Large hydrovolcanic field in the Pannonian Basin: general characteristics of the Bakony-Balaton Highland Volcanic Field, Hungary

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Abstract

The Bakony-Balaton Highland Volcanic Field (BBHVF), active in late Miocene, is located in the Central Pannonian Basin (Hungary) and comprises approximately 100 mostly alkaline basaltic eruptive centers as scoria cones, tuff rings, maar volcanic complexes and shield volcanoes. We summarize the basic elements of the BBHVF volcanic characteristics according to geological mapping and rock characterization. A detailed physical volcanology map is given showing monogenetic alkaline basaltic volcanic field characteristics of the BBHVF. In areas where thick Pannonian Sandstone beds build up the pre-volcanic strata, normal maar volcanic centers are found with usually thick late magmatic infill in the maar basins. In the areas where relatively thin Pannonian Sandstone beds overly thick Mesozoic or Paleozoic rocks, characterized by fractures which control karstwater bearing aquifers, large unusual maar volcanic sequences are found (Tihany type maar volcanoes). In the northern part of the volcanic field large scoria cones and shield volcanoes are found. This area represents a zone where ground and surface water had minor significance in controlling the volcanic activity. The Tihany type maar volcanic centers are usually filled by thick maar lake deposits, which form Gilbert type gravel sequences of scoria in the northern side of the maar basins, suggesting mostly north to south fluvial system in the pre-volcanic surface.

1. Introduction

The Bakony- Balaton Highland Volcanic Field (BBHVF) is located in the Central Pannonian Basin, Hungary and extends from the Keszthely Mts. in the west to the southernmost slopes of the High Bakony Mts. in the east. The region abounds to the Lake Balaton north shore. The volcanic centers of the BBHVF were active approximately between 7.54 Ma and 2.8 Ma (Balogh et al., 1982, 1986, Balogh, 1995; Borsy et al., 1986) (Fig. 1) and mainly erupted alkaline basaltic volcanic products (e.g., Embey-Isztin et al., 1993a,b; Szabó et al., 1992; Downes & Vaselli, 1995; Downes et al., 1995; Harangi in press) (Table 1). The volcanism was related to post-extensional tectonic processes in the middle part of the Pannonian Basin (Szabó et al., 1992). The volcanic centers of the BBHVF are closely related to those of the Little Hungarian Plain according to their composition, age and eruptive mechanism (Harangi & Harangi, 1995). Most likely these two volcanic fields operated simultaneously but the paleo-environment and its hydrogeology could have caused different styles of eruptive mechanism (Kázmér, 1990).

Previous estimates that the BBHVF comprises more than 50 basaltic volcanoes (Lóczy, 1913; Jámbor et al., 1981; Jugovics, 1969), appear to be conservative with actual number clear to 150-200 centers. Several of the eruptive centers are complex with a large number of individual vents (Fig. 1). The volcanic field belongs to the Transdanubian Central Range unit, which is correlated with the Upper Austroalpine nappes of the Eastern Alps (e.g., Majoros, 1980; Tari et al., 1992). The basement of the volcanic field consists of thick Silurian schist, Permian Red Sandstone and Mesozoic carbonate beds. This unit forms a large-scale anticline structure, which is locally covered by Tertiary sediments. The Silurian schist formation is 400-600 m thick and comprises alternating, very low-grade metamorphosed psammitic and pelitic beds (Lelkes-Felvári, 1978). The Permian Red Sandstone is a thick (400-600 m) continental alluvial formation (Majoros, 1980). The Mesozoic formations are represented by Triassic limestones and dolomites which are direct related to the Eastern Alps Triassic formations. The younger sediments were deposited on an erosion surface in local sedimentary basins. In the Neogene, just shortly before the volcanism started, a large lake occupied the Pannonian Basin, the Pannonian Lake (Kázmér, 1990). The lacustrine sandstones, mudstones and marl of the brackish Pannonian Lake are widespread in the Pannonian Basin (Müller & Szónoky, 1989). These usually fine-grained clastic quartz-feldspathic sediments show gradual transition into a shallower sedimentary environment. Before volcanism started, the area was most likely characterized by an alluvial plain (Kázmér, 1990). Major duration of volcanism took place in a subareial environment but locally there is evidence of subaqueous or emergent settings (term by Kokelaar, 1983; 1986). Volcanism was related to the distribution of paleovalleys which formerly were stream occupied longitudinal systems with good water supply. These stream valleys were related to ancient probably rejuvenated pre-Neogene tectonic lines (similar to West Eifel, Germany described by Büchel (1993). Post-volcanic activity, fluvial sedimentation was widespread in the area, but the recent Lake Balaton basin was filled during Quaternary time (Csernyi & Bodor-Nagy, 1997).

