

Gold Mineralization in Karelia: Endogenic Formation Regimes, Genetic Types, and Ore Associations

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Precambrian gold deposits and occurrences in Karelia (3.1–1.65 Ga) are primarily confined to island-arc and continental-margin settings, as well as shear strain and metasomatic alteration zones of the collision stage (figure, table). Strike-slip zones commonly associate with larger (regional) tectonic displacements as complementary or auxiliary structures. Thus, they serve as conduits for deep and metamorphic fluids. The late stages of the Lopian and Svecofennian orogenic cycles appeared to have been most favorable for the formation of gold deposits and occurrences. Complex PGM ores with traces of Au are associated with the Sumian riftogenic regime. Orogenic zones of the Sumian evolution stage and continental sedimentary formations in superimposed Jatulian depressions also have some gold potential.

The *late Lopian epoch* (3.1–2.55 Ga) embraces three age domains with a recurrent series of calc-alkaline and Na–K granitoids in the upper portions of sections. They include massive sulfide, molybdenum, gold–base metal, gold–sulfide, and gold–quartz associations. Island-arc rock associations of early greenstone belts are confined to the oceanic crust in the framing of the East Karelian geoblock. They host massive sulfides with low concentrations of base metals and Au. The early orogenic stage was marked by the emplacement of plagiogranites of the Shilos Complex (2.86 Ga) and porphyry bodies and dikes (2.807 Ga). They were accompanied by beresites and gold–sulfide–quartz mineralization. Ore occurrences in the Zalomaevo, Taiginitsa, and Rybozero ore fields formed in NE-, NS-, and NW-extended foliation zones at the contact with porphyry dikes in the aureole of the Shilos Massif [6, 8]. The Au content in the ore occurrences varies from 1 to 25 g/t (average 1.82–10 g/t). In each ore occurrence, the possible resource (category P₂ in the Russian classifica-

tion of ore reserves and resources) varies from 10 to 15 t. Later island-arc associations of the greenstone belts appeared at the continental margin. The North Vozhma and Upper Vozhma Au-bearing massive sulfide base metal (hereafter, MSBM) occurrences are associated with acid and intermediate volcanism. In the North Vozhma ore occurrence, the Au content is up to 2.8 g/t (average 0.9 g/t) and the potential resource (category P₁ in the Russian classification) is 0.6 t. In the Upper Vozhma occurrence, the Au content is as high as 20 g/t.

The accretion stage of greenstone belts in western Karelia is characterized by the accumulation of acid volcanics of the Shurlovaara Suite (2.8 Ga) and sulfide mineralization with high Au concentrations. In the Kostomuksha structure, collision at the 2.72–2.7 Ga boundary provoked the folding of all rock sequences; the formation of submeridional and sublatitudinal strike-slip zones; and the emplacement of granites of the framing, diorites and granite porphyries of the Taloveis Complex (2.72 Ga), felsites (gelleflint) of the Rautaoi Complex (2.705 Ga), and potassic granitoids (2.7–2.65 Ga). Diorites, granite porphyries, felsites, and metasomatites of strike-slip zones host gold–sulfide (arsenopyrite and pyrite) and gold–quartz mineralization in the Taloveis deposit (Au 1–47 g/t, average 10.8–12.9 g/t; possible resource 12 t) and the Berendei, S-16P, and South Kostomuksha ore occurrences [5, 7].

The Tikshezero–Parandovo greenstone belt (2.8–2.65 Ga) originated and evolved as a continental-margin structure at the boundary between the Karelian Craton and the Belomorian foldbelt. The emplacement of granites of the Lobash Complex on the western wall of the Lehta structure was accompanied by greisenization and copper–molybdenum mineralization. Foliation and biotitization zones at the contact with porphyry dikes accommodate gold–base metal mineralization (with Ag, Bi, and Te) in the Lobash deposit [Au 0.5–216 g/t, average 2.64–3.04 g/t; inferred reserve (category P₂ + C₂ in the Russian classification) and possible resource 8.7 t] [9].

