Geology, Geochemistry and Mineralogy of the Gneissic Trondhjemites, Tonalities, Granodiorites and Related Rocks within the Proterozoic Idzhek-Nuiam and Tyrkanda Faults of the Aldan Shield (North Asian Craton)

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Abstract. Researched magmatic rocks, which undergone the process of polymetamorphism in granulite, amphibolite and greenschist facies, earlier by some geologist was defined as paragneisses and (or) intrusive rocks. In this paper based on geological and geochemical data argue the magmatic nature of rocks and identity to the calc-alkaline series. The series consists of gabbros, diorites, quartz diorites, granodiorites, tonalites and trondhjemites. Contents of the rock-forming oxides and rare earth elements in these rocks are close to the widely known early Proterozoic gabbro-diorite-tonalite-trondhjemite series of the South-West Finland. These features indicate the probability of formation of the researched rocks with the participation of the subduction. As a results of studies established what in M complex possible inclusion of rocks and bodyes from other sites such as Ust-Timpton, Idzhek-Seym and Upper-Gonam pluton. The features of the MS include the linkage with the long-lived faults and associated dynamometamorphic changes of the bodies, polymetamorphism, superimposed chemical changes in the composition of primary rocks, as well as rarely preserved migmatite veinlets in the host rocks. Geochemical similarity of trondhjemite-, tonalites, granodiorites Mariin series and associated rocks with well-known early Proterozoic differentiated series of southwest Finland typical for the Proterozoic and Paleozoic continental margins suggests that the plutons of the Mariin series formed in an active continental margin setting.

1. Introduction
Rocks of trondhjemite, tonalite and granodiorite compositions throughout the Earth's geological history were formed under different geodynamic settings. Specifically, important the studies of such rocks in the Early Precambrian highly metamorphosed areas, where they exist at the extensive space and form separate plutons among the greenstone belts and along the continental margins [1]. On the Aldan Shield such rocks of different age levels are known on all terrains and in zones of tectonic melange [2,3,4]. One of such zones is Tyrkanda mélange zone, which is restricted by the Idzhek-Nuiam and Tyrkanda faults. In this zone, like at the various Precambrian areas, series of the trondhjemite, tonalite and granodiorite compositions are accompanied by more mafic plagiogneiss and the crystalline schists. For a long time, the combination of these rocks on the basis of petrographic data were included in the stratigraphic suites allocated along the faults. However, E. P. Maximov and his colleagues identified [5]...
gabbro-plagiogranite formation in the Tyrkanda fault zone. They showed on the geological map a number of the plutons "composed of diorites, granodiorites, plagiogranites, less gabbroid facies", but did not provide the geochemical data. In addition, the geological survey of the "Yakutskgeologiya" state company in the North-West of the Idzheke-Nuiam fault identified a pluton and small bodies of plagiogranites [6]. This article presents the results of geological observation and the first study of the chemical composition of minerals and rocks, distinguishing them in the rank of a single series. The series compared by us with the widely known early Proterozoic gabbro-diorite-tonalite-trondhjemite series of the South-West Finland. It should contribute to the development of arguments about geodynamics of the Aldan Shield in the Early Precambrian.

2. Geology and petrography of locations

The Mariin site. The Mariin migmatic pluton and the concordant bodies of the tonalites and plagiogranites (plagiogneisses) were highlighted by D.V. Utrobin in 2003 in the state map sheet O-52-VII. Previously, these plagiogneisses were involved in Sunnagin [5]. For the considered intrusions of the Mariin site, the isochrons were obtained: U-Pb by zircons 2113±12 million years and Sm-Nd by rocks, plagioclase and apatite 1960±190 million years.