All types of volcanic centers in the BBHVF (Fig. 1) show characteristic of monogenetic basaltic volcanic field (e.g. Hopi Buttes, Arizona, Western Snake River, Idaho, Auckland Volcanic Field, New Zealand, Newer Volcanics, Victoria, West Eifel, Germany). The most widespread geomorphological formations are circular, which are often lava-capped buttes (Fig. 3). These centers are usually related to underlying maar structures but eroded tuff ring rim remnants are also present in areas where lava flows

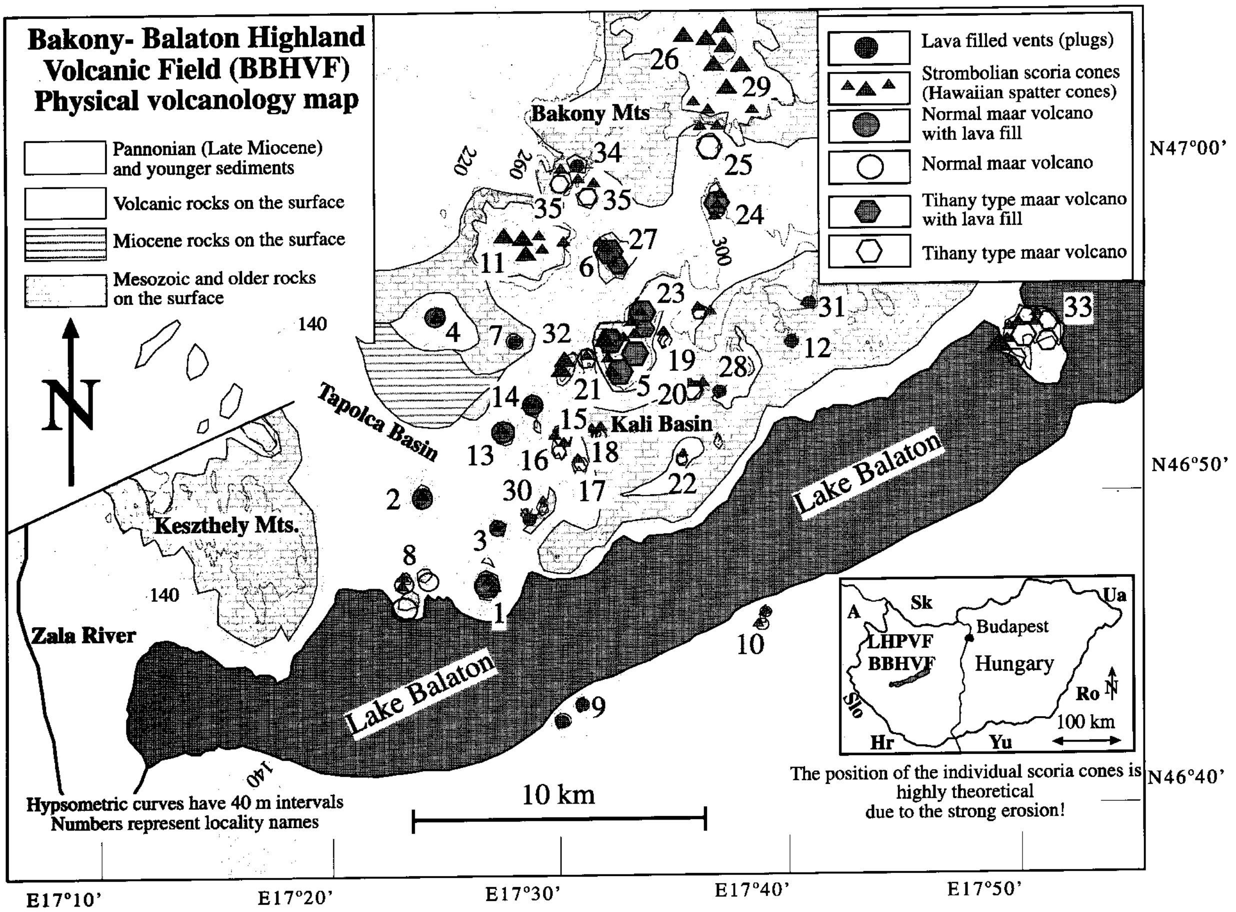

Fig. 1 – Physical volcanology map of the BBHVF according to physical volcanology data. Numbers are locality numbers: 1. Badacsony; 2. Szentgyörgyhegy; 3. Gulács; 4. Haláp; 5. Fekete-hegy south; 6. Bondoró south: 7. Hegyesd; 8.Szigliget; 9. Fonyód; 10. Boglár; 11. Agártető; 12. Tagyon; 13. Csobánc; 14. Hajagos-hegy; 15. Kopasz-hegy; 16. Pipa-hegy; 17. Kékkuti-hegy; 18. Kerekimajor; 19. Öreg-hegy; 20. Horog-hegy; 21. Füzes-tó; 22. Kishegyestű; 23. Fekete-hegy north; 24. Tálodi-erdő; 25. Pula; 26. Kabhegy north; 27. Bondoró; 28. Hegyestű; 29. Kabhegy south; 30. Tóti-hegy; 31. Tagyon north; 32. Sátorma-hegy; 33. Tihany; 34 Taliándörögd north; 35. Taliándörögd south.

preserved them (definitions after Lorenz, 1986 and White, 1991; Fig. 2). Individual maar structures without lava infill are less common, and hard to identified in the field. They are usually remnants of late maar crater lake filling sediments. Mainly in the northern part of the BBHVF Strombolian scoria cone remnants and Hawaiian spatter cone deposits are common although individual Strombolian scoria beds, interbedded with hydrovolcanic deposits are also common in the volcanic field. Large columnar jointed pahoehoe lavaflows represent the recently higher elevated areas in the Bakony Mountains. Small lava flows as valley fillings are also present (Hajagos-hegy). The largest areas covered by lava in the Bakony Mountains form shield volcanoes (Kab-hegy; Agártetö). Large lava plugs as eroded vent filling remnants are usually associated with adjacent volcaniclastic sediments (Hegyestû).

