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Research Article

AMPHIBOLES AND BIOTITES OF PLAGIOGRANITOIDS FROM THE SOUTH GISSAR ZONE (SOUTH TIEN SHAN)

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ABSTRACT
This article examines the typomorphic and typochemical characteristics of amphiboles and biotites from the gabbro–plagiogranitoid series rocks of the South Gissar Zone (Southern Tian Shan, Tajikistan). It has been established that the amphiboles belong to the magnesian hornblende of the calcic group, while the biotites are iron-rich micas. Based on the TiO_2 and Al_2O_3 oxide contents in amphiboles and biotites from the plagiogranitoids, the depth conditions of their crystallization have been determined, corresponding to the mesoabyssal facies (3.0–5.0 km). The mineral associations containing biotite and amphibole reflect the formation of the plagiogranitoids in a subduction-related island arc geodynamic setting during the Late Paleozoic evolution of the region. The obtained data provide a more accurate reconstruction of the emplacement depths and tectonic regime of pluton formation within the gabbro–plagiogranitoid series of the South Gissar Zone in the Southern Tian Shan.

***Keywords**: gabbro–plagiogranitoid series, South Gissar Zone Southern Tian Shan, amphiboles and biotite's,*

INTRADUCTION
The South Gissar Zone, as part of the Paleozoic South Tian Shan accretion–collision orogenic belt, is distinguished by its unique geological structure, which reflects the geodynamic evolution of sedimentation, metamorphism, and magmatism. This tectonic zone is primarily characterized by the widespread development of Late Paleozoic magmatic complexes, particularly granitoid complexes of various genetic types.

The basement of the South Gissar Zone is composed of high-grade metamorphic crystalline schists, migmatites, gneisses, and granitoid rocks, which are exposed within the Garm Precambrian Block — an exposed fragment of the Karakum–Tajik microcontinent.

During the Early to Middle Carboniferous (C_1–C_2), the South Gissar Zone functioned as an island arc system with active subduction-related magmatism of low-potassium basaltic and calc-alkaline andesitic composition. The island arc volcanic series are genetically associated with plutons of the gabbro–plagiogranitoid series (C_{1-2}) and the gabbro–granitoid series (C_2), as well as with magmatic complexes formed under collisional (rhyolite–granite association, C_3–P_1) and post-collisional (shoshonite–latite–monzonite association, P_1) settings. Permian–Triassic plume-related magmatism is represented by diatremes and explosive pipes of mantle-derived alkaline basaltoids of the Gissar–Karategin complex.

The gabbro–plagiogranitoid series of the South Gissar Zone in the Southern Tian Shan, within the territory of Tajikistan, includes the Kharangon, Khojamafrach, Khojabed, Gafilabad, and Khanakin intrusions, located north of the Bogainsky Fault. These intrusions are represented by sub-latitudinal, lens-shaped bodies of varying size, emplaced into the basalts of the Karatag Series of Early to Middle Carboniferous age (C_{1-2}) (Baratov et al., 2012; Khodzhiev et al., 2022).

U–Pb isotopic dating of accessory zircons from gabbros, tonalites, and plagiogranites indicates a crystallization age of 323–316 Ma (Konopelko et al., 2017, our unpublished dates), corresponding to the Early to Middle Carboniferous period (Serpukhovian to Bashkirian) and reflecting the true geological age of the plutonic gabbro–plagiogranitoid series.

In this study, we present the morphological and chemical characteristics of amphiboles and biotites from the gabbro–plagiogranitoid series rocks of the South Gissar Zone, focusing on the plagiogranitoids of the Khojamafrach and Kharangon intrusions.

GEOLOGY AND PETROGRAPHY OF GABBRO-PLAGIOGRANITOIDS

The gabbro–plagiogranitoid series has a polyphase structure and includes the products of five intrusive phases: Phase I – gabbros; Phase II – diorites and quartz diorites; Phase III – tonalites; Phase IV – plagiogranites; and Phase V – leucoplagiogranites. Dike-related derivatives of the series include plagioaplite, microgabbro, and lamprophyres of the spessartite series.

