

Mafic enclaves in peraluminous Variscan granitoid in the Battonya Unit from Southeast Hungary



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ABSTRACT

Variscan granitoids occur in the southeastern part of the Tisza Mega Unit of Hungary. The presence of amphibole, calc-alkaline-type Mg-rich biotite in metaluminous basic enclaves, and muscovite and Fe-Al-biotite in peraluminous granitoids, suggests a mixed I-S-type origin. Two types of muscovite have been identified: a primary euhedral to subhedral, Ti-Na-Al rich variety, crystallized after Fe-rich peraluminous biotite in the two-mica granite and in muscovite granite, and a secondary subhedral Si enriched and Mg-bearing, Ti-poor mica formed as a hydrothermal alteration product of feldspars, and is present in all rock types. Given the compositional continuum of “white micas”, we suggest that magmatic crystallization was followed by autometasomatic and hydrothermal activity, due to a water-rich liquid trapped in the rock during the final stages of magmatic activity. Based on the bulk composition of the prevailing rock-type, the abundance of primary muscovite, the majority of the granitoid magma crystallized from a water-saturated peraluminous melt for which the pressure was 490–600 MPa, the temperatures were 650–685 °C and the depth of the intrusion was a minimum of 15 km.

Keywords: basic enclave, peraluminous granitoid, Variscan, I/S-type, primary-, secondary muscovite, P, T, depth of intrusion, SE Hungary

1. INTRODUCTION

Variscan granitoids occur in the Carpathian Basin (Hungary). The present geology and tectonic setting of the Carpathian or Pannonian Basin (fig. 1/A), are the result of a multi-step evolution of geological structures (HAAS et al., 2000; KOVÁCS et al., 2000, HAAS et al., 2004; SCHMID et al., 2008).

The complexity is due to the tectonic position of the territory. It is situated in the collision zone of the European and African continental plates. The history began with spread-

ing, followed by a series of collisions. During the Alpine orogenesis, the drifting and welding of the individual fragments was accompanied by folding processes and nappe formation. At the end of the Miocene, attenuation of the crust (upward bulging of the mantle) resulted in the development of a large basin that determines the present structural setting of the area.

The greatest proportion of the Pre-Neogene basement of the Pannonian Basin is composed of two megatectonic units: in the north the ALCAPA Mega Unit (the southern part of which is named the Pelso Composite Unit) and in the south

the Tisza Mega Unit (TMU, KOVÁCS et al. 2000) or Tisia Composite Terran (KOVÁCS et al., 2010).

In the Hungarian part of the Variscan TMU (fig. 1/B) two types of granitoids can be distinguished: an older (354 Ma, KLÖTZLI et al., 2004) deep-seated metaluminous and slightly peraluminous, K- and Mg-rich, I- and allanite-type granitoid, with K-Mg-rich basic durbachitic enclaves (BUDA et al., 2004/a), occurring in the southwest part of the TMU outcropping in the Mórógy Unit (Mecsek Mts) and a slightly younger granitoid which is mostly strongly peraluminous with mafic enclaves, I/S- and monazite-type (BUDA et al., 2009) in the southeastern part of the TMU located in the characteristic uplift of the basement of the Battonya Unit, studied only from oil prospecting drill-core samples. One of the main purposes of this study to distinguish primary muscovite from secondary muscovite in the peraluminous granitoid in order to estimate the P/T of crystallization and the depth of intrusion of the Battonya granitoids. For this estimation it was important to prove the presence of primary muscovite in these altered rocks because the breakdown curve of primary muscovite (CLARKE et al., 2005), which intersects the experimentally determined watersaturated peraluminous granite solidus (JOHANNES & HOLTZ), can give a rather good estimation for the physical parameters of crystallization and depth of intrusion. Due to the volatile enriched environment, subsolidus muscovite is also widespread; con-

sequently we had to use different criteria to distinguish them from primary muscovite. The role of basic enclaves in the peraluminous granitoid is not clear, and requires further research.

2. OUTLINE OF GEOLOGICAL SETTING

The TMU comprises the crystalline basement of south Hungary, east Croatia, north Serbia, and the western part of Transylvania (Romania, Fig. 1/A). It is bordered by the Mid Hungarian Lineament, the Száva-Moslavima-Zombor-Bečej-Lipova line, (the Northern border of the Srem – Mureş ophiolite belt), and the Someş lineament in the Northwest, South and Northeast, respectively. As a consequence of the fact that at present, the basement is covered by 1000–6500 m of Miocene-Pliocene sediments, its structure and petrology can only be investigated by geophysical methods and borehole samples. The seismic research of the past decades has shown that during the Neogene, the Pannonian Basin underwent a complex tectonic evolution that has principally modified the original Variscan structures of the area (TARI et al., 1999; CSONTOS et al., 1999).

As an independent unit, the TMU existed from the Late Cretaceous, when its rotation began, until the Early Miocene (CSONTOS, 1995; MÁRTON, 2000, 2001; KOVÁCS et al., 2000). Separation from the Moldanubian Zone of Variscan

