GEOLOGY

The Genetic Diversity and Convergence of Epithermal Gold--Silver Mineralization

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The majority of researchers believe that epithermal deposits form in near-surface (300--500 m) and low-temperature (50--200^{o}C) conditions from hot solutions in open fissures. The facts that have been accumulated to date suggest that epithermal deposits are associated with postaccretionary volcanogenic belts, subduction zones, and tectonomagmatic reactivation regions. However, some researchers include epithermal deposits into a single genetic model (porphyry copper ore-forming system), in which gold--silver deposits are divided into low- and high-sulfidation types [1]. This model does not appear to encompass the entire diversity of gold--silver deposits (Fig. 1, Table 1).

The obvious association of epithermal deposits with global structures, which governed the Pacific and Mediterranean volcanism, provoked an illusion of the formation of ore material in the adular--chalcedony-quartz veins from deep (subcrustal or lower crustal) sources. Convergence of the adular--chalcedony--quartz veins depends on the near-surface physicochemical conditions of the deposition of mineral aggregates. Our works have revealed that the epithermal deposits were no less developed in ancient epochs, beginning from the Precambrian. The degree of preservation of near-surface deposits inversely correlates with their age. Moreover, gold--silver deposits demonstrate a paragenetic relationship with gold--sulfide, massive sulfide, ferruginous--quartzite, uranium--polymetal, and porphyry copper--molybdenum ore associations (complexes) and gold ore associations of basic--ultrabasic complexes (Table 2). It is obvious that the primary material for such diverse ore associations could not be derived from cognate sources. However, the available data indicate a common source of ore material for the epithermal and mesothermal deposits of the porphyry copper, porphyry tin, and gold--sulfide associations in ore districts of the Russian Northeast (Fig. 2). Fluid inclusion data on quartz suggest that gold--sulfide ores formed at temperatures ranging from 50 to 420@C (with interstadial inversions reaching 100--150@C) and corresponding pressures in the hydrothermal system varying from 5 to 250 kbar [3]. One cannot rule out that the higher pressure estimates are erroneous because of the imperfection of determination methods. Nevertheless, the explosive mode of epithermal ore formation is confirmed by the presence of numerous hydrothermal explosion zones and diatremes.

The relationship between epithermal vein deposits and specific ore associations is not incidental. This is indicated by regular variations of mineral and geochemical paragenesis in ores (Tables 1, 2). However, the genetic relation of mineral types in epithermal deposits to other ore associations can only be recorded by scrutinization of their mineralogical and geochemical features. Generally, epithermal veins from different ore associations often demonstrate analogous structures, textures, and mineral compositions. For example, one can see mosaic-lamellar (agate-type) and banded metacolloidal aggregates of quartz, adular, and carbonates with a small amount of sulfides, sulfosalts, along with occasional tellurides and selenides (1--3%). Moreover, the major part of barren or low-grade epithermal veins is distinguished from the Au- and Ag-rich varieties only in terms of the contents of these noble metals.

The gold (or silver) potential of epithermal deposits is governed by the respective metal potential of deposits of the entire ore association (Table 2). In the porphyry copper association, the gold--silver mineralization is observed as diverse mineral types, although copper sulfides and sulfosalts are the most widespread (polybasite mineral type). We have established that the gold--silver deposits of the gold--sulfide association in the Chukot and Okhotsk--Kolyma regions are also diverse in terms of mineral types. They contain Au--Ag selenides and Sb--As sulfosalts. In addition, they are conjugated with both porphyry copper--molybdenum and porphyry tin--silver ore associations in space and time.

