Polyformational Agdai Massif (Verkhoyansk-Kolyma Orogenic Region)

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Abstract. The earliest Mesozoic granitoid formations of the Verkhoyansk-Kolyma orogenic region are derivatives of the Late Jurassic-Early Cretaceous gabbro-diorite-granodiorite formation, involving gold and polymetallic mineralization. Late Cretaceous alkaline-feldspar or alkaline granite s with associated rare-earth mineralization complete the granitoid magmatism of the region. The Agdai massif, which combines both of the mentioned groups of rocks, was the object of our research. Therefore, understanding their petrological and genetic features is of great interest. It is determined that the eastern part of the massif is composed of diorites and granodiorites and includes autoliths and xenoliths of gabbro-diorite composition. The isotopic K-Ar age of gabbro-diorites is 154 Ma, diorites – 148 Ma, granodiorites – 117–124 Ma, and dike granites – 114 Ma. The rocks are characterized by disequilibrium mineral assemblages: early magmatic pyroxene-Labrador, typical for the basic rocks, and late - micropegmatite granitoid. The origin of the parent melts occurred within the lower crust in amphibolite substrates at temperatures of 1000–1150°C and a pressure of 1.4–1.6 GPa under the influence of the mantle main melt and the partial mixing of the latter with the resulting crustal melt. The western part of the outcrop was formed at the beginning of the Late Cretaceous (the isotopic K-Ar age of the granites is 92+/-3 Ma) and is composed of alkaline feldspar leucogranites. According to all petro- and geochemical parameters, the rocks are defined as post-orogenic or rift-related granites of the A-type. The presence of inclusions of pyroxene-labrador composition, titanomagnetite, zircon of morphotype D and the ratio of the basic petrochemical parameters allow us to refer them to A-type granites related to continental rifting. High melt temperatures (990-1030°C) at relatively low pressures during magma generation (0.7–0.8 GPa) could be achieved only when additional heat was supplied from an external (deep) source. The presence of nonequilibrium mineral associations indicates a possible syntax of the granite and the main melt. In general, the Agdai massif is a polyformational, polygenic structure formed by the intrusion of melts through common or closely located magma conduits.

1. Introduction
The Mesozoic magmatism of the Verkhoyansk-Kolyma orogenic region begins with the formation of gabbro-diorite-granodiorite-granite massifs, which are considered as multiphase intrusions of crustal or mantle-crustal origin or polyformational structures of unknown genesis. They are associated with ore occurrences of gold and polymetals. Therefore, an understanding of their petrological and genetic features and the conditions of crystallization is of interest. One of these massifs is the Agdai massif, localized within the Syachan volcanic field of the Uyandina-Yasachnen enclavial island arc (Figure 1).
2. Research methodology

The methods of work included: studying the structure of massifs, establishing relationships between igneous rocks of different compositions, sampling all varieties of igneous rocks, studying petrographic thin sections, complete silicate analysis, quantitative spectral analysis of rocks, microprobe determination of the compositions of rock-forming, accessory and restite minerals on a Camebax-micro microanalyzer. All analyses were performed at the Laboratory of Physicochemical Methods of Analysis of the IGABM SB RAS. The analytical results were processed using modern software (CGDkit, Igpet, etc.).

![Figure 1. Geological map of the Agdaisky region.](image)

1 – Quaternary deposits, 2 – leucogranites \( K_2 \), 3 – granodiorites and quartz diorites \( K_1 \), 4 – diorites and quartz diorites \( K_2 \), 5 – subvolcanic dacite and rhyodacite porphyry \( K_1 \), 6 – dikes of gabbro-diorites and dolerites \( J_3-K_1 \), 7 – Dogdinskaya formation: rhyolites, dacites, their tuffs, tuffites; 8 – Emtandzinskaya formation: andesites, andesidacites, their tuffs, tuffites; 9 – Mukdukanskaya formation: basaltes, andesites, 10 – marlstones and marbles \( D_2-3 \); 11 – Keberininskaya strata \( D_1 \): breccias-conglomerates, conglomerates, gritstones, dolomites, marlstones; 12 – Syryuktyakhskaya formation \( S_{1,2}r \): dolomites, limestones, marlstones; 13 – faults; 14 – supposed faults.

