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The Oleninskoe Gold Sulfide Deposit (Kola Peninsula, Russia)

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Abstract—The paper deals with the results of geological–structural, mineralogical–geochemical, thermobarogeochemical, and isotopic studies of the Oleninskoe gold deposit in the Archean Kolmozero–Voron'ya greenstone belt. According to isotopic dating, pre-ore pegmatoid veins and wallrock metasomatites are of Early Proterozoic age (1.9 Ga); i.e., they are considerably younger than magmatic and metamorphic rocks of the greenstone belt (2.9–2.7 Ga). A peculiar feature of the Oleninskoe deposit is the multistage nature of ore-forming processes from pre-ore metasomatites and pegmatoid veins to auriferous disseminated sulfides and epithermal mineralization. The isotope analysis of sulfide sulfur yielded a great similarity between the Pellapahk and Oleninskoe deposits, as well as their dissimilarity from other deposits of the Baltic Shield. The isotope composition of galena lead from the Oleninskoe deposit is analogous to that from the deposits of the Late Archean greenstone belts of Finland. According to data obtained though thermobarogeochemical studies of non-opaque minerals, pre-ore metasomatites of the deposit formed from low-concentration (1.1 wt %) fluids at a temperature of 350°C, whereas pegmatoid veins, at the temperature of 250–220°C; the temperature interval of 140–200°C and solutions with concentration 22–25 wt % ($CaCl_2$) were found to correlate with the gold–arsenopyrite mineralization.

INTRODUCTION

Several deposits and ore occurrences of rare metals, gold, copper, molybdenum, and tungsten (Table 1) are known in the northwestern part of the Kolmozero–Voron'ya greenstone belt (Figs. 1, 2). Three deposits, Oleninskoe, Nyal'm 1, Nyal'm 2 (Afanas'ev *et al.*, 1997), and more than 300 occurrences, 60 secondary dissemination halos of gold, which span 23.6 km^2, are located in this part of the belt. Moreover, gold is an important associated component in ores of the Pellapahk porphyry copper–molybdenum deposit (Table 1). The above-listed deposits, occurrences, and geochemical anomalies make up a characteristic auriferous belt extending for 20 km along the Oleninsk Ridge from the Pellapahk Mount to the Nyal'mchechuaiv Mount.

This paper presents new data on the geological structure, mineral and chemical compositions, and conditions of ore deposition of the Oleninskoe deposit. Hence, we addressed the following problems: (1) the study of geodynamic conditions and geotectonic setting of the deposit; (2) geological–structural and mineralogical–geochemical peculiarities of the deposit; (3) the study of relation between disseminated and vein ore mineralization; and (4) the analysis of formation conditions of the deposit using new thermobarogeochemical and isotopic data.

A special emphasis was given to epithermal gold–silver mineralization developed in pipes of the Oleninskoe deposit. The formation of epithermal gold–silver ores in Archean greenstone belts is the subject of a wide discussion in recent years. In the first half of the former century, most researchers believed the epithermal deposits to be characteristic only of the Mesozoic–Cenozoic time (Lindgren, 1934).

Tens of Mesozoic (East Asian volcanogenic belts) and a series of Paleozoic (the Omolon craton and volcano–plutonic belts of Kazakhstan, Uzbekistan, and Australia) epithermal gold–silver deposits were revealed in 1950–1970. Gold deposits of the Precambrian schist belt of North Carolina (United States), some deposits in Archean rocks in Rhodesia (Zimbabwe), as well as a series of ore occurrences of the Baikal volcanic belt were also categorized as the epithermal type. Within the Kola Peninsula, low-temperature quartz veins and related gold and silver mineralization were revealed in rocks of the Archean iron ore formation (Ivanyuk *et al.*, 2001). The Kola superdeep borehole penetrated the gold–silver mineralization within a considerable interval (*Kol'skaya...*, 1984, 1998).

GEOLOGICAL AND TECTONIC SETTING OF THE GREENSTONE BELT

The Kolmozero-Voron'ya greenstone belt is located at the conjunction of the Murmansk and Central Kola blocks of the Baltic Shield (Fig. 1) and extends for more than 150 km from west to east with average width of 10 km. The belt can be related to classic Archean greenstone belts in terms of the tectonic setting, a characteristic succession of volcanic, sedimentary, and intrusive rocks, and compositions of volcanics (Vrevskii, 1989). In contrast to classic greenstone belts of the Republic of

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Table 1. Promising deposits of the Kolmozero–Voron'ya greenstone belt (Afanas'ev *et al.*, 1997)

Raw material	Deposits	Average content of useful components	Reserves, resources (category)
Gold	Nyal'm 1	Au–4.3 g/t	7.5 t (P_1)
	Nyal'm 2	Au–3.7 g/t	3.4 t ($P_1 + P_2$)
	Oleninskoe	Au–3.1 g/t; Ag–28 g/t	28.0 t (P_2)
Copper, molybdenum	Pellapahk	Mo–0.062 (0.111)%;	Mo–184 (79) kt (P_1)
		Cu–0.25 (0.48)%;	Cu–745 (346) kt (P_1)
		Au–0.1 g/t; Ag–2.12 g/t	Au–24 t; Ag–631 t (P_1)
Pegmatites (Li, Be, Ta, Nb)	Polmostundra	Li_2O–1.25%; BeO–0.027%; Ta_2O_5–0.004%; Nb_2O_5–0.007%	($B + C_1 + C_2$)
	Kolmozero	Li_2O–1.13%; BeO–0.037%; Ta_2O_5–0.009%; Nb_2O_5–0.011%	($B + C_1 + C_2$)
	Vasin-Myl'k	Li_2O–0.9%; BeO–0.053%; Ta_2O_5–0.03%; Cs_2O–0.37%	($C_1 + C_2$)

Note: In brackets, rich ore bodies.

South Africa (RSA), Canada, and Australia, where the metamorphism grade mainly corresponds to the greenschist facies (Condie, 1981), in the Kolmozero–Voron'ya belt, rocks are metamorphosed in the granulite and amphibolite facies (main minerals are amphibole, pyroxene, sphene, andalusite, staurolite, garnet, and cyanite).

The tectonic isolation of the Kolmozero–Voron'ya greenstone belt from framing structures was not doubted by any of the researchers, but this fact did not culminate in the elaboration of a commonly accepted model.

In the first stages of studies, a synclinal structure for the Kolmozero–Voron'ya belt was suggested. Later, this structure was assumed to be a zone of a deep-seated fault generated in the Archean (Nikitin, 1980; Belolipetskii *et al.*, 1987). According to Nikitin's (1980) assumptions (confirmed by data of seismic-refraction sounding), a series of granite-gneiss nappes of the Murmansk block is thrust from northeast at an angle of 50°–70° over the subvertical zone of the deep-seated fault.

