Mio-Pliocene Phreatomagmatic Volcanism in a Fluvio-Lacustrine Basin in Western Hungary

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ABSTRACT. Late Miocene to Pliocene eroded maar complexes and tuff rings are preserved in the Pannonian Basin. They belong to the Bakony–Balaton Highland (BBHVF) and the Little Hungarian Plain Volcanic Field (LHPVF). The bulk of the volcanic fields are considered to have developed subaerially. Base surge and fallout deposits were formed around maars and tuff rings by phreatomagmatic explosions, caused by interactions between water-saturated sediments and alkali basalt magma locally carrying peridotite lherzolite xenoliths as well as pyroxene and olivine megacrysts. Particularly well exposed is a great variety of peperites, which commonly constitute the root of the volcanic vent as a result of non-explosive to very mildly explosive interaction of magma with wet, unconsolidated sediments. A slight time delay was found between the formation of initially phreatomagmatic landforms and lava effusion. The composition of the initial volcanic products is more evolved (tephrite, phonotephrite) in contrast to more basic composition of subsequent lavas. The time difference between phreatomagmatic explosive and effusive eruptions and the bimodality of melt involved in these eruptions suggests a dual melt involvement in volcanic eruptions in western Hungary.

KEY WORDS: phreatomagmatic, basalt, scoria, tuff ring, maar, sideromelane, peperite, geochemistry.

Introduction

The Little Hungarian Plain (LHPVF) and Bakony–Balaton Volcanic Fields (BBHVF) are located in the western part of the Pannonian Basin, Hungary (Fig. 1). The Pannonian Basin is considered to be a back-arc basin with a subduction-related Neogene calk-alkaline volcanic chain at its northern to eastern margin (Szabó et al. 1992). The Miocene extensional tectonic events resulted in lithospheric thinning and asthenospheric upwelling (Stegena et al. 1975, Horváth 1993). From Late Miocene to Pleistocene, this region was characterized by alkaline