3. Research results

3.1. Geologic structure of the territory

The Agda massif intrudes the Oxfordian-Kimmeridgian volcanogenic-sedimentary deposits. At their base lies a substantially andesite formation with a subordinate amount of basalts, tuffs, and tuff lavas of medium and basic composition. The total thickness of the section is 700–900 m. Higher up lies the shale-rhyolite strata with a thickness of up to 500 m. Volcanites are represented by alternating rhyolites, dacites, tuffs, and clastolaves of acidic composition. At the top of the section, ash tuffs, pyroclastics in the cement of terrigenous rocks, interbeds of carbonaceous claystones, marking the transition to a subaerial conditions. The pre-Late Mesoic base of the belt is a system of blocks and thrust sheets composed of igneous and sedimentary rocks [1, 2].

The eastern part of the massif is composed of a complex of rocks from gabbro-diorites to granodiorites, and the western part is composed of leucocratic alkaline-feldspar granites. Isotopic K-
Ar age of the gabbro-diorites is 154 Ma, diorites –148 Ma, granodiorites –117–124 Ma, and dike granites – 114, alkaline feldspar granites – 92+/−3 Ma. Earlier the massif was considered as a multiphase structure with a composition of rocks from gabbro to leucogranites. The formation of the massif is preceded by small gabbro stocks and. and dolerite dikes.

3.2. Petrography and mineralogy of magmatic rocks. The eastern part of the Agdai massif is composed of diorites, quartz dikes and granodiorites with gradual transitions between them. The xenoliths contain gabbro-diorites. The massif cover is inclined to the south-east, where a number of small satellites of mainly diorite composition can be traced. The vein facies is represented by fine-grained granites and aplices.

### Table 1. Representative chemical composition of pyroxenes and amphibole of the magmatic rocks of Agdai massif.

| massif | East Agdai | West Agdai |
|--------|------------|------------|
| Oxides, % | 572 | 518/2 | 518/2a | 517/1 | 1025/4 | 1015/4 | 1015/4a | 95/4 | 100/1 | 100/1a | 100/1b | 95/4b | 95/4c |
| SiO₂ | 55.02 | 50.90 | 43.00 | 42.80 | 47.80 | 46.40 | 40.53 | 50.51 | 49.75 | 54.29 | 41.12 | 43.06 | 43.25 |
| TiO₂ | 1.05 | 1.15 | 3.26 | 2.67 | 0.76 | 0.89 | 0.03 | 0.09 | 0.09 | 1.60 | 1.56 | 1.33 | 0.71 |
| Al₂O₃ | 1.83 | 3.32 | 10.80 | 10.23 | 5.40 | 5.07 | 19.23 | 0.25 | 0.16 | 3.40 | 6.14 | 5.65 | 4.56 |
| Cr₂O₃ | 0.04 | 0.16 | 0 | 0.03 | 0 | 0.03 | 0.02 | 0.01 | 0 | 0.02 | 0 | 0 | 0.01 |
| Fe₂O₃ | 0 | 0.94 | 5.17 | 3.90 | 2.20 | 0 | 0 | 0.60 | 0.74 | 0 | 6.54 | 0 | 8.81 |
| FeO | 9.19 | 6.30 | 7.42 | 8.45 | 16.04 | 18.92 | 14.24 | 26.70 | 25.85 | 9.47 | 26.13 | 30.81 | 26.11 |
| MnO | 0.13 | 0.98 | 0.27 | 0.27 | 0.21 | 0.51 | 0.42 | 1.38 | 1.34 | 0.07 | 0.96 | 0.81 | 0.85 |
| MgO | 14.71 | 13.60 | 15.16 | 15.38 | 11.04 | 13.13 | 1.79 | 2.69 | 2.67 | 14.36 | 1.64 | 3.44 | 1.83 |
| CaO | 18.27 | 21.60 | 11.02 | 11.27 | 12.25 | 9.29 | 19.85 | 18.40 | 19.00 | 18.22 | 9.58 | 8.80 | 9.32 |
| Na₂O | 0.09 | 0.35 | 2.07 | 2.49 | 0.96 | 2.04 | 0.09 | 0.39 | 0.39 | 0.11 | 1.85 | 2.09 | 1.31 |
| K₂O | 0 | 0 | 0.51 | 0.50 | 0.80 | 0.66 | 0.04 | 0.01 | 0.01 | 0.09 | 1.21 | 0.96 | 1.19 |
| Cl | 0.20 | 0.21 | 0.20 | 0.28 | 0.06 | 0.84 | 0.53 | 1.40 |
| F | 0.20 | 0.13 | 0.72 | 0 | 0.94 | 1.18 | 0.73 |
| H₂O | 1.90 | 1.91 | 1.94 | 1.56 | 1.96 | 1.08 | 1.09 | 1.05 |
| Total | 100.33 | 99.30 | 100.98 | 100.24 | 99.60 | 99.50 | 99.24 | 101.03 | 100.00 | 101.72 | 99.59 | 99.75 | 101.13 |
| f% | 26.0 | 22.8 | 31.0 | 30.4 | 47.8 | 45.4 | 82.1 | 85.0 | 84.8 | 27.0 | 91.2 | 83.4 | 78.5 |
| T°C | 1163 | 1101 | 957 | 965 | 784 | 825 | 790 | 1053 | 1136 | 1172 | 827 | 835 |
| P, GPa | 0.81 | 0.55 | 0.53 | 0.54 | 0.16 | 0.07 | 1.03 | 0.76 | 0.58 | 0.83 | 0.26 | 0.21 |
| Log fO₂ | -9.6 | -9.3 | -14.4 | -12.2 |
| H₂O% melts | 5.0 | 4.4 | 4.7 |