Gold--silver deposits in the porphyry ore associations mentioned above are supplemented with various proportions of the gold--sulfide (disseminated), gold--sulfide--quartz, gold--rare metal, tin--silver, base metal, antimony, and mercury mineralization. Epithermal deposits of the porphyry tin--silver association are characterized by different shares of the silver and tin--silver sulfosalts. It is well-known that massive sulfide deposits are developed in the green tuff provinces of island-arc terranes. In these deposits, gold--silver mineralization is typically developed as electrum--chalcopyrite--sphalerite--galena or silver--sphalerite--galena (Kuroko type) assemblages. Gold--silver deposits of the five element (uranium--polymetal) association are characterized by the specific electrum (kustelite)--uraninite--sulfide mineral type. However, near-surface deposits of this association are commonly eroded or rejuvenated because of their predominant confinement to the Precambrian, except for some small deposits in central Europe (the Ore Mountains region) and North America. The epithermal deposits of copper--nickel and chromite ore associations in the basic--ultrabasic and alkaline-basic complexes have been insufficiently studied. Ores and rocks in these complexes are characterized by an abundance of accessory and telluride minerals, indicating their genetic (paragenetic) relationship with the gold--silver--telluride type [2].

The comparison of different ore associations demonstrates a higher gold potential of the epithermal porphyry copper deposits. The gold potential of the uranium--polymetal association is, apparently, outstanding. However, the uranium--polymetal association has not yet been sufficiently studied and only two giant deposits (Witwatersrand and Olympic Dam) have been discovered in this ore association. The tin--silver--sulfide and porphyry tin--silver associations were previously considered Au-poor varieties. However, the recently discovered gold--sulfide deposits in Chukotka (e.g., the Maisk deposit) and gold--antimony deposits in Bolivia are confined to (or paragenetically associated with) these ore associations.

The gold--silver mineralization is usually observed as Au-rich deposits (Au : Ag = 1 : 1--1 : 50) in ore districts characterized by a complete series of ore associations [2] with well-developed antimony, mercury, or fluorite deposits. In districts with an incomplete series of ore associations, i.e., insignificant development of low-temperature mineralization, gold--silver association mainly includes Ag-rich deposits (Au : Ag = 1 :100--1 : 300 or less). Table 1 shows that the gold--silver--telluride mineralization associated with the subvolcanic alkaline-ultrabasic and basic rocks is mainly represented by Au-rich deposits (Au : Ag = 1 : 1 or more).

Our works in ore districts in the Russian Northeast showed that gold mineralization is pervasive in various ore associations ranging in age from the Precambrian to Miocene--Pliocene [4]. Inheritance of mineralization is the most important criterion of ore potential of specific geological provinces. Roots of many epithermal gold--silver deposits, such as the Cortez, Getchell, and Tuscarora deposits in the Basin and Range Province (United States) and the Sopka Rudnaya and Promezhutochnoe deposits in central Chukotka (Russia), are composed of disseminated gold--sulfide zones of the Carlin (or Maisk) type. Regenerated (Tertiary) gold mineralization has been discovered within the Precambrian Homestake ore field [5]. Epithermal gold--silver veins are also known at the Natalka and Nezhdaninsk gold--sulfide--quartz deposits in the Russian Northeast [2].

Inheritance of mineralization is also an essential criterion for the formation of large deposits. For example, the porphyry copper--molybdenum deposits (Peschanka, Chukotka; Bingham, Utah, United States), porphyry tin--silver deposits (Dukat district), and porphyry gold deposits (Shkol'noe, Kolyma) include productive and other coeval mineral types that can always be recognized in the preporphyric mineral assemblage of sedimentary rocks in the framing. Moreover, the Dukat ore district incorporates the early (silver--sulfide) and late (porphyry tin--silver) associations [6]. The process of volcanogenic ore formation in deposits of the early ore association was interrupted by the intrusion of Sn-bearing granitoids in the Okhotsk--Chukot Belt, resulting in the rejuvenation of early hydrothermal systems.

Thus, the epithermal gold--silver deposits are characterized by a significant genetic diversity. Their convergence is caused by similar physicochemical conditions of ore formation. Within the Circum-Pacific tectonomagmatic belt and conjugated structures, the epithermal gold--silver mineralization is most abundant as disseminated and vein ores (gold--sulfide and gold--quartz associations). Gold--sulfide mineralization is also developed in the porphyry copper--molybdenum and massive sulfide ore groups, basic--ultrabasic complexes (gold--silver--telluride deposits), and ferruginous quartzites. Porphyry tin--silver ore groups incorporate the Ag-rich variety of gold--silver deposits.

