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Review

# Stages of Gold Deposits Formation in the Precambrian of the North-Eastern Fennoscandia

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**Abstract:** Two main stages of formation of gold deposits are identified in the north-eastern part of the Fennoscandian Shield—Neoarchean (2.7–2.6 Ga) and Paleoproterozoic (1.92–1.74 Ga). These were the stages of rapid growth of the continental crust of the Earth and the consolidation of the ancient supercontinents, Kenorland in the Neoarchean, and Fennoscandia (or Columbia) in the Paleoproterozoic. Gold deposits and occurrences, which formed in the Archean (Oleninskoe and Nyalm in the Kolmozero–Voron'ya belt, and the Olenegorsk group of BIF deposits) were later metamorphosed in the Paleoproterozoic, and isotope data for the rocks and minerals of these deposits detect both Archean and Paleoproterozoic events. The Paleoproterozoic stage was the most important for the formation of gold deposits in the region, as at this stage the deposits formed not only in the Proterozoic greenstone belts, but in those Archean belts as well, which were involved in the Svecofennian tectonic processes in the Paleoproterozoic. As it is shown in the example of the deposits in the Central Lapland Paleoproterozoic belt, gold mineralization formed with a series of impulses of hydrothermal activity, and these impulses correlate with the formation of different generations of minor granite intrusions and dykes.

**Keywords:** gold; Fennoscandian Shield; Kola Peninsula; greenstone belts; metamorphism



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## 1. Introduction

The previous review of gold deposits and occurrences in the western segment of the Russian Arctic [1] was based on data available by the beginning of 2018. It showed that gold deposits and occurrences are located in the region mainly in the Archean and Paleoproterozoic greenstone belts. The location of the majority of deposits and occurrences is controlled by tectonic zones of regional scale at the boundaries of major segments of the Fennoscandian Shield. Those are the system of the Neoarchean greenstone belts, the Kolmozero–Voron'ya, the Ura-guba along the Murmansk craton, the Kola–Norwegian terrane boundary, a suture delineating the core of the Lapland–Kola orogen in the north, and the series of overthrusts and faults at the eastern flank of the Salla–Kuolajarvi belt.

The primary composition of rocks hosting gold mineralization is variable: the most common are mafic–ultramafic metavolcanics, metasedimentary terrigenous rocks, and diorite porphyry intrusions. The metamorphic grade of mineralized rocks in the studied deposits varies from greenschist to upper amphibolite facies.

The deposits formed within the metamorphic–hydrothermal and magmatic–hydrothermal mineral systems during two main periods: the Neoarchean, 2.7–2.6 Ga, and the Paleoproterozoic, 1.9–1.7 Ga.

Data published in recent years significantly supplement and clarify information on gold deposits in the western segment of the Russian Arctic and in northern Finland. In the article below, data on the age of pre-ore, syn-ore, and post-ore processes in the mineralized rocks, and on the geodynamic conditions of the formation of gold deposits, are arranged, and this provides an opportunity to compare the gold mineralization in the Kola region with the better-studied gold deposits in the Finnish Lapland.

## 2. Distribution of Gold Deposits and Occurrences in the NE Part of the Fennoscandian Shield

The most significant gold deposits in the western segment of the Russian Arctic are the Oleninskoe (number 1 in Figure 1, Au resources 10 t [2]) and Nyal'm (number 2 in Figure 1, 7.5 t [2]) deposits in the Kolmozero–Voron'ya greenstone belt, the Sergozerskoe (number 5 in Figure 1, 13 t [2]) in the Strelninsky belt, and the Mayskoe (number 8 in Figure 1, 0.122 t Au [2]) in the Salla–Kuolajarvi belt. The latter is the only gold deposit ever developed in the region (51 kg mined in 1998–2000) [2]. Gold occurrences are known in the Strelninsky belt (Vorgovy, number 4 in Figure 1), in the Pechenga belt (Porojarvi, number 7 in Figure 1), and in the Tiksheozero belt (Kichany, number 6 in Figure 1). Gold mineralization in the iron-producing BIF deposits of Olenegorskoe and Kirovogorskoe (number 3 in Figure 1) have a statute of gold occurrences as well. All gold deposits, occurrences, and the majority of points of mineralization (>1 g/t), totaling 84 of 90 gold-mineralized objects in the region, are located in the Archean and Paleoproterozoic greenstone belts, being near equally divided among them: 6 deposits and occurrences and 38 points of mineralization are registered in the Archean belts, and 3 and 37, correspondingly, in the Paleoproterozoic.

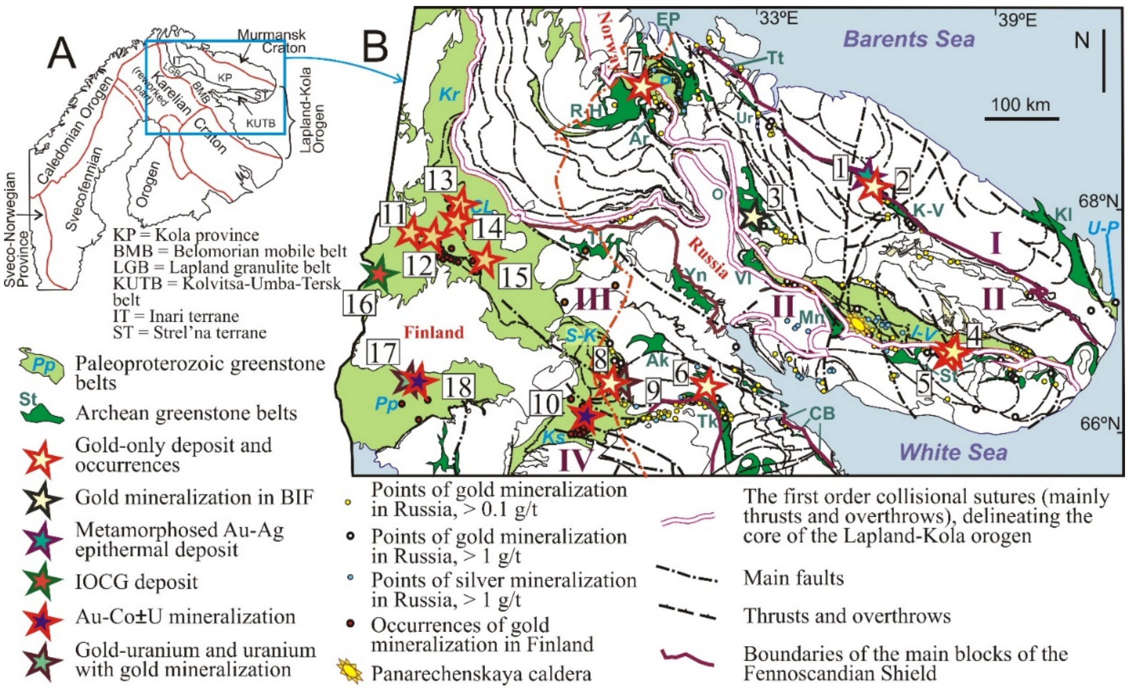


**Figure 1.** (**A**) Schematic tectonic map of the Fennoscandian Shield and (**B**) location of gold deposits, occurrences, and points of mineralization in the scheme of greenstone belts in the north-eastern part of the Fennoscandian Shield, modified after [3] (greenstone belts, thrusts and faults in (**B**)), and [4] (tectonic map (**A**) and the boundaries of the core of the Lapland–Kola orogen in (**B**)).The following abbreviations are used in Figure 1: Archean greenstone belts: K-V—Kolmozero–Voron'ya; Ol—Olenegorsky; St—Strelninsky; Tk—Tiksheozersky; EP—East Pechengsky; R-H—Runijoki–Hihnajarvi; Kl—Kachalovsky; Mn—Munozersky; Vl—Vochelambinsky; Ak—Alakurtinsky; Yn—Yonsky; CB—Central Belomorian; Tl—Tulpio; Ur—Uragubsky; Tt—Titovsky. Paleoproterozoic greenstone belt: P—Pechengsky; I-V—Imandra–Varzuga; Kr—Karasjok; CL—Central Lapland; S-K—Salla–Kuolajarvi; Ks—Kuusamo; Pp—Peräpohja. Gold deposits and occurrences, mentioned in the article: 1—Oleninskoe; 2—Nyalm; 3—Olenegorsk group of BIF deposits; 4—Vorgovy; 5—Sergozerskoe; 6—Kichany; 7—Porojarvi group of occurrences; 8—Mayskoe; 9—Ozernoe; 10—Juomasuo and Hangaslampi; 11—Saattopora; 12—Levijarvi–Loukkinen; 13—Iso-Kuotko; 14—Suurikuusikko; 15—Pahtavaara; 16—Kuervittikko and Laurinoja; 17—Rompas; 18—Raiapalot, Palokas. Blocks of the Fennoscandian Shield in (**B**): I—Murmansk craton; II—Kola–Norwegian Province; III—Belomorian mobile belt; IV—Karelian craton.