**Notes:** 572, 518 – magnesioaugite from diorites; 518/2a,517/1 – magnesiogastengsites from diorites; 1025/4 and 1015/4 – Mg-hornblends from granodiorites; 1015/4z – ferruginous tschermakite from granodiorite; 1015/4 – ferrodioipside and 1001 – ferroaugite from granites; 10081a – – magnesioaugite from granite; 100/1b and 85/4b – ferroedenites from granites; 95/4c – errogedrite from granite. Calculations T°C and P GPa during crystallization of the pyroxenes – by [3]; T°C amphiboles and H₂O* in melt – by [4]; P- pressure during crystallization of the amphiboles – by [5].

In rocks of diorite composition, idiomorphic labradorite grains are the first to crystallize (50–58% an) and magnesioaugite (ferruginosity f = 22–26%) (Table 1) forming pandiomorphic-granular autoliths. The gaps between them are filled with subidiomorphic grains of amphibole, zonal andesine oligoclase (44–22% an) and quartz, or fine-grained pegmatite aggregate. Amphibole – magnesiohastingsite and Mg-hornblende (f = 30–48%), as a rule, it is replaced by canniloite. It
crystallizes in an oxidizing environment at the water content in the melt 4.4–5% (Table 1) [3–5]. Grains of restitic ferruginous tschermakite are also found. Biotite is moderately ferruginous, low-alumina. It begins to crystallize together with amphibole and oligoclase at high water and chlorine activity and water content in the melt from 4% to 8%, and it ends after quartz, to which interstitial grains it is sometimes confined (Table 2) [6–9]. The most high-temperature generation in terms of composition parameters corresponds to biotites of mantle and crustal-mantle derivatives (Figure 2) [10–11]. Potassium-sodium feldspar is observed as part of an xenomorphic or micropegmatite aggregate. It is represented by a crypto- and micropertite intermediate-to-low microcline with a content of $ab$ up to 22%.

Table 2. Representative chemical composition of biotites of the magmatic rocks of Agdai massif

