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THE DACITE FLOWS OF THE MIOCENE TOKAJ-NAGYHEGY STRATOVOLCANO: AN EXAMPLE OF MAGMA MIXING

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Abstract: The Tokaj Mountains is the easternmost of the Miocene volcanic ranges in Hungary. The volcanic pile mainly consists of andesitic and rhyolitic rocks, but the dacitic types are also important. The banded, quartz-containing dacite of Tokaj-Nagyhegy is one of the most interesting rock in the mountain range. In the interpretation of this paper, the mixing of andesitic and rhyolitic magmas played the main role in the genesis of the dacite. The diorite-porphyrite inclusions in the dacite can be derived from an andesitic melt, whereas the dihexahedral quartz crystals are relicts of a rhyolitic material. The numerical determination of the rhyolite/andesite admixture has been also attempted.

Key words: Tokaj Mountains, pyroxene dacite, mixing of magmas.

Introduction

The term "mixed rocks" is relatively widely used but not properly defined. In general, it involves rocks in wich two more or less well-separable components with different mineralogical and chemical compositions mixed in a chaotic or ordered way and/or contain minerals not being in equilibrium. Rocks that are the homogeneous products of this process are frequently referred to as hybrid rocks, while when magmas are mixed together physically but the rock product has compositional heterogeneities (e.g. banding, xenoliths), the term commingled magmas is used (Sparks & Marshall 1986). The evolution of hybrid rocks may have taken place in various way. Magma may assimilate solid wall rock, or components thereof. It may become contaminated by wall rock of a different composition. The hypothesis that the above mentioned processes played a role in the evolution of the volcanic rocks, particularly the dacites, in the Tokaj Mountains, has been presented in previous research. The Tokaj Mountains are the easternmost members of the Inner Carpathian Volcanic Belt in Hungary. Acidic pyroxene andesite, rhyolite and rhyolitic tuffs, and dacite are the most common rocks in the mountain range. Andesites and dacites form mostly lava flows and laccoliths. The most abundant dacites are pyroxene dacites. From the petrological point of view, the pyroxene dacites show a close relationship to the acidic pyroxene andesites. According to Gyarmati (1977), the main process in the evolution of the suite was multiphase sial contamination involving a smaller or greater degree of acidification. Pantó et al. (1966) emphasized that pyroxene dacite eruption centres have different individual features as a consequence of depth, environment, and degree of acidification. The origin of the pyroxene dacites, therefore, can only be generally outlined. Each eruption centre should be investigated separately to determine whether its material is hybrid, and if so, which process played the main role in its hybridization (Rózsa 1987). One possible way of pyroxene dacite evolution is illustrated by the example of Tokaj-Nagyhegy (17.5 km^2, 515 m) at the southern part of the mountain (Fig. 1). The choice is justified by two facts:

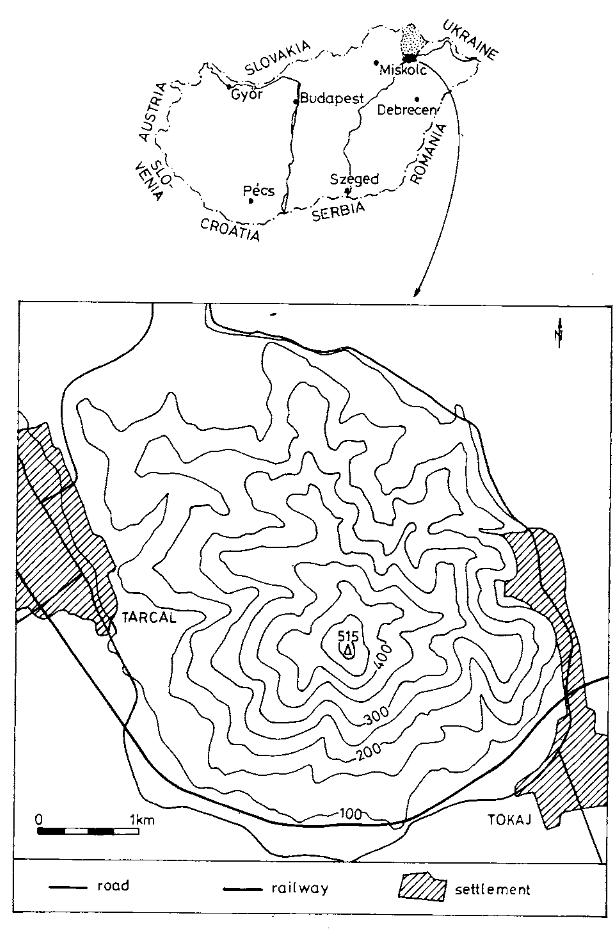

Fig. 1. Location of the Tokaj Mountains (dotted field) and topographical sketch map of the Tokaj-Nagyhegy.