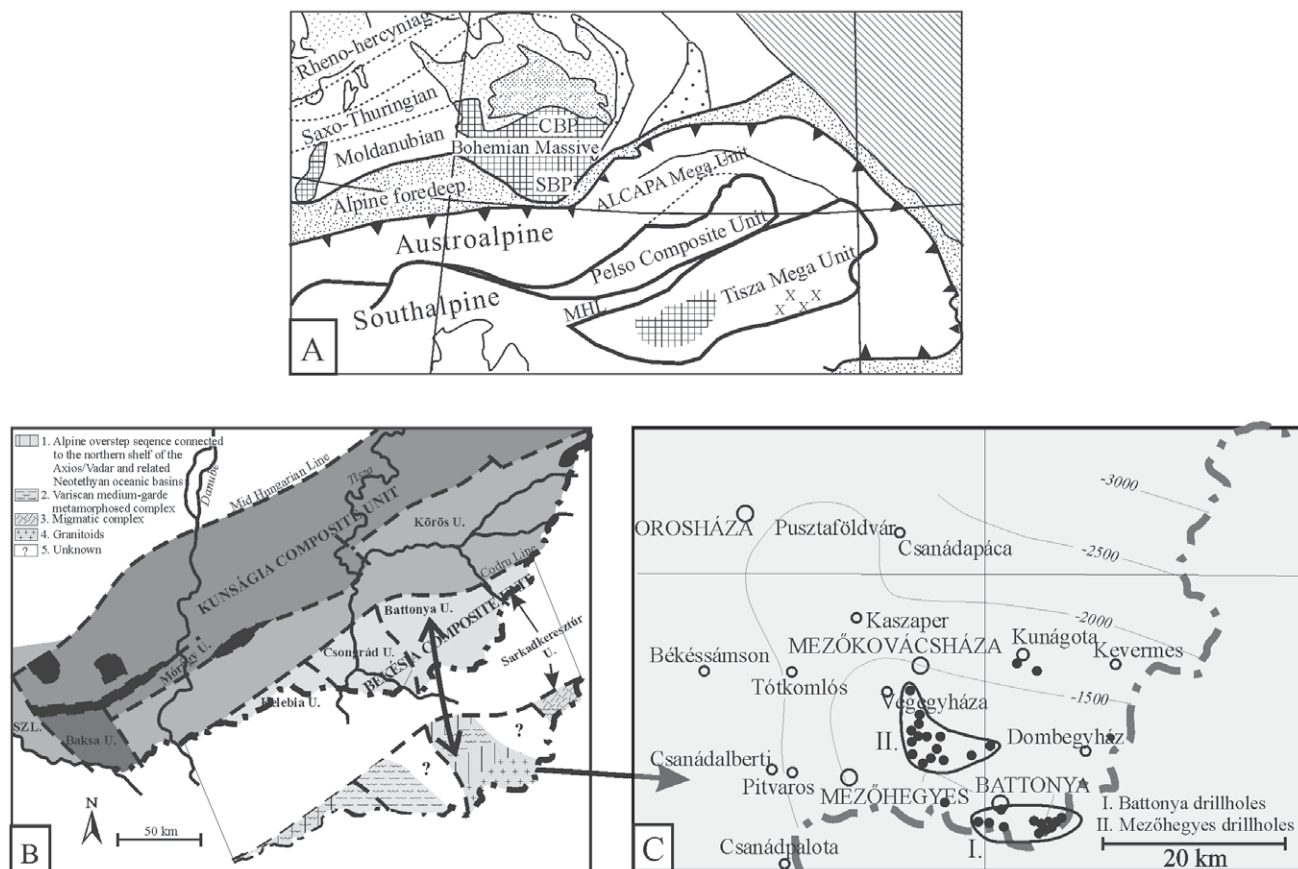


Figure 1: A – Sketch map of the main tectonic units of Central Europe (CBP= Central Bohemian Pluton, SBP=South Bohemian Pluton, MHL=Mid Hungarian Lineament). B – Structural units of the Hungarian part of the Tisza Mega Unit. Inset: simplified geological map of Békésian Composite Unit after KOVÁCS et al. (2000), modified by PÁL-MOLNÁR et al. (2001). C. Location of bore-holes of the Battonya Unit.

Europe started in the Late Triassic–Early Cretaceous, as recorded by crystalline rocks (BUDA et al., 2004/b) and sedimentary sequences (HAAS et al., 2004; CSONTOS et al., 2004; SCHMID et al., 2008). The Hungarian part of the TMU is called the Kunságia Composite Unit and the Békésia Composite Unit (BCU). The BCU can be divided into four units: Kelebia, Csongrád, Battonya, and Sarkadkeresztúr (fig. 1/B). The areas of interest are located in the BCU, which is part of the Békés-Codru Alpine Zone (HAAS et al., 2004). The Battonya Unit is a 15–25 km long and 10–15 km wide body forming a flat anticline covered by 1000–1500 m of Miocene and Pannonian sediments.

The present study first of all deals with the genesis of “white micas” of mostly two-mica and muscovite granitoids, occurring in the uplifted basement of the Battonya Unit. These plutonic rocks are surrounded by regional metamorphic and migmatitic rocks and are partly covered by Alpine sequences. The rocks were metamorphosed at about 6–700 MPa and 500–570°C (350–330 Ma) and are locally affected by dynamo- and retrograde metamorphism (330–315 Ma) according to SZEDERKÉNYI (2001).

3. SAMPLING AND ANALYTICAL METHODS

The studied samples were obtained from boreholes of the Battonya Unit around the Battonya and Mezöhegyes (Fig. 1/C/I., II.) settlements. The rocks were acquired from the rock collection of the Department of Mineralogy, Geochemistry and Petrology of the University of Szeged. The samples are drill-cores and consequently their numbers are limited.

The major and trace element analyses of the rocks were carried out using ICP-AES methods at the University of Stockholm and at ALS Chemex in Canada (Vancouver). Most of the analyses were published by PÁL-MOLNÁR et al. (2001). Detection limits for major components are

0.01 Wt %, FeO content was determined by titrimetric and H_2O^- and H_2O^+ by gravimetric methods. Major element compositions of minerals were determined by a CAMECA SX-100 electron probe X-ray microanalyser at the Department of Lithospheric Research of the University of Vienna. During the measurements an accelerating voltage of 15 kV and a beam current of 10 nA were used. A beam size of 1–2 μm was used for amphiboles, micas and other minerals, for feldspar minerals a beam size of 5 μm was used. The counting time was for each element ranged from 20–40 sec. For calibration, well defined mineral standards were used (quartz for Si, rutile for Ti, almandine for Al and Fe, a chromite for Cr, spessartine for Mn, olivine for Mg, wollastonite for Ca, albite for Na and an orthoclase for K). Afterwards, standard ZAF corrections were applied. Approximately 500 spot analyses were carried out. We analyzed 3 to 5 points in each mineral grain, but in the case of zoned crystals, as many as 20–30 points were analyzed, depending on the number of distinguishable zones.

4. PETROGRAPHY

The Battonya granitoid has light greenish grey, grey and pinkish grey colours. It is generally medium-grained, equigranular, sometimes with pinkish microcline megacrysts. The majority contains biotite and/or muscovite. Three rock types have been distinguished:

Type I.: *quartzmonzodiorite* (Fig. 2/A, I.) is the greenish grey variety containing amphibole and biotite but no primary muscovite. The chemical composition is mostly metaluminous or slightly peraluminous (Fig. 2/B, I.). They are most probably basic enclaves in the prevailing two mica and muscovite granitoid pluton.

Amphiboles form large euhedral and subhedral crystals or aggregates. The large amphibole is zoned; the core is Mg-