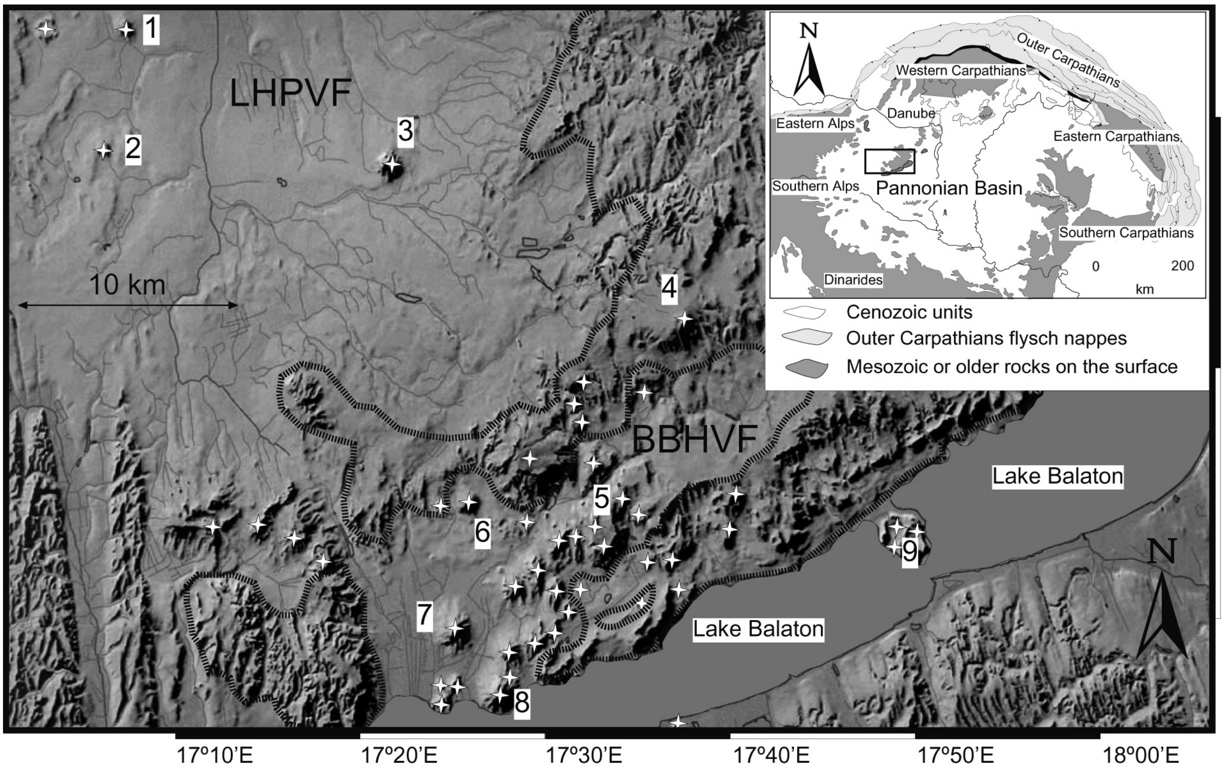

Fig. 1. Location map of the Bakony–Balaton Highland Volcanic Field (BBHVF) and the Little Hungarian Volcanic Field (LHPVF). Numbers represent erosional remnants of volcanic edifices. (1) Ság-hegy, (2) Kissomlyó, (3) Somló, (4) Kab-hegy, (5) Fekete-hegy, (6) Haláp, (7) Szentgyörgy-hegy, (8) Badacsony, (9) Tihany.

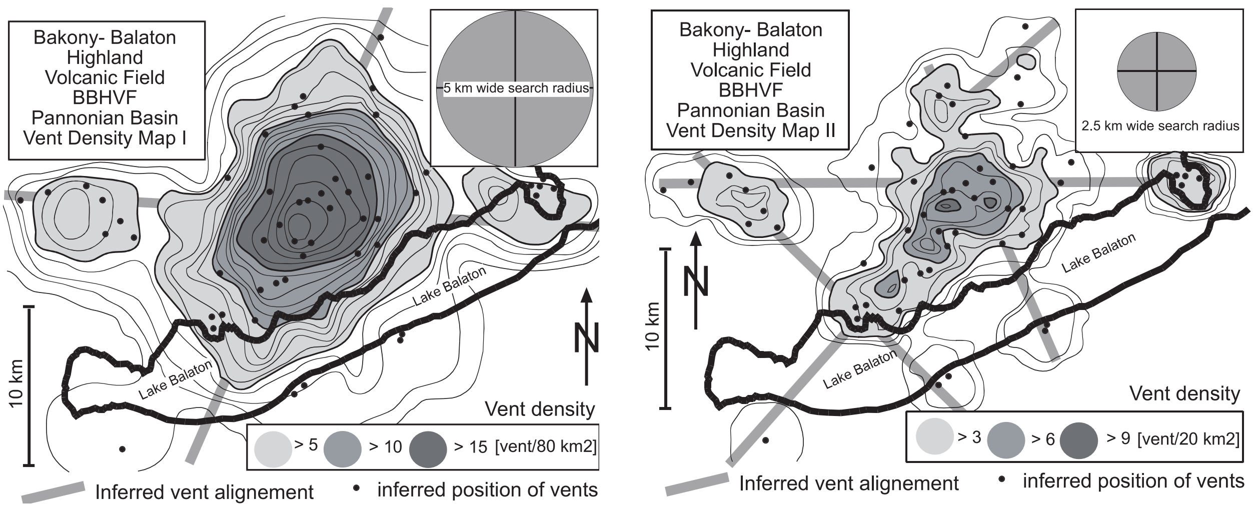

Fig. 2. (a) vent density map contours based on rectangular grid with spacing of 2 km and a search radius of 5 km. (b) vent density map contours based on rectangular grid with spacing of 1 km and a search radius of 2.5 km.

basaltic volcanism (Szabó et al. 1992). Both the BBHVF and the LHPVF consist of remnants of scoria cones, tuff rings, and maars (Jugovics 1968, 1971, Jámbor et al. 1981, Németh and Martin 1999a, b). In this paper we give an overview of the distribution and characteristics of different volcanic remnants in the western Pannonian Basin, and an account of current research in a joint German–Hungarian project.