In northern Finland, the Archean greenstone belts occupy only a small part of the area at the Russian–Finland boundary (Figure 1), and the gold deposits and occurrences are located here mainly in the Paleoproterozoic greenstone belts. Farther south, in the central and southern parts of the Archean Karelian craton in Finland and Russian Karelia, specifically Archean greenstone belts host the majority of gold deposits and occurrences [5,6]. However, in spite of the location in the Archean belts, some of those deposits were formed during Paleoproterozoic geological events [7,8].

The deposits and occurrences in the NE part of the Fennoscandian Shield are located in volcanic–sedimentary rocks, metamorphosed under different PT conditions from greenschist to upper amphibolite facies (Figure 2).

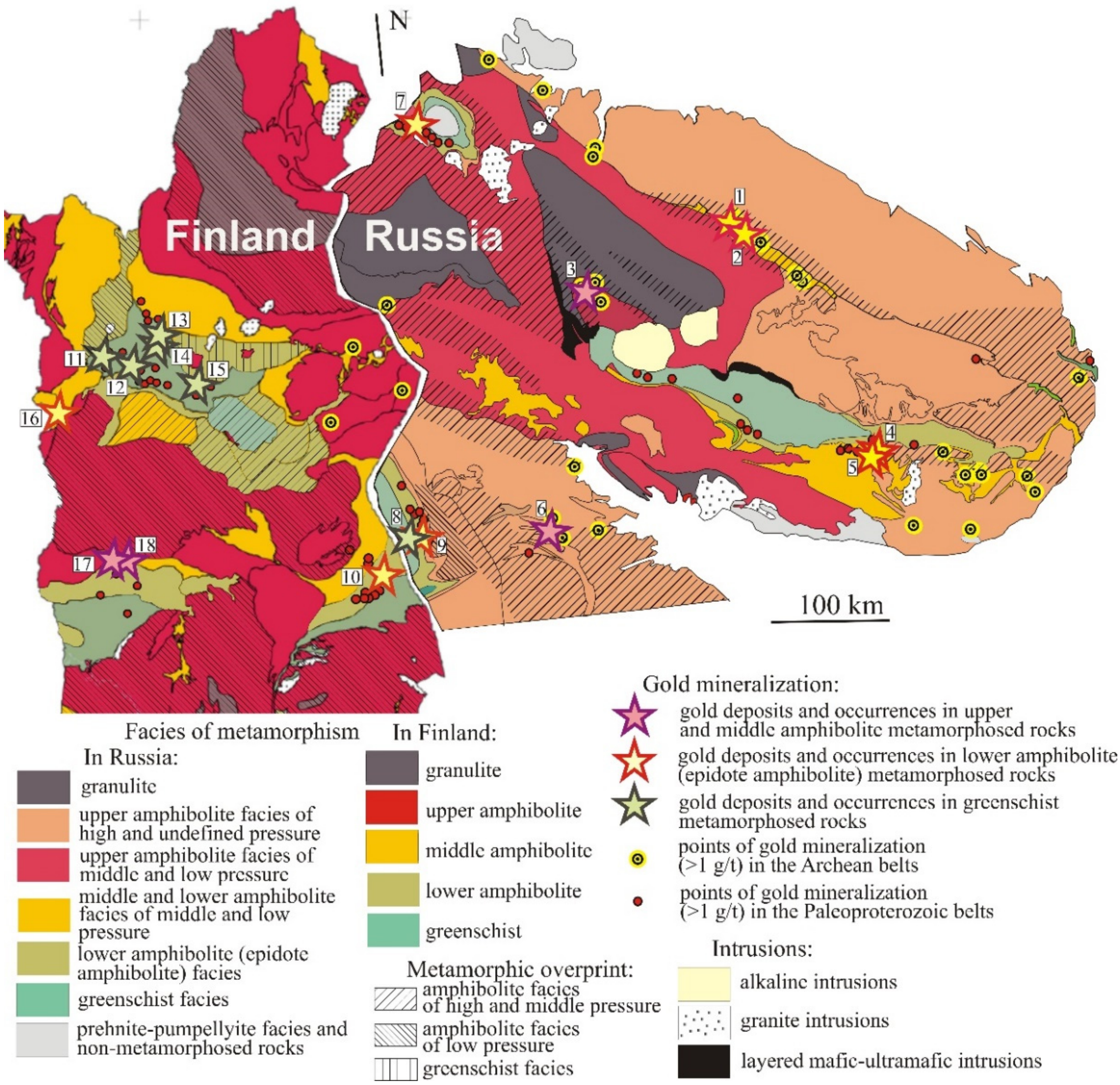


**Figure 2.** Distribution of gold deposits and occurrences in metamorphic complexes in the NE part of the Fennoscandian Shield. Modified after [9] for Finland and after [10] for Russia. Metamorphic facies for Finland and those for Russia were mapped on the basis of different legends of metamorphic facies, and due to this reason, Russian and Finnish parts of the figure do not fully correspond. Deposit numbers—see caption for Figure 1.

In the Archean greenstone belts, the rocks with gold mineralization are amphibolite-metamorphosed. The highest PT parameters (high-pressure amphibolite facies, T = 665–700 °C, *p* = 7–11 kbar) were defined for the rocks in the Tiksheozersky greenstone belt [11]. The rocks of the Olenegorsk group of BIF deposits are middle amphibolite-metamorphosed under medium pressure: T = 650–780 °C, P = 4–7 kbar [12]. Additionally, the rocks of the Oleninskoe and Nyalm deposits in the Kolmozero–Voron'ya belt are lower amphibolite (epidote amphibolite)-metamorphosed [13].

Metamorphism in the Paleoproterozoic greenstone belts in the region is zonal, from greenstone to lower and middle amphibolite facies (Figure 2). Gold deposits and occurrences were found in different metamorphic zones. Greenschist-metamorphosed mafic volcanics host gold deposits in the Central Lapland and Salla–Kuolajarvi belts. Low amphibolite-metamorphosed sedimentary and volcanic rocks host gold mineralization in the Kuusamo, Salla–Kuolajarvi, Pechenga belts, and in the frame of the Imandra–Varzuga belt. In the Perapohja belt, gold occurrences in Rompas and Rajapalot are located in the zone of middle amphibolite metamorphism (Figure 2).

Some specific features of gold deposits and occurrences in the region can be explained with the metamorphism of host rocks higher than the greenschist facies. The deposits in the zones of amphibolite metamorphism formed under conditions of ductile deformations. The foliation of mineralized rocks was reported in the Porojarvi occurrences in the Pechenga belt [14], in the Sergozerskoe deposit (Strelninsky belt) [15], and in the Kichany occurrence (Tiksheozersky belt) [16].

The ductile folded rocks contain no open cavities, hence quartz and carbonate mineralized veins, typical for orogenic gold deposits in greenschist-metamorphosed rocks [17–19], do not form. In this case, the infiltration of fluids is controlled by wide zones of shearing, which causes the formation of thick zones of metasomatically altered rocks with disseminated mineralization. The zones of altered rocks with disseminated sulfide with gold mineralization are seen in the Sergozerskoe deposit, Kichany, the Porojarvi gold occurrences, the gold–cobalt deposits in Juomasuo and Rajapalot, and in Suurikuusikko.

The deposits located in the zone of greenschist metamorphism (the deposits in the Central Lapland belt and in the central part of the Salla–Kuolajarvi belt) formed under conditions of brittle–ductile deformations which were favorable for the formation of hydrothermal veins. The gold mineralization of the vein type is rare in the region: quartz–carbonate veins are mineralized in the Saattopora deposit, quartz–dolomite–barite veins contain gold in the Pahtavaara, and quartz veins were mined for gold in the Mayskoe.

## 3. Gold Deposits and Occurrences in the Archean Greenstone Belts in the Region

The *Oleninskoe* Au-Ag deposit in the Kolmozero–Voron'ya belt is controlled by a shear zone of the NW strike in the amphibolite sequence with numerous granodiorite porphyry sills up to 6.0 m thick [20]. Quartz-rich metasomatic rocks (quartz–muscovite–albite, quartz–tourmaline, and quartz rocks) replace amphibolite and granodiorite porphyry and form an echelon-like series of three lens bodies. These quartz-rich rocks control the distribution of gold–silver mineralization, described in detail in [20,21].