| massif       | East Agdai | West Agdai |
|--------------|------------|------------|
|              | 1025/4     | 518/2      | 100/1 | 100/2 | 100/4 |
| SiO$_2$      | 37.16      | 37.00      | 35.24 | 34.65 | 34.52 | 34.06 | 34.41 |
| TiO$_2$      | 4.59       | 4.39       | 4.58  | 3.68  | 3.51  | 3.48  | 3.34  |
| Al$_2$O$_3$  | 12.21      | 12.48      | 13.40 | 11.49 | 11.56 | 11.16 | 11.04 |
| Cr$_2$O$_3$  | 0.07       | 0          | 0.06  | 0.03  | 0     | 0.02  | 0     |
| Fe$_2$O$_3$  | 1.99       | 2.73       | 2.45  | 4.40  | 5.29  | 4.98  | 5.74  |
| FeO         | 17.07      | 17.61      | 22.20 | 32.02 | 32.81 | 31.49 | 32.47 |
| MnO         | 0.11       | 0.18       | 0.48  | 0.48  | 0.47  | 0.50  | 0.044 |
| MgO         | 12.00      | 11.70      | 7.65  | 1.13  | 0.65  | 1.16  | 1.15  |
| CaO         | 0.02       | 0.72       | 0     | 0.07  | 0.03  | 0.06  | 0     |
| Na$_2$O     | 0.02       | 0.16       | 0.21  | 0.05  | 0.01  | 0     | 0     |
| K$_2$O      | 9.45       | 8.62       | 9.57  | 9.47  | 8.95  | 9.54  | 8.96  |
| Cl          | 1.13       | 0.20       | 0.45  | 0.93  | 0.85  | 1.08  | 1.05  |
| F           | 0.36       | 1.06       | 0.31  | 1.08  | 0.90  | 1.13  | 1.02  |
| H$_2$O      | 2.83       | 2.87       | 3.02  | 1.12  | 1.75  | 2.35  | 1.38  |
| Total       | 99.03      | 99.69      | 99.62 | 100.60| 101.30| 101.01| 101.00|
| f           | 46.8       | 49.1       | 64.2  | 94.7  | 97.0  | 64.6  | 96.6  |
| T°C         | 753        | 747        | 732   | 692   | 685   | 656   | 673   |
| P, GPa      | 0.083      | 0.11       | 0.13  | 0.062 | 0.13  | 0.14  | 0.14  |
| Log f H$_2$O | 3.19      | 3.17       | 2.61  | 3.05  | 2.99  | 3.12  | 3.08  |
| Log f HF    | -0.58      | -0.19      | -1.21 | 0.15  | -0.09 | -0.03 | 0.11  |
| Log f HCl   | 3.91       | 2.91       | 2.14  | 2.17  | 1.84  | 1.99  | 2.16  |
| H$_2$O% melt | 3.5        | 4          | 4     | 5.5   | 6.5   | 8     | 6.5   |

Notes: 1025/4 and 518/2 – diorites; 100/1 and 95/4 – granites/ The analyzes were performed at IGABM SB RAS – analysts of D. A. Kulagina, Determination of temperatures: T [6]; pressure P – [7]; log f H$_2$O, log f HF, log f HCl – [8]; H$_2$O% in melt – water content in the melt [9].

Typomorphic accessory minerals: titanomagnetite (7.4% TiO$_2$, 4.4% SiO$_2$), magnetite; allanite, magnesium-containing ilmenite (2–5% MgO at 0.05–0.2% MnO), apatite, rich in chlorine and fluorine (0.6–0.8% Cl and 3.6–5.4% F), zircon (ZrO$_2$/HfO$_2$ = 56–66), single grains of pyrope-almandine (29% py).
Dike granites are porphyric, with autoliths of amphibole-plagioclase composition, plunged in a micropegmatite matrix. Plagioclase of autoliths – zonal andesine-oligoclase and oligoclase (30–15% an), amphibole – magnesial-ferruginous hornblende (f = 47.8%).

The western part of the Agdai massif is in contact with the eastern part through a system of faults. It is composed of leucocratic granites and contains large blocks of diorite-granodiorite composition. The vein facies is represented by rare thin veinlets of fine-grained porphyric leucogranites and aplites. The early mineral association in granites is represented by sanidine or anorthoclase of the composition ab 45–50 ort 48–54 an 0.7–1.8, containing idiomorphic inclusions of hedenbergite or ferroaugite (f = 84–86%). The latter is characterized by the stable presence of the aegirine molecule (0.7–2.8%). Sporadically, rounded inclusions of fayalite are also observed in sanidine (f = 80–90%). In the second stage, mesoperthite potassium-sodium feldspar and a small amount of oligoclase-albite and quartz are crystallized. Calculations [12] determine the melt temperature at this stage in 850–856°C. The vast majority of plagioclase is represented by oligoclase-albite and albite. Large independent grains composed of indistinctly zonal oligoclase and oligoclase-albite (from 27% an to 12% an) are rare. The groundmass contains oligoclase-albite and albite (15–4% an). In the third stage, xenomorphic quartz grains or fine-grained pegmatite are formed. Amphibole and biotite are late- and postmagmatic.

Amphibole has the composition of hastingsite or ferriedenite (f = 83–92%) and is characterized by a high total content of alkalis and halogens (Table 1). In one case, the content of Cl is defined 3.29% at 0.65% F. In crushed samples single corroded ferrigedrite grains were determined (f = 78.5%), also rich in alkalis and halogens. In most cases, amphibole is replaced by secondary cannyloite. Biotite – lepidomelane (f = 94.4–97%) replaces amphibole at the grain periphery. It is enriched with halogens and crystallizes from a water-saturated melt (5.5–8% H2O) in the temperature range 692–656°C, at high water activity and moderate halogen activity. In terms of the ratio of ferruginosity and fluoride content, it is comparable to the biotites of the late differentiates of the gabbro-granite associations, and in terms of low OH/F values and high ferruginosity, it is is close to biotite of A-type granites.