Distribution of volcanic remnants

The distribution of identified vent remnants in the BBHVF is represented by contouring vent density on the basis of a rectangular grid with uniform spacing of 2 km and a search radius of 5 km (Fig. 2a). On this map, the BBHVF is characterized by one major vent cluster in the geometrical centre of the field and by two additional clusters, one in the east and one in the west, all together forming a more or less east–west-trending alignment (Fig. 2a). The highest vent density reaches 20 vents in an area of 80 km^2 (0.25 vents/km^2), centred around the location of a nested maar system (Fekete-hegy). This location is where mafic volcaniclastic flow deposits (hydroclastic flow) (Németh and Martin 1999c), large amounts of dm-size peridotite lherzolite (Németh and Szabó 1998), mantle and/or deep crustal nodules (Török 1995), and pyroclastic deposits indicative of high-energy phreatomagmatic explosive eruptions have been identified. Further individual vent clusters were revealed in a vent density map on the basis of a 1km rectangular grid and 2.5km search radius (Fig. 2b), mimicking major known crustal structural zones orientated mainly NE–SW and NW–SE (Tari 1991, Dudko 1999). In general, using larger search radius and larger steps on grid, it is inferred that vent-distribution features are shown to be related with deep subsurface features such as the geometry of the melting anomaly. In contrast, smaller search radius and steps on the grid give information on the surface structure of the pre-volcanic system (Connor 1990). It has been thus inferred that the Mio-Pliocene volcanism in the BBHVF was related to a characteristic melting anomaly from where the magma intruded into shallow subsurface crustal inhomogeneities, such as fault lines. Along with the vent clustering and alignments, north–south elongation of individual vents is prominent, likely to be related to valley pattern and inherited structural elements of the basement rocks. In the LHPVF, however, the vents are scattered. It is also noteworthy that major volcanic complexes such as Ság-hegy, Somló, Kab-hegy and Tihany (Fig. 1) fall on a straight line that has no obvious surface expression in the form of faults or other structural elements.

Characteristics of volcanic remnants

The wide range of types of magma/water interaction led to the formation of different types of volcanic edifices, including maars, tuff rings and scoria cones with a great variety of depositional features as preserved in their pyroclastic units. Different types of volcanoes were identified on the basis of volcanic textures, shape and composition of their pyroclasts, sedimentary structures, and the presence of pillow basalts and peperites. Base surge and fallout tephra were deposited around maars and tuff rings by phreatomagmatic explosions, caused by interactions between water-saturated sediments and alkali basalt magma locally carrying peridotite lherzolite xenoliths as well as pyroxene and olivine megacrysts, which are well exposed in *nested maar complexes* such as Tihany (Németh et al. 2001) and Fekete-hegy (Fig. 1). Fekete-hegy is volumetrically one of the largest in the BBHVF; it is a representative example demonstrating the architecture of complex multivent systems with chains and/or groups of predominantly phreatomagmatic vents. It forms a lava-capped butte in the central part of the BBHVF with basaltic lava flows overlying ~50 m of pyroclastic unit. At least 3 vents were identified at Fekete-hegy on the basis of facies relationships of pyroclastic rocks, distribution of volcanic and non-volcanic underlying rocks, paleocurrent indicators, asymmetry of impact sags caused by ballistic bombs, and study of geophysical data similar to studies that have been carried out succesfully in other volcanic fields such as the Eifel (Lorenz and Büchel 1980, Bogaard and Schmincke 1984, Lorenz 1985, 1986). Every single vent eruption started