The Jalonvaara–Hattu–Tulos greenstone belt appeared in the southwestern Karelian Craton 2.76–2.7 Ga ago.

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Au-rich MSBM ores are associated with volcanism in the Jalonvaara structure. The emplacement of granitoids (2.74–2.72 Ga) was accompanied by the formation of base metal and Cu–W–Au–Mo (with Bi and Te) ores of the Jalonvaara deposit (Au 0.1–3.4 g/t) and gold–quartz veins of the Hattu belt (average Au content 4–18 g/t, resources 5–10 t) [3, 12].

The Late Archean collision of the Karelian Craton and the Belomorian mobile belt promoted the formation of shear strain zones at deep levels and the origination of intracontinental basins. Late orogenic events (2.7–2.55 Ga) terminated with the emplacement of potassic granites and syenites into the craton, intense metasomatism, and development of gold–quartz veins and gold–sulfide mineralization. Metasomatic alterations related to the Late Archean and Proterozoic collisions had a strong impact on the formation of gold deposits, such as Pedrolampi (Au 1–40 g/t, average 1–5.9 g/t; inferred reserve and possible resource 7.97 t), Taloveis, and Rybozero (possible resource 15 t), as well as the Zolotye Porogi and other ore occurrences [5–10].

The *Sumian–Sariolian epoch* (2.55–2.3 Ga) is marked by the formation of gold ore occurrences associated with the orogenic regime. They are confined to domains of the Sumian acid magmatism (2.4 Ga) at the northeastern margin of the Karelian Craton. Quartz–feldspar porphyries of the Lehta structure were accompanied by beresites. Gold–sulfide–quartz veins occur in the Paiozero sector [1]. These structures and older veins served as a source of ore material during the destruction and the subsequent accumulation of the Sariolian and Jatulian Au- and U-bearing quartz conglomerates.

The *Jatulian epoch* (2.3–2.1 Ga) is marked by the accumulation of sediments and basalts in intracratonic depressions. Gold and uranium were simultaneously accumulated in channel and coastal sediments of ancient placers (metamorphosed quartz conglomerates). Such lithological horizons and stratigraphic

unconformities are usually characterized by a high gold potential in the case of their juxtaposition with the younger NW-oriented shear strain zones and the Svecofennian metasomatism, e.g., the Maimjärvi gold occurrence (Au up to 10 g/t, average 3.5 g/t; possible resource 18.8 t). The hydrothermal copper sulfide mineralization and cupriferous sandstones of Voronov Bor (Au up to 2.4 g/t) are associated with Jatulian basaltic magmatism.

The *Ludicovian epoch* (2.1–1.9 Ga) is marked by the opening of continental rifts, formation of troughs in marginal basins, basic–ultrabasic magmatism, and accumulation of sulfide-containing carbonaceous shales enriched in Cu, Co, V, and Ti. The redeposition of these shales and the input of U, Au, Pt, Pd, Mo, and Se into metasomatic alteration zones promoted the formation of noble metal–uranium–vanadium deposits of the Padma group (Au 0.16–0.33 g/t, inferred reserve 0.12–0.73 t) located in NW-oriented zones of the Onega structure [11].

The *Svecofennian epoch* (1.9–1.65 Ga) is marked by the formation of suprasubduction island arcs (1.9–1.86 Ga) and tonalites of the collision stage (1.88–1.8 Ga) in the Svecofennian zone of the southwestern Karelian Craton. Island-arc magmatism of this epoch fostered the formation of the Vihanti and Pyhäsalmi base metal deposits in the Raahe–Ladoga zone (Finland). Synorogenic tonalites accommodate the Osikonmäki and Pirila gold–sulfide–arsenide–quartz deposits in Finland and the Päkylä gold ore field (possible resource 10 t) in Karelia [4, 13].

