Ore Geology, RE–OS Isotope Geochemistry of the Au and Au-Sb Mineralizations, Kular–Nera Terrane, Northeast Asia: Implications for Time of Formation and Ore Genesis

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Abstract. The paper presents the first results of investigation of the Re–Os isotope system of native gold from the Malo-Tarynskoe, Khangalas, Bazovskoe, and chalcopyrite from the Dvoinoe orogenic gold deposits and stibnite from the Maltan Au-Sb deposit in the Kular–Nera terrane, Northeast Asia. The deposits are spatially related to NW-trending lithospheric-scale major brittle faults or controlled by subsidiary faults and fracture zones. Such zones served as pathways for fluids rising from below the crust, and they have a long tectonic and reactivation history. The Kular–Nera terrane consists of Upper Permian, Triassic, and Lower Jurassic clastic sedimentary-rock sequences, metamorphosed to initial stages of greenschist facies. Magmatism is manifested by Kimmeridgian–Berriasian S- and I-types granitoids and mafic dikes of the Tas–Kystabyt magmatic belt. Re concentration in gold varies from 0.168 to 6.997 ppb, and that of osmium from 0.068 to 1.443 ppb. Chalcopyrite from the Dvoinoe deposit occurrence contains 0.1522 ppb Re and 0.499 ppb Os. Stibnite from the Maltan Au-Sb deposit occurrence contains 0.236 ppb Re and 0.903 ppb Os. The Re–Os ages of gold from the Malo-Tarynskoe (147.8 ± 3.8 Ma) and Bazovskoe (147.2 ± 1.8 Ma) and Khangalas (137.1 ± 7.6 Ma) orogenic deposits and the Maltan Au-Sb deposits (69.7±1.9 Ma) are determined. Malo-Tarynskoe and Bazovskoe represent the earliest known orogenic gold mineralization in the Kular–Nera terrane. The data obtained permit us to correlate the initiation of orogenic gold-ore systems with the completion of the formation at the end of the Late Jurassic Uyandina–Yasachnaya volcanic belt, crystallization and subsequent cooling in the Late Jurassic–early Early Cretaceous of granitoid massifs of the Tas–Kystabyt magmatic belt, and subduction–accretionary events at the northeastern active continental margin of the Siberian craton. Maltan Au-Sb deposit is related to completion of the formation of the Albai-Late Cretaceous Okhotsk–Chukotka volcano-plutonic belt. Contrasting mantle and/or crustal sources of ore-forming material are established. The osmium initial isotopic ratio in gold \(^{187}\text{Os}/^{188}\text{Os} = 0.2210-0.4275\) and antimonite (0.2543-0.2976) is typical for the ore-forming material from the fertile mantle reservoir, and for chalcopyrite (3.1904) – from the crust.

1. Introduction
The Kular–Nera terrane (KNT), Northeast Asia, comprises international-class gold (Natalka, Pavlik, Degdekan, Drazhnoe, etc.) and gold-stibnite (Sarylakh, Sentachen, etc.) deposits [1-3]. The precise age of mineralization and the sources of ore-forming components remain unknown. Solution to these problems is critical in our understanding the relationship between gold mineralization and tectono-magmatic events in the region.
The paper presents the first results of investigation of the Re–Os isotope system of native gold from the Malo-Tarynskoe, Khangalas, Bazovskoe, chalcopyrite from the Dvoine oroic gold deposits (OGDs) and stibnite from the Maltan Au-Sb depositin the Indigirsky sector of the Kular–Nera terrane, Northeast Asia. Re–Os isotope systems of minerals such as pyrite, arsenopyrite, chalcopyrite, molybdenite, and stibnite and of native gold have great potential use not only in geochronology but also as a tracer of the metal sources to estimate the contribution of different-depth reservoirs [4-7, etc.]. The data obtained provide constraints on the timing of the main gold and Au-Sb mineralization, the sources for the ore-forming components, and the relationship of Au and Au-Sb mineralization with regional tectono-magmatic events, all of which are important in constructing exploration models in the KNT.

