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*DOI: 10.31897/PMI.2020.3.266*

# The age of mineralization of Mayskoe gold ore deposit (Central Chukotka): results of Re-Os isotopic dating

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The article presents the results of the sulfide mineralization dating of the Mayskoe gold ore deposit using the Re-Os isotope system and isochron age estimation method of the main sulfide minerals: arsenopyrite, pyrite, and antimonite. The complex multistage formation of the studied sulfides, as well as the close intergrowths of genetically different mineral phases, did not allow obtaining a single rhenium-osmium isochron corresponding to the formation time of sulfide mineralization. Isochrones for single minerals, collected from each sulfide sample, turned out to be the result of isotopically distinct components mixture (radiogenic crustal and non-radiogenic mantle) and do not make sense from the geochronological point of view. In terms of geology, the most significant result of the study is an age estimation of $128.8 \pm 4.4$ Ma, obtained for the sulfide mineralization of Mayskoe deposit using Re-Os isotope dating of single fractions of pyrite and antimonite of the ore mineralization stage. While arsenopyrite is most closely associated with gold mineralization, one of the arsenopyrite varieties corrodes framboidal pyrite of the pre-ore stage, has a maximum of the crust component in the osmium isotopic composition and forms a mixing line in the isochron diagram with an apparent formation age of $458 \pm 18$ Ma. The initial osmium isotopic composition of the studied sulfides indicates a mixed mantle-crust source of sulfide mineralization. The issue of simultaneous ore genesis and granitoid magmatism in the Mayskoe deposit remained unresolved (the age of granitoids according to the U-Pb zircon system is 108 Ma). However, a possible solution could be the further determination of the Re-Os isochron age of the ore mineralization sulphides from the single paragenesis of a specific sample containing both arsenopyrite and pyrite (+ antimonite) with gold.

*Key words*: Central Chukotka; Re-Os isotopic dating; Cretaceous magmatism; age of mineralization; ore body

**Introduction.** Modern isotope geochemistry has a diverse set of analytical techniques that allows performing geochronological studies on geological objects of different mineral composition and obtaining estimates of the event's age with the necessary accuracy. But most of these techniques use isotope systems of lithophile elements as a radiological clock, in which both radioactive and radiogenic isotopes are accumulated in the silicate matrix of rocks and minerals (Rb, Sr, K, Ca, Sm, Nd, Lu, Hf, U, Th, and Pb). The main advantage of the Re-Os isotope system is that it behaves in geological processes according to the chalcophile and siderophile features of these elements [18], which allows its successful use in dating sulfides from deposits of various genetic types [8, 19] even at relatively low rhenium and osmium concentrations at the level of $1 \times 10^{-1}$ ppb [6]. At the same time, the obtained ore minerals ages sometimes significantly differ from the age of magmatic and hydrothermal events received using U-Pb and Rb-Sr isotopic systems of silicate rocks and minerals [6, 23]. The reason for such discrepancies often lies in complex alterations of sulfide minerals both during ore genesis and supergene processes.

Knowing the age and using the initial isotopic composition of Os-bearing sulfides (isotope ratio $(^{187}Os/^{188}Os)_0$), we can estimate the contribution of various sources of the substance to the ore-forming fluid/melt. Rhenium and osmium behave quite differently in the formation of silicate melts from the mantle substrate [6, 16]. Rhenium is moderately compatible with silicate melt and accumulates over time in the earth's crust, while osmium is incompatible and enriches mantle restites. Thus, comparing the initial isotopic composition of osmium of various ore minerals, it is possible to assess which of the sources – mantle or crust – prevailed during their formation.

The main goal of this work is to determine the age of ore mineralization of the Mayskoe deposit and to compare the ore formation and magmatic processes.

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**Geological structure of the Mayskoe deposit.** The geological structure of the Mayskoe field is described in detail by N.S.Bortnikov [9], A.V.Volkov [3, 5], M.M.Konstantinov [7] et. al. This article provides only a brief description and elements of the geological structure that can be used in interpreting the obtained isotopic dating of ore mineralization.

The Mayskoe deposit is located within the Central Chukotka folded region. It has an isometric shape, covering 10 km$^2$ and is confined to a complex horst structure located at the intersection of the northwestern, northeastern, sublateral and submeridional faults. The host rocks are represented by sandy-silt-schist flyschoid deposits of the Keveyem, Vatapvaam, undivided Relkuveyem and Mlelin , Kuveemkay suites of the presumably middle and upper Triassic age (Fig.1). The fauna is determined only in the Relkuveyem and Mlelin, Kuveemkay suite rocks and it helps to assign them to the Karnic stage. The underlying strata are barren and conditionally assigned to the Middle Triassic. Authors and previous researchers [3] noted numerous syngenetic nodules of framboidal pyrite in the silt-shale rock varieties.
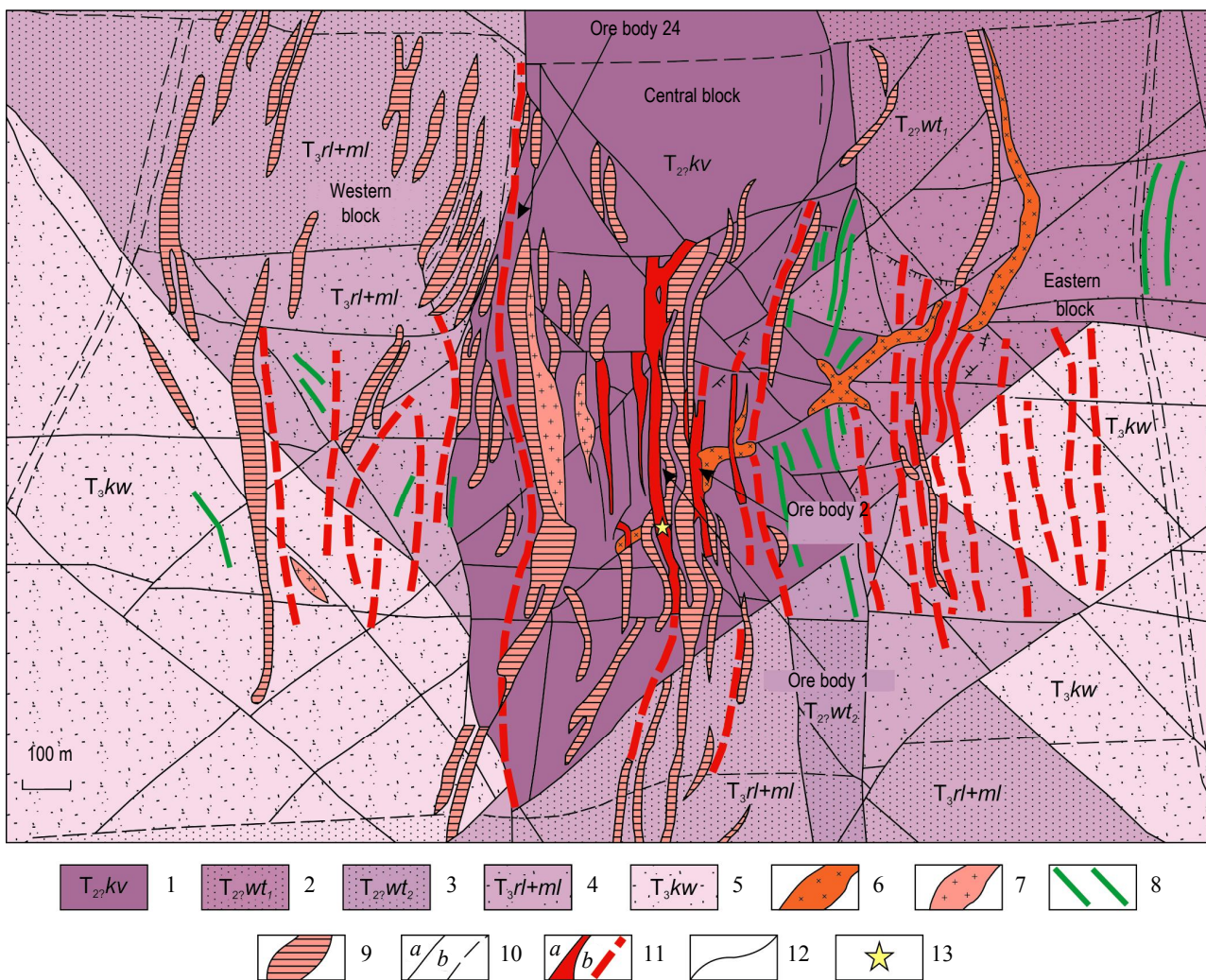