The Kolmozero–Voron'ya greenstone belt is clearly traced by exposures of metamorphosed gabbro–

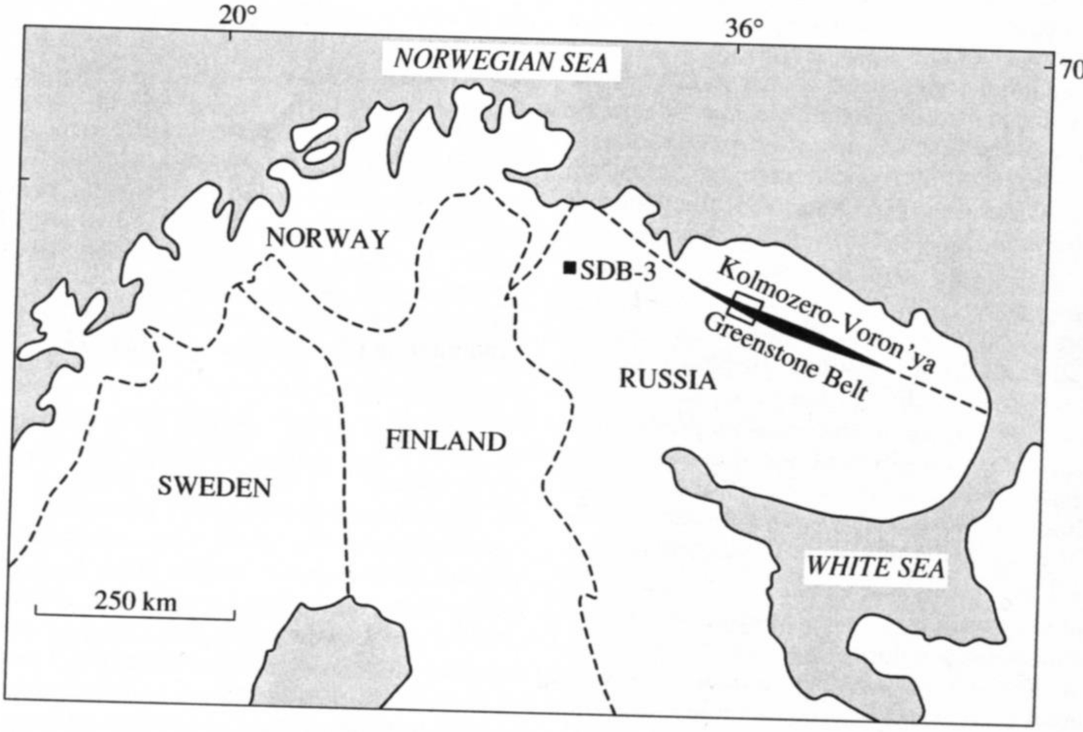


Fig. 1. Geographic setting of the Kolmozero–Voron'ya greenstone belt. SDB-3, the Kola superdeep borehole.

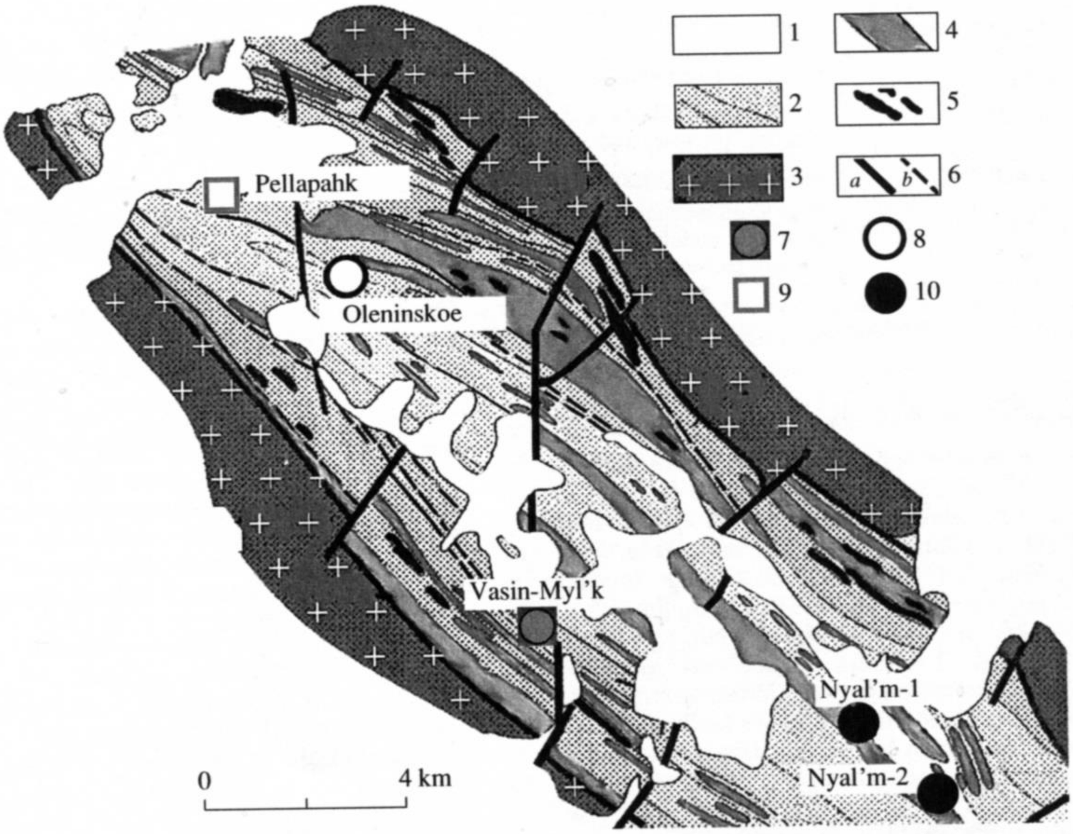


Fig. 2. Geologic map of the northwestern flank of the Archean Kolmozero–Voron'ya greenstone belt (the Kola Peninsula). (1) Quaternary, loose terrigenous deposits; (2) schists, amphibolites, garnet–biotite gneisses (Ar_{1-2}); (3) Early Archean granites, granite gneisses of the greenstone belt framing; (4) metagabbroids and plagioclase amphibolites along them (Ar_{1-2}); (5) metaperidotites and tremolite–actinolite schists along them (Ar_{1-2}); (6) faults: principal (*a*) and minor (*b*); (7–10) types of deposits: (7) rare-metal pegmatites, (8) copper–molybdenum–porphyry, (9) gold sulfide, (10) gold quartz.

anorthosite, gabbro, ultrabasic rocks, and amphibolite bodies. Transverse and diagonal strike faults (Fig. 2) are widely developed in the belt, owing to which it acquires a block–mosaic structure with a distinctive position of neighboring blocks in the present erosion level. Such a structure is likely to indicate a rifting nature of the belt. The belt tectonics is complicated by numerous discordant intrusive bodies.

In the context of the plate tectonics, the Kolmozero–Voron'ya greenstone belt represents a suture zone occurring at the junction of the Murmansk and Central Kola terranes (the gray gneissess and amphibolite–granites terranes respectively) (Mitrofanov *et al.*, 1995). The belt formation is related to processes of evolution and a subsequent closure of a microocean.

The Archean period in the formation of the greenstone belt involved two tectonometamorphic cycles: the early and late Lopyan (Belyaev *et al.*, 1977). During the early Lopyan cycle (3000–2750 Ma ago), metamorphism was of low-pressure, high-temperature amphibolite and granulite facies (640°–725° and 4.3–5.6 kbar). The cycle terminated in the crust consolidation and intrusions (2720–2680 Ma ago). During the late Lopyan cycle (2700–2550 Ma ago), sequences making up the greenstone belt were metamorphosed in the amphibolite low-pressure facies (530–620°C and 3.6–4.5 kbar). The metamorphism culminated 2650 Ma ago. Metamorphism was accompanied by intense duck-file deformations and by the formation of plagiogranite and migmatite (2630 Ma ago). The intrusion of pegmatite concluded the cycle (2550 Ma ago). The Precambrian history of the Kolmozero–Voron'ya greenstone belt ended in the tectonomagmatic activation megastage (Belolipetskii *et al.*, 1987). North-south- and north-east-trending gabbro–diabase dikes formed during that megastage. According to recent geochronological studies, rocks of the Kolmozero–Voron'ya greenstone belt are of the Late Archean age and formed during 100 Ma (2.9–2.8 Ga ago). The formation of the belt terminated in the granodiorite intrusion 2.733 ± 6 Ga ago, metamorphism and subsequent acid intrusions (Kudryashov *et al.*, 1999). Stratified sequences are represented more completely directly in the area of the Oleninskoe deposit in the northwestern part of the belt (Table 2).