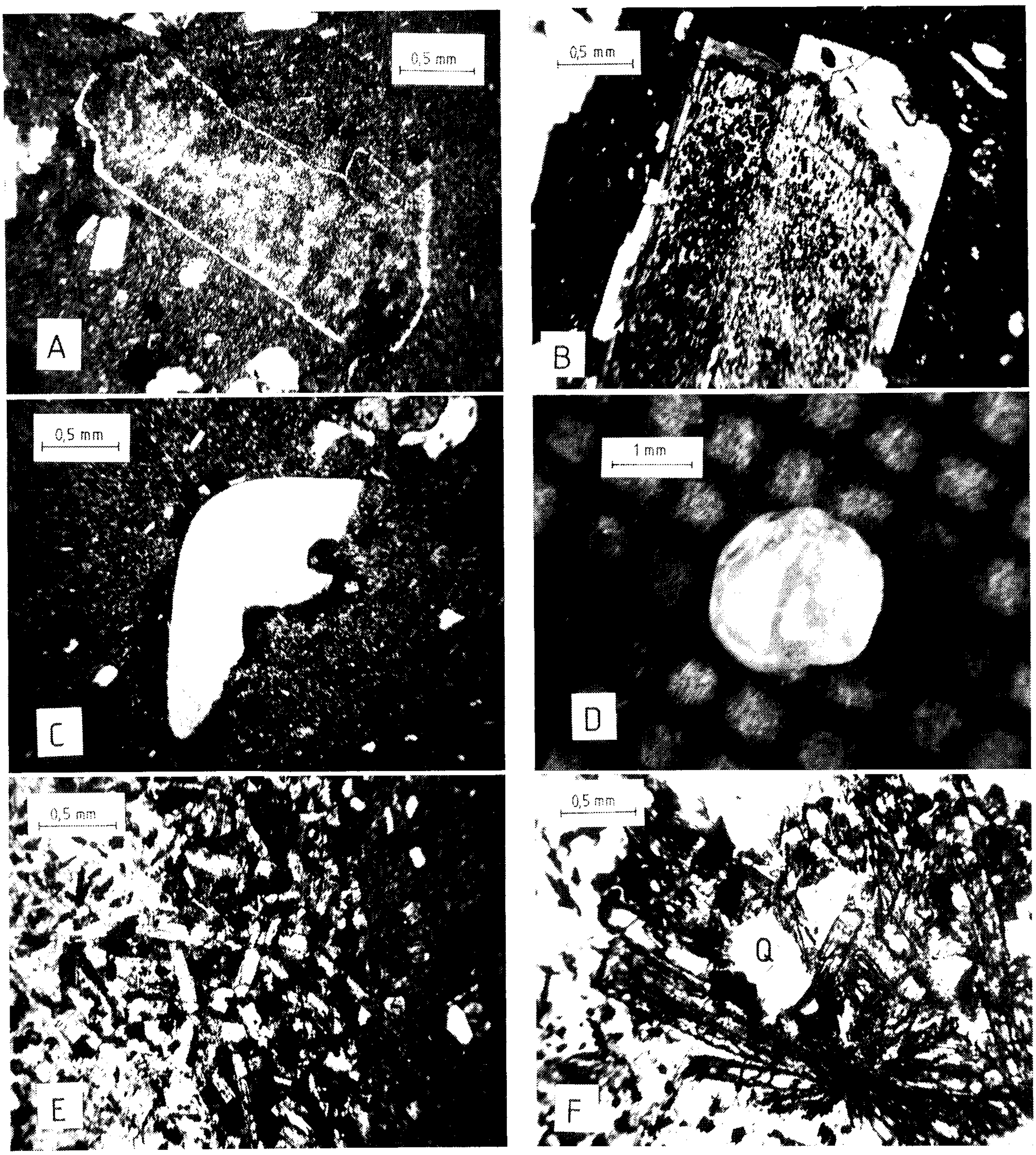

Fig. 2. A - F. **A** - Plagioclase crystal with "dust" inclusion from dacite of Tokaj-Nagyhegy [1N]. **B** - Plagioclase crystal with "honey-combed" structure from dacite of Tokaj-Nagyhegy [xN]. **C** - Resorbed quartz crystal from weathered dacite of Tokaj-Nagyhegy [1N]. **D** - Dihexahedral quartz crystal from weathered dacite of Tokaj-Nagyhegy. **E** - Boundary zone of a diorite-porphyrite inclusion (left) and the host dacite [1N]. **F** - Quartz crystal (Q) girdled by a pyroxene rim in a diorite-porphyrite inclusion [1N].

a - the hybrid character of this characteristic rock has been widely discussed in the literature for a hundred years; *b* - a great number of chemical analyses are available.

Studies and results

Petrographical characterization

The rock contains 65 - 70 volume per cent of groundmass. The most common phenocrysts are feldspars, mostly plagioclase. Highly characteristic of the larger crystals are fine inclusions of cloudy glass. These crystals may in part correspond to the so called "dust inclusion" described by Kuno (1950), and in part to the so called "honey-combed" structure. It is noteworthy that the cloudy or dusty crystals are rimmed by an intact border, which shows, in some cases, strong zonality (Fig. 2 A, B). These types of plagioclase is T-2 by Halsor & Rose (1991). In such zoned crystals chemical profiles were determined by electron microprobe. These profiles show a reverse, slightly oscillating zonality. The core shows a composition corresponding to labradorite, the more basic zone to bytownite (in Gyarmati 1977; see Tab. 1). Sanidine also occurs in very low amounts, its crystals being frequently resorbed.

Mafic phenocrysts are hypersthene and augite. Their crystals can occur independently and can form glomeroporphyric nodules with plagioclase as well.

Table 1. Variation in the CaO and Na_2O composition of zoned plagioclase from pyroxene dacite of Tokaj-Nagyhegy (data from Gyarmati 1977).

Measure point		CaO [%]	Na_2O [%]
margin	1.	11.5	4.0
	2.	9.6	5.3
	3.	11.1	4.6
	4.	14.0	3.1
	5.	10.9	4.8
centre	6.	11.6	4.4
	7.	13.1	3.6
margin	8.	12.8	3.5

A special mention must be made of the quartz crystals in the rock of the Nagyhegy. Microscopically, the highly resorbed character is obvious. According to thin section observation its grain-size ranges from 0.1 to 2 - 3 mm; the size below 0.1 mm it occurs only sporadically (Fig. 2 C). From weathered dacite samples complete crystals can be separated; some, the dihexahedral form could be recognized in spite of the high resorption (Fig. 2 D).