Phase I gabbros are predominantly developed within the Kharangon intrusion, with isolated bodies also occurring in the Khojamafrach pluton. They form stock-like bodies ranging in area from 0.05 to 5 km², exposed in the valleys of the Varzob, Kharangon, and Semiganch rivers. Within the Kharangon intrusion, Phase I gabbros are exposed in its southeastern part (right bank of the Semiganch River), central part (right slope of the Darayagnobi stream), and northwestern part (left bank of the Varzob River), where they are emplaced primarily into the basalts of the Karatag Series. Gabbro consists of plagioclase of the bytownite-labradorite series (60-70%), hornblende (20-30%), a small amount of augite (0.0-5.0%) and biotite (0.0-3.0%). Potassium feldspar and quartz are postmagmatic minerals. Accessory minerals found in gabbro include zircon, magnetite, apatite, and very rarely orthite, sphene, etc.

Phase II diorites and quartz diorites form elongated bodies ranging in area from 0.3–1 up to 40 km². The largest body (approximately 40 km²) is identified in the Khojamafrach intrusion, in the upper reaches of the Karatag River. In the Kharangon intrusion, Phase II bodies are localized near the Fanfarok stream (about 7 km²) and in the watershed area between the Odzhuk and Kharangon rivers. The diorites host xenoliths of volcanic rocks and S_2–D_1 limestones, and are intruded by tonalites, plagiogranites, as well as porphyritic granites of the South Varzob intrusion. Contacts are generally intrusive, sharp, dipping at angles of 45–50°, and locally tectonic. The host rocks are hornfelsed (volcanic rocks) and skarnified (carbonate rocks). Quartz diorites are also widely distributed in the Khojabed massif.

Diorites and quartz diorites are medium-grained, uniformly grained, gray massive rocks with a hypidiomorphic-granular structure. They consist of plagioclase-andesine (60-65%), quartz (5.0-12%), amphibole (15-20%), biotite (3.0-5.0%) and K-feldspar (0.2-0.3%). The amount of quartz in diorites is 5.0-6.0%. Zircon, apatite, allanite, monazite, sphene and magnetite are accessory minerals of diorites.

Phase III tonalites occur in the Khojamafrach, Khojabed, and Kharangon intrusions. They form bodies ranging in area from 0.1 to 2.5 km² and are associated with Phase II diorites, exhibiting both active contacts and gradual transitions. In the Kharangon intrusion, tonalites are observed near the Fanfarok stream, where they intrude quartz diorites and are themselves intruded by plagiogranites of Phase IV.

Tonalites are medium-grained, light-gray, uniform-grained rocks with a massive texture. The structure of tonalites is hypidiomorphic-granular. Mineralogical composition: plagioclase (andesine-albite) - 55-65%, potassium feldspar (orthoclase, microcline) - 0.0-5.0%, quartz -15-25%, biotite - 0.5-5.0%, amphibole - 0.0-7.0%. Characteristic accessory minerals of tonalites are apatite, sphene, and zircon.

Phase IV plagiogranites form both polyphase and monophase intrusions. In the Kharangon intrusion, they cover more than a third of its area (~26 km² out of ~70 km²). They are also widely developed in the Khojamafrach pluton (~10 km²). The Khanakin pluton is entirely composed of plagiogranites.

Plagiogranites are light-grey, uniformly grained rocks consisting of plagioclase - andesine No. 30-40 (40-50%), quartz (30-45%), potassium feldspar (0-5.0%), hornblende (4.5%) and biotite (10-15%). Accessory minerals of plagiogranites are apatite, magnetite, zircon, and orthite.

Phase V leucoplagiogranites form steeply dipping dike- and stock-like bodies. The largest body (~10 km²) is recorded in the Kharangon intrusion, with additional occurrences in the Khojabed and Khojamafrach intrusions. leukoplagiogranites are light-colored fine-grained rocks consisting of albite, albite-oligoclase (60%) and quartz (40%) and accessories - apatite, zircon, magnetite, etc.