Principally we have studied and sampled the main bodies of these rocks in outcrops on the Aldan river coastline (Figure 1). The most extensive outcrop (300 m) of the amphibolites is located in the point marked as 4212 (Figure 1). In the points marked as 4207, 4209, 4211, 4213, 1051 crystalline schists of Kholbolokh stratum were transformed to the injection migmatites whith trondhjemites leucosomes (2-5 cm) and melanosomes of comparable thickness. The main rocks of the series are the leucocratic plagiogneisses which are compose more or less monotonous outcrops up to 400 m.

Different proportions of Opx, Cpx, Hbl, Bi, Pl, ±KFs, Q1 form mineral parageneses corresponding to granulite and high-temperature and lower-temperature amphibolite facies. In association of Hbl and Bi in granulite-facies rocks content of TiO2 is higher than in the associations of amphibolite-facies rocks. The appearance of minerals of the greenschist facies is usually associated with second cleavage and mylonitisation of rocks. Sulfide mineralization in that rock is represented by pyrite and chalcopyrite and is associated with chlorite and calcite, which replace hornblende, and with epidote, which replace plagioclase. In addition to sulfides, there are microinclusions of native gold with an admixture of silver from 4 to 8 %, microinclusions of barite, native copper and copper 65-75% with an admixture of tin 25-35%.

Ust-Timpton pluton (UTP). At the site of the Timpton river mouth in 1936 discovered the presence of gneissic granodiorites [7]. Later, on a number of maps the outcrops of these rocks were contoured as a granite massif [5] or were not mapped at all. But as a result of petrochemical data, we restored the initial diagnosis [8].

UTP is located in the axial part of the Tyrkanda fault and represents a tectonic lens with a length of over than 8 km, and thickness up to 1.5 km. 6 km to the South-East in the basin of B. Kurikan river there is another lens-shaped body. Upstream there are several granite massifs in the fault zone on geological maps. UTP and small body are composed of monotonous blastocataclasites Bi and BiHbl plagiogneiss dissected by a network of the low-thickness blastomylonite seams. In the plagiogneisses there are the bodies which are similar to the layers (up to 4 m), also as boudins and small fragments (autolite) of more melanocratic plagiogneiss and amphibolites.

1 Abbreviations: Ab – albite, Act – actinolite, Al – allanite, Ap – apatite, Bi – biotite, Chl – chlorite, Cor – cordierite, Cpx – clinopyroxene, Ep – epidote, Gr – garnet, Hbl – hornblende, Kfs – K-feldspar, Ilm – ilmenite, Mn – monazite, Mt – magnetite, Mu – muscovite, Opx – orthopyroxene, Ort – orthite, Pl – plagioclase, Q – quartz, Ser – serizite, Sil – sillimanite, Sph – sphene, 2Px – two-pyroxene, Zc – zircon, Zo – zoisite
Figure 1. Schematic geological map of the Aldan river area above the mouth of the Timpton river (after [6] with changes to geological boundaries according to the own field observations). 1- alluvium, 2- deposits of platform cover (Vend). The early Precambrian basement (3-7): 3- Na-K granites without disjunction, 4- syenitic gneisses, 5- bodies of the Mariin series, 6- Kholbolokh stratum, 7- Kurikan stratum, 8- faults, 9- mylonites, foliated rocks, 10- most studied outcrops. On the inset – the Scheme of the geological structure of the Central part of the Aldan Shield. Archean series: WAD- West Aldan granite-greenstone composite terrane. Proterozoic series: Granulite blocks (terranes) of the East Aldan superterrane: SN- Sunnaginsky, GN- Gonamsky. Granulite blocks (terranes) of the Central Aldan superterrane: NM- Nimnysky, SM- Seymsky, ST- Sutamsky. Tectonic mélange zones: am- Amga zone, kl- Kalar zone, tr- Tyrcanda zone. Faults: IN- Idzhek-Nuiam, Tr- Tyrcanda fault. Circles (1-6) show sites of the research: 1- the Mariin, 2- Ust-Timpton, 3- Idzhek, 4- Lower-Seym, 5- Middle- Seym, 6- Upper-Gonam. Grey areas are the sedimentary cover of the Siberian Platform.