In the Tokaj-Nagyhegy are very characteristic and, from the petrological point of view, very important, usually spherical, so called diorite-porphyrite inclusions which are more basic than dacite. Their mean diameter is 2 - 6 cm. Owing to their pronounced porosity they are sharply separeted from the dacitic host rock. The texture of the inclusions is micro-holocrystalline. Predominant among their mineral constituents is plagioclase. The pyroxenes (hypersthene and augite) are partly decomposed, opacitised (Fig. 2 E). According to electron microprobe examinations (in Gyarmati 1977) there is no essential difference in composition between the plagioclase and pyroxene in the inclusion and the phenocrysts in dacite. Very rarely, quartz crystals can also be found at the edges of the inclusions. In thin section it can be observed that quartz is surrounded by a pyroxene rim (Fig. 2 F).

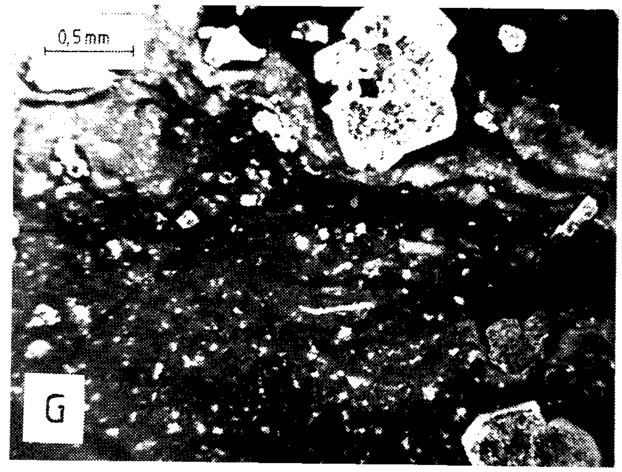

Fig. 2. G - Rhyolite bands (light) smeared into veins in the dacite of Tokaj-Nagyhegy (dark) [1N].

Some rhyolite inclusions were also found in the pyroxene dacite of the Tokaj-Nagyhegy. In one case, the solution of rhyolite and its smearing into a vein can be traced (Fig. 2 G).

Interpretation of major elements compositions

There are 44 analyses from pyroxene dacite of the Tokaj-Nagyhegy, 4 from diorite-porphyrite inclusions and 7 from rhyolite and rhyolite tuffs of the region (see Tab. 2). It is feasable to recalculate the values to 100 % on a water-free basis, and to represent them in Harker-diagrams in which the amount of one of the oxides is plotted as a function of SiO_2 (Fig. 3). Linear variation can suggest mixing of magmas, although similar variation can develop during assimilative processes (Cox et al. 1979; Best 1982). It is noteworthy that the points of the presumed hybrid as well as those of the acidic and basic components fit approximately on a line in the cases of TiO_2, Al_2O_3, FeO_{total}, K_2O and P_2O_5. However, MgO, CaO and Na_2O do not follow the linear trend. This fact can be explained by (1) a possible contamination of diorite-porphyrite inclusions by dacitic magma (see Fig. 2 F), or (2) the fact that four analyses cannot represent the major element composition of the inclusions. All in all, diorite-porphyrite inclusion can be considered to be only comparable to the mafic end member.

In the comparison of the modal and chemical analyses, it was possible to give the quantity of silica contained in the quartz crystals:

$$[1] \qquad Q * W_q / W_d$$

where Q: quartz content of the dacite (3.8 vol. %); W_q: density of quartz (2.7); W_d: measured density of dacite of the Tokaj-Nagyhegy (2.6). Silica content of the rest of the rock can be given by the equation:

$$[2] \qquad S_d - Q * W_q / W_d$$

where S_d: the silica content of the dacite (63.74 weights %). One can calculate the silica content of a so called "quartz-free" dacite (S_{qf}). This hypothetical rock is identical with the pyroxene dacite of Tokaj-Nagyhegy without quartz crystals. To get the actual silica content of this hypothetic rock, this value has to be recalculated to 100 %:

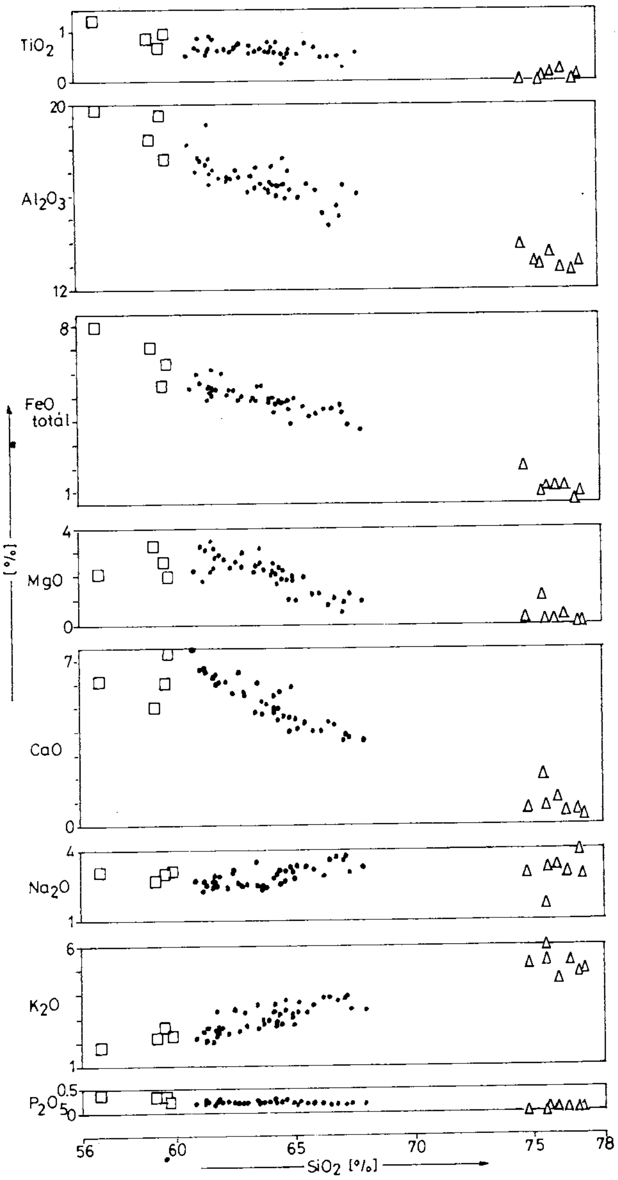

Fig. 3. Variation diagram of the oxides of diorite-porphyrite (open squares), dacite (solid circles) and rhyolite (open triangles) as a function of their SiO_2 contents. (Explanation see in the text).

[3] $$S_{qf} = \frac{100(S_d - Q * W_q / W_d)}{100 - Q * W_q / W_d}$$

If there is magma mixing, presuming that quartz crystals have rhyolitic origin, the S_{qf} value should be higher than SiO_2 content of basic inclusions and, of course, less than that of dacite. Since rhyolitic material assuming as an acidic member of magma mixing should be dominantly melted during the mixing process, S_{qf} has to be closes to SiO_2 of dacite than that of diorite-phorpyrite inclusions. Indeed, average silica content of basic inclusions is 58.84 %, while calculated silica content of the "quartz-free" dacite is 62.25 %.

Having the major elements content, the possibility of the magma mixing can be checked. On the grounds of two average composition, if the SiO_2 content of the third is presumed to be given, the other oxides of the third member can be graphically estimated; this estimated composition should be similar to the real one. Fig. 4 shows the estimation and the values obtained. The similarity between the diorite-porphyrite and the calculated basic member is striking. On the grounds of the major elements contents the degree of mixing can also be estimated (Cox et al. 1979). Taking assumed rhyolite composition into account, it can be obtained as a 1:3 rhyolite/diorite-porphyrite proportion.

Table 2. Average major-elements composition of pyroxene dacite, diorite-porphyrite and rhyolite as well as rhyolitic tuffs of Tokaj-Nagyhegy and its surroundings.

