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Geology, physical-chemical and geodynamic conditions for the formation of Sokolovsk and Krasnokamensk granitoid massifs (South Ural)

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Abstract. The article describes the geological structure of the Sokolovsk and Krasnokamensk massifs located in the central part of the Western subzone of the Chelyabinsk-Adamovka zone of the Southern Urals. They are of Lower Carboniferous age and break through the volcanogenic-sedimentary deposits of the Krasnokamensk (D3kr) and Bulatovo (S1-D1bl) strata. It was found that these intrusions belong to the gabbro-syenite complex and are composed of gabbroids (phase I) and syenites, quartz monzonites, less often monzodiorites (phase II). The rocks of the second phase predominate (90–95%). Gabbros belong to the normal alkaline series of the sodium series and are close to tholeiitic mafic rocks, the formation of which is associated with riftogenic structures; syenites correspond to moderately alkaline series with K-Na type of alkalinity. It has been proved that in terms of their petrographic, petrochemical, geochemical, and metallogenic features (content of TiO_2, K_2O, Na_2O, Rb, Sr, distribution of REE, the presence of skarn-magnetic mineralization), the rocks of the massifs under consideration undoubtedly belong to the gabbro-granite formation. Crystallization of the Sokolovsk and Krasnokamensk intrusions occurred at a temperature of 880–930 °C in the mesoabyssal zone at a depth of about 7–8 km (P = 2.2–2.4 kbar). At the postmagmatic stage, the transformation parameters of the initially igneous rocks were, respectively, T = 730–770 °C, P = 4.0–4.2 kbar. The fact that these massifs belong to the gabbro-granite formation makes it possible to include them, together with Bolshakovsk, Klyuchevsky, Kurtmaksky and Kambulatovo, into the Chelyabinsk-Adamovka segment of the South Ural Early Carboniferous rift system.

Keywords: Sokolovsk massif, Krasnokamensk massif, Chelyabinsk-Adamovka zone, granites, syenites, pressure, temperature, geodynamics, melt inclusions, biotite-amphibole thermobarometer

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Introduction

The works of V.N. Puchkov (Puchkov, 2000), G.B. Fershtater (Fershtater, 2013), D.N. Salikhov et al. (Salikhov et al., 2014), A.V. Snachev et al. (Snachev et al., 2009) showed that in the axial region of the Magnitogorsk and Chelyabinsk-Adamovka megazones of the Southern Urals and in the Tagil megazone of the Middle Urals in the Early Carboniferous, a rift system formed in the back-arc basin of the Devonian island arc. Within its limits, the accumulation of moderately alkaline and high-Ti volcanogenic rocks of the Grekhovskaya (C_1t_2-v_1) and Berezovskaya (C_1t_2-v_2) formations took place, as well as intrusions of the gabbro-granite formation (Rb-Sr and Sm-Nd age – 333 ± 4 and 330 ± 20 Ma (Ronkin, 1989), which are characterized by suprasubduction and riftogenic geochemical features (Fershtater, 2013). Along the entire length of the Magnitogorsk segment of the rift system, in addition to gabbroids, tonalites, granitoids of normal alkalinity, syenites, granosyenites, and alkaline granites of the final stages of granitoid massifs formation. However, subalkaline and alkaline rocks in the gabbro-granite formation have not been identified in the Chelyabinsk-Adamovka segment to date. Only gabbro (Bol'shakovsky massif), diorites, granodiorites (Klyuchevskoy massif) and granites (Kurtmaksky and Kambulatovsky massifs) are noted here. At the same time, in the immediate vicinity of the Bolshakovskaya intrusion (1.8 and 3.7 km to the west) there are the Sokolovsk and Krasnokamensk massifs belonging to the gabbro-syenite complex. There were no data on formational referencing for them, as well as physicochemical and geodynamic conditions of

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formation were unknown. Geological surveys conducted in 2010–2018 (sheets: N-41-VII Miass and N-41-XIII Plast, scale 1: 200,000 (Petrov et al., 2003; Puzhakov et al., 2018)) and scientific-research work made it possible to fill this gap.

The purpose of this article is to prove that the Sokolovsk and Krasnokamensk massifs belong to the Chelyabinsk-Adamovka segment of the South Ural Early Carboniferous rift system. To achieve it, the following main tasks were solved: 1) to give a comprehensive petrographic, geochemical and metallogenic characteristics of the rocks of the Sokolovsk and Krasnokamensk massifs; 2) to establish the formational affiliation of the considered intrusions; 3) evaluate the physicochemical conditions (temperature, pressure and depth zone) of their crystallization; 4) to reconstruct the geodynamic environment of the formation of the massifs. A number of analytical studies, including: homogenization of melt inclusions in quartz of granitoids, microprobe study of the chemical composition of biotite-amphibole parageneses, petrographic description of rocks, silicate and neutron activation analyzes of all their varieties for petrogenic, rare-earth and trace elements.

Research methodology

Silicate analysis was performed according to the standard method at the Institute of Geology of the Ufa Federal Research Center of the Russian Academy of Sciences (Ufa, analyst S.A. Yagudina), neutron activation analysis – for rare earth elements (REE) and minor elements (K, Rb, Cs, Ca, Sr, Ba, Sc , Cr, Fe, Co, Ni, Zn, Se, As, Sb, U, Th, Br, Hf, Ta, Zr, Ag, Au – 37 elements in total) – at the Central Laboratory for Substance Analysis (CLSA) (Moscow, Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, analyst D.Yu. Sapozhnikov), X-ray radiometric (Ta, Nb, Y) – at the CLSA test center (analyst A.L. Lorentz).