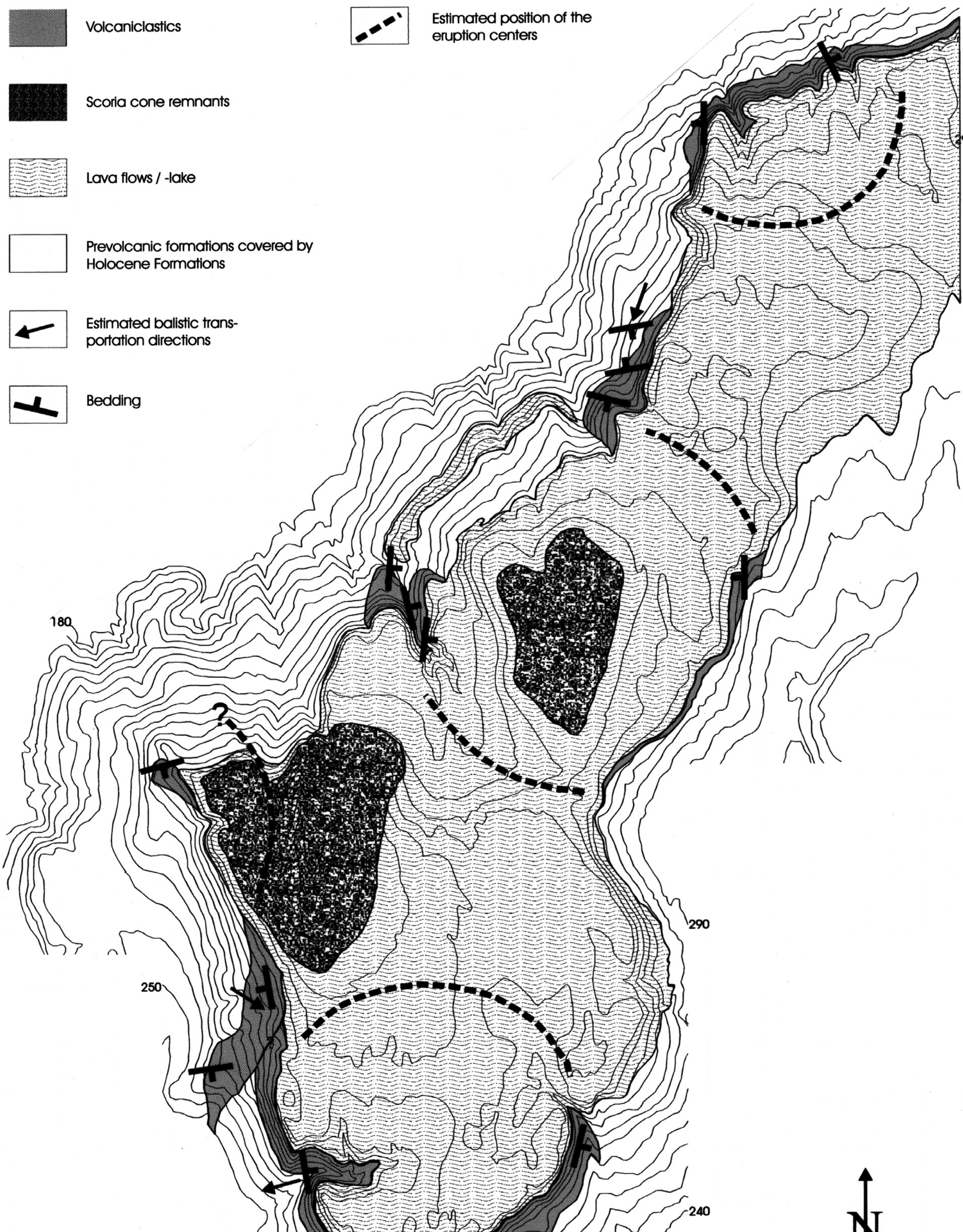

Fig. 3. Geological map of the nested maar complex of Fekete-hegy.

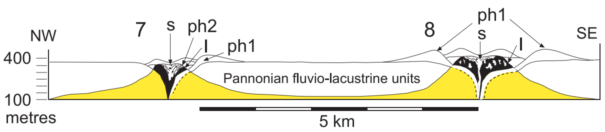

Fig. 4. A NW–SE cross section of multiple vent complexes of Szentgyörgy-hegy (7) and Badacsony (8) showing interrelation of phreatomagmatic tephra ring (ph1 and ph2), intra-vent scoria cones (s) and lava lakes (l).

with phreatomagmatic activity, interpreted on the basis of the presence of chilled, angular, blocky, slightly to moderately vesicular sideromelane glass shards, accidental lithic clasts and bedding characteristics of the pyroclastic units (Heiken 1974, Fisher and Schmincke 1984). Locally, successions were formed by simultaneous activity of two (or more) closely spaced (100 ms-scale) vents indicated by the presence of overlying or interstratified beds recording different transport directions indicative of different sources. The explosive interaction of the ascending magma with water occurred in water-saturated sediment such as Late Miocene shallow marine to fluvio-lacustrine siliciclastic sediments as well as with karst groundwater from the widespread and multilevel karst system in Mesozoic carbonate rocks. The final phase of the activity in the maar/tuff ring complex is represented by effusive eruptions of lava flows and lava lakes which are filling and covering the pyroclastic deposits in an area of at least 10 km^2. The change in the eruptive style was presumably caused by the termination of water supply in the basement. The youngest deposits are represented by two scoria cones (Fig. 3), which also started with a short period of phreatomagmatic activity indicated by accidental lithic clast-rich basal units. They are generated by a Strombolian-type explosive activity followed by the extrusion of small-volume lava flows. Lava fountaining is inferred to have been an important stage of the eruptive history of these scoria cones, based on the presence of clastogenic lava flows and welded agglutinate beds at several locations. The roughly NNE–SSW-trending chain of identified volcanic edifices suggests that the Fekete-hegy maar complex either developed in a NNE–SSW valley system and/or is associated with pre-existing structural elements of the same orientation (Fig. 3).