Fig. 1 shows microphotographs of characteristic thin sections of plutonic rocks of the studied gabbro-plagiogranitoid series.

The main rock-forming minerals of the gabbro–plagiogranitoids are plagioclase, amphibole, biotite, quartz, and a minor amount of potassium feldspar. **Plagioclase** is the dominant mineral, varying in composition from bitownite and labradorite (in gabbros), to andesine (in diorites and tonalites), and oligoclase-albite and albite (in plagiogranites), forming intergrown and zoned crystals. **Amphibole** is predominantly represented by magnesian hornblende. **Biotite** is iron-rich. **Potassium feldspar** is present in small amounts in the more acidic varieties (tonalites, plagiogranites, leucoplagiogranites). **Quartz** is a crucial rock-forming component, with its content in the series ranging from 5 to 50%.

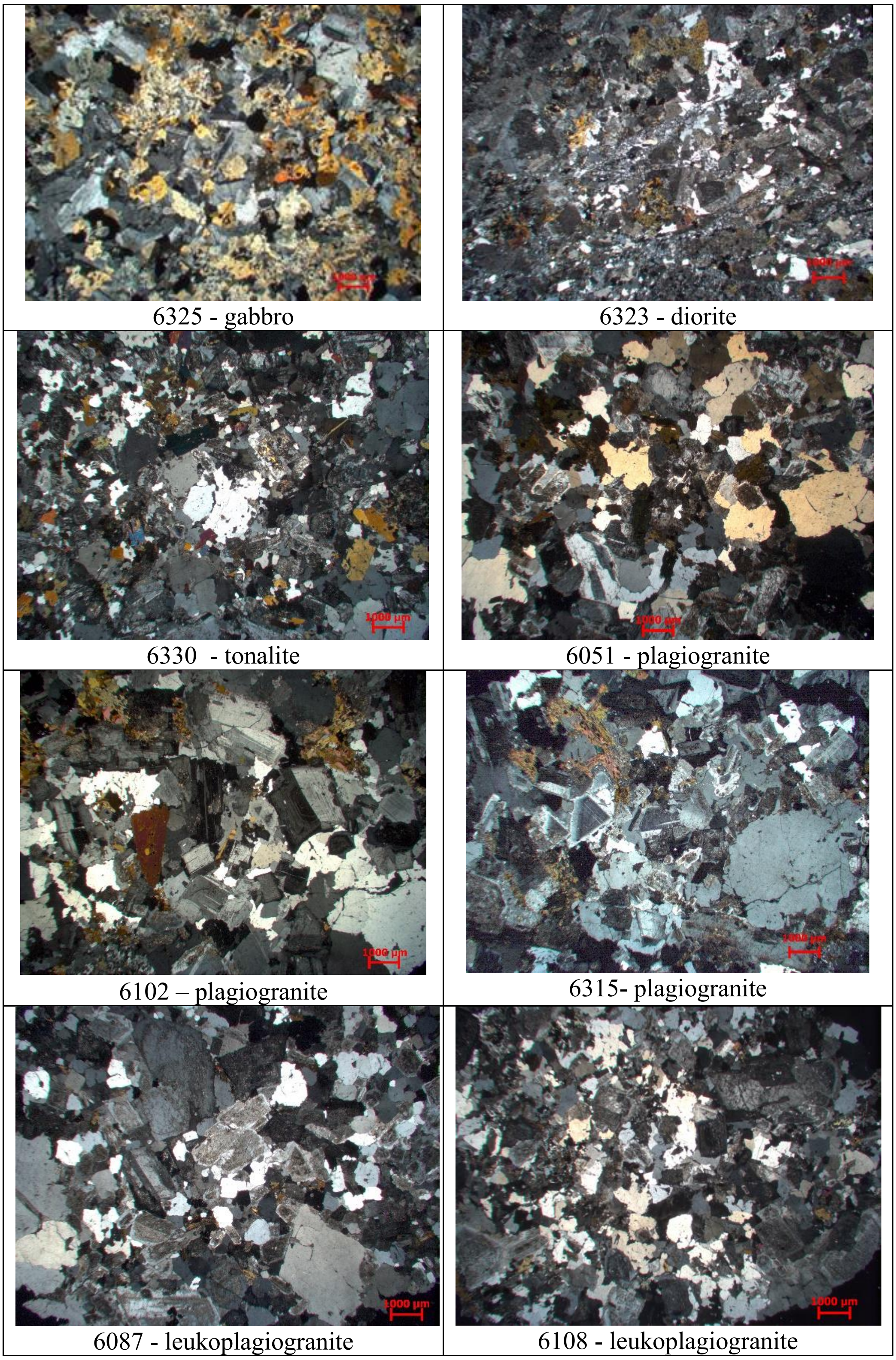

Figure 1: Microphotographs of thin sections of plutonic rocks of the gabbro-plagiogranitoid series of the South Gissar zone. The nicoli are crossed.

MATERIALS AND METHODS

To study the typochemical features of femic rock-forming minerals — amphibole and biotite — in the plagiogranitoids of the South Gissar Zone, samples of tonalites and plagiogranites from the Khojamafrach and Kharangon plutons were used. These samples were kindly provided by Professor V. S. Lutkov.

After crushing and rinsing with water to remove dust particles, the samples were separated into electromagnetic and non-electromagnetic fractions using a magnetic separator.

From the electromagnetic fraction of the crushed plutonic rocks, clean grains of amphibole and biotite were hand-picked under a binocular microscope. Electron microprobe analyses of the chemical composition of these minerals, selected from the plagiogranites, were carried out using a **Cameca MS-46** X-ray microanalyzer (France) at the Analytical Laboratory of the All-Russian Geological Research Institute named after A. P. Karpinsky (St. Petersburg, Russian Federation; analyst V. N. Kuranova).