Table 2. Rock succession in the Kolmozero–Voron'ya greenstone belt (from periphery to axial zone)

Suite, sequence	Composition	Thickness, m
Lyavozero	Biotite and garnet–biotite gneisses	200
Polmostundra	Apotholeiite–basaltic and apokomatiite metamorphites with interlayers of biotite gneisses and jaspilites	>1000
Voron'yatundra	Metavolcanics, from basic to rhyodacites (the latter dominating in the section)	<1000
Chervurt	High-alumina schists, garnet–biotite and amphibole–garnet–biotite gneisses, often with andalusite, cordierite, disthen, and staurolite, lenses of polymictic metaconglomerates	600

Note: Some researchers refer the axial part of the rock exposure of the Chervurt suite with dominating orthoamphibolites in the section to a separate Oleninskaya suite, within which gold deposits of the western part of the belt occur.

GEOLOGICAL STRUCTURE OF THE DEPOSIT

The deposit is situated on the eastern flank of the Pellapahk ore field. The geological setting of the deposit is determined by a tectonic block bounded by east-west- and northeast-trending faults (Fig. 3). To the latter, there are confined rather thick tourmaline–quartz, pegmatite-like veins. Making up the largest part of the block, amphibolites are overlain by plagioshists and gneisses. The contact between gneisses and amphibolites is tectonic. Amphibolites extend for 4 km in the eastward direction. The ore zone of the Oleninskoe deposit, which has an observable thickness up to 50 m, occurs sub-conformably with host rocks. The zone is traced by underground workings for 800 m along the strike and 80 m along the dip. The ore zone is not outlined; according to geophysical data, it is assumed to extend for more than 1.5 km. Prospecting and assessing yielded four ore bodies (1, 1[a], 2, 2[a]) about 4 m thick and 50–70 m long. The northwest-trending and steeply dipping (more than 75°) ore bodies occur conformably with host rocks (Fig. 3). The ore bodies are outlined on the basis of sampling data. According to our observations, however, the ore bodies of the Oleninskoe deposit represent typical mineralized shear-brittle zones, which have well-defined tectonic boundaries.

Host rocks of the deposit are represented by orthoamphibolites alternating with metasomatically altered plagioshists. The inner zone is made up of metasomatites of the acid leaching facies which formed on the background of the input of K^+ and, to a lesser extent, silica and boron. Since the silica intup was insignificant, silicification proceeded at the expense of the removal of basic elements (Fe, Mg, Ca). As a consequence, the hostrocks lost up to 30% of their original volume, which resulted in the formation of contraction microfissures which got filled with neogenetic miner-

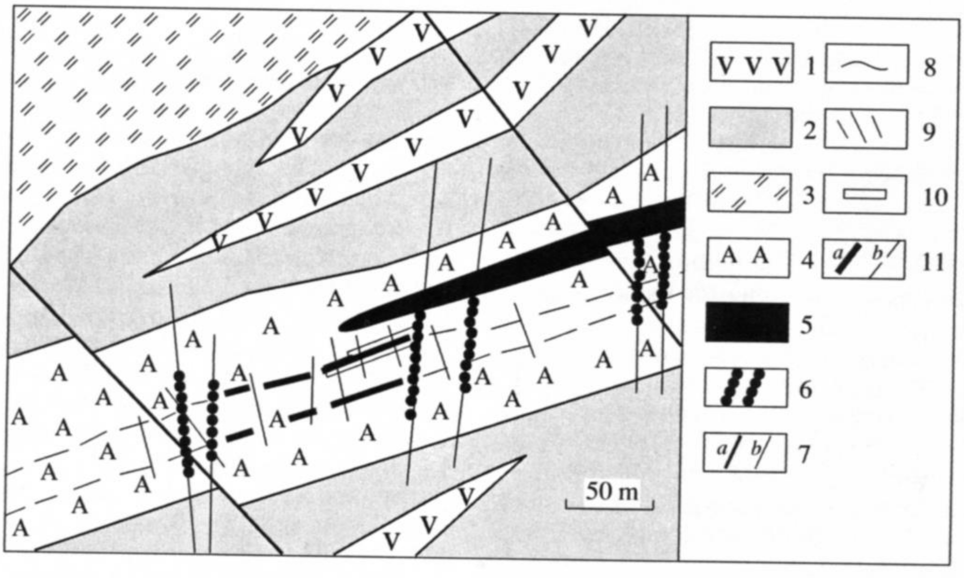


Fig. 3. Sketch geological map of the Oleninskoe deposit. (1–5) Archean greenstone rocks: (1) the Oleninskaya sequence: plagioclase amphibolites; (2) the Chervurt sequence: aluminiferous metadiabases; (3) the Voron'yatundra sequence: schists after porphyrites; (4) amphibolites; (5) metagabbrodiabases; (6) pegmatite veins; (7) faults: proved (*a*), inferred (*b*); (8) geological boundaries; (9) trenches; (10) quarry; (11) ore bodies: traced (*a*), inferred (*b*).

Table 3. K–Ar ages

Deposit	Mineral	K, % ±σ	$^{40}Ar_{rad}$, ng/g ±σ	Age, Ma ±1.6σ
Pellapahk	Muscovite	6.26 ± 0.05	1462 ± 8	1900 ± 30
Pellapahk	"	6.65 ± 0.05	1638 ± 9	1965 ± 30
Oleninskoe	"	7.9 ± 0.05	1900 ± 10	1935 ± 30

Note: The Ar_{rad} content was determined with mass-spectrometer MI-1201IG by the isotope dilution method using ^{38}Ar as a tracer; the K content was established by the flame spectrophotometry method in the Laboratory of Isotope Geochemistry and Geochronology, IGEM RAS.

als. Basic metasomatic rocks formed due to elements removed to outer zones (Fe, Mg, and Ca). The mineral composition of these metasomatites is extremely nonuniform, probably depending on local peculiarities of hostrocks.

A zone of biotization is distinguished (biotite amounts to 70–90 vol %) in the deposit. In addition to this zone, pockets, microveinlets, and porphyroblasts of diopside, andradite, biotite, ilmenite, epidote, and other minerals were developed in a random manner in amphibolites. However, the zone of skarnoids is impossible to distinguish because of its fragmented nature. The metasomatosis evolution proceeds against the background of continuous recrystallization of amphibole. Quartz-sericite and holmquistite–biotite apoamphibolite rocks of the Pellapahk deposit are developed within the ore body as well. Ilmenite, closely associated with sphene, formed in the deposit during the pre-ore megastage. Both minerals are syngenetic to metasomatites (about 1 wt % of Ti in rock, according to data of the chemical analysis). Sphene and biotite aggregates (multiple intergrowth of regularly oriented microcrystals on the cleavage planes of biotite) were also revealed in ores and wallrocks. Stellar aggregates of rutile on sphene are rare.