2. Regional Tectonic Framework and Geology of the deposits

The deposits are localized within the Kular–Nera terrane, in the central part of the Verkhoyansk-Kolyma fold area (Figure 1) [3]. They associate spatially with the lithospheric-scale NW-trending major brittle faults or are controlled by subsidiary faults and fracture zones. The early thrust and the late strike-slip motions are established on the faults [3]. The fracture zones served as pathways for fluids rising from below the crust, and they have a long tectonic and reaction history. The Kular–Nera terrane consists of Upper Permian, Triassic, and Lower Jurassic clastic sedimentary-rock sequences metamorphosed to initial stages of greenschist facies. Magmatism is represented by Kimmeridgian–Berriasian S- and I-types granitoids and mafic dikes of the Tas–Kystabyt magmatic belt.

The OGD ore body styles are veins, stockworks, and disseminations localized within the fault zones. Gold in veins is free, with an average grade as high as several hundreds of g/t Au. The disseminated gold–sulfide mineralization is localized both in the fault zones up to several tens of meters thick and in the altered host clastic rock that underwent sericitization, chloritization, and silicification. Mineral content of the veins is: 85-95% quartz, 5-15% carbonate (ankerite), and about 1% ore minerals. Mineral assemblages in the ores are: pyrite-arsenopyrite-sericite, metasomatic, pyrite-arsenopyrite-quartz, veined, gold-chalcopyrite-sphalerite-galena, and sulfosalt-carbonate [8]. Native gold forms disseminations in quartz and early sulfides (pyrite, arsenopyrite) and/or occurs in intergrowths with sphalerite, galena, chalcopyrite, and, rarely, sulfoantimonites. Gold of the metasomatic pyrite-arsenopyrite-sericite-quartz assemblage is mostly invisible. The mineralization formed as a result of progressive fold and-thrust deformations in the Verkhoyansk–Kolyma fold belt. These were initiated by orogenic processes in late Late Jurassic–early Early Cretaceous.

Malo-Tarynskoe OGD is localized in the axial part of the lithospheric-scale brittle Adycha-Taryn fault (Figure 1) [9, 10]. It occurs on the SW limb of the Taryn-Elga synclinorium complicated by the Egelyakh anticline and the Golubichnaya syncline. The ore bodies consist of NW- and NS-trending mineralized fault zones with vein-veinlet-disseminated gold-sulfide-quartz mineralization. The Au-bearing fault-fill zones are up to 40 m thick and can be traced over a 6 km distance.
Figure 1. Geological sketch map for the Indigirsky sector of the Kular–Nera terrane and location major gold and gold-stibnite deposits discussed in this paper. VFTB – Verkhoyansk fold-and-thrust belt; KNT – Kular–Nera terrane; PDT, Polousny–Debin terrane; CI, Charky–Indigirka fault; CY, Chai–Yureya fault; AT, Adycha–Taryn fault, K – Khangalas fault

**Bazovskoe OGD** occurs in the southwestern wall of the Adycha-Taryn fault, northwestward of the Malo-Tarynskoe deposit [11, 12]. The main folds are the NW-trending Egelyakh syncline and the Bezmyannaya anticline. The major Diagonalny fault and subsidiary faults and fracture zones of NW trend (Vostochnaya, Centralnaya, Srednyaya and Zapadnaya) are the principal ore-controlling features. The ore-body styles are veins and stockworks spatially associated with sandstone beds in the walls of the fault zones. The Au-bearing fault-fill zones are up to 6.5 km long, up to 50-60 m thick, have a NE dip (40-60° to vertical), and flatten out with depth.