Fig.1. Scheme of the geological structure of the Mayskoe deposit according to A.V.Volkov et. al. [3] with additions

Middle (?) Triassic: 1 – siltstones of the Keveyem suite; 2 – uneven-grained sandstones of the Vatapvaam suite, lower subsuite;
3 – uneven-grained sandstones of the Vatapvaam suite, upper subsuite.
Upper Triassic: 4 – interstratified sandstones and siltstones of the Relkuveyem and Mlelin suites; 5 – interstratified sandstones and siltstones of the Kuveemkay suite; 6 – granodiorites and granite porphyries; 7 – aplites; 8 – lamprophyres; 9 – rhyolite porphyry;
10 – identified (*a*) and inferred (*b*) faults; 11 – outcropping (*a*) and blind (*b*) ore bodies;
12 – geological boundaries; 13 – sampling location

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Igneous rocks within the deposit are represented by a complex of dikes of the Early Cretaceous age, which occupy 25 % of the total deposit area. The granite porphyry and granodiorite porphyry dikes age of 108 ± 1 Ma was determined based on a local U-Pb zircon dating [1]. The dikes outcrops form a belt of about 3 km in width and more than 4 km in length. Within the belt, dikes are grouped into a series of close bodies of a north-south strike, with which ore-bearing zones are spatially connected.

The Mayskoe deposit is divided by deep faults into three tectonic blocks – Western, Central and Eastern (Fig.1), where dikes and ore bodies are combined into eight submeridional ore zones with a width of 100 to 300 m and a length of 300 to 2500 m. In the Central block of the deposit there are the main, largest industrial ore bodies 1 and 2 with the most constant thickness and dip values. Many ore bodies are located along the dikes, occupying their exocontact zones. Ore body 1 intersects the dike closer to the surface, while the gold content in the mineralized dike is an order of magnitude lower than in sedimentary rocks.

More than 90 % of gold in the Mayskoe deposit is associated with needle-shaped arsenopyrite, far less frequently with As-bearing pyrite and pyrrhotite [5]. Mineralization is concentrated in sulfidized linear crushed and shear zones of submeridional strike. Arsenic and gold show a significant positive correlation of more than 0.85. Along with refractory ores, gold is contained in ore columns, which formed later than pyrite-arsenopyrite disseminated mineralization. Ore columns, which are vertical formations with increased secondary gold content [2], cross finely dispersed ores. Weakened tectonic cracks are often located in the core of the gold vein. They are composed of quartz-antimonite veins and breccias with visible gold and fragments of refractory ores.

Since there are practically no newly formed minerals containing a sufficient amount of potassium in the metasomatites and ores of the Mayskoe deposit, A.V.Volkov et. al. [3] determined the age of ore mineralization by the Pb isotopic composition from galena. The calculated model ages of galena are in a wide range from 50 to 100 Ma.

**Samples and methods.** In the present work, the Re-Os isotopic system of arsenopyrite, pyrite, and antimonite from ore body 1 of the Mayskoe deposit was studied for the first time. Sample 140-1yu was taken at +140 horizon, on the southern flank of the crushing zone of black carbonaceous berezitized siltstones containing disseminated, less often vein-disseminated ore mineralization presented by arsenopyrite and pyrite. An Od-100 sample was taken at +100 horizon of the central part of ore body 1; it represents the contact of mineralized berezitized dike of granodiorite porphyry and berezitized siltstone. The sample contains vein-disseminated mineralization of pyrite, arsenopyrite, and chalcopyrite. Ant sample represents the vein core at the +200 horizon – ore column, taken from the quartz-antimonite brecciation zone with visible gold.

Polished sections were made for study in reflected light on a Leica DM 2500 microscope with a DFC 420 camera and for microprobe studies on a CamScan MV 2300 instrument equipped with a LINK Pentafet EDS microanalyzer (Oxford Instruments). The remaining material of 140-1yu and Ant samples was crushed to a particle size of less than 0.1 mm. In the Od-100 sample, pyrite is coarse and giant-grained, so the material was crushed by hand in a cast-iron mortar. After processing in a heavy liquid, single mineral fractions of arsenopyrite (140-1yu sample), pyrite (Od-100 sample), and antimonite (Ant) were hand-picked under a binocular. Sulfides were removed from the single fraction in the presence of visually noted silicate inclusions, as well as intergrowths with silicates.

Re-Os dating of sulfides was carried out at the Center for Isotope Research of the A.P.Karpinsky All-Russian Scientific Research Geological Institute. Five sulfide single fractions with the weight of 0.19-0.31 g were taken from each sample (see Table). The minerals were dissolved in direct and reverse aqua regia followed by the osmium and rhenium separation using bromine extraction, microdistillation, and liquid extraction with isoamyl alcohol [20]. The concentrations of Re and Os and the $^{187}$Re/$^{188}$Os ratio were determined by isotopic dilution using a calibrated isotope

$^{185}$Re-$^{190}$Os indicator, which was added to the sulfide single fraction before the sample decomposition. The osmium isotopic composition was measured on a TritonTI (ThermoScientific) solid-phase multicollector mass spectrometer in a static mode and negatively charged ions. The rhenium isotopic composition was measured on a single-collector ICP-mass spectrometer Element-2 (Thermo-Scientific) using a 3 % nitric acid sample solution.