The studies carried out suggest a relatively young age of pegmatites and pegmatite-like hydrothermal veins with respect to the pre-ore metasomatites of the Oleninskoe deposit. A random orientation of principal rock-forming minerals implies the formation of metasomatites independent of the regional metamorphism. The geochemical specialization (the presence of a considerable amount of K, B, as well as Li and Cs) relates the formation of pre-ore metasomatites to the formation of microcline–tourmaline granitoids. The study of primary fluid inclusions in low-ferruginous diopside of the outer zone of metasomatites made it possible to determine a temperature interval of mineral formation as 349–365°C, which is inconsistent with temperatures typical of the amphibolite–granulite facies of regional metamorphism.

Being developed on vast areas, rare-metal pegmatites play an important role in the geology and metallogeny of the Kolmozero–Voron'ya belt (Table 1). Pegmatites formed during the final stage of the formation of microcline–tourmaline granites and filled in complicated systems of echelon-like detachment fractures regularly dipping from parent intrusives. It is likely that the tectonic activity of the territory, which contributed much to the formation of detachment fractures, was of a pulsating nature. This is indicated by the simultaneous formation of zones of holmquistite–biotite metasomatites and low-temperature tourmaline–microcline–albite–quartz veins several meters thick, which were previously regarded as pegmatites, in the Pellapahk ore field. One such vein was stripped in a small quarry in the Oleninskoe deposit (Fig. 3). The study of primary fluid inclusions in albite from this vein suggested a mineral-formation temperature of 220–250°C.

MINERAL AND CHEMICAL COMPOSITIONS OF ORES

The pyrrhotite–chalcopyrite disseminated and veinlet-disseminated mineralization is widely developed on the deposit area, as on the whole ore field. The mineralization halo is as wide as 300 m. An intense dissemination of fine arsenopyrite, overlapped by gold–silver mineralization accompanying small quartz veins and veinlets, is noted in the central part of the halo, in ore shoots of the Oleninskoe deposit confined to sheared and brecciated rocks. In some areas of ore bodies, sulfide mineralization reaches 25–30 vol %. High Au and Ag contents are established in ore shoots of the deposit, which are determined by the silver–galena–sulfosalt mineral assemblage typical of epithermal volcanogenic deposits. The formation of the assemblage can likely be accounted for by a certain relation between the discussed deposit and the adjacent Pellapahk copper–molybdenum–porphyry deposit. The temporally close formation of these two deposits is confirmed by age dating as well (Table 3). The content of gold in ores of the deposit clearly correlates with that of arsenic, whereas the content of silver, with that of lead, gold, and antimony (Fig. 4).

Several mineral assemblages formed consecutively during the ore megastage in the deposit.

The chalcopyrite–pyrrhotite–ilmenite mineral assemblage, as was mentioned above, forms a persistent, areal, disseminated halo. Pyrrhotite accumulations in the halo spatially associate with albite–quartz

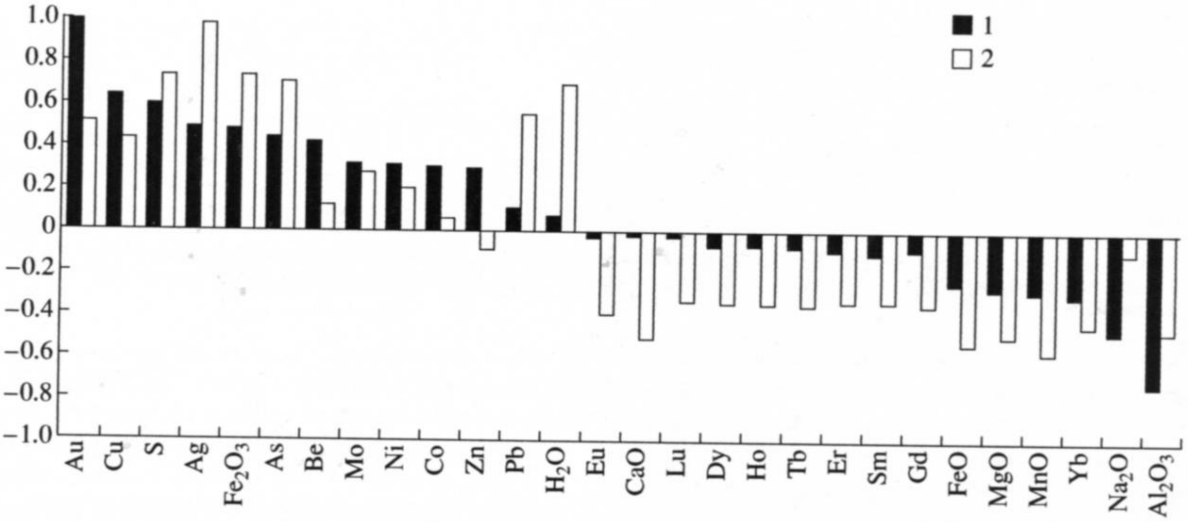


Fig. 4. Values of the correlation factor for gold (1) and silver (2) with other elements in samples of the mineralogical–geochemical profile across the ore body. (1) Used are data of the ASP and silicate analyses carried out in laboratories of the IGEM RAS.

microveinlets. The dominant mineral is pyrrhotite, although its true content in ore bodies is difficult to establish due to the intense irregularly manifested disulfidization. As a result of these alterations, about 60% of all pyrrhotite in the deposit is replaced by iron disulfides, complete pseudomorphs being rather common. Pyrite and marcasite aggregates formed on pyrrhotite along with unaltered pyrrhotite make up about 40–45% of all ore minerals of the deposit. Ilmenite is a typical mineral of pre-ore metasomatites and ores of the Oleninskoe deposit, in which it is found in at least three generations. Independent chalcopyrite segregations in ores are extremely rare, while its intergrowths with pyrrhotite are very common. Chalcopyrite is of platy, wedge-shaped, or lance-shaped morphology. Segregations are up to 1 mm in size.

The gold–arsenopyrite mineral assemblage. Several morphological varieties of arsenopyrite are found in ores: (1) acicular disseminated (magnetic) arsenopyrite (0.01–0.03 mm) in central parts of ore bodies; (2) fine-grained arsenopyrite (0.1 mm) constituting large intergrowths and aggregates and often enveloping the relics of chalcopyrite and pyrrhotite; and (3) coarse-grained arsenopyrite (0.2–0.8 mm) making up short veinlets in host rocks. Löllingite relics are often found in large arsenopyrite crystals. Microprobe analysis yielded a high Au content in disseminated sulfides, which averages (on the basis of 15 measurements) ±340 g/t for arsenopyrite and 170 g/t for pyrite grains. Rare segregations of native gold confined to central parts of grains are found in arsenopyrite (Fig. 5). Such native gold segregations in arsenopyrite are typical of primary ores of the Olimpiada gold sulfide deposit (the Enisei Ridge) and indicate the regenerated nature of gold.

The quartz–scheelite–arsenopyrite mineral assemblage. This assemblage occurs as systems of subparallel veinlets, the size of which varies from centimeters to millimeters (Fig. 6). It should be noted that the strike and dip of these veinlets and the pegmatoid veins coincide. The assemblage is composed of arsenopyrite II, scheelite, gold, küstelite, as well as quartz. Evidence for nearly simultaneous formation is established for minerals, with an exception of küstelite because of its superimposed nature. Most küstelite segregations range in size from 20 to 65 μm, the maximal being 105 μm. Independent segregations in quartz are rare, and as a rule they are oval or isometric, idiomorphic. küstelite inclusions are usually encountered in defect zones of arsenopyrite crystals. küstelite inherits negative crystallographic forms of a host mineral there. The mineral composition matches 24.3–34.4 wt % of gold (the average is 29.6 wt % of Au).