**Khangalas OGD** is localized in the crest of the Dvoynaya anticline of the Nera (Nera–Omachug) anticlinorium (Figure 1) [13]. The main ore-controlling tectonic structure is the Khangalas fault with a NW strike. This is represented at the Khangalas deposit by five extensive (up to 1400 m) mineralized ore zones (Severnaya, Promezhutnoyaya, Centralnaya, Yuzhnaya, Zimnyaya) with low-sulfidation Au-type mineralization localized in the Dvoynaya anticline crest. The ore zones are up to 32 m thick and dip to the SW, S, and SE at 30–50 to 70–80° [13]. Ore bodies are represented by concordant and cross-cutting quartz veins a few cm to 1-2 m thick (in swells up to 5 m), veinlets, and disseminated sulfide mineralization. They are mainly localized in sandstones and at their contacts with siltstones, and have conformable and crossing relations with the host rocks.

**Dvoinoe OGD** is confined to the eastern slope of a NW-trending anticline made of Upper Permian clastic rocks. The main ore-controlling feature is the eastern branch of the Graniity fault that adjoins the Khangalas fault on the north. The EW-oriented ore bodies are represented by mineralized fault...
zones with quartz veins and veinlets, ranging from 0.3 to 1.8 m (avg. 1.0 m) in thickness. The 0.7-5 m thick ore bodies dip steeply (60 to 90°) to the S and NE.

*Maltan Au-Sb deposit* is controlled by the Adycha-Taryn fault (Fridovsky et al., 2014). Deposit occurs on the SW limb of the Taryn-Elga synclinorium, composed of the Upper Triassic terrigenous rocks dipping to the northeast at angles of 30-60°. There are transverse folds of the WE and NE strike with steep hinges. They are related to shear movements along the Adycha-Taryn fault. The deposit records mineral associations of two stages of mineral formation – early gold-quartz and late quartz-stibnite [14]. Antimony mineralization was formed in the same structures as gold, but re-activated ones. The Maltan Au-Sb deposit belongs to the epithermal type of hydrothermal deposits, which detailed description on the example of the large Sarylakh and Sentachan deposits of the KNT is given in [1].

3. **Sampling and analytical methods**

For analyses, we selected samples of milky-white quartz with visible gold (Malo-Tarynskoe – sample MT-B-6-16; Khangalas – sample Kh-45-14; Bazovskoe – Bz-93-15) and chalcopyrite (Dvoinoe –Dv-28-18) taken from a low-sulfide Au-quartz vein consisting of the gold-chalcopyrite-sphalerite-galena (polysulfide) mineral association. Stibnite samples are taken from multi-grain monomineral sub-samples (Maltan – sample Mt-1-1, Mt-z-19, Mt-z-34). The samples were crushed, and gold and chalcopyrite and stibnite were hand-picked using a binocular microscope. Gold has a flattened, irregular, cloddy-dendritic form and a grain size of 0.5–1 × 0.5–4 mm. Samples of gold separates were prepared from which individual gold particles or their fragments were selected. Gold is bright yellow in color. Composition and fineness (836-930 ‰) of gold particles were determined by microprobe analysis. The main impurity is Ag. Rhenium and osmium concentrations in gold were determined by the isotope dilution method at the Center for Isotopic Research of the VSEGEI, St. Petersburg following the technique described in [15, 16, 17].

4. **Results**

Re, Os concentrations and isotope compositions of native gold from Malo-Tarynskoe, Khangalas, Bazovskoe and of chalcopyrite from Dvoinoe and stibnite from Maltan deposits are listed in Table 1. They differ in the studied minerals. Re concentration in native gold varies from 0.168 to 6.997 ppb, and that of osmium – from 0.068 to 1.443 ppb. The native gold Malo-Tarynskoe deposit averages 3.79 ppb Re and 0.739 ppb Os. At Bazovskoe, gold contains, on average, Re=2.046 ppb and Os=0.149 ppb. The lowest Re value (avg. 0.439 ppb) is reported for native gold the Khangalas deposit, with its Os content being rather high (avg. 0.683 ppb). Re and Os concentrations in native gold of the Malo-Tarynskoe, Khangalas, and Bazovskoe deposits are close to those at the gold Moeda deposits related to conglomerates and at the Mayskoe gold-quartz deposit in the Baltic shield but are higher than the average crustal values [5, 15, 18] (Figure 2). Re and Os contents in chalcopyrite from Dvoinoe deposit (0.1522 ppb and 0.499 ppb, respectively). In stibnite from Maltan deposit Re concentration varies from 0.360 ppb to 0.903 ppb, and that of Os – from 0.057 ppb to 0.10 ppb, averages Re=0.617 ppb and Os=0.072 ppb. The content of Os and Re is less than in stibnite from Maiskoe orogenic gold deposits (Chukotka, NE Russia) [16].
Figure 2. Re versus Os concentration plot for gold, chalcopyrite, stibnite and based on data from this study and from [5, 15, 16]; Average crustal values are taken from [18].

