Structural Evolution of Ore-Controlling Trans-Crustal Faults of the Olchan-Nera Zone: Constraints from the Khangalas Ore Cluster, Yana-Kolyma Metallogenic Belt, NE Russia

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Abstract. The article studies the structural evolution of ore-controlling trans-crustal faults of orogenic deposits and occurrences of the Khangalas ore cluster located in the southeastern part of the Olchan–Nera metallogenic zone, in the Upper Indigirka sector of the Yana–Kolyma metallogenic belt, North–East of Russia. Studies have shown that the formation of tectonic structures occurred during four Mesozoic deformation stages. Accretionary thrust stage D1 resulted in formation of the main pattern of the Mesozoic tectonic structures of the region. Further tectonic evolution occurred in a strike–slip setting of the accretionary D2 and post-accretionary D3–D4 stages. Post-ore strike-slip faults activate and complicate the earlier formed structures of the reverse and thrust paragenesis. Mineralization associated with the strike–slip faults has not been established, whereas formation of the gold-antimony mineralization is associated with sinistral strike-slip faults in the Adycha–Taryn metallogenic zone located to the southwest. The new data obtained are consistent with the previously proposed model of the evolution of the deformation structures of the Khangalas deposit.

1. Introduction
In regionally metamorphosed terranes, trans-crustal faults are one of the most important factors of the orogenic gold deposits localization [1-3, etc.]. The importance of fluid pathways for focusing ore fluid emplacement is highlighted in [e.g. 4, 5, etc.]. In the Olchan–Nera metallogenic zone (ONMZ), studies of the trans-crustal faults, their impact on the localization of gold mineralization and their relationship to regional geodynamic events are presented in [2, 6, 7]. Meanwhile, there are only limited data on post-ore deformations. We have studied them in the ore cluster located in the southeastern part of the Olchan–Nera metallogenic zone, in the Upper Indigirka sector of the Yana–Kolyma metallogenic belt (YKMB) (Figure 1). ONMZ, with a width up to ~50–70 km, stretches in the northwestern direction for ~200 km. Tectonically, the zone is located within the Kular–Nera terrane and partially overlies the southwestern side of the Polousny–Debin terrane of the Verkhoyansk–Kolyma orogenic belt [2]. The Kular–Nera terrane is mainly composed of the Upper Permian, Triassic, and Lower Jurassic black shales that are metamorphosed at lower greenschist facies conditions. The Late Jurassic – Early Cretaceous granitoid massifs and dikes of varying composition cut clastic rocks [2, 8]. The main ore–controlling and ore-localizing trans-crustal faults of the Olchan–Nera zone are the NW Chai–Yureya and Nera faults. The Nera (Nera–Omcchug) anticlinorium is the main ore localizing fold structure. The Khangalas ore cluster is located in its arch, complicated by the branches of the Nera trans-crustal fault.
To the south–east, within the Upper Kolyma sector of the YKMB, large gold deposits such as Natalka, Degdekan, Pavlik, Vetrenskoye, Chai–Yureya, and others are located in similar structures [9].

In recent years, studies of the Khangalas ore cluster deformation structures have revealed a multi-stage tectonic evolution associated with the Late Jurassic – Cretaceous tectonic events in the Verkhoyansk–Kolyma orogenic belt [6, 10, 11]. Four deformation stages have been identified [6]. The first D1 stage is characterized by progressive deformations in the reverse and thrust fault stress field, with NE-SW-oriented σ3/σ1. This stage starts with the development of NW-striking tight to isoclinal folds and interstratal detachment thrusts, followed by formation of the major folds, extensive thrusts, boudinage, and cleavage. The stage concludes with formation of the auriferous mineralized fault zones and quartz-vein gold mineralization. Post-ore deformation is widely manifested in the region. Structures D2 and D3 are coaxial under prevailing W-E compression. Sinistral strike-slip motions (D2–3) occurred along NW-striking faults. Associated with them were submeridional and NE-trending F2–3 folds with steep hinges, as well as deformation of the earlier, including ore-controlling, structures. Further, dextral strike-slip faulting (D4) occurred along the NW faults with compression of the predominant N-S direction, formation of steep hinges and deformation of the earlier structures, including ore-controlling ones.