Rock name	Dacite	Rhyolite and rhyolitic tuffs	Diorite-porphyrite
Number of analyses	44	7	4
SiO_2	62.58	74.55	56.48
TiO_2	0.63	0.08	0.90
Al_2O_3	16.32	12.95	18.04
Fe_2O_3	2.32	0.86	5.55
FeO	2.88	0.34	1.43
MnO	0.14	0.01	0.09
MgO	2.15	0.29	2.43
SiO_2	5.22	0.89	5.87
TiO_2	2.83	2.97	2.82
K_2O	2.92	5.06	2.08
P_2O_5	0.20	0.02	0,29
LOI	1.87	2.18	4.22
Data recalculated on a water-free basis			
SiO_2	63.74	76.06	58.84
TiO_2	0.64	0,08	0.94
Al_2O_3	16.62	13.21	18.80
Fe_2O_3	2.36	0.88	5.78
FeO	2.93	0.35	1.49
(FeO_{total}	5.06	1.14	6.69)
MnO	0.14	0.01	0.09
MgO	2.19	0.29	2.53
CaO	5.32	0.91	6.12
Na_2O	2.88	3.03	2.94
K_2O	2.97	5.16	2.17
P_2O_5	0.21	0.02	0.30

Discussion

The majority of earlier researchers regarded assimilation as the most important process in the evolution of the pyroxene dacite of Tokaj-Nagyhegy. More than 100 years ago, however, József Szabó described part of its component minerals as biotite-orthoclase trachytic (i.e. rhyolitic) in origin. He established: "...the hot-flowing masses of the two types intruded into each other without having necessary time to form a uniform melt" (Szabó 1894). According to Lengyel (1924) the evolution of the dacite was primarily the

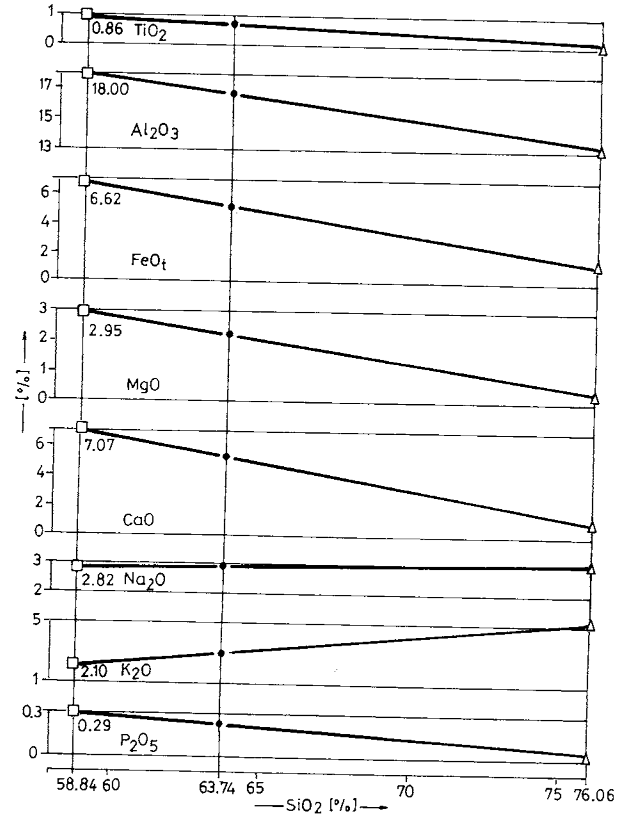

Fig. 4. Geometrical calculation of chemical composition of the hypothetical basic member (open squares) on the basis of the average chemical composition of the dacite (solid circles) and rhyolite (open triangles). (Explanation see in the text).