To determine the P-T conditions of crystallization of granitoids, biotite-amphibole parageneses were studied according to the methods of L.L. Perchuk, I.D. Ryabchikov (Perchuk, Ryabchikov, 1976) and S.V. Pribavkin (Pribavkin, 2019). The compositions of biotites and amphiboles sampled from syenite of the Krasnokamensk massif were analyzed by V.A. Kotlyarov (Institute of Mineralogy, Ural Branch of the Russian Academy of Sciences, Miass) on an REMMA-202M scanning electron microscope with an LZ-5 energy dispersive spectrometer (SiLi detector, resolution 140 eV). Accelerating voltages of 20 or 30 kV at probe currents of 4–6 nA, beam diameter 1–2 μm (biotite standards for biotite, amphibole for amphibole).

To study the physicochemical conditions of the formation of granitoids in the Sokolovsk massif, we carried out studies of melt inclusions in quartz at IGEM RAS (Moscow, analyst V.Yu. Prokofiev). It contains small (7–21 μm) formations of silicate melt containing anisotropic silicate crystals (quartz, feldspars), gas bubbles (0.4–6.0 vol.%), and an aqueous solution in the interstices.

Homogenization of melt inclusions was carried out by quenching in a muffle designed by V.B. Naumov (Naumov, 1969) with a temperature determination accuracy of ± 10 °C (Koval and Prokofiev, 1998). The method involves long (1–3 hours) holding of the preparations at a stable temperature, quenching in air, and observation at room temperature of phase transformations with stepwise heating. The magnitude of the “step” (i.e., the increase in temperature between experiments) decreased as the phase transitions were approached, which made it possible to determine with a sufficient degree of accuracy not only the homogenization temperature, but also the beginning of melting of silicate phases. Microthermometric studies of the aqueous fluid were carried out in a THMSG-600 microthermal chamber (Linkam). The fluid pressure and the concentration of water in the melt were estimated by the method of V.B. Naumov (Naumov, 1969). For each sample, three groups of inclusions with the same phase relationships were examined in order to obtain representative information.

Geological structure of granitoid massifs

The Krasnokamensk gabbro-syenite complex, which, in addition to the Krasnokamensk and Sokolovsk massifs, includes small bodies in their framing, is located in the western part of the Chelyabinsk-Adamovka zone and is represented by syenites, quartz monzonites, less often monzodiorites and gabbros (Fig. 1). Syenite and quartz monzonite predominate.

The Krasnokamensk massif has an isometric shape and a diameter of about 3 km. According to prospecting drilling and gravity survey data, its maximum vertical thickness is about 1 km. The massif breaks through the volcanic-sedimentary rocks of the Krasnokamensk strata (D_3kr), and in the east it tectonically joins with the Bulatov (S_1-D_1bl) carbonaceous deposits, which represent a very favorable geochemical environment for the primary accumulation of Au, Mo, W, Pt, Pd and other elements (Yudovich, Ketris, 2015; Shumilova et al., 2016; Maslov et al., 2017; Gadd et al., 2019). In the Southern Urals, several gold objects have recently been discovered in black shale strata (Rykus et al., 2009; Snachev, Snachev, 2014). The host rocks near the contact are hornfelsed. The hornfelsing zone in some areas is up to 1 km wide and is an area of removal of some metals, primarily gold (Lecomte et al., 2017; Parnell et al., 2017).

The massif has a two-phase structure: the gabbroids of the first phase compose the body (0.8 × 1.0 km)