This paper presents the results of the latest field studies in 2018 and 2019, conducted at the Khangalas and Nagornoye deposits, the Ozhidanie and Dvoinoye occurrences. Based on these results, we discuss ore-controlling structure evolution of the Khangalas cluster. Modern structural-kinematic methods of research were used [12, 13]. Structural data were plotted on the upper hemisphere of the Wulff stereographic net.

2. Research Objects
Orogenic deposits and gold occurrences in the clastic carbonaceous Upper Permian and Middle Triassic rocks of the Khangalas ore cluster (KOC), the Upper Indigirka sector of the YKMB, represent the research objects (Figure 1). The detailed geological structure of these rocks is described in [6], the mineralogy, geochemistry, isotopic composition, and gold content of disseminated mineralization of the Khangalas orogenic gold deposit – in [14, 15]. The Khangalas ore cluster is located in the arch of the Nera anticlinorium that is represented in the study area by the NW–striking Dvoinaya anticline composed of dislocated Upper Permian and Lower–Middle Triassic clastic rocks. The Upper Permian (P₃) deposits make up the core of the Dvoinaya anticline. The lower part of the section consists of massive brownish–grey and grey greywacke sandstones with thin siltstone interbeds. The upper part is dominated by an 800 m–thick sequence of dark–grey and black siltstones with inclusions of pebbles of sedimentary, magmatic, and metamorphic rocks. The limbs of the Dvoinaya anticline are made of 680–750 m–thick Lower–Middle Triassic deposits (T₁) – mainly dark–grey shales, mudstones, and siltstones with rare interbeds of light–grey sandstones. The Middle Triassic deposits of the Anisian strata (T₂a) are represented by a 700–800 m–thick sequence of alternating sandy siltstones and siltstones with rare fine–grained sandstone interbeds. The Ladinian strata (T₂l) are chiefly made of interbedded siltstones and sandstones with a total thickness of 850–950 m.

The main ore–controlling rupture dislocations are the Khangalas, Dvoinoy, and Granitny faults represented by zones of breccia and fracture, low sulfidation of rocks, and quartz–carbonate vein mineralization (Figure 1). The Khangalas Fault crosses the Khangalas ore cluster in a northwest direction. It controls localization of the Khangalas deposit and Ampir and Klich–Kontroloynoe occurrences. Within the study area the exposed fault changes its strike from NW–SE to E–W and has the dip direction to S–W and S. The bedding of rocks exposed in the S–W wall strikes N–W, and rocks of the N–E wall strike NE–SW and E–W. The Dvoinoy Fault strikes E–W, its fault plane is subvertical. In the central part of the KOC, northward of the Klich–Kontroloynoe occurrence, the Dvoinoy Fault adjoins the Khangalas Fault. The northeastern branch of the Dvoinoy Fault controls...
mineralization at the Nagornoye deposit. The rocks of the S wall of the fault have N–E strike, while those of the N one strike E–W. The Granitny Fault is located in the southwestern part of the KOC. Outside the Khangalas ore cluster, the Ala–Chubuk massif of biotite granites is confined to it.

Recent mining operations carried out by subsoil users provided new data that complemented the previously obtained results [6, 10, 11]. This is important for understanding the evolution of the transcrustal fault zones controlling localization of the orogenic gold deposits of the YKMB.