In the plagioclase of the cataclasites and in the intergranular aggregations of the granulites, Ser(Mu)EpZoKFsAb is observed. In Bi and zoned Hbl (green → blue-green) Chl and Act grew up. Exceptionally rare, mainly in the amphibolites, the relics of Opx, Cpx and brownish Hbl are remained. Associations of low-temperature amphibolite facies in the rocks are clearly dominant. In UTP rocks are often found as a result of optical Mt, Sd (pyrite, chalcopyrite, etc.), Sph, F-Ap.

Idzhek-Seym plutons (ISP). These plutons were identified by V.L.Duk and colleagues [2] at three sites. On the Idzhek site (submeridiona 1 30 x16 km area near the mouth of the streams Idzhekchan, Right, Left and Middle Idzhek) according to the data of geological survey 12 bodies of metagabbro and metadiorite are mapped. The largest of them has a whimsical branchy (folded) shape, 8 x 3 km. Other bodies also have curved borders or a lenticular shape. They are located within the marked the IN fault granitic rocks and to the West from the fault in the field of enderbites of Seym block (Duk et al., 1986;
Beryozkin, et al., 2015b), and also to the East in the area of rocks of Kholbolokh stratum. Previously these bodies were included in Sunnagin stratum called crystalline schists [5]. 13 samples of Hbl2Px(±Bi), Cpx,Hbl(±Bi) crystalline schists (gabbro) and 1 sample of HblCpxBi plagiogneisses (quartz diorites) from the Idzhek site were analyzed. Middle-Seym site is located near the mouth of the Mamulay river, the right inflow of Seym river. Here in the sublatitudinal area ~ 10 x 6 km V. L. Duk and S. N. Pavlov passed a network of routes of scale ~ 1: 100 000. More than half of the site is occupied by NaK granitic rocks of the IN fault. At the site and to the North on the adjacent to the IN fault areas of granite rocks, Seym and Kholbolokh stratum rocks, several plutons and small bodies of CpxHbl, 2PxHbl plagiogneisses (number of diorites – 4, of quartz diorites – 2, of tonalites – 1) were mapped. Unfortunately, ore and accessory minerals due to the loss of samples have not been studied. Lower-Seym site is located in the lower flow of the river Seym 4.5 km above the mouth of the Yerga river to the West from the IN fault. According to the data of A. N. Zedgenizov on the coastal outcrops, we mapped the pluton elongated in the submeridional direction ~ 5x1 km which intruded the rocks of the Seym stratum and contained the amphibolites, CpxHbl and 2PxHbl crystalline schists (gabbro – 6 analyses) and CpxBiHbl plagiogneisses (diorites – 2 analysis).

Upper-Gonam pluton (UGP) was selected according to the materials of K.A. Lazebnik of 1967 year and was correlated with ISP. Later, as for the ISP, additional analyses were obtained. K. A. Lazebnik described the discontinuous outcrops of the Gonam river in the range 7-9 km (in a straight line) above the mouth of the Itymjga river. At the beginning and at the end of the interval, rarely in the middle, granite gneiss is exposed. In the middle of the interval BiHbl 205 plagiogneiss with the different content of dark-colored minerals, rare Opx-bearing (to 1-2 %) plagiogneiss and amphibolites (±Bi, Opx, Cpx) occur. The latter observed in 1.5 km outcrop of the plagiogneiss as the small fragments. According to the observations of K.A. Lazebnik plagiogneiss markedly predominate over amphibolites. Some plagiogneiss contain porphyroblasts of Kfs up to 5-7 %. In all rocks the veins and veinlets of granites and pegmatites are observed. Low-temperature minerals (Ser, Mu, Chl, Zo) are observed much less frequently than in Marin site and UTP. According to mineral paragenesis and TiO2 content in Bi and Hbl metamorphism of rocks corresponds to amphibolite facies, with transition to granulites.