The granites contain single intergrowths of magnesioaugite grains (f = 15.3–28.5%) and labradorite, plunged in a fine-grained pegmatoid matrix. In terms of the ratio of ferruginosity and TiO2 contents (1.33–1.55%) magnesioaugite is comparable to clinopyroxenes of tholeiitic basalts and
basite-hyperbasite associations (Table 1). The rocks of the vein facies are characterized by intensive albitization and greisenization, up to the transformation into albite-muscovite-quartz greisen.

The accessory minerals of granites: allanite, monazite, sphen, titanomagnetite (α 14.3% TiO₂), manganous and magnesium ilmenites, monazite; fluorite, zonal zircon of D morphotype, with high values ZrO₂/HfO₂ (121–52), pyrite, rare grains of F-and F-OH apatite, single grains of pyrope-almandine with the content of py 12.9% to 43.3%.

3.3. Petro- and geochemical features of magmatic rocks.
The eastern part of the Agdai massif is composed of a complex of rocks from gabbro-diorites to granodiorites of the low-potassium calcareous-alkaline series. The rocks are magnesian, metaaluminiferous, similar in composition to the derivatives of the calcareous-alkaline series of island arcs (Figure 3, Table 3) [14–19]. The temperatures of the parent melt calculated by different authors are close: 1000–1150°C [20], 1101–1155°C [21], 1007–1093°C [22]. The calculated magma generation pressure for the least differentiated samples is 1.4–1.6 GPa [23] or 1.2–1.5 GPa according to [20]. The temperature range of crystallization, determined by the ratios Al₂O₃/TiO₂ – MgO [20] – 1100–800°C. The ratio of Al/(Mg+Fe) – Ca/(Mg+Fe) in rocks (Figure 3g) indicates the generation of the melt during the selective melting of amphibolites. Dike granites are also magnesian, metaaluminiferous, diopsid-hypersthene-normative, with the predominance of normative albite (31–58%) over orthoclase (22–27%). The formation of the melt took place at the level of dacite-tonalite or metagraywacke substrates (0.7–0.9 TT1a), that determined its temperatures at 907–931°C [22], a variations in crystallization temperatures at 900–800°C.

Table 3. Chemical composition of magmatic rocks of Agdai massif

| Massif    | East Agdai | West Agdai |
|-----------|------------|------------|
| Oxides, % | 338/5 339/2 386/6 27/3 27/9 28/4 21/1 20/3 22/4 23/1 | 96/4 95/4 95/1 100/1 98/13 96/7 |
| SiO₂      | 51.02 57.11 59.42 60.95 62.17 64.07 65.15 67.07 68.02 68.30 | 70.41 71.85 73.71 74.02 74.78 76.23 |
| TiO₂      | 1.51 1.37 0.92 0.66 0.61 0.51 0.54 0.59 0.48 | 0.43 0.20 0.18 0.61 0.34 0.23 |
| Al₂O₃     | 16.69 16.53 15.70 15.84 15.76 15.20 14.09 14.80 14.15 14.69 | 13.52 12.75 12.56 12.43 12.04 11.60 |
| Fe₂O₃     | 4.47 3.16 2.43 1.95 2.23 1.50 1.31 1.20 0.81 0.64 | 1.42 0.40 1.70 1.51 1.46 0.08 |
| FeO       | 5.80 5.92 5.65 4.92 4.35 3.99 4.46 4.32 3.42 3.23 | 2.30 2.09 1.33 1.91 1.91 2.93 |
| MnO       | 0.17 0.18 0.11 0.15 0.14 0.05 0.05 0.03 0.04 0.08 | 0.08 0.10 0.06 0.09 0.08 0.05 |
| MgO       | 3.79 2.63 1.53 2.55 2.37 2.23 1.43 0.76 1.12 1.14 | 0.40 0.18 0.12 0.22 0.29 0.16 |
| CaO       | 7.37 5.54 4.88 5.05 5.00 4.59 5.54 1.98 2.60 2.73 | 1.70 2.02 1.47 0.50 0.39 0.01 |
| Na₂O      | 2.38 4.12 4.72 3.25 3.28 3.25 4.64 4.75 3.60 3.55 | 4.27 4.36 4.01 4.63 4.18 3.49 |
| K₂O       | 0.96 1.65 1.63 3.01 3.24 3.23 0.74 4.13 4.47 3.83 | 3.88 3.94 3.61 4.03 4.01 4.53 |
| H₂O       | 2.12 0.72 1.80 1.21 1.03 0.96 0.97 0.81 1.05 0.85 | 0.66 0.61 0.34 0.25 0.46 0.30 |
| P₂O₅      | 0.22 0.24 0.40 0.11 0.12 0.10 0.37 0.13 0.09 0.08 | 0.06 0.06 0.06 0.03 0.04 0.01 |
| CO₂       | 2.69 0.47 0 0 0 0 0.14 0 0 | 0 0 0 0 0 0 |
| F         | 0.05 0.08 0.07 0.13 0.11 0.15 0.07 0.11 0.09 0.13 | 0.10 0.07 0.10 0.09 0.10 0.08 |
| Li₂O      | 0.006 0.009 0.009 0.004 0.007 0.002 0.007 0.009 0.003 0.006 | 0.003 0.009 0.002 0.003 0.005 0.003 |
| Rb₂O      | 0.01 0.006 0.007 0.01 0.01 0.008 0.004 0.019 0.01 0.01 | 0.014 0.015 0.012 0.012 0.015 0.016 |
| S         | 0.25 0 0.01 0.01 0.01 0 0 0 0 0.03 | 0.05 0.08 0.10 0.25 0.25 0.525 |
| Total     | 100.5 99.99 99.28 99.64 99.68 99.90 99.40 99.69 99.96 99.64 | 99.43 99.24 99.33 100.6 100.35 99.96 |