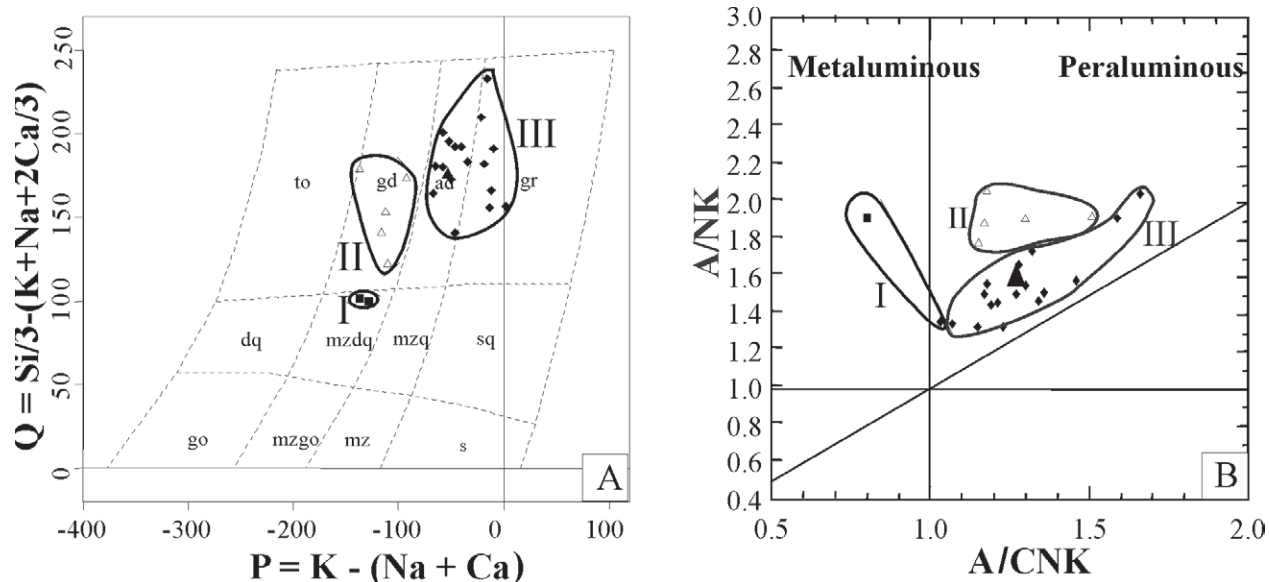


Figure 2: A – Rock classification: I. Quartzmonzodiorite; II. Granodiorite; III. Granite; (DEBON et al., 1983). B – A/CNK v. A/NK of Battonya granitoids (I. Quartzmonzodiorite; II. Granodiorite III. Granite; after SHAND, 1947).

hornblende with a low Si (6.823 pfu) and high Al (1.627 pfu, A/CNK = 0.70), Ti (TiO₂ = 0.66 Wt %), and Cr (Cr₂O₃ = 0.2 Wt %) content (table I.). According to HOLLAND & BLUNDY's (1994) amphibole-plagioclase thermometer, it formed about 700°C and at 440 MPa pressure (ANDERSON et al., 1996). The rim is actinolite (Fig. 3/A) which additionally forms small aggregates (A/CNK=0.31–0.45). It probably formed at similar P/T conditions to secondary muscovite.

Table I: Representative compositions of amphiboles from Battonya Unit determined by electron microprobe.

Battonya N-2							
	1	2	3	4	5	6	7
SiO ₂	46.55	50.61	51.93	51.69	51.02	50.93	52.83
TiO ₂	0.66	0.30	0.27	0.16	0.25	0.22	0.25
Al ₂ O ₃	9.42	5.87	4.85	4.97	5.52	5.90	4.27
FeO	11.15	9.23	8.69	8.48	8.90	9.30	8.43
Cr ₂ O ₃	0.20	0.10	0.02	0.07	0.08	0.16	0.00
MnO	0.46	0.38	0.35	0.33	0.33	0.37	0.27
MgO	14.56	16.75	17.39	17.38	16.96	16.65	17.31
CaO	12.05	12.47	12.67	12.61	12.75	12.59	12.53
Na ₂ O	1.34	0.76	0.59	0.73	0.76	0.78	0.54
K ₂ O	0.45	0.33	0.22	0.18	0.21	0.25	0.17
Total	96.84	96.80	96.97	96.60	96.77	97.13	96.60
Structural formulae calculated on an anhydrous basis of 23 (O)							
TSi	6.823	7.299	7.434	7.426	7.343	7.316	7.559
TAI	1.177	0.701	0.566	0.574	0.657	0.684	0.441
Sum_T	8	8	8	8	8	8	8
CAI	0.450	0.295	0.254	0.266	0.279	0.314	0.280
CCr	0.024	0.011	0.002	0.008	0.009	0.018	0
CTi	0.073	0.033	0.029	0.018	0.027	0.024	0.028
CMg	3.181	3.600	3.711	3.722	3.639	3.565	3.691
CFe ²	1.273	1.061	1.005	0.987	1.046	1.079	0.997
CMn	0	0	0	0	0	0	0.005
Sum_C	5	5	5	5	5	5	5
BFe ²	0.094	0.053	0.036	0.032	0.025	0.038	0.012
BMn	0.057	0.046	0.042	0.040	0.041	0.045	0.028
BCa	1.849	1.901	1.922	1.928	1.934	1.918	1.921
BNa	0	0	0	0	0	0	0.039
Sum_B	2	2	2	2	2	2	2
ACa	0.043	0.026	0.022	0.013	0.032	0.019	0
ANa	0.381	0.213	0.165	0.203	0.211	0.216	0.111
AK	0.084	0.061	0.041	0.034	0.038	0.045	0.032
Sum_A	0.509	0.300	0.229	0.250	0.281	0.281	0.143
Sum_cat	15.509	15.300	15.229	15.250	15.281	15.281	15.143

1. Core of the large grain. 2. Outer zone of a large grain. 3. Larger crystal. 4–6. Small acicular grains. 7. Small acicular grain.

Biotite is subhedral, Mg-rich ($Fe/(Fe + Mg) = 0.31$, Table II.) and Al poor ($Al = 2.84$ pfu) with phlogopitic (Fig. 3/B, I.) composition, having a calc-alkaline (ABDEL-RAHMAN, 1994; BUDA et al., 2004/c) chemical character (Fig. 3/C, I.).

Sometimes biotites occur as anhedral patches in amphibole showing replacement texture. Alteration of biotite to chlorite is common. Primary muscovite is absent but a secondary variety (sericite) is common in plagioclase. The plagioclases have oscillatory zoning between andesine (An_{43-40} , Fig. 3/D) and oligoclase (An_{17-13}) with secondary albitization and sericitization. Sometimes unzoned oligoclase (An_{17-10}) can also be observed.

A cross-hatched microcline is present but not common; it shows replacement texture without perthitic exsolution and has a low Na content (Or_{94} , Fig. 3/D, insert). Quartz is deformed with wavy extinction, and secondary calcite is observed. Accessory minerals are acicular apatite, zircon and rare monazite.

Type II and type III: *granodiorite and granite* (Fig. 2/A, II, III.). These granitoids are the most common. Differences between the granodiorite and granite are not well defined because autometasomatism, and hydrothermal processes obscure the primary rock and mineral compositions (e.g., the K-feldspar/plagioclase ratio). Granodiorite-granite is grey with either biotite and muscovite or with muscovite alone, and sometimes contains microcline megacrysts. These rocks are strongly peraluminous (Fig. 2/B II., III., $A/CNK = 1.1-1.7$, $CIPW_{avg}$ corundum = 4). In the two mica granitoid the biotite is Fe-rich ($Fe/(Fe + Mg) = 0.58$, Table II, Fig. 3/B, II.) and strongly pleochroic ($\gamma =$ dark brown $\alpha =$ yellowish brown) with peraluminous ($Al = 3.02$ pfu) compositions (Fig. 3/C, II.) and sometimes entirely altered to chlorite. Euhedral or subhedral large primary muscovite is common. Sometimes muscovite grew across the biotite (Fig. 4/1, 2) indicating later crystallization from an Al-rich water-saturated melt.

According to MILLER et al. (1981), Al-rich biotite (>3.00 Al pfu) coexists with quartz, K-feldspar, and Na-plagioclase in peraluminous granite.

The plagioclase is sometimes oscillatory zoned. The cores are mostly oligoclase (An_{25-18} , fig. 5/A) and the rims are albite (An_{2-0}) in the two mica granitoid and the muscovite granitoid, the plagioclases are richer in Na (An_{18-0} , fig. 5/B).