3. Results and discussions
The *Khangalas deposit* is located within the same name ore field at the junction of the Khangalas fault and the Dvoinaya anticline fold [6, 10, 11] (Figure 2A). Ore bodies are represented by mineralized fault zones with quartz veins and veinlets and disseminated sulfide mineralization. Ore zones demonstrate varying strike – from the NE (the Yuzhnaya zone) and EW (the Centralnaya, Zimnyaya, and Promezhutchnaya zones) to the NW (the Severnaya zone), with length up to 1400 m, thickness up to 32 m, and dip at 30–50° to 70–80°. Within the ore zones, concordant and cross quartz veins have a thickness of 0.1–1 m, in swells up to 5 m. Previously [6], it was noted that the hinge of the ore-localizing Dvoinaya anticline dips to the WSW at 28°. The structures of the anticline fold with siltstone containing mineralization were studied at the left flank of the Uzkiy tributary (Figure 2C). At the contact zone between quartz sandstones and siltstones, an interstratal NW-strike quartz vein with a thickness of 65–70 cm was exposed (V–230/20). It is probably an extension of the Centralnaya vein in the Khangalas deposit. Analysis of the quartz veins and veinlets occurrences revealed four variously-oriented systems (Figure 2C, diagram). The V1 system is formed by veins that have persistent parameters; they are conformable with the host rocks. Quartz veins of the V2 system follow the orientation of the bedding plane, but they dip in the opposite NE-direction and are characterized by an unstable thickness. The veins of the V3 system are also conformed to the V1 system and have a steep...
SW-dip. The V4 vein system is subvertical in accordance with the $\sigma_3/\sigma_1$ plane. In some areas, all four systems of veins and veinlets are present, which form linear stockworks. The vertical position of the belt of poles of the $\sigma_3/\sigma_1$ quartz veinlets and veins in the diagram indicates their formation in the reverse and thrust fault stress field. Similar results were obtained in the analysis of quartz veinlets occurrence on the 938 m horizon of the drift 2 in the Khangalas deposit (Figure 2D, diagram), where their close spatial relationship with the S faults (detachment thrusts) corresponding to the occurrence of the S0 bedding is noted. Reverse and thrust fault stress field have been also recognized in the evolution stage of the other orogenic gold deposits of the Yana–Kolyma belt, such as Badran, Bazovskoe, Malo–Tarynskoe, etc. [2, 16, 17]. The structures of the reverse and thrust fault D1 stage are complicated by the late dextral strike-slip faults of the D4 stage (Figure 2B) with evident displacement up to 10–25 cm; the walls of these faults are characterized by sub-horizontal slickenlines.

**Figure 2.** Geological structure diagram (A), syn-ore (B) and post-ore structures of the Khangalas deposit. B – post-ore dextral strike-slip faults, back of drift 2; C – conformable vein, left flank of the Uzkiy tributary; D – syn-ore reverse fault

The **Ozhidaniye occurrence** is located in the interfluve of the Ozhidaniye and Bolotny creeks in the southwestern part of the Khangalas ore field, it is controlled by the branches of the Granitny fault characterized by NW strike with a steep dip to the southwest (Figure 3). The host rocks are primarily composed of the Anisian siltstones of the Upper Triassic crushed into folds of the NW strike F1. The ore body is represented by the crush belt with quartz veins and veinlets, with thickness varying from
0.3 to 1.8 m, with an average of 1.0 m. In the Granitny fault limbs, there are fault-line folds with steep hinges (b – 150/80), formed in the course of sinistral movement (Figure 3E).

