Petrology of Granitoids of the Selennyakh Ridge (Verkhoyansk-Kolyma Orogenic Belt)

Vera Trunilina

1Diamond and Precious Metal Geology Institute, SB RAS, 677000, Yakutsk, Lenin av., 39, Russian Federation

trunilina40@mail.ru

Abstract. The Verkhoyansk-Kolyma orogenic belt is characterized by intense Late Mesozoic granitoid magmatism. Numerous granitoids plutons form longitudinal belts, elongated parallel to the boundaries of major tectonic structures (Main and Northern), and transverse belts, oriented across or at an angle to them. The Main belt is dominated by massifs of granodiorite-granite composition, accompanied by tin-tungsten, boron-tin, and gold mineralization of various scale. Therefore, understanding their petrological and genetic characteristics and crystallization conditions leading to the generation of mineralization is of not only theoretical but also practical interest. The aim of the research was a detailed study of petrography, geochemical features and crystallization conditions of granodiorite-granite massifs of the Selennyakh block of the Omulevka terrane of the Kolyma-Omolon microcontinent that forms part of the Verkhoyansk-Kolyma orogenic belt. It was found that the formation of granitoids took place in an active continental margin setting and was long-term and complex. During the evolution of magmatism, the homodrome character of development (granodiorites → granites → leucogranites and aplites) was replaced by the antidrome one (granite-porphyries and granodiorite-porphyries). The Rb-Sr isotopic age of the rocks varies from 136 to 122 Ma. The generation of the parent melts for the granitoid massifs occurred within the lower crust at the boundary between amphibolite and dacite-tonalite substrates at temperatures of 1070–990° C and a pressure of 1.1–0.9 GPa. These parameters are comparable to those of the melt that formed the granodiorite-porphyry dikes: 990° C and 0.94 GPa. Maintaining high temperatures of the melt formation from initial to final derivatives at deeper levels of the magma chamber with a simultaneous increase in their fluid saturation requires the supply of juvenile heat and fluids. The main mineral in the territory is tin. The formation of mineralization is associated with late fluid-saturated derivatives of the granitoid melt. During the crystallization of leucogranites and pegmatites, fluorine was the main Sn-extracting agent. With depth, in the course of crystallization of granite and granodiorite porphyries, boron and then sulfur became the major extractants of tin.

1. Introduction

The Verkhoyansk-Kolyma orogenic belt is characterized by intense Late Mesozoic granitoid magmatism. The most widespread are massifs of granodiorite-granite composition with associated boron-tin, tin-tungsten, and gold mineralization of various scale [1]. Therefore, understanding their petrological and genetic characteristics and crystallization conditions leading to the formation of mineralization is of not only theoretical but also practical interest. The subject of research were granitoid massifs localized within the Selennyakh block of the Omulevka terrane of the Kolyma-
Omolon microcontinent (Figure 1). State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

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, gas chromatographic analysis of water extracts and inclusions in quartz, 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. Structure of the Selennyakh block of the Omulevka terrane [1].
1–2 – Omulevka terrane, Lower-Middle Paleozioc rocks; carbonate and terrigenous-carbonate, greenschist-metamorphosed (2); 3 – Nagondzha terrane, Triassic-Jurassic terrigenous deposits; 4–6 – Munilkhan terrane: 4 – Lower Paleozioc volcaniclastic polymetamorphic rocks, 5 – Lower-Middle Paleozoic basic and ultrabasic rocks, 6 – alkaline-ultrabasic rocks of the Tommot massif; 7 – Cenozoic deposits of the Uyandina (UI) and Tommot (Tm) basins; 8 – Aptian–Upper Cretaceous volcanogenic rocks of the Dzhakhurdakh field; 9 – Cretaceous granitoids (St - Syachan Sh - Sakhanya, K - Kuturuk massifs); 10 – Upper Jurassic volcaniclastic rocks of the Uyandina-Yasachnaya arc; 11 – thrusts, 12 – reverse faults and reverse – strike-slip faults; 13 – normal faults and normal – strike-slip faults.
3. Research results