The BBHVF is of great volcanological interest both from a volcanological and a paleogeomorphological point of view. Due to the relatively long volcanic history of the area (7.54 –2.8 Ma) and the adjacent lake\fluviatile environment, the BBHVF is an ideal area for studying the sublacustrine, perilacustrine and post-lacustrine volcanism and the paleogeomorphological evolution of the Late Miocene landscape. The field gives a great opportunity for developing our knowledge about eruption mechanisms resulting from magma\water interactions across the entire magma\water-ratio spectrum with special relations to the paleoenvironment, and the related paleohydrology and physical characteristics of the pre-volcanic units. We can state that the large volcanic centers always represent longer period of volcanic activity with complex eruptive processes where mostly phreatomagmatic and magmatic phases alternated. Apparently there is little evidence of phreatic explosion processes. Usually the early phreatomagmatic processes were followed by late magmatic explosive and effusive processes.

2. Lava flows, scoria and spatter cones

Clear evidence for fissure-vent systems on the BBHVF is given by the occurrence of elongated (NE/EW) lava outcrops around the northern part of the Keszthelyi Mountains (e.g. Sümegpräga). The appearance of the lava is strongly related to shallow subsurface intrusions and probably adjacent small lava flows, plugs. The age distribution of the different eruptive centers also shows alignment which is probably related to older structural zones in the basement. Elongated structures of individual centers, or eruption complex-

Table 1 – Representative major element composition data from different eruptive centers of the Bakony-Balaton Highland Volcanic Field.