The silver–galena–sulfosalt mineral assemblage is typical of many gold–sulfide deposits (the Nezhdaninsk, Maisk, Natalkinsk, Vysokovol'tnoe, Kokpatas, and others). The Au–Ar mineralization occurs as thin veinlets. The latter usually cut veinlets of the scheelite–arsenopyrite assemblage (Fig. 6). Galena, which forms numerous small segregations in ores, is the most abundant mineral of the association. Segregations are as large as 0.3–0.4 mm. Galena overgrows pyrite and younger ore minerals without any visible corrosion. Argentite forms replacement rims along galena; furthermore, it originates as one of the products on exsolution of composite sulfosalts. Segregations are extremely small. Electrum and küstelite are rarely developed integrally or replace argentite; more frequently, they make up independent aggregates in quartz, tens of microns in size. Microanalysis revealed no chemical heterogeneity of peripheral parts of grains relative to their central parts. The Au content in electrum makes up 25.3–55.4 wt %. Sulfosalts are represented in this assemblage by the pearceite–polybasite

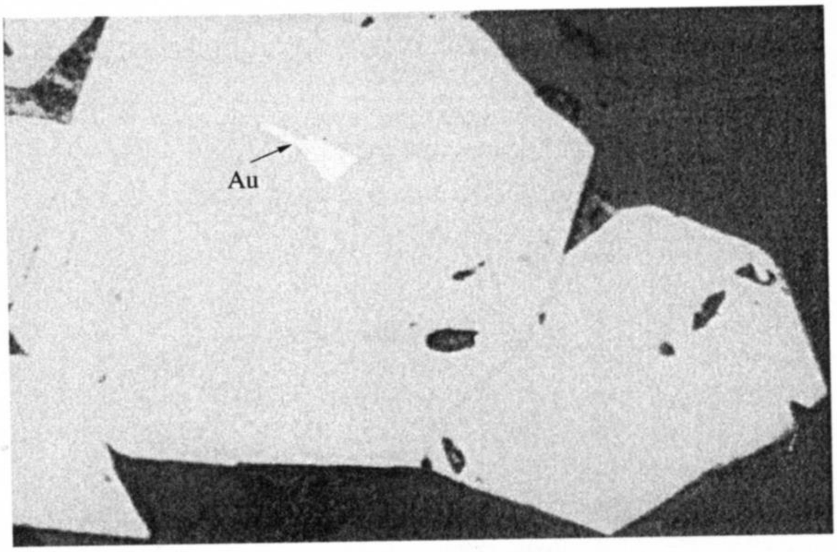


Fig. 5. Gold in arsenopyrite. Ore body 1. Magnification ×80.

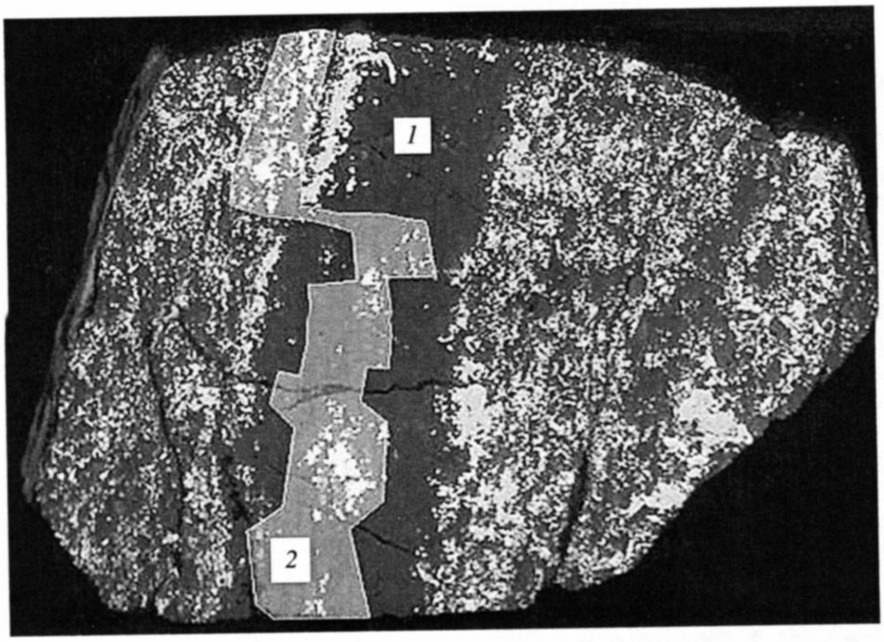
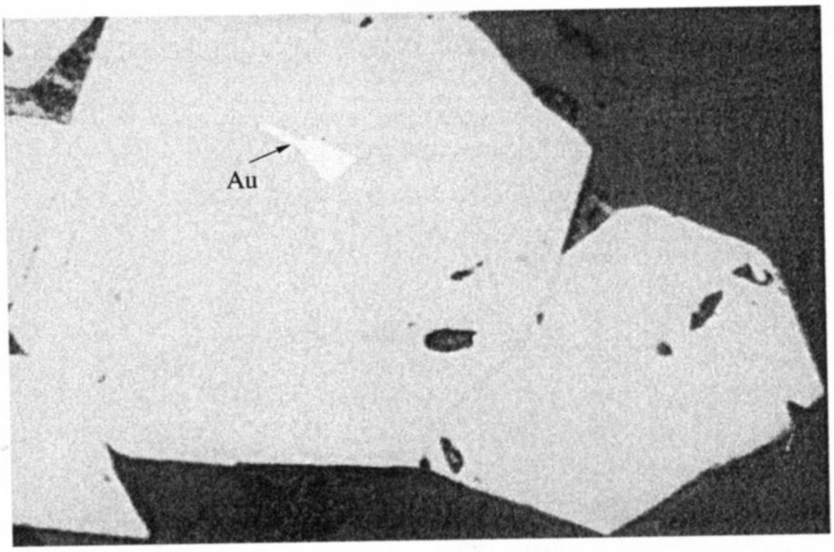


Fig. 6. Sulfide ores of the Oleninskoe deposit. Ore lump, a full size image. A clearly defined crossing of disseminated ores by a quartz–arsenopyrite–scheelite veinlet (*1*), the latter is intersected by a quartz veinlet with silver–galena–sulfosalt mineral assemblage (*2*).

series $(Ag,Cu)_{16}As_2S_{11}$–$(Ag,Cu)_{16}Sb_2S_{11}$. In addition to tend members of the series, numerous intermediate varieties are encountered. Peripheral parts of some sulfosalt grains are replaced by a composite micromineral mixture (Ag,As,Sb,Pb,Au). Copper is not found. Aggregates measure up to 0.1 mm, whereas homogenic phases within them amount to some microns. The average composition approaches $(Ag,Au)_{15.5}(As,Sb)_{2.1}S_{11}$, where Au/Ag approximates 1/20.

