Metallogenic specialization of the Precambrian crystalline complexes in the Tyrkanda tectonic zone between granulite terranes of the Aldan-Stanovoy shield (North-Asian craton)

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Abstract. The study of the composition of the Precambrian crystalline complexes raised and exposed along the margins of the North Asian craton allows us characterizing the conditions of formation and clarifying metallogenic typification of the geological structures of various stages of evolution of the lithosphere. Based on these data identification of the promising metallogenic zones and local potentially ore-bearing objects can also be achieved. The goal of the research was to characterize the chemical composition features of geological complexes in the Tyrkanda tectonic zone between the granulite terranes of the Aldan-Stanovoy shield in the south of the North Asian craton. The object is interesting due to the presence of a large number of different types of metamorphic and magmatic rocks. Complex geological structures with numerous stages of intensive ductile and brittle deformations of various kinematics are observed. As a part of the research for the rocks of the zone, the petrographic observation was done and chemical composition was studied. Characteristics and typification of rocks were carried out. Reconstruction of the primary (premetamorphic) types of rocks was performed using the methods of Predovsky and Neelov. A cluster analysis of geochemical data was performed. The excess of background concentrations of chemical elements in clusters was calculated. According to the calculation results, metamorphosed ultramafic and mafic rocks of tholeiitic magmatic series form a single cluster. These rocks are richer with indicator elements for diamond and precious metals. A short description of the probable types of mineralization in these rocks was provided. The most promising for precious metals surrounding areas was determined.

1. Introduction
When studying the outcrops of the crystalline basement of the North Asian craton, and in particular the Aldan-Stanovoy shield, many methodological approaches to their stratigraphic breakdown and tectonic zoning were used: formation, metamorphic, structural, etc. [1-5]. The rocks of the area that were metamorphosed mainly in the conditions of granulite facies, passed a complex deformation history, and experienced various superimposed changes in places. These rocks belong to formations
that have completely lost reliable petrographic and many geological features of igneous and sedimentary rocks. In this regard, when determining the primary nature, petro- and geochemical features of the rocks come first. Petro- and geochemical methods are used based on the assumption of fundamental similarity of the composition of igneous and sedimentary rocks of all geological epochs from the Early Precambrian to the present day, as well as the possibility of preserving the features of their chemical composition during the regional metamorphism. Most Russian researchers currently support both assumptions. The idea of the isochemical character of regional metamorphism is based on petro- and geochemical studies in zonal and areal metamorphosed complexes [6-8]. Therefore, as part of this work, not only the petrographic but also chemical compositions of the rocks were studied.

2. Geological characteristics of object

Studies of the last decade proved that the Paleoproterozoic granulite complexes, as well as fragments of the earth's crust composed of granite-greenstone formations of both Archean and Paleoproterozoic age, play a significant role in the structure of the Aldan-Stanovoy shield [9]. A wide development of deep thrusts, thrust sheets and large shifts have been established, and several metallogenic zones have been identified, which formation is related to the amalgamation of the Early Precambrian terrains into a single large continental block. Paleoproterozoic platinum [10] and gold [11-13] and single diamonds [14, 15] were described.

Between the granulite terrains of the shield – at the boundaries of the Nimnyr, Sutam and Uchur terrains, the Paleoproterozoic (remobilized in Mesozoic) Tyrkanda-Stanovoy gold-bearing zone with gold and polymetallic mineralization was identified [11] (figure 1 and 2).