Amphiboles in the plagiogranitoids are represented by green hornblende. In these rocks, amphibole coexists with biotite and occurs in grains of various sizes and shapes – rhombohedral, prismatic, and sometimes even amorphous. The amphibole grains are often surrounded by quartz and feldspars.

The pleochroism of amphibole ranges from brownish-green and dirty-green shades along Ng to pale green and colorless along Np. Crystal-optical characteristics are as follows: angles with Ng range from 14–26°, 2V from 75 to 82°, and birefringence (Ng–Np) is between 0.016 and 0.022. These parameters correspond to ordinary hornblende. Hornblende is often replaced by secondary minerals, such as chlorite and biotite. Additionally, metasomatic amphiboles of actinolite–tremolite composition, colored pale green, are observed. Accessory minerals associated with the amphibole grains include magnetite, ilmenite, and sphene.

RESULTS AND DISCUSSION

Amphibole chemistry. The chemical composition and crystal-chemical formulas of amphiboles from the tonalites of the Khojamafrach massif (sample no. 6434) and plagiogranites from the Kharangon massif (samples no. 6102 and 6051) are presented in Table 1. The crystal-chemical formulas were calculated using the 12-cation method with the Minfile program.

Table 1: Chemical composition and crystal-chemical formulas of amphiboles in plagiogranites of the South Gissar Zone, wt. %

Compositions	6434	6102	6051	f.u.	6434	6102	6051
SiO_2	45.70	45.50	44.70	Ca	1.27	1.36	1.22
TiO_2	1.60	1.10	1.70	Mn^{2+}	0.04	0.15	0.04
Al_2O_3	7.20	6.80	11.40	Fe^{2+}	0.69	0.49	0.74
Fe_2O_3	5.37	5.79	1.17	***B_2***	***2.00***	***2.00***	***2.00***
FeO	11.27	12.16	9.45	Mg^{2+}	2.65	2.40	2.82
MnO	0.30	1.10	0.30	Fe^{2+}	0.81	1.15	0.53
MgO	11.20	10.10	11.80	Fe^{3+}	0.64	0.70	0.14
CaO	11.10	11.40	10.60	Al	0.80	0.75	1.47
Na_2O	1.30	0.80	0.90	***C_5***	***4.90***	***5.00***	***4.96***
K_2O	0.40	0.70	0.60	Si	7.26	7.33	7.16
Sum	95.44	95.45	92.62	Al	0.55	0.54	0.64
Na	0.40	0.25	0.28	Ti	0.19	0.13	0.20
K	0.08	0.14	0.12	***T_8***	***8.00***	***8.00***	***8.00***
Ca	0.62	0.61	0.60	*f*	44.68	49.38	33,33
A	***1.00***	***1.00***	***1.00***	Mg#	0.64	0.59	0.69

