.

REFERENCES

1. A. A. Sidorov, *Ore Formations and Evolutional-Historical Analysis of Noble Metal Mineralization* (SVKNII DVO RAN, Magadan, 1998) [in Russian].
2. A. A. Sidorov and A. V. Volkov, Dokl. Earth Sci. **375A**, 1382 (2000) [Dokl. Akad. Nauk **375**, 807 (2000)].
3. V. S. Popov, *Geology and Genesis of Porphyry Copper–Molybdenum Deposits* (Nauka, Moscow, 1977) [in Russian].
4. N. E. Savva, *Geodynamics, Magmatism, and Mineragenу of Continental Margins of the Northern Pacific* (SVKNII DVO RAN, Magadan, 1998) [in Russian].
5. A. A. Sidorov and A. V. Volkov, Dokl. Earth Sci. **390**, 516 (2000) [Dokl. Akad. Nauk **390**, 374 (2003)].
6. M. E. Gorodinskii, V. V. Gulevich, and V. A. Titov, *Materials Related to Geology and Mineral Resources of the Northeast USSR* (Magadan, 1978), Issue 24, pp. 151–158 [in Russian].
7. T. I. Trenina, in *Proceedings of VNII-1* (Magadan, 2001), Vol. 14, pp. 125–158 [in Russian].
8. V. T. Matveenko, in *Proceedings of VNII-1* (Magadan, 2001), Vol. 14, pp. 203–224 [in Russian].
9. T. Nolan, *Geology of Ore Deposits in Western States of the United States* (ONTI, Moscow, 1937).