**Results of the Re-Os isotope analysis of arsenopyrite, pyrite and antimonite from the Mayskoe deposit**

| Sample | Single fraction number | Single fraction weight, g | Re, ppb | Os, ppb | $^{187}$Re/$^{188}$Os | ±2σ, % | $^{187}$Os/$^{188}$Os | ±2σ, % | ($^{187}$Os/$^{188}$Os)$_0$ |
|---|---|---|---|---|---|---|---|---|---|
| Od-100, pyrite | 55 | 0.19487 | 0.262 | 0.030 | 43.232 | 0.076 | 0.38114 | 0.873 | 0.2874 |
| | 56 | 0.20061 | 0.435 | 0.029 | 76.450 | 0.291 | 0.51728 | 1.212 | 0.3515 |
| | 57 | 0.20536 | 0.172 | 0.052 | 16.435 | 0.215 | 0.39225 | 0.944 | 0.3566 |
| | 58 | 0.20360 | 0.393 | 0.021 | 92.472 | 0.630 | 0.48900 | 0.643 | 0.2885 |
| | 59 | 0.20113 | 0.230 | 0.100 | 11.253 | 0.133 | 0.26293 | 0.829 | 0.2385 |
| 140-1yu, arsenopyrite | 60 | 0.20327 | 1.155 | 0.101 | 59.196 | 0.406 | 0.74300 | 0.749 | 0.6364 |
| | 61 | 0.19455 | 0.841 | 0.106 | 40.159 | 0.850 | 0.59454 | 1.477 | 0.5222 |
| | 62 | 0.22194 | 0.912 | 0.093 | 50.423 | 0.389 | 0.67322 | 0.829 | 0.5824 |
| | 63 | 0.28865 | 0.779 | 0.104 | 38.576 | 0.346 | 0.72090 | 0.578 | 0.6514 |
| | 74 | 0.21450 | 0.930 | 0.136 | 34.596 | 0.473 | 0.55425 | 0.958 | 0.4919 |
| Ant, antimonite | 78 | 0.25905 | 0.600 | 0.040 | 74.294 | 0.165 | 0.33582 | 1.318 | 0.1747 |
| | 80 | 0.25380 | 0.206 | 0.029 | 34.168 | 0.095 | 0.25255 | 0.806 | 0.1785 |
| | 81 | 0.31377 | 0.165 | 0.037 | 21.825 | 0.198 | 0.22468 | 0.956 | 0.1774 |
| | 82 | 0.27760 | 0.181 | 0.022 | 40.793 | 0.074 | 0.27387 | 1.376 | 0.1854 |
| | 83 | 0.21701 | 0.254 | 0.029 | 42.860 | 0.141 | 0.27612 | 0.934 | 0.1832 |

*Note.* ± 2σ,% – relative error of the corresponding isotopic ratio. ($^{187}$Os/$^{188}$Os)$_0$ – initial isotopic composition of osmium, calculated for the time of the expected sulfides formation: 100 million years ago for sample 140-1yu, and 130 million years ago for samples Ant and Od-100 (Analyst R.Sh.Krymsky) [6].

**Results of Re-Os dating.** The rhenium and osmium contents in the studied sulfides are significantly different. If the level of rhenium in pyrite and antimonite varies from 0.17 to 0.6, and osmium from 0.02 to 0.1 ppb, then in arsenopyrite the content of rhenium reaches 1.2, and the osmium content of about 0.10 ppb is almost constant (see table). The rhenium content in the studied sulfides is comparable with that for the pyrites of the Ventersdorp Contact Reef (South Africa) (Fig.2). It is noteworthy that the concentrations of rhenium and osmium in pyrite and antimonite are comparable with their concentrations in gold of Moeda conglomerates, while they differ from the contents of other ore occurrences in gold both upstream (hydrothermal) and downstream (komatiites).

The correlation of the Re/Os ratio change and the osmium isotopic composition for the studied sulfide samples does not allow to calculate a single linear trend in isochron coordinates, the slope of which could correspond to the age of ore mineralization (Fig. 3). Nevertheless, the points matching the isotopic composition of each analyzed sulfides form certain trends on this graph. So, four out of five single fractions of arsenopyrite from 140-1yu sample determine a trend with a slope corresponding to an age of $458 \pm 18$ Ma with MSWD=0.3 (Fig.4, *a*) and an initial ratio of osmium isotopes ($^{187}$Os/$^{188}$Os)$_0$=0.288 ± 0.014. For the pyrite from the Od-100 sample, the linear trend was calculated from three analytical points, and its slope corresponds to an age of $229 \pm 91$ Ma (Fig.4, *b*) with an initial isotopic ratio ($^{187}$Os/$^{188}$Os)$_0$= 0.219 ± 0.049 (MSWD = 7.5 ) Antimonite from the Ant sample, to a first approximation, determines the isochron from all performed analyzes with an age of $126 \pm 24$ Ma (Fig.4, *c*) and an initial isotopic ratio ($^{187}$Os/$^{188}$Os)$_0$, equal to 0.182 ± 0.018 (MSWD = 9.1).

**Discussion.** The age calculated using Re-Os isochrons of ore minerals (except antimonite) differs significantly from the known dating results for ore mineralization and magmatism within the Mayskoe deposit and is not supported by direct geological observations of the structural and tex

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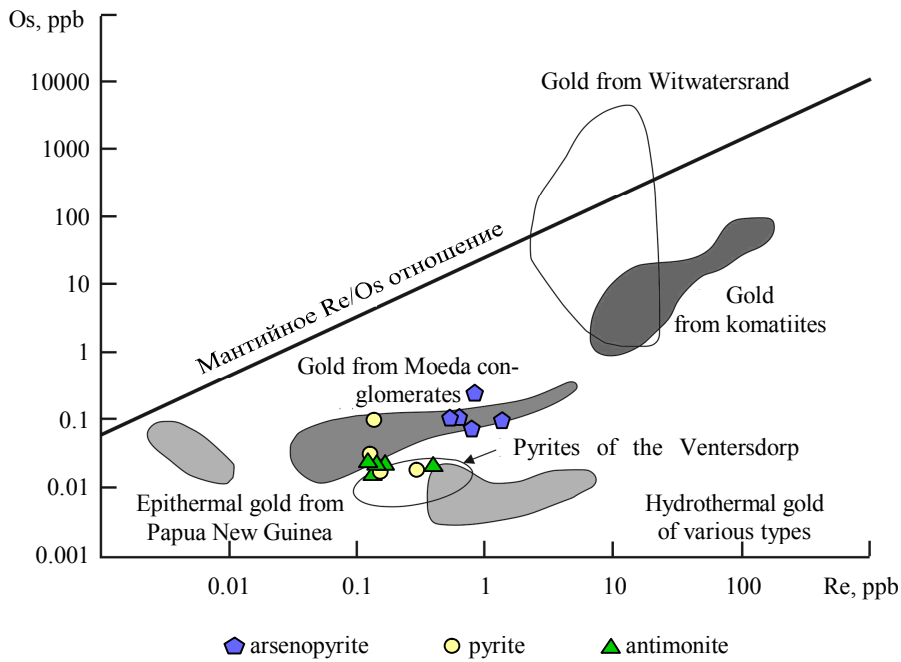*DOI: 10.31897/PMI.2020.3.266*