The plagioclase cores are strongly sericitized or altered to clay minerals, partly replaced by cross-hatched microcline and albite. Albite and microcline with low Na (Or_{95-97}) is widespread, occurring in replacement textures. Secondary albite also forms vein fillings. Sometimes large primary albite (An_{3-4}) is replaced partly by microcline (e.g. two-mica granite). Maximum or nearly maximum microcline ($\Delta = 0.74$, BUDA, 1975) occurs as megacrysts with low Na content (Or_{95-98}) indicating a low crystallization temperature and slow rate of cooling. Quartz is ubiquitous and displays wavy extinction; it also occurs as myrmekite in plagioclase. Stubby apatite, zircon, and monazite crystals are common accessory minerals.

Table II: Representative compositions of biotites from Battonya Unit determined by electron microprobe.

	biotite coexists with amphibole									biotite coexists with muscovite						
	Battonya N-2								average	Mezőhegyes-5					average	
	1	2	3	4	5	6	7	8		9	10	11	12	13		14
SiO ₂	38.99	39.17	38.79	37.51	37.90	38.02	38.00	38.21	38.32	34.88	35.49	34.64	34.89	35.09	35.16	35.02
TiO ₂	1.45	1.89	2.16	1.84	1.64	1.98	2.03	2.19	1.90	3.33	3.18	3.51	3.36	3.62	3.56	3.42
Al ₂ O ₃	16.16	16.34	16.12	16.30	16.23	16.33	16.39	16.27	16.27	16.59	16.21	16.70	16.60	16.46	16.22	16.46
Cr ₂ O ₃	0.00	0.00	0.00	0.12	0.14	0.06	0.06	0.04	0.05	0.02	0.01	0.01	0.02	0.00	0.02	0.01
FeO	13.44	12.15	12.63	13.41	13.07	12.02	12.19	11.78	12.59	21.46	21.08	21.67	21.32	21.24	21.58	21.39
MnO	0.21	0.19	0.16	0.23	0.23	0.22	0.20	0.21	0.21	0.32	0.31	0.35	0.33	0.34	0.29	0.32
MgO	14.68	14.93	14.88	15.20	15.40	15.63	15.74	15.94	15.30	8.64	8.67	8.45	8.52	8.36	8.27	8.49
BaO	0.00	0.00	0.00	0.12	0.08	0.15	0.23	0.18	0.09	0.29	0.16	0.23	0.30	0.35	0.31	0.27
CaO	0.00	0.04	0.02	0.03	0.01	0.02	0.01	0.01	0.02	0.00	0.03	0.01	0.02	0.00	0.02	0.01
Na ₂ O	0.11	0.13	0.09	0.07	0.10	0.09	0.10	0.09	0.10	0.14	0.11	0.14	0.11	0.10	0.09	0.11
K ₂ O	9.90	9.94	9.98	9.24	9.50	9.70	9.79	9.69	9.72	9.57	9.14	9.43	9.52	9.44	9.50	9.43
Total	95.94	94.78	94.80	94.08	94.30	94.20	94.74	94.63	94.56	95.23	94.37	95.12	94.98	95.00	95.01	94.95
Structural formulae calculated on an anhydrous basis of 22 (O)																
Si	5.778	5.777	5.740	5.619	5.657	5.658	5.634	5.653	5.689	5.420	5.528	5.392	5.431	5.456	5.475	5.450
Al ^{IV}	2.222	2.223	2.260	2.381	2.343	2.342	2.366	2.347	2.311	2.580	2.473	2.609	2.569	2.544	2.525	2.550
Al ^{VI}	0.598	0.615	0.550	0.493	0.509	0.519	0.495	0.488	0.533	0.456	0.500	0.452	0.474	0.470	0.449	0.467
Ti	0.162	0.210	0.240	0.208	0.184	0.222	0.226	0.244	0.212	0.389	0.372	0.411	0.393	0.424	0.417	0.401
Fe ²⁺	1.666	1.499	1.563	1.680	1.632	1.495	1.512	1.458	1.563	2.789	2.746	2.820	2.775	2.762	2.810	2.784
Cr	0.000	0.000	0.000	0.015	0.016	0.007	0.008	0.005	0.006	0.003	0.001	0.002	0.002	0.000	0.002	0.001
Mn	0.026	0.024	0.020	0.029	0.029	0.027	0.025	0.027	0.026	0.042	0.040	0.046	0.043	0.045	0.038	0.042
Mg	3.243	3.283	3.282	3.395	3.425	3.467	3.480	3.517	3.387	2.002	2.012	1.960	1.978	1.938	1.920	1.968
Ba	0.000	0.000	0.000	0.007	0.005	0.008	0.014	0.011	0.006	0.017	0.010	0.014	0.018	0.022	0.019	0.017
Ca	0.000	0.006	0.003	0.005	0.001	0.004	0.001	0.001	0.003	0.000	0.005	0.002	0.003	0.000	0.003	0.002
Na	0.032	0.037	0.025	0.021	0.030	0.025	0.028	0.027	0.028	0.042	0.034	0.041	0.034	0.030	0.027	0.035
K	1.872	1.870	1.885	1.766	1.809	1.841	1.852	1.830	1.840	1.898	1.816	1.873	1.890	1.873	1.887	1.873
Cations	15.599	15.544	15.565	15.619	15.640	15.615	15.641	15.607	15.604	15.638	15.534	15.619	15.611	15.561	15.572	15.589
Fe/ FeMg	0.340	0.310	0.320	0.330	0.324	0.300	0.302	0.293	0.315	0.580	0.580	0.590	0.583	0.585	0.590	0.585

1. – Small crystal with amphiboles. 2–6. – Small crystals near to amphiboles. 7–8. – Large crystals with amphiboles. 9–14. – Large crystals with muscovite sometimes transecting by muscovite.

5. WHITE MICA PETROGRAPHY AND CHEMISTRY

We distinguished the primary (magmatic) muscovite from secondary muscovite in order to obtain information of the P/T conditions of crystallization and depth of the intrusion of a mainly peraluminous granitoid melt in the Battonya area, where knowledge is limited as these rocks are only studied in drill-cores from 1000–1500 m depth.

There are textural and chemical criteria for distinguishing primary (magmatic) muscovite from secondary muscovite (SPEER, 1984): 1) Textural criteria: the grains of primary muscovite are subhedral to euhedral with sharp grain boundaries; grain sizes are similar to those of other, coexisting magmatic minerals. Often the textural evidence is uncertain, and chemical criteria are also needed. 2) Chemical cri-

teria: the magmatic muscovite is enriched in Ti, Na, and Al and contains lower amounts of Si and Mg compared to secondary muscovite.

Primary and secondary muscovites can be distinguished in the granite-granodiorite of the Battonya Unit based on these criteria.