Notes: The analyzes were performed at IGABM SB RAS – analysts of D. A. Kulagina, G. N. Okhlopkova, S.E.
Figure 3. Parameters of the chemical composition of the magmatic rocks of Agdai massif

1 – East Agdai, 2 – West Agdai. a) SiO$_2$ – (Na$_2$O+K$_2$O) ratio in magmatic rocks. Diagram fields [14]: I – gabbro; II – gabbro-diorites; III – diorites, IV – granodiorites, V – granites; VI – subalkaline gabbro; VII–VIII – monzonites; IX–X – syenites; XI – alkaline granites. b) Petrochemical series of magmatic rocks [15]: I – low-potassium tholeiitic, II – medium-potassium lime-alkaline, III – high-potassium lime-alkaline, IV – shoshonite. c) Alumina content of granitoids. Diagram fields, granitoids [16]: IAG – island – arc, CAG – continental arcs, CCG – continental collision, POG – postorogenic, CEUG – continental epeirogenic uplift, RRG – riftogenic; d) Sr–Rb/Sr in granitoids. Trends of differentiation of typical series [17]: I – theoleitic series of island arcs, II – calcareous-alkaline series of island arcs, III – calcareous-alkaline series of active margins, IV – series of rift zones of continents; I, S, A-petrotypes of granitoids; e) Magnatic series of granites. Symbols [18]: Ac – cation activity; trends of evolution: CAI – calcareous low-alkaline (island-arc), CA – calcareous-alkaline (crustal), HKO – high-potassium (orogenic), L-latte, T-trachite, AB – alkaline-basalt. f) Substrates of magma generation [19].

According to the composition parameters, the granites are close to late- or post-orogenic formations (Figure 3 d, f). According to the contents of Ba, Sr, Li, Rb and the coefficient of
rare metal content, the rocks of the eastern part of the massif belong to latite series, which is inherent in the magmatism of the active margins and rear zones of island-arc systems. The content of ore elements is low, only for Ag and Sn they are twice as high as clarkes. According to the high Ba (900–1500 ppm), low Li (18–41 ppm) and Rb (40–100 ppm) contents and low values of the rare metal index (28–38), the rocks of the eastern part of the massif show a clear latite slope, which is inherent in the magmatism of the active margins and rear zones of the island – arc systems [24].

The western part of the Agdai massif is composed of alkali-feldspar granites of the high-potassium calcareous-alkaline series (Figure 3a, b, Table 3). The rocks are diopside-hypersthene-normative, ferruginous, metaaluminiferous or slightly supersaturated with alumina. In the diagram of L. S. Borodin (Figure 3f), the points of their compositions indicate a trend that cuts (crosses) the trends of the normal evolution of granitoid melts. According to all parameters of the composition, they are defined as post-orogenic or rift-related granites of the A-type. The rocks are diopside-hypersthene normative, highly differentiated (Dl = 84–93%). The magmatic melt was generated at a pressure of 0.7–0.8 GPa at a temperature of 990–1030°C [22]. Determined by the GCDkit program [25] for a series of granite samples, temperatures Zr-, apatite- and REE-saturation was 836–690°C.