Fig. 2. Diagram of the rhenium and osmium content distribution in ore minerals
of gold ore deposits according to J.Kirk [19]. Imaging points of single fractions
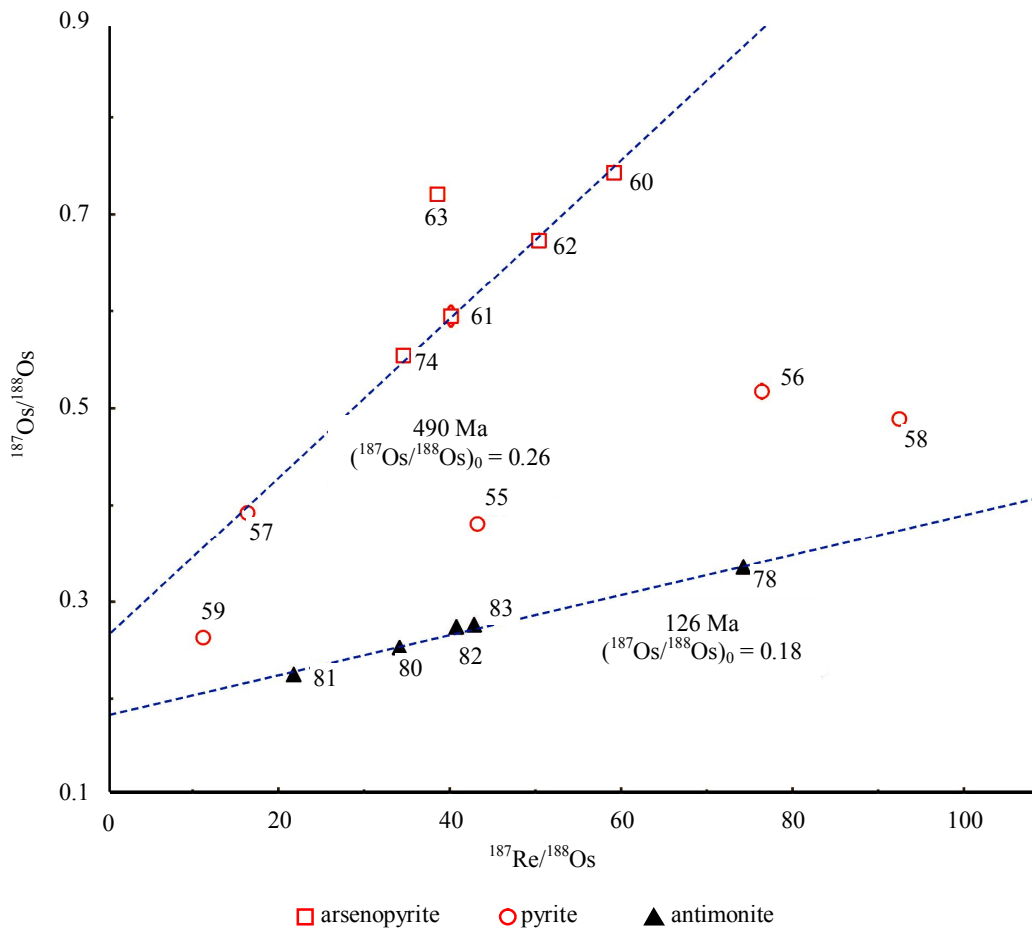of ore minerals from the Mayskoe deposit



Fig. 3. Re-Os diagram for the studied sulfides of the Mayskoe deposit.
The point numbers correspond to the numbers of the analyzed single fractions (see Table).
The image of the measured ratio error is less than the characters the size. Reference isochrons of the corresponding age
and initial isotopic composition are given to discuss the results

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tural features of ore bodies and dikes. So, the age of galena, according to model estimates, does not exceed 50-100 Ma [3], and the K-Ar age of igneous rocks in the region varies in the range of 97-115 Ma. The age of the Kukeneysky granite massif, located 10 km northeast of the Mayskoe deposit and dike complex, was previously determined by the U-Pb zircon dating as 108 ± 1 Ma [1]. Considering that all researchers pointed out that gold mineralization is superimposed on these dikes [2, 3], the age of ore mineralization cannot be older than the Early Cretaceous. At the same time, it is obvious that the more ancient age obtained for pyrite and arsenopyrite should not be ignored since these minerals form the ore paragenesis with fine-grained gold. Therefore, further we provide a more detailed interpretation of the obtained isotopic and geochemical data for each of the studied samples.

*Arsenopyrite.* The obvious similarity of the rhenium and osmium content, as well as the values of Re/Os ratio in the studied arsenopyrite from the 140-1yu sample (see Table), suggests the genetic affinity of all grains of the studied mineral. Nevertheless, detailed mineralogical observations show that two phases of arsenopyrite can be distinguished (Fig.5, 6, *a*, *b*). In polished sections, the first phase of arsenopyrite grains are euhedral, have an elongated prismatic and pseudo-rhombic shape; cruciform twins are rare; aggregate sizes reach 1.5 mm. Arsenopyrite of the second phase forms a thick impregnation of small needle-like crystals; cruciform twins and star-shaped trillings are frequent. Such arsenopyrite corrodes framboidal pyrite crystals. The aggregates sizes ranges from the first hundredths of millimeter to 0.5-0.7 mm (Fig.5). Arsenopyrite of the second generation is usually supersaturated with arsenic and contains a structural gold impurities [3]. The average sizes of arsenopyrite crystals in the studied samples vary within 0.5-1 mm. It turned out to be almost impossible to select the grains of specific phase under the binocular, more so especially since ar
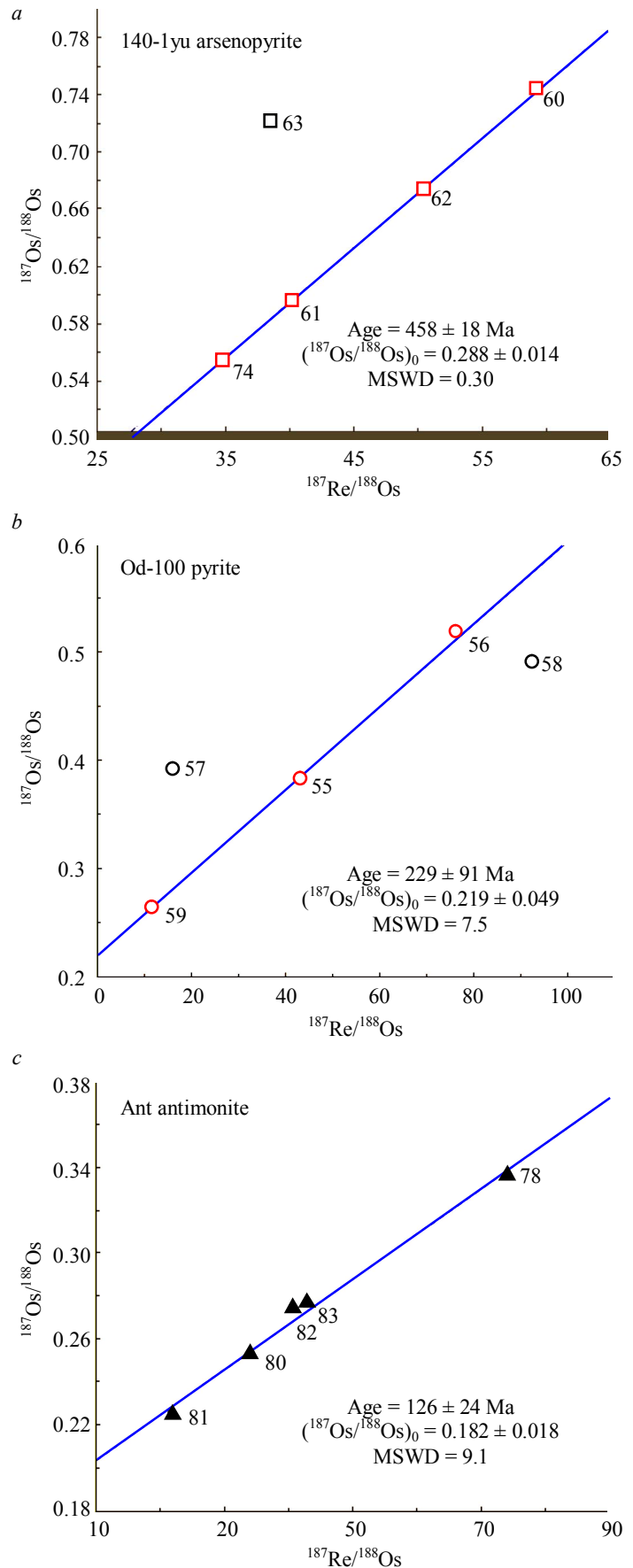