3.1. Geological structure of the territory. The Selennyakh block is composed of Early-Middle Paleozoic carbonate and terrigenous-carbonate sediments, pre-Ordovician marbles, amphibolites, amphibole-biotite and two-mica schists, plagiogneisses and green schists. The Upper Paleozoic, Triassic and Lower-Middle Jurassic deposits are insignificant and represented by siltstones and mudstones with rare interlayers of sandstones, limestones, marls, andesite and basalt flows. In the center of the Selennyakh block, three granitoid massifs are exposed: Syachan, Sakhanya and Kuturuk, with the areas of 700 km², 400 km² and 40 km², respectively. Granodiorites predominate in the Sakhanya and Kuturuk massifs, and granites prevail in the Syachan massif. At contacts with terrigenous rocks, fine-grained leucocratic granites are observed; at contacts with carbonate rocks there is a zone of endo- and exoskarns of monzonite, granosyenite, and K-feldspar-pyroxene composition. The massifs are accompanied by aplite and leucogranite dikes. Dikes and small stocks of granodiorite-porphyry and granite-porphyry are confined to numerous fault zones. The Rb-Sr isotopic age of the Sakhanya massif granodiorites is 146–136 Ma (t0 = 0.7084), that of granites of the Syachan massif – 133–126 Ma (t0 = 0.7107) and of granite and granodiorite porphyries – 122–125 Ma. The 40Ar/39Ar isotopic age of granodiorites of the Sakhanya massif is 142–132 Ma, and that of granites – 136–134 Ma [2]. Granites along fault zones and granite-porphyry dikes are intensely greisenized and impregnated with cassiterite and wolframite. Calcareous boron-bearing skarns with Sn-W mineralization are developed after terrigenous-carbonate rocks. Quartz-chlorite-carbonate metasomatites have associated gold-base metal mineralization with accompanying tin.

3.2. Petrography and mineralogy of granitoids. The massifs are composed of amphibole-biotite granodiorites and granites with gradual transitions between them. In granodiorites, an early mineral association of andesine-labradorite (52% an 39% ab 9% or) and magnesian hornblende (f = 38.5–45%) crystallized at 900–850°C with a water content in the melt estimated at 4.1–5.3 wt. % [3, 4]. Peripheral plagioclase (40% an, 53% ab, 7% ort) was formed at 780–800°C. Then, with a decrease in temperature to 760–770°C and an increase in water content to 6–6.5wt. %, acidic plagioclase (32–20% an, 7–2% or) and ferruginous hornblende (f = 60–65%) crystallized, followed by allotriomorphic-granular biotite-quartz-K-feldspar aggregate. K-feldspar is represented by intermediate to low orthoclase and microcline. Magnesian-ferruginous biotite and lepidomelane (f = 51–67%), with a decrease in temperature and an increase in water content in the melt from 5–6 to 8wt. %, are replaced by ferruginous biotite (f = 77%) (Table 1) [5–8]. In terms of composition, biotite corresponds to that of the crustal granodiorite-granites of the ilmenite series, and only the most highly magnesian varieties correspond to biotites of the mantle-crustal rocks of the ilmenite-magnetite series (Figure 2) [8–10]. Granites differ from granodiorites in the almost complete absence of minerals of the early amphibole-plagioclase paragenesis and the predominance of microcline among K-feldspars.

The accessory minerals of granitoids include ilmenite, F-apatite, zircon, sphene, allanite, garnet, and rare magnetite grains. Zircon is mainly represented by low-temperature crustal morphotypes P, with ZrO2/HfO2 = 30–60 typical for granodiorites and granites. There are also single crystals of crustal-mantle morphotype D with ZrO2/HfO2 = 68–88 [11]. In intergrowth with amphibole, the lower crustal pyrope-almandine (up to 29% py) is observed. Microinclusions of gold are found in amphiboles, and single grains of cassiterite occur in leucogranites at endocontacts.

Aplites and leucogranites are composed of oligoclase (15–22% an, 4–5% ort), cryptoperthitic potassium-sodium feldspar (ort 70–75%, ab 25–30%, an 0–0.5%), and Fe-biotite. The latter is enriched in fluorine (1.6%) and lithium (0.25–0.27% Li2O) and crystallized from the water-saturated melt (Table 1). These rocks often contain pockets of quartz-feldspar pegmatites up to 15 cm in diameter. They contain large scales of lepidomelane, nests of schorl and fluorite in association with muscovite and cassiterite.
Granite- and granodiorite-porphyries have a porphyritic and glomeroporphyritic texture. The phenocrysts in the porphyry granite are composed of quartz and biotite. The latter is completely replaced by fine siderophyllite flakes (f = 85%, F = 1.05%, Cl = 0.16%). The accessories include ilmenite, F-apatite, zircon, fluorite, and thorite. content in the melt of 4.5–6wt. %. Biotite of the groundmass is ferruginous (f = 69.3%), richer in fluorine (1.36%), crystallized from a water-saturated melt with the H₂O content of 7wt. %.

