Magmatic Evolution of the Mórágy Granite (SE Transdanubia, Hungary)

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Abstract

The interpretation of the magmatic evolution of the Mórágy Granite (≈340 Ma)—as a part of the Tisza Unit—is based on fieldwork, and detailed petrographic, mineral, chemical and geochemical investigations carried out during the exploration for a low- and intermediate-level radioactive waste disposal site. Instead of the formerly postulated migmatitic origin, mixing and mingling is now the accepted genesis for the Mórágy Granite.

Monzogranite crystallised from a single felsic melt which occurred synchronously with the crystallisation of mafic microgranular enclaves from a mafic magma. At the beginning of this process the felsic and the mafic melts evolved separately. The mafic melt (with Newtonian liquid behaviour) intruded into the felsic magma around the time of its first rheological threshold. The cooler felsic melt re-crystallised the previously-formed minerals of the mafic melt; this produced a knotty appearance due to the contact effect. Afterwards the two melts evolved together; however, the connection between them was limited. The felsic melt already had a visco-plastic behaviour. Only partial homogenisation and mingling were taken into account. The mingling resulted in the creation of hybrid rocks.

Evidence of magma-mixing is only present in hybrid rocks. Plagioclase has an internal zone and is composed of labradorite, microcline (with a rapakivi-like texture), and amphibole (which has a more tschermakitic rim). Monzogranite and mafic enclaves demonstrate only mingling. Evidence demonstrating mingling is represented by the presence of xenocrysts (pyroxene, amphibole, biotite, plagioclase), microcline megacrysts, quartz pools, and biotite- and accessory-rich and coarse-grained leucocratic contact zones. During the late magmatic melt, magmatic and metamorphic fluids migrated on these contacts, and these served as main channels. The highest Ba content and strong alterations are associated with the late magmatic melt and fluids.

The mafic melt dispersed in the felsic magma and evolved in individual enclave magmas. Consequently, the distribution of their geochemical characters is more dispersed as well. Around the end of magma evolution, the cooling of the mafic melt slowed down and produced grain-size growth. The late magmatic felsic melt (Si, K, P, water) penetrated into the mafic melt and built crystals in there. Thin apatite needles and quartz pools developed, and poikilitic microcline was formed by K-overcompensation.

After the second rheological threshold of the felsic melt, synplutonic dykes developed along the early fractures. The almost solidified magmatic complex (crystallised from a felsic and a mafic melt) was cut during many phases, including leucocratic segregations, schlieren, and then leucocratic dykes. The magmatic history was followed by an upper greenschist (>350–400 °C) facies metamorphism with a strike direction of NE–SW, and then mylonitisation; the latter was restricted to narrow zones before folding.

Introduction and Geological Background

The Mórágy Granite, which has an age of around 340 Ma (KLÖTZLI et al. 2004, GERDES 2006), outcrops on a 19x7 km-large area and is elongated in a NE–SW direction on the SE Transdanubian section of the Tisza Unit. Tectonic contact with the Mecsekalja Zone confines the magmatic body in the north to such an extent that it is possible for the southern contact to be under a large thickness of Cenozoic sediments. The original size and contacts of the granitoid complex are unknown. The nearness of the Mecsekalja Zone and the elongation of the Mórágy Granite in a NE–SW direction indicate the occurrence of an intrusion into the active stress field (MAROS et al. 2003). The exploration area...
of low- and intermediate-level radioactive waste disposal lays on the NE part of the Mórágy Granite.

Various theories have been put forward relating to the magma genesis. The main supposition was magmatic crystallisation followed by metamorphism (JANTSKY 1953), although later the formation of the granitoid complex was believed to be of migmatitic-metasomatitic genesis (SZÁDECZKY-KARDÓSS :1959, and CSALOGOVITS :1964). The development of K-feldspar megacrysts was explained in terms of metasomatism by BUDA (1985).

During the exploration for a low- and intermediate-level radioactive waste disposal site the idea of magma mixing was first mentioned by BUDA (1999). However, the high potassium content of the mafic enclaves was derived from lamprophyre (BUDA, DOBOSI 2004).

After the magmatic crystallisation the whole complex underwent metamorphism (KIRÁLY 2001). During further research at least two phases (flattening, shearing) of ductile deformation were distinguished by KOROKNAI (2003).

Since that time the magmatic evolution of the Mórágy Granite has been outlined in the light of new data obtained during the exploration and mining for radioactive waste disposal sites.