**Figure 3.** Geological structure diagram (A) and fault-line axonocline (B) of the Ozhidaniye occurrence

The Dvoinoye occurrence is located within the same name ore field in the northwestern part of the Khangalas ore cluster (Figure 4). The host rocks are sandstones with lesser siltstones of the Middle Geoidskaya sub-formation of the Upper Permian. The limb of the NW-striking Dvoinaya anticline (Figure 4A, diagram) is comprised of the rocks complicated by EW-trending folds (Figure 4). The characteristic difference of the occurrence is that it is transverse (orthographic) in relation to the major Granitny fault and regional strike of the rocks (Figure 4A, B). The ore bodies consist of mineralized fault zones and quartz-vein mineralization. They follow the orientation of the $\sigma_3/\sigma_1$ bedding plane of the D1 thrust stage, similar to the V4 vein systems of the Khangalas field (Figure 2C, diagram). We have mapped the limb fragments of the Dvoinaya anticline, complicated by strike slip movement along the NW-strike faults with formation of the NE-strike folds with a moderately steep (up to 28°) dip of the hinges in the SW direction (Figure 4B).
The Nagornoye deposit is located in the northwestern part of the KOC within the Duk ore field (Figure 5). Ore bodies are between bedding planes within mineralized faults of an ESE-WNW trend. In some places, the fault zones are accompanied by discontinuous concordant (up to 100 m in extent) and feathering quartz veins and veinlets. The thickness of ore zones on the Nagornoye deposit varies from 0.6 to 3–4 m (average 1.0 m). The host rocks are mostly represented by Upper Permian sandstones with siltstone interbeds. They have a steep (70–75°) to vertical, sometimes overturned bedding (Figure 5A, B, F). They form F1 folds associated with thrusts characterized by predominant sublatitudinal strike and horizontal hinges (b – 85/4) (Figure 5E). Their axial surfaces are deformed by late strike-slip faults, thus the F1 folds are changed into ESE-WNW folds with formation of the late open folds and NE-striking steep hinges (Figure 5A, G).
Figure 5. Geological sketch map (A), cross-section (B), F1 tight and isoclinal folds in trench 8 (C, D), syncline F1 fold and diagram of the pole of bend (E), diagrams of the pole of bend of the F1 folds (F), F2–3 folds (G), and gold-quartz veins (H) of the Nagornoye deposit.
Based on the Khangalas deposit, an evolution model of the deformation structures in the gold-bearing trans-crustal faults in the southeastern part of the Olchan–Nera zone have been developed (Figure 6). It is consistent with the earlier evolution model of the Khangalas deposit [6]. The formation of the tectonic stages of the Khangalas ore cluster occurred during four Late Mesozoic deformation events in the Verkhoyansk–Kolyma orogenic belt [6].

**Figure 6.** Evolution model of the deformation structures in the Khangalas deposit

D1 deformations occurred in the Late Jurassic – Early Cretaceous during frontal (D1) and then oblique (D2) subduction and accretion processes on the eastern active continental margin of the Siberian craton [2, 6]. Post-accretionary D3–D4 tectonic stages are associated with the Albian – Campanian Okhotsk-Koryak subduction paleozone. Maastrichtian-Early Eocene strike-slip D4 deformation is inferred to be related to oblique subduction of the Paleo-Pacific Ocean plates beneath the eastern margin of north Asia [18] and/or to the formation of a transform margin in northeast Asia [19].

The *D1 stage* is characterized by progressive deformation in the reverse and thrust fault stress field with NW-SE striking rock transportation. In the initial stage, decollement zones, decollement folds and ramps (Figure 6A, D) are formed, and regional greenschist facies metamorphism occurs. During subsequent progressive deformation, major fold-thrust structures are formed [6, 7]. Early interstratal detachment thrusts transform into thrusts with formation of slice systems (frontal, oblique and lateral ramps). The NW-striking large folds are formed (such as the Dvoinaya anticline and Nera anticlinorium) with small tight and isoclinal folds on their limbs. A NW-striking cleavage of the axial surface follows the folds. Slickenlines orthogonal to the strike of the rocks and boudinage structures with conformable subhorizontal axis are formed on the limbs of the folds. The stage concludes with formation of the granitoids, mafic and intermediate dikes of the Late Jurassic Nera complex, and orogenic ore systems. The gold mineralization is primarily confined to the thrust faults.