The primary muscovite grains are large, up to a few millimetres in size, with euhedral and subhedral outlines. In the two-mica granitoids they usually grew across biotite (Fig. 4./1,2), and in the muscovite granite they also form large euhedral and subhedral grains with sharp boundaries that clearly separate them from the grain boundaries of neighboring minerals, such as feldspars and quartz (Fig. 4./3). The secondary muscovites are smaller than the primary grains

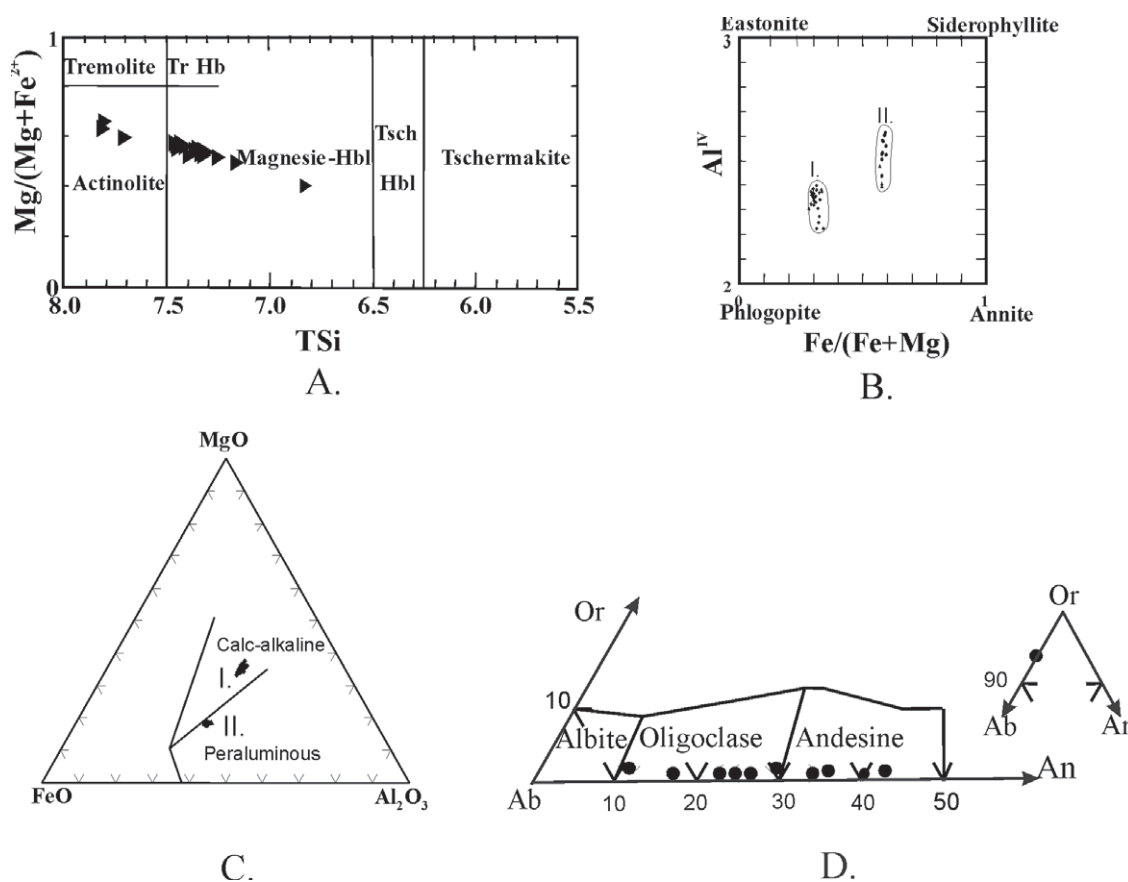


Figure 3: A – Amphibole composition of quartzmonzodiorite. B-C – Plot of biotite composition coexisting with amphibole (I) and muscovite (II). B – Plagioclase and microcline composition of quartzmonzodiorite.

(100–250 μm or less), and have subhedral shapes and, in most cases, they occur in plagioclases or microcline as alteration products (Fig. 4./4–7), usually together with secondary anhedral albite and microcline.

Chemically, the primary muscovite (Fig. 6) has more Ti (Table III, avg.: 0.12 pfu), Na (avg.: 0.14 pfu), and Al (avg.: 5.21 pfu) and less Mg (avg.: 0.20 pfu) and Si (avg.: 6.16 pfu) than the secondary muscovite, which has avg.: Ti 0.05 pfu, Na 0.07 pfu, Al 5.06 pfu, Mg 0.28 pfu, Si 6.28 pfu. A high Ti content is a good indicator of primary muscovite because it is not affected by secondary processes such as subsolidus oxidation or exchange of cations (ZEN, 1988). The Mg, Fe, Na, Al, and Si contents of the two types of muscovite can overlap according to SPEER (1984). A very slight enrichment in Fe can be observed in the secondary muscovite (Fe in secondary: 0.46 pfu; Fe in primary: 0.43 pfu). According to MONIER et al. (1984), the ratio of Na/(Na+K) is also a good indicator for distinguishing the origin of muscovite (primary: Na/(Na+K) = 0.06–0.12; post- and late-magmatic: 0.01–0.07; hydrothermal: < 0.04). In the case of the Battonya granitoids, primary muscovite has a higher Na/(Na+K) ratio (0.07) compared to secondary muscovite (0.04, Table III). Therefore the primary muscovites can be distinguished from secondary muscovite both texturally and compositionally. Textures show that primary muscovite crystallized from the melt after biotite. The secondary muscovite originated by

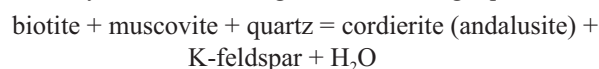
low-temperature hydrothermal processes compared with late- to post-magmatic muscovites. The primary (magmatic) muscovite crystallization was followed by secondary (subsolidus) mica formation as a continuous postmagmatic process during the Variscan orogeny. This is also supported by K/Ar, Sr/Rb ages (average white mica age 350–330 Ma) published by SZEDERKÉNYI (2001).

6. DISCUSSION AND CONCLUSION

The relationship of quartzmonzodiorite to the two mica and muscovite granitoid is not clear but it is most probably a basic enclave showing I-type characters e.g. low initial $^{87}\text{Sr}/^{86}\text{Sr}_{330\text{Ma}}$ ratio (0.7005) and the presence of amphibole. Similar enclaves are known in the other variscan granitoids in Hungary (Mórág Unit) or in the other granitoids of Moldanubian zone of the Variscan orogenic belt.

The average composition of the Battonya granite-granodiorite generally corresponds to the composition of the water-saturated peraluminous near eutectic granite melt called “granite low” (Fig. 7/A, WINKLER et al., 1974, CLARKE, 1992).