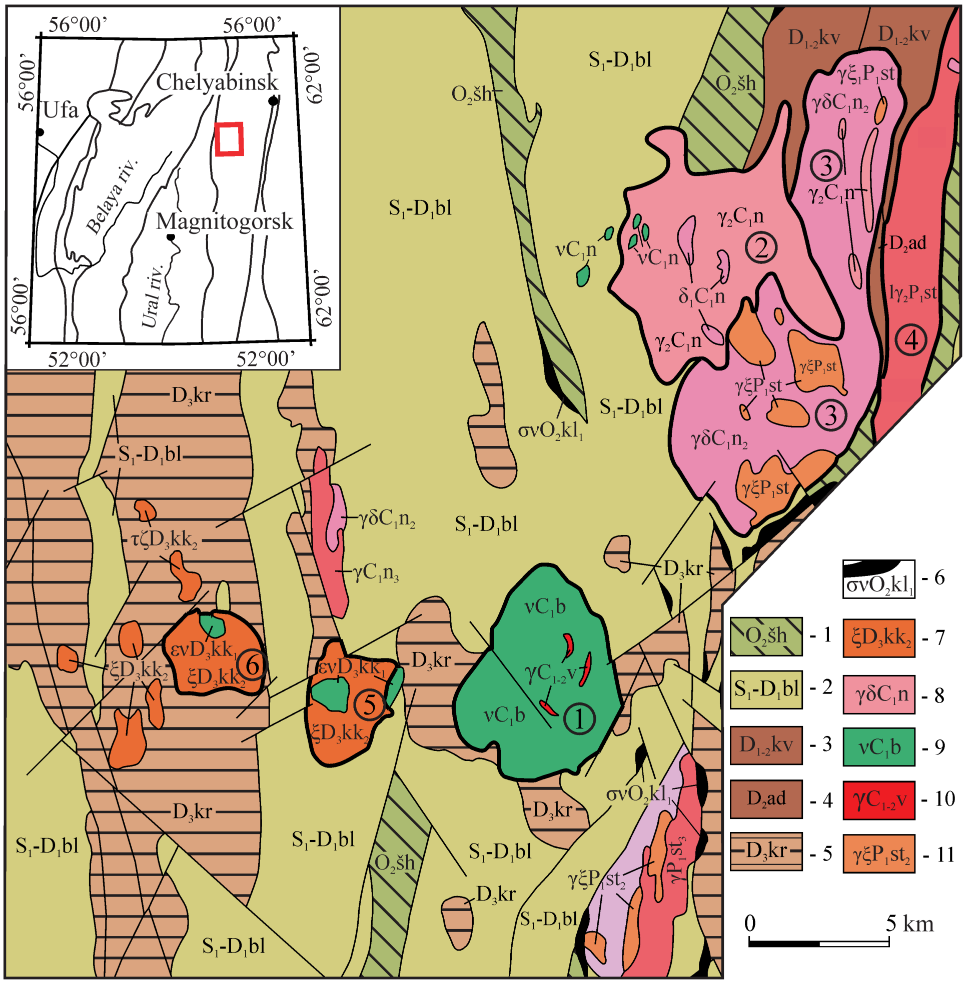

Fig. 1. Schematic geological map of the framing of the Sokolovsk and Krasnokamensk massifs. 1 – Shemetov strata – aphyric and fine-porphyric basalts; 2 – Bulatov strata – carbonaceous shales and siltstones; 3 – Kuluyev suite – basalt lavas and lava breccias; 4 – Adjatar strata – basalts, andesites and their tuffs; 5 – Krasnokamensk strata – trachybasalts and their tuffs, volcanomictic sandstones and siltstones; 6 – Kulikov complex – apodunite, apogharzburgite serpentinites; 7 – Krasnokamensk complex – gabbro, syenite; 8 – Neplyuev (Kukushkin) complex – gabbro (ν), diorites δ), granites (γ); 9 – Bolshakovsky complex – gabbro, gabbro-diabase; 10 – Warsawsky complex – granites, leucogranites; 11 – Stepninsky complex – granites. Numbers in circles are massifs: 1 – Bolshakovsky, 2 – Klyuchevskoy, 3 – Kurtmaksky, 4 – Kalinovsky, 5 – Sokolovsk, 6 – Krasnokamensk.

in its northern part, and the base is the syenite of the second phase. All varieties of rocks of the second phase are interconnected by gradual transitions. In terms of prevalence, gabbroids make up 7%, monzodiorites and quartz monzonites up to 34%, syenites up to 59%. Under the microscope, gabbro is 50% composed of epidotized plagioclase, dense blue-green amphibole (45%), chlorite (2%), ore mineral (2%), apatite (2%); magnetite is constantly associated with amphibole. Usually syenites are massive, medium- and coarse-grained rocks, sometimes porphyritic. Their composition: potassium feldspar (40–60%) with frequent perthite ingrowths (microcline-micropertite of a low degree of order), plagioclase (30–50%), biotite (5–10%), hornblende (up to 5%), quartz (up to 5%); secondary minerals – epidote (5–20%) and sericite (up to 10%); accessory – apatite, sphene; ore – magnetite, leucoxenized titanomagnetite. Potassium feldspar contains numerous perthite ingrowths of albite; as a rule, it is pelitized. Plagioclase corresponds in composition to oligoclase and oligoclase-andesine No. 27–30, along which a fine-scaled aggregate of epidote, sericite, and biotite develops. Hornblende has an iron content lower than that of biotite and is usually replaced by epidote. Accessory minerals in the rocks are represented by apatite, sphene, magnetite, titanomagnetite, and leucoxene. Monzodiorites differ from syenites by a slightly higher content of mafic minerals and more basic plagioclases, while quartz monzonites contain an increase in the proportion of quartz. The vein series of the complex is represented by syenite-porphyries composing vein-like bodies along the periphery of the Krasnokamensk massif. The rocks have porphyritic texture; among the phenocrysts, potassium-sodium feldspar and plagioclase are noted; in the groundmass – plagioclase, potassium-sodium feldspar, sporadic grains of quartz and biotite.

The Sokolovsk massif is poorly exposed and has an area of about 4.5 × 3.0 km. It breaks through the rocks of the same strata as Krasnokamensk and is characterized by a deeper erosional cut, as well as a more melanocratic composition. In the northwestern part of the massif, a body of gabbroids with an area of about 1 km^2 was identified. Gabbro belongs to the first phase, and monzodiorites, quartz monzonites and syenites – to the second. According to the results of the interpretation of the gravity field, its western contact falls to the west at an angle of 60°, and the eastern one, exposed by mine workings, has an eastern dip (70–75°). Near the contact, syenites contain a large amount of host rock xenoliths. The thickness of the zone repleted with xenoliths is 200–250 m.

The absolute age of syenites of the Sokolovsk massif obtained by V.F. Turban in 1975 by the K-Ar method, is 323 ± 16 Ma. Skarn-magnetite and copper-molybdenum mineralization is spatially and genetically related to the considered gabbro-syenite complex. The Krasnokamensk skarn-magnetite occurrence is located in the zone of the northwestern contact of the massif of the same name and is associated with skarns and feldspar metasomatites, presumably along trachybasalts and their tuffs. According to the structural and textural features, there are two main types of ores: massive and vein-disseminated. The average iron content in solid ores occurring at depths of about 1 km is from 46% to 61%, in disseminated ores – from 26% to 44%. Inferred iron ore resources, calculated by Yu.N. Pavlenin in 1980, make up 80–100 million tons. The Trans-Ural copper-molybdenum occurrence is also located in the western exocontact zone of the Krasnokamensk massif and is represented by dissemination of molybdenite (up to 0.48%) and copper sulfides. It is noteworthy that large titanomagnetite and skarn-magnetite deposits are associated with the granitoid intrusions of the Magnitogorsky complex, and the rocks themselves have a distinct specialization for molybdenum (Fershtater, 2013).