The early orogenic granitoid magmatism is virtually absent in the Laplandian (Proterozoic) greenstone belt, which represents a rift initiated in the continental crust, and the Paano–Kuolajärvi structure in northwestern Karelia. Gold deposits and occurrences appeared in strike-slip zones of this belt owing to extensive magmatism above the subsiding zone of Laplandian granulites,

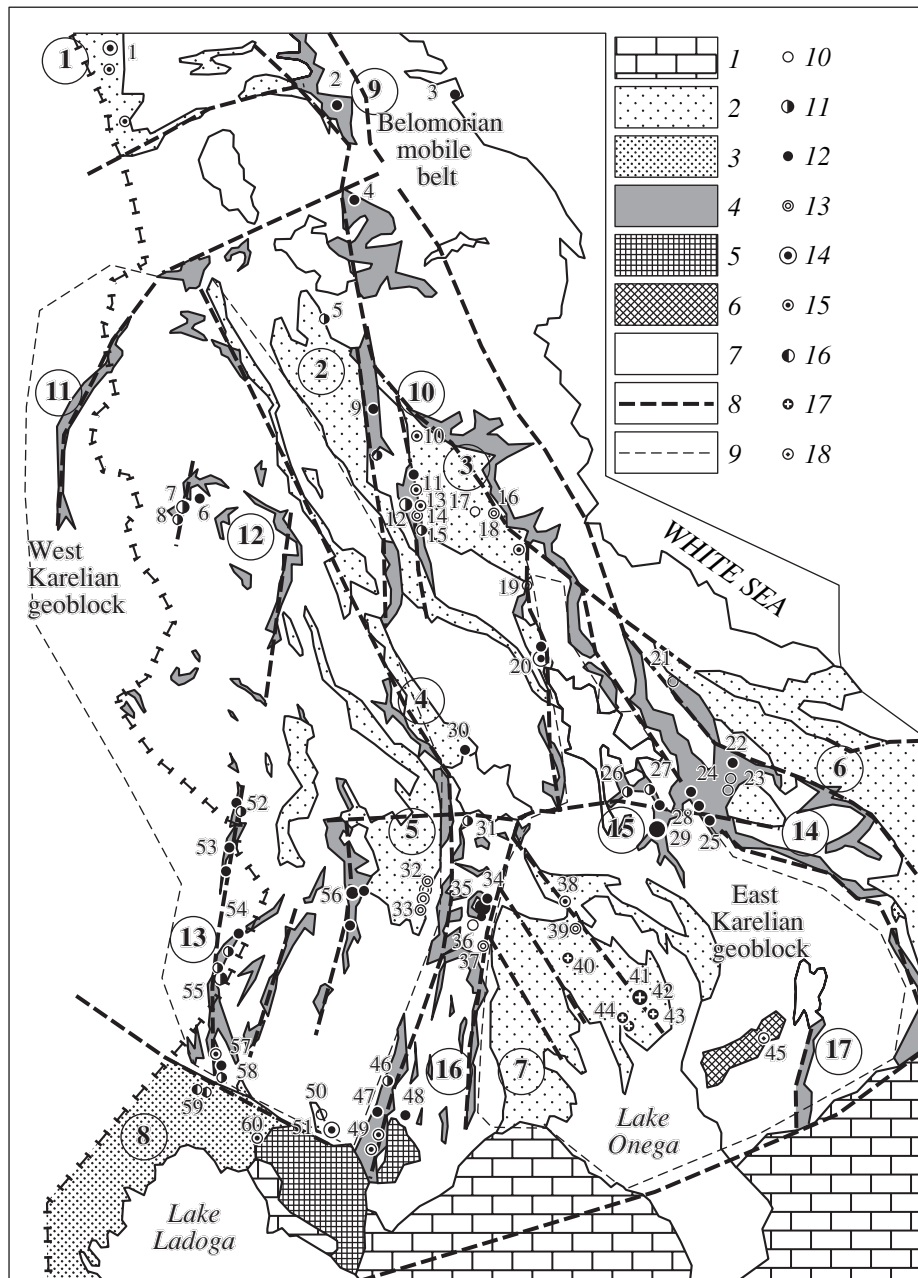
Schematic location of gold deposits and occurrences in Karelia. (1) Paleozoic and Vendian; (2) Svecofennian fold zone; (3) Paleoproterozoic structures (encircled numbers): (1) Paano–Kuolajärvi, (2) Kompakovo, (3) Lehta, (4) Elmozero–Segozero, (5) Maslozero–Yangozero, (6) Vetrenyi Poyas, (7) Onega, (8) Ladoga; (4) greenstone belts: (9) Tikshezero–Avnezero, (10) Avnezero–Parandovo, (11) Kuhmo–Suomussalmi, (12) Kostomuksha–Gimol, (13) Jalonvaara–Hattu–Tulos, (14) Sumozero–Kenozero, (15) South Vygozero, (16) Segozero–Vedlozero, (17) Matkalakhta; (5) gabbro–anorthosite–rapakivi–granite complex (Lower Riphean Ulyalega and Salma massifs); (6) layered intrusions (Lower Proterozoic); (7) granite gneiss zones; (8) deep faults; (9) contours of blocks: (10–18) gold deposits (large signs) and occurrences: (10) Au-bearing massive sulfide and MSBM deposits (Middle Archean), (11) gold–sulfide–quartz and gold–polysulfide deposits associated with granitoids and dikes (Middle Archean), (12) gold–sulfide and gold–quartz deposits in foliation and metasomatic alteration zones (Middle Archean), (13) gold–uranium deposits in quartz conglomerates and Au-bearing cupriferous sandstones (Lower Proterozoic), (14) gold–sulfide and gold–quartz deposits in shear strain and stratigraphic unconformity zones (Lower Proterozoic), (15) gold–sulfide deposits in albitites (Lower Proterozoic), (16) gold–sulfide–arsenide–quartz deposits in tonalites, porphyry dikes, and foliation zones (Lower Proterozoic), (17) noble metal–uranium–vanadium deposits in metasomatic alteration zones in black shales (Lower Proterozoic), (18) gold–sulfide deposits in foliation zones in basic–ultrabasic intrusions (Lower Proterozoic). Ore deposits and occurrences: (1) Maiskoe, (2) Vinga, (3) Kartesh, (4) Hizovara, (5) Dmitrii, (6) South Kostomuksha, (7) Taloveis, (8) Berendei and S-16P, (9) Mustanoja and Särkijärvi, (10) Kolgevara, (11) Sävvalla and Churozh, (12) Lobash-1, (13) Khakhlozero, (14) Zheleznnye Vorota, (15) Nigalma, (16) Rigovarak, (17) Shuezero, (18) Paiozero, (19) Parandovo, (20) Voitskoe, (21) Pulozero, (22) Polovnino, (23) North and Upper Vozhma, (24) Shchyuchinskoe and Savinskoe, (25) Zolotye Porogi, (26) Zalomaevo, (27) Petrovoyam, (28) Taiginitsa, (29) Rybozero, (30) Orchen Guba, (31) Bergaul, (32) Maimjärvi, (33) Jatulian-1, (34) Orekhzero, (35) Pedrolampi, (36) Talpus and Elmus, (37) Paleozero, (38) Svetloe, (39) Voronov Bor, (40) Shulginov, (41, 42) Padma group, (43) Tsarev, (44) Kosmozero, (45) Aganozero, (46) Tsentral'noe, (47) Hyselä, (48) Novye Peski, (49) Nyalmozero, (50) Kolos, (51) Faddein Kelea, (52) Kadilampi, (53) Valkeasuo, (54, 55) Kuittila group, (56) Mezhozero, (57) Soanvara, (58) Jalonvaara and Hatunjoja, (59) Päkylä and Alattu, (60) Luppiko.

which were later exhumed in the northeastern area. Such objects are found in Finland (Kuosamo ore field and Pahtovaara deposit) and Karelia (Maiskoe deposit, Au 1–580 g/t, average 7.63 g/t; inferred reserve and potential resource 0.66 t [11]).