Descriptions of trenches, drill cores and inclines were carried out during the field observations (BALLA et al. 2009). Some thousands of thin sections of the chosen rock samples were studied by KIRÁLY et al. (2008). Some hundreds of electron microprobe analyses were carefully taken from rock-forming minerals and accessories in different textural positions (HORVÁTH, NAGY 2003, HORVÁTH, DOBOSI 2006, DOBOSI et al 2009); in addition, more than a hundred whole rock (main and trace element) analyses (KIRÁLY 2006) were carried out. Metamorphism overprinting the magmatic evolution is not discussed in the present study but it is examined in detail in MAROS (2006) and KOROKNAI (2009).

**Observations on the Field**

The Mórágy Granite is divided into monzogranite and mafic microgranular enclaves (DIDIER, BARBARIN 1991). Because of the mixing and mingling of a felsic and a mafic melt, transitional types also occur: these are the so-called hybrid rocks (contaminated monzogranite and hybrid mafic rocks). The whole complex was cut by leucocratic dykes and it underwent metamorphism.

The most widespread rock type is the monzogranite (Photo 1). It is a grey, medium- (1–3 mm) to coarse-grained (2–6 mm) rock, with some centimetres of pink or white microcline megacrysts, and it is characterised by a porphyritic subhedral granular texture. Monzogranite often contains mafic enclaves in various sizes and quantities. Its rock-forming minerals are plagioclase, microcline, quartz, biotite, and ±amphibole. Plagioclase and microcline appear in two generations. The rate of deformation varies significantly from weakly-deformed samples to mylonites. Alteration is also changeable, from the fresh monzogranite to the starkly fragmented monzogranite. Carbonate, chlorite, limonite and clay minerals are the main alteration products.

The contacts of the monzogranite with mafic enclaves have well-defined surfaces, with irregular shapes produced by plagioclase phenocrysts. In rare instances, mafic amoeboids lengthen to monzogranite. In some other cases strong alteration (chlorite, epidote, sericite and opaque minerals) occurs at the point of contact. Biotite-rich bands and coarse-grained leucocratic segregations also appear as interfaces. Biotite-rich bands enriched in accessories (allanite, zircon, titanite and apatite)—some millimetres thick in size—have developed at the sides of mafic enclaves. The amount of biotite increases at the expense of amphibole (and in its absolute value as well) at the point of contact with mafic enclaves (Photo 2). The leucocratic segregations consist of feldspars, quartz and large amphibole laths which, in some cases, are re-crystallised to fine-grained amphibole aggregates (Photo 3). The influence which the two rock types have on each other can also be followed further on from the contacts. Monzogranite nearby the larger mafic bodies is sometimes full with mafic enclaves wrapped by bands of microcline megacrysts in a 0.3–3 m-wide zone. Besides this, quartz pools and xenocrysts also get into the other melt.

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**Photo 1.** Monzogranite (Interconnecting Passageway 3, 8.60 m from west)

The size of the largest microcline megacrysts is 4–5 cm

1. fénykép. Monzogránit (3. összekötő vágat nyugatról 8,60 m)

A fényképen látható legnagyobb mikroklin-megakristályok mérete 4–5 cm

**Photo 2.** Contact zone between the monzogranite and mafic enclave with large and twinned amphibole laths and feldspars (Úh–26, 391.1 m)

2. fénykép. Nagymeretű íkres amfibolból és földpárból álló kontaktus a monzogránit és a mafikus közet határán (Úh–26, 391.1 m)
The contaminated monzogranite (Photo 3) is dark-grey, greenish-grey and not as pink as the monzogranite. It is characterised by several centimetre-wide leucocratic and melanocratic bands and (albeit rarely) with microcline megacrysts. Its grain size is medium and its deformation varies from moderate to weak. Although this rock type is fresh, red-and-green colouring occurs along fractures due to chlorite, carbonate and clay minerals. Besides feldspars, quartz and biotite, the monzogranite contains amphibole as well. In some cases titanite can also be seen during field observations. The proportion of plagioclase is often higher than that of microcline, with respect to monzogranite. The transition between monzogranite and contaminated monzogranite can very rarely be discerned and there are no sharp contacts. It appears with a very tight thickness (<5 m) around large mafic bodies.