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TABLES

Table 1. Characteristics of gold--silver deposits in the Circum-Pacific Belt

№	Месторождение	Страна	Среднее содержание, г/т		Рудный комплекс района	Тип по [1]
			Au	Ag		
1	Уайхи	Новая Зеландия	12	5	Au–Cu–Sf	LS
2	Емпериор	Фиджи	13	5	Au–Cu–Sf	LS
3	Поргера*	Папуа–Новая Гвинея	4.7	11.3	Au–Cu, Au–Sf	LS
4	Ладолам*	Там же	4.4	7	Au–Cu	LS
5	Келиан*	Индонезия	1.9	3.8	Au–Cu	LS
6	Акупан	Филиппины	7.5	15	Au–Cu	LS
7	Хишикари*	Япония	44	22	Au–Cu	LS
8	Тайохо	Там же	0.5	80	Pb–Zn–Cu	LS
9	Многовершинное	Россия	8	16	Au–Sf, Au–Cu	LS
10	Хаканджа	Там же	15	650	Au–Sf, Ag–Sn	LS
11	Аметистовое*	»	10	150	Au–Sf, Ag–Sn	LS
12	Агинское	»	25	15	Au–Cu	LS
13	Карамкен	»	25	150	Au–Cu	LS
14	Джульетта*	»	19	420	Au–Cu, Ag–Sn	LS
15	Дукат	»	1.0	550	Ag–Au–Sn	LS
16	Кубака*	»	20	40	Fe, Au–Cu?	LS
17	Биркачан*	»	15	45	Au–Cu	LS
18	Клен*	»	15	26	Au–Cu	LS
19	Весеннее*	»	3.6	18	Au–Cu	LS
20	Купол*	»	33	372	Au–Cu, Au–Sf	LS
21	Валунистое*	»	25	150	Au–Cu, Au–Sf	LS
22	Крипл-Крик	США	23	15	Au–Cu–Te	LS
23	Раунд Маунтин*	Там же	0.9	1.5	Au–Cu–Te	LS
24	Комшток	»	14.6	150	Au–Cu–Te	LS
25	Теллурид-Силвертон	»	10	10	Au–Cu–Te	LS
26	Голдфилд	»	10.5	10	Au–Cu–Te	HS
27	Пачука	Мексика	1.4	500	Ag–Au–Sn	LS
28	Эль-Оро	Там же	17	500	Ag–Au–Sn	LS
29	Гуанохуато	»	11	450	Ag–Au–Sn	LS
30	Параль	»	14.5	700	Ag–Au–Sn	LS
31	Закатекас	»	7.0	500	Ag–Au–Sn	LS
32	Пуэбло-Вьехо*	Доминиканская республика	3.5	5	Au–Cu	HS
33	Кори-Колло*	Боливия	2.3	15	Au–Cu	LS
34	Янакоча*	Перу	1.4	3	Au–Cu	HS
35	Эль-Индио*	Чили	6.6	50	Au–Cu	HS

Notes: (*) Deposits discovered and explored in the recent 25 yr; deposit types: (LS) low sulfidation (adular--sericite--quartz), (HS) high sulfidation (alunite--quartz).

Key: 1. Ord. no.; 2. Deposit; 3. Waihi; 4. Emperor; 5. Porgueras; 6. Ladolam; 7. Kelian; 8. Akupan; 9. Hishikari; 10. Taioho; 11. Mnogovershinnoe; 12. Khakandzha; 13. Ametistovoe; 14. Aginsk; 15. Karamken; 16. Dzhul'etta; 17. Dukat; 18. Kubaka; 19. Birkachan; 20. Klen; 21. Vesennee; 22. Kupol; 23. Valunistoe; 24. Cripple Creek; 25. Round Mountain; 26. Comstock; 27, Telluride Silverton; 28. Goldfield; 29. Pachuca; 30. El Oro; 31. Guanojuato; 32. Paral; 33. Zacatecas; 34. Pueblo Viejo; 35. Kori Kollo; 36. Yanacocha; 37. El Indio; 38. Country; 39. New Zealand; 40. Fizi; 41. Papua New Guinea; 42. The same; 43. Indonesia; 44. Philippines; 45. Japan; 46. The same; 47. Russia; 48. The same; 49. United States; 50. The same; 51. Mexico; 52. The same; 53. Dominican Republic; 54. Bolivia; 55.Peru; 56. Chile; 57. Average content, g/t; 58. Ore complex of the region; 59. Type [1]