Research results and discussion

According to the chemical composition, the gabbros of the Sokolovsk and Krasnokamensk massifs belong to the normal alkaline series of the sodium series. They have average contents of TiO_2 (0.92-1.78%), low – total iron (7.90-9.03%), CaO (6.71-9.82%) and increased – Na_2O (3.75 –5.57%) and P_2O_5 (0.23–0.59%) (Table 1). Syenites correspond to the moderately alkaline series with potassium-sodium type of alkalinity. They are characterized by low titanium content (0.20–0.60% TiO_2) and high alumina content (17.26–19.38% Al_2O_3). In the rocks of the complex, there are higher-grade contents ($n \times 10^{-3}$ %): Co (1-3), Cr (15-50), V (12-18), Sc (0.5-0.7), Cu (7 –10), Zn (7–13), Pb (2–5), Ba (70–100).

To clarify the formational affiliation and reconstruct the paleogeodynamic conditions of the formation of the intrusions of the Krasnokamensk complex, we mainly used gabbroids. This is due to the well-known fact that they originate at deeper depths than low-melting granitoids and correspond best of all to the initial melt (Fershtater, 2013; Snachev et al., 2019). According to the petrochemical characteristics listed above, they belong to tholeiitic basic rocks, the formation of which is associated either with riftogenic structures or with island arcs (Geodynamic reconstructions, 1989).

Let us consider diagram 2A (Fig. 2), in which the gabbroids of the Sokolovsk and Krasnokamensk massifs, as well as the Magnitogorsky and Neplyuevsky (Bol'shakovsky and Klyuchevskoy massifs) complexes are shown in the coordinates TiO_2 – (K_2O + Na_2O). It is clearly seen that all the main rocks of the above intrusions form a single area in the field of the gabbro-granite formation. This is confirmed by the analysis of the contents of Rb, Sr, and REE in gabbroids. Thus, the plots of the distribution of REE in gabbroids of the Krasnokamensk complex (Table 2, Fig. 2B), normalized

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Loss of ignition	∑
1	51.24	0.92	17.82	3.82	4.11	0.21	5.60	9.82	3.75	0.23	0.59	2.58	100.60
2	51.08	1.56	16.81	2.27	5.63	0.17	5.73	9.64	4.70	0.34	0.36	1.40	99.69
3	50.60	1.63	16.25	3.41	5.62	0.09	5.18	8.06	5.57	0.28	0.23	2.61	99.23
4	51.96	1.78	15.49	4.16	4.08	0.15	6.36	6.71	4.06	0.64	0.56	3.51	99.46
5	49.11	1.60	18.53	4.07	4.28	0.12	6.07	8.00	5.30	0.17	0.32	2.30	99.87
6	56.82	0.57	18.03	4.60	2.71	0.08	1.71	5.67	3.77	5.06	0.33	0.12	99.46
7	57.04	0.41	18.43	1.30	4.17	0.09	1.44	2.96	4.00	6.30	0.22	3.24	99.40
8	57.28	0.60	18.82	4.80	2.05	0.11	1.87	3.68	5.00	5.27	0.36	1.06	100.45
9	57.94	0.50	17.58	3.30	3.12	0.12	2.60	4.77	3.75	4.90	0.37	1.00	99.95
10	59.39	0.20	19.38	2.16	2.47	0.08	0.71	3.26	4.12	6.50	0.18	1.16	99.51
11	59.46	0.28	18.51	1.49	3.21	0.10	0.71	3.40	4.06	6.44	0.22	1.70	99.48
12	59.55	0.45	17.26	0.86	6.13	0.13	2.20	3.41	3.60	4.90	0.20	1.82	100.46
13	60.01	0.46	17.86	2.38	2.47	0.14	1.34	4.73	4.30	5.00	0.23	0.90	99.72
14	61.24	0.47	18.10	3.82	1.08	0.09	1.06	3.44	3.96	5.92	0.29	0.96	100.37
15	65.56	0.28	17.71	1.87	0.51	0.05	0.92	2.70	5.00	5.13	0.20	1.02	100.50

Tab. 1. Chemical composition (wt.%) of intrusive rocks of the Krasnokamensk complex. 1–5 – gabbro; 6-13 – syenite; 14, 15 – quartz syenite.