Table 1. The representative compositions of biotite magmatic rocks.

| Oxides, % | T1055/7 | R10694 | R10466 | T535/1 | T541/4 | T5043/3 | T503/7 | T548/3 | T544/6 | R1073/15 | T5102 | T507/2 |
|-----------|---------|---------|---------|--------|--------|---------|--------|--------|--------|----------|--------|--------|
| SiO₂      | 35.20   | 35.30   | 35.01   | 36.08  | 33.60  | 34.40   | 33.31  | 34.40  | 34.29  | 37.31    | 36.97  | 33.73  |
| TiO₂      | 3.34    | 3.48    | 3.30    | 3.94   | 3.08   | 3.25    | 2.45   | 1.96   | 1.55   | 4.28     | 3.88   | 3.51   |
| Al₂O₃     | 14.43   | 14.06   | 14.31   | 14.68  | 14.40  | 13.60   | 15.84  | 16.92  | 19.12  | 14.56    | 13.68  | 13.80  |
| FeO       | 2.49    | 3.07    | 3.35    | 2.44   | 3.63   | 3.28    | 5.33   | 3.48   | 3.48   | 1.55     | 3.11   | 4.52   |
| MnO       | 0.50    | 0.84    | 0.42    | 0.09   | 0.84   | 0.92    | 0.77   | 0.87   | 0.71   | 0.40     | 0.37   | 0.5    |
| MgO       | 10.47   | 8.36    | 7.05    | 11.20  | 4.37   | 6.02    | 2.94   | 3.28   | 2.76   | 9.32     | 9.57   | 6.76   |
| CaO       | 0.44    | 0.42    | 0.65    | 0.41   | 0.41   | 0.86    | 0.48   | 0.10   | 0.33   | 0.10     | 0.51   | 0.24   |
| Na₂O      | 0.11    | 0.09    | 0.10    | 0.24   | 0.10   | 0.09    | 0.74   | 0.33   | 0.31   | 0.10     | 0.25   | 0.87   |
| K₂O       | 7.84    | 8.48    | 8.36    | 8.70   | 7.71   | 8.05    | 6.92   | 8.39   | 7.20   | 9.34     | 8.20   | 8.56   |
| Cl        | 0.51    | 0.26    | 0.30    | 0.41   | 0.46   | 0.50    | 0.25   | 0.16   | 0.43   | 0.50     | 0.29   |        |
| F         | 0.52    | 0.58    | 0.42    | 0.35   | 0.91   | 0.90    | 0.60   | 1.60   | 1.05   | 0.88     | 0.34   | 1.36   |
| H₂O⁺      | 4.73    | 4.14    | 4.02    | 2.63   | 6.27   | 4.94    | 3.17   | 3.54   | 3.55   | 2.97     | 2.98   | 2.91   |
| P₂O₅      | 0.10    | 0.12    | 0.33    | 0.14   | 0.15   | 0.11    | 0.08   | 0.16   | 0.05   | 0.43     | 0.11   | 0.05   |
| Li₂O      | 0.036   | 0.074   | 0.05    | 0.016  | 0.16   | 0.08    | 0.27   | 0.25   | 0.14   | 0.036    | 0.096  |        |
| Rb₂O      | 0.084   | 0.05    | 0.055   | 0.045  | 0.11   | 0.10    | 0.12   | 0.075  | 0.07   | 0.047    | 0.06   |        |
| Cs₂O      | 0.007   | 0.003   | 0.007   | 0.0046 | 0.004  | 0.012   | 0.006  | 0.03   | 0.003  | 0.012    |        |        |
| f, %      | 542     | 564     | 58      | 50.7   | 77.1   | 71.3    | 85.7   | 82.8   | 85.0   | 55.2     | 57.1   | 69.3   |
| T°C       | 693     | 691     | 679     | 723    | 672    | 675     | 617    | 578    | 610    | 725      | 707    | 691    |
| P, kbar   | 29      | 1.5     | 1.5     | 1.6    | 1.3    | 1.3     | 2.2    | 1.4    | 4.1    | 1.2      | 1.1    | 1.8    |
| log fH₂O  | 3.69    | 3.26    | 3.19    | 3.41   | 2.97   | 3.05    | 3.23   | 3.70   | 4.23   | 3.20      | 3.26   | 2.90   |
| H₂O in    | 7       | 6.5     | 5       | 5      | 7      | 8       | 12     | 4.5    | 6      | 7        |        |        |