	A Bondoró (6)	B Hajagos (14)	C Agártető (11)	D Kab-hegy (26,29)	E Haláp (4)	F Hegyesd (7)	G Szigliget (8)	H Gulács (3)	*I Boglár (10)*	*J Horog-hegy (20)*	*K Hajagos (14)*	*L Fekete-hegy (5)*	*M Fekete hegy (5)*	*N Szigliget (8)*	*O Tihany (33)*	*P Pula (25)*
SiO_2	45.58	46.02	48.59	49.09	49.14	45.86	46.21	46.30	*49.53*	*49.51*	*49.39*	*48.81*	*66.38*	*48.47*	*47.04*	*47.58*
TiO_2	1.74	2.07	2.16	2.18	2.07	2.41	2.27	2.16	*3.03*	*1.68*	*2.74*	*2.35*	*1.28*	*2.56*	*3.00*	*2.88*
Al_2O_3	13.81	15.40	16.59	15.41	15.90	15.98	15.79	15.55	*19.19*	*19.12*	*17.33*	*19.19*	*15.68*	*18.25*	*17.88*	*18.24*
Fe_2O_3	10.09 t	3.07 t	10.53 t	10.65 t	10.27 t	5.48	10.15 t	10.42 t	-	-	-	-	-	-	-	-
FeO	-	6.54	-	-	-	4.18	-	-	*9.24 t*	*10.29 t*	*9.48 t*	*8.16 t*	*6.04 t*	*9.30 t*	*9.80 t*	*10.89 t*
MnO	0.16	0.16	0.17	0.16	0.14	0.15	0.15	0.17	*0.13*	*0.26*	*0.06*	*0.16*	*0.07*	*0.12*	*0.15*	*0.16*
MgO	13.94	8.17	6.56	7.96	7.84	7.55	8.36	8.19	*3.79*	*3.19*	*3.82*	*3.60*	*1.89*	*3.86*	*3.97*	*3.41*
CaO	8.13	9.13	8.41	8.19	8.34	9.52	9.64	9.30	*8.90*	*7.81*	*9.35*	*8.77*	*1.45*	*9.39*	*10.31*	*8.86*
Na_2O	3.88	3.23	3.44	3.23	3.67	2.98	2.66	3.16	*2.17*	*2.77*	*2.37*	*2.43*	*0.46*	*2.54*	*2.53*	*2.40*
K_2O	1.97	2.35	1.83	1.59	2.01	2.33	2.39	2.70	*3.62*	*3.01*	*2.75*	*2.63*	*1.88*	*3.22*	*2.90*	*2.86*
P_2O_5	0.75	0.74	0.72	0.53	0.52	0.66	0.59	0.78	-	-	-	-	-	-	-	-
H_2O	-	2.31	-	-	-	2.75	-	-	-	-	-	-	-	-	-	-
Total	99.88	99.79	99.00	98.99	99.90	99.83	98.21	98.73	*99.59*	*97.64*	*97.29*	*96.09*	*95.12*	*97.72*	*97.59*	*97.28*
Name	Basanite	Basanite	Trachy basalt	Basalt	Trachy basalt	Basanite/ Trachy basalt	Trachy basalt	Trachy basalt	*Trachy basalt*	*Trachy basalt (tephrite/ phono-tephrite)*	*Trachy basalt (phono-tephrite)*	*Tephrite/ phono-tephrite*	*Dacite (trachy dacite)*	*Trachy basalt (tephrite/ phono-tephrite)*	*Trachy basalt (tephrite)*	*Trachy basalt (tephrite/ phono-tephrite)*

Data from A - H are from Embey-Isztin et al., (1993) using XRF method. They used relatively fresh lava rocks from the top of the lava sequences. Data set from I - P (italic) are recent electron microprobe analysis of freshly preserved volcanic glass shards from tuff, lapilli tuff samples, collected mostly from pyroclastic beds (base surge, fall out) (I-N) or maar lake reworked volcaniclastics beds (O,P). Numbers represent locality numbers as it shown in Fig.1. FeO or Fe_2O_3 represents total $Fe_{(t)}$ unless their values are shown. The microprobe analysis were made using JEOL 8600 probe, 15 kV acceleration current.

