Petrogenesis of the basaltic magmas feeding the monogenetic volcanic fields of the Bakony–Balaton Highland and Kemenesalja

THESES OF THE DOCTORAL (PHD) DISSERTATION

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I. Introduction, aims

Monogenetic volcanism represents a specific style of volcanic activity when not a given large volcano (like for example the composite volcanoes in subduction zone settings) but a volcanic field forms that consists of many - several hundreds or even thousand - individual small-volume (<1 km^3) volcanoes (e.g., Walker, 1993). These small volcanic centres are most commonly basaltic in composition (scoria cones, maars, tuff cones, tuff rings, small shield volcanoes) and they occur as scattered, clustered or aligned volcanic vents. The individual volcanic centres are short-lived (several days – decade), however the total duration of volcanism in a volcanic field expands over millions of years (e.g., Valentine and Perry, 2007). The eruptions in the volcanic fields occur in periodically recurrent active phases which are separated by long quiescence periods. In these monogenetic volcanic fields densely populated towns were built in many cases, therefore their investigation is of emphasised importance from the viewpoint of volcanic hazard forecast. Since the nature of volcanic eruptions are significantly influenced by the deep magmatic processes, it is essentially important to study the pre-eruptive history of basaltic magmas.

Based on the former view, the monogenetic volcanic centres can be characterized by a single brief eruption without the subsequent rejuvenation of volcanic activity and the formation of a given eruptive centre can be related to the ascent of a single batch of magma (e.g., Connor and Conway, 2000). In contrast, the results of recent and more detailed studies infer that these “simple” small-volume volcanoes can be characterized in many cases by far more complex evolution history than previously thought. Nowadays the monogenetic volcanic fields represent one of the frontlines of the international volcanological research, their novel investigation has been begun in the last decade. Today we already know more examples for volcanic centres which consist of several different eruptive units representing distinct magma batches (e.g., Brenna et al., 2010), moreover between the eruptions of different types even significant time breaks can be detected (Shane et al., 2013). Through the high-resolution analysis of given volcanic centres significant chemical variations were detected through the succession in many cases which were explained by the successive eruption of magma batches having different compositions, formed in distinct depths by differing degrees of partial melting and derived from mantle sources characterized by dissimilar natures (e.g., McGee et al., 2012). All of these case studies were carried out by using whole-rock major and trace element and isotopic compositions, but they did not attend to the analysis of the texture, zoning and chemical composition of the rock-forming minerals of basalts which provide a unique insight into the details of the magma evolution and processes operating in the magmatic systems (Roeder et al., 2003; Longpré et al., 2014).

The Carpathian-Pannonian Region (CPR) includes several monogenetic volcanic fields which were formed during the Late Miocene – Quaternary alkaline basaltic volcanism occurred in the period of the post-rift thermal subsidence of the Pannonian Basin (e.g., Harangi and Lenkey, 2007). In the last century the products of these volcanic fields have been the subjects of extensive research during which on the one hand the physical volcanological features of the eruptive centres were investigated (e.g., Martin and Németh, 2004) and on the other hand the petrographic characteristics and whole-rock geochemistry of the alkaline basaltic rocks were analysed (e.g., Embey-Isztin et al., 1993). The latter together with the investigational results of the peridotite xenoliths found in the basalts (e.g., Szabó and Taylor, 1994; Embey-Isztin et al., 2001) established our present-day knowledge about the characteristics of the upper mantle beneath the area, the nature of the mantle source regions of the alkaline basaltic magmas and the partial melting processes. Nevertheless, however, there were fewer studies aimed at the combined analysis of the texture, zoning and chemistry of rock-forming minerals in the basalts (e.g., Dobosi, 1989; Dobosi and Fodor, 1992), so less attention was paid to the processes occurring during the ascent of basaltic magmas. Additionally, earlier no such studies has been carried out in the Pannonian Basin which would have dealt with the integrated mineral textural and chemical as well as whole-rock geochemical investigation of the different eruptive units through the succession of individual monogenetic volcanic centres.

The aim of my research was the investigation of the alkaline basaltic rocks in the CPR in a new approach during which I have worked on three different volcanic centres in the Bakony–Balaton Highland and Kemenesalja Volcanic Fields. The applied new approach includes two parts: on the one hand it takes into consideration all that we know from the literature about the features of monogenetic volcanism, on the other hand it principally rests on the detailed mineral-scale analysis of the basalts. In the case of monogenetic volcanic centres the high-resolution investigation of the textures, zoning patterns and chemical compositions of olivines and their spinel inclusions representing the liquidus phases of the alkaline basalts is a novelty both in the inland and international research. With the stratigraphically controlled sampling of the volcanic centres and with the petrogenetic analysis of the basaltic rocks derived from the individual eruptive units my aim was to recognise the features and evolution of the successively erupted magma batches as well as the activity of and the processes in the deep magmatic system that fed the eruptions.