The complex study of the Oleninskoe Au-Ag deposit and the neighboring Cu-Mo porphyry deposit in Pellapahk have helped to postulate a hypothesis of their genesis within a porphyry–epithermal system [20,22]. Hence, the primary mineralization in these deposits formed at the time close to the age of granite and granodiorite porphyry: 2828 ± 8 Ma for the Pellapahk intrusion and 2817 ± 9 for the Oleninskoe sills (Table 1, Figure 3). The ores were later metamorphosed twice under conditions of the lower amphibolites facies: in the Neoarchean, 2770 ± 40 Ma [23], and again in the Paleoproterozoic, 1965–1900 Ma (K-Ar, muscovite [24]), and the fact that the ores were metamorphosed is confirmed by the formation of structures of sulfide anatexis [20,25].

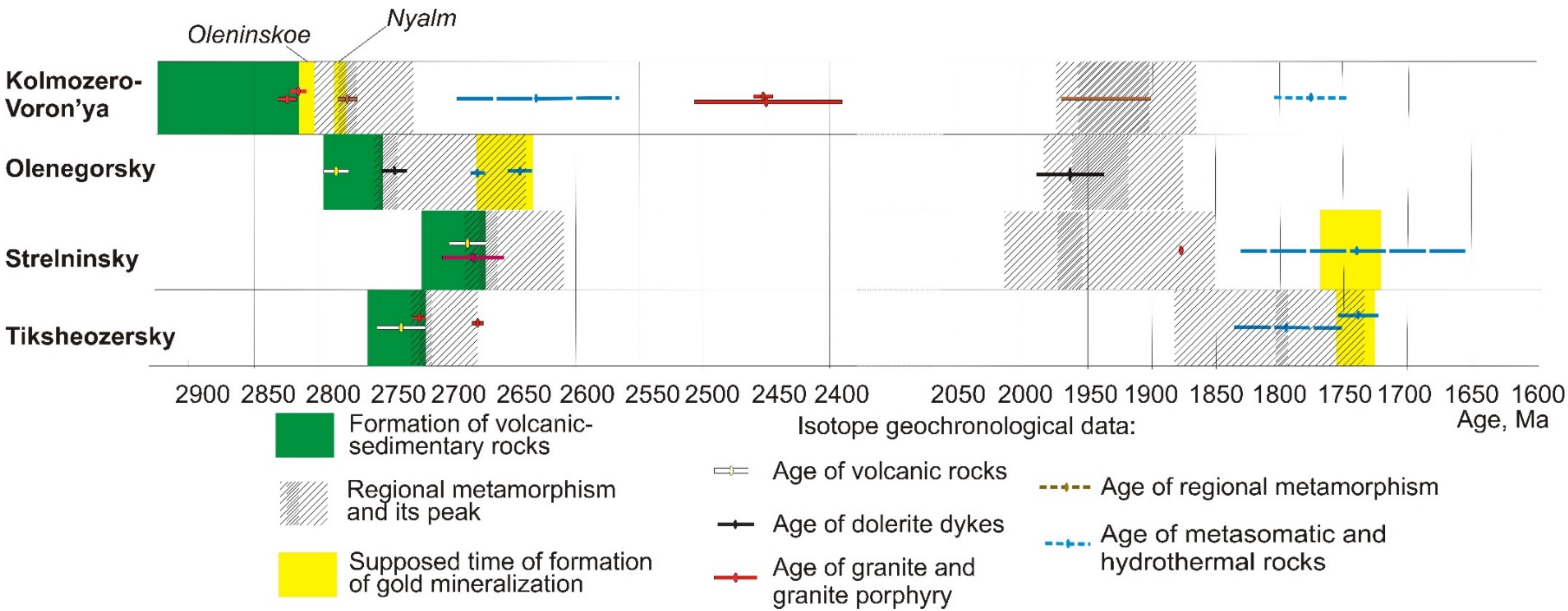


**Figure 3.** Time of formation of gold deposits and occurrences in the Archean greenstone belts in the north-eastern part of the Fennoscandian Shield. Drawn using data from Table 1.

The gold-only deposit Nyalm consists of two linear stockworks of quartz–carbonate veins and veinlets at the tectonized contacts of a small diorite–granodiorite porphyry intrusion. The stockworks are up to 15 m thick, orientated parallel to elongation of the intrusion [1]. The age of the Nyalm intrusion is similar to that of the Pellapahk: 2825 $\pm$ 7 Ma [26]. The intrusion was metamorphosed in the Neoarchean (the Rb-Sr isochrone age of metamorphism is 2779 $\pm$ 72 Ma), and we assume the formation of gold-mineralized stockworks at the regressive stage of the regional metamorphism [26] (Table 1, Figure 3).

Another history of the formation of the Nyalm deposit was proposed by Vrevsky, who defined 2775 $\pm$ 10 Ma (U-Pb, zircon, SHRIMP-II) for the inner zone of a zircon grain from the Nyalm intrusion but interpreted it, not as the time of metamorphism, but as the age of the xenogene zircon [27]. The rim of the same zircon grain showed 1775 $\pm$ 29 Ma, and the author of article [27] supposed that the formation of the intrusion and of the mineralized gold altered the rocks at this time in the Paleoproterozoic.

In the Olenegorskoe and Kirovogorskoe BIF deposits, gold mineralization was found: (1) in the magnetite–sulfide quartzite in the area with numerous pegmatites and pegmatitic granite veins and dolerite dykes [28], (2) in skarnoids at the contact of the magnetite–sulfide quartzite and host high-alimina gneiss, and (3) in quartz, quartz–calcite, and quartz–calc-silicate hydrothermal veins associated with the skarnoids [12,29,30]. Gold mineralization in skarnoids and hydrothermal veins associates with the gangue minerals formed during alteration processes—with calcite, andradite, greenalite, and other minerals filling fractures in rock-forming ferropargasite, hedenbergite, almandine, and with sulfides (pyrrhotite, pyrite, chalcopyrite, galena, sphalerite, molybdenite) and tellurides (hessite, altaite, bismuth tellurides). The age of the skarnoid with gold mineralization was determined as 2644 $\pm$ 9 and 2675 $\pm$ 3 Ma with the U-Pb method (SHRIMP-II) in the marginal parts of the zircon grains [31]. The central parts of the same grains gave 2784 $\pm$ 9 Ma, which was interpreted as the age of the regional metamorphism [31]. Gold mineralization in the skarnoid and hydrothermal veins in the BIF deposits is considered as a metamorphic–hydrothermal mineralization formed at the regressive stage of the regional metamorphism [1].

Gold deposits in Sergozerskoe and gold occurrences in Vorgovy are located in the zone of regional overthrust of the Strelninsky Archean greenstones onto the Paleoproterozoic rocks of the Imandra–Varzuga belt. This system of thrusts and overthrows borders the core of the Lapland–Kola orogen in the north (Figure 1).

Ore occurrence in Vorgovy is located close to the zone of tectonic contact of the Archean and Paleoproterozoic complexes, where biotite gneiss sequences with interbeds of mafic–ultramafic metavolcanics of the Strelninsky belt are uptrown over the metavolcanics of the Imandra–Varzuga belt.

Mineralization in the Vorgovy occurrence relates to a stockwork system of quartz and carbonate–quartz veins and veinlets hosted by chlorite–sericite–quartz metasomatic rocks after biotite gneiss. The increased gold concentration, up to 4 ppm, agreed with the increase in the arsenic content, and have been found in a 1 m interval immediately at the contact of the sericite–chlorite–quartz schist and the sericite quartzite [15].

The Sergozerskoe deposit is located 1.5–2 km south from the mentioned regional overthrust, at a second order shear zone parallel to the main fault. Sulfide pyrrhotite–arsenopyrite dissemination with gold is controlled by the strata of the amphibolite and amphibole schist (komatiite, komatiitic, and tholeiitic basalts) within a series of fine-grained muscovite–biotite and biotite schists. The main mineralized zone follows the zone of the calcite–biotite–chlorite alteration at the contact of the komatiitic and tholeitic metabasalts [15].