Magmatic cordierite, andalusite was not present due to the water-saturated high pressure melt. The two-mica granite could crystallize according to the following equation:



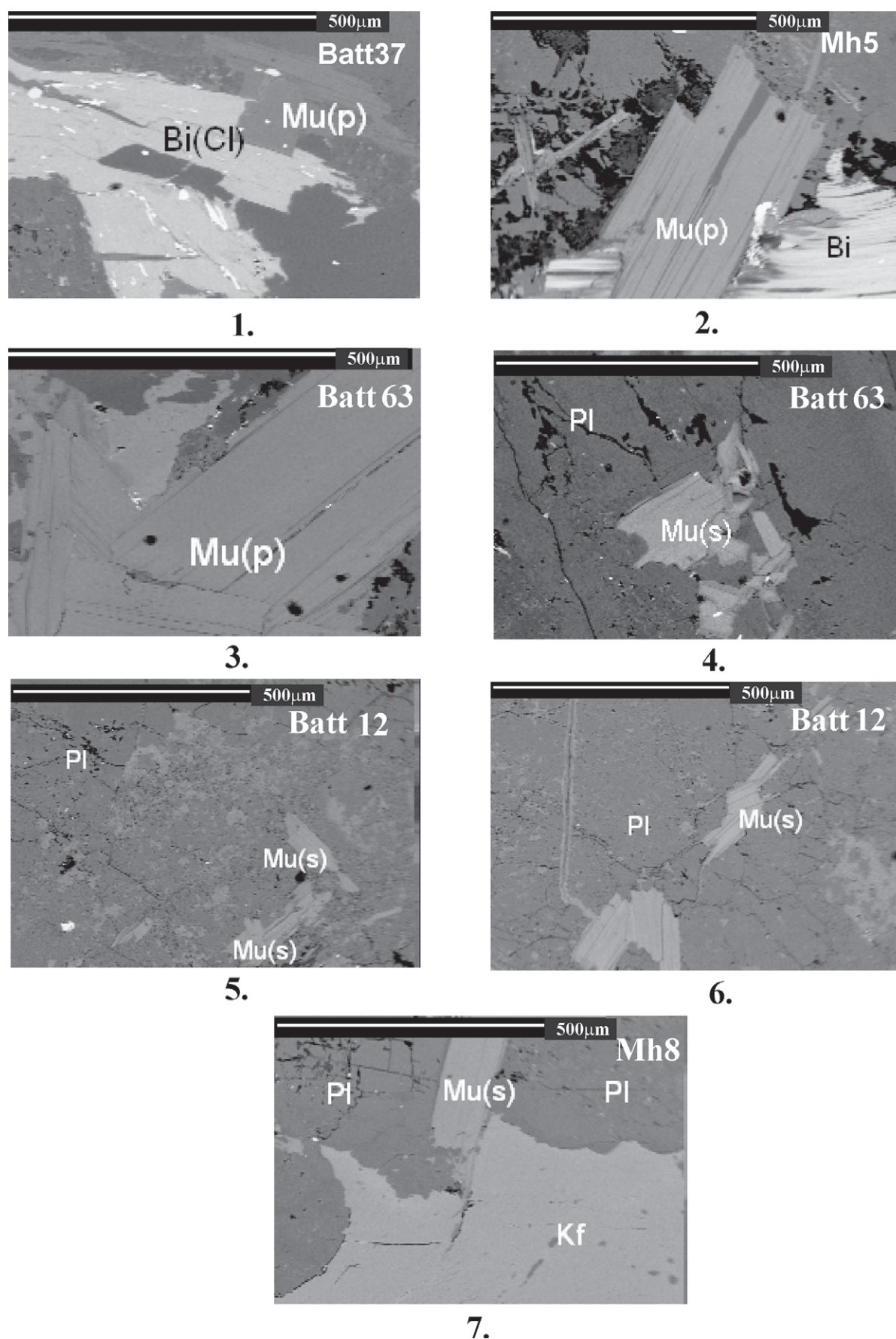


Figure 4: 1, 2 – Backscattered electron images of coarse, subhedral, clearly terminated primary muscovite [Mu(p)] grown across slightly chloritized Al-rich biotite (Bi). 3 – Coarse grained euhedral primary muscovite. 4,5,6 – Subhedral small grains of secondary muscovite [(Mu(s)) in plagioclase (Pl). 7 – Coarse grained secondary muscovite in plagioclase.

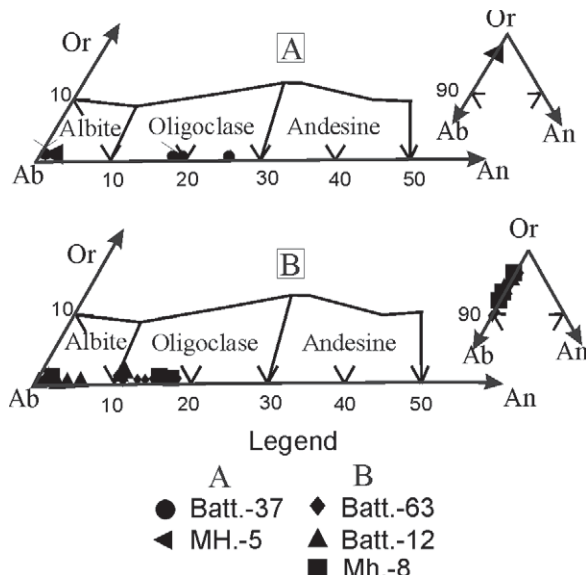


Figure 5: Plot of plagioclase and microcline composition in two mica (A) and in muscovite granitoid (B).

The increasing f_{H_2O} and high $a_{KAISi_3O_8}$ increases the stability of muscovite (CLEMENS et al., 1988). Muscovite is stable if the An content of coexisting plagioclase is low (albite-oligoclase). At higher An content, the solidus temperature of the granitoid melt is higher, and primary muscovite cannot crystallize as in the case of quartzmonzodiorite.

The bulk composition of the two mica and muscovite granitoid and the presence of primary muscovite indicates a low temperature water-saturated "minimum" peraluminous granite melt (Fig. 7/A, B). The pressure of crystallization of magmatic muscovite without magmatic andalusite could be 490–600 MPa according to CLARKE et al. (2005), because below this pressure, magmatic cordierite or andalusite can crystallize instead of or in addition to the muscovite. The P/T

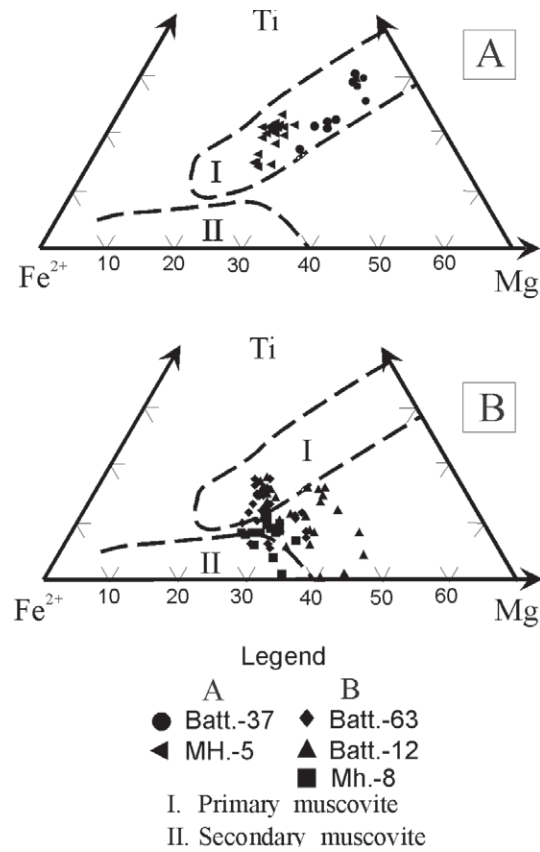


Figure 6: Composition of muscovite in two mica (A) and muscovite granitoids (B). I, II. fields according to MONIER et al. 1986.