![Figure 1. Scheme of metallogenic zoning of the Early Precambrian complexes of the Aldan-Stanovoy shield (based on [11; 14-17]): 1 – geological blocks with a predominance of the Archean rocks; 2 – tectonic zones (with red boundaries) and terranes with a predominance of the Paleoproterozoic rocks; 3 – accretionary and collisional granites and anorthosites; 4 – faults; 5 – Precambrian gold deposits, ore clusters; 6 – deposits and areas with gold-polymetallic mineralization; 7 – finds and areas with platinoids in alluvial deposits; 8 – single finds of Precambrian diamonds in primary rocks and placers; 9 – metallogenic zones in terranes: West Aldan 2.6-1.8 Ga, Dyos-Leglier 2.1-1.9 Ga, Uchur and Timpton 1.9-1.8 Ga, 10 – zones with gold in blastomylonites and quartz veins (1.9-1.7 Ga); 11 – manifestation of the Mesozoic activation.](image-url)
Figure 2. Geological scheme of the Early Precambrian complexes of the Tyrkanda-Stanovoy metallogenic zone (breakdown of geological complexes according to [3; 11; 18], mineral resources are shown based on the materials of "Yakutskgeologia" JSC). (A) Scheme of the northern half. (B) Scheme of the studied area. Conventional signs: NM – Nimnyr terrane, SU – Sutam terrane, UC – Uchur terrane, IN – Idzhek-Nuyam fault, T – Tyrkanda fault; 1 – Seimskaya strata; 2 – Idzhekskaya strata; 3 – Kyurikanskaya strata; 4 – Kholbolokhskaya A strata; 5 – Kholbolokhskaya B strata; 6 – Fedorovskaya strata (NM) and similar rocks in composition (UC); 7 – crystalline schists and ultramafites; 8 – hypersthene gneisses and granite gneisses; 9 – Ust-Timpton massif; 10 – granitoid massifs (undivided); 11 – dikes of dolerites (only studied); 12 – sedimentary cover of the craton; 13 – Mesozoic syenites; 14 – thrusts; 15 – faults; 16 – zones of greenschist diaphtorites, faults with recrystallization of granulite complexes in the conditions of greenschist, amphibolite and epidote-amphibolite facies; 17 – intersections of granulite complexes used for this work; 18 – gold-bearing
areas; 19 – findings of chromite; 20 – platinum-bearing area. The characteristics of the complexes are below in the text part.

The studied area of the metallogenic zone (figure 2) characterized by numerous stages of intensive ductile and brittle deformations of various kinematics [19]. The structure of the zone involves tectonic plates composed of various associations of rocks of the surrounding terranes (in descending order of age): 1) enderbite-, charnockite- and granite gneisses (orthogneisses of infracrustal complex); 2) hypersthenic-containing diopside±amphibole plagiogneisses with interlayers and lenses of two-pyroxene-hornblende schists, calcareous-silicate and diopside rocks, garnet-hypersthene-biotite plagiogneisses and gneisses (Idzhekskaya strata); 3) rhythmical alternation of strata of amphibole-biotite-garnet gneisses, two-pyroxene-hornblende schists with layers and lenses of calciphyre, calcareous-silicate and diopside rocks (Kyurikanskaya strata); 4) monotonous garnet-biotite plagiogneisses with rare interlayers of calcareous-silicate rocks, quartzites, high-alumina gneisses (Kholbolokhskaya A strata) or two-pyroxene-hornblende schists (Kholbolokhskaya B strata) [3; 11] (figure 2). The plates plunge gently to the east [20] and are restricted by narrow zones of blastomylonites, sometimes saturated with granitoid bodies [11]. The values of TNd(DM) obtained in the IPGG RAS (St. Petersburg) for the studied sites are as follows: 1) Seimskaya strata 2972-2478 Ma; 2) Idzhekskaya strata 2603-2381 Ma; 3) Kyurikanskaya strata 2398-2303 Ma; 4) Kholbolokhskaya strata 2374-2193 Ma. The lower age limits of protolith formation of these complexes in the area are close to the limits of their formation in other areas of the shield [21]. The ancient structures of the terrane were repeatedly activated in PR3, PZ and MZ-KZ. Ore regions inherited more ancient heterogeneities [22; 23]. Petrographic data according to observations in thin sections are systematized in the table. The chemical composition of geological complexes is described in the following sections.