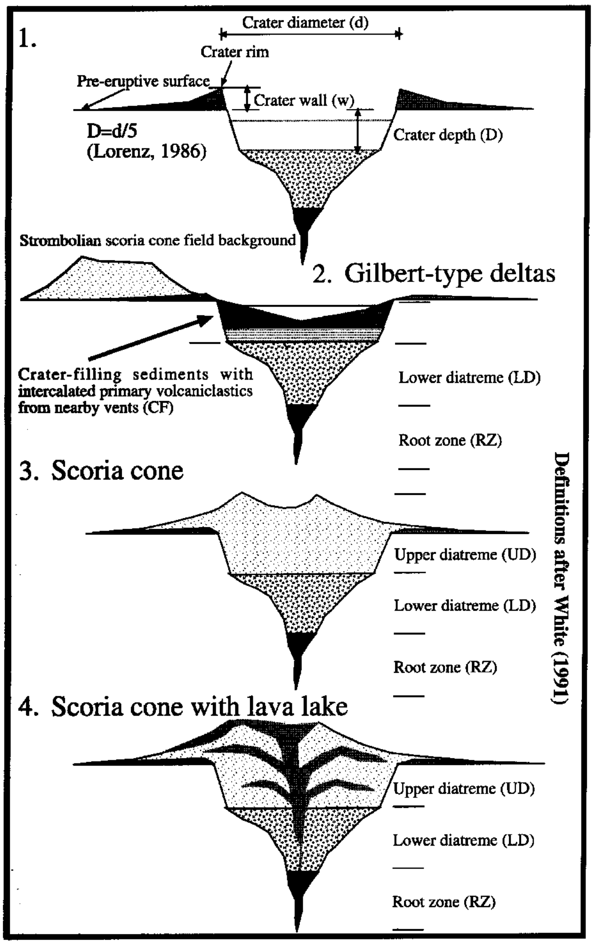

Fig. 2 – Definitions of maar volcanic landforms after Lorenz (1986) and White, (1991).

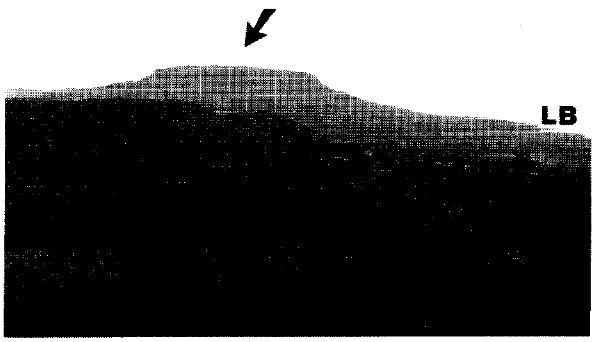

Fig. 3 – General landscape of the Bakony- Balaton Highland Volcanic Field with large, symmetric, lava capped, eroded buttes (Badacsony – western side of the field, in the background the Lake Balaton - LB)

es, especially in the middle part of the BBHVF (Hajagos-hegy, Sátorma-hegy, Fekete-hegy) also suggest longitudinal orientation of individual vents. A good example is the Hajagos-hegy with a north to south trending lava lake, which overflowed in southward direction (Kõ-hegy). The original lava lake was probably 700-1000 m long and 800 m wide. The buttes of Badacsony, Szentgyörgy-hegy, Csobánc, Haláp show slightly north-south elongation. In the middle part of the BBHVF, there is a large volcanic complex (Fekete-hegy Volcano) (Fig. 1), with several smaller eruptive centers and different intercalated lava layers (Németh & Szabó, 1998). Lava which filled the individual centers also show a north-east-southwest trend. The Fekete-hegy is interpreted as a complex lava channel, spatter cone and scoria cone system with several large lava lakes (Németh & Martin, 1998). The southernmost outcrops clearly show irregular shapes of the former lava lake and volcaniclastic borders.

In the BBHVF there are two main shield volcanic complexes with a large number of eruptive vents. The largest one is represented by the highest topographical point in the Transdanubian Central Range (Kab-hegy) (Fig. 1). Individual lava flows tend to be around 5 to 8 km long and cover around 50 km^2 area. The total thickness of the lava cover reaches several tens of meters. Adjacent to the lava field small remnants of Strombolian scoria cone and Hawaiian spatter deposits are common. Thin lava foot breccias are present between the individual lava flows. The other large shield volcanic complex is the Agártetösouthwest of the Kabhegy at 499 m (Fig. 1). The wide range of calculated K\Ar ages (5.25-2.8 Ma, Balogh et al., 1986), the different lava flow units and the slightly different petrographic characteristics suggest a long-lived steady stage of volcanic activity, which could be related to fault systems. This long-lived, steady magmatic explosive and effusive volcanic activity, and the presence of elevated Mesozoic blocks under the volcanic sequences (200-300 m higher than the southern part of the BBHVF) suggest that the possibility of magma\water interaction was very low during the eruptive history.

Shield volcanoes are common and the major sources of lavas in intraplate provinces. Eruptive centers of Hawaiian-type are usually related to fissure-vent systems, but in small plain-basalt provinces, eruptions are related to central vent systems (Johnson,1989), even though there are several examples where shield volcanoes developed along basement fissure systems (Johnson, 1989). The shield volcanoes of the BBHVF compared to east-Australian examples, are relatively small with less than 1 km^3 volume of lava product (7 km^3 in east-Australia, Johnson, 1989). The Agártetöhill with the thin phreatomagmatic base shows similar characters to the Rangitoto Island (Auckland Volcanic Field, New Zealand) which also has a small phreatomagmatic base and adjacent satellite Strombolian and Hawaiian vent systems (Ballance & Smith, 1982). The initial phreatomagmatic explosion at Agártetö formed a small tuff ring, which was filled shortly after by subsequent lavaflows similarly to Rangitoto, New Zealand. The small spatter deposits on the top zone of the Agártetö represents eroded summit craters (few tens of m diameter and high). The recent deposits represent small vent zones of this former explosion centers. Small remnants of lava cone structures are traceable everywhere where large crater fill lava lakes are presented. These areas usually represent small (few tens of metres) irregularities in the large lava fields. They are intercalated with lava flows, and consist of spatter deposits (Badacsony, Szentgyörgy-hegy, Fekete-hegy, Sátorma-hegy).