Complex multiple vents with solidified large volume lava lakes are characteristic volcanic remnants especially in the western part of the BBHVF, such as Badacsony (Fig. 1), one of the largest lava-capped buttes in the BBHVF (Fig. 4). A thick (>50 m), black, strongly chilled, aphanitic basanitic lava overlies a coarse-grained, unsorted yellow lapilli tuff. The lapilli tuff consists of finely dispersed accidental lithic fragments of quartz or quartzofeldspathic sandstone, and blocky, weakly to highly vesicular microlite-poor sideromelane (tephrite, phonotephrite), indicative of phreatomagmatic origin, near-surface vesiculation and possible excavation of pre-volcanic country rocks. In addition, xenocrysts of olivine and pyroxene may reach 5 vol.%. The lava lake at Badacsony exhibits irregular lower contacts with the pyroclastic units, often displaying peperite structures. The peperite encloses highly vesicular scoriaceous lava spatter clasts, with vesicles filled with clay, calcite or quartzofeldspatic fragments as well as strongly palagonitized, often red blocky volcanic glass shards. The irregular shape of the tumuli features and their irregular geographical distribution indicate that they formed rather accidentally upon the contact between wet uncon-solidated tephra and the basanite lava. Between lava units, a thin sedimentary veneer and their associated peperite indicate short interruptions between lava emplacement into a wet, very likely water-filled crater of a phreatomagmatic volcano of Badacsony. Similar volcanic architectures were recognized at other lava-capped buttes such as Haláp or Szent-György-hegy (Fig. 1), all suggesting rejuvenation or longevity of volcanic vents at the same site.

Single phreatomagmatic vents are also widespread, such as Kissomlyó (Martin and Németh 2002a), Kereki-domb or zánkai Várhegy (Németh et al. 2002). They consist of moderately to strongly eroded pyroclastic mounds, forming small hills and exposing phreatomagmatic lapilli tuff beds, often in chaotic setting, which are commonly covered by lava flows. The presence of chilled, angular, moderately vesicular sideromelane fragments and the predominantly Neogene sediment-derived accidental lithic clast population in the exposed pyroclastic rocks allow to infer that these volcanic remnants represent near-vent to vent-fill pyroclastic units of former phreatomagmatic volcanoes, such as maars surounded by tuff rings, which were topped by lava flows in the last stage of volcanic activity.

Typical *scoria cones* or their remnants are relatively rare in western Hungary. Even in areas where highly vesicular scoriaceous deposits are accumulated and preserved in relatively high thickness (tens of metres: e.g., Sag-hegy, Fig. 1), accidental lithic clasts (ash to lapilli size) are still common constituents (up to 15 vol.%), indicating active quarrying of volcanic conduits into the subsurface rocks and/or presence of water-rich slurry in the vent zones during more magmatic fragmentation of magma.

Peperites

Particularly well exposed is a wide variety of peperites (White et al. 2000, Skilling et al. 2002), which commonly constitute the root of a volcanic vent as a result of non-explosive to very mild explosive interaction of magma with wet, unconsolidated sediments. Peperites in the study area are commonly formed by the interaction of lava flows, lava lakes (Martin and Németh 2002b), shallow subvolcanic sills (Martin and Németh 2002c), feeder dykes with either lacustrine sediments deposited in crater lakes or with wet phreatomagmatic tephra forming volcanic edifices. Several types of peperite occur in the Pannonian Basin. These include 1) blocky and globular peperite (Busby and White 1987) related to feeder dykes in the centre of maar/tuff ring (BBHVF) and phreatomagmatic volcanic complex (LHPVF) and 2) globular peperite associated with lava flows/lakes filling tuff rings (BBHVF and LHPVF). Abundant development of peperite at BBHVF and LHPVF indicates that the host sediments were still wet and unconsolidated at the time of intrusion and/or effusion. Peperite clearly demonstrates almost synchroneity of volcanism and sedimentation (Hanson and Schweickert 1982, Busby-Spera and White 1987, White et al. 2000) and their im-