Sinistral strike-slip motions of the *D2 stage* occurred along NW-striking faults under prevailing WE compression (Figure 6B, E). The early sinistral strike-slip faults are associated with F2 folds of various morphologies: from open symmetric to tight overturned ones. Steep hinges and various strike patterns (from NE and submeridional to NW strike) characterize the folds.
Structures of the *D3 stage* are coaxial to those of the D3 stage and also characterized by sinistral kinematics (Figure 6B, E). To the south-west of the Olchan–Nera metallogenic zone, the Sarylakh, Sentachan, and Maltan antimony deposits are associated with the post-orogenic sinistral strike-slip faults of the Adycha–Taryn fault [20, 21].

The deformation *D4 event* is characterized by dextral strike-slip faulting, refolding of rocks, reactivation of the earlier ore-controlling structures, as well as the formation of E-W folds and cleavage (Figure 6C, F). The final structure of the region was established as a result of these events.

### 4. Conclusions

Thus, the formation of the tectonic stages of the Khangalas ore cluster occurred during four deformation events (Figure 6). During the progressive frontal fold-thrust deformations of the D1 stage, the main pattern of the Mesozoic tectonic structures of the region was formed. Further tectonic evolution of the Khangalas ore cluster occurred in a strike-slip setting of the accretionary D2 and post-accretionary D3–D4 stages. Post-ore strike-slip faults activate and complicate significantly the early structures.

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### References

[1] D. I. Groves, R. J. Goldfarb, M. Gebre–Mariam, S. G. Hagemann, F. Robert, “Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types,” *Ore geology reviews*, vol. 13(1–5), pp. 7–27, 1998.

[2] V. Y. Fridovsky, “Structural control of orogenic gold deposits of the Verkhoyansk–Kolyma folded region, northeast Russia,” *Ore Geology Reviews*, vol. 103, pp. 38–55, 2018.

[3] J. Deng, L. Q. Yang, D. I. Groves, L. Zhang, K. F. Qiu, Q. F. Wang, “An integrated mineral system model for the gold deposits of the giant Jiaodong province, eastern China,” *Earth–Science Reviews*, 103274, 2020.

[4] J. M. A. Hronsky, “Deposite–scale structural controls on orogenic gold deposits: an integrated, physical process–based hypothesis and practical targeting implications,” *Mineralium Deposita*, vol. 55(2), pp. 197–216, 2020.

[5] R. S. Davies, D. I. Groves, J. G. Standing, A. Trench, M. Dentith, J. P. Sykes, “Litho–structural controls on orogenic gold deposits within the Sandstone greenstone belt, Yilgarn Craton, Western Australia: implications for exploration targeting,” *Applied Earth Science*, vol. 128(4), pp. 136–145, 2019.

[6] V. Yu. Fridovsky, M. V. Kudrin, L. I. Polufuntikova, “Multi–stage deformation of the Khangalas ore cluster (Verkhoyansk–Kolyma folded region, northeast Russia): ore–controlling reverse thrust faults and post–ore strike–slip faults,” *Minerals*, vol. 8(7), pp. 270, 2018.

[7] V. Yu. Fridovsky, L.I. Polufuntikova, Ya. A. Tarasov, “Mineralogy, Geochemistry and Localization of Regional Pyritization Zones – Constraints from Early Mesozoic Deposition in the Chay–Yureya Fault of the Kular–Nera Terrane, NE Russia,” *6th World Multidisciplinary Earth Sciences Symposium*, vol. 609, pp. 1–11, 2020.

[8] A. I. Zaitsev, V. Y. Fridovsky, M. V. Kudrin, “Granitoids of the Ergelyakh Intrusion–Related Gold–Bismuth Deposit (Kular–Nera Slate Belt, Northeast Russia): Petrology, Physicochemical Parameters of Formation, and Ore Potential,” *Minerals*, vol. 9(5), pp. 297, 2019.
[9] N. A. Goryachev, F. Pirajno, “Gold deposits and gold metallogeny of Far East Russia,” *Ore Geology Reviews*, vol. 59, pp. 123–151, 2014.