conditions correspond to a minimum 15 km depth of crystallization of the intrusion not far from source rocks. In Battonya, the temperature of melts were probably higher because of the presence of metaluminous amphibole-biotite quartzmonzodiorite, but the majority of the rock such as the

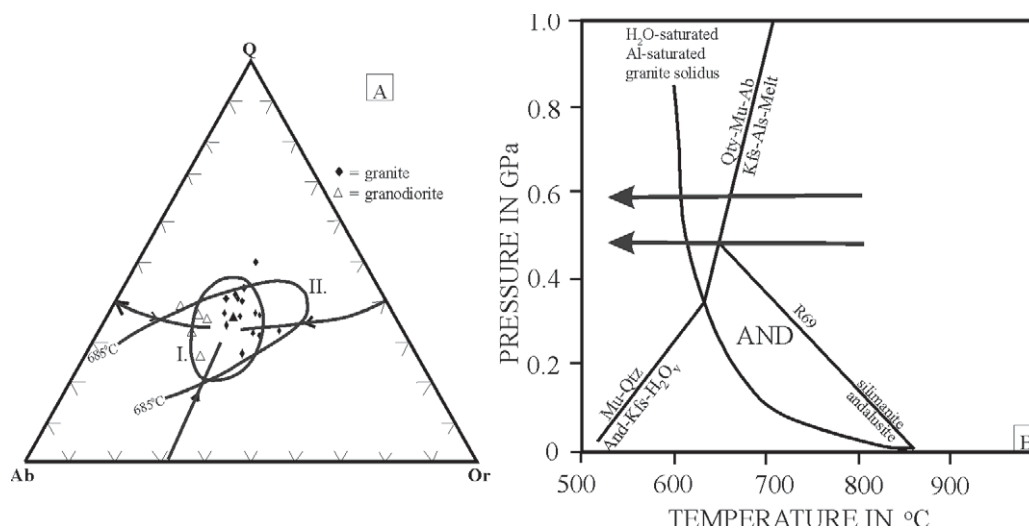


Figure 7: A – Plot of Battonya granitoid in "granite low" system (I. Isotherm at 685°C projected on a cotectic surface, $P_{H_2O} = 500$ MPa, An_{0-14} , WINKLER, 1975). II. The same system after CLARKE, 1992. B – Possible P/T conditions of crystallization of peraluminous granitoids of the Battonya Unit. Experimental phase equilibrium diagram of watersaturated peraluminous granite solidus (I). (JOHANNES & HOLTZ, 1996) and stoichiometric muscovite breakdown curve (II), and andalusite = sillimanite reaction (R69, RICHARDSON, et al. 1969). The possible isobaric cooling path of Battonya peraluminous granitoids is shown between the two arrows, (after CLARKE, et al., 2005).

Table III: Representative compositions of primary (magmatic) and secondary (hydrothermal) muscovites from the Battonya Unit determined by electron microprobe.

	primary muscovite										secondary muscovite												
	Batt-37	Mh-5					Batt-63					Batt-12	aver-age	Batt-63	Batt-12	Mh-8	aver-age						
SiO ₂	45.40	45.30	45.22	45.40	45.17	45.02	44.94	45.15	45.48	45.00	45.16	46.01	45.25	45.16	45.16	45.25	45.99	46.11	45.70	46.62	45.59	46.19	46.03
TiO ₂	0.79	0.90	1.11	1.79	1.75	1.77	1.03	1.08	0.88	1.09	1.03	1.16	1.01	1.23	1.15	1.18	0.64	0.65	0.71	0.04	0.80	0.29	0.52
Al ₂ O ₃	35.93	36.03	31.95	31.80	31.39	31.57	32.74	32.73	31.36	32.03	32.39	29.69	32.84	32.60	32.27	32.49	31.71	32.46	31.27	31.78	31.24	30.47	31.49
Cr ₂ O ₃	0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.03	0.01	0.03	0.00	0.02	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00
FeO	1.29	1.12	4.18	4.24	4.16	3.99	4.14	3.95	4.41	4.24	4.06	4.58	3.95	4.06	4.04	3.76	3.62	3.37	4.37	3.31	4.72	4.69	4.01
MnO	0.02	0.01	0.01	0.03	0.01	0.01	0.05	0.04	0.06	0.04	0.06	0.10	0.06	0.05	0.05	0.04	0.06	0.05	0.11	0.07	0.02	0.03	0.06
MgO	0.53	0.54	1.02	1.03	1.04	0.97	0.95	0.92	1.25	1.00	1.01	1.77	0.97	1.02	1.07	1.01	1.38	1.24	1.41	1.35	1.26	1.49	1.35
CaO	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.02	0.02	0.00	0.01
Na ₂ O	1.21	1.18	0.39	0.38	0.38	0.36	0.49	0.52	0.39	0.38	0.50	0.24	0.47	0.42	0.55	0.52	0.25	0.31	0.29	0.17	0.37	0.24	0.27
K ₂ O	9.49	9.54	10.85	10.62	10.74	10.80	10.41	10.59	10.85	10.99	10.59	10.80	10.72	10.83	10.41	10.55	11.17	11.02	10.80	10.56	10.80	11.25	10.93
Total	94.67	94.63	94.74	95.29	94.67	94.52	94.76	95.00	94.69	94.82	94.82	94.39	95.28	95.39	94.70	94.82	94.81	95.23	94.68	93.93	94.81	94.65	94.68
Structural formulae calculated on an anhydrous basis of 22 (O)																							
Si	6.066	6.053	6.181	6.166	6.182	6.167	6.126	6.139	6.228	6.158	6.158	6.327	6.138	6.129	6.159	6.158	6.265	6.237	6.253	6.360	6.240	6.340	6.283
Al ^{IV}	1.934	1.947	1.819	1.834	1.818	1.833	1.874	1.861	1.772	1.842	1.842	1.673	1.862	1.871	1.841	1.842	1.735	1.763	1.747	1.640	1.760	1.660	1.718
Sum_T	3.720	3.723	3.324	3.252	3.241	3.260	3.382	3.380	3.285	3.320	3.359	3.135	3.384	3.339	3.342	3.363	3.352	3.407	3.292	3.465	3.275	3.266	3.343
Al ^{VI}	0.079	0.090	0.114	0.183	0.180	0.182	0.106	0.110	0.091	0.112	0.106	0.120	0.103	0.126	0.118	0.121	0.066	0.066	0.073	0.004	0.082	0.030	0.054
Fe ²⁺	0.144	0.125	0.478	0.482	0.476	0.457	0.472	0.449	0.505	0.485	0.463	0.527	0.448	0.461	0.461	0.429	0.412	0.381	0.500	0.378	0.540	0.538	0.458
Cr	0.001	0.000	0.001	0.001	0.002	0.002	0.002	0.002	0.001	0.003	0.001	0.003	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.001	0.001	0.000	0.001
Mn	0.002	0.001	0.001	0.003	0.001	0.001	0.006	0.005	0.007	0.005	0.007	0.012	0.007	0.006	0.006	0.005	0.007	0.005	0.013	0.009	0.002	0.004	0.007
Mg	0.106	0.108	0.208	0.209	0.212	0.198	0.193	0.186	0.255	0.204	0.205	0.363	0.196	0.206	0.218	0.204	0.279	0.250	0.287	0.275	0.257	0.304	0.275
Ca	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.002	0.002	0.002	0.000	0.001
Na	0.313	0.306	0.103	0.100	0.101	0.096	0.130	0.137	0.104	0.101	0.132	0.064	0.124	0.111	0.145	0.138	0.065	0.081	0.076	0.044	0.097	0.065	0.071
K	1.618	1.626	1.892	1.840	1.875	1.888	1.810	1.837	1.895	1.919	1.842	1.895	1.855	1.875	1.811	1.832	1.940	1.901	1.885	1.837	1.886	1.969	1.903
Cations	13.984	13.979	14.121	14.070	14.088	14.085	14.101	14.107	14.144	14.150	14.115	14.120	14.117	14.126	14.102	14.094	14.121	14.093	14.128	14.015	14.142	14.176	14.113
Na/(Na+K)	0.162	0.158	0.052	0.052	0.051	0.048	0.067	0.069	0.052	0.050	0.067	0.033	0.063	0.056	0.074	0.070	0.032	0.041	0.039	0.023	0.049	0.032	0.036
Mg/FeMg	0.420	0.460	0.300	0.300	0.310	0.300	0.290	0.290	0.340	0.300	0.310	0.410	0.300	0.310	0.320	0.331	0.400	0.400	0.360	0.420	0.320	0.360	0.377