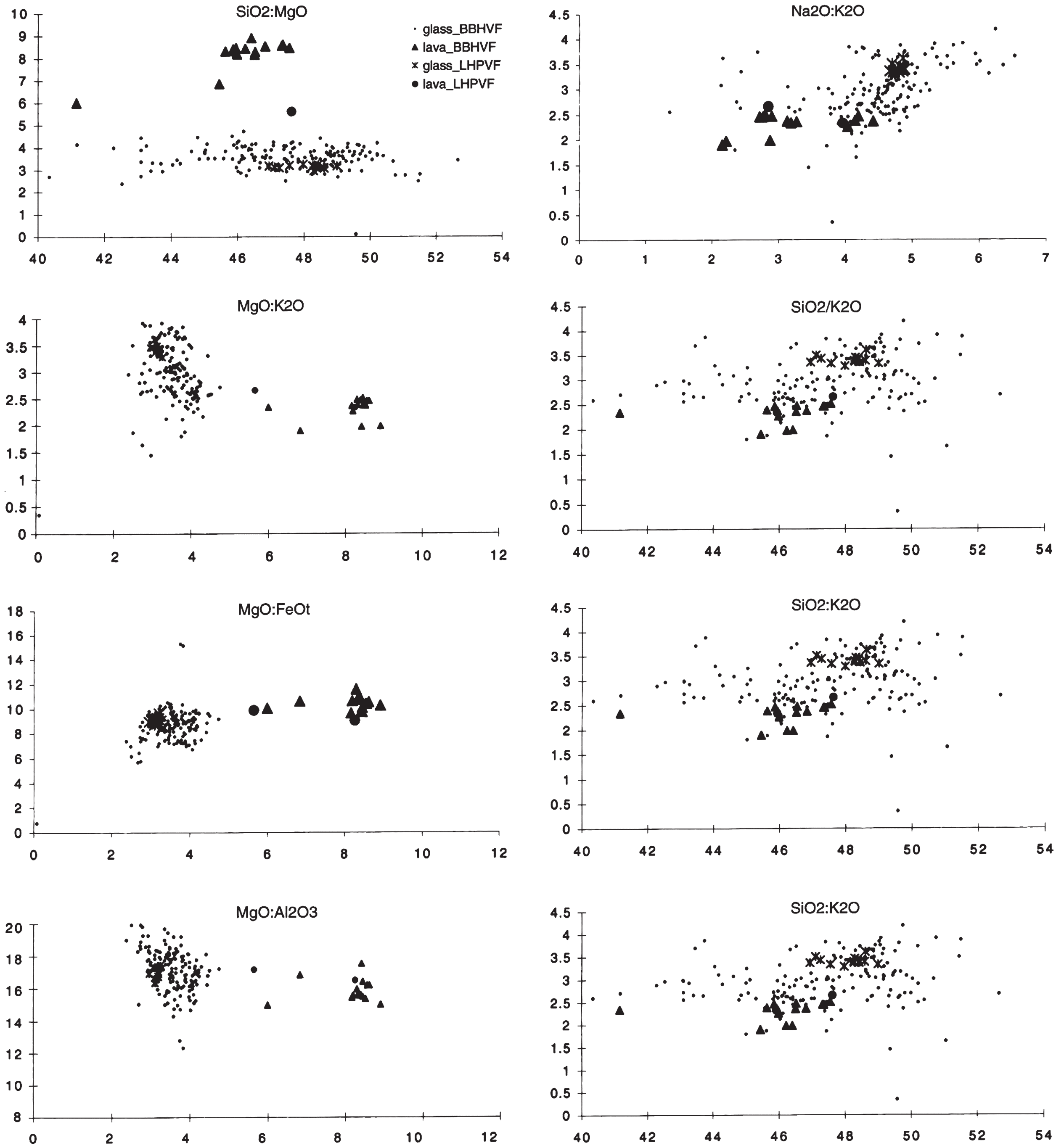

Fig. 5. Major element diagrams of volcanic rocks from western Hungary. Glass BBHVF and glass LHPVF indicate data derived from volcanic glass shards of pyroclastic deposits. Lava BBHVF and lava LHPVF indicate data derived from capping lava rocks. Note the separation of volcanic glass and lava rock data fields. Volcanic glass data were derived from electron microprobe analyses of glass shards and compared with XRF whole rock data from lava rocks.

portance for paleoenvironmental modelling of the Pliocene in western Hungary.