CONDITIONS OF ORE FORMATION BY ISOTOPE DATA

Sulfur isotopes. Dominant sulfide minerals were analyzed from ore bodies and wall rock haloes of the Oleninskoe and Pellapahk deposits: arsenopyrite, pyrrhotite, pyrite. Pyrrhotite appeared to be the earliest mineral of ores in the deposit. We obtained close $\delta^{34}S$ values for it (the average for five samples was +1.1‰), which differentiate it greatly from other sulfides of



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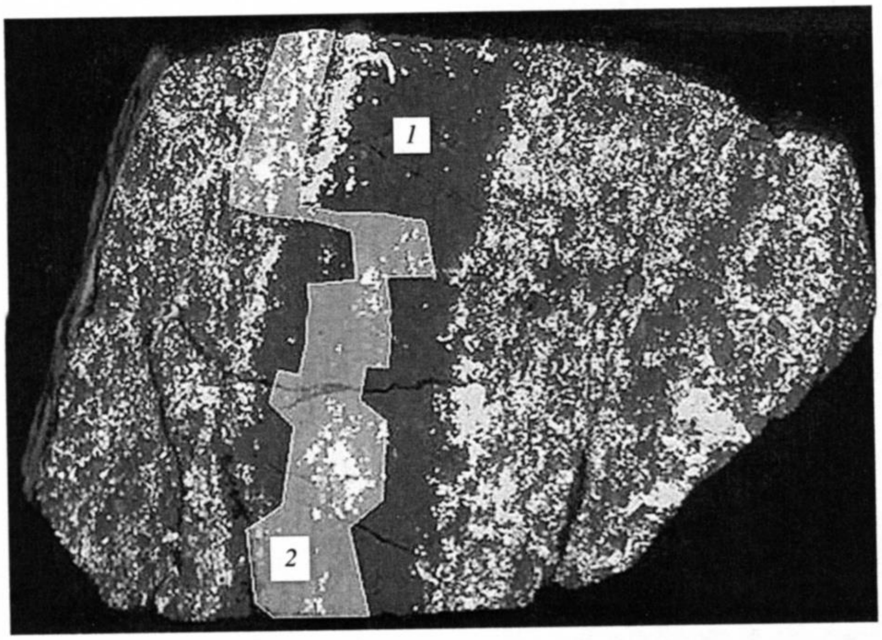

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Table 4. Isotope analysis of sulfide sulfur

Sample no.	Deposit	Mineral, sampling site	δ^{34} S, ‰
1	Oleninskoe	Arsenopyrite, quartz veinlets, ore body 1	−2.37
2	"	Disseminated arsenopyrite, ore body 1	−6.17
3	"	Pyrrhotite, northern flank of deposit	+1.26
4	Pellapahk	"	+1.66
5	"	"	+1.48
6	"	"	+0.49
7	"	Pyrite, northern flank of deposit	−6.89
9	"	"	−8.9
10	"	"	−5.23
11	"	"	−5.29
12	"	"	−8.61
13	"	"	−9.04
14	"	Pyrite, central ore zone	−5.29
15	"	"	−1.19
16	"	"	−5.18
17	"	"	−2.46
18	"	Pyrrhotite, central ore zone	+0.57

Note: Analyses were made in the Laboratory of Isotope Geochemistry and Geochronology, IGEM RAS; L.P. Nosik, the analyst.

deposits. The δ^{34}S value obtained for later sulfides, arsenopyrite, and pyrite ranges from −1.19 to −9.04‰ (Table 4). These values may correspond to different sulfur sources. The values for arsenopyrite and pyrite of ore bodies of the Oleninskoe and Pellapahk deposits fall within a narrower interval, ranging from −1.19 to −6.17‰ (the average value for five samples is −3.78‰), whereas those of wall rock zones vary from −5.23 to −9.04‰ (the average value for four samples is −7.32‰).

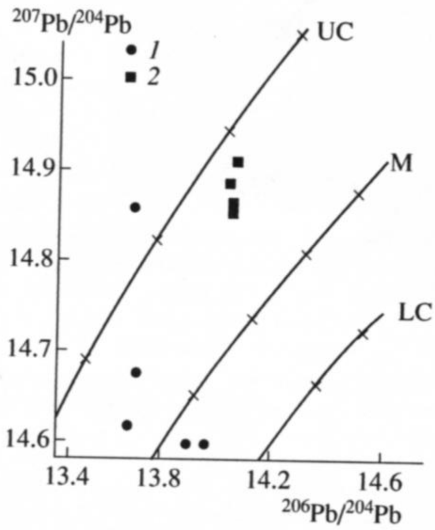

Fig. 7. Relationship between Pb isotopes and sulfides of the Oleninskoe (*1*) and Maiskoe (*2*) deposits, Karelia (Zartman and Doe, 1981). (UC) Upper crust; (M) mantle; (LC) lower crust.

The average δ^{34}S value for sulfides from gold deposits of greenstone belts makes up +3.79‰ (Manttari, 1995). The δ^{34}S values for sulfides from magmatic copper–nickel deposits of the Baltic Shield vary from +2.4 to +3.4‰ (*Nickel–Copper…*, 1985), which may be indicative of similar regional sulfur sources in ore-forming processes. In general, isotope values of sulfide sulfur from gold deposits of Finland greenstone belts are similar to values for sulfides from gold–quartz veins of the Barberton greenstone belt, South Africa (+1…+4‰), the Proterozoic Flin-Flon greenstone belt, Saskatchewan, Canada (+2.8…+5.5‰), and Archean gold deposits of Australia (+1…+4‰) (Manttari, 1995).

Hence, judging from sulfur isotope values, the Pellapahk and Oleninskoe deposits differ greatly from other gold deposits of the Baltic shield and the Archean greenstone belts as a whole.

Stable Pb isotopes. The Pb isotope investigation for sulfides (galena, arsenopyrite, pyrite, sphalerite, and pyrrhotite) of the Oleninskoe deposit was carried out by Pushkarev (1990). Two distribution intervals were revealed. The first interval is characterized by a primitive Pb isotope composition with average values for five samples: ^{206}Pb/^{204}Pb = 13.77; ^{207}Pb/^{204}Pb = 14.67; ^{208}Pb/^{204}Pb = 33.44. The values correspond to the model age 2600 Ma, according to Steacy–Kramers. The position of figurative points on the Doe–Zartman diagram (Fig. 7) indicates the possible mantle–upper crust source of lead, which is not contradictory to inferences made previously by Pushkarev (1990). Judging from the obtained age of 2.6 Ga, it is not unlikely that Pb and,

Table 5. Thermocryometric data on primary inclusions

In diopside					In albite						In quartz in intergrowths with pyrrhotite			
inclusion no.	T_{hom}, °C	T_{fr}, °C	T_{eut}, °C	$T_{ice\ melt}$, °C	inclusion no.	T_{hom}, °C	T_{fr}, °C	T_{eut}, °C	$T_{ice\ melt}$, °C	inclusion no.	T_{hom}, °C	T_{fr}, °C	T_{meltCO_2}, °C
1 (0026)	349	–38.0		0.0	3	220.4				9 (0026)	–29.3	–106.5	–63.x
2 (0026)	348	–35.x		–0.6	4a	209.8				10 (0026)	–29.2	–104.2	–64.2
3 (0026)		–33.5	–14.x	–0.7	4b	216.8				11 (0026)	–28.4	–105.1	–63.8
3a (0026)		–33.5	–14.x	–0.7	6	N.d.	–17.3		–0.1	11a (0026)	–28.4	–106.7	–62.1(?)
4 (0026)	349	–37.4		–0.6	7	"	–18.1		–0.1	12 (0026)	–29.1	–104.4	–63.8
4a (0026)	349	–37.4		–0.6	8	248.6	–22.6		–0.9	13 (0030)	–28.x	–104.x	–64.2
4b (0026)	349	–37.4		–0.6	8a	230.9	–25.0	–1.2	–0.6	14 (0030)	–30.0	–102.x	–62.3
4c (0026)	349	–37.5		–0.6	8b	230.9	–20.2	–1.3	–0.6	15 (0030)	–29.4		–61.x
5 (0028)		–32.1	–13.8	0.0	8c	230.9	–22.3	–1.3	–0.6	16 (op-8)	–28.5	–105.x	–64.5
6 (0030)	351	–37.x	–13.x	–0.4	8d	238.0	–22.9		–0.9	16a (op-8)	–28.x	–105.x	–64.x
7 (0030)	348	–38.0	–13.x	–0.6	8e	231.9	–23.6		–0.8	17 (op-8)	–29.0		–63.5
8 (0030)	341	–37.3	–13.x	–0.4	9a	N.d.	–17.6	–1.2	–0.6				
					9b	"	–18.0	–1.2	–0.7				