The other hybrid rock types are the hybrid mafic rocks (Photo 4). They can reach two kilometres in length. They are very dark-grey rocks—the more altered rocks are red-and-green—with a high amphibole content which has been penetrated by late magmatic, felsic melt-forming leucocratic segregations and enrichments in microcline megacrysts. These leucocratic schlieren, patches, and clouds often have soft contacts. Their branching and diffuse presence in mafic enclaves supports their invasive character. The microcline and quartz of the leucocratic segregations infiltrate the mafic rocks. Clouds and veins enriched in microcline—and sometimes also in quartz—are elongated to the mafic bodies near the leucocratic schlieren. These minerals are strongly poikilitic and might contain more than 50% inclusions. The grain size of the leucocratic segregations is coarser than the grain size of mafic enclaves. Besides leucocratic minerals the leucocratic segregations contain xenocrysts (amphibole, biotite, titanite) of the mafic enclaves.

The contacts of the monzogranite and hybrid mafic rocks look like the contacts of the monzogranite and mafic enclaves.

Mafic microgranular enclaves are slightly elongated, most frequently in the direction of NE–SW (MAROS 2006). The size of the enclaves varies from some centimetres to several hundred metres. These rocks are greenish-grey or dark-grey in colour and fine-, small- or medium-grained. Their most typical appearance is the spotty development containing amphibole aggregates with feldspar in the interstitial space (Photo 5). Mafic rocks influenced by the felsic melt include more biotite and feldspars, as well as plagioclase and phenocrysts. Their colours are lighter, or red-and-green in more altered cases (Photo 6). Their deformation is not as developed as in their immediate surroundings, and they are only weakly deformed or not deformed at all.

The orientation of small (<20 cm), black or greenish-grey, shred-like mafic enclaves with plagioclase phenocrysts (Photo 7) is more obtrusive than that of the other mafic enclaves, but this is a magmatic orientation without deformation.

The contacts of the very fine-grained enclaves to the monzogranite, to the hybrid rocks and to other mafic enclaves are sharp.

The most widespread leucocratic dyke rocks (Photo 8) are aplites (in some cases with pegmatitic lenses or bands), or coarse-grained quartz. Besides aplite, microgranite and...
Aplite and microgranite are very fine-grained equigranular pink dyke rocks. They are constituted by feldspars, quartz, and a few biotites or chlorites. The content of biotite is higher in microgranite and therefore the slower rate of its deformation means it is better preserved. These rocks are more rigid than their environment and are very often strongly crushed. Individual pegmatoids are very rare and they rather occur inside the aplite or in its nest.

The leucocratic monzogranite (Photo 9) differs from the aplite or microgranite, respectively, due to its coarser grain size and unequigranular character. It also occurs in small magmatic bodies. It is characterised by moderately developed foliation and high quartz content. The amount of biotite, muscovite and chlorite is higher than in aplite or microgranite. Small dispersed flakes of biotite give the rock a dark colour.

Contacts between leucocratic dyke rocks and monzogranite are well-defined and straight. In some dykes coarse-grained leucocratic zones are formed with grown-up feldspars at right angles to the dyke wall. Feldspar-rich bands sometimes occur as ghost images on the side of monzogranite.

**Petrographical Studies**

The composition of monzogranite changes from biotitic monzogranite through syenogranite to quartzdiorite. The composition of contaminated monzogranite is similar to that of the monzogranite; however, it is more inhomogeneous and the respective biotite and amphibole contents are higher. The proportion of the plagioclase and microcline is predominantly higher in contaminated monzogranite, so they occur as quartzdiorite, quartzmonzonite, granodiorite, and (rarely) monzogranite.

The dark part of the hybrid mafic rocks is similar to mafic microgranular enclaves, while the composition of leucocratic segregations varies over a wider spectrum. They

Leucocratic monzogranite also occur. The latter occurs both in dykes and in small bodies. Leucocratic dykes often cut into each other and they were probably formed throughout many phases. Leucocratic monzogranite is cut by aplite.
range from plagioclase–rich variations to veins enriched in microcline and quartz, where amphibole, titanite, and biotite are present as xenocrysts of the mafic rocks. The melt of leucocratic segregations infiltrates as patches or veins into the mafic rocks.

The mafic microgranular enclaves are monzonite, syenite and diorite (with or without quartz), and with a high proportion of biotite and amphibole, and in some cases diopside.

Some characteristics of rock–forming minerals in monzogranites contrast strikingly to those of hybrid rocks or mafic enclaves.

Phenocrysts of plagioclase in monzogranite display polysynthetic twinning and oscillatory zoning. A few larger biotite inclusions (rarely zircon or apatite) are involved in them. Plagioclase phenocrysts in hybrid rocks have zoning with many small drop–like biotite inclusions in their core. These zoned phenocrysts partly appear in the mafic enclaves as well. The equilibrium texture of plagioclase, amphibole, pyroxene and titanite confirms the early paragenesis in the mafic enclaves containing amphibole aggregates.

