Petrology of granites in the Geramdachansky massif (Verkhoyansk-Kolyma orogenic region)

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Abstract. The authors identified several varieties of different ore content of the late-orogenic and anorogenic granites of the North-east of the Verkhoyansk-Kolyma orogenic region. The purpose of the research was a detailed study of petrography, chemistry, crystallization conditions and geochemical features of granites of one of such massifs – Geramdachansky, which is associated with rare-earth mineralization. The belonging of granites to A-type of the late-orogenic or anorogenic geodynamic setting and wide development of dikes of leucogranites and pegmatites is determined. Typomorphic features of the composition of rock-forming and accessory minerals of granites indicate the beginning of crystallization from the high-temperature melt of the lower crust genesis and saturation of the residual melt of water. Isochronous Rb-Sr age of granites 86-94 million years. Considering the value of primary isotopic ratios of strontium (I from 0.71246+/-0.00072 to 0.7213+/-0.0034), granites are derivatives of melting of the crustal material with a model age of protolith on average 2223±151 million years. The presence of almandine-grossular garnet, comparable to eclogite garnets, among the minerals of granites; high-temperature zircon of crust-mantle morphotypes D and J and enriched with native iron chromium can be explained by the presence of the basic rocks within the magma-forming substrates. A rapid increase of the content of all rare earth elements, as well as uranium and thorium from the granites of the main facies to leucogranites and pegmatites up to commercial values, was identified. The melts that formed all these rocks have close and stable high (920-1000°C) temperatures, which suggest the presence of an external heat source,
constantly active during the process of formation. These facts and the presence of the dikes of alkaline-basic composition near the granite outcrops with high concentrations of REE allow us to conclude that massif was formed under the impact of heat and fluids produced by deep mantle magmas.

1. Introduction
Works of the last decades on the territory of the Verkhoyansk-Kolyma orogenic region have identified a wide-spread occurrence of intraplate A-type granites [1]. These granites attract the attention of researchers as possible sources of rare metals and rare piles of earth; however, their geodynamic position and genesis remain largely debatable. In the article, we try to approach these issues on the basis of typomorphic features of rock-forming, accessory, and restite minerals, petro- and geochemical nature of the rocks and their Rb-Sr isotope systems on the example of Geramdachansky massif, localized in the eastern spurs of the Tas-Khayakhtakh Ridge.

2. Structure, petrography and mineralogy of the massif
The massif is exposed in the Late Jurassic volcanogenic-sedimentary strata on the left slope and the divide of the Geramdachan river in the form of three domes with a total area of 20 km² (Figure 1). K-Ar isotopic ages of granites 92 million years, Rb-Sr isochron age 86-94 million years. The massif is cross-cut by dikes of aplite-like granite, and fine-, medium-grained leucogranites. Its apical zone often records miaroles and vein bodies of block amphibole-biotite-feldspar pegmatites. Nests of violet fluorite occur in all rocks. Quartz veins with nests of rare-earth minerals and large crystals of piezoquartz (up to 30 cm along the long axis) are mainly confined to the apical zone. Zones of hematitization and greisenization are less common.

![Figure 1](image)

**Figure 1.** Geological map of the basin of the Suordakh [2, 3], 1 - Quaternary deposits (Q); 2 - late Jurassic, lower Volga stage (J1v1). Rhyolites, dacites,
andesites and their tuffs, sandy-argillaceous slates and sandstones; 3 - Kimmeridgian stage (J 3 km). Siltstones; 4 - Kimmeridgian and lower Volga stage (J 3 (km 2 -v 1 ). Rhyolites and their tuffs, clay and sand-clay shales and sandstones; 5 - late Cretaceous dikes of diabase, basalt porphyrites (βπK 2 ); 6 - early Cretaceous granites (γK 1 ); 7 - late Jurassic dikes of rhyolites (λJ 3 ); 8 - geological boundaries; 9 - tectonic contacts.