Notes: T1055/7 – granodiorite of the Kutuluk massif, R10694/ and R1046/6 – granodiorites of the Sakhanya massif, T535/1 – granite and T541/4– granodiorite of the Syachan massif, R1043/3 and T503/7 – pegmatite, T548/3 – leucogranite, T544/6 – granite-porphyry; R1073/15, T510/2 and T507/2 – granodiorite-porphyry. Calculations by: T+C [5], by P [6]; log f H₂O [7]; H₂O in the melt [8]. The chemical analyses. Analyst D. A. Kulagina.
Figure 2. Composition of biotites from granitoids of the Selennyakh block.
1–3 – granitoids of the Kuturuk (1), Sakhany (2) and Syachan (3) massifs; 4 – aplices and leucogranites, 5 – granite-porphyries, 6 – granodiorite-porphyries. a) F vs. f diagram for biotites. Fields of the diagram [9]: I–III – biotites from rocks of granite-leucogranite and granodiorite-granite associations; IV–V – gabbro-granite associations; VI – derivatives of mantle magmas; b) F/OH – Mg/Fe diagram for biotites of magmatic rocks. Fields of biotite derived from melts [10]: I – contaminated and assimilated marine metasediments; II – mantle; III – crustal-mantle; IV – mantle-crustal; V – crustal anatectic. c) P – T diagram of the granite–water system at independent $P_{tot}$ and $H_2O$ [8].

Porphyritic phenocrysts of granodiorite-porphyry are composed of andesine-labradorite (56–45% an), amphibole, and biotite. Amphibole has a composition of magnesian hornblende with f = 45.6–45.8%, Cl = 1.01%, F = 0.15–0.28%. It crystallized at 852°C, a pressure of 0.6–0.9 GPa, and a water content in the melt of 4.9–6.5wt.%. Fe-biotite or lepidomelane (f = 55.2–57.1%) is enriched in lithium (1.07–1.15% Li$_2$O), formed at 780–707°C and the water The accessories include ilmenite, magnetite, Cr- and F-apatite, zircon of morphotypes D and P, sphene, allanite, and a sulfide complex (pyrite, arsenopyrite, chalcopyrite) with increased concentrations of Sn (0.1–0.6%), Ag (0.05–0.2%), Sb (0.04–0.3%), and Bi (0.03–0.5%). Quartz-chlorite-carbonate metasomatites also contain galena and sphalerite. The greisenized rocks are characterized by tourmaline, fluorite, cassiterite, and wolframite.

3.3. Petro- and geochemical features of granitoids. The chemical composition of igneous rocks of the studied massifs corresponds mainly to granodiorites and granites. (Table 3, Figure 3a) [12]. In the normative composition of the rocks, ab slightly prevails over or (avg. 21–32% and 16–27%, respectively). At the endocontacts, alkali granites and quartz monzonites are developed. All the rocks are ferruginous (f = 0.56–0.85 in granitoids of the main facies and up to 1 in leucocratic rocks at endocon- tact), the high-K calc-alkaline series (Figure 3b) [13], metaluminous or weakly peraluminous (Figure 3c) [14]. In terms of composition, they correspond to granitoids of continental arcs or granitoids of the calc-alkaline series of active continental margins (Figure 3c, d) [14, 15].

The calculated depth of magma generation [16] corresponds to a pressure of 0.9–1.1 GPa. The Al/(Mg + Fe) – Ca/(Mg+Fe) ratios in the rocks (Figure 3c) correspond to the initiation of magma chambers in dacite-tonalite substrates or at the boundary between dacite-tonalite and amphibolite substrates [17]. The composition points of the least differentiated granitoids are localized within the melting field of amphibolite. Taking this into account, the maximum temperature of melts for the Kuturuk and Sakhany massifs was determined at 1000–1020°C, and for the Syachan massif at 960–980°C [18]. From the Al$_2$O$_3$/TiO$_2$ vs. MgO ratios [19], the crystallization temperature of the first two massifs was estimated at 1000–650°C and for the third massif at 900–630°C, at a pressure of 0.9–0.2 GPa.
The aplites and leucogranites of dikes correspond in composition to alkali granites of the high-K cale-alkaline series (see Figure 3a, b). They have a high Fe index (0.85–1), are metaluminous or weakly peraluminous (Figure 3c). Pegmatites are distinguished by higher K contents with a transition from the high-K to shoshonitic series. The crystallization temperature of rocks of this group is 820–472°C at 0.5–0.2 GPa. According to the Sr – Rb / Sr ratios, they are classified as A-type granites. The granite and granodiorite porphyries of the dikes differ from the rocks of the main facies of the massifs with corresponding SiO₂ contents only in the higher values of volatiles (H₂O, F, S, P). The maximum crystallization temperatures are 960°C and 990°C, and the maximum pressures during magma generation are 0.75 GPa and 0.94 GPa.