Note: *f = Fe·100/(Fe+Mg) – total iron content of the mineral, Mg# = Mg/(Mg+Fe^{2+}) – magnesium content of the mineral.*

Based on their chemical composition, hornblendes from the plagiogranitoids belong to the calcium amphibole group, characterized by the following parameters: (Mg, Fe^{2+}, Mn^{2+}) < 0.50; (Ca, Na) ≥ 1.00 and Na < 0.50 formula units, in accordance with the classification proposed by W.A. Deer et al. [Deer et al., 2013]. On a Mg/(Mg+Fe^{2+}) – Si (f.u.) diagram, recommended by the Amphibole Nomenclature Subcommittee of the International Mineralogical Association (IMA) for amphiboles with (Na+K) < 0.5 (Leake et al., 1997], the amphiboles from the Khojamafrach and Kharangon intrusions are classified as magnesian hornblende (Fig. 1). Analysis of the oxide ratios of TiO_2 and Al_2O_3 in the amphiboles allows the conclusion that the plagiogranitoids of the Khojamafrach and Kharangon plutons were formed under mesoabyssal facies conditions — at depths of approximately 3.0–5.0 km (Fig. 2).

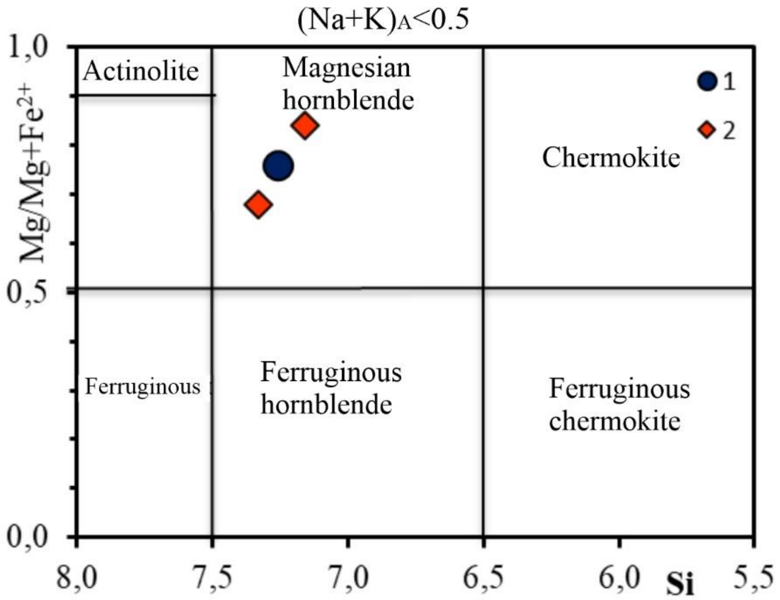

Figure 2: Composition of amphiboles from the plagiogranitoids of the Khojamafrach and Kharangon intrusions on the Mg/(Mg+Fe^{2+}) – Si (formula units) diagram. 1 - Amphiboles from the tonalites of the Khojamafrach massif, and 2 - Amphiboles from the plagiogranites of the Kharangon intrusions.

CHEMISTRY OF BIOTITE'S

Biotite is also a typomorphic ferromagnesian rock-forming mineral in the plagiogranitoids. Its content in the rocks ranges from 0.5 to 8.0%. Biotite occurs as individual flakes and scales of brownish-brown color, with sizes ranging from 0.2 to 2.0 mm, and is often replaced by secondary minerals such as chlorite and epidote. The chemical composition and crystal-chemical formulas of biotites, calculated using the 22-cation method (Stevens, 1946), from the plagiogranitoids of the Khojamafrach (sample no. 6434) and Kharangon (samples no. 6046, 6315) intrusions are presented in Table 2.