**Table 1.** Geochronological data for the rocks and ores of gold deposits and occurrences in the NE part of the Fennoscandian Shield.

| Greenstone Belt, Deposit or Occurrence | Pre-Ore Rocks | | | Mineralized and Syn-Ore Rocks | | | Post-Ore Rocks and Minerals | | |
|---|---|---|---|---|---|---|---|---|---|
| | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference |
| Kolmozero–Voron'ya, Oleninskoe | | No data | | 2817 ± 9 | U-Pb, zircon granodiorite porphyry | [20] | 2770 ± 40 | Not indicated, regional metamorphism | [23] |
| | | | | 2826 ± 11 | U-Pb, zircon, quartz–andalusite schist (altered granite porphyry) | [32] | 2629 ± 64 | U-Pb, zircon, SHRIMP-II, metasomatic rock after biotite–andalusite schist | [23] |
| | | | | | | | 1965–1900 | K-Ar, muscovite | [24] |
| Kolmozero–Voron'ya, Nyalm | 2825 ± 7 | U-Pb, zircon granodiorite porphyry | [26] | 2779 ± 72 | Rb-Sr, granodiorite, regional metamorphism | [26] | 1775 ± 29 | U-Pb, SHRIMP-II, zircon (marginal zone of the grain), granodiorite, Paleoproterozoic regional metamorphism? | [27] |
| | | | | 2775 ± 10 | U-Pb, SHRIMP-II, zircon (central zone of the grain), granodiorite, regional metamorphism? | [27] | | | |
| Olenegorsky, Olenegorsk group of BIF deposits | 2784 ± 9 | U-Pb, SHRIMP-II, zircon (central zone) from skarnoid—regional metamorphism? | [31] | 2644 ± 9 | U-Pb, SHRIMP-II, zircon (marginal zone) from skarnoid | [31] | 1960 ± 30 | U-Pb, apatite from the dyke aged 2740 ± 11 Ma | [32] |
| | 2740 ± 11 | U-Pb, dolerite | [32] | 2675 ± 3 | U-Pb, SHRIMP-II, zircon (marginal zone) from skarnoid | [31] | | | |
| Tiksheozersky, Kichany | 2735 ± 20 | U-Pb, zircon, metatuff | [33] | 1789 ± 47 | U-Th-Pb, chemical estimating of the age, monazite from metasomatic rocks with arsenopyrite | [16] | | No data | |
| | 2720 ± 4 | U-Pb, zircon, meta-andesite | [34] | | | | | | |
| | 2674 ± 4 | U-Pb, zircon, plagiomicrocline granite | [35] | 1739 ± 15 | U-Pb, titanite from mineralized metasomatic rocks | [16] | | | |
| Strelninsky, Sergozerskoe | 2680 ± 14 | U-Pb, zircon, the 1st generation, metavolcanics | [36] | 1739 ± 86 | Rb-Sr, minerals and WR, mineralized metasomatic rock | [15] | | No data | |
| | 2677 ± 25 | U-Pb, zircon, alkaline granite | | | | | | | |
| | 1966 ± 13 | U-Pb, zircon of the 2nd generation, metavolcanics, regional metamorphim | [37] | | | | | | |
| | 1874 ± 3 | U-Pb, zircon, diorite porphyry dyke | [15] | | | | | | |

**Table 1.** *Cont.*

| Greenstone Belt, Deposit or Occurrence | Pre-Ore Rocks | | | Mineralized and Syn-Ore Rocks | | | Post-Ore Rocks and Minerals | | |
|---|---|---|---|---|---|---|---|---|---|
| | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference |
| Pechengsky, Porojarvi | | No data | | 1888 ± 22 | Sm-Nd, mineralized albite–carbonate–quartz rock, Zagadka occurrence | [38] | | No data | |
| | | | | 1928 ± 12 | Sm-Nd, metasomatic quartzite, South Bragino occurrence | [38] | | | |
| | | | | 1865 ± 58 | Rb-Sr, metavolcanics of the Bragino formation, regional metamorphim? | [39] | | No data | |
| | | | | 1855 ± 54 | Rb-Sr, metavolcanics of the Kaplinskaya formation, regional metamorphim? | [39] | | | |
| Central Lapland, Suurikuusikko | 1914 ± 3<br>1905 ± 5 | U-Pb, zircon, Ruoppalo intrusions | [40] | 1916 ± 19 | Re-Os, arsenopyrite | [41] | | No data | |
| | 1916 ± 7 | U-Pb, monazite, porphyry dyke | [40] | | | | | | |
| Central Lapland, Iso-Kuotko | 1914 ± 4 | U-Pb, monazite, porphyry dyke | [40] | 1862 ± 14 | U-Pb, monazite co-genetic to pyrite | [40] | 1718 ± 9 | Rb-Sr, lamprophyre dyke | [41] |
| | | | | 1853 ± 12 | U-Pb, monazite co-genetic to pyrrhotite | [40] | | | |
| | | | | 1763 ± 7 | U-Pb, monazite with pyrrhotite | [40] | | | |
| Central Lapland, Saattopora | | No data | | from 1985 to 1907 | Pb-Pb sulfide–gold concentrate | [42] | 1781 ± 18 | Pb-Pb, monazite and thucholite | [42] |
| | | | | 1894 ± 46 | Pb-Pb, sulfides and carbonates | [42] | 1684 ± 5<br>1707 ± 8 | Pb-Pb, rutile | [42] |
| Central Lapland, Pahtavaara | | No data | | 1821 ± 43 | Pb-Pb, WR, magnetite, pyrite | [42] | | No data | |
| | | | | 1811 ± 87 | Pb-Pb, carbonates | [42] | | | |
| Central Lapland, Levijarvi–Loukkinen | | No data | | 1902 ± 8 | U-Pb, monazite | [43] | 1783 ± 9 | U-Pb, monazite | [43] |
| | | | | 1857 ± 13 | U-Pb, monazite | [43] | 1789 ± 5 | U-Pb, xenotime | [43] |
| Central Lapland, Hannukainen | 1864 ± 5 | U-Pb, zircon, diorite | [44] | 1797 ± 5 | U-Pb, zircon from skarn | [44] | 1766 ± 5 | U-Pb, zircon, granite dyke cutting the mineralized rock | [44] |
| | | | | 1805 ± 5 | U-Pb, titanite from skarn | [44] | | | |
| Kuusamo, Juomasuo | No data | | | 1847 ± 1 | Pb-Pb, brannerite inclusion in pyrite | [42] | | | |
| | | | | 1822 ± 5 | Pb-Pb, brannerite inclusion in pyrite | [42] | | | |
| Kuusamo, Hangaslampi | 1872 ± 4 | U-Pb, monazite from metavolcanics | [45] | 1849 ± 8 | U-Pb, monazite from biotitizated rock | [45] | | No data | |
| | | | | 1812 ± 10 | U-Pb, monazite from carbonate vein | [45] | | | |

**Table 1.** *Cont.*

| Greenstone Belt, Deposit or Occurrence | Pre-Ore Rocks | | | Mineralized and Syn-Ore Rocks | | | Post-Ore Rocks and Minerals | | |
|---|---|---|---|---|---|---|---|---|---|
| | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference | Age, Ma | Method, Minerals and Rocks, Notes | Reference |
| Salla–Kuolajarvi, Mayskoe | 1770 ± 9 | Rb-Sr, minerals and WR, propylite | [46] | 1403 ± 24 | Rb-Sr, actinolite metasomatic rock | [46] | | No data | |
| | 1610 ± 30 | Rb-Sr, minerals and WR, magnesium metasomatic rock | [47] | 1380 ± 40 | K-Ar, feldspar from altered rock | [48] | | | |
| | | | | 397 ± 15 | Re-Os, native gold | [46] | | | |
| Salla–Kuolajarvi, Ozernoe | No data | | | 1756 ± 8 | U-Pb, rutile from albitite | [48] | 416 ± 14 | U-Pb, rutile from albitite | [49] |
| | | | | 1754 ± 39 | Rb-Sr, albitite—minerals and WR | [49] | | | |
| | | | | 1759 ± 11 | Sm-Nd, albitite—minerals, including molybdenite and chalcopyrite, and WR | [50] | 385 ± 2 | U-Pb, brannerite from albitite | [49] |
| | | | | 1748 ± 13 | U-Pb, zircon from granite dyke | [51] | | | |
| Perapohja, Rompas (Rm) and Rajapalot (Rp) | 2050 ± 8 | U-Pb, zircon, felsic porphyry | [52] | | | | | No data | |
| | 1973 ± 11 | U-Pb, zircon, metatuff | [54] | 1775 ± 12 | U-Pb, zircon, Matalavaara tourmaline granite | [53] | | | |
| | 1989 ± 8 | U-Pb, zircon, Kierovaara granite | [53] | | | | | | |
| | 1879 ± 3 | U-Pb, titanite, Haaparanta inrusions | [52] | | | | | | |
| | from 2022 to 1912 | U-Pb, uraninite-1 (Rm) | [55] | | | | | | |
| | from 2035 to 1910 | U-Pb, uraninite-2 (Rm) | [53] | 1819 ± 37 | U-Pb, uraninite-3 | [55] | | | |
| | 2007 ± 9 | Re-Os, molybdenite (Rm) | [55] | | | | | | |
| | 2023 ± 7 | Re-Os, molybdenite (Rm) | [55] | | | | | | |
| | 2043 ± 8 | Re-Os, molybdenite (Rm) | [55] | | | | | | |
| | 2016 ± 17 | U-Pb, monazite (Rp) | [56] | 1713 ± 11 | U-Pb, monazite (Rp) | [56] | | | |
| | 1916 ± 11 | U-Pb, monazite (Rp) | [56] | 1778 ± 13 | Re-Os, molybdenite (Rp) | [55] | | | |
| | | | | 1782 ± 6 | Re-Os, molybdenite (Rp) | [55] | | | |

The geological position and the geochemical and mineralogical characteristics of the Sergozerskoe and Vorgovy generally correspond to the metamorphic–hydrothermal ore systems in the greenstone belts. The age of the host rocks in the deposits is Archean because they have normal magmatic contacts with, and are affected by, the alkaline granites dated 2.68 Ga [37]. The lower limit of the time of formation of the gold mineralization is defined by the age of the youngest mineralized rock: that is, the diorite porphyry dyke (~1.87 Ga), which cuts the metavolcanics in the Sergozerskoe deposit [15]. Probably the mineralization formed at 1739 ± 86 Ma, and this age was determined with the Rb-Sr method for the rock-forming minerals in the zone of the calcite–biotite–chlorite alteration [15].