The $^{187}\text{Re}/^{188}\text{Os}$ ratio in gold from the studied deposits ranges from 2.329 to 146.09. The highest value ($^{187}\text{Re}/^{188}\text{Os}=52.0075$) is recorded in gold Bazovskoe deposit, moderate (31.4142) in Malo-Tarynskoe deposit, and the lowest (12.8712) in Khangalas deposit. Chalcopyrite from the Dvoinoe deposit has the $^{187}\text{Re}/^{188}\text{Os}$ ratio of 96.142. The $^{187}\text{Re}/^{188}\text{Os}$ ratio in stibnite from the Maltan deposits ranges from 17.162 to 75.859.

The initial $^{187}\text{Os}/^{188}\text{Os}$ ratio in the native gold varies from 0.2210 to 0.5431. The native gold Khangalas deposit is characterized by uniform $^{187}\text{Os}/^{188}\text{Os}$ ratios (0.2210 – 0.2906), while the native gold Malo–Tarynskoe and Bazovskoe deposits exhibit less homogeneous $^{187}\text{Os}/^{188}\text{Os}$ values (0.2618 – 0.4275). The $^{187}\text{Os}/^{188}\text{Os}$ ratio in chalcopyrite from the Dvoinoe deposit is 3.1904 and in stibnite from the Maltan deposits values ranges from 0.2294 to 0.2976.

On the Re–Os isochron diagram, native gold samples from the Malo–Tarynskoe deposit form a linear trend corresponding to their formation time (147.8 ± 3.8 Ma) and the initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.2475 ± 0.0012 (MSWD = 1.5). For native gold samples from the Bazovskoye deposit if one assumed an initial ratio of $^{187}\text{Os}/^{188}\text{Os}=0.1844 ± 0.0032$, then the age of the samples would be 147.2 ± 1.8 Ma, which is in good agreement with the ages obtained for the Malo–Tarynskoe deposit. Re–Os isotope systems of four gold samples from the Khangalas deposit are not uniform. One may observe a positive correlation between the $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios, which corresponds to the time of formation (137.1 ± 7.6 Ma) of the Khangalas gold mineralization and its initial $^{187}\text{Os}/^{188}\text{Os}=0.2212 ± 0.0014$. For stibnite from the Maltan deposit at the initial isotopic ratio $^{187}\text{Os}/^{188}\text{Os}=0.2095 ± 0.0017$ the age estimation will be 69.7 ± 1.9 Ma.
Table 1. Re–Os data for Malo–Tarynskoe, Khangalas, Bazovskoe, Dvoinoe orogenic gold deposits and Maltan Au–Sb deposit, Kular–Nera terrane, northeast Asia