Table 2. Gold--silver deposits of various ore associations

Рудноформационный ряд* (рудный комплекс)	Минеральный тип золото-серебряных руд	Связь с минерализацией базовых месторождений	Типы террейнов	Примеры
Медно-никелевый и хромитовый (базит-ультрабазитовый) (Au–Cu–Te)	Золото-серебро-теллуридный	Эпигенетическая	Океанической коры, островодужные	Агинское (Камчатка), Зод (Армения), Калгурли (Австралия)
Медно-порфировый (Au–Cu)	Электрум-халькопирит-пиритовый, сфалерит-галенитовый	Парагенетическая с поздними минеральными ассоциациями	Островодужные, континентальных рифтов, пассивных континентальных окраин	Песчанка (Чукотка), Бингем (США)
Олово-серебро-порфировый (Ag–Sn)	Электрум-аргентитовый, сфалерит-галенитовый	Парагенетическая допорфировая и с поздними минеральными ассоциациями	Турбидитных бассейнов пассивных континетальных окраин, (перивулканические зоны)	Дукат (Северо-Восток России), Потоси (Боливия)
Золото-сульфидный вкрапленных руд (Au–Sf)	Электрум-арсенопирит-пиритовый, сульфо-антимонитовый	Парагенетическая с поздними минеральными ассоциациями	Турбидитных бассейнов пассивных континентальных окраин (перивулканические зоны)	Майский рудный район (Чукотка)
Колчеданный полиметаллический (Pb–Zn–Cu)	Электрум-халькопирит-сфалерит-галенитовый	Парагенетическая с поздними минеральными ассоциациями	Островодужные	Провинции “зеленых туфов” (Япония)
Железистых кварцитов (Fe)	Электрум-пиритовый	Эпигенетическая	Кратонные	Кубака (Омолонский террейн)
Пятиэлементный (U–Sf)	Электрум (кюстелит)-уранинит-сульфидный, золото-суль-фидный	Эпигенетическая	Кратонные, рифтогенные	Рудные горы (Европа), Олимпик-Дам (Австралия)

(*) In our works, "ore association" is a more rigorous notion than "ore complex."

Key: 1. Ore association@* (complex); 2. Copper--nickel and chromite (basic--ultrabasic) (Au--Cu--Te); 3. Porphyry copper (Au--Cu); 4. Porphyry tin--silver (Ag--Sn); 5. Gold--sulfide disseminated ores (Au--Sf); 6. Massive sulfide base metal (Pb--Zn--Cu); 7. Ferruginous quartzites (Fe); 8. Five element (U--Sf); 9. Mineral type of gold--sulfide ores; 10. Gold--silver--telluride; 11. Electrum--chalcopyrite--pyrite, sphalerite--galena; 12. Electrum--argentite, sphalerite--galena; 13. Electrum--arsenopyrite--pyrite, sulfoantimonite; 14. Electrum--chalcopyrite--sphalerite--galena; 15. Electrum--pyrite; 16. Electrum (k@ustelite)--uraninite--sulfide, gold--sulfide; 17. Relation to mineralization with typical deposits; 18. Epigenetic; 19. Paragenetic with late mineral types; 20. Paragenetic (including the preporphyric variety) with late mineral types; 21. Paragenetic with late mineral types; 22. Paragenetic with late mineral types; 23. Epigenetic; 24. Epigenetic; 25. Terrane type; 26. Oceanic crust, island arc; 27. Island arc, continental rift, passive continental margins; 28. Turbidite basins of passive continental margins (perivolcanic zones); 29. Turbidite basins of passive continental margins (perivolcanic zones);30. Island arc; 31. Cratonic; 32. Cratonic, riftogenic; 33. Examples; 34. Aginsk (Kamchatka), Zod (Armenia), Kalgoorlie (Australia); 35. Peschanka (Chukotka), Bingham (United States); 36. Dukat (Russian Northeast), Potosi (Bolivia); 37. Maisk ore district (Chukotka); 38. Green tuff province (Japan); 39. Kubaka (Omolon terrane); 40. Ore Mountains (Europe), Olympic Dam (Australia)