Fig.4. Isochron Re-Os diagrams for the studied sulfide's single fractions from the Mayskoe deposit: *a*– arsenopyrite from 140-1yu sample, *b* – pyrite from Od-100 sample, *c* – antimonite

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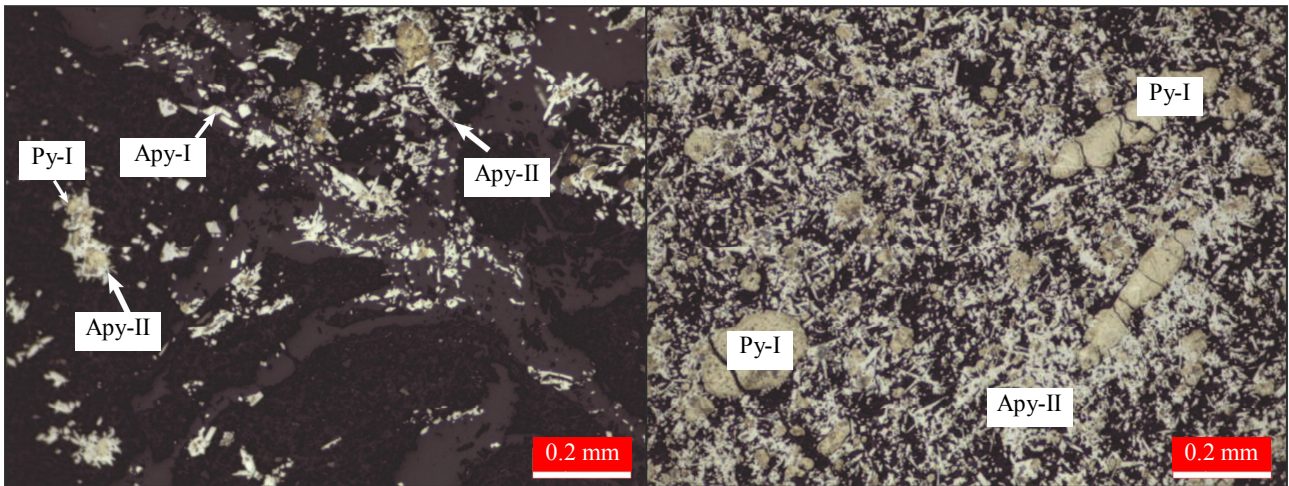
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Fig.5. The relationship between the arsenopyrite different phases (I and II) and pyrite from the 140-1yu sample (reflected light image).
Hereinafter, the literal abbreviations of minerals are given according to D.L.Whitney and B.W.Evans [25]: Py – pyrite,
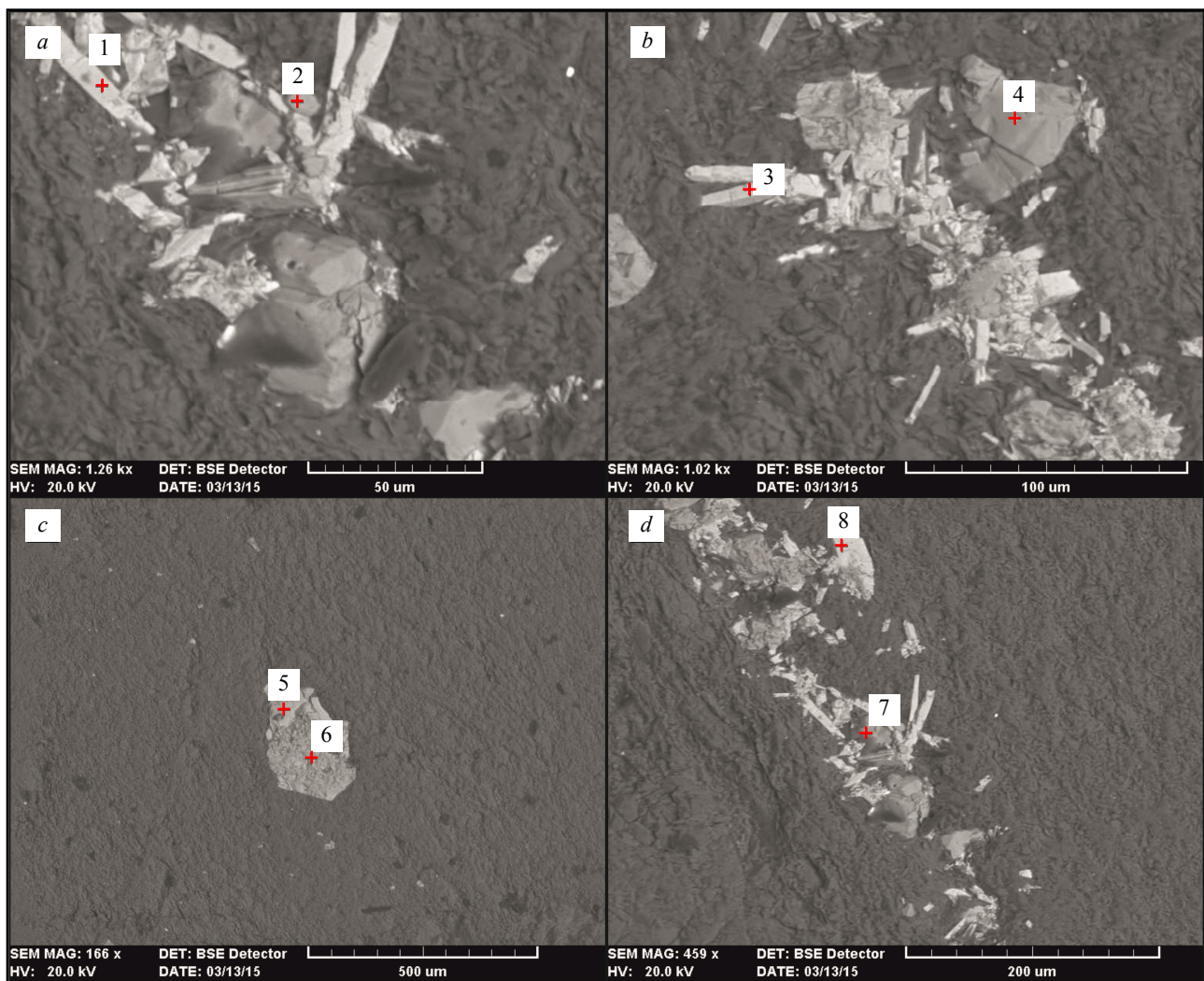Apy – arsenopyrite