Table 1. Petrographic characteristics of geological complexes of studied area with conventional sign number on figure 2

| №  | Index | Rocks of southern site | Index | Rocks of northern site |
|----|-------|------------------------|-------|------------------------|
| 1  | cs sm | OpxCpxHblPl±Bt±Ap±Carb crystalline schists | gn1sm | GrtBtPlQtz±Kfs±Opx gneisses |
|    | gn2sm | OpxCpxHblPlQtz±Kfs±Ap gneisses | kv sm | Qtz±Di±Pl±Bt quartzites |
|    | evl sm | GrtQtzOre±Opx±Pl±Bt eulysites |      |                         |
| 2  | cs id | OpxCpxPlBt±Hbl±Amp±Ap crystalline schists | gn1id | OpxPlQtz±Hbl±Bt±Kfs±Cpx±Ap gneisses |
|    | gn2id | GrtBtPlKfsQtz±Zrn gneisses |      |                         |
| 3  | cs1kr | CpxAmpBtPl±Opx±Qtz±Chl±Ser±Carb crystalline schists | cs kr | OpxCpxHblBtPl±Qtz±Ap crystalline schists |
|    | cs2kr | OpxAmpBtPl±Cpx±Qtz±Ser±Ap crystalline schists | mc kr | DiCarbQtz±Pl±Scp±Sph calciphyre |
|    | gn1kr | GrtPl±Kfs±Qtz±Hyp±Bt±Ser±Carb±Chl gneisses | gn1kr | OpxBtPl±Qtz±Hbl±Ap±Sph±Ser±Carb gneisses |
|    | gn2kr | OpxKfsPl±Qtz±Cpx±Hbl±Bt gneisses | gn2kr | GrtBtPlQtzMs gneisses |
|    | gn3kr | PlQtz±Opx±Cpx±Amp±Bt±Ap plagiogneisses | gn3kr | CpxPlQtz±Kfs±Bt±Carb plagiogneisses |
Continuation of Table