Microcline megacrysts in monzogranite contain inclusions dispersed or arranged in rings. Zoned megacrysts with an amoeboid–shaped overgrowth at the rim occur in hybrid rocks. Plagioclase inclusions with the same extinction are arranged in lines or in one or more rings in microcline, which demonstrates their rapakivi–like texture. The microcline infiltrates into the mafic parts of the hybrid mafic rocks from the leucocratic schlieren. Its size is the same as in leucocratic segregations—some millimetres to a centimetre—and it forms strongly–poikilitic invasive grains (Photo 10).

The distribution of microcline is very noticeably inhomogeneous in all rock types. Around the megacrysts the melt is depleted in potassium and consequently only a very few matrix microclines have been able to develop. There is no microcline megacryst if a matrix microcline has formed to a large size.

Inhomogeneity of the distribution of microcline also exists on a greater scale, especially points of contact. Bands enriched in microcline are parallel to the contacts. At the contacts of monzogranite and mafic enclaves, monzogranite often consists of less microcline than mafic enclaves.

Quartz appears in bands, lenses and in interstitial spaces (depending on the rate of deformation) or as an inclusion in monzogranite; it constructs drop–like inclusions or fills the interstitial space among amphibole laths in the hybrid rocks. Quartz pools are formed in mafic enclaves (Photo 11).

The most widespread mafic mineral in monzogranite is biotite. It occurs as large (a few millimetres) tables, smaller aggregates with or without amphibole, inclusions in

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**Photo 10.** Poikilitic microcline in mafic enclaves (Üh–44, 214.9 m)
The long edges of each photo are 4.25 mm, obj. 4×, +N

10. fénykép. Poikilites mikroklin mafikus zárványban (Üh–44, 214.9 m)
A képek szélessége 4,25 mm, 4× obj, +N

**Photo 11.** Quartz pool in mafic microgranular enclaves
(Üh–29,100.3 m)
obj. 4×, +N

11. fénykép. Kvarcmedence mafikus mikrogranuláris zárványban
(Üh–29, 100.3 m)
4× obj, +N
feldspars, and as an alteration product of amphibole. If the amphibole content is higher, a thin biotite rim develops around the amphibole aggregate (Photo 12) as an effect of the felsic melt. Biotite appears together with amphibole not only in aggregates, but also in hybrid rocks with long, thin melanocratic bands. The well-developed large tables are rare in mafic enclaves, and are more frequent as slim and long tables (individually or as inclusions in microcline) which have formed in a chaotic magmatic orientation.

The biotite-rich bands at the contact point of monzogranite and mafic enclaves are composed of large biotite tables full with inclusions of accessories. Allanite and zircon, which characterise the monzogranite, are enriched in biotite bands. However the amount of titanite and apatite also demonstrates an increase.

The proportion of amphibole is less than a few percent in monzogranite. It occurs in two textural positions. The first appearance is as large, individual amphibole laths and the second one is as smaller grains (0.1–0.3 mm) which constrain the aggregates. The amphibole aggregates have often altered partly or totally to pseudomorphs of carbonate, chlorite and opaque minerals. The appearance of amphibole in laths became apparent in a part of the hybrid rocks while most of the mafic enclaves consist of aggregates of smaller grains which have re-crystallised after large amphibole laths. Re-crystallisation is caused by the heat of the felsic melt. Amphibole aggregates produce the knotty-like appearance of the rock.

Pyroxene only exists in hybrid and mafic rocks which are enriched in microcline. The microcline protects the pyroxene from uralitisation. There is no pyroxene in monzogranite. Two types of pyroxene have developed. Individual, stocky tables with drop-like inclusions of opaque minerals (Photo 13) formed during the early phase of the mafic melt. It is in equilibrium with large titanite and plagioclase. It has been re-crystallised to aggregates—such as amphibole—due to the influence of the felsic melt.

The accessories in monzogranite are allanite, zircon,apatite and titanite. Hybrid rocks are characterised by zoned allanite, and at the contact points zircon, apatite and titanite are enriched. Titanite and apatite are present in leucocratic segregations. The mafic enclaves are characterised by large amounts of titanite and apatite. The titanite is in equilibrium with pyroxene, amphibole and plagioclase. The apatite has developed as slim needles dispersed in the enclaves; however, elongated or stocky prisms also occur at the edge of biotite and amphibole.