3. Geochemistry

The Marin site. Figure 2 shows widely spread of rock analyses by SiO2 and Na2O+K2O. At the same time, most of the points with SiO2 < 57% lays in the field of subalkaline rocks, and all the points of rocks with SiO2 > 60% lays in the field of normal alkalinity, despite the wide variations of Na2O+K2O. By the analogy with other similar rocks [9] this distribution of the figurative points of the granulite crystalline schists and plagiogneiss we can explain by the content changes of alkalis during metamorphism in the rocks of the MS. As a result of introduction of alkalis in the basic and the intermediate-basic rocks they have changed from normal alkalinity to subalkaline chemical composition. Rare samples with low SiO2 and high MgO (> 8%) remained unchanged. Tonalite-trondjemite under a slight adding or removal of alkalis or were not changed. Apparently, in their protoliths, contents of Na2O and K2O were close to the average composition of these plagiogneiss. A clear example of adding of K2O is the sample of probably changed trondjemite 4219: SiO2 =72.4 %, K2O=2.64 %, with Ser and Mu. In general, the addition of Na2O+K2O in MS rocks did not exceed 1-1.5 %, which is much lower than in similar rocks [10]. Taking into account the mobility of alkalis, calc-alkaline primary nature of the protoliths' of MS is assumed (Figure 2,3). This conclusion is consistent with the higher content of Al2O3, CaO and lower TiO2, ΣFeO. As a rule trondjemite rocks have SiO2 < 70 % and Al2O3 > 15 %, which allows to consider them also as the high-alumina type [1].

Tonalites and trondjemites of the Marin site (samples 4207/1A, 2836, 4209/1, 4206) by the concentration of REEs are almost identical to trondjemites of SWF (Figure 4a). Only leucosome of QPI migmatite 1051/1 is extremely poor inREE, especially heavy elements, but has a remarkably similar distribution of REE with trondjemite UK [9]. Diorite 4208, the most saturated by the rare earth
elements, by the amount and distribution of them is comparable to quartz diorite UK-6 and gabbro UK-9 SWF, with the exception of the deficit of the Eu. Quartz diorite 4215, gabbro 4212, leucogabbro 4212/2, hornblendite 4212/3, despite the strong differences by concentration of the rock forming oxides, are close by the REE concentration. These rocks differ from the rocks of the upper field of SWF at the Figure 4a by low contents, low differentiation of REEs and (+) Eu-anomalies (in gabbro Eu-anomaly is hardly noticeable). The distribution line of HREEs in these rocks lies in the upper part of the lower field and in the area of the gap between the fields, and the LREE lines are mainly in the lower field (Figure 4a).

**Figure 2.** The distribution of the figurative points of analyses of the studied gneissic trondhjemites, tonalites and granodiorites with associated rocks in the diagram SiO2 – (Na2O+K2O). Above the line there are the fields of magmatic rocks of moderate alkaline family, below the line there are the fields of rocks of normal alkaline family [11]. Figurative points of analyses of rocks (1-5): 1 – Mariin site, 2 – Ust-Timpton site, 3 - plutons on the Idzhek and Seym rivers, 4 – Upper-Gonam pluton, 5 - rocks of the South West Finland [9]. The analyses of rocks were recalculated to 100% excluding the volatile components. The samples with identified concentrations of REE marked by the blue color, the area of the blue field corresponds to the Σ REE (Table 2).

The highest Sr content (1020 ppm) is associated with high Al2O3 and CaO (plagioclase) in leucogabbro. Other types of rocks in the Mariinsky site are characterized by increased Sr and low Rb sometimes more significant (up to 55 ppm), as well as higher K2O up to 1.6 %. Variations of Zr = 72-200 ppm.