Fig. 6. BSE image of the studied samples: *a, b* – 140-1yu; *c, d* – Od-100.
The numbers correspond to the identified mineral phases: 1, 3, 8 – arsenopyrite, 2, 4-7 – pyrite

senopyrite often forms intergrowths with pyrite. As a result, the analyzed single fractions probably represent a mineralogical mixture of two genetic types of arsenopyrite, mixed with pyrite in varying degrees. The composition of the Re-Os isotope system of the studied arsenopyrite sample confirms this assumption. Thus, the isochron diagram (see Fig.3) shows that the pyrite analytical point (fraction 57) also falls on the linear trend passing through the four points of the arsenopyrite isotopic composition. At the same time, a point of 63 arsenopyrite lies significantly higher than this trend, which can be attributed to a partial loss of rhenium in the analysis process (in this case, at least 26 % is lost) and a decrease in the arsenopyrite content in the fraction due to mixing with pyrite (in this case, the proportion of pyrite in the analytical fraction could reach 33 %).

The obtained linear trend in isochron Re-Os coordinates for four analytical points of 140-1yu sample allows us to formally consider it as an isochron with an age of $458 \pm 18$ Ma (see Fig.4, *a*), assuming that the mineral-forming source at the moment of isotope system closure characterized by a homogeneous isotopic composition of osmium, which subsequently changed only as a result of the $^{187}$Re decay in proportion to the Re/Os ratio in a particular arsenopyrite aggregate. The low mean squared weighted deviation (MSWD) value of 0.30 formally confirms the fulfillment of these conditions. The initial osmium isotope ratio calculated from this isochron corresponds to $(^{187}Os/^{188}Os)_0 = 0.288 \pm 0.014$, which differs from the upper mantle composition (0.1262 [21]), but is significantly lower than in typical crustal rocks ($\geq 1$ [6]), which may indicate a mixed osmium composition in the mineral-forming fluid from various sources with an insignificant role of the crustal material.

An alternative explanation of the obtained linear relationships in the isochron diagram is the proportional mixing of the substance of two isotopically different compositions, for example, due to different mineral generations. In this case, the obtained trend does not have a geochronological meaning and allows only indirectly estimate the age of the mixing components. If we assume that the extreme analyzed isotopic compositions of arsenopyrite (recalculated on the estimated formation time, see Table) reflect the isotopic composition of the mineral-forming medium at the time of formation, and the initial parameters of the isotopic system were comparable with the composition of the primitive mantle, then the age of these components would be 520-730 Ma (the maximum possible age of the sources according to the evolution model of the Re-Os isotope system [21]), i.e. the alleged crustal source of osmium in arsenopyrite must be not older than the Late Riphean. It should be noted that within the Mayskoe field, such ancient rocks have not yet been discovered. The most ancient formations are terrigenous rocks of the Middle Triassic. However, the Precambrian metamorphic basement, consisting of metavolcanic rocks of basic, intermediate, less frequently acid composition, meta sandstones, shales of the Wrangel complex and granitoids, is exposed in the Arctic Ocean, on Wrangel Island. The U-Pb age of the intrusive rocks of the Wrangel complex is 600-700 Ma [24], while the age of the basement rocks, determined by the thermal-evaporation Pb-Pb method is 590 Ma, K-Ar method gives the age values of 550-600 Ma, and the Rb-Sr age is 475 Ma [11]. The age of inherited cores of zircon from metagranite varies in wide range – from 2600, 1435, 1200, 1170, 1010 Ma, while the age of metagranite itself is determined by concordant dating of zircon as 680-710 Ma [10].

Obviously, the Early Cretaceous magmatism, which widely occurred in the Central Chukotka and formed batholiths and granite massifs (including Kukeneysky) triggered the process of ore formation at the Mayskoe deposit. While studying the petrogeochemistry of granites of the Kukeneysky massif, A.I.Gusev came to the conclusion that the massif was formed with the participation of mantle melts and lower crust material – amphibolites and graywacke [4]. A similar origin is assumed for the Peekinei and Moltykansky granite massifs of the Chaunskaya folded zone located 100-200 km to the northwest and southeast, respectively, and formed in geological conditions similar to the Kukeneysky massif, which has the similar age: Moltykansky massif 117-109 and 107 Ma (K-Ar and U-Pb system, respectively) [14, 15]; Kukeneysky massif is 111–107 and 108 Ma (K-Ar and U-Pb systems, respectively) [1, 3], as well as identical petrographic and geochemical characteristics [14]. P.L.Tikhomirov notes that "the Peekinei and Moltykansky massifs were formed during

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melting of a non-uniform crustal source, with the direct participation of mafic melts originating in the mantle wedge region over the existing subduction zones" [14].

The Kuulskoye and Kiberovskoye uplifts in the north of Central Chukotka, as well as the Kuekvunskoe uplift in the northeast of the region, are considered as granite-metamorphic domes. Within these domes orthogneisses, granite gneisses, and granite massifs are exposed. The age of metamorphic and igneous rocks of these structures is defined using various techniques as Paleozoic. Thus, the age of granitoids of the Kiberovsky massif $439 \pm 32$ Ma is established on the basis of isochron Rb-Sr dating of bulk rock samples [13]. The local U-Pb zircon dating (SHRIMP-II) gave the Devonian age of the orthogneisses of the Velitkenaisky massif – $363 \pm 44$ Ma and the Late Devonian age of the granite gneisses of the Kuekvunskoe uplift – 380 Ma [17, 22]. At the same time, the local U-Pb dating of zircon from leucocratic granites of the Velitkenaisky massif varies from 388, 492-561, and up to 620 Ma (SHRIMP-II [12]). In addition, U-Pb age of zircon from granites and quartz syenites of the Kiberovsky and Kuekvunsky massifs, respectively, as well as from granite pebbles of conglomerate at the base of coal deposits of the Kuulskoye and Kuekvunskoe uplifts corresponds to an interval of 352-359 Ma [12]. Paleozoic age estimates of rocks composing granite-metamorphic domes correspond to the time of tectonic events of Ellesmerian orogeny that occurred at the turn of the Late Devonian – Early Carboniferous in the Arctic region, within the territory of Chukotka, Arctic Alaska, Yukon and Arctic Canada [12]. Thus, within the Central Chukotka fold region, there is an ancient Late Archean-Early Proterozoic basement, overlaid with metamorphic formations of the Late Proterozoic-Early Paleozoic, penetrated by granite intrusions of the Devonian-Carboniferous age.