Mineral Chemistry

Evidence of magma mixing located in hybrid rocks is based on careful electron microprobe analyses of rock-forming minerals and accessories of all kinds of rocks types. An anorthite-rich internal zone was measured in the plagioclase phenocrysts of the hybrid rocks. It was found in zoned plagioclase tables and there were many small biotite inclusions in the cores of these tables. The composition of the core is andesine-oligoclase (25.2–35.3 An%) followed by a labradoritic internal zone (50.6–61.2 An%—Photo 14). The core with small biotite inclusions crystallised from the felsic melt; this was followed by labradoritic overgrowth which indicates the effect of mafic melt. The crystallisation of plagioclase is finished by an oligoclase-andesine rim (29.5–36.0 An%). The proportion of K-feldspar is only 1.0–1.1% in the core and the rim, while there is no potassium in the internal zone.

There is no internal labradoritic zone in the plagioclase of monzogranite. The highest anorthite content (48.1 An%)
was measured from an inclusion of plagioclase in microcline megacryst and from a core of a plagioclase phenocryst. Plagioclase, which crystallised in the early stage of the felsic magma, indicates a slightly more felsic melt than the melt from which the hybrid rocks crystallised. Plagioclase compositions from mafic rocks (average 30.7 An%) are not characteristically different from those of monzogranite (average 23.9 An%). The most basic plagioclase composition in mafic rocks is 50.6 An%.

Zoned microcline megacrysts of mafic enclaves (analysed by electron microprobe) suggest magmatic crystallisation from the melt. The K-feldspar component varies between 89.4 and 94.5 Or% while the albite component changes from 4 to 11%. The An content is less than 2.5%; however, two weakly developed zones with an anorthite component were also analysed. The BaO content of the Ba-rich internal zones is 1.86–3.25% while the Ba-poor zones consist of 1.42% of BaO or rather less than 1%. The so-called shell structure of the Ba-rich zones (Photo 15) confirms the formation of the microcline from the melt, but a more complex history of mixing can be also suggested (VERNON, personal communication).

In contrast to the mixing, normal weak magmatic zoning is developed in microcline megacrysts in monzogranite. The
core contains both albite and anorthite components while the rim is clearer (1.6–4.5 Ab%).

Reverse zoning, as evidence of mixing, cannot be detected in any of the mafic minerals of the rock types. The mg values of biotite are 0.47–0.77, the Al content in the octahedral site is 0.02–0.76, while the Al content in the tetrahedral site is 1.9–2.56 pfu. The maximum variability in the TiO₂ content (0.65–4.55%) took place during the metamorphic overprint.

The changeable compositions of the inclusions of biotite in both feldspars (plagioclase and microcline) reveal variable pT conditions due to the long-lasting and parallel crystallisation of both feldspars and biotite.

The biotite of the monzogranite is homogeneous, without any well-developed zoning. Only weak to normal magmatic zoning can be observed. The mg values of biotite in monzogranite vary from 0.47 to 0.6, while its TiO₂ content is between 1.48 and 3.84%. The mg values of biotite in mafic enclaves indicate a slight shift towards the higher values (0.5–0.77) while its TiO₂ content is lower (1.33–2.37%).

The biotite in very fine-grained enclaves has a high TiO₂ content (1.4–3.3%). This suggests a magmatic origin in conjunction with the non-deformed but oriented texture.

BaO (≈0.85%) appears in biotite at the points of contact. The amphibole is actinolite and “actinolitic hornblende” (Leake et al. 1978) in monzogranite, while magnesio-hornblende is present in the mafic enclaves (Figure 1). The tschermakitic component is low in amphibole. Normal magmatic zoning indicates that there was no mixing during the formation of the amphibole.

There was only one case where the plagioclase revealed the labradoritic internal zone in the hybrid rocks: this was where the rim of the amphibole becomes slightly more...
tschermakitic. The rim is enriched in Altot (1.18–1.34), in contrast to its Si content (Siin: 7.11–7.17 and Siout: 6.8–7.0), which decreases towards the rim. This change might have been brought about by the mafic melt. Consequently, at around the time of the end of the formation of the amphibole, the mafic melt was intruded and more tschermakitic components on the rim of amphibole grains developed from the melt (which was enriched with mafic components).