FIGURE CAPTIONS

Fig. 1. Distribution of mineral types in gold--silver deposits of various ore associations in the Circum-Pacific (modified after [7]). (1) Continental-margin volcanic belts; (2, 3) volcanic areas with Cenozoic rift zones: (2) dominated by acid ignimbrites, (3) dominated by subalkaline and alkaline basalts; (4, 5) plateau basalts of the trap formation: (4) Jurassic, (5) Neogene; (6--10) areas and zones of volcanotectonic reactivation of uncertain type: (6) Cenozoic tholeiitic, subalkaline and alkaline basalts, (7) dominated by Late Cenozoic alkaline basalts, (8, 9) dominated by calc-alkaline volcanics: (8) Paleozoic and Mesozoic, (9) Cenozoic; (10) products of andesitic volcanism: (a) Cascade Range, (b) Transmexican; (11) deep-water troughs; (12--16) profiles with the abundance of various ore associations (complexes): (12) gold--sulfide (Au--Sf) and porphyry copper--molybdenum (Au--Cu), (13) gold (silver)--sulfide (Au--Ag--Sf) and porphyry tin--silver (Ag--Sn), (14) undifferentiated sulfide (Sf), (15) massive sulfide (Pb--Zn--Cu), (16) basic (ultrabasic) copper sulfide (Au--Cu--Te) with gold--telluride deposits; (17) epithermal gold--silver deposits (nos. 1--35 as in Table 1). Continental-margin volcanic belts: (O) Okhotsk--Chukot; (S) Sikhote Alin, (H) Honshu--Korean, (C) Eastern China, (Ch) Chile--Peru, (E) Ecuador, (M) Mexico; volcanic areas: (1) Smolensk (Devonian), (2) Southern Argentine (Jurassic), (3) Khingan (Jurassic--Neocomian), (4) Tasmania, (5) California--Columbia, (6) Patagonia, (7) Sungaria, (8) Eastern Australia; (9) New Zealand.
Key: 1. km

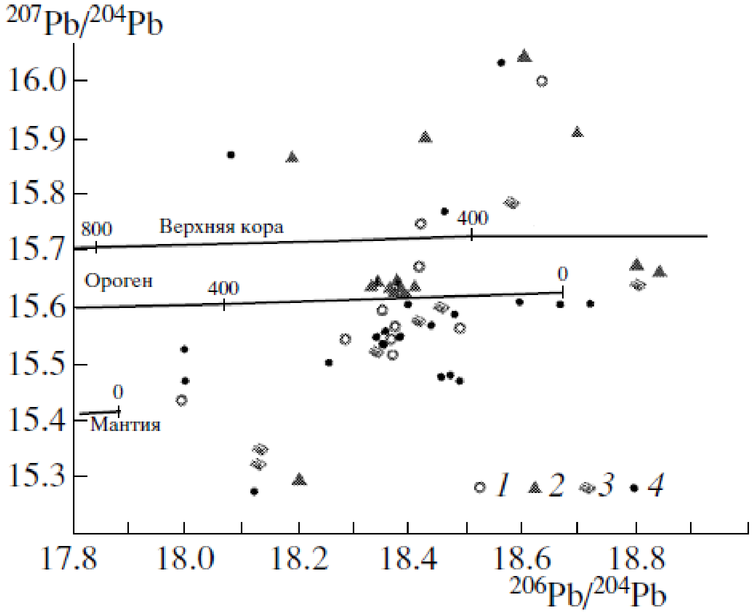

Fig. 2. The 206Pb/204Pb--207Pb/204Pb plot showing the lead isotopic composition of epithermal and mesothermal deposits in eastern Asia (based on [8--10]). Deposits: (1) Epithermal gold--silver; (2--4) mesothermal: (2) tin, (3) complex gold--sulfide disseminated ores, (4) gold--quartz.

Key: 1. Upper crust; 2. Orogen; 3. Mantle