4. Discussion of results

The eastern part of the Agdai massif was formed in the Late Jurassic – Early Cretaceous. Diorites and granodiorites of the low-potassium calcareous-alkaline series, containing autoliths and xenoliths of gabbro and gabbro-diorites, prevail here. The rocks are characterized by disequilibrium mineral associations: early magmatic pyroxene-labradorite, typical for the primary rocks, and late – micropegmatite granitoid. Al/(Mg+Fe) – Ca/(Mg+Fe) ratio in rocks corresponds to the origin of the parent melt in the amphibolite horizons of the lower crust. This is also confirmed by the ratios in the rocks of normative values La/Yb – Yb(7.4 – 8.5; 5.7 – 10; 3.8 –10), corresponding to the melting of amphibolites or garnet amphibolites [26], as well as the presence in the restites of ferruginous tschermakite – a typical mineral of amphibolites and single grains of lower-crust pyrope-almandine (29% py). Variations in the K/Rb – Rb (180-320) values also correspond to the generation of melts in substrates that were mantle matter or a mixture of crustal and mantle matter [27].

Thus, obtained actual material indicates the origin of the parent melt for the East Agdai due to the selective melting of lower-crust amphibolites when they are exposed to the mantle basic melt and the latter is partially mixed with the resulting crustal melt.

The western part of the massif was formed at the beginning of the Late Cretaceous and is composed of alkaline feldspar granites and leucogranites. According to all petro- and geochemical parameters, the rocks are defined as post-orogenic or rift-related granites of the A-type. They are characterized by a combination of high-temperature minerals typical for the primary rocks (magnesioaugite, titanomagnetite, maganese ilmenite, zircon of D morphotype), and low-temperature, typically granite, minerals (oligoclase-albite, manganous ilmenite, F-apatite, fluorite). High melt temperatures (990-1030°C) at relatively low pressures (0.7–0.8 GPa) could only be achieved when additional heat was supplied to the magma generation levels from an external source.

In Figure 4 [28], the points of granite compositions are localized in the field of granites A1, which formation is related to plumes or hot spots [29] and continental rifts [29]. This is consistent with the opinion of most researchers who have dealt with the problems of A-granites, who showed that such temperatures are usually not reached in the earth's crust, that is, "the involvement of mafic magmas, or high mantle heat flows, is a necessity" for the generation of melts forming A-type granites [30].
Figure 4. Ratios of molar values of petrochemical components in granites West Agdai. Diagram fields [28]: A₁-granites of oceanic islands, continental rifts, and hotspots formed from a basaltic source of oceanic islands, intraplate, or rift environments; A₂-post-collisional, post-rhogenic, and anorogenic granites formed from a basaltic source of island arcs and continental margins, or a crustal source of tonalite and granodiorites, or by partial melting of the crust.

5. Conclusions
The actual material obtained in the course of research indicates the polyformational nature and polygenesis of the Agdai massif, formed during the intrusion of melts through common or closely located conduits. Its eastern part is formed at the end of the Late Jurassic – Early Cretaceous and is composed of gabbro-diorite-granodiorite association of rocks. The parent melt was formed in the lower-crustal amphibolites when the basic mantle melt arrived at the magma generation level and the latter partially mixed with the resulting crustal melt. The western part of the massif is composed of alkaline feldspar granites formed at the beginning of the Late Cretaceous. According to all petro- and geochemical parameters, they are defined as A-type granites related to the processes of continental rifting. High melt temperatures at relatively low pressures during magma generation could only be achieved when additional heat was supplied from an external (deep) source. The presence of nonequilibrium mineral associations indicates a possible syntax of the granite and the main melt.