II. Analytical methods

For the petrogenetic investigations I carefully analysed the textures of the alkaline basaltic rocks and the textural and chemical features of the rock-forming minerals. The rock textures as well as the mineral textures and zoning patterns were examined with a Nikon YS2-T polarizing microscope and an AMRAY 1830 I/T6 scanning electron microscope (using 20 kV accelerating voltage) at the Department of Petrology and Geochemistry, Eötvös Loránd University. For the determination of the tiny mineral phases qualitative chemical analyses were also performed with the EDAX PV9800 type energy-dispersive spectrometer. The in situ analyses of the mineral phases and glasses (point and line measurements) were determined using a CAMECA SX100 electron microprobe equipped with four WDS and one EDS at the University of Vienna, Department of Lithospheric Research. I used 15 kV accelerating voltage and 20 nA beam current. The in situ chemical measurements of the minerals of the lava samples from Bondoró-hegy were carried out by Prof. Gábor Dobosi using a JEOL Superprobe 733 equipped with wavelength-dispersive spectrometers at the Institute for Geological and Geochemical Research (Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences) in Budapest. The accelerating voltage was 20 kV and the beam current was 35 nA.

Whole-rock major and trace element geochemical compositions were analysed at AcmeLabs (Vancouver, Canada; http://acmelab.com/). Major and minor elements were determined by ICP-emission spectrometry and trace elements were analysed by ICP-MS.

III. New scientific results (theses)

1.) The alkaline basaltic rocks of the Bondoró-hegy and Füzes-tó scoria cone (Bakony–Balaton Highland Volcanic Field) are unique among the alkaline basalts of the CPR because they are unusually rich in crystals and xenoliths of diverse origins. Using this speciality I revealed the ascent history of these basaltic magmas. Through the detailed textural and chemical analysis of the rock-forming minerals I determined the origins of the different crystals: most of them did not crystallized from the host magma but they are xenocrysts and megacrysts derived from different levels of the lithospheric mantle and from the lower crust. In these depths an effective magma – wall rock interaction can be assumed based on the presence of these extremely abundant fragments and crystals. In contrast, the ascending basaltic magmas did not incorporate additional crustal material in the middle and upper part of the crust suggesting a change in the style and possibly also in the rate of the magma ascent. The effective magma – wall rock interaction at lithospheric mantle and lower crustal depths is comparable with the ascent style of kimberlitic magmas. The exploration of the reason for this effective interaction (e.g., the peculiarity of these magmas - as for example dissimilar volatile contents - and/or the physical state of the lithosphere) requires additional investigations.

2.) The presented stratigraphically ordered, mineral-scale and whole-rock geochemical analyses carried out on the Kissomlyó volcanic centre (Kemenesalja Volcanic Field) confirmed the chemical similarity of the magma batches representing the eruptive units that was also observed earlier (Harangi et al., 1995). However, my detailed investigations of the textures, zoning patterns and compositions of the minerals pointed out that this small geochemical variation through the succession is due to open-system petrogenetic processes (magma replenishments, magma mixing), and in fact the chemical diversity of the deep magmatic system was considerably larger than what is indicated by the whole-rock compositions. Beneath Kissomlyó a stable magma generation zone can be inferred yielding compositionally similar primary magmas, additionally the magma batches erupted to the surface in the distinct eruptive phases underwent similar magma differentiation processes.

3.) The Fekete-hegy volcanic complex (Bakony–Balaton Highland Volcanic Field) was previously less known from a petrological and geochemical point of view, my study presents the first detailed petrographic and geochemical investigations from these basaltic rocks. The high-resolution analysis of the rocks and their mineral phases from the different eruptive units within a given volcanic centre can be regarded as a novelty in the Balaton Highland. Studying the features of the basaltic magmas erupted in different localities and times within this complex monogenetic system I have come to the conclusion that the differing eruptions were fed by dissimilar magmas. In the evolution of the magmatic system feeding the phreatomagmatic eruptions open-system petrogenetic processes played a dominant role: as the result of magma accumulation a magma reservoir had been formed into which more primitive magmas of different compositions intruded (replenishments) and mixed with the more fractionated magma found in the reservoir. In contrast, during the evolution of the magmatic system feeding the subsequent magmatic explosive – effusive volcanic activity open-system processes were not detected, only closed-system fractional crystallization occurred in a magma accumulation zone.