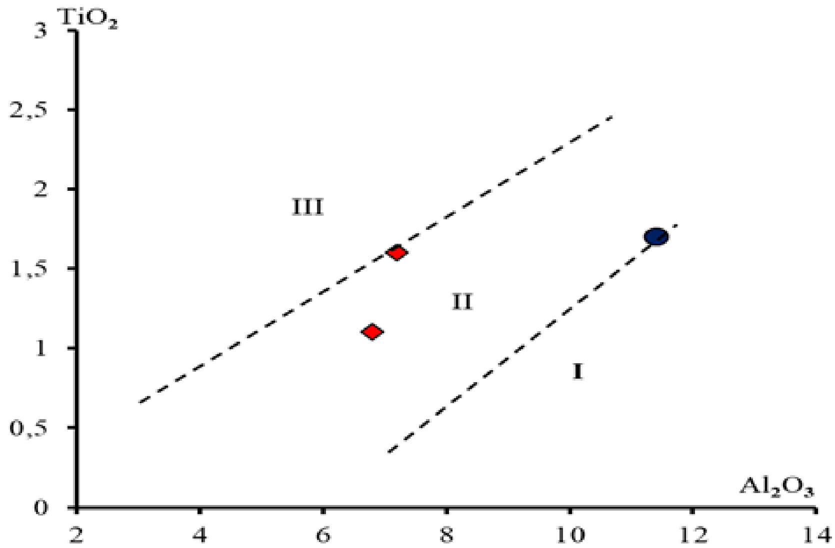

Fig. 3. Compositions of amphiboles from the plagiogranitoids on the TiO_2-Al_2O_3 diagram (Fershtater, Borodina, 1975). I-III - Fields of amphiboles from granitoids of abyssal (I), mesoabyssal (II), and hypabyssal (III) facies depth conditions. Other symbols are as in Fig. 2.

Table 2: Chemical composition and crystal-chemical formulas of biotites in the plagiogranites of the South Gissar Zone, wt. %

Oxides	6434	6046	6315	f.u.	6434	6046	6315
SiO_2	35.00	35.50	34.90	Si	2.71	2.70	2.68
TiO_2	3.60	3.50	3.50	AI_{IV}	1.29	1.30	1.32
Al_2O_3	14.10	14.50	14.60	**Z**	**4.00**	**4.00**	**4.00**
Fe_2O_3	5.60	6.60	5.50	Fe^{3+}	0.33	0.38	0.32
FeO	19.30	19.40	20.80	Fe^{2+}	1.26	1.24	1.34
MnO	0.40	0.60	0.20	Mg	0.93	0.92	0.92
MgO	8.10	8.00	8.10	Ti	0.21	0.19	0.20
CaO	1.70	1.70	1.70	Mn	0.02	0.04	0.01
Na_2O	0.20	0.20	0.20	***Y***	***2.75***	***2.77***	***2.79***
K_2O	6.90	6.20	6.70	K	0.70	0.60	0.65
P_2O_5	0.10	0.10	0.10	Na	0.05	0.04	0.03
H_2O +	3.50	3.60	3.60	Ca	0.14	0.13	0.14
F	0.20	0.40	0.50	***X***	***0.89***	***0.77***	***0.82***
∑	98.20	99.90	99.50	OH	1.82	1.83	1.85
F_2=0	0.04	0.10	0.14	F	0.05	0.09	0.14
∑	98.36	99.50	99.36	***(OH,F)***	***1.87***	***1.93***	***1.99***

According to their chemical composition, biotites belong to the high-iron mica group. The total iron oxide content (∑FeO) ranges from 24.60% to 26.30%, while MgO is between 8.00% and 8.10%. On the AlVI+Fe^{3+}+Ti^{3+} – Mg – Fe^{2+}+Mn diagram proposed by M. Foster (Foster, 1960), these biotites correspond to the iron-rich varieties of biotite (Fig. 4).