Granites of the main facies are medium- and coarse-grained, composed of potassium-sodium feldspar, quartz, oligoclase-albite, amphibole and biotite. Potassium-sodium feldspar is mesoperthitic, it is intensively albitized, up to transformation into the chessboard albite. In the porphyritic rocks of the endocontact zone in the center of its phenocrysts, euhedral cores of water-transparent sanidine are preserved. Quartz forms isometric grains and skeletal intergrowths with potassium-sodium feldspar. In the porphyritic phenocrysts of the rocks, quartz is euhedral; it contains small inclusions of sanidine. Individual grains of plagioclase are rare; they occupy interstices of potassium-sodium feldspar and quartz. Amphibole forms xenomorphic grains and their assemblages in interstices of salic minerals. During the rise of the melt, its composition varies from Fe-pargasite to hastingsite and Fe -edenite with a simultaneous decrease in ferruginosity against the background of an increase of the crystallization temperature (Table 1). It is characterized by a high content of alkalis and chlorine and low content of fluorine.

**Table 1.** Composition of the amphibole of granitoids of the Geramdachan massif (weight. %)

| Oxydes, elements, parameters | T978/3 | T983/1 | T978/3b |
|-----------------------------|-------|-------|--------|
| SiO₂            | 39.52 | 38.10 | 39.50  |
| TiO₂            | 0.06  | 0.52  | 1.04   |
| Al₂O₃           | 12.98 | 8.57  | 6.54   |
| Cr₂O₃           | 0.02  |       |        |
| Fe₂O₃           | 3.79  | 8.48  | 0.76   |
| FeO             | 24.46 | 24.82 | 30.69  |
| MnO             | 0.45  | 0.43  | 0.14   |
| MgO             | 0.67  | 0.86  | 2.31   |
| CaO             | 12.58 | 11.30 | 10.05  |
| Na₂O            | 0.62  | 1.19  | 2.05   |
| K₂O             | 2.14  | 1.92  | 1.24   |
| Cl              | 1.09  | 2.09  | 0.66   |
| F               | 0.05  | 0.07  | 0.58   |
Biotite replaces amphibole. Biotite is represented by low-alumina, chlorine-rich lepidomelane. Considering the high ferruginosity, low alumina content and the value of OH/F ratio in the modal composition (less than 10), the biotite corresponds to A-type granite biotites [5]. It is crystallized in reducing conditions at very high water activity and increased chlorine activity (Table 2). Water content in the melt is estimated at 5–10%, but the water vapor pressure in the melt exceeded the lithostatic one only at the end of the crystallization process.

### Table 2. Composition of the biotite of granites of the Geramdachan massif

| Oxydes, elements, parameters | T978/3 – granite | T983/1 – leuco-granite | T981-greisen | T987/1 - pegmatite |
|------------------------------|-----------------|------------------------|--------------|-------------------|
| SiO₂                         | 35.27           | 35.58                  | 35.00        | 36.12             | 34.68             | 36.69             |
| TiO₂                         | 3.58            | 3.51                   | 3.58         | 3.41              | 2.37              | 1.19              | 2.93              |
| Al₂O₃                        | 11.83           | 11.33                  | 11.31        | 11.72             | 11.48             | 11.88             | 10.92             |
| Fe₂O₃                        | 4.14            | 5.68                   | 5.01         | 4.77              | 6.26              | 5.92              | 5.42              |
| FeO                          | 26.69           | 26.39                  | 27.94        | 28.41             | 29.65             | 27.13             | 28.56             |
| MnO                          | 0.37            | 0.37                   | 0.42         | 0.27              | 0.41              | 0.33              | 0.01              |
| MgO                          | 3.01            | 2.23                   | 3.23         | 2.83              | 2.16              | 1.73              | 2.67              |
| CaO                          | 0.01            | 0.16                   | 0.02         | 0.01              | 0.02              | 0.01              | 0.14              |
| Na₂O                         | 0.12            | 0.72                   | 0.21         | 0.12              | 0.14              | 0.07              | 0.17              |
| K₂O                          | 9.28            | 8.06                   | 8.64         | 8.81              | 7.69              | 8.99              | 8.90              |
| Cl                           | 3.58            | 8.17                   | 1.05         | 0.82              | 1.26              | 2.21              | 1.45              |
| F                            | 1.17            | 1.24                   | 0.07         | 0.07              | 0.21              | 0.68              | 0.97              |
| H₂O                          | 2.24            | 2.84                   | 2.90         | 2.17              | 3.25              | 4.09              | 1.85              |
| Total                        | 101.29          | 99.28                  | 99.38        | 99.52             | 99.65             | 98.91             | 100.68             |
| f,%                          | 85.0            | 88.8                   | 84.9         | 86.6              | 90.2              | 91.3              | 87.5              |
| al**                         | 17.6            | 17.0                   | 16.6         | 17.0              | 16.7              | 16.6              | 15.8              |
| T°C                          | 693             | 685                    | 686          | 674               | 616               | 464               | 651               |
| P, GPa                       | 0.04            | 0.07                   | 0.12         | 0.10              | 0.12              | 0.03              | 0.05              |
H₂O% melt 5 6 6.5 10 10 8