| №  | Index | Rocks of southern site | Index | Rocks of northern site |
|----|-------|------------------------|-------|------------------------|
| 4-5| cs1ha | 2PxPl+Hbl+Bt+Qtz=Grt crystalline schists | cs1hl | OpxCpxHblPl+Grt+Qtz+Bt+Ap crystalline schists |
|    | cs2ha | OpxPl+Cpx+Am+Bt+Ap+Qtz crystalline schists | cs2hl | OpxCpxHblPl+Grt+Qtz+Bt+Ap crystalline schists |
|    | cs1hb | Pl+2Px+Am+Bt crystalline schists | cs3hl | OpxCpxPl+Hbl+Bt crystalline schists |
|    | cs2hlb| Cpx+2Pr+Omp+Bt crystalline schists | sc hl  | DiPlSp+Carb+Bt+Am+Ser crystalline rocks |
|    | sc hlb| Cpx+Pl+Gr+Sp+Phl+Qtz+Carb skarnoids | mc hl  | DiScpCarbSp+Am+P+Pl calciphyres |
|    | mc hl | CarbSrP[Ol] calciphyres | gn1hl | OpxPlQtz+Bt+Bt+Kfs+ Cpx+Am+Carb gneisses |
|    | gn1hl | GrtSilPl+Kfs+Qtz+Gr gneisses | gn2hl | PIQtzBt+Grt+Sil+Cr+Rt+Kfs gneisses |
|    | gn2hl | GrtPlQtzBt+Kfs+Sil+Ser+Ap gneisses | gn3hl | GrtPtPlQtz+Opx+Kfs+Ap+Ch+Rt gneisses |
|    | gn3hl | GrtPlPtz+Kfs+Sil+Ch+Ser gneisses | gn4hl | OpxPlPtz+Kfs+Gpx+Gnt+Ap gneisses |
|    | qtz hla| OpxPlQtz+Kfs+Gnt+Ap gneises | QtzKfs quartz |
| 7  | idc1  | Ol+Cpx+Amp+Phl ultramafites | dc1   | OpxCpxHbl+Bt+Am+Pl |
|    | idc2  | 2PxAmPl+Bt+Ser crystalline schists | dc2   | OpxCpxBt+Pl+Hbl+Olt+Qtz+Am+Carb crystalline schists |
|    | idc3  | OpxPl+Cpx+Kfs+Hbl+Bt+Ser+Carb+Qtz crystalline schists | dc3   | OpxCpxPl+Hbl+Am+Ap crystalline schists |
|    | idc4  | SplOpx+Ol+Cpx+Am+Bt ultramafites | dc4   | HblBtPl amphibolites |
| 8  | mg1   | GrtPlQtz+Bt melanosome | enm   | PIQtz+Opx+Bt+Ap enderbites |
|    | mg2   | PkfsQtz+Grt+Bt+Ap+Ser migmatite | ggn   | BtPfKfsQtz+Ser+Ap granite gneisses |
|    | mg3   | PkfsQtz+Ser leucosome | xen utm | CpxHbl+Opx+Bt xenoliths |
| 9  | grn   | PkfsQtz+Am+Bt+Grt granites with skoliths | chm   | BtPfKfsQtz+Opx+Hbl+Ap granites |
|    | grd   | KfsPlQtz+Ser+Carb leucogranites | lgr   | PIQtz+Kfs+Bt+Chl+Ms+Carb leucogranites and pegmatites |
| 11 | dol   | PfKfsPx+Oli+Bt+glass dolerites | | |
| 14 | f     | PkfsQtz+Grt+Ser+Carb mylonites | fgn1  | OpxPlPtz+Bt+Am+Kfs blastomylonites and blastocataclasites |
| 15 | f     | PkfsQtz+Grt+Ser+Carb mylonites, blastocataclasites | fgn2  | GrtPlQtz+Kfs+Opx+Bt+Ser+Ap blastomylonites, blastocataclasites |
|    | f     | ChlSerQtz+Kfs+Car+Ap+Grt+Pl diaphoritites | fgn3  | SiGrtBtPfKfsQtz blastocataclasites |
| 16 | Q f   | Qtz+Chl+Fb+Bt+Lm quartz | dgn1  | GrtBtChlPlSerQtz+Rt+Ap+Kfs diaphoritoned gneisses |
|    | cs f  | Pl(Cpx+Bt)+Am+Bt+Gnt+Ap boudins of crystalline schists | dgn2  | BtChlPfKfsQtz+Ser+Sp+Ap+Zrn diaphoritoned gneisses |
|    | FS f  | KfsPlQtz+Chl+Ser+Carb metasomatites | q     | Qtz+Qtz Px quartz |

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Abbreviations of minerals: Act – actinolite, Amp – amphibole, Ap – apatite, Bt – biotite, Carb – carbonate mineral, Chl – chlorite, Cpx – clinopyroxene, Crd – cordierite, Di – diopside, Ep – epidote, Fo – forsterite, Fs – feldspar, Grt – garnet, Gr – graphite, Hbl – hornblende, Hyp – hypersthene, Qtz – quartz, Kfs – K-feldspar, Lim – limonite, Ms – muscovite, Ol – olivine, Opx – orthopyroxene, Ore – abundant ore mineral, Phi – phlogopite, Pl – plagioclase, Px – pyroxene, Rt – rutile, Ser – sercite, Scp – scapolite, Sil – sillimanite, Sph – sphene, Spl – spinel, Srp – serpentine, Zrn – zircon.

3. Research methods

In thin sections, associations of minerals were determined; diagnostics and description of rocks were performed. The chemical composition of rocks was determined in DPMGI SB RAS by wet chemistry. The content of impurity elements was determined by x-ray fluorescence spectral analysis using the NitonXL3t device. The contents of rare and rare earth elements were determined in DPMGI SB RAS by the ICP-MS method. Average contents have been calculated for the identified groups of rocks. The calculation results were processed using Statistica 8 software. For the cluster analysis, the Pearson parametric correlation and the Complete Linkage method have been used. Reconstruction of the primary (premetamorphic) type of rocks was performed using the method of A. A. Predovsky [24, 25], supplemented by the method of A. N. Neelov [26]. Classification of rocks is given in accordance with the material composition and recommendations of the Terminological Commission of the petrographic Committee of the USSR [27].