Table 2. Average compositions of granitoids.

| Oxides, wt.%; elements, ppm | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|-----------------------------|----|----|----|----|----|----|----|----|----|
| SiO₂                        | 66.82 | 66.53 | 71.15 | 66.94 | 70.93 | 76.01 | 74.14 | 73.70 | 66.81 |
| TiO₂                        | 0.45  | 0.51  | 0.31  | 0.42  | 0.27  | 0.06  | 0.13  | 0.14  | 0.48  |
| Al₂O₃                       | 16.02 | 16.15 | 14.65 | 15.84 | 14.65 | 12.92 | 13.45 | 14.06 | 15.60 |
| FeO₃                        | 0.92  | 1.27  | 0.85  | 0.50  | 0.68  | 0.35  | 0.50  | 0.70  | 0.78  |
| FeO                         | 3.20  | 3.24  | 2.05  | 3.34  | 2.42  | 1.31  | 1.62  | 1.23  | 3.72  |
| MnO                         | 0.07  | 0.06  | 0.05  | 0.06  | 0.08  | 0.03  | 0.03  | 0.06  | 0.06  |
| MgO                         | 1.78  | 1.24  | 0.67  | 1.18  | 0.61  | 0.12  | 0.28  | 0.44  | 1.28  |
| CaO                         | 3.86  | 3.30  | 2.24  | 3.62  | 2.16  | 0.88  | 0.82  | 0.90  | 3.11  |
| Na₂O                        | 3.04  | 3.38  | 3.37  | 3.15  | 3.37  | 3.35  | 2.64  | 3.58  | 3.28  |
| K₂O                         | 3.37  | 3.62  | 4.25  | 3.93  | 4.17  | 4.66  | 6.40  | 4.49  | 3.20  |
| P₂O₅                         | 0.11  | 0.12  | 0.10  | 0.07  | 0.06  | 0.03  | 0.06  | 0.08  | 0.12  |
| CO₂                         | 0.26  | 0.26  | 0.27  | 0.27  | 0.27  | 0.27  | 0.27  | 0.27  | 0.27  |
| S                            | 0.04  | 0.07  | 0.06  | 0.02  | 0.06  | 0.06  | 0.10  | 0.08  | 0.17  |
| F                            | 0.06  | 0.08  | 0.08  | 0.09  | 0.10  | 0.08  | 0.12  | 0.12  | 0.11  |
| H₂O                         | 0.08  | 0.05  | 0.13  | 0.07  | 0.08  | 0.07  | 0.07  | 0.09  | 0.05  |
| H₂O²⁺                       | 0.92  | 1.02  | 0.75  | 0.80  | 0.79  | 0.69  | 0.56  | 0.88  | 1.43  |
| Li₂O                        | 0.014 | 0.008 | 0.010 | 0.008 | 0.013 | 0.012 | 0.013 | 0.006 | 0.003 |
| Rb₂O                        | 0.014 | 0.010 | 0.013 | 0.018 | 0.015 | 0.021 | 0.014 | 0.012 | 0.007 |
| Total                       | 100.70 | 100.87 | 100.7 | 100.05 | 100.54 | 100.58 | 100.97 | 100.62 | 100.48 |
| Fe³⁺/(Fe³⁺+Mg)              | 0.70  | 0.77  | 0.80  | 0.76  | 0.83  | 0.93  | 0.88  | 0.80  | 0.77  |
| B (12.5 and 12.5)           | 31    | 21    | 13    | 12.5  | 13    | 36    | 56    | 55    | 35    |
| Sn (1.9 and 3)              | 3.9   | 3.5   | 3     | 2.6   | 2.6   | 3.5   | 9     | 7     | 4.9   |
| W (1.6 and 2.20)            | 4.6   | 2.1   | 2.1   | 2.3   | 5.2   | 10.6  | 6.1   | 3.2   | 5.3   |
| Pb (15 and 19)              | 36    | 28    | 18    | 24    | 20    | 35    | 36    | 21    | 48    |
| Zn (59 and 39)              | 60    | 54    | 30    | 45    | 35    | 22    | 28    | 53    | 28    |
| Cu (29 and 10)              | 25    | 16    | 17    | 16    | 16    | 36    | 16    | 23    | 20    |
| Ag (56 and 38 mg)           | 0.3   | 0.15  | 0.15  | 0.1   | 0.1   | 0.13  | 0.08  | 0.18  | 0.44  |
| Au (2.8 and 2.7 mg)         | 0.0054 | 0.0023 | 0.002 | 0.0006 | 0.0006 | 0.0021 | 0.002 | 0.0045 | 0.0010 |
| Ba                          | 2000  | 1900  | 990   | 1100  | 880   | 122   | 260   | 1030  | 1210  |
| Sr                          | 170   | 530   | 310   | 220   | 130   | 31    | 31    | 118   | 118   |
| La                          | 18    | 16    | 24    | 23    | 15    | 20    | 14    | 14    | 14    |
| Yb                          | 2.4   | 2     | 3.5   | 3.8   | 3     | 3.18  | 1.24  | 1.24  | 1.24  |
| Eu                          | 1.7   | 1.1   | 0.96  | 0.22  | 0.05  | 1.04  | 1.89  | 1.89  | 1.89  |