| log f O₂ | -18.7 | -17.6 | -17.8 | -17.9 | -17.8 | -18.6 | -18   |
| log f H₂O | 3.20  | 3.72  | 3.38  | 3.24  | 3.45  | 3.68  | 3.51  |
| log f HF | -0.11 | 0.22  | -1.17 | -1.13 | -0.73 | -0.16 | 0.30  |
| log f HCl | 2.70  | 2.03  | 2.31  | 2.22  | 2.04  | 2.23  | 2.72  |

Notes: analyses are performed in IGABM SB RAS on microanalyzer Camebax-micro S. P. Roev. Determination of temperatures: T – by [6]; pressure P – by [7]; log f O₂ – [8]; log f H₂O, log f HCl, log f HF – [9]; water content in the melt – by [10].

Aplitic granites and leucogranites of dikes are characterized by more intense albitization and greisenization, up to transformation into albite-muscovite-quartz greisens. Pegmatites are composed of blocks of microperthite potassium-sodium feldspar, xenomorphic-granular coarse-grained quartz, arrow-shaped scales of almost black, halogen-rich lepidomelane (1,5–3%), and single grains of hastingsite. Lepidomelane was crystallized in reducing conditions with high activity of water and halogens, favorable for the formation of rare-metal and rare-earth mineralization. Nests of fluorite, carbonate, intense albitization are typical for pegmatites.

The most common accessory minerals are fluorite, orthite with REE sum of about 30%, zonal zircon. In zircons of granites of the main facies, the value of ZrO₂/HfO₂ varies from 65 to 21, and in zircons of leucogranites of dikes and pegmatites reaches 93-97 in center of the grains, which is common for zircons of the main rocks. Along with them, there are metamict grains with uranium content up to 8.1%, thorium – up to 2.6% and a value of ZrO₂/HfO₂ 27-20 and grains of complex oxides of uranium and thorium. Single grains of garnet are represented by pyrope-almandine, they contain (17-23,6% of pyrope minal, that corresponds to the garnets of derivatives of low-crust magmas. Along with it, xenogenic almandine-grossular, typical for restites of eclogites, sometimes occurs (60-65% gross, 32-35% alm). All rocks contain rare grains of apatite, ilmenite and titanomagnetite (up to 14% TiO₂). Native iron with Cr₂O₃ content of 5.73% was identified in one of the samples.

3. Petrochemical features of granites

The petrochemical composition of granites is characterized by high alkalinity (Table 3), moderate alumina content (Figure 2) and high ferruginosity (80-98%). Ferruginosity decreases to moderate values (56-62%) only in endocontact rocks. Composition parameters correspond to parameters of A-type granites of postorogenic conditions (Figure 3). Estimated parameters of magma generation P=1.3 GPA at a temperature of 950–1000°C and depth of the seismic focal zone – 220-240 km (Table 3). Leucocratic and aplitic granite dikes are characterized by identical chemical activity, whereas the pegmatites have dramatically increased potassium and sodium alkalinity, corresponding to the composition of the quartz syenites of shoshonitic
series. In addition, the content of fluorine increases sharply (up to 2.12%). Calculated parameters of crystallization (922–983°C), P = 1.3 GPA are similar to those of granites of the main facies. At the same time, the total concentration of rare earth elements increases spasmodically. If granites of the main facies contain only clarke of concentrations, then in the vein rocks and especially in pegmatites they increase to two orders of.