The accessories of leucocratic segregations exhibit complex zoning. Using electron microprobe analyses (Photo 16), three zones could be distinguished in titanite. The respective distributions of rare earth elements are distinct in each zone. The internal zone consists of less Ti and more La, Ce, and Nd than the core and rim. The content of light REEs is low in the core and the rim. The REE (La, Ce, Nd) content of allanite is still less in the core; however, it increases towards the rim and this corresponds to the normal magmatic formation. The composition of titanite enclosed in allanite is very similar to that of the core and internal zone of the individual titanite (Photo 16). This textural position and composition change support the evolution history, in which the early crystallisation of the titanite from the mafic melt was followed by the intrusion of the mafic melt into the felsic magma (where allanite was formed). The development of allanite caused a decrease in the REE content of the rim of titanite.

**Geochemistry**

The database of 223 main, and 147 trace elements analyses of the Mórágy Granite provided the base for geochemical modelling (Király 2006). Mixing is a long symbiosis in the melt phase and thus the main and trace element analyses of monzogranite and mafic enclaves are not separated from each other; consequently, only fine diversities and differences in trends can be observed (Debon 1991).

Monzogranite is typified by a slightly asymmetrical and peaked distribution, while mafic enclaves present more flattened distributions and higher average values (TiO₂, FeOtot, MnO, MgO, CaO, K₂O, P₂O₅) on histograms showing the main element oxides (Figure 2). Distributions of elements (for example Mg, Ca, Fe, Ti) built in mafic minerals, both in monzogranite or in mafic enclaves, are clearly divided and characterised by individual peaks and average values. This outlines that at an early stage there was a distinct evolution in monzogranite and in mafic enclaves.

Histograms of Ba and Cs (Figure 3) record late- or post-magmatic processes in both rock types. The frequencies of these two elements are characterised by a double modus in mafic enclaves, and by an asymmetrical shoulder drawn towards higher values in monzogranite. Ba is enriched in mafic enclaves (1054.9 ppm in monzogranite; 1762.66 ppm in mafic enclaves); the highest values also occur in the enclaves.

The main and trace element analyses of mafic enclaves are more dispersed than those of the monzogranite; this is in agreement with the macroscopic and microscopic observations. In some cases a few groups or trends can be distinguished within the mafic enclaves. Analyses of Al₂O₃, MgO, TiO₂, or P₂O₅ plotted on Harker and Fenner diagrams fit to different trends in the respective cases of monzogranite and the mafic enclaves (Figure 4).

Distributions of elements (Na₂O, K₂O) built in late magmatic minerals (microcline, acid plagioclase) are scattered. They do not correspond to trends. The mafic and felsic melts are meanwhile in interaction and they tended towards the chemical equilibrium; however overcompensation also played a role (K-overcompensation —Debon 1991).

**Mixing and Mingling**

The felsic and mafic melts which evolved to become the Mórágy Granite were initially formed separately. The distinct frequencies of elements built into mafic minerals (Mg, Ca, Fe) in monzogranite (and in mafic enclaves) support the supposition that the development of felsic and mafic melts occurred separately.

The monzogranite with an age of 340 Ma (Klotzli et al. 2004, Gerdes 2006) crystallised from a single magma. Its geochemical character can be matched with a definite trend. The diverse appearance of monzogranite arose from magma mixing, mingling and metamorphic overprint.

At the early stage of the felsic melt, zircon, stocky apatite, biotite, plagioclase and microcline developed. Before the formation of biotite, amphibole might, albeit rarely, also have developed from the felsic melt. The amphibole rim enriched with a tschermakitic component in hybrid rocks signifies the formation of an amphibole core from the felsic melt. As a result of mafic melt further development of the tschermakitic rim took place. The initial plagioclase which formed in monzogranite demonstrates a slightly more felsic environment than that of the hybrid and mafic rocks. This indicates that separate crystallisation occurred at the beginning. Biotite was formed both from monzogranite and from mafic enclaves under similar conditions. The biotite in mafic enclaves is enriched in Mg and depleted in Ti.

There is no inverse zoning or internal mafic zone in magmatic amphibole, biotite and plagioclase of monzogranite which would suggest the presence of mafic melt. Thus the mafic melt had no effect on the minerals which developed from the felsic melt.