The Kichany occurrence is located in the central part of the Tiksheozersky greenstone belt, in the Kichany synform, in a stratum of amphibolite (tholeiitic metabasalt) with interbeds of plagiogneiss–metatuffite. A series of thrusts at an angle of 30–40° splits the stratum to thin slabs, and these thrusts control the zones of intense rock alteration. Gold associates with arsenopyrite–pyrrhotite mineralization in quartz- and quartz–diopside–scapolite-altered amphibolite.

The volcanic and sedimentary rocks of the greenstone belt are of Neoarchean age (2.75–2.72 Ga) [33,34], but the titanite with inclusions of gold formed a billion years later, 1739 ± 15 Ma [16], which is probably the time of the tectonic events (thrusting) and rock alteration. The age of the titanite corresponds to the age of the monazite (1789 ± 47 Ma, U-Th-Pb chemical dating) from arsenopyrite- and tourmaline-rich altered rocks close to the contact of the tourmaline granite intrusion [16].

The Kichany occurrence differs from other gold deposits in NE part of the Fennoscandian Shield in high metamorphic grade: the rocks of the Tiksheozersky belt were high-amphibolite metamorphosed in the Neoarchean and again in the Paleoproterozoic. The geological position and the mineralogical and geochemical characteristics of the Kichany occurrence are in agreement with the model of the hypozonal orogenic (metamorphic hydrothermal) ore system.

Thus, gold mineralization in the Strelninsky and Tiksheozersky belts formed in the rocks of the Archean age during the Paleoproterozoic Svecofennian tectonic events.

## 4. Gold Deposits and Occurrences in the Paleoproterozoic Belts in the NE Part of the Fennoscandian Shield

In the *Porojarvi* group of occurrences in the South Pechenga structure of the Pechenga belt, gold mineralization was found in the metasomatic quartzites and in quartz–albite–carbonate metasomatic rocks. The disseminated sulfide mineralization with gold makes not more than 3 vol.% of the rocks. The main sulfides are pyrrhotite, arsenopyrite, and pyrite, and the oxides are represented by magnetite, ilmenite, and rutile. Gold associates with arsenopyrite or forms fine inclusions in the gangue minerals [14].

Gold mineralization formed in the altered volcanic–sedimentary rocks at the stage of regional metamorphism, before the peak of metamorphism (~1.83 Ga), under the conditions of plastic deformation (the metasomatic rocks are folded together with the host rocks). The Sm-Nd isochrone age of the gold-mineralized quartz–albite–carbonate rock is 1888 ± 22, and the age of the metasomatic mineralized quartzite is 1928 ± 12 Ga [38] (Table 1, Figure 4).

In the Central Lapland belt (Finland), the distribution of gold deposits and occurrences is controlled by the shear zones of Sirkka and Kiistala (Figure 1). The deposits are located at the main shear zones proximately or, more often, at the second-order faults at the distance of less than 3 km. Mineralization is hosted mainly by greenschist metamorphosed mafic–ultramafic metavolcanics of the Savukoski and Kittila groups [57,58].

The deposits and occurrences in the shear zones of Sirkka and Kiistala can be divided into two geochemical groups: gold-only deposits with the geochemical associations of Au, As, Ag, As, Bi, Sb, Te, and W, typical for orogenic deposits, and multimetal with anomaly geochemical association, including Cu, Ni, Co, and U [57]. The deposits of the second group are concentrated mainly in the western part of the shear zone of Sirkka.

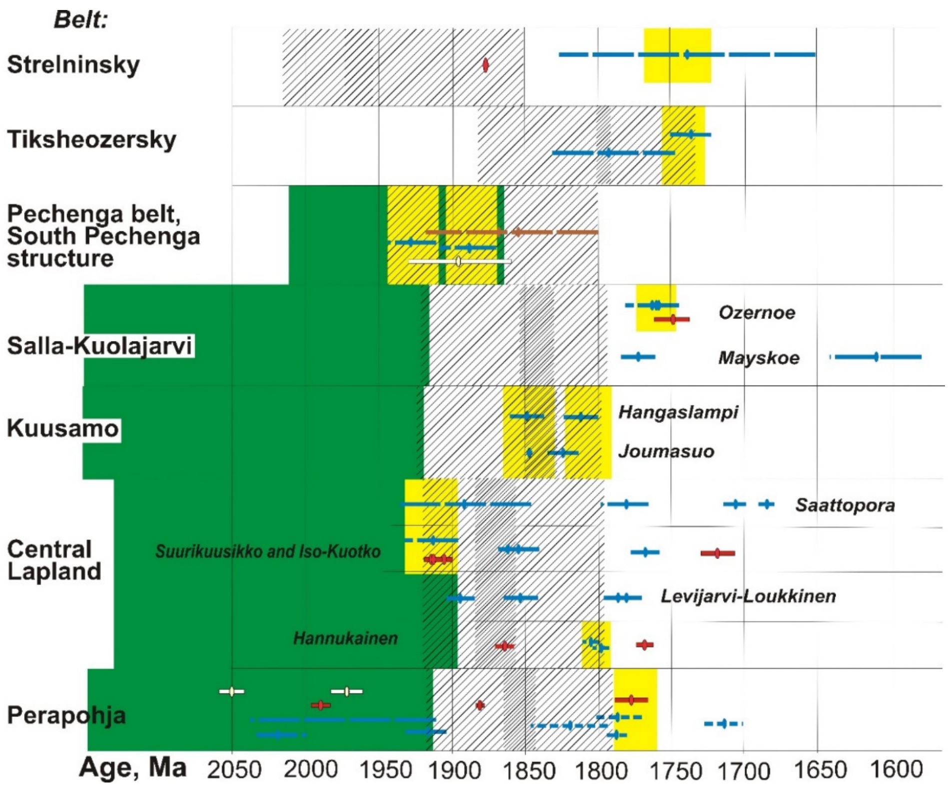


**Figure 4.** Geochronological data for gold deposits and occurrences formed in the Paleoproterozoic. See Figure 3 for the legend.

The biggest gold deposit in Europe, Suurikuusikko (>260 t Au), is located at the shear zone of Kiistala, at the contact of sequences of magnesium and ferrous tholeiitic basalts, separated by a thin horizon of sedimentary rocks (argillite, phyllite, chert, BIF) [40]. A small gold deposit, Iso-Kuotko, is located 12 km north from the Suurikuusikko, at the cross of the Kiistala and Koutko shear zones [41].

The mineralized zone in the Suurikuusikko deposit was traced for 5.5 km along strike, and to the depth of 1.5 km, its thickness reaches 46 m. The host rocks are mafic metalavas, intensely albitized, graphitized, with numerous carbonate–quartz veinlets. The highest gold grades were found in the rocks with signs of extrusive origin (pyroclastics, autobreccia, and lapillas in volcanic–sedimentary rocks) and intensely tectonized [58].

Gold-bearing arsenopyrite and pyrite crystallized at the carbonatization stage of the rocks (dolomite and ankerite veinlets). The age of mineralization, 1916 $\pm$ 19 Ma, was defined with the Re-Os method for gold-bearing arsenopyrite [40] (Table 1, Figure 3).

The age of monazite, co-genetic to pyrite and pyrrhotite, is 1.86–1.85 Ga in the Iso-Kuotko deposit [41]. In the Levijarvi–Loukkinen occurrence in the Sirkka shear zone, a few generations of monazite were identified: 1.90, 1.86, 1.79, and 1.78 Ga [43]. The age of the mineralization in the Saattopora and Pahtavaara deposits was defined with the Pb-Pb method less precisely, but it indicated the formation of gold mineralization during the period 1.86–1.85 Ga [42] (Table 1, Figure 4).