Large spatter and scoria cones are strongly eroded in the BBHVF. They remained only as erosional remnants. They usually consist of a near vent, strongly baked, red, slightly bedded sequences with large spindle or highly vesiculated fluidal bombs (Figs. 4, 5). These deposits usually reflect strong reworking of volcaniclastics in near vent position. Strombolian scoria and spatter deposits in the BBHVF are common in relation with maar volcanic centers similarly to the Eifel maars (Schmincke, 1977). There are examples in the Tihany Volcano maar volcanic complex (Fig. 1) for this kind of deposits in the northern part of the maar complex. A remnant of Strombolian scoria cone in the Füzes-tó region (Fig. 1) shows near vent scoriaceous volcaniclastic breccia in peperitic matrix representing water saturated slurry in the vent during the Strombolian activity (Németh & Szabó, 1998).

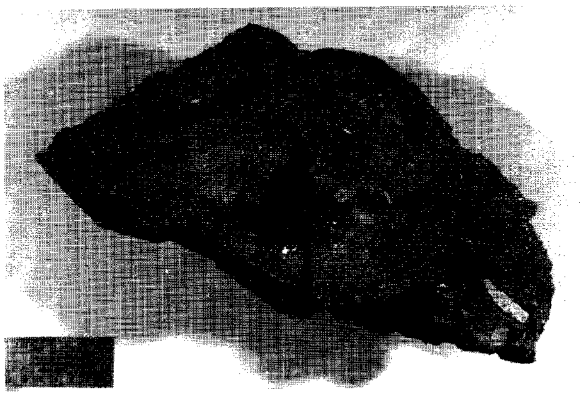

Fig. 4 – Vesicular spindle bombs from the Füzes-tó region (North Káli Basin).

Fig. 5 – Dense spindle bomb from the Füzes-tó region, cored with a large semirounded, elongated, protogranular textured spinel peridotite lherzolit.

These features are interpreted as Hawaiian and Strombolian style eruptive phases of maar volcanic centers from several distinguished eruption points in the maar system, leading to form agglutinates or even clastogenic lavas, like at Ukinrek Maar, Alaska (Büchel & Lorenz, 1993).

No original lava surface on the BBHVF with pahoehoe or aa lava formations is present. Direct surface remnants of tumuli, hornitos, pressure ridges, lava tubes, caves or lava channels are not known from the BBHVF, but several surface irregularities from the Kab-hegy lava field suggest that this kind of surface formations probably were widespread, but the erosion process has erased them.

Columnar jointings in the BBHVF are mainly multiple joint systems. One columnar joint package reaches several meters in thickness. The best examples are in Badacsony, Hajagos-hegy, Hegyestû. Radiating, rosette-like joints in thick lava flows are found in former individual lava channels or feeder dykes. Rosette-like joints with related to lava tubes are in the upper level of the Hajagos-hegy basalt quarry, and the Badacsony basalt quarry. Radiating joints representing feeder dykes are in the lower level of the Hajagos-hegy basalt quarry.

Columnar jointing is a product of the progressive cooling of lavas or intrusions (Waters, 1960; Spry, 1962), widespread in the BBHVF. Usually the simple thin sheet-like lava bodies produce simple, upright joints. Thicker lava bodies have two or multiple-tiered layering with lower, well developed upright joints (colonnade) and irregular, semi or wholly radial small joint systems in the top (entablature) (Waters, 1960, Spry, 1962; Yamagishi, 1987). The irregular, upper part is related to the cooling irregularities of the surface of the lava flows.

3. Peperite, hyaloclastite

Hydroclastic rocks formed from mainly glass-shards are historically called hyaloclastites because of their non explosive spalling and granulation (Rittmann, 1962). In the BBHVF hyaloclastites occur only in the alluvium as debris, so their original position is not known except for an outcrop of hyaloclatites with chilled pillow-rinds next to the columnar jointed basalt at Hegyestû. These hyaloclastites have been interpreted as vent-filling sediments, formed when basalt invaded the vent and reacted non-explosively with water.