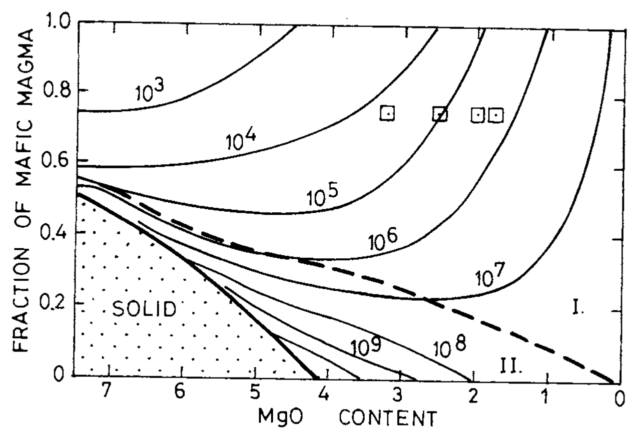

Fig. 5. Composition - mixing diagram showing the two fliud (I, II) and solid fields and viscosity (in poise) representing the physical condition of mafic magma after mixing (Sparks & Marshall 1986). Open squares indicate points of diorite-porphyrite.

consequence of the incorporation of large amounts of quartz-bearing sediment. The explanation to the geological map of the Tokaj Mountains (Pantó et al. 1966) mentions sandstone inclusions, and describes the quartz crystals as xenocrysts of non-magmatic origin. On the other hand, our experience in the field (Rózsa & Kozák 1981) suggests that such quartz-sandstone could occurs, at most, only sporadically, which is also suggested by the fact that Gyarmati (1977) does not mention such inclusion.

On the ground of the petrographic observations and investigations, I suggest that in the evolution of the pyroxene dacite of Tokaj-Nagyhegy the main role was played by mixing of magmas, whereas assimilation (primarily the assimilation of rhyolitic material) played a subordinate part. The "dust" inclusion and "honey-combed" structure inclusion in the plagioclases also suggest mixing of magmas. Similar phenomena are described by Kuno (1950), Eichelberger (1978a, 1978b), Halsor & Rose (1991) who explained the evolution of the feature by mixing of fairly basic and acidic material. It is suspected that the features are partly from partial melting of the crystals during the mixing event, and partly from invasion of the host melt (groundmass). The appearence of reverse zonality is correlated, among other things, with the mixing of magmas (Lofgren 1980). In disagreement with some earlier views I regard the quartz as of magmatic origin. This is verified by the recognizably dihexahedral form of the separated crystals. Another indication for the mechanism of the mixing of magmas is the size, composition, shape and porosity of the diorite-porphyrite inclusions. Eichelberger (1980) described the process of replenishment of an acidic magma chamber by a mafic magma with high volatile content, as the "foaming up" of the mafic high volatile-content magma due to rapid cooling and resultant second boiling. The bubble rich mafic inclusions penetrate into the acidic magma. In this way holocrystalline, rounded and porous inclusions more basic than enclosing rock form. Concurrently, heat released from crystallizing mafic magma causes resorption of plagioclase, sanidine and quartz