4.) In contrast to the former general view, my investigational results revealed that beneath certain volcanic centres in the Bakony–Balaton Highland and Kemenesalja Volcanic Fields diverse open-system petrogenetic processes (magma accumulation and storage, magma mixing, effective magma – wall rock interaction) occurred similarly to what is known in the case of polygenetic volcanoes with more complex evolution. Additionally, in many cases the different eruptive phases of given volcanic centres were fed by dissimilar magma batches. Differences can be detected between the evolution histories of the magmas forming the individual eruptive centres even within a given centre. Through my high-resolution mineral-scale analyses and with the involvement of the phreatomagmatic products which were usually neglected during the earlier research focused on whole-rock geochemistry, I managed to reveal such deep magmatic processes that have not been discovered in the alkaline basaltic rocks of these two volcanic fields before.

5.) Based on the presented results magma accumulation and storage occurred during the evolution of the deep magmatic systems feeding certain volcanic centres (Kissomlyó, Fekete-hegy) of the Bakony–Balaton Highland and Kemenesalja Volcanic Fields, i.e., in many cases the alkaline basaltic magmas did not ascend directly to the surface but stalled and differentiated in the lithosphere (near the crust-mantle boundary or at other density and/or rheological boundaries). In this region, this study provides the first thermobarometric calculations based on clinopyroxene-melt equilibria which suggest that the magma accumulation beneath the Kissomlyó centre could have occurred near the Moho. Consequently, beneath Kissomlyó and other volcanic centres of Kemenesalja the layered Moho indicated by geophysical methods can imply former magma accumulation zones. In contrast, in the case of other volcanic centres (Bondoró-hegy, Füzes-tó scoria cone) it can be confirmed that the basaltic magmas could have reached the surface directly (single-stage ascent), i.e., they could not have stopped in the lithosphere during their continuous ascent.

6.) Based on the results of my research the olivine crystals and their spinel inclusions are excellent witnesses to record the evolution history of magmas feeding monogenetic volcanic centres. The advantage of using these two mineral phases is that they are abundant in the alkaline basalts and provide information about the earliest stage of magma evolution since they represent the liquidus phases in alkaline basaltic magmas in general. Through the high-resolution analysis of texture, zoning and chemistry of olivines, i.e., mapping their chemical stratigraphy and through determining the compositions of their spinel inclusions (taking into account the texture and zoning type of the host olivine together with the observation that which part and zone of the olivine contain the given spinel) we can recognise the magmatic systems feeding the basaltic volcanic eruptions as well as reveal the closed- and open-system processes and the features of the involved magmas. In contrast to what is known in the Nógrád-Gömör Volcanic Field, in the case of the eruptive centres in the Bakony–Balaton Highland and Kemenesalja Volcanic Fields the open-system processes are more cryptic and characteristically they could have occurred in the early stage of magma evolution, thus they can be principally detected by the detailed SEM and EMPA analysis of olivines and spinels. The application of this method is a path-finder both in the inland and international research of monogenetic basaltic volcanic fields.

7.) I performed calculations to estimate one of the most important parameters of the volcanic hazard forecast in monogenetic volcanic fields: the magma ascent rate concerning which there are scarce examples in the case of the inland basalts. I used several methods independent from each other for which the crystal-rich alkaline basalts of the Bondoró-hegy and Füzes-tó scoria cone provided an outstanding opportunity. I got differing results with the different methods whose comparison and joint evaluation requires careful attention. With this I tried to carry out a comparative work considering several viewpoints that can be regarded as a novelty not only in the CPR but also internationally. Based on the results the studied alkaline basaltic magmas could have passed through the lithosphere within days. Comparing with the available magma ascent rates from other alkaline basalts in the Pannonian Basin, a significant difference cannot be inferred between the ascent velocities of the unusually xenolith- and xenocryst-rich basalts and those of the xenolith-poorer ones. This implies that in the case of the former basalts the reason for the presence of extremely abundant xenoliths and xenocrysts probably can be explained not by the different (higher) ascent rates of these magmas but the effective magma – wall rock interaction.

IV. Conclusions

During my research I investigated the alkaline basaltic rocks of the Bakony–Balaton Highland and Kemenesalja monogenetic volcanic fields in a new approach, for which I have used the products of three different volcanic centres. My results based chiefly on detailed mineral textural, zoning and chemical analyses imply that the basaltic magmas forming the eruptive centres of these volcanic fields underwent various deep processes as well as differences can be detected between their evolution histories even within a given centre. In the evolution of the magmatic systems feeding the eruptions open-system processes played a dominant role (magma accumulation and storage, magma mixing, effective magma – wall rock interaction) and in many cases the different eruptive phases were fed by dissimilar magma batches. The deep magmatic processes discovered through the high-resolution analysis of the textures, zoning patterns and chemistry of olivines and their spinel inclusions representing the liquidus phases provide important knowledge to the better understanding of the magmatic systems feeding monogenetic volcanic centres. By means of my results the inland alkaline basaltic volcanic fields can join the recent international research dealing with the novel investigation of monogenetic volcanism.

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