In central areas of the Karelian Craton, gold deposits of the Svecofennian epoch are confined to thrust-fold, foliation, and metasomatic alteration zones [2], e.g., gold–uranium and gold–sulfide mineralization in the Lehta, Tuolmozero, Yangozero, and other structures; gold–quartz veins (Voitskoe deposit); and Aurich chalcopyrite mineralization in albitites (Shuezero deposit, Au up to 20 g/t).

The Raahe–Ladoga zone merged with the Karelian Craton by the beginning of the *Early Riphean epoch* (1.65–1.45 Ga). The northeastern tectonic zone at the southern framing of the craton was marked by the initiation of the Riphean rift, accumulation of sediments and alkaline basalts of the Salma Suite, and emplacement of the Salma gabbro–anorthosite–rapakivi granite complex (1.65–1.45 Ga). The emplacement of granites was accompanied by skarns, greisens, late quartz veins, and various ores in the Paleoproterozoic country rocks. Skarn tin and tungsten ores were superimposed on the gold–base metal mineralization (Au up to 8.6 g/t).

Thus, the largest gold deposits of Karelia are related to several Late Archean orogenic events of acid and



Ore-formation and geologic-genetic systematics of gold ore occurrences in Precambrian greenstone belts of Karelia

Geological setting	Genetic type of gold deposits (orogenic and platformal evolution stages)			
	Hydrothermal deposits in volcanosedimentary complexes	Hydrothermal deposits associated with diorites, tonalites, granites, and porphyry dikes	Hydrothermal deposits in strike-slip zones (foliation and metasomatic alteration of rocks)	Metasedimentary (ancient placer)
Ore formation	(1) Au-bearing massive sulfide. (2) Au-bearing MSBM. (3) Au-bearing cupriferous sandstones	(1) Gold-sulfide-quartz. (2) Low-sulfide gold-quartz. (3) Gold-polysulfide (with Bi, Te, Mo, and W)	(1) Gold-quartz. (2) Gold-sulfide and gold-arsenide-quartz. (3) Gold-sulfosalt-arsenide. (4) Noble metal-uranium-vanadium. (5) Gold-uranium	(1) Gold-uranium and sulfide. (2) Gold-uranium-hematite
Mineral composition of ores	(1) Pyrite and pyrrhotite; less common chalcopyrite, sphalerite, and arsenopyrite. (2) pyrite, chalcopyrite, sphalerite, pyrrhotite, and galena; less common arsenopyrite, bornite, and chalcocite. Fine-dispersed gold in both types	(1, 2) Gold, pyrite, pyrrhotite, chalcopyrite, Bi-Te minerals, scheelite, and less common arsenopyrite. (3) Molybdenite, pyrrhotite, chalcopyrite, sphalerite, galena, Bi-Te minerals, gold, electrum, and scheelite	(1) Gold, other rare minerals (less common), and scheelite. (2) Gold, pyrite, chalcopyrite (or arsenopyrite), pyrrhotite, chalcopyrite, and subordinate Sb-As minerals. (3) Gold, pyrite, arsenopyrite, and sulfosalts. (4, 5) Minerals of U, V, Cu, and PGM; gold and selenides	(1) Gold, pyrite, and uranium minerals. (2) Gold, hematite, pyrite, and uranium minerals
Wall-rock alterations	Albite-chlorite-carbonate-quartz-sericite, beresites, and propylites	Quartz-sericite, beresites, listvenites, gumbesites, propylites, and carbonate-chlorite; preore biotites, skarns, and greisens	Quartz-sericite, beresites, listvenites, and gumbesites; preore metasomatites of different <i>PT</i> conditions	Quartz-sericite
Ore-enclosing complexes	(1, 2) Acid and intermediate volcanosedimentary rocks, carbonaceous shales, and banded formations. (3) Quartzite-sandstones and quartz conglomerates	Granitoids, dikes, and various country rocks near contacts	Various igneous rocks (ranging from ultrabasic to acid), granitoids, volcanosedimentary, and sedimentary sequences	Quartz conglomerates and quartzite-sandstones
Igneous complexes coeval with mineralization	Diorite-rhyolite and andesite-dacite volcanism	Diorites, quartz diorites, granites (Ca-Na, K-Na), granite porphyry bodies, and dikes	No link; link with Na-K granites for metasomatites in some cases	Greenschist
Metamorphism facies	Regional. Greenschist-amphibolite (different <i>PT</i> regimes)	Greenschist-amphibolite	Dislocation type in shear strain zones. Greenschist-amphibolite (elevated <i>P</i> values)	Lithological horizons
Control of mineralization	Lithostratigraphic and structural	Fissure-dome structures. Foliation zones in granitoids, country rocks, and contact zones with dikes	Submeridional, NW- and NE-oriented strike-slip zones, brittle-plastic strains, foliation zones, and structural unconformities	Disseminated and banded
Morphology of orebodies	Stratified, disseminated, banded, lenticular, disseminated-stringer, and vein	Veins, stringers, disseminated-stringer bodies, and stockworks	Veins, linear stockworks, and disseminated-stringer bodies	Disseminated and banded
Development stage and geodynamic setting	Accretion stage. Back-arc basins and island-arc setting	Collision stage. Island-arc and continental-margin settings	Collision of the Karelian Craton and Archean island-arcs, Karelian and Kola cratons, and the Proterozoic Svecofennian fold zone	Platformal. Intracraton depressions
Examples of ore deposits and occurrences	(1) Parandovo, Nyalmozero, Vedlozero, Elmus, Zolotye Porogi, and Ruv-invaara. (2) Soanvaara, North and Upper Vozhma. (3) Voronov Bor	Zalomaevo ore field; Faktornoe, Taloveis, Berendei, Lobash-1, Nigalma, Tsentral'noe, Jalonvaara, Kadilampi, and Alattu ore occurrences	Pedrolampi, Talpus, Novye Peski, Zolotye Porogi, Polovnino, Rybozero, Taloveis, South Kostomuksha, Faddein Kelea, Voitskoe, Maiskoe, Päkylä, Padma group, Shuezero, and others	Rigovarak, Maimjärvi, Jatulian-1, Paleozero, and Chernyi Navolok