Based on these facts about the ancient basement of the Chukotka continent, Re-Os dating data can be used to construct the following hypothesis for the arsenopyrite formation. In the Mesozoic period, a magma chamber arose in the mantle wedge area above the active subduction zones. It was formed due to the upper mantle substance during anatectic melting of the lower crust – the Late Archean – Early Proterozoic and Early Paleozoic basement, according to A.I.Gusev [4], M.V.Luchitskaya [12] and P.L.Tikhomirov [14 ]. Then the magmatic melt rose, and crystallization of the Kukeneysky massif and a series of dikes began. At a certain stage, the ore-bearing supercritical fluid containing radiogenic osmium of the ancient basement was separated from the melt. Hydrothermal solutions rose to the day surface through cracks in the sedimentary cover and along dikes of acidic composition. The solutions were discharged in fracture zones and gave rise to the formation of ore mineralization in Triassic sedimentary rocks.

*Pyrite.* The Re-Os isochron of pyrite single fraction from the Od-100 sample shows an age of $229 \pm 91$ Ma (see Fig.4, *b*). Three out of five fractions of the sample (55, 56, 59) determine the linear trend, but the mean squared weighted deviation of 7.5 is quite large, which is probably due to variations in the initial osmium isotopic composition in various pyrite samples. If we use four single fractions with the closest osmium concentrations to estimate age (excluding single fraction 59, assuming the presence of a significant admixture of arsenopyrite), then the calculated slope of this trend corresponds to an age of 103 Ma and an initial ratio of osmium isotopes of 0.35, but is characterized by extremely high MSWD values and age errors (380 and 190 Ma, respectively). Nevertheless, this age value has strong correlation with the ages of granitoid massifs given above. The mixing of mantle and crust osmium is indicated by both the values of the measured osmium isotopes ratios (0.26293; 0.51728) and $(^{187}Os/^{188}Os)_0$ values recalculated for the estimated age of mineralization (see Table).

The excess scatter of the above Re-Os isotope system parameters is explained by the possible presence of various pyrite types in the Od-100 sample, each of which can be characterized by its own osmium isotopic composition. This assumption is supported by the presence of three generations of pyrite in the sulfide mineralization of the Mayskoe deposit (Fig.7). *Pyrite I* of the pre-ore stage is the most widespread and characterized by a rounded framboidal grains shape with a netted

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structure, corrosion, and skeletal edges substituted with marcasite. It occurs as an uneven fine and coarse-grained clusters in the host stratum. The size of individual grains is 0.02-0.3, while aggregates reach 0.6 mm. *Pyrite II* of the ore stage is characterized by a heterogeneous structure and the presence of arsenic in the pyrite structure (Fig.6, *c, d*). This is evidenced by its bright anomalous optical anisotropy and mosaic structure. The arsenic content in pyrite reaches 11.9% [2]. Pyrite II forms euhedral grains of a pentagonal dodecahedron habit, 0.06-1 mm in size. These crystals form equigranular single grains, as well as nests, veins, and crosscuts. Pyrite has a light fracturing and sieve texture. Euhedral grains overgrown with elongated arsenopyrite needles of about 0.2-0.5 mm in size were noted in massive ores. Pyrite and arsenopyrite intergrowth were also observed. *Pyrite III* of the late ore stage is associated with quartz-antimonite veins, occurred in thin veins and crosscuts, and is represented by grains and aggregates filling the quartz veins. The habit of such pyrites has the form of netted, skeletal aggregates with regular cube faces of 0.04-0.7 in size, sometimes reaching 1.5 mm.
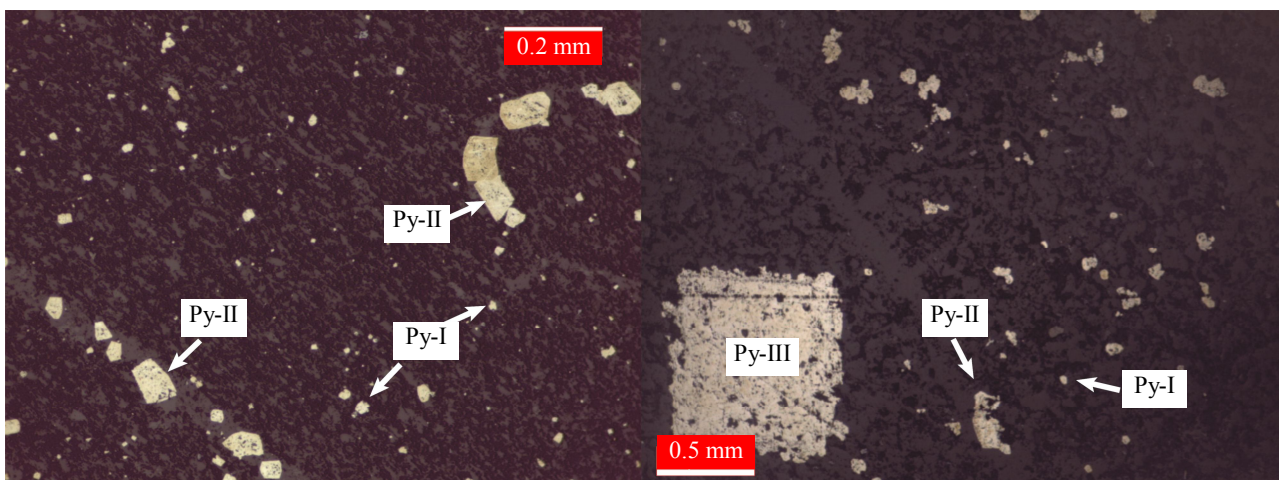


Fig. 7. Pyrite generation from Od-100 sample (reflected light)
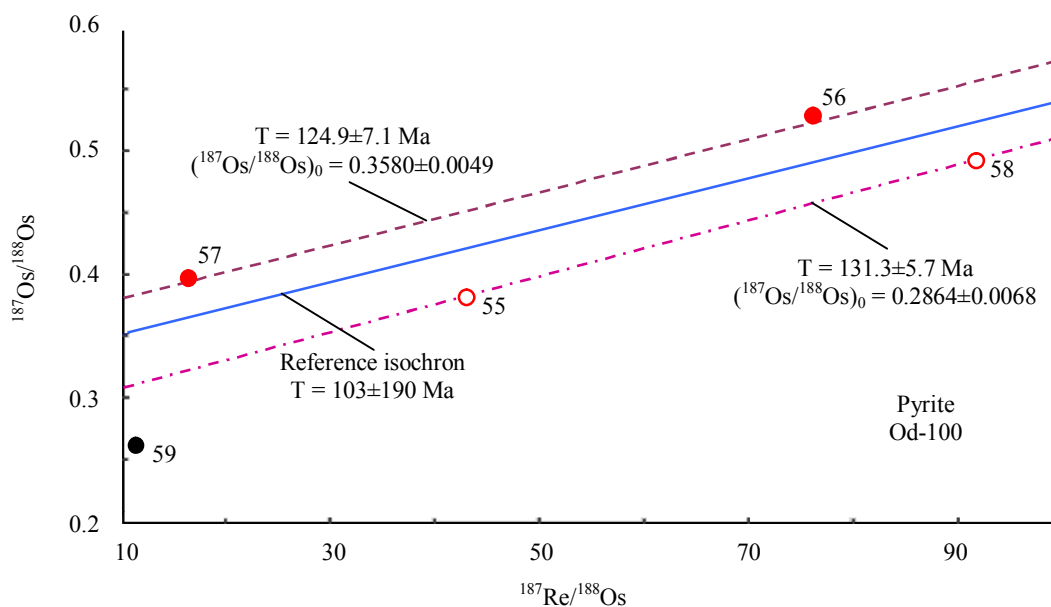