* Batt = Battonya core samples; Mh = Mezőhegyes core sample

Remarks: Two mica granitoids: Batt-37, Mh-5; Muscovite granitoids: Batt-63, Batt-12, Mh-8.

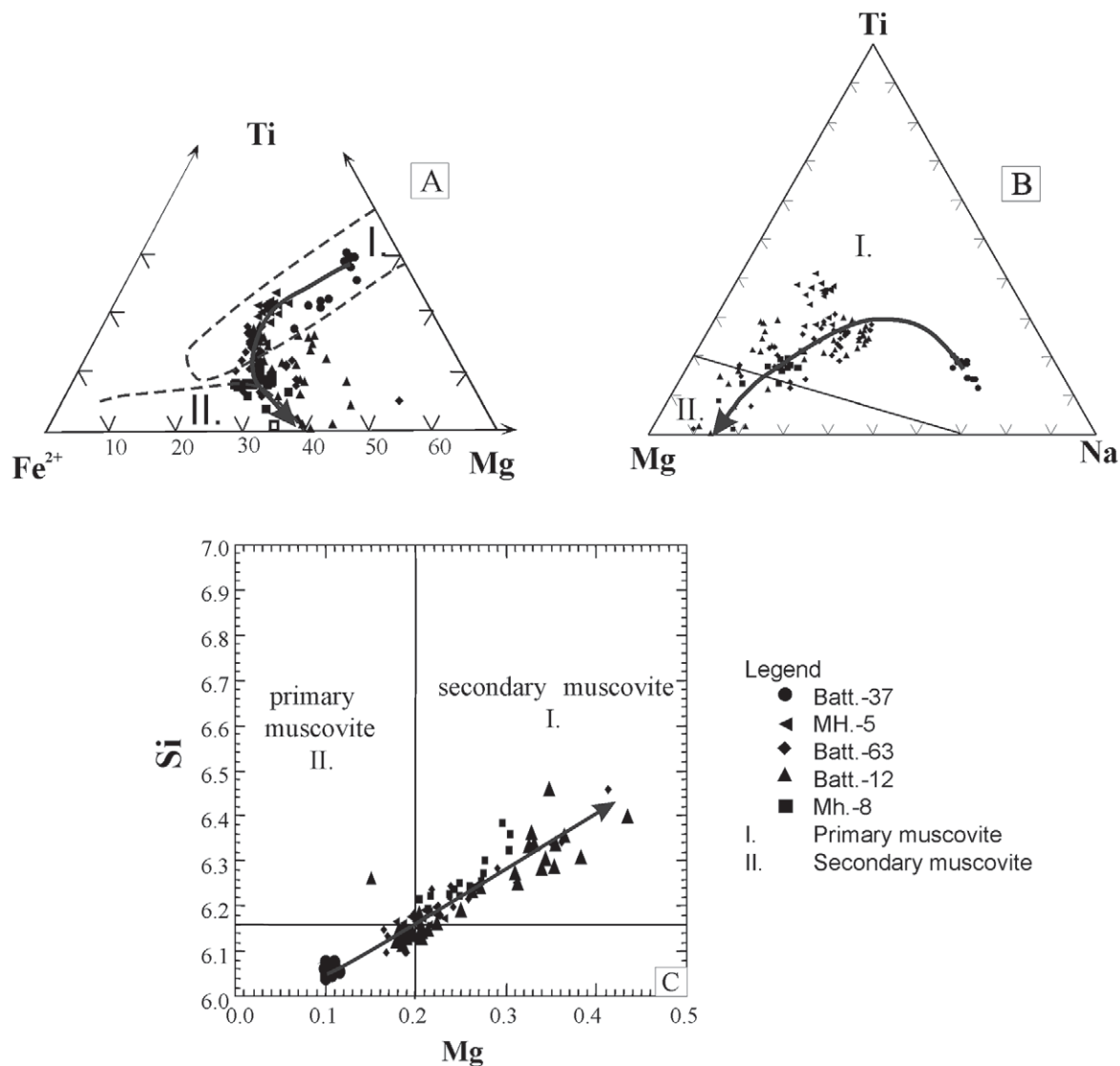


Figure 8. A, B, C – Plot of muscovite compositions in the Battonya granitoids (arrows show the changing of composition from primary to secondary muscovites).

two-mica and muscovite granitoids, crystallized at about 650–685°C and above 490 MPa pressure. Afterwards, the granitoids were affected by alkali metasomatism, indicated by the replacement of microcline and albite, and by hydrothermal alteration evidenced by widespread secondary mica and chloritization of biotite. Magmatic crystallization, metasomatism, and hydrothermal processes were continuous events in the plutonic rocks as suggested by the continual decrease in Ti and Na, and the increase in Si and Mg contents of white micas (Fig. 8/A, B, C). The hydrothermal activity increased the A/CNK indices of the granitoids in some parts of the intrusion due to the leaching of alkalis. Different rates of hydrothermal alteration caused the wide range of A/CNK ratios. These alterations are common in the granitoid plutons due to the saturation of water vapour at the temperature of solidus of peraluminous granite melt (CLARKE, 1992). The origin of the granitoid melts was mixed I and S sources. The absence of andalusite, cordierite and a hornfelsic contact zone indicates a high pressure, low temperature, water-saturated nearly “in situ” crystallization.

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