probably, Au and Ag closely associated with it were mobilized by fluids from metamorphic sequences of the Kolmozero–Voron'ya greenstone belt, which are of nearly similar age. The second interval is anomalous: $^{206}Pb/^{204}Pb = 21.645$; $^{207}Pb/^{204}Pb = 16.243$; $^{208}Pb/^{204}Pb = 38.733$. Interpreting these data on the basis of the Stesie–Kramer model, Pushkarev suggested that old lead in the studied minerals could be contaminated by radiogenic lead about 400 Ma ago. The comparative analysis with data obtained by Finnish researchers shows that the isotope composition of lead from the Oleninskoe deposit (the first interval) is similar to that from deposits (the low-radiogenic lead group) of the Late Archean greenstone belts of Finland (Vaasjoki, 1989). We also may infer that sources of lead of the Oleninskoe deposit were the Archean heterogenic mantle or the contamination of greenstone rocks of the Kolmozero–Voron'ya belt by Early Archean crustal rocks.

RESULTS OF INVESTIGATION OF FLUID INCLUSIONS

Fluid inclusions were studied by methods of microthermometry and gas chromatography in non-opaque minerals. Microthermometry was carried out within the temperature interval from –196 to +600°C in the heating-freezing stage Linkam-THMS600 (England) with a 80× long-focus Olympus lens (Japan) installed in a MBI-15 microscope equipped with a video camera. The measurements were accurate to ±0.2° within the temperature interval from 0 to –196°C and to ±1.5° within the temperature interval of 0–600°C. The composition of inclusions and the concentration of solutions were determined by the freezing method on phase transition points when heating the inclusions after freezing them. The compositions of the solutions were established on the basis of the melting point of the eutectic, whereas their concentration, on the basis of the melting point of ice. The results were interpreted in accordance with the work by Goldstein and Reynolds (1994). Temperatures of homogenization are cited in the text without the correction for pressure and correspond to minimal temperatures of mineral formation. Gas chromatography was carried out with a LHM-8MD chromatograph using helium as carrier gas and polysorb as sorbent. The inclusions were studied in polished plates 0.2 mm thick.

Sophisticated treatment of quartz from different zones of pre-ore metasomatites revealed the absence of inclusions of the mineral-forming fluid in it, a result that is likely to be related to repeated recrystallization. In local areas, the impregnation of the quartz matrix with very fine plates of muscovite and acicules of tourmaline and amphibole is encountered. Among relatively transparent metasomatic minerals suitable for thermobarogeochemical studies, large, light-colored, high-idiomorphic clinopyroxene (diopside) crystals confined to outer zones of metasomatites and varying in size up to some centimeters were found. Despite clear indications of metacrystallization, pyroxenes comprise numerous, undoubtedly primary, fluid inclusions (Figs. 8a, 8b). The study was carried out with the selection of 12 inclusions (five isolated pyroxene aggregates). Measured for all inclusions, the temperature of homogenization varies within 345–350°C. In spite of different morphology, the phase relationship in fluid inclusions is identical (the gas phase: 30–35 vol %). Cryometric data (Table 5) exhibit a low concentration

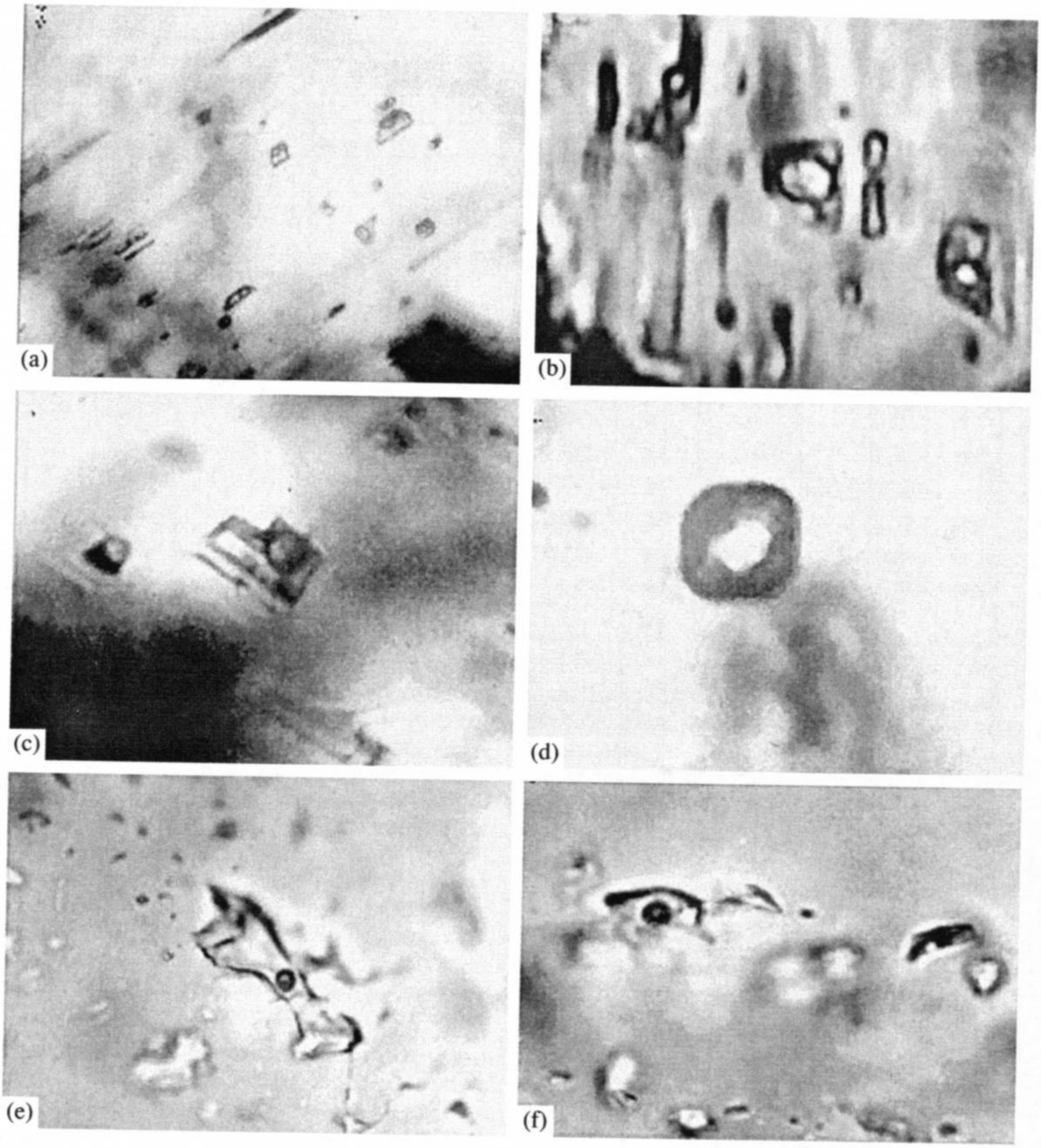

Fig. 8. Types of inclusions in minerals of the Oleninskoe deposit: (a, b) groups of fluid inclusions in diopside (pre-ore metasomatites); (c) primary inclusion in albite (pegmatoid vein); (d) inclusion comprising carbon dioxide and nitrogen in quartz, syngenetic to pyrrhotite; (e, f) groups of secondary inclusions, syngenetic to arsenopyrite.

of source solutions (up to 1.1 wt %, NaCl-equiv.). The eutectic range of thawing with a lower boundary of the temperature at 14°C suggests the possibility for salts of weak mineral acids (HCO_3^-, SiO_3^{2-}) with Na^+ cation to be present in the solution.