Notes: granitoids of the Kuturuk massif; 2 – granodiorites and 3 – granites of the Sakhania massif; 4 – granodiorites and 5 – granites of the Sychansky massif; 6 – leucogranites, 7 – pegmatites, 8 – granite-porphyry, 9 – granodiorite-porphyry. The values of clarks for granodiorites of granites are given in parentheses. n – number of samples.
The contents of the majority of ore elements in the granitoids of the studied massifs are close to the clarks by [20]. Only in the granodiorites of the Kuturuk massif do their concentrations slightly exceed the clarks concentration (Table 2). The amounts of Sn and W in the leucogranites of the apical zones of the massifs are somewhat increased due to weakly manifested processes of emanation differentiation. Dikes of leucogranites and aplites concentrate B, W, Cu, and Ag. Pegmatites are enriched in Sn, B, and W. In the granite-porphyrries, the contents of Sn, B, W, Cu, and Ag exceed the clark values, and in the granodiorite-porphyrries, Sn, B, W, Au, Ag, and Pb are above the clark.

Generally, the concentrations of ore elements are but a little higher than the clarkes. The exceptions are contents of Sn and B in pegmatites and of B and Au in granodiorite porphyries (4–10 times higher than the clark). During greisenization, B, Sn, W were added; during skarn formation Sn, B, Zn, Au, and W were introduced. In the host terrigenous rocks, the concentrations of all ore elements and boron sharply increased during contact metamorphism (Table 2).

**Figure 3.** Parameters of the chemical composition of the granitoids

1–3 – granitoids of the Kuturuk (1), Sakhanya (2) and Syachan (3) massifs; 4 – aplites and leucogranites, 5 – granite-porphyrries, 6 – granodiorite-porphyrries/a) SiO2 – (Na2O+K2O) ratio in granites. Diagram fields [12]: I – diorites, II – granodiorites, III – granites; IV – monzonites, V – quartz syenites, VI – alkaline granites; b) Petrochemical series of granitoids [13]: I - low-potassium tholeiitic, II-medium-potassium lime-alkaline, III-high-potassium lime-alkaline, IV-shoshonite; c) alumina content of granitoids. Diagram fields, granitoids [14]: IAG – island–arc, CAG – continental arcs, CCG-continental collision, POG-postorogenic, CEUG-continental epeirogenic uplift, RRG-riftogenic; d) The ratio of Sr – Rb/Sr in granitoids. Trends of differentiation of typical series [15]: I-tholeiitic series of island arcs, II-calc-alkaline series of island arcs, III-calc-alkaline series of active margins, IV-series of rift zones of continents; I, S, A-petrotypes of granitoids; e) Substrates of magma generation [16]

The main mineral in the region is tin. In granodiorites, it is concentrated mainly in mafic minerals containing from 10 ppm to 100 ppm Sn in amphiboles and from 8 ppm to 44 ppm in biotites, which is
67–95% of the total Sn content in the rocks. Thus, during the formation of the massifs, crystal-
chemical dispersion of this element predominated. With an increase in SiO₂ content and with the
growing importance of fluorine as the Sn-extracting agent (correlation coefficient r Sn – F = 0.35), the
degree of residual tin concentration increases up to 30–40%. The association of tin with volatiles in
pegmatites becomes even stronger (r Sn – F = 0.56–0.68, r Sn – B = 0.36). In the rock-forming
minerals of the granite porphyry, the Sn content is low: 20–24 ppm in amphiboles, 6–8 ppm in
biotites.

The maximum total Sn content in these minerals does not exceed 40% of the total content in the
rocks. That is, the accumulation of tin in the fluid phase sharply prevails here. Sn, together with W and
Ag, were mainly supplied during greisenization. In this process, Sn closely associates with B and, less
so, with F (r Sn – B = 0.7, r Sn – F = 0.4). The simultaneously forming calcareous skarns concentrate,
in addition to boron, tin (r Sn – B = 0.87). Many ore bodies consist, by almost 75–90%, of tin-bearing
lewigite (up to 1% Sn), vonsenite (0.23% Sn) and magnetite (up to 0.4% Sn). The factor analysis of
granodiorite-porphyry showed the joint accumulation of Sn, Pb, Zn, Cu, and Ag, concentrated in
sulfides. The formation of quartz-chlorite-carbonate metasomatites was accompanied by an intense
supply of Sn, Pb, Zn, and Cu (r Sn – Pb = 0.6; r Sn – Zn - 0.46; r Sn – Au = 0.39).