| Sample      | Mineral | Wt (mg) | Re, ppb | Os, ppb | $^{187}\text{Re}/^{188}\text{Os}$ | $\pm 2\sigma$, % | $^{187}\text{Os}/^{188}\text{Os}$ | $\pm 2\sigma$,abs. |
|-------------|---------|---------|---------|---------|----------------------------------|----------------|---------------------------------|------------------|
| **Malo–Tarynskoe deposit** |         |         |         |         |                                 |                 |                                 |                  |
| MT-B-9-16 (1) | Au     | 0.0137  | 1.007   | 0.811   | 5.931                            | 1.80            | 0.2618                          | 0.0012           |
| MT-B-9-16 (2+4)* | Au   | 0.0115  | 3.366   | 1.046   | 15.029                           | 0.58            | 0.2854                          | 0.0017           |
| MT-B-9-16 (3)  | Au     | 0.1658  | 6.997   | 0.360   | 73.282                           | 1.74            | 0.4275                          | 0.0027           |
| **Khangalas deposit** |         |         |         |         |                                 |                 |                                 |                  |
| Kh-45-14 (1)   | Au     | 0.0380  | 0.916   | 0.205   | 21.395                           | 0.09            | 0.2701                          | 0.0026           |
| Kh-45-14 (2)   | Au     | 0.0187  | 1.862   | 0.354   | 24.883                           | 0.13            | 0.2906                          | 0.0022           |
| Kh-45-14 (3)   | Au     | 0.0289  | 0.439   | 0.731   | 2.878                            | 0.66            | 0.2210                          | 0.0011           |
| Kh-45-14 (4)   | Au     | 0.0123  | 0.702   | 1.443   | 2.329                            | 0.37            | 0.2265                          | 0.0013           |
| **Bazovskoe deposit** |         |         |         |         |                                 |                 |                                 |                  |
| Bz-93-15 (1)   | Au     | 0.0253  | 0.461   | 0.170   | 12.737                           | 1.50            | 0.3816                          | 0.0020           |
| Bz-93-15 (2)   | Au     | 0.0220  | 6.406   | 0.211   | 146.09                           | 0.15            | 0.5431                          | 0.0023           |
| Bz-93-15 (3)   | Au     | 0.0729  | 0.168   | 0.068   | 11.694                           | 2.29            | 0.3788                          | 0.0041           |
| Bz-93-15 (4)   | Au     | 0.0692  | 1.147   | 0.146   | 37.509                           | 0.51            | 0.2765                          | 0.0023           |
| **Maltan deposit** |         |         |         |         |                                 |                 |                                 |                  |
| Mt-1-1-12     | Stn    | 0.21987 | 0.360   | 0.101   | 17.162                           | 0.53            | 0.2294                          | 0.0013           |
| Mt-z-19-12    | Stn    | 0.22678 | 0.590   | 0.060   | 47.062                           | 0.21            | 0.2543                          | 0.0009           |
| Mt-z-34-12    | Stn    | 0.20475 | 0.903   | 0.057   | 75.859                           | 1.04            | 0.2976                          | 0.0010           |
| **Dvoinoe deposit** |         |         |         |         |                                 |                 |                                 |                  |
| Dv-28-18      | Chp    | 0.1522  | 0.499   | 0.035   | 96.142                           | 0.29            | 3.1904                          | 0.0229           |

Note: gold samples consist of individual gold particles or their fragments, stibnite and chalcopyrite – multi-grain sub-samples; $\pm 2\sigma$, % – isotope ratio determination error (internal), in relative units; $\pm 2\sigma$, abs. are the absolute error of the measured isotope ratio; * indicates that the weighed samples were combined and the isotopic composition was averaged; Au – native gold, Stn – stibnite, Chp – chalcopyrite.

5. Discussion

The age data obtained in this study permit interpreting in a new way a spatial relationship between tectonic events, igneous rocks, and orogenic lodes in the Indigirka sector of the KNT. Our results showed that orogenic Malo–Tarynskoe and Khangalas gold deposits was formed in the Late Jurassic (Tithonian). A similar age (142.7 ± 1.8 Ma) was obtained earlier from 40Ar/39Ar dating of sericite from quartz veinlets in the fault zones of the Malo–Tarynskoe deposit [9]. Formation of productive gold mineralization was preceded by the intrusion of mafic dikes (162 ± 4 Ma, whole rock, Rb–Sr [19]. The Re–Os dating of gold showed that the timing of the Malo–Tarynskoe and Khangalas deposits is comparable, on a regional scale, with the crystallization age of the Nelkan (147.8 ± 1.1 Ma, U–Pb zircon; [20]) and Trud (151.4 ± 1.5 Ma, U–Pb zircon; Prokopiev et al., 2008[20]) granitoid plutons. Petrogenetically, the Tas–Kystabyt magmatic belt granitoids are transitional between subduction-related I-type and collision-related S-type granites [21].