Geochronological data for gold-mineralized rocks in the Central Lapland belt, presented in Table 1 and Figure 4, fall in four intervals: 1930–1900, 1880–1850, 1790–1760, and 1720—1680 Ma.

The first of the indicated periods (before the peak of regional metamorphism) includes data on the age of the Ruoppapalo tonalite–diorite pluton and the Nyssäkoski felsite dyke, the age of sulfide mineralization in the Suurikuusikko and Saattopora deposits, and the age of monazite in the Levijarvi–Loukkinen occurrence. The second and the third intervals include data on the age of monazites from the Iso-Kuotko, the Saattopora deposits, and the Levijarvi–Loukkinen occurrence. The second interval corresponds to the peak of metamorphism and correlates with the age of the intrusions of the Haaparanta formation. The third refers to the time after the peak of metamorphism and to the age of the Nattanen granite formation. The latest, the fourth interval, includes data on the lamprophyre dyke in the Iso-Kuotko and the Pb-Pb age of rutile from the Saattopora. Geochronological data indicate the multistage formation of gold mineralization during hydrothermal events, which correlate with intrusive and dyke magmatism in the Central Lapland belt.

In the western part of the Central Lapland belt, close to the Swedish border, a group of iron ore deposits, with associated gold and copper mineralization, are located at the Kolari submeridional shear zone. Massive and banded magnetite–sulfide ores were found in skarn at the contact of monzonite diorite intrusions with volcanic–sedimentary rocks of the Savukoski group in the Hannukainen (Laurinoja) and Kuervittiko deposits. Sulfide mineralization with gold forms dissemination in magnetite ore, in skarn, and in host rocks. Gold associates with gangue silicate minerals, chalcopyrite, and magnetite [44,59,60]. The deposits were classified as IOCG deposits [44,59,60].

Gold-bearing sulfide mineralization probably formed concurrently with the magnetite ore, or a little later. The U-Pb data for zircons and titanites in skarn indicate the formation of this metasomatic rock at ~1800 Ma, i.e., 60–65 million years later than formation of monzonite diorite intrusions (1864 $\pm$ 5 Ma), and it was probably the time of the tectonic movements. The upper time limit of gold mineralization formation is 1766 $\pm$ 5 Ma, the age of the granite dykes which cut and brecciate the ore [44].

In the central part of the Kuusamo belt, the gold deposit at Juomasuo, and more than 20 small gold deposits and occurrences, are hosted by the sedimentary sericite quartzite of the Petajavaara formation, which are intensely albitizated and low-amphibolite metamorphosed. The deposits/occurrences are located at the intersections of the Hyvaniemi–Maanikavaara and Kayla–Konttiaho anticlines by NW-oriented shear zones [61].

The biggest deposit in the Kuusamo belt is the Juomasuo Au-Co (with U) deposit. This deposit consists of a series of Co-rich (>1000 g/t Co, <1 g/t Au) and Au-rich (>1 g/t Au) mineralized zones [62]. Cobalt minerals in the deposit are cobaltite and cobalt pentlandite. Early native gold form inclusions in pyrite, pyrrhotite, rarer in cobaltite and molybdenite, and small gold grains were noted in the silicate minerals. Gold of the late generation fills fissures in uraninite or occurs together with tellurides at the boundary of the uraninite with gangue minerals [62].

Cobalt-rich mineralization is located in the zones of chloritization and biotitization (Fe-Mg alteration), and Au-rich mineralization is controlled by sericitization (potassium alteration). The alteration processes and, consequently, the formation of the two types of mineralization were separated in time according to the results of the petrographic investigations [62,63], which was confirmed by geochronological data [45]. In the Hangaslampi occurrence, neighboring the Juomasuo, the age of monazite in biotite-altered rock is 1.85 Ga, and monazite from the carbonate vein is younger, at 1.81 Ga [45]. In the Juomasuo deposit, 1.85 and 1.82 Ga were defined for brannerite in inclusions in pyrite and pyrrhotite, correspondingly, with the Pb-Pb method [42] (Table 1, Figure 4).

The Rompas and Rajapalot gold occurrences are located at the northern edge of the Perapohja belt. Two types of mineralization are defined in the area: (1) Au-U in quartz–carbonate–amphibole veins (the Rompas type); (2) Au and Au-Co-disseminated mineralization in altered metasedimentary rocks (the Rajapalot type) [64,65].

The Rompas occurrence is composed mainly of metabasalts with small amounts of pyroclastics, carbonate rocks, and metapelite. Au-U mineralization was found in quartz–carbonate–amphibole veins up to 30 cm thick and in the vein exocontact zones in metabasalts. Three generations of uraninite are distinguished in the veins, the first and the second formed in 2.03–1.91 Ga, and the third at ~1.82 Ga. Uraninite of the third generation associates with pyrobitumen, and big pyrobitumen grains are overgrown with carbonates and siliceous matter. Native gold fill fractures in uraninite-3 and pyrobitumen, form fine disseminations in carbonates near the uraninite grains, or overgrow pyrobitumen [65].

Native gold associates with galena, altaite and other tellurides, and with niccolite. Gold–galena–telluride mineralization probably formed in the interval 1.75–1.78 Ga, and this is close to the age of the tourmaline granite intrusions at 1.76–1.79 Ga, which were outcropped north of the Rompas area [53] (Table 1).

The Rajapalot area is located 8 km to the east from the Rompas and consists of a number of gold occurrences (Palokas, Raja, Joki, Rumajarvi, etc.). High-amphibolite metamorphosed and intensely altered sedimentary quartzites, and carbonate-bearing rocks, intercalated with amphibolites–metavolcanics, compose the Palokas occurrence. The sedimentary–volcanic sequences contain horizons of orthoamphibole–cordierite rocks of probable metasomatic origin, with cordierite porphyroblasts and amphibole asterisks in the biotite–plagioclase matrix [66–68]. Sulfide dissemination makes up to 5 vol.% of the orthoamphibole–cordierite rock, and pyrrhotite is the most abundant sulfide mineral. The rocks are cut and brecciated by tourmaline veins up to 30 cm thick, and the veins contain rich sulfide mineralization (pyrrhotite, galena, molybdenite, tetradymite, and some nonidentified tellurides) and gold [67–70].

Gold in the orthoamphibole–cordierite rocks does not associate with the sulfide mineralization and forms grains which are isolated in silicate minerals. In the tourmaline veins and the vein exocontact zones, gold fills the fractures in tourmaline grains [68,69], where it associates with galena, molybdenite, and tellurides. Gold in the orthoamphibole–cordierite rocks and in tourmaline veins probably belong to different generations, with the gold in the tourmaline veins formed later [67,68]. Molybdenite in the tourmaline veins formed at 1.78 Ga [55], and this corresponds well to the age of the tourmaline granite intrusions at 1.76–1.79 Ga (Table 1).

In the Salla–Kuolajarvi belt, gold mineralization was found in quartz veins of the Mayskoe deposit and in uranium occurrences in albitite [1,71].

The small deposit of Mayskoe (#8 in Figure 1) is located in the central part of the Salla–Kuolajarvi belt. Quartz veins in the deposit are hosted by metavolcanics (basalts, andesite, and mafic tuffs), intruded by dolerite dykes and ultramafic sills. The dykes form two subparallel bodies controlled by northeast trending faults. The faults play the role of ore-hosting tectonic structures and control the pre-vein metasomatic alteration and location of two mineralized quartz veins [48].

The wallrocks underwent processes of propylitization, Mg–metasomatism (Mg–amphibole–biotite–quartz assemblage and chloritization) and Si–K–Ba metasomatism (formation of quartz–K–Ba–feldspar–carbonates assemblage) [48,72]. Propylitic alteration is of regional character, but Mg- and Si–K–Ba-alteration occur only within the vein-hosting fault zones.

Visible gold was noted in fractures in quartz, often in the intergrowths with galena and chalcopyrite. The time of formation of the gold mineralization is very controversial. Pre-ore propylites formed at 1770 $\pm$ 9 Ma (Rb–Sr, minerals and rock) [48], i.e., at the regressive stage of regional metamorphism. The age of magnesium alteration is 1610 $\pm$ 30 Ma (Rb–Sr, minerals and rock) [46], and the age of feldspar in the Si–K–Ba-altered rock was estimated at 1380 $\pm$ 40 Ma (K–Ar) [48]. No geological events of this age were reported for the Salla–Kuolajarvi belt, and the age of the alteration processes must be checked. Finally, the Re–Os age of gold is 397 $\pm$ 15 Ma [46]. This is the time of the Paleozoic tectonic–magmatic activation in the region, when the alkaline ultramafic intrusion formed: the Sallanlatva alkaline ultramafic intrusion in the Salla–Kuolajarvi belt is 372 $\pm$ 3 Ma old [73] (Table 1).