If two Newtonian liquids are mixed, the result is complete homogenisation. In the case of melts with visco-plastic behaviour, the mixing or homogenisation is very restricted and mingling plays the main role. After the first rheological threshold of the felsic melt (more than 30% of melt is already crystallised), the melt becomes visco-plastic liquid and it is no longer Newtonian (Figure 5). There is no more mixing of the felsic and mafic melts.
Figure 2. Histograms of the main elements

Red = monzogranite, black = mafic rocks, turquoise = cut of the histograms of monzogranite and mafic rocks

2. ábra. Főelemek hisztogramjai

Piros = monzogránit, fekete = mafikus kőzetek, türkiz = a monzogránit és a mafikus kőzetek hisztogramjainak metszete
The ages of mafic enclaves from single zircon grains are the same as the age of monzogranite (Gerdes 2006). The Newtonian mafic melt coming from deeper levels intruded into the felsic magma. The mafic melt already contained crystal seeds but still did not reach its first rheological threshold. Large titanite, pyroxene, amphibole, and, possibly, seeds of plagioclase in equilibrium could have formed the solid phase in the mafic melt when it was intruded into the felsic magma. At that time the temperature of the mafic melt was higher and the mafic melt was more liquid—still with Newtonian behaviour—than the visco-plastic felsic melt.

The felsic and mafic melts evolved together; however, the mixing did not take place completely and only partial homogenisation occurred because of the visco-plastic behaviour of the felsic melt. Accordingly, the Mórágy Granite did not crystallise from a homogeneous melt but rather it mixed completely in the proportion of the felsic and mafic melts. Therefore it is a complex of monzogranite and mafic rocks with many transition types.

The relative liquid mafic melt dispersed in the more viscous and cooler felsic melt which evolved on the discrete enclave magmas. The latter are not in close connection with each other and thus their appearance is more diverse and their composition is more scattered; furthermore, sometimes their geochemical characters are arranged in individual trends (see also on Figure 4).

Mineral-chemical evidence of magma mixing appears only in hybrid rocks. The internal zone of labradorite in plagioclase represents the intrusion of the mafic melt into the felsic magma. The anorthite-rich zone is not followed by another, suggesting the mafic intrusion probably took place only once. The zone of plagioclase inclusions with the same extinction on the microcline rim has constructed a rapakivi-like texture; this also developed due to the intrusion of the mafic melt. The low potassium content of the mafic melt caused the crystallisation of plagioclase instead of microcline.

No complex zoning in mafic minerals occurred due to mixing. However, in the neighbourhood of the internal zone of labradorite in plagioclase, amphibole was analysed and this indicated a rim more tschermakitic than the core of the amphibole. This more tschermakitic rim might have formed due to mafic intrusion.

There is no evidence of homogenisation or mixing outside the hybrid zones. Here mingling and chemical equilibration took the main role.

The evidence of mingling is indicated by the interfaces between the monzogranite and mafic enclaves. This is characterised by biotite bands enriched in accessories (allanite, zircon, stocky apatite) and large plagioclase phenocrysts, microcline megacrysts and biotite tables concentrated at the side of monzogranite. The interfaces were the main sites for the late magmatic and metamorphic fluids, as indicated by Ba enrichments in both the microcline and biotite. Here, there are coarser-grained leucocratic contact zones or concentrations of microcline megacrysts. Leucocratic segregations are similar to these very coarse-grained contact zones, where the melt could infiltrate into the mafic part of the rock. The Ba content in K-feldspar and the rate of alteration are highest in these leucocratic segregations.

Xenocrysts are also products of mingling. Plagioclase, biotite, and, possibly, microcline developed in felsic melt and amphibole (and, rarely, pyroxene), crystallised in the mafic melt. These crystals, as already solid minerals, get into the other melt. Amphibole might move to granitic magma while microcline, for example, might get into the mafic melt.

Early formed minerals in the enclave magmas were re-crystallised to aggregates (with a knotty appearance) by the cooler (a few hundred degrees) felsic melt, similar to a contact effect (Vernon 1991). Pyroxene tables and amphibole laths were re-crystallised to form smaller grains of aggregates.

The respective temperatures of felsic and mafic melts
Figure 4. Fenner diagram. Distributions of main elements in the function of MgO content
Red = monzogranite, green = mafic rocks, lilac = leucocratic dykes and segregations; arrows = distinct trends

4. ábra. Fenner-diagramok. Főelemeloszlások ábrázolása a MgO függvényében
Piros = monzogránit, zöld = mafikus kőzetek, lila = leukokrata telérek, illetve szegregációk; nyilak = elkülönült trendek
Magmatic Evolution of the Mórágy Granite (SE Transdanubia, Hungary)

approached each other at the end of the magma evolution (Figure 5). If the viscosity of the mafic melt became larger than that of the felsic melt (at the temperature of inversion), the developing minerals became larger as a result of the retardation of the cooling of enclave magmas.