On the ternary diagram ∑FeO – MgO – Al_2O_3 (Fig. 5), after R. Nockolds (Nockolds, 1947), the biotites from the plagiogranitoids of the South Gissar Zone are located in field III — the area corresponding to micas associated with hornblende, pyroxene, and olivine. However, in the studied plagiogranites, neither olivine nor pyroxene were found, and biotites occur together with hornblende. The association of biotite with amphibole (hornblende) is typical for granitoids genetically linked to deep magmatic melt sources.

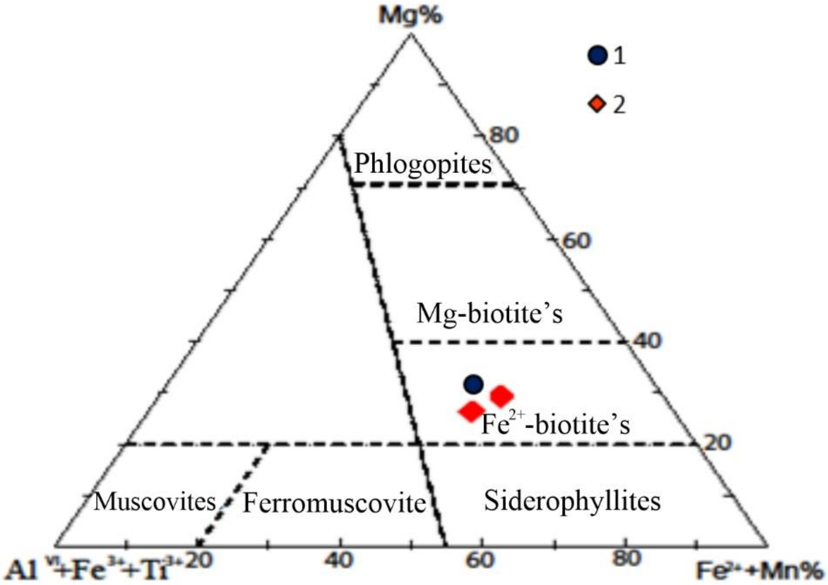

Figure 4: Compositions of biotite's from the plagiogranites of the Khojamafrach and Kharangon intrusions on the AlVI+Fe^{3+}+Ti^{3+} – Mg – Fe^{2+}+Mn diagram (Foster, 1960). 1, 2 - Biotite's from the plagiogranites of the Kharangon (1) and Khojamafrach (2) intrusions.

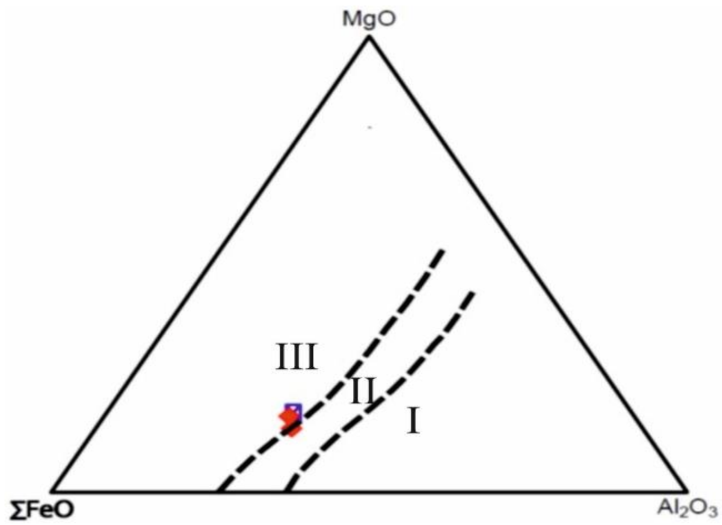

Figure 5: Position of biotites from the plagiogranitoids of the South Gissar Zone on the ΣFeO - MgO – Al_2O_3 diagram (Nockolds, 1947).
Fields of biotites: I — biotites associated with muscovite; II — biotites not associated with other ferromagnesian minerals; III — biotites in association with hornblende, pyroxene, and olivine. Other symbols are as in Fig. 4.