**Ust-Timpton pluton.** The dominant granodiorites contain higher K2O at narrower limits of variations of the alkali sum than the acid rocks of the Mariin site (Figure 2). However, the probability of a slight (up to 0.5%) addition of K2O is not excluded. In the more basic rocks of UTP the addition of alcalis is determined, especially K2O. The sample 1955/2 of diorite gneiss with K2O = 3.64 %, Na2O =to 3.77 % and increased KFs and Bi can serve an example of explicit addition of K2O. In the quartz diorites high concentration of K2O up to 3.6 % is also defined. With the exception of these samples, changes in Na2O+K2O are less than in the rocks of the Mariin site, not exceeding 1 %, and unchanged samples are present (Figure 2). At the same time, the average compositions and the contents of other oxides of quartz diorites, diorites and gabbro UTP and the Mariin site are very close. In UTP boudin and amphibolite fragments were sampled more often than in MC.
Figure 3. The distribution of the points of the studied gneissic trondhjemites, tonalites and granodiorites with associated rocks in the diagram, Al – (FeT+Tl) – Mg [12].

Figure 4. a - REE distribution in the rocks of the Mariin site, normalized by chondrite [13]. Sample numbers correspond to the numbers in the table. 2. Gray fields – area compositions of rocks of gabbro-diorite-tonalite-trondhjemite series of SouthWest Finland [9]: bottom field – trondhjemites, upper field – other differentiates. b - REE distribution in the rocks of the Ust-Timpoton pluton, Middle-Seym site (numbers 16, 18) and Upper-Gonam pluton (numbers 19, 20), normalized by chondrite [13]. Gray fields – area compositions of rocks of gabbro-diorite-tonalite-trondhjemite series of SouthWest Finland [9]: bottom field – trondhjemites, upper field – other differentiates.
According to the chemical composition, they are quite clearly divided into autoliths and xenoliths. Analyses of the autoliths were included as average values for amphibolites of the UTP, for the xenoliths - their own average composition was calculated. Most of inclusions are changed. In some of them, except alkalis, it is assumed to add SiO2 (samples with SiO2 > 54 %). Similar in the chemical composition with xenoliths, tholeiitic crystalline schists are typical for the country rocks of Kholbolokh and Kurikan stratum.

A sample of granodiorite 4243 UTP is much richer in REE, especially light, it is characterized by the (-)Eu anomaly, than is markedly different from trondhjemites and tonalites MC (Figure 4b). Quartz diorite (1047/1), diorite (1048/2) and gabbro (2076/6) are more enriched with the HREE and depleted by LREE than granodiorite, and have a flat distribution of REEs and negative or missing Eu anomalies. The lines of HREEs in these rocks, including granodiorite, are located in the region of the gap between the fields of rocks SWF, and the lines of LREEs are located in the lower part of the upper field. The gabbro line (1956/5) was isolated in the upper field due to high REE content and in all parameters REE is very close to the diorite 4208 of the Mariinsky site (Figure 4b).

Higher Sr (up to 1300 ppm), Rb (slightly higher) and Ba (up to 1460 ppm) (much higher) in UTP rocks than in Mariinsky rocks have been discovered. In these rocks, the content of Ba and Rb directly depend on the content of K2O. The contents of Zr, Hf and Y are comparable with the Mariin rocks, and U and Th are higher and much higher (4243).

Idzhek-Seym plutons. In contrast to the others, these plutons are composed mostly of gabbro and diorite. Chemical affinity of these rocks with the same species of the Mariin site, UTP and UGP is presented in Table 1 and Figure 2. In addition, it can be noted that the most leukocratic gabbro from the Idzhek site with Al2O3 = 21% are comparable to the Mariin leucogabbro. High Na2O+K2O concentrations are mainly related to addition of K2O. One sample of the tonalites at low total alkalinity is comparable with the Mariin trondhjemite with alkalis removed, and two samples of quartz diorite are subordinate to the general trend of gabbro and diorite.