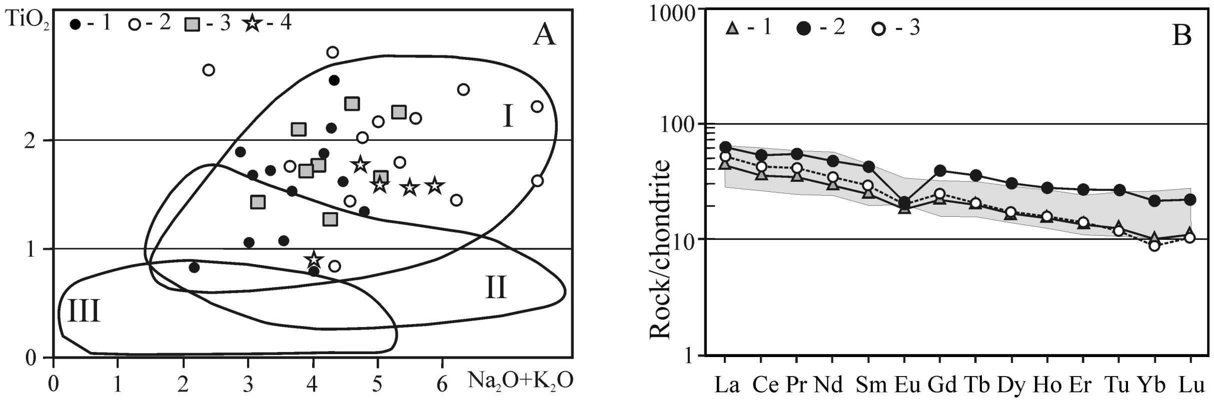

Fig. 2. Diagrams ($Na_2O + K_2O$) – TiO_2 (A), according to A.V. Snachev et al. (Snachev et al., 2009), and REE – C_{REE}/C_N (B) for gabbroids of the gabbro-granite formation: (A) 1 – Bol'shakov massif, 2 – Magnitogorsk complex, according to G.B. Fershtateru (Fershtater, 2013), 3 – Klyuchevskoy massif, 4 – Krasnokamensk complex (Table 1). Formation fields: I – gabbro-granite, II – dunite-clinopyroxenite-gabbro, III – dunite-harzburgite; (B) 1-3 – gabbroids (Table 2). The gray field corresponds to gabbroids of the gabbro-granite formation.

No.	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1	16.1	35.7	4.50	20.1	5.70	1.58	7.20	1.13	6.01	1.27	3.30	0.48	2.39	0.41
2	22.3	51.6	6.88	32.9	9.87	1.78	12.73	2.00	10.9	2.29	6.58	1.01	5.03	0.80
3	18.3	40.2	5.20	23.0	6.71	1.73	8.00	1.13	6.07	1.30	3.33	0.44	2.07	0.38
4	22.4	49.8	5.77	24.1	5.19	1.24	3.86	0.58	3.05	0.64	1.90	0.29	2.05	0.37
5	28.6	65.2	8.01	34.2	7.39	1.86	6.29	0.82	3.92	0.63	2.10	0.33	2.49	0.34

Tab. 2. The content of rare earth elements (ppm) in gabbroids (1–3) and granitoids (4–5) of the Krasnokamensk and Sokolovsk massifs: Sample numbers in rows – 4 correspond to No.15 in the Table 1; 5 – corresponds to No.8 in the Table 1.

according to H. Wakita et al. (Wakita et al., 1971), are characterized by the accumulation of light REE contents from Sm (K_N = 23.6–33, 6) to La (K_N = 47.4–84.1), weak differentiation of heavy REE at the level of K_N = 8.4–14.1 (Er_N = 8.4–14.1; Yb_N = 9.0–11, 0; Lu_N = 9.7–11.7) and the absence of a clearly pronounced Eu anomaly. And on the Rb-Sr diagram for the intrusive series of the Southern Urals, formed in different geodynamic settings (Fershtater et al., 1984), they practically all fit into the field limited by the intervals in Rb – 30–120 ppm and Sr – 150–420 ppm, which also corresponds to the gabbro-granite formation (Fig. 3) and sharply differ from the granitoids of the Stepninsky massif (Snachev et al., 2018). It is noteworthy that, according to the contents of Rb, Y, Nb, Ta, and Yb (Table 3), the rocks of the Krasnokamensk complex in all the Pearce diagrams (Pearce et al., 1984) (Fig. 4) are located in fields belonging to granitoids of volcanic arcs and intraplate geodynamic settings.

Let us turn to the reconstruction of the physicochemical conditions of the formation of granitoid intrusions. The results of thermometric studies of melt inclusions in quartz of syenites of the Sokolovsk massif are shown in Table 4. The beginning of melting of silicate phases and complete homogenization of the smallest inclusions occurred at T = 610–640 °C and 880–930 °C, respectively. The homogenization of the fluid with the transition to the fluid is recorded at T = 345–365 °C. The pressure value calculated according to the method of V.B. Naumov (Naumov, 1979), for the interval between the temperature of homogenization of the aqueous fluid

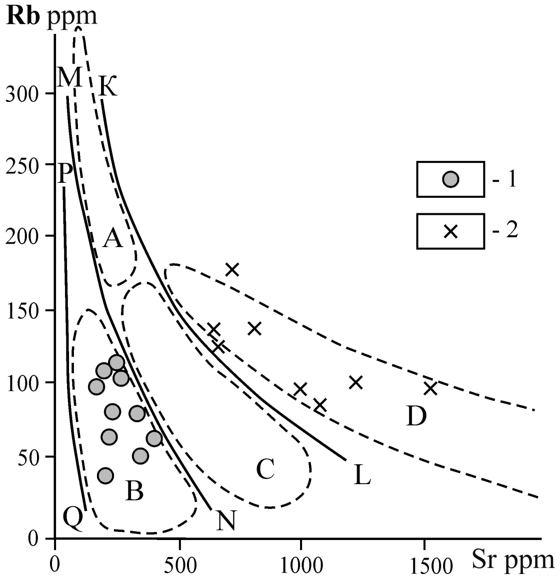

Fig. 3. Rb-Sr diagram according to Fershtater (Fershtater, 2013) for granitoids of Sokolovsk, Krasnokamensk (1) (own data) and Stepninsky (2) (Fershtater, 2013) massifs: rock fields – derivatives of various initial magmas: to the left of the PQ line – tholeiitic oceanic; NQPM, tholeiitic continental island arc; LNMK – orogenic andesitic, tholeiitic, tholeiitic high alkalinity, latitic; above the LK line – latite, alkaline-basalt. Areas of distribution of the South Ural granitic formations: A – granite-migmatite, B – gabbro-granite, C – tonalite-granodiorite, D – monzonite-granite.