Geochemistry

In this study, volcanic rocks were subjected to XRF whole-rock analyses (Embey-Isztin 1993, Harangi et al. 1994) and pyroclastic rocks to electron microprobe analyses on polished thin sections from fresh volcanic glass shards using a JEOL 8600 Superprobe, housed in the University of Otago, Geology Department (15 kV acceleration voltage, 5–20 mm electron beam diameter, OXIDE9 standard, and ZAF correction method). The composition of the erupted magmas in the studied areas falls to the alkali basalt field, with the dominant magma type being basanitic (Fig. 5). The pyroclastic rocks are commonly more evolved than the lava flows from the same sites. Volcanic glass shards from all sites are predominantly tephritic, phonotephritic in composition with a minor proportion of tephriphonolitic or trachybasaltic glass shards. Compositional variations of the initial pyroclastic sequences and subsequent lava flows and/or dykes suggest a complex magma evolution within a relatively short period of time (hours to weeks). This compositional bimodality of tuff ring formation and lava flow sequences can be explained in two different ways: 1) by the presence of "readily" evolved tephritic – phonotephritic melt at upper crustal level, which – after a short period of residence (days to weeks) – continued its way to the surface and interacted explosively with external water or water-saturated sediments. Shortly after emptying these shallow-level "micro" magma storage places, a deep-sourced basanitic melt reached the surface and generated scoria cones and/or subsequent lava flows and lava lakes, which were commonly involved in peperite-forming processes at each locality. This model is similar to the one described from the Canary Islands (Klügel et al. 2000). Alternatively, 2) the ascending melt evolved during its way to the surface, producing individual chemically zoned magma batches with evolved top levels and less evolved bottom parts, as suggested for the Rothenberg volcano in the German Eifel (Schmincke et al. 1983, Houghton and Schmincke 1989). The top level of each initial magma batch interacted with external water causing phreatomagmatic explosions. After exhausting the external water supply, a lower magma batch which was less evolved (basanite) managed to reach the surface without phreatomagmatic interaction, filling the craters and experiencing intensive interaction with the unconsolidated water-rich slurry (Kokelaar 1983, 1986) that occupied the vent zones leading to peperite-forming processes (Lavine and Aalto 2002, Martin and Nemeth 2002c). However, further isotopic studies are required to rule out any contamination of the magma during ascent.

Conclusion

The BBHVF and the LHPVF are eroded phreatomagmatic fields, with remnants of nested maar complexes, multiple vent systems and individual tuff rings. Phreatomagmatism played an important role in the formation of these volcanic landforms, because of the extensive water availability from the surface (lakes and swamps) and shallow subsurface siliciclastic sediments (late Miocene sands) as well as karst aquifers of different depths. All studied volcanic sites in the western Pannonian Basin exhibit evidence of magma–water interaction in the form of explosive eruptive products and/or peperites. Even during the late stage of volcanic activity, the vents are inferred to have been filled with pyroclast-rich slurry, a mixture of siliciclastic and volcanic debris with water, formed by the remobilization of mud from the host sediment (both siliciclastic and volcaniclastic) in the vent zone due to the heat effect of the magma and the inflow of groundwater. Thus even during periods of high magma discharge rate dominated by magmatic fragmentation, a combination of phreatomagmatic and magmatic fragmentation led to the formation of transitional textural characteristics of the deposits. In this respect, the Mio-Pliocene volcanic fields in the western Pannonian Basin are exceptionally good examples for the study of phreatomagmatism and its complex interaction in a fluvio-lacustrine setting.

Acknowledgements

Partial financial support from the DAAD within the DAAD German–Hungarian Academic Exchange Program 2002/2003 and the Hungarian Science Foundation (OTKA F 043 346 granted to K. Németh) are acknowledged. Special thanks for the support of this project by Tamás Budai and Gábor Csillag (MÁFI Budapest). Constructive suggestions by Volker Lorenz (University of Würzburg) and an anonymus reviewer as well as by Jaromir Ulrych (Institute of Geology, AS CR), editor of the volume, helped to improve the manuscript.

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