References
[1] V.A. Trunilina, S.P. Roev, Yu.S Orlov, and V.S Oxman. “Magmatism of various deodynamic environments (zone of junction of the Verkhoyansk margin of the Siberian continent and the Kolyma-Omolon microcontinent)”. Yakutsk: YaNTs SO RAN, 168 p., 1999 (in Russian).
[2] A.P. Stavskiy, M.I. Ged’ko, and Danilov, V.G., 1994. “The Uyandina-Yasachnaya island arc. In: Geological mapping of volcano-plutonic belts”. Moscow: Nedra pp.. 265-297, 1994 (in Russian).
[3] F, Yavuz. “Win Pyrox: A Windows program for pyroxene calculation classification and thermobarometry”. Amer. Miner., vol. 98, ppl. 1338–1359, 2013.
[4] R.Rudilfi, and A. Renzolli. “Calcic amphiboles in calc-alkaline and alkaline magmas: thermobarometric and chemometric empirical equations valid up to 1130°C and 2.2 Gpa”. Contrib. Miner. Petrol. vol. 163, pp. 877–895, 2012.
[5] J.M.Hammerstrom, and E. Zen. "Aluminium in Hbl an empirical igneous melt. Amer. Miner. , vol. 71, № 11–12, pp. 1297–1313,986.
[6] D.A. Henry, Ch.V. Guidotti, and J.A. Thompson. “The Ti-saturation surface for low-to-medium pressure metapelitic biotites: implication for geothermometry and Ti-substitution mechanmus”. Amer. Miner., vol. 90, pp. 316–328, 2005.
[7] E. Uchida, S. Endo, and V. Makino. “Relationship between solidification depth of granitic rocks anf formation of hydrothermal ore deposits”. Resource Geology, vol. 57, № 1, pp. 47–56, 2007.
[8] D.R. Wones and H.P. Eugster, H.P. “Stability of biotite: experiment, theory and application”. Amer. Miner., vol. 9, pp.1228–1272, 1985.
[9] G.G. Brown. “A comment on the role of water in the partial fusions of crystal rocks”. Earth and
IOP Conf. Series: Earth and Environmental Science 906 (2021) 012085   doi:10.1088/1755-1315/906/1/012085

P.L. King, A.J.R. White, B.W. Chappell, and C.M. Allen. “Characterization and Origin of aluminous A-type granites from the Lachlan Fold Belt, Southeastern Australia”. J. Petrol., vol. 38, № 3, pp. 371–391, 1997.

V. Janoušek, V.L. Towson. “Post-igneous thermometers and barometers based on plagioclase + liquid equilibria: Tesis of some existing models and new calibrations”. Amer. Minel., vol. 90, pp. 336–346, 2005.

V.V. Ryabov and V.V. Zolotukhin. “Minerals of differentiated traps”. Novosibirsk: Nauka, 387 p., 1977 (in Russian).

M. Wilson M. “Igneous petrogenesis”. London: Unwin Hayman, 1989.

A. Gerdes, G. Worner and A. Henk. “Post-collisional granite generation and HT-LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith”. Geol. Soc. London, vol. 157, pp. 577–587, 2000.

V.M. Datsenko. “Petrogeochemical typification of granitoids of the south-western framing of the Siberian platform”. Materials Of The Second All-Russian Petrographic Meeting, Syktyvkar, pp. 270–274, 2000 (in Russian).

L.S. Borodin. “Petrochemistry of magmatic series”. Moscov: Nauka, 241 p., 1987 (in Russian).

A. Gerdes, G. Worner and A. Henk. “Post-collisional granite generation and HT-LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith”. Geol. Soc. London, vol. 157, pp. 577–587, 2000.

G.M. Belyaev and V.A. Rudnik. “Formational-genetic types of granitoids”. Leningrad: Nedra, 168 p., 1978 (in Russian).

L.V. Towson. “Typification of magmatites and their ore potential”. The 27th International Geologic Congress. Petrology. Moscow: Nauka, vol. *, pp. 221–228, 1984 (in Russian).

V. Janoušek, C.M. Farrow, and V. Erban. “Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit)”. J. Petrol., vol. 47, pp. 1255–1259, 2006.

B.M. Zhang and Z.K. Zhang. “Radiometric Age (Rb-Sr, Sm-Nd, U-Pb) and geochemistry of rare earth elements in Archean granulite gneisses of Eastern Hebei Province, China”. In: “Geochemistry of the Archean”. Moscov: Nedra, pp. 250–284, 1987 (in Russian).

M.G. Rub, N.A. Ashikhmina, and N.I. Gladkov. “Typomorphic features of accessory minerals and their significance for identification of genesis and ore content of granitoids”. In: “Granitoids of folded and activated regions and their ore content”. Moscov: Nauka, pp. 197–235, 1977 (in Russian).

A.V. Grebennikov. “Granitoids of A-type: problems of diagnostics, formation and systematics”. Geology and Geophysics, vol. 55, № 9, pp. 1356–1373, 2014 (in Russian).

G.N. Eby. “Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications”. Geology, vol. 20, pp. 641–644, 1992.