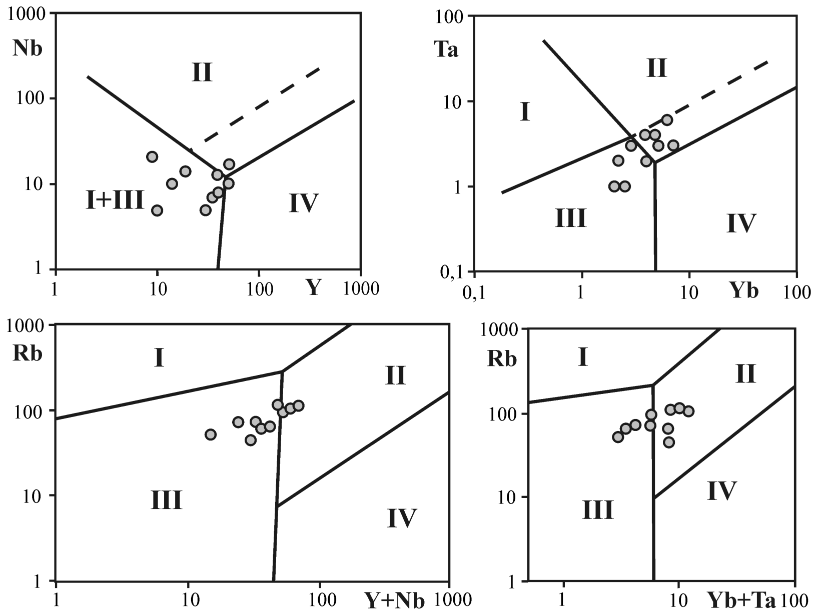

Fig. 4. Pearce diagram (Pearce et al., 1984) for the granitoids of the Sokolovsk and Krasnokamensk massifs (Table 3): I – collisional granites, II – intraplate granites, III – granites of volcanic arcs, IV – granites of oceanic ridges.

and the temperature of the appearance of the silicate melt (610 °C), is 2150–2370 bar.

Its similar values are typical for depths of about 7–8 km (mesoabyssal zone). If the salt components of the fluid are represented only by sodium chloride, then the chlorine concentration in the melt is estimated at 0.11–0.15 wt. %, and water – 2.4–2.9 wt. %. At temperatures from (–5.5) to (–4.7) °C, ice melted, which corresponds to a concentration of 7.5–8.6 wt. % NaCl solution (Bodnar, Vityk, 1994). The content of chlorine and salts in the fluid, as well as the fluid saturation of the melt, are very important parameters that play a significant role in the extraction and transfer of a number of metals (Koval and Prokofiev, 1998). In the syenites of the Sokolovsk massif, the concentration of salts in the fluid is in the range of 7.5–8.6 wt. %, which, according to the above authors, is very close to the rare-metal granitoids of the Mongol-Okhotsk zone.

For the Krasnokamensk massif, the P – T conditions of crystallization of granitoids were determined based on the study of biotite-amphibole paragenesis (Perchuk, Ryabchikov, 1979; Thermo and barometry..., 1977; Henry et al., 2005; Mutch et al., 2016; Angiboust, Harlov, 2017). Monofractions of biotite and amphibole were taken from three syenite samples and analyzed using a scanning electron microscope (Table 5).

The crystallochemical formulas of minerals were calculated by the method of I.D. Bornemann-Starynkevich (Bornemann-Starynkevich, 1964). From Table 5 it follows that: 1) the compositions of both minerals in the three analyzed samples are very close to each other, and the oxide variations in them are

No.	Rb	Y	Nb	Ta	Yb
1	109	51	17	4	4.7
2	52	10	5	1	2.0
3	65	35	7	3	5.2
4	65	30	5	1	2.5
5	96	40	13	2	4.0
6	115	40	8	3	7.1
7	105	50	10	6	6.2
8	45	9	21	4	4.3
9	73	14	10	3	2.9
10	72	19	14	2	2.2

Tab. 3. The contents of Rb, Y, Nb, Ta, Yb (ppm) in the granitoids of the Sokolovsk and Krasnokamensk massifs. Y, Ta, Nb – obtained by X-ray radiometric method; Rb, Yb – by neutron activation method.

Parameters	Pl 7/3		
	1	2	3
n	3	3	2
T fluid homogenization, °C	365	358	345
	L	L	L
T ice melting, °C	-5.5	-4.9	-4.7
C salts, mass. % eq. NaCl	8.6	7.7	7.5
V fluid, vol. %	10.6	9.8	8.4
dP/dT, bar/°C	8.6	7.9	8.4
P, bar	2370	2150	2230
d fluid, g/cm^3	0.69	0.70	0.71
C (H_2O), mass. %	2.9	2.7	2.4
C(Cl), mass. %	0.15	0.13	0.11
T solidus, °C	640	630	610
T liquidus, °C	930	910	880

Tab. 4. Results of investigation of melt inclusions in quartz of granitoids of the Sokolovsk massif (sample No.7/3). "n" is the number of studied inclusions in each of the three groups with the same phase relationships. Studies of melt inclusions were carried out by V.Yu. Prokofiev (IGEM, Moscow). The technique is briefly described in the text of the article, and in detail – in the works of V.B. Naumov (Naumov, 1969; Naumov, 1979).