Uranium occurrences with Te-Se and Au mineralization in albitite are located at the eastern flank of the Salla–Kuolajarvi belt. The better-studied *Ozernoe* occurrence is composed by a series of albitite lenses up to 10 m $\times$ 90 m in size, which cut the amphibolite of the Jatulian age at an angle of ~30° [49,50]. Carbonate–albite and carbonate (dolomite) metasomatic rocks make the central parts of the zonal albitite lenses, and these rocks contain uranium, sulfide, and telluride–selenide mineralization: pyrite, chalcopyrite, marcasite, molydbenite, uraninite, uranophane, brannerite, melonite, altaite, kawazulite, clausthalite, and other mineral phases [49,71]. Native gold associates mainly with the tellurides altaite and melonite [71].

The uranium occurrences formed in the interval 1760–1745 Ma, according to the results obtained with the U-Pb, Sm-Nd, and Rb-Sr methods [49,50], corresponds to the age of the granite dykes, 1748 ± 13 Ma, within the error limits. This indicates (in complex with the characteristics of the fluid inclusions [74]) the possible role of magmatic fluids in the formation of albitite with uranium mineralization. The uranium (with gold) mineralization was recrystallized during the Paleozoic tectonic–magmatic activity: the U-Pb age of brannerite is 385 ± 2 Ma and the lower intersection of the U-Pb discordia for rutile is at 416 ± 14 Ma [49] (Table 1).

## 5. Discussion: The Principal Stages and Conditions of Formation of Gold Mineralization in the NE Part of the Fennoscandian Shield

The principal stages of the development of the NE part of the Fennoscandian Shield in the Archean and Paleoproterozoic, and the correlating stages of the formation of gold mineralization, are shown in Table 2. The succession of geodynamic events is compiled in accordance with the models presented in [3,4,75–79]. According to the reconstructions by Mints with coauthors [3], three small continents were formed in the NE part of the Fennoscandian Shield 2.93 Ga ago: those were, from NE to SW in the modern coordinates, the Murmansk, Inari–Kola (or simply Kola), and Khetolambina continents (the latter now is a part of the Belomorian mobile belt). The oldest greenstone belt in the region is the Kolmozero–Voron'ya belt, a Mesoarchean island arc. Volcanic–sedimentary rocks formed in this belt in 2.88–2.83 Ga, and at the final stage of sedimentation they were intruded by diorite-granodiorite-granite porphyry intrusions (2.83–2.82 Ga). These intrusions produced a porphyry–epithermal ore system with a Cu-Mo porphyry occurrence in Pellapahk and a Au-Ag deposit in Oleninskoe, which is probably the most ancient porphyry–epithermal system, preserved in the Fennoscandian Shield [20,25]. The island arc Kolmozero–Voron'ya was accreted to the Murmansk continent during the period 2.78–2.76 Ga [3].

Greenstone belts of the Tiksheozero system are considered as accretionary orogens of the Khetolambina continent [3,80], and they formed during the period 2.84–2.76 Ga. The epicontinental rift greenstone belts Strelninsky and Olenegorsky formed in the marginal part of the Inari–Kola continent a little later, during the period 2.80–2.66 Ga [3].

The Mesoarchean continents amalgamated and formed the Kenorland supercontinent during the period from 2.87 to 2.66 Ga [3], and according to [81], these events took place during the period 2.73–2.68 Ga. The process started with the conflict of the Khetolambina and Inari–Kola continents, and the subduction of the Khetolambina continent under the Inari–Kola caused the eclogite metamorphism of the rocks [3].

The Murmansk (with the accreted Kolmozero–Voron'ya belt) and the Inari–Kola continents consolidated a little later, between 2.76 and 2.66 Ga. The zone of junction was of a shift–transpressive character, where the intensity of the compression increased eastwards. This resulted in a higher metamorphic grade (middle amphibolite compared to low amphibolite) of the rocks in the south-eastern part of the Kolmozero–Voron'ya belt [3].

The gold deposit Nyalm in the Kolmozero–Voron'ya belt and the occurrences of gold mineralization in skarnoids and hydrothermal veins in the Olenegorsky BIF deposits formed during this Archean metamorphic event under conditions of 'continent–continent' collision.

The time from 2.68 to 2.66 to 2.10 Ga was the period of relatively stable craton, but from time to time it was subjected to mantle plumes activity and rifting in the areas of the earth crust thinning. The first definite event of this kind was the formation of layered mafic–ultramafic intrusions with age 2.50 Ga. The intrusions contain the Pt-Pd-Cu-Ni deposit with gold as an associated metal. The intrusive magmatism caused intraplate rifting with the initial formation of two rift systems (Pechenga–Imandra–Varzuga and the Karasjok–Central Lapland–Salla–Lehta–Vetreny belt), oriented NW–SE in the modern coordinates (Figure 1). The rift troughs were filled with the Sumian mafic volcanics [76,77].

**Table 2.** The principal stages of formation of gold deposits and occurrences in the north-eastern part of the Fennoscandian Shield.

| Geodynamic Conditions | Time Interval, Ga | Metallogenic Events | Geological Structures (Greenstone Belts, Intrusions) | Deposits and Occurrences |
|---|---|---|---|---|
| Formation of core of the Murmansk, Inari–Kola, Khetolambina microcontinents | >2.93 | | | |
| Formation of ancient island arc systems and their accretion to microcontinents | 2.88–2.77 | Deposition of volcanic–sedimentary rocks, which host epigenetic gold mineralization | Kolmozero–Voron'ya belt (paleosuture), Central Belomorian paleosuture, Tiksheozero belt system | Pellapahk (Cu-Mo porphyry), Oleninskoe (Au-Ag) |
| Formation of epicontinental rift greenstone belts | 2.80–2.66 | Deposition of volcanic–sedimentary rocks, which host epigenetic gold mineralization | Strel'na, Ura-Guba, Allarechka, East Pansky, Olenegorsk, epigenetic rift greenstone belts | |
| Consolidation of microcontinents into Kenorland supercontinent ("continent–continent" collision) | 2.72–2.66 | Epigenetic gold deposits in metamorphic complexes | Kolmozero–Voron'ya belt Olenegorsk belt | Nyal'm-1 Epigenetic Au mineralization in BIF deposits |
| Rifting (mantle plume—initial stage of Kenorland break) | 2.53–2.42 | Layered mafic–ultramafic intrusions (PGE and Ni–Cu deposits with gold) | Fyodorovo–Pansky massif (2.50 Ga) Pennikat, Suhanko, Narkaus, Olanga group (2.43–2.42 Ga) | Fyodorova Tundra, Kievey, N.Kamennik, E.Chuarvy Konttijarvi, Ahmavaara, Pennikat |
| "Dormant tectonic" period (sedimentation in intracontinental basins) | 2.3–2.11 | Deposition of volcanic–sedimentary rocks, hosting epigenetic gold mineralization | Salla–Kuolajarvi, Pechenga, Imandra–Varzuga, Kuusamo, Perapohja, Central Lapland belts | |
| Rifting and reactivation of intracontinental basins, formation of intra-continental rifts (mantle plume, break of Kenorland supercontinent) | 2.11–1.92 | Layered mafic–ultramafic intrusions | Central Lapland | Kevitsa (Ni, Cu + PGE, Au) |
| | | Intrusions of gabbro–verlite formation | Pechenga belt | Pechenga deposits (Cu, Ni + PGE, Au) (Zhdanovske, Zapolyarnoe, etc.) |
| | | Deposition of volcanic –sedimentary rocks, hosting epigenetic gold mineralization | Salla–Kuolajarvi, Pechenga, Imandra–Varzuga, Kuusamo, Perapohja, Central Lapland belts | Pahtavaara VMS deposit, gold- bearing VMS ores in South Pechenga and Panarechenskoe |
| Formation of Columbia supercontinent; accretionary orogenes of "igneous arc—continent" type | 1.93–1.86 | Epigenetic gold deposits | South Pechenga zone of the Pechenga belt, Central Lapland belt (Sirkka and Kiistala shear zones) | Porojarvi group of occurrences Suurikuusikko, Saattopora, Levijarvi–Loukkinen, etc. |
| Intracontinental collisions of "continent–continent" type; formation of Lapland–Kola orogen | 1.87–1.70 | Epigenetic gold deposits Deposit and occurrences associated with late-orogenic magmatic events | Strel'ninsky Tiksheozersky Kuusamo, Salla–Kuolajarvi Perapohja Central Lapland belt (Kolari shear zone) | Sergozero, Vorgovy, Kichany Juomasuo and other occurrences Mayskoe, Ozernoe Rompas, Rajapalot Laurinoja, Kuervittikko |

The next stage of intrusive activity took place at 2.44–2.43 Ga, when the layered mafic–ultramafic intrusions of the Pennikat, Suhanko, Narkaus, and Olanga groups formed; these intrusions contain Pt-Pd and Cu-Ni deposits with gold as well. At the new stage of rifting, a system of perpendicular-orientated rifts formed in the northern part of the Karelian craton (Karasjok–Central Lapland–Salla and the perpendicular Kuusamo and Perapohja rifts) (Figure 1) [76,81–83]. The Sariolian formations (2.44–2.30 Ga), consisting mainly of terrigenous sediments with minor continental and subaqueous volcanics, overlap the Sumian volcanics or lie discordantly on the Archean basement.