4. The results of the research

High-alumina gneisses and plagiogneisses of the studied strata (gn1hl, gn2hl) correspond in chemical composition to hydromicaeous, less often vermiculite clays. High-ferrigenous rocks (evl sm) are close to mixed products of weathering of basic and ultra-basic rocks. Garnet-biotite, garnet-orthopyroxene-biotite gneiss and granulites (gn1sm, gn2id, gn1kr, gn2hl, gn3hl), as well as graphite-bearing gneiss of different strata (grp), can be defined as analogs of graywackes, polymeric sandstones and arkoses. Garnetless gneisses (gn2sm, gn1id, gn2kr, gn3kr, gn1kr, gn3kr, gn4hl, gn1hl) have alternative solutions regarding their primary nature: Na andesites, dacites and rhyodacites and/or tuffites, graywackes, calcareous sandstones. Carbonate rocks of the Kyurikanskaya strata (mc kr) contain admixture of clastic material that is reconstructed as tuffites. Diopside calciphyles of the Kholbolohskaya strata (mc hl) do not differ from these rocks. The calciphyles with a small admixture of serpentine probably represented calcareous dolomites. The silicate component of these rocks corresponds to vermiculite clays in the composition.

The presence of rocks of the basic composition of both tholeiitic and calcareous-alkaline series is identified in the crystalline schists of the Kyurikanskaya and Kholbolokhskaya strata (cs1kr, cs2kr, cskr, cs...hl...). Gneisses and amphibolites composing the Ust-Timpton massif (gn1utm, gn2utm) are analogous with granodiorites, diorites and gabbro of the calcareous-alkaline series.

Crystalline schists of the Seimskaya and Idzhekskaya strata (cs sm, cs id) belong exclusively to the tholeiitic series, for which the supply of K2O and other mobile elements associated with superimposed processes is recorded. Fragments (dc 1-4) of crystalline schists interpreted as intrusive complexes have a similar composition. Ultramafites and crystalline schists of the fragments (idc1-4) in the chemical composition correspond to lherzolites, and pyroxenites and olivine gabbro of tholeiitic series. Chromite interlayers are observed in these rocks.

Migmatites (mg 1-3), enderbite and granite gneisses (enm, ggn) spatially interlinked with faults (figure 2). These rocks show significant variations in compositions. Small bodies of granites, pegmatites, and feldspar-quartz rocks vary in SiO2 content from granodiorites to predominant leucogranites, and in amounts of alkalis correspond mainly to a sub-alkaline series with transitions
into the field of rocks of normal alkalinity. Granodiorites-granites (grm, chm), often being porphyritic, compose massifs. Leucogranites (grd, lgr) form unmapped veins.

The faults of the area contain milonites, blastomylonites, cataclasites (f, N-NW f, fgn1, fgn2, fgn3), diaphtorites (d f, Q f, cs f, dcs, dgn1, dgn2) and metasomatites (FS f, q) of various composition. Changes related to foliation, mylonitization, and diaphthoresis are represented by the redistribution of Na2O, K2O (supply/loss), and CaO (loss/supply). Supply of SiO2, chloritization, sericitization, pelitization is not frequently identified. Albinitization (zoning) of plagioclase, irregular biotization within the same metabasite body, rarely K-feldspatialization are noticeable. Small bodies are often changed in their entirety.

Just a few samples of the quartz-feldspar metasomatites and quartz have been analyzed. The metasomatic K-feldspatialization of rocks leads to the fact that K2O strongly prevails over Na2O. Such rocks are rich in potassium feldspar and quartz and their chemical composition is indistinguishable from leucogranites. SiO2-rich rocks, including veins, are found near them in fault zones.

Cluster analysis of the obtained average values of chemical elements and rock-forming oxides by petrographic groups shows that two large groups of rocks can be identified (figure 3).