**Table 3.** Average compositions of granitoids of the Geramdachan massif (w.%)

| Oxydes, elements, parameters | granite | leucogranite | pegmatite | A-granite [11] |
|------------------------------|---------|--------------|-----------|----------------|
| SiO₂                         | 73.88   | 76.37        | 61.81     | 73.80          |
| TiO₂                         | 0.18    | 0.11         | 0.12      | 0.26           |
| Al₂O₃                        | 13.38   | 12.44        | 15.78     | 12.40          |
| Fe₂O₃                        | 0.72    | 0.57         | 0.73      | 1.24           |
| FeO                          | 1.46    | 1.22         | 2.21      | 1.58           |
| MnO                          | 0.04    | 0.08         | 0.01      |                |
| MgO                          | 0.23    | 0.03         | 0.32      | 0.20           |
| CaO                          | 0.65    | 0.51         | 3.97      | 0.75           |
| Na₂O                         | 3.85    | 4.01         | 5.54      | 4.07           |
| K₂O                          | 4.76    | 3.98         | 5.65      | 4.65           |
| H₂O⁻                         | 0.10    |              |           | 0.48           |
| H₂O⁺                         | 0.61    | 0.49         | 1.46      |                |
| P₂O₅                         | 0.05    | 0.01         | 0.07      |                |
| CO₂                          | 0.10    |              | 0.82      |                |
| F                            | 0.10    | 0.09         | 2.12      |                |
| Li₂O                         | 0.004   | 0.004        | 0.004     |                |
| Rb₂O                         | 0.015   | 0.0152       | 0.0163    |                |
| Total                        | 100.39  | 100.49       | 100.63    |                |
| K/(Na+K)                     | 0.45    | 0.40         | 0.57      | 0.43           |
| Ca/(Na+K)                    | 0.10    | 0.08         | 0.17      | 0.12           |
| (Na+K)/Al                    | 0.86    | 0.88         | 0.64      | 0.95           |
| Al/(2Ca+Na+K)                | 1.06    | 1.05         | 1.16      | 0.95 – >1      |
| Fe*/(Fe*+Mg)                 | 0.84    | 0.95         | 0.81      | 0.88           |
| T°C                          | 982     | 952          | 922       | 1012           |
| Pmax, GPa                    | 1.3     | 0.8          | 1.3       |                |
| H, km                        | 242     | 202          | 315       | 237            |

**Notes:** analyses performed in the laboratory of physicochemical methods of research IGABM SB RAS. Determination of the temperature for the granitic melt [12], pressure in [13], H – depth of the seismic focal zone in [14].
Figure 2. Alumina content of granitoids, 1 – granites, 2 – leucogranites and aplites, 3 – pegmatites

Fields of the diagram [15]: OP – oceanic plagiogranites, IAG – island-arc granitoids, CAG – granitoids of continental arcs, CCG – continental collision granitoids, POG – postorogenic granitoids, CEUG – granitoids of continental epirogenic uplift, RRG – riftogenic granitoids.

Figure 3. Types of granites Geramdachan massif, 1-3 – see Figure 2. Field diagrams [16]: A – rare-metal alkaline granites, L – latite granite, Li-F – plumasite lithium-fluoric granites
Magnitude, reaching commercial values (3400 g/t La, 1400 g/t Ce) (Table 4, Figure 4). The high potential of water and halogens during crystallization contributes to the formation of their ore occurrences.