Peperite is a special rock type of magma and wet sediment mixture (Fisher, 1960; Williams & McBirney, 1979; McPhie et al., 1993). The matrix could be either the magmatic or sedimentary part of the mixture. Peperites are common next to intrusive bodies (Hanson & Schweickert, 1967; Hanson & Wilson, 1993) and where lava flows into a water rich environment (Jones & Nelson, 1970; Bull & Cas, 1989). Rapid heat transfer causes small-scale phreatomagmatic or phreatic explosions (Kokelaar, 1982, 1986), where fluidisation plays an important role of forming peperite structures. Busby-Spera & White (1987) were able to distinguish two different kinds of end member peperite textures. The blocky peperite consists of angular magmatic fragments in sedimentary matrix, with common jigsaw fit structure, mainly along large magmatic clasts. The other end-member (globular peperite), which is primarily related to fine-grained sediment and magma interaction is formed by fluidisation of fine-grained sediment due to the hot magmatic body.

Peperites are wide spread in the BBHVF and important in determining the timing of volcanic activity. They are described and interpreted in detail by Martin & Németh (in prep.) with a brief description below. Different type of peperite structures have been identified, which are related to the following processes:

1. Lava-foot peperites, which form when was lava trapped into water rich, probably swampy area. There are typical lava foot peperite on the southern hillside of the Hajagos-hegy. This pillowed zones are usually not thicker than 1 m. Next to the pillowed zone, the fine grained, black basalt contains elongated vesicles, which are usually filled with sand, or secondary minerals. The vesicles are elongated and orientated parallel to the lava layers. Between the pillow lobes, there are light yellow sandy fragments, which is the same kind of sand filling the vesicles in the pillow lobes. The pillow zone is interpreted as a lava foot peperite zone, which formed in very shallow water, probably not more than few metres. Either the peperites formed while a lava flows out the former tuff ring rim and flow into the surrounding swampy area or while lava emplaced into a water filled vent zone.

2. Blocky peperite at Hajagos-hegy is related to fluidisation processes of emplacing feeder dikes. This peperites always appear in the centre of the Hajagos-hegy basalt quarry in its deepest level. The breccia-like rock is always related to columnar jointed basalt, with radial distribution of columns. The space between the columns is often filled by brownish sandy matrix, similar to the brecciated rock matrix. In the sandy matrix there are several large (meter scale) blocks which show jig saw fit structure and placed far from the columnar jointed areas, into the middle of brecciated zones. The jig saw fit structures are more common next to the columnar jointed, massive basalt areas. Further away the brecciated zone is more matrix rich and the original bedding structures of the sandy matrix is more visible in these zones (in the centre). The lava rock is interpreted as a crater fill feeder-dike. This feeder dike cuts through the muddy slurry of the volcanic centre, filled with muddy watersaturated Pannonian Sand and probably volcaniclastics. The intruding magma with its hot body was able to fluidise the originally water saturated, unconsolidated sediments, thus the fluidised sediment- slurry moved in between the volcanic feeder dikes.

4. Phreatic and phreatomagmatic eruptive centers

The majority of the eruptive centers of the BBHVF have a phreatomagmatic history. There are several characteristics for the identification of phreatomagmatic eruption products. The small average grain size, chilled, blocky sideromelane glassy shards with few vesicles (Wohletz & Heiken, 1982; Sheridan & Wohletz, 1983; Wohletz & Sheridan, 1983) are important characteristics to identify phreatomagmatic explosion products. Generally the phreatomagmatic products from the BBHVF show chilled semiangular juvenile fragment content (Fig. 6). The sideromelane lapilli fragments are light brownish, yellowish and often slightly palagonitized. The glass shards usually contain few elongated microvesicles. The wide range of vesicularity of the juvenile clasts is very characteristic of most of the basal lapilli tuffs and tuffs. The shards are slightly stretched and rich in microliths (Fig. 6). The fine-grained pyroclastic rocks (lapilli tuff, tuff, block bearing lapilli tuff) of the mostly initial basal volcanic sequences of the eruptive centers of the BBHVF are usually rich in accidental lithic fragments such as wall rock fragments. They are mostly fragments from beds of Mesozoic dolomite, limestone, Permian red sandstone, Silurian schist or even older metamorphic rocks from uncertain deep stratigraphy position. These accidental lithics are