The Re–Os age of nativegold from Khangalas (137.1 ± 7.6 Ma) is close to the K-Ar date (135±4 Ma) of sericite from the Nagornoe deposit [22] in the Khangals ore cluster. Age of the Khangals deposit (~137.1 Ma ago, Valanginian, early Cretaceous) it is close to the cooling time of the Early Cretaceous magmatic complexes (Kurdat, Ergelyakh plutons) [21, 23]. Thus, a close age/spatial relationship with the Late Jurassic-Early Cretaceous magmatism is typical for orogenic gold deposits.
Obtained Re–Os age dating of stibnite (69.7 ± 1.9 Ma) from the Maltan Au-Sb deposit confirms the previously determined Late Cretaceous-Paleogene age of the formation of the KNT Au-Sb deposits [24]. It is possible to assume the formation of epithermal Au-Sb deposits at the completion of subduction at the end of the Late Cretaceous under the continent of the Paleo-Pacific Plate. This is evidenced by the position of antimony deposits in the rear of the Albian-Late Cretaceous Okhotsk-Chukotka volcano-plutonic belt.

Values of the $^{187}$Os/$^{188}$Os ratio of native gold at the Malo–Tarynskoe, Chiangalas and Bazovskoe orogenic deposits and in stibnite from the Maltan Au-Sb deposit are more than 0.20, exceeding those typical of the mantle (0.1290; [25]), but are markedly lower than crustal values (>1.0; [18]). The determined 187Os/188Os ratio of chalcopyrite (3.1904) is inherent in the crustal ore-forming systems. This likely reflects a mixed mantle–crustal source for OGD and mantle source for Au-Sb deposit. A necessary condition for OGD formation is the mantle-to-crust heat transfer that provided the supply of juvenile material into the crust and the uprise of the deep-seated gold-bearing fluids that were focused into the ore-controlling fault systems [26]. The ore-forming fluids OGDs began to be supplied into the lithospheric-scale faults and fracture zones at the end of the Upper Jurassic occurred at the end of subduction processes, closure of the Oymyakon minor ocean basin, and subsequent accretion/collision of the Kolyma–Omolon superterrane (microcontinent) with the margin of the Siberian craton.

6. Conclusions
The Re–Os dates we obtained are only preliminary, thus requiring further research into Re–Os isotope systems of OGDs and Au-Sb deposit in the Kular–Nera terrane. The obtained ages for Malo–Tarynskoe and Bazovskoe gold mineralization allow us to conclude that formation of OGDs in the central part of the Kular–Nera terrane occurred in relation to crystallization (148–151 Ma) and subsequent cooling of the Tas–Kystabyt magmatic belt granitoid intrusions and to Late Jurassic–early Early Cretaceous subduction–accretion/collision events at the eastern active continental margin of the Siberian craton. However, despite the temporal association between the gold and adjacent batholiths, the main controlling factor for the OGDs localization is the motion of the regional fluid flow along the Adyga–Taryn and Chai–Yureya faults. The measured $^{187}$Os/$^{188}$Os ratio of gold is characteristic of the ore-forming material derived from a fertile mantle–crustal reservoir, and that of chalcopyrite suggests the role of crustal contamination. The formation of epithermal Au-Sb deposits occurred in the rear of the Albian-Late Cretaceous Okhotsk–Chukotka volcano-plutonic belt at the end of the Late Cretaceous subduction of the Paleo-Pacific plate under the Siberian continent. The submerged slab and its overlying fertile sediments were probably the source of hydrothermal Sb fluids. The Re–Os dates we obtained are only preliminary, thus requiring further research into Re–Os isotope systems of OGDs and Au-Sb deposit in the Kular–Nera terrane.

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