Mineral	SiO_2	TiO_2	Al_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	Total	X_{Mg}*
Bi-1	38.28	1.74	15.24	22.26	0.32	-	10.06	0.00	8.90	96.79	0.44
Bi-2	37.64	1.44	15.46	22.69	0.29	-	9.75	0.47	8.60	96.33	0.43
Bi-3	37.31	1.46	15.79	23.16	0.31	-	9.04	0.00	8.78	95.85	0.41
Amf-1	54.08	0.06	2.09	16.46	0.43	11.46	13.48	0.20	0.18	98.44	0.59
Amf-2	51.51	0.28	3.34	18.25	0.33	11.04	12.40	1.00	0.42	98.58	0.54
Amf-3	53.73	0.11	1.36	18.57	0.64	10.34	12.35	0.58	0.23	97.91	0.53

Bi-1 – $(K_{0.87}Na_{0.00})_{0.87}(Mg_{1.15}Fe_{1.42}Mn_{0.02}Ti_{0.10}Al_{0.30})_3(Si_{2.93}Al_{1.07})_4O_{10}[O_{0.28}(OH)_{1.72}]_2$

Bi-2 – $(K_{0.85}Na_{0.07})_{0.92}(Mg_{1.12}Fe_{1.46}Mn_{0.02}Ti_{0.08}Al_{0.32})_3(Si_{2.91}Al_{1.09})_4O_{10}[O_{0.31}(OH)_{1.69}]_2$

Bi-3 – $(K_{0.87}Na_{0.00})_{0.87}(Mg_{1.05}Fe_{1.50}Mn_{0.02}Ti_{0.09}Al_{0.34})_3(Si_{2.90}Al_{1.10})_4O_{10}[O_{0.29}(OH)_{1.71}]_2$

Amf-1 – $(Ca_{1.76}Na_{0.06}K_{0.03})_{1.85}(Fe_{1.97}Mg_{2.87}Ti_{0.01}Mn_{0.05}Al_{0.10})_5(Si_{7.75}Al_{0.25})_8O_{22}[O_{0.48}(OH)_{1.52}]_2$

Amf-2 – $(Ca_{1.72}Na_{0.28}K_{0.07})_{2.07}(Fe_{2.21}Mg_{2.68}Ti_{0.03}Mn_{0.04}Al_{0.04})_5(Si_{7.47}Al_{0.53})_8O_{22}[O_{0.36}(OH)_{1.64}]_2$

Amf-3 – $(Ca_{1.61}Na_{0.16}K_{0.04})_{1.81}(Fe_{2.24}Mg_{2.66}Ti_{0.01}Mn_{0.08}Al_{0.01})_5(Si_{7.77}Al_{0.23})_8O_{22}[O_{0.22}(OH)_{1.78}]_2$

$X_{Mg}* = X^{Bi.Amf}_{Mg/(Mg+Fe+Mn)}$

Tab. 5. Chemical composition of biotite (Bi) and amphibole (Amf) from syenite (sample No. 2126) of the Krasnokamensk massif (wt.%)

insignificant; 2) the Mg of biotite is lower than that of amphibole ($X_{Bi}^{Mg}/(Mg + Fe + Mn) = 0.41–0.44$; $X_{Amf}^{Mg}/(Mg + Fe + Mn) = 0.53–0.59$); 3) the crystal chemical formula of amphibole corresponds to actinolite, which is characterized by low contents of TiO_2 (0.06–0.28%), Al_2O_3 (1.36–3.34%), alkalis ($K_2O + Na_2O$ = 0.38–1.42 %); 4) the distribution coefficient of Mg and Fe between biotite and amphibole – $K_D = (X_{Mg}^{Bi}/X_{Fe}^{Bi})/(X_{Mg}^{Amf}/X_{Fe}^{Amf})$ – used as a criterion for distinguishing between biotites (Pribavkin, 2019) crystallizing directly from the melt ($K_D > 1$), and those, which are formed upon replacement of hornblende ($K_D < 1$), is 0.56–0.64 for the Krasnokamensk massif. All of the above indicates that the considered biotite-amphibole paragenesis was formed at the postmagmatic stage.

The transformation temperature of the initially igneous rocks was obtained using the diagram of the phase relation of the magnesianities of biotite and amphibole (Perchuk, Ryabchikov, 1976). The compositions of these minerals transferred to it are located between the 730 °C and 770 °C isotherms (Fig. 5).

In addition to the temperature, using a biotite-amphibole thermometer, using a biotite-garnet thermobarometer, it is possible to calculate the pressure purely theoretically (although the rocks of the considered massifs do not contain garnet). Knowing the temperature and coefficient $X_{Mg/(Mg+Fe+Mn)}$) for biotite of three samples, using another diagram ($X^{Bi}_{Mg/(Mg+Fe+Mn)} – X^{Gr}_{Mg/(Mg+Fe+Mn)}$) (Perchuk, Ryabchikov, 1976) you can get the coefficient $K = X^{Gr}_{Mg/(Mg+Fe+Mn)}$ for garnet (K = 0.20 for the 1st pair, K = 0.17 – for the 2nd, K = 0.16 – for the 3rd). Then the coefficient $K* = X^{Gr}_{Mg/(Mg+Fe+Mn)}/X^{Bi}_{Mg/(Mg+Fe+Mn)}$ is calculated (lnK* = –0.79 for the 1st pair; lnK* = –0.93 – for the 2nd; lnK* = 0.94 – for the 3rd) and is displayed on the P – T diagram, which allows one to determine the pressure by T and lnK* in the biotite-garnet paragenesis (Fig. 6) (Thermo- and barometry..., 1977).

According to this diagram, the pressure at the time of the formation of mafic minerals (biotite and amphibole) at the postmagmatic stage was about 4.0–4.2 kbar.