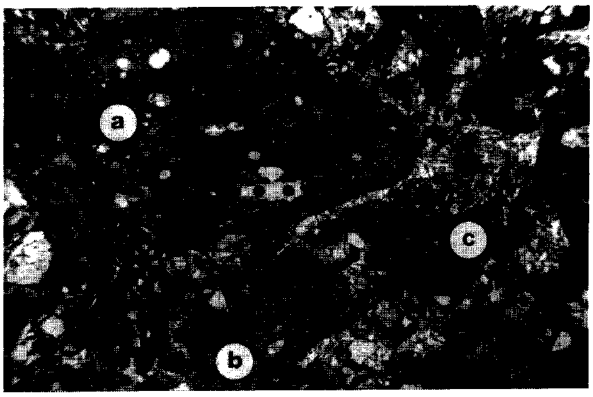

Fig. 6 – Blocky sideromelane glass pyroclast shards (a., b., c.) from phreatomagmatic bed from the Szentbékkálla locality (North Káli Basin). Note the slightly oriented microlith and microvesicle. (shorter side of the picture is 2 mm).

ballistic blocks and bombs as well as groundmass of the pyroclastic rocks. Impact sags are usually present under the larger blocks and they are usually plastically deformed. Fractured impact sags are known from few localities at Tihany, and from the eruptive centers of the Tapolca Basin (Fig. 1). In the western part of the volcanic field (Tapolca Basin – Fig. 1) the Pannonian sandstone and mudstone fragments are the major accidental lithics. Quartz-feldspatic sand and mud grains are common in the groundmass, and large bombs and blocks with usually baked outer rims are present in most of the sequences of the eruptive centers (e.g. Szigliget, Boglár – Fig. 1). Fine-grained quartz-feldspatic fragments are also present in the matrix of the lapilli tuffs, tuffs from the eruptive centers of the central and eastern part of the volcanic field. Accretionary lapilli beds, mainly rim type, are common associated with base surge and fine grained fall out beds in each eruptive centers in the BBHVF, but they are more widespread in the central and eastern region. Fine grained, well bedded, antidune and dune bedded, unsorted units with microrelief-dependent lateral thickening and thinning as well as coarsening and fining of individual beds commonly with U-shaped erosion channels are widespread of the basal lapilli tuff and tuff units in the eruptive centers of the BBHVF. They are more characteristic to the central and eastern part of the field. In the western areas, the basal units consist of mostly well bedded, mantle bedded rarer dune or antidune bedded juvenile lapilli rich beds of deposits. Vesiculated tuffs have not been described yet from the BBHVF. Palagonitization is widespread in the pyroclastic rocks from the BBHVF, and it is common in fine-grained tuffs. Surprisingly most of the pyroclastic rocks of the BBHVF contain very fresh sideromelane fragments even the fine groundmass is fully palagonitized (Table 1).

The usually high amount of accidental lithics in the phreatomagmatic volcaniclastics of the BBHVF and the regular gravimetric and geomagnetic anomaly around the major eruptive centers suggest deep excavated maar\diatreme structures, where the explosion focus was underground. Maar volcanoes (sensu latto) are low volcanic cones with bowl shaped craters that are wide relative to rim height (Fisher & Schmincke, 1984). They range from explosion craters cut into country rock below ground level (maar sensu stricto), to craters with low rims composed of phreatic, phreatomagmatic, and magmatic debris (tuff ring). During the eruptive process the explosion locus migrates down (Lorenz, 1986; Mitchell, 1986; Büchel & Lorenz, 1993), producing deeper seated accidental lithics in the volcaniclastics upward in the stratigraphy column (Figs. 7, 8). Generally the major transportation agent of explosion product is base surge and fall out (Fisher & Schmincke, 1984). Base surges are highly expanded, turbulent, gravity-driven pyroclastic currents (Moore, 1967; Fisher & Schmincke, 1984; Cas & Wright, 1987). Deposits of base surges are typically wavy, contain bedforms, accretionary lapilli (Fig. 7), ballistic impact sags (Fig. 8) and show evidence for cohesiveness (Fisher & Schmincke, 1984; Cas & Wright, 1987). Hot gaseous surges are termed dry surges, and cooled steam rich surges are termed wet surges (e.g. Lorenz, 1974; Frazetta et al., 1983, 1989; Dellino et al., 1990; Wohletz & Heiken