Tectonic activity was not high during the period 2.3–2.1 Ga (the Jatulian). This stage was characterized by the formation of terrigenous clastic sediments (quartzite, arcose), evaporate sedimentation/precipitation with a restricted supply of volcanic material (continental basalts), and later the terrigenous rocks were changed by more deepwater carbonate sediments. In particular, the Jatulian rocks host numerous gold occurrences and deposits in the Kuusamo, Salla–Kuolajarvi, Central Lapland (the Sirkka shear zone), and Perapohja belts.

A new large-scale plume event in the subcontinental mantle initiated the break-up of the Archean continent at 2.10–2.05 Ga and the formation of the Kola and Kittila paleo-oceans [81]. This time was the period of intrusive activity, with the formation of anorogenic granite intrusion, a series of tholeiitic dykes and, a little later (2.06–2.05), of mafic–ultramafic-layered massifs (the Kevitsa intrusion).

During the period 2.05–1.95 Ga, the Fennoscandian Shield was broken to fragments by the Kola, Kittila, and Jormua paleo-oceans [78]. The rifts in the Kola paleo-ocean were filled with sedimentary clastic rocks and deeper water turbidite and carbonate sediments, and with thick sequences of oceanic tholeiitic basaltic lava. Oceanic basalts with subsidiary clastic and carbonate sediments of the Savukoski group, Kittila, and Sattasvaara suites formed in the Kittila paleo-ocean. The basalts of the Kittila suite host the Suurikuusikko and other deposits and occurrences in the Kiistala shear zone in the Central Lapland belt. Komatiitic basalt and pyroclastic rocks of the Sattasvaara suite host gold-mineralized VMS ores and quartz–barite veins of the Pahtavaara deposit.

The period from 1.95 to 1.87 was the main collisional stage in the NE part of the Fennoscandian Shield. The Kola paleo-ocean closed during the period 1.95–1.93 Ga, and the subduction of the oceanic crust in the paleo-ocean changed with the "continent–continent" collision. The formation of the Lapland–Kola orogen started with this event, and it was the beginning of the Svecofennian orogeny in the Fennoscandian Shield. The peak of the collision events moved gradually to the south-east, and at 1.91–1.89 Ga it reached the boundary of the Belomorian mobile belt with the Karelian craton [4].

The Panarechenskaya tectonic–volcanic structure (caldera) formed at this collisional stage in the southern flank of the Imanra–Varzuga belt (Figure 1) [84]. The Panarechenskaya caldera is of oval form, 21 × 8 km, and it is filled with volcanics from mafic to acidic composition and clastic sediments, and the volcanic–sedimentary rocks are cut by intrusions from ultramafic to granite. Calderas of the Mesozoic and Cenozoic age, filled with medium-acid volcanics and porphyry intrusions, are known to contain porphyry–epithermal and VMS gold deposits [85]. The oldest porphyry–epithermal systems with gold mineralization in the calderas were reported in Western Australia in the Pilbara and Yilgarn cratons [85]. The Panarechenskaya caldera can be considered as a structure, promising for gold, due to findings of VMS ores with gold–telluride mineralization [86] and quartz veins with 4 g/t Au [2] in the northern part of the caldera.

The Kittila paleo-ocean closed at ~1.92 Ga at the beginning of the Savo–Lapland orogeny (1.92–1.89 Ga) [79]. The fragments of the Archean continent amalgamated again by 1.87 Ga and formed the protocontinent Fennoscandia [79].

During the period from 1.95 to 1.87, orogenic (metamorphic–hydrothermal) gold deposits and occurrences formed in the Central Lapland belt in the shear zones of Sirkka and Kiistala (including the Suurkuusikko deposit), and in the South Pechenga zone of the Pechenga belt, in the suture zone at the northern boundary of the core of the Lapland–Kola orogen.

The consecutive accretion of island arcs of different ages to the Karelian craton from the south-west lasted during the period 1.87–1.84 Ga (the Fennian orogeny) and 1.83–1.80 Ga (the Svecobaltic orogeny) [78], and these orogenies caused regional metamorphism, foliation and faulting, and syn- and late-orogenic granite magmatism. These events are displayed in the activation of the magmatic and hydrothermal activity in the geological structures of the Karelian craton and in the Belomorian mobile belt as well. Metamorphic–hydrothermal (?) Au-Co( ± U) deposits and occurrences in Juomasuo, Hangaslampi, etc., formed in the Kuusamo belt during the period 1.85–1.82 Ga, and later (~1.74 Ga) in the Tiksheozersky (Kichany) and Strelninsky (Serozerskoe, Vorgovy) Archean belts.

Late orogenic (or postorogenic?) magmatic activity during the period 1.87–1.70 Ga promoted the formation of magmatic–hydrothermal Au-U deposits and occurrences in the Perapohja belt (Rompas, Rajapalot, ~1.78 Ga), in the Salla–Kuolajarvi belt (U ± Au Ozernoe occurrence, ~1.75 Ga), and in the Central Lapland belt (IOCG deposits Laurinoja and Kuervittikko in the Kolari shear zone, ~1.80 Ga).

## 6. Conclusions

Two main stages of the formation of gold deposits are identified in the north-eastern part of the Fennoscandian Shield, the Neoarchean and the Paleoproterozoic, and these stages correspond well to the main global stages of gold deposit formation in the Precambrian (2.7–2.5 and 2.1–1.8 Ga [87–90]). The Paleoproterozoic stage was more important in the region, as, at this stage, the gold deposits formed not only in the Proterozoic greenstone belts, but in those Archean belts as well, which were involved in the Svecofennian tectonic processes in Paleoproterozoic. Within each stage, gold deposits and occurrences formed during the deposition of volcanic–sedimentary complexes (porphyry–epithermal, VMS deposits), the regional metamorphism of the rocks (metamorphic–hydrothermal, orogenic deposits), and in consequence of the late- and postorogenic magmatism (IOCG deposits).

Gold deposits and occurrences of the Archean age (the Oleninskoe, Nyalm, and Olenegorsk group of BIF deposits) were metamorphosed in the Paleoproterozoic, and the isotope data for the rocks and minerals of these deposits detect both Archean and Paleoproterozoic events. The Oleninskoe Au-Ag deposit is probably the most ancient gold deposit in the NE part of the Fennoscandian Shield, and this deposit is considered as a part of the porphyry–epithermal ore system of the Mesoarchean age (~2.82 Ga [20]). Gold occurrence of Nyalm and occurrences in the Olenegorsk BIF deposits were formed at the Neoarchean stage of regional metamorphism, at the time of the consolidation of the Murmansk and Inari–Kola blocks into the Kenorland supercontinent (2.7–2.6 Ga).

Gold deposits and occurrences of the Paleoproterozoic age are dated in more detail, and they formed during the period from ~1.92 Ga (Suurikusikko and South Bragino) to 1.74 Ga (Sergozero, Kichany). As it is shown on the example of the deposits in the Central Lapland belt (Suurikuusikko and Iso-Kuotko), gold-mineralized rocks formed with a series of impulses of hydrothermal activity [40]. These impulses correlate with magmatic events—the formation of different generations of minor granite intrusions and dykes. However, the participation of magmatic fluids in the formation of gold mineralization is shown only for the Rompas and Palokas occurrences in the Perapohja belt [67,68,70]. Other deposits and occurrences of the Paleoproterozoic age are considered as products of metamorphic–hydrothermal ore systems (deposits in the Central Lapland, Kuusamo, Pechenga, Strelninsky, and Tiksheozersky belts), or the role of magmatic fluids in their formation is also presumable (Mayskoe, Ozernoe in the Salla–Kuolajarvi belt).

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