[10] M. V. Kudrin, V. Yu. Fridovsky, “Structural conditions for the localization of mineralization of the Khangalas ore cluster (North–East of Yakutia),” *Geologicheskie processy v obstanovkah subdukcii, kollizii i skol'zheniya lithosfernykh plit: Materialy IV Vserossijskoj konferencii s mezhdunarodnym uchastiem, Vladivostok, 17–23 sentyabrya 2018*, pp.266–269, 2018 (in Russian).

[11] V. Yu. Fridovsky, M. V. Kudrin, “Deformation structures of the Khangalas ore cluster,” *Geology and mineral resources of the North–East of Russia: materials of the All–Russian scientific–practical conference. Yakutsk: Izd. dom SVFU*, pp. 537–540, 2015 (in Russian).

[12] H. Fossen, “Structural geology,” *Cambridge University Press: New York, USA*, p. 463, 2010.

[13] S. I. Sherman, Yu. I. Dneprovsky, “Stress fields of the Earth’s crust and geological structural methods of their study,” *Nauka: Novosibirsk, Russia*, p.158, 1989 (in Russian).

[14] M. V. Kudrin, L. I. Polufuntikova, V. Yu. Fridovsky, V. V. Aristov, Ya. A. Tarasov, “Geochemistry and form of «invisible» gold in pyrite from metasomatites of the Khangalas deposit, NE Russia,” *Arctic and Subarctic Natural Resources*, vol. 25(3), pp. 7–14, 2020. https://doi.org/10.31242/2618–9712–2020–25–3–1.

[15] M. V. Kudrin, V. Yu. Fridovsky, L. I. Polufuntikova, L. Yu. Kryuchkova, “Disseminated Gold–Sulfide Mineralization in Metasomatites of the Khangalas Deposit, Yana–Kolyma Metallogenic Belt (Northeast Russia): Analysis of the Texture, Geochemistry, and S Isotopic Composition of Pyrite and Arsenopyrite,” *Minerals*, 11(4), pp.403, 2021. https://doi.org/10.3390/min11040403.

[16] V. Yu. Fridovsky, L. I. Polufuntikova, N. A. Goryachev, M. V. Kudrin, “Ore–controlling thrust faults of the Bazovskoye gold deposit (Eastern Yakutia),” *Doklady Akademii nauk*, vol. 474(4), pp. 462–464, 2017.

[17] V. Yu. Fridovsky, G. N. Gamyanin, L. I. Polufuntikova, “The structure, mineralogy, and fluid regime of ore formation in the polygenic Malo–Taryn gold field, northeast Russia,” *Russian Journal of Pacific Geology*, vol. 9(4), pp. 274–286, 2015 (in Russian).

[18] L. M. Parfenov, M. I. Kuzmin etc., “Tectonics, Geodynamics, and Metallogeny of the Sakha Republic (Yakutia) territory,” Parfenov L.M., Kuzmin M.I., Eds. *MAIK “Nauka/Interperiodika”: Moscow*, p. 571, 2001 (in Russian).

[19] A. I. Khanchuk, V. V. Ivanov, “Meso–Cenozoic geodynamic settings and gold mineralization of the Russian Far East,” *Russ. Geol. and Geoph.*, vol. 40(11), pp. 1607–1617, 1999.

[20] N. S. Bortnikov, G. N. Gamynin, O. V. Vikent’eva, V. Y. Prokof’ev, A. V. Prokop’ev, “The Sarylakh and Sentachan gold–antimony deposits, Sakha–Yakutia: a case of combined mesothermal gold–quartz and epithermal stibnite ores,” *Geol. of Ore Deposits*, vol. 52(5), pp. 339–372, 2010 (in Russian).

[21] V. Y. Fridovsky, G. N. Gamyanin, L. I. Polufuntikova, “Gold quartz and antimony mineralization in the Maltan deposit in northeast Russia,” *Russian Journal of Pacific Geology*, vol. 8(4), pp. 276–287, 2014 (in Russian).