![Figure 4](image-url)

**Figure 4.** Normalized to chondrite [17] the distribution of rare earth elements in rocks Geramdachan massif, 1 – granite, 2 – aplite, 3 and 4 – leucogranites, 5 and 6 – pegmatites

| Elements | T978/3 | T979/1 | T981/1 | T980 | T983/1 | T979/4 | T984/5 | T984/5a |
|----------|--------|--------|--------|------|--------|--------|--------|--------|
| La       | 5      | 36     | 38     | 34   | 61     | 97     | 491    | 3400    |
| Ce       | 8      | 81     | 76     | 90   | 131    | 186    | 908    | 1400    |
| Pr       | 1.5    | 9.3    | 8.2    | 7.8  | 16     | 20     | 95     | 20      |
| Nd       | 5      | 34.5   | 30     | 27.5 | 64     | 69     | 323    | 150     |
| Sm       | 1.3    | 7.45   | 5.95   | 5.05 | 14.5   | 12.25  | 52     | 30      |
| Eu       | 0.1    | 0.39   | 0.315  | 0.165| 0.585  | 1.075  | 0.975  | 1       |
| Gd       | 1.2    | 7.8    | 6.45   | 5.05 | 15     | 11.3   | 37     | 8.5     |
| Tb       | 0.45   | 1.28   | 1.125  | 0.795| 2.555  | 1.675  | 4.285  |         |
| Dy       | 1.5    | 8.45   | 7.85   | 5.95 | 16     | 10.4   | 22.5   | 3.2     |
| Ho       | 0.7    | 1.76   | 1.76   | 1.33 | 3.43   | 2.11   | 4.3    | 1       |
| Er       | 2.2    | 5.65   | 5.7    | 4.525| 10.65  | 6.55   | 13.55  | 5       |
| Tm       | 0.32   | 0.92   | 0.92   | 0.75 | 1.60   | 0.99   | 1.94   | 1       |
| Yb       | 2.9    | 6.3    | 6.1    | 5.3  | 10.5   | 6.6    | 13.3   | 0.5     |
| Lu       | 0.3    | 0.93   | 0.88   | 0.83 | 1.48   | 0.90   | 2.15   | 1       |
| Total REE| 30.47  | 201.73 | 189.25 | 189.09| 348.3  | 425.86 | 1969.0 | 5021.2  |
4. Discussion of results
It is found that the composition of granites of the Geramdachansky massif corresponds to the composition of A-type granites - increased and high alkalinity of postorogenic and anorogenic geodynamic setting. Considering the value of the primary isotopic ratios of strontium, granites of the massif being derivatives of the melting of the crustal material. Calculated Rb-Sr model parameters of the relatively primitive mantle have high positive values, and the model age of the protolith average 2223±151 million years. Typomorphism of minerals and calculated parameters of generation and crystallization of parent melts indicate the lower crustal magma formation and the presence of the basic rocks among the magma-forming substrates. The established strontium age and isotopic nonequilibrium of granites with a variation of dates from 120 to 86 million years and I0 from 0.71246+-0.00072 to 0.7213+/-0.0034 may be associated with the duration of rock cooling.

On the other hand, pay attention to the stable high design temperatures of the melts, formed granites of the main facies and vein derivatives and pegmatites, which are difficult to explain without a presence of external heat source, constantly acting in the process of the massif formation. Increase in the content of all rare earth elements, from granites of the main facies to their vein derivatives and pegmatites, also contradicts the normal evolution of the parent melt. The content of all rare-earth elements in all rocks of the massif is much higher than those in the primitive mantle, and in the lower-and upper-crust formations. Select the text to see examples. Such concentrations of these elements are mainly typical of the derivatives of melts generated in the metasomatized mantle [18]. Taking into account the presence of dikes of the alkaline-basic composition very close to the granite outcrops, and the above-mentioned stability of the temperatures of the granite melt and its derivatives, it can be concluded that the formation of the parent melt and its evolution occurred under the impact of heat and fluids, produced by deep mantle magmas.

5. Conclusions
Granites of the Geramdachan massif belong to A-type rocks of late-orogenic or anorogenic geodynamic setting. The parental melt was formed in the lower crustal substrata under the influence of heat fluxes and fluids produced by deep-seated mantle magmas. Geochemical specialization and in REE and crystallization at high water and elevated chlorine fugacities promoted formation of Ce and La occurrences at the final stage of the massif formation.

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