**Figure 3.** Tree diagram of correlations between the groups of the rocks listed in table 1. The excess of background concentrations of chemical elements and oxides in groups are signed above the clusters (normalized to background). Similar compositions marked with color. The sign indicates that there are no anomalies that exceed the background value by two times. Numbers and signs are listed in the order of the marked indexes.
The first group is presented by analogs of tholeiitic ultrabasic-basic igneous rocks, products of their weathering with geochemical anomalies: iron, magnesium, titanium, vanadium, manganese, chlorine and volatile substances, nickel, cobalt, zinc, copper, arsenic and sulfur, tungsten, antimony, barium and heavy rare-earth elements (marked with red for the figure 3). The second group is presented by analogs of quartzites, arkoses, polymicts, graywackes, medium and acidic igneous rocks and tuffites with anomalies of silicon, potassium, rubidium, radioactive and light rare-earth elements, lead and bismuth (marked with blue for the figure 3). In the same group, we can add analogs of carbonate sandstones, diorites and gabbro of the calcareous-alkaline series, some of the crystalline schists without geochemical anomalies (figure 3, sc hl – cs kr cluster). The third small group is presented by carbonate rocks with barium and strontium in chemical composition. This group (figure 3, mc cluster) is slightly correlated with other rocks.

5. Discussion
According to the results of cluster analysis, the elements-indicators of diamond and precious metals are more common in analogues of the rocks of the tholeiitic series and weathering products of the basic and ultrabasic rocks. Such rocks are common in the Seimskaya strata, Idzhekskaya strata and in the intrusive complexes. The geochemical specialization of these rocks is similar to komatites in the Olondinsky greenstone belt, which are associated with finds of Au, Pt, and diamond (Olondo in figure 1) [28]. The absence of garnet in lherzolites of the studied area does not allow us to state that, they belong to the deep, potentially diamondiferous rocks, which fragments are known within Numnyr terrain [14]. But the presence of the significant concentrations of chromite in serpentinized peridotites of the studied area does not allow us to exclude the possibility to detect not commercial diamonds like associated with Cordilleran ultramafic complexes [29].

According to data [16], ⁹⁰Pt-⁴He age determinations of sperrylite from placers surrounding the studied areas show values from the Neoarchean to Mesoproterozoic, which allows us to assume sources among the analyzed rocks. The sperrylite of some placers was subjected to thermal transformation under the influence of superimposed metamorphic or hydrothermal processes. Similar mineralization is known in the peridotite-serpentinite Hitura massif on the Baltic shield [30] where sperrylite is associated with pyrrhotite, pentlandite and chalcopyrite and is located in the chlorite-serpentine matrix of changed rocks [16]. Crystalline schists and ultramafites with anomalies of copper, nickel and arsenic should be examined on a platinum content.

Faults and diaphtorites along the outcrops of the crystalline schists (figure 2) have the potential for gold content. Submeridional faults and diaphtorites of the area contain anomalies of copper, lead and zinc (figure 3), and in the northern part of the area - gold-bearing quartz. Forecasting-prospecting criteria for the Precambrian and Mesozoic diaphtorites are discussed in detail in the works [13; 31].

In the crystalline schists confined to the thrusts, molybdenum-bearing objects of the Sis ore occurrence type can be detected. This ore occurrence located in the south of the studied area. Tungsten-molybdenum-bearing plagioclase (70-90%), diopside, quartz, potassium feldspar, apatite, scheelite, and scapolite metasomatites in it form lenses on the contact of mafic-ultramafic rocks with granites.

6. Conclusion
The Precambrian crystalline complexes in the Tyrkanda tectonic zone between the granulate terranes of the Aldan-Stanovoy shield are divided into two groups according to the results of the cluster analysis of chemical composition: 1) metamorphosed ultrabasic-basic tholeitic complexes and weathering products enriched with siderophilic and chalcophilic elements; 2) granitoids, metamorphosed igneous rocks of the calcareous-alkaline series and terrigenous complexes enriched with lithophi lic elements. The first association and the surrounding areas are more promising for searching for deposits of precious metals.
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