intermediate magmatism (2.88–2.85, 2.81–2.8, and 2.75–2.72 Ga), shear strain zones (2.7–2.6 Ga), and Paleoproterozoic magmatism (1.86–1.8 Ga). As in other regions of the world, the geodynamic setting of gold ore occurrences in Karelia is associated with the evolution of geological structures above subduction zones and the formation of collision-induced strike-slip zones. Volcanism related to processes of accretion in the Late Archean and late Paleoproterozoic fostered the formation of Au-bearing massive sulfide deposits. The collision stage was marked by the formation of gold–quartz, gold–sulfide, gold–sulfide–arsenide (or sulfide–arsenide–quartz), and gold–polysulfide (with Bi and Te) occurrences characterized by the zonal association with W–Cu–Mo ores. Au-rich complexes of the orogenic accretion and the subsequent accretion–collision stages are represented by volcanosedimentary sequences coupled with subvolcanic and intrusive bodies of both acid and intermediate compositions. The collision stage is characterized by the development of metasomatic alteration and silicification zones superimposed on diverse country rocks and ore-producing granitoids. The mineral composition of ores and their formation types became more complicated with time. Wall-rock alterations mainly fit the beresite–listvenite association irrespective of the erosion level and metamorphism. Preore metasomatites (skarns, greisens, biotitites, and various metamorphic and metasomatic rocks) formed under different *PT* conditions. The volcanic-associated orebodies formed stratificated or lenticular-stratified deposits. Orebodies confined to granitoids and deformation zones made up veins, stringer (or disseminated–stringer) zones, and stockworks.

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