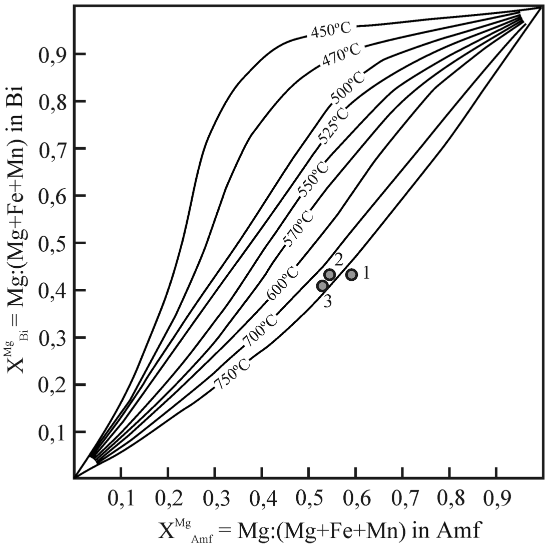

Fig. 5. Composition of biotites and amphiboles from syenite of the Krasnokamensk massif (Table 5) on the phase correspondence diagram, according to L.L. Perchuk, I.D. Ryabchikov (Perchuk, Ryabchikov, 1976): 1 – the 1st pair of minerals (Bi-1, Amf-1), 2 – the 2nd pair of minerals (Bi-2, Amf-2), 3 – the 3rd pair of minerals (Bi-3, Amf-3).

Conclusion

The new geological and scientific research material presented in the work made it possible to draw the following main conclusions:

1. The Sokolovsk and Krasnokamensk massifs are located in the axial part of the Western subzone of the Chelyabinsk-Adamovka zone, are part of the gabbro-syenite complex and are composed of gabbroids (phase I) and syenites, quartz monzonites, less often monzodiorites (phase II). The rocks of the second phase predominate (90–95%). Gabbros belong to the normal alkaline series of the sodium series, syenites correspond to the moderately alkaline series with potassium-sodium type of alkalinity.

2. In terms of petrographic, petrochemical, geochemical and metallogenic features (content of TiO_2, K_2O, Na_2O, Rb, Sr, distribution of REE, presence of skarn-magnetic mineralization), the rocks of the intrusions under

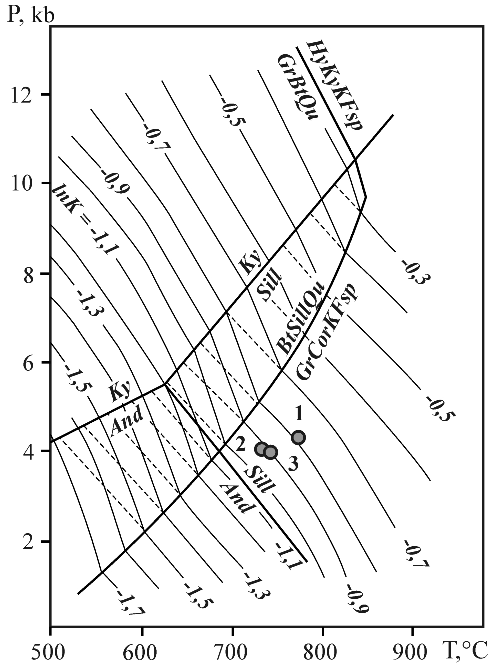

Fig. 6. P – T diagram for determining the pressure by T and lnK in the biotite – garnet association in syenites of the Krasnokamensk massif (Thermo and barometry…, 1977): points 1–3 – Table 5. 1 – the 1st pair of minerals (Bi-1, Amf-1, calculated parameters for garnet – XGrMg /(Mg + Fe + Mn) = 0.20, lnKGr-BiMg/(Mg + Fe + Mn) = – 0.79), 2 – the 2nd pair of minerals (Bi-2, Amf-2, calculated parameters for garnet – XGrMg/(Mg + Fe + Mn) = 0.17, lnKGr-BiMg/(Mg + Fe + Mn) = –0.93), 3rd – the 3rd pair of minerals (Bi-3, Amf-3, calculated parameters for garnet – XGrMg/(Mg + Fe + Mn) = 0.16, lnKGr-BiMg/(Mg + Fe + Mn) = –0.94).

consideration undoubtedly belong to the gabbro-granite formation.

3. Crystallization of the considered intrusions occurred at a temperature of 880–930 °C in the mesoabyssal zone at a depth of about 7–8 km (P = 2.2–2.4 kbar). At the postmagmatic stage, the transformation parameters of the initially igneous rocks were, respectively, T = 730–770 °C, P = 4.0–4.2 kbar.

4. Together with the Bolshakovsky, Klyuchevsky, Kurtmaksky and Kambulatovsky massifs (Fig. 1), Sokolovsk and Krasnokamensk massifs are part of the Chelyabinsk-Adamovka segment of the rift system, traced in the submeridional direction at a distance of about 400 km and traced by a chain of small intrusions belonging to the gabbro-granite formation (Magnitogorsky, Krasnokamensk and Kanzafarovsky complexes). According to their petrochemical characteristics, the gabbroids of the Krasnokamensk and Sokolovsk massifs belong to tholeiitic basic rocks, the formation of which is associated with riftogenic structures.

Based on the data obtained in this work, it can be assumed that the formation of the rift took place in the Early Carboniferous time in the back-arc basin of the Devonian island arc. In the collisional stage of development of the region that followed in the second half of the Carboniferous-Permian, the northern part of the Magnitogorsk megazone and the border region of the Southern and Middle Urals were in severe collision, as a result of which the formation of their eastern flank, including the gabbro-granite formation (Chelyabinsk-Adamovka zone), were overthrusted on the western edge of the East Ural uplift (Snachev et al., 2019).

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