Pegmatite-like veins. Fluid inclusions were studied in albite of the tourmaline–albite–quartz vein (Fig. 8c, Table 5). The results obtained testify that minerals of hydrothermal veins formed from low-concentration chloride, sodium-potassium solutions.

Pyrrhotite–chalcopyrite–ilmenite mineral assemblage. Fluid inclusions were studied in quartz in intergrowths with pyrrhotite. Quartz makes up veinlets and lenses varying in thickness from microns to 3 cm. Quartz grains reach 10–15 mm. Organic matter of a very complicated morphology was encountered in quartz as rare accumulations. In some cases, a spatial relationship between these accumulations and fluid inclusions was revealed. Inclusions of the source fluid in quartz grains are irregularly disseminated. The inclusions are extremely small (a few microns), but in spite of this, their primary nature was clearly established. Vacuoles of the inclusions are bounded by negative forms of two main rhombohedrons of quartz (Fig. 8d). At standard conditions, the inclusions are single-phase. When cooled, the behavior of the inclusions is indicative of the fluid affiliation to the system CO_2–N_2–CH_4 (Table 5). This is confirmed by data of gas chromatography, which revealed the presence of all the three components. In samples with the highest methane content, the ratio of the components is as follows (mol %): $CO_2 : N_2 : CH_4 = 90.9 : 8.2 : 0.9$. Taking into account the insignificant share of methane in the fluid, the contents were calculated on the basis of a two-component system (without regard for the methane constituent) that yielded 40–60 mol % N_2.

The gold–arsenopyrite mineral assemblage. Difficulties in reconstructing the fluid regime of the formation of this assemblage are related to minor deposition of quartz which is in paragenesis with arsenopyrite metacrystals. Inclusions are revealed in quartz healing up the system of cryptoveinlets. The inclusions are necked down to a high extent, nonpersistent by the relation of phases. Averaged values at standard conditions are as follows: 93–95 vol % for liquid phase; 2–4 vol % for gaseous phase; the rest for solid phase. The solid phase exhibits a moderate anisotropy when studying crossed nicols. At first, the morphology of microcrystals is pseudo-isometric; after that, with complete dissolution and cooling to 20°C, as well at subsequent crystallization, the habitus changes into elongated prismatic. The diagnostics of the solid phase were hampered by the small dimensions (up to 5–6 μm). Though, the behavior of the solid phase during cooling indicates the possibility of the existence of chlorides of bivalent metals (Ca^{2+}, Mg^2, and others) in it. The temperature of complete homogenization was measured for inclusions (heterogenic) with nearly persistent phase relation in the group (Figs. 8e, 8f, 9). An attempt to obtain data on the fluid chemical composition by the cryometric method failed due to the unusual behavior of the inclusions. The fact of the freezing of the liquid phase was established only in one case among 24 vacuoles directly observed. The inclusions behaved as follows: (1) during the entire cooling process, the volume share of the gaseous phase markedly increased; (2) in cooling, an abrupt increase in the liquid-phase viscosity was observed at the temperature interval of –20 to –45°C, which was detected by the gas bubble behavior; (3) at lower temperatures (below –50°C), the liquid phase turned to glass, which inhibited its crystallization; (4) in cooling down to –196°C, fragile glass of some inclusions collapsed inward generating some isolated gas bubbles during subsequent heating.

The fact of the preventive vitrification of the liquid phase in inclusions suggests a remarkable viscosity of the fluid caused by a high concentration of mineral salts in it. A single inclusion with a valuable cycle of phase transitions at supercooling allowed us to measure the following temperatures (the experiment was repeated

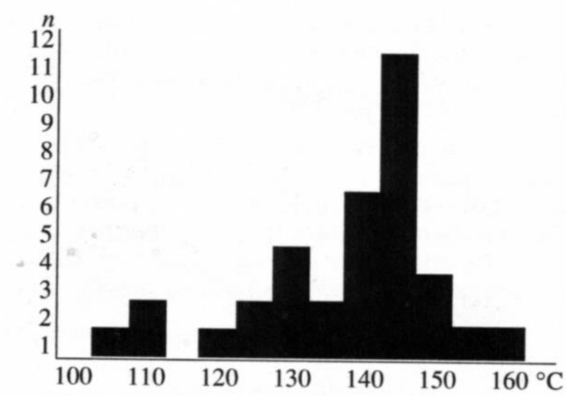

Fig. 9. Histogram of homogenization temperatures. (*n*, amount of measurements).

five times; the reproducibility of the results was 0.3°C; presented below are average values): $T_{fr} = -90.1$°C; $T_{eut} = -79.8$°C; $T_{melt} = -28.9$°C. The melting point of the eutectic, equal to –79.8°C, is indicative of the presence in the solution of chlorides Ca^{2+}, Na^+, and probably Li^+, with $CaCl_2$ dominating.

The silver–galena–sulfosalt mineral assemblage. Two necked-down inclusions were revealed, for which temperature characteristics were measured in the range of negative temperatures. Inclusions were liquid-vapor, of irregular shape, slightly elongated. The host mineral was quartz, syngenetic to ore minerals of the assemblage, which along with them incrusts a quartz veinlet belonging to the gold–scheelite–arsenopyrite assemblage.

For the first inclusion:

$$T_{fr} = -50.4°C; \quad T_{eut} = -44.3°C; \quad T_{melt} = -9.5°C;$$

for the second inclusion:

$$T_{fr} = -53.3°C; \quad T_{eut} = -44.3°C; \quad T_{melt} = -9.6°C.$$

Cryometric data are indicative of the concentration of source solutions within the range of 13.40–13.51 wt % NaCl-equiv. The eutectic range of thawing with a lower temperature limit at –44.3°C suggests that NaCl with a possible admixture of ions of bivalent metals (Ca^{2+}, Mg^{2+}) is likely to be a component of the fluid.

CONCLUSIONS

The last decade was noted for a remarkable success in gold prospecting in Scandinavia (Eilu and Nurmi, 1999). From 1984–1999, the commercial development of some gold deposits (Bjorkdal, Enasen, Eidsvoell and others) was commenced. Moreover, gold ores were revealed in polymetallic deposits, as well as *Bidjovagge* (Norway), *Aitik* (Sweden), *Yuomasuo* (Finland) deposits (Pankka and Vanhanen, 1992; Kjell and Bjorlykke, 1991; *Gold'99...*, 1999). The main concern of Scandinavian geologists is prospecting giant gold-ore deposits similar to deposits of the Abitibi greenstone belt in Canada or the Yilgarn craton in Australia (Nurmi, 1991). The large Suurikuusikko deposit with disseminated gold sulfide ores has recently been discovered in Finland (Eilu and Nurmi, 1999).

Taking into account that Scandinavian countries are similar in geology to the Russian part of the Baltic Shield, gold-ore and gold-bearing deposits of the Archean Kolmozero–Voron'ya greenstone belt acquire a great importance for the economic and industrial development of the Kola region and deserve further investigation and exploration.

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