Trace elements discovered in the samples 349B gabbro, 1327/2 and 1150/2 diorites of the Middle-Seym site. Gabbro 349B in the parameters of the REE, except for the lack of Eu-anomalies is comparable with the Mariin 4208 diorite and UTP 1956/5 gabbro. This rock it is close to quartz diorites UK-6, 7, 10 South-West Finland (Figure 4b) [9]. Diorite 1327/2 differs from all mentioned species of rocks due to the enrichment of the HREEs. Another diorite has the highest sum and (-)Eu anomaly in REE pattern. In 349B gabbro and 1327/2, 1150/2, 1956/5, 4208 diorites discovered high contents of Zr, Y and Nb. The highest contents of Yb and Nb are determined in 1150/2.

Upper-Gonam pluton is characterized only with ten analyses. The single point of preserved primary (presumably) composition of trondhjemite, is in the middle of the swarm of points of analyses of Mariin tonalites and trondhjemites. Other rocks have more or less experienced the addition of alkalis. In the most modified quartz diorite, the added share of Na2O+K2O is estimated at 1.5-2 %. In Table 1 and Figure 2, 3 it is noticeable that the rocks of UGP are closer to the rocks of UTP in the chemical composition. Granodiorite 94A in the parameters of the REE and the content of other trace elements is close to the 4243 granodiorite and 1047/1 quartz diorite of UTP. And quartz diorite 99A differs from these rocks by the strong depletion of LREE, Rb, Ba, Zr (Figure 4b).

4. Results and discussions
The presented materials allow including into the Mariin series (MS) not only the rocks of the Mariinsky site, but also the rocks of plutons and bodies of other sites. Despite some differences, we note the similarity of the MS with the gabbro-diorite-tonalite-trondhjemite series of South-West Finland [9].
The features of the MS include the linkage with the long-lived faults and associated dynamometamorphic changes of the bodies, polymetamorphism, superimposed chemical changes in the composition of primary rocks, as well as rarely preserved migmatite veinlets in the host rocks. The geochemical variations in the compositions of MS rocks are slightly more extensive than in the SWF series. In the latter, there are no granodiorites and leucogabbro. Rocks of MS in general are more aluminous and less titaniferous. Differences also exist and in the content of trace elements. The low contents of the REEs, their patterns and (+) Eu-anomalies in tonalites and trondhjemites of MS are almost identical with trondhjemite from South-West Finland. In the UTP, UGP granodiorites and quartz diorite the REE contents are several times higher than in tonalites and trondyemites from the Mariin site. With the similar relation of La/Yb\(_{Np}\) in these rocks Eu-anomalies are absent or weakly negative. Diorites and gabbro of MS are sufficiently close in high and very high contents of REE and their distributions with the rocks of SWF, but in contrast they are usually with (-) Eu-anomalies. Gabbro of Mariin site are differ due to low and very low contents of the REEs and usually (±) Eu anomalies. A variety of parameters of REE in gabbros and diorites, can be related with the presence or absence of monazite, allanite and other accessory minerals which are detected by the microprobe in the rare preparations.

In general, in the rocks of MS, as in SWF, there is a tendency to decrease the content of REE with increasing SiO\(_2\). Following [9] it is proposed to link the origin of the Mariin series with the fractional crystallization of a high-alumina basalt melt and suggest that the different types of MS rocks correspond to a series of crystallization differentiation. During the early crystallization of the melt the gabbro cumulates of Mariin site were formed. As a result of some sorting of non-ferrous minerals and plagioclase, hornblendites and leucogabbro were separated. Stage of formation of the diorites was accompanied by the most active crystallization of Mn, Ort and other accessory minerals containing REEs, which led to the depletion of REEs the late stage of differentiation – tonalites and trondhjemites.

5. Conclusions
Geochemical similarity of trondhjemite-, tonalites, granodiorites Mariin series and associated rocks with well-known early Proterozoic differentiate series of southwest Finland typical for the Proterozoic and Paleozoic continental margins [1] suggests that the plutons of the Mariin series formed in an active continental margin setting.

Acknowledgment
The article is produced within the research project №0381-2019-0003.

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