Fig. 8. Age estimation of pyrite from the Mayskoe gold ore deposit. The point numbers correspond to the numbers of the pyrite single fractions (see Table). The reference isochron was calculated for all five analyzed pyrite single fractions (MSWD = 380)
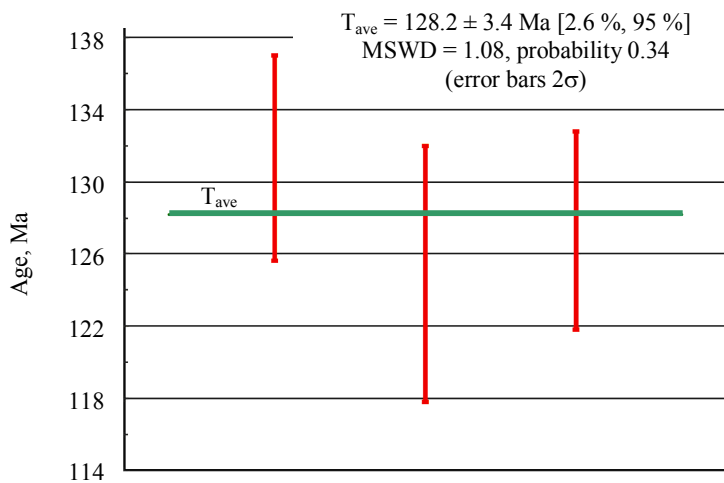
Fig. 9. The weighted average age estimations for sulfide mineralization of the Mayskoe gold ore deposit based on isochronous Re-Os dating of pyrite and antimonite

The age-corrected osmium isotopic composition of the studied pyrite single fractions forms two groups with close values (55 and 58, 56 and 57 samples), which may reflect the primary isotopic homogeneity of the sources and allows the construction of two-point isochrons on this basis (Fig.8). The age parameters of the plotted trends coincide within the error, and the average age of sulfide mineralization (pyrite) can be determined as $128.8 \pm 4.4$ Ma. But, despite the age-related unity, the sources of osmium in pyrite differed: $(^{187}Os/^{188}Os)_0$ ranged from 0.2385 to 0.3580, and the least radiogenic composition (single fraction 59) was comparable with the measured ratios in antimonite.

*Antimonite.* For all analyzed antimonite single fractions from the Ant sample, a Re-Os isochron was constructed with an age of $126 \pm 24$ Ma (see Fig. 4, *c*) and an initial isotopic ratio $(^{187}Os/^{188}Os)_0$ $0.182 \pm 0.018$. Obviously, all five samples are characterized by very similar measured parameters of the isotope system, but the mean squared weighted deviation value is quite high – 9.1 (i.e., the constructed isochron is formally an errorchron), which is due to local variations in the initial isotopic composition in different antimonite single fractions. If we recalculate the initial osmium isotopic composition of each antimonite single fraction for the time of the isotope system formation, determined by isochron, then the closest ratios $(^{187}Os/^{188}Os)_0$ in the 0.1747-0.1785 range will be characterized by samples 78, 80 and 81 (see Table). If we construct the Re-Os isochron through the imaged points of these analyzes, we obtain a linear trend corresponding to the age of 127.3 million years with the smallest error ($\pm 5.5$ Ma) and an MSWD of 1.5. In this case, the initial isotopic ratio, determined by isochron – $0.1791 \pm 0.0033$, is closest to the estimates of the osmium composition of the upper mantle (0.1262 [21]) in comparison with samples 140-1yu and Od-100 (minimum 0.4792 and 0.2385, respectively), i.e. the fraction of crustal osmium in antimonite is significantly lower than in arsenopyrite and pyrite. Thus, the obtained estimate of the antimonite age is only 15-20 Ma greater than the age of granitoid dikes of the Mayskoe deposit and granites of the Kukeneysky massif (108 Ma, zircon), and within the framework of the isochron model can be considered as the best estimate of the sulfide mineralization age.

The source of antimonite was the hydrothermal fluid, which separated from the Cretaceous magma chamber, and, based on the initial ratios of osmium isotopes, the fraction of the crust component in such a fluid was minimal. The antimonite isochron age reflects the Early Cretaceous time of the formation of gold mineralization at the Mayskoe deposit and, together with the obtained pyrite age, allows us to estimate the time of ore formation as $128.2 \pm 3.4$ Ma (Fig.9). However, the obtained age estimation exceeds the age of granitoid magmatism, previously determined by zircon. Thus, the question of the ore genesis and coeval magmatism is not completely resolved. Perhaps the solution lies in the further determination of isochron age of sulfides of the ore stage from a single paragenesis of a specific sample containing both arsenopyrite and pyrite (+ antimonite) with gold.

**Conclusions.** 1. The results of the Re-Os isotope dating of sulfide mineralization of the Mayskoe gold ore deposit confirmed that the formation of the deposit took place in several stages and was a complex and long-term process. According to the osmium isotopic composition in arsenopyrite, the crystalline granite-metamorphic basement was its predominant source, and the pre-ore stage

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began in the Early Paleozoic or perhaps even in Precambrian, with the formation of the Chukotka continent basement. Then the territory of Chukotka developed for a long time: in the Late Triassic, with the accumulation of terrigenous flyschoid strata, formed syngenetic pyrite nodules, which later took part in the formation of ore stage pyrite. And finally, in the Early Cretaceous period, the formation of a magma chamber occurred. The intrusion of these melts led to the substance redistribution on the scale of the ore field, and the residual fluid enriched in the ore component became the main source of antimonite.

2. The source of osmium sulfide mineralization of the Mayskoe deposit was material of both mantle and crust origin. Comparison of the osmium initial isotopic composition in the studied sulfides shows that the mantle osmium fraction was the largest in antimonite, and the smallest in arsenopyrite.

3. The estimated values of antimonite and pyrite Re-Os isochron age are close to the time of granitoid magmatism occurrence and to the estimated time of gold ore mineralization. However, the genetic diversity of pyrite of sulfide mineralization and the limited possibility of these morphotypes separation, does not allow one to obtain an exact age values and correlate the magmatism and ore formation in time.

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