The content of TiO_2 in biotites of granitoids serves as an important indicator of their formation conditions. According to I.V. Bushlyakov (Bushlyakov, 1969), the concentration of titanium in biotite correlates with the crystallization temperature and depends on factors such as depth, pressure, melt hydration, and other geological conditions. In biotites of granitoids from mesoabyssal and hypabyssal levels, the TiO_2 content typically exceeds 3.0%, whereas in biotites of abyssal granites, this value is usually lower than 3.0% (Bushlyakov, 1969).

The TiO_2 content in biotites from the plagiogranites varies within narrow limits, ranging from 3.50% to 3.60%. Along with titanium-containing components, the content of Al_2O_3 in the micas is an important indicator of the crystallization depth. As noted by G.B. Fershtater and N.C. Borodina (Fershtater and Borodina, 1975), this parameter also reflects the conditions of granitoid formation. In the studied samples, the Al_2O_3 content in the biotites of the plagiogranitoids ranges from 14.10% to 14.50%. Based on the TiO_2 and Al_2O_3 ratios, it can be concluded that the plagiogranitoids of the Khojamafrach and Kharangon intrusions, like the gabbro-plagiogranitoid series of the South Gissar Zone as a whole, formed under mesoabyssal facies conditions (at depths of approximately 3.0–5.0 km) (Fig. 6).

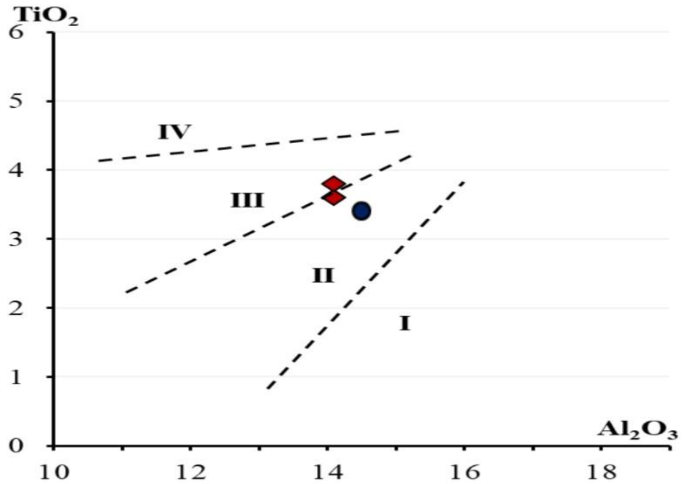

Figure 6: Compositions of biotites from the plagiogranites on the TiO_2-Al_2O_3 diagram (Fershtater, Borodina, 1975).

CONCLUSION

The results of the mineralogical-chemical study of amphiboles and biotites from the tonalites-plagiogranites of the gabbro-plagiogranitoid series of the South Gissar Zone (Southern Tien Shan) lead to the following conclusions:

- Amphiboles, predominantly represented by ordinary hornblende, belong to the calcium group based on their chemical composition and are classified as magnesium-rich hornblendes. Their typochemical characteristics indicate crystallization under moderate depth conditions.
- Biotites are characterized by a high iron content ($\sum FeO$ = 24.6–26.3%) and a moderate magnesium content (MgO = 8.0–8.1%), which classifies them as iron-rich micas.
- Based on the content of TiO_2 (3.50–3.60%) and Al_2O_3 (14.10–14.50%) in both amphiboles and biotites, it has been established that the plagiogranitoids of the Khojamafrach and Kharangon intrusions, and the gabbro-plagiogranitoid series of the South Gissar Zone of the Southern Tien Shan as a whole, formed under mesoabyssal facies conditions at depths of 3–5 km.

Thus, the rock-forming amphiboles and biotites are reliable indicators of the thermodynamic conditions and depth of granitoid formation as a whole, and can be effectively used for reconstructing the crystallization conditions of different granitoid plutons and complexes in the South Gissar Zone and other orogenic regions.

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