4. Discussion of results
The data of isotope analyses and geochemical features of the studied rocks make it possible to attribute
them to long-evolved granitoids of continental arcs, formed in the conditions of an active continental
margin (Figure 3c, d). Magma chambers were formed within the lower crustal amphibolites or at the
boundary between amphibolite and dacite-tonalite substrates (Figure 3e) at a pressure of 0.9–1.1 GPa
and a temperature of 1020–990°C. Low chondrite-normalized La/Yb values (2.9–5.6) also testify to
magma generation in amphibolite substrates [21]. The presence of basic rocks in magma-forming
substrates is also indicated by the high content of pyrope minal in accessory garnet, restite zircons of
morphotype D with ZrO₂ / HfO₂ values up to 88, and K/Rb values (200–400) in granitoids. According
to experimental data [22, 23], melting of amphibolites can lead to the formation of granitoid melts in
the presence of a fluid phase (primarily H₂O and NaCl), which agrees well with the high water content
(913–1025 mg / kg) in magmatogenic inclusions and the composition of water extracts from quartz of
granitoids of the studied massifs (Na⁺ = 12–16 mg-equ/l, Cl⁻ = 13–27 mg-equ/l).

The granitoid massifs crystallized at temperatures from 1000°C to 630°C. Granodiorite- and
granite-porphyries differ from the rocks of the main facies of the massifs with corresponding SiO₂
content only in higher contents of volatiles (H₂O, F, S, P), which indicates their comagmatic nature.
The maximum temperatures and pressures of their magma generation (990°C and 960°C at 0.94 GPa
and 0.75 GPa) are also comparable. The retention of high temperatures of melt formation to the latest
derivatives requires the supply of juvenile heat and fluids to the root parts of magma chambers during
the development of magmatism. Crystallization of rocks took place in the presence of aqueous fluids.
According to the results of gas chromatography, the H₂O content in inclusions in quartz from
leucogranites was 1740 mg/kg, in quartz from granite porphyry – 1807 mg/kg.

The contents of the majority of ore elements in the granitoids of the studied massifs are close to the
clarks. Only in the granodiorites of the Kuturuk massif do their concentrations slightly exceed the
Clarks concentration. This can be explained by the long co-existence of Melts and fluids extracting ore
elements [24]. The main mineral in the territory is tin. In the granitoids of the massifs, it was dispersed
in the rock-forming minerals. But already in leucogranites and pegmatites, most of Sn was
concentrated in the fluid phase, mainly in complex compounds with fluorine (r Sn – F = 56–0.68). The
most enriched in ore elements are granite and granodiorite porphyries originated from deeper levels of
the magma chamber. According to experimental data, the separation of a fluid from the melt is
possible already at temperatures of 830–810°C and pressures of about 0.4 GPa [25]. Under high
pressure conditions, the most complete extraction of ore elements into the fluid occurs, and boron
becomes the main extractant of ore elements [26]. Accordingly, in the granite-porphyry, the Sn – B correlation coefficient is higher than that for Sn – F. The increased pressure during the generation of melts that formed the granodiorite-porphyry bodies enhances the chalcophilic properties of metals and the separation of sulfur from the melt [24]. This is confirmed by the high content of Sn, Ag, Sb, and Bi and the presence of microinclusions of Au in the sulfide fractions of granodiorite porphyries and the high correlation of Sn with ore elements. Fluids associated with melts, in addition to Sn, concentrate Pb, Zn, Cu, Au, and Ag with the formation of quartz-chlorite-carbonate metasomatites with Au ore occurrences and accompanying Sn, Ag, Pb, and Zn at the ore deposition front.

5. Conclusions
The emplacement of the granitoids of the Selenyakh block of the Omulevka terrane took place in an active continental margin setting and was long-term and complex. During the evolution of magmatism, the homodrome character of development (granodiorites → granites → leucogranites and aplites) was replaced by antidrome one (granite-porphyries and granodiorite-porphyries). Maintaining high temperatures of the melt formation from initial to final derivatives at deep levels of the magma chamber with a simultaneous increase in its fluid saturation requires the supply of juvenile heat and fluids during the development of the magma system. The formation of mineralization is associated with late fluid-saturated derivatives of the granitoid melt. In course of crystallization of leucogranites and pegmatites, fluorine was the main Sn-extracting agent. With depth, during the crystallization of granite and granodiorite porphyries, boron and then sulfur became the major extractants of tin.