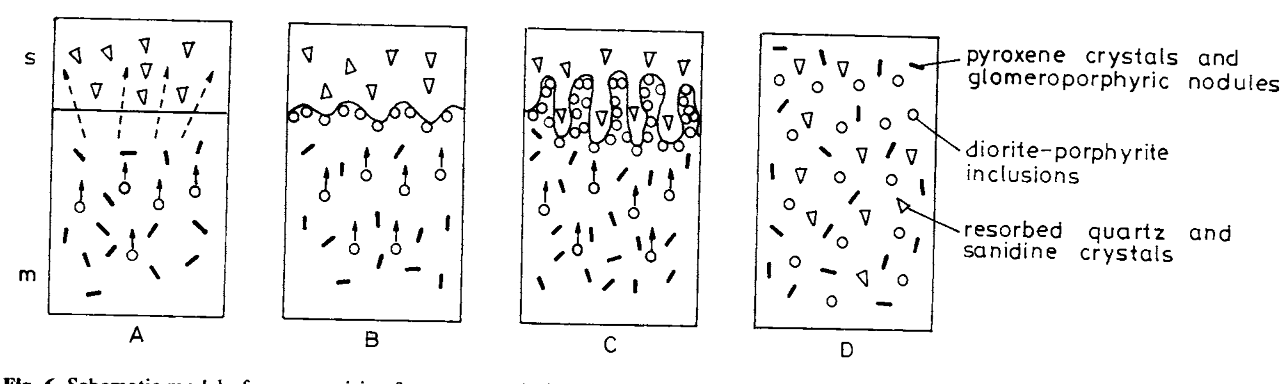

Fig. 6. Schematic model of magma mixing for pyroxene dacite of Tokaj-Nagyhegy on the basis of models proposed by Eichelberger (1980), Huppert et al. (1982) and Thomas et al. (1993). **A** - mafic magma (m) loses heat to the surroundings, crystallizes and vesiculates, while crystals of silicic magma (s) begin to be resorbed. **B** - bubbles accumulate at the interface. **C** - formation of plumes because of instability of the mixed layer. **D** - overturning, i.e. hybridization of the magmas.

phenocrysts in the acidic magma. The mixing was studied from physical point of view by Huppert et al. (1982). They regarded foaming up and ascension of bubbles as prelude to mixing. In their opinion it is the change taking place in the density relations of two melts that brings about the "overturn" and the hybridization of the magmas. Recently, Thomas et al. (1993) suggest that even when convection in a layer of mafic magma is vigorous, segregation of bubbles can occur. Their results are good agreement with the model originally proposed by Eichelberger (1980).

Studying thermal and mechanical constraints on mixing of magmas, Sparks & Marshall (1986) constructed a so called composition-mixing diagram showing the fraction of mafic magma in the mixture versus the MgO content of the mafic magma (Fig. 5). The diagram is divided into three fields (fluid I, fluid II, solid); the silicic end member is assumed to be with an initial temperature of 850 °C. According to them, hybridization can only occur when points of mafic magma fall into field fluid I or fluid II. Taking the supposed 1:3 rhyolite/diorite-porphyrite mixing ratio into account, points of MgO contents diorite-porphyrite samples fall into field of fluid I. The obtained viscosity values (ranging from 10^4 to 10^6) are in an accordance with the values of Murase & McBirney (1973). According to this diagram, complete mixing can occur.

Accepting conceptual model of Eichelberger (1980) and assuming convection of lower layer (Huppert et al. 1982), model of magma mixing in the case of pyroxene dacite of Tokaj-Nagyhegy can be summarized as it is shown by Fig. 6.

On the grounds of what has been said before the more basic component in the mixture is at least as basic as the chemical composition of diorite-porphyrite inclusions. It may be more basic if the inclusions themselves are contaminated, as occassional occurence of reacted or resorbed host derivated phenocrysts suggests. The real composition of the acidic component is not known, however, it can only be assumed on the basis of the rhyolites and rhyolite tuffs in the area.

Conclusions

On the basis of **1** - compositions and types of a part of plagioclase crystals; **2** - size-range and habit of resorbed quartz; **3** - resorption of sanidine; **4** - porosity, size, shape and chemical composition of diorite-porphyrite inclusions; and **5** - linear and nearly linear variation of most major elements of dacite, diorite-porphyrite and rhyolite, it is suggested that magma mixing played the main role in the genesis of pyroxene dacite of Tokaj-Nagyhegy. The scarcity of rhyolite inclusions suggests the comparatively subordinate role of assimilation.

On the other hand, it would be incorrect to generalize the conclusion over the whole of dacites in spite of the fact that magma mixing has been suggested to be the most important factor in andesite and dacite evolution in island-arc and continental margin volcanism (e.g. Anderson 1976; Eichelberger 1978b). However, several observation (black-white pumice in mixed tuff of Kőporos, high frequency of diorite-porphyrite inclusions in intermediate rocks) suggest that the process mentioned is not an extraordinary one in Tokaj Mountains. In the future, in the petrogenetical investigation of intermediate rocks of the mountain range, greater attention should be paid to the possibility of mixing of magmas.

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