During the slow cooling, chemical equilibration, transfers and migration began (Vernon 1991). Components which were still present in the late felsic melt (Si, K, P, H₂O) penetrated into the mafic melt and were built into the late magmatic minerals. Distributions of Na₂O and K₂O, built into the microcline and sodic plagioclase, are scattered and they are not divided between monzogranite and mafic enclaves. The formation of apatite needles at grain boundaries and in the microcline of mafic enclaves can be explained by this late magmatic effect of the felsic melt. Needles of apatite developed quickly from the melt after the main formation of amphibole and plagioclase (Spry 1969; Tindale, Pearce 1983).

Figure 5. Rheology of felsic and mafic melts (after Fernandez, Barbarin 1991)

During the slow cooling, potassium overcompensation (Debon 1991) played the main role. The mafic melt was originally potassium-poor but the late magmatic felsic melt provided potassium; the latter formed late magmatic invasive poikilitic microcline in mafic microgranular enclaves. The microcline first occupied the interstitial spaces, and then became larger and larger (≈ cm), with more and more amphibole, pyroxene, biotite and plagioclase inclusions. The invasive and poikilitic characters of the microcline indicate that it had not developed in the mafic enclaves before (Vernon 1991). The quartz pool has the same origin, having formed in mafic enclaves from the infiltrated felsic melt.

The uralitisation of clinopyroxene and the biotitisation of amphibole in mafic enclaves were facilitated by the felsic melt (unless they were enveloped and protected from the further effect of felsic melt by the microcline.

The felsic melt forced its way into the almost solid mafic bodies as “devious” leucocratic schlieren, or sometimes penetrated into the mafic enclaves, where microcline or quartz developed in patches or segregations. Leucocratic segregations contain amphibole, titanite, plagioclase, and biotite as xenocrysts (formed in the mafic melt). The contacts of leucocratic segregations are not always sharp, and evidence of infiltration and xenocrysts can be observed. These leucocratic segregations which enmesh mafic bodies were the main sites of the late magmatic melts and fluids. Accordingly, the xenocrysts of leucocratic segregations have been strongly altered. Actinolite, prehnite, epidote and albite were formed after them.

Following the second rheological threshold of the felsic melt, synplutonic dykes (aplite, microgranite and leucocratic monzogranite) were intruded along early fractures.

Summary

The interpretation of the evolution of the Mórágy Granite is based on fieldwork, on petrographical studies, on mineral chemistry and on geochemical analyses.

The Mórágy Granite is an intrusion which has its origins in the mixing and mingling of felsic and mafic melts, and which was intruded into a compressive stress field of NW–SE direction (Maros et al. 2003). This is in contrast to the earlier magmatic theory given for its origins.

The monzogranite crystallised from a single felsic melt, at the same time as the mafic enclaves were developed from the mafic melt. At the beginning, the mafic melt evolved separately and then intruded into the felsic melt around its first rheological threshold. Afterwards, mafic enclaves evolved in distinct enclave magmas. Early formed mafic minerals were re-crystallised by the cooler felsic melt. Consequently, amphibole aggregates characterising the mafic enclaves were formed. Following this, the two melts evolved together; however, the connection was limited to partial mixing and mingling.

The evidence for magma mixing is present in the internal labradoritic zone in the plagioclase, in the rapakivi-like texture of the microcline, and in the slightly more tschermakitic rim of the amphibole (noticed only in the hybrid rocks). Mingling (not mixing) only occurred in the monzogranite and mafic enclaves. The evidence for mingling is shown by the interfaces enriched in biotite, the accessories, and xenocrysts (pyroxene, amphibole, biotite, plagioclase). The interfaces represent the main sites of the migration of the late magmatic melt, and the magmatic and metamorphic fluids. The highest Ba content and the strong alterations join this zone.

At the end of the magma evolution, the felsic and mafic melts tended towards chemical equilibrium. The late magmatic felsic melt (Si, K, P, water) penetrated into the...
mafic melt and built crystals there. As a result of this process, thin apatite needles were formed, poikilitic microcline was developed by K-overcompensation, and quartz pools were crystallised.

The felsic melt forced its way into the almost solid mafic bodies and it constructed meandering leucocratic schlieren, patches or segregations, respectively.

Following the second rheological threshold of the felsic melt, synplutonic dykes intruded along early fractures of the almost solidified mafic complex which had evolved from the felsic and mafic melts. The magmatic history is overprinted by an at least two-phase upper greenschist facies metamorphism.

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