References
[1] L.M. Parfenov and M.I. Kuzmin, M.I. Eds. “Tectonics, geodynamics and metallogeny of the territory of the Republic of Sakha (Yakutia)”. MAIK "Nauka/Interperiodika": Moscow, Russia, 571 p., 2001 (in Russian).
[2] P.V. Layer, R. Newberry, K. Fujita, L.M. Parfenov, V.A. Trunilina and A.G. Bakharev. “Tectonic setting of the plutonic belts of Yakutia, Northeast Russia, based on 40Ar/39Ar and trace element geochemistry”. Geology, vol. № 29, pp. 167-170, 2001.
[3] 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.
[4] F.S. Spear. “An experimental study of hornblende stability and compositional variability in amphibolite”. Amer. J. Sci., vol. 281, № 6, pp. 355-364, 1981.
[5] 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 mechanisms”. Amer. Miner., vol. 90, pp. 316–328, 2005.
[6] E. Uchida, S. Endo and V. Makino. “Relationship between solidification depth of granitic rocks and formation of hydrothermal ore deposits”. Resource Geology, vol. 57, № 1, pp. 47–56, 2007.
[7] D.R. Wones and H.P. Eugster, H.P. “Stability of biotite: experiment, theory and application”. Amer. Miner., vol. 9, pp.1228–1272, 1985.
[8] G.G. Brown. “A comment on the role of water in the partial fusions of crystal rocks”. Earth and Planet. Sci. Lett., vol. 9, pp. 355–358, 1970.
[9] I.N. Bushlyakov and V.V. Kholodnov. “Halogens in petrogenesis of granitoids”. Nedra: Moscow, 192 p., 1986 (in Russian).
[10] G.H. Brimhall and D.A. Crerar. “Ore fluids: Magmatic to supergene. In thermodynamic modeling of geological materials”. Minerals, Fluids and Melts. Reviews in mineralogy, Michigan, vol. 17, pp. 235-321, 1987.
[11] J.P. Pupin. “Zircon and Granite Petrology”. Contrib. to Miner. and Petrol., vol. 73, pp. 207–220, 1980.
[12] M. Wilson M. “Igneous petrogenesis”. Unwin Hayman. London, 1989.
[13] D.G. Whiteford, I.A. Nicholls and S.R. Taylor. “Spatial variations in the geochemistry of Quaternary lavas across the Sunda arc in Java and Bali”. *Contribs. Mineral. And Petrol.*, vol. 70, pp. 341-356, 1979.

[14] P.D. Maniar and P.M. Piccoli. “Tectonic discrimination of granitoids”. *Geological Society of America Bulletin*, vol. 101, pp. 635–643, 1989.

[15] 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).

[16] 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.

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

[18] Jung S., Pfander J.A. Source composition and melting temperatures of orogenic granitoids – constrains from CaO/Na₂O, Al₂O₃/TiO₂ and accessory mineral saturation thermometry // Europen Journal of Mineralogy, 2007, № 1. Pp. 5–40.

[19] V.V Kulikova and V.S. Kulikov. “Petrochemical classification of magmatic rocks”. – *Karelian Scientific Center: Petrozavodsk*, 152 p., 2001 (in Russian).

[20] L.N. Ovchinnikov. “Applied geochemistry”. *Nedra: Moscow, Russia*, 248 p., 1990 (in Russian).

[21] 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”. *Nedra: Moscow, Russia*, pp. 250–284, 1987 (in Russian).

[22] J.S. Beard and G.E. Lofgren. “Effect of water on the composition of partial melts of greenstone and amphibolite”. *Science*, vol. 244, № 4901, ph. 195–197, 1989.

[23] L.I. Khodorevskaia. “Granitization of amphibolites. 2. Basic laws of physical and chemical phenomena in the processes of fluid filtration through the rock”. *Petrology*, vol. 12, № 3, pp. 321–336, 2004.

[24] I.Ya. Nekrasov. “Tin in magmatic and postmagmatic processes”. *Nauka: Moscow, Russia*, 238 p., 1984 (in Russian).

[25] I.V. Veksler, R. Thomas and C. Schmidt. “Experimental evidence of three coexisting immiscible fluids in synthetic granite pegmatite”. *Amer. Miner*, vol. 87, pp. 775–779, 2002.

[26] S.Z. Smirnov, V.G. Thomas, S.O. Demin and V.A. Drebushchak V.A. “Experimental study of boron solubility and speciation in the Na₂O–B₂O₃–SiO₂–H₂O system”. *Chemical Geology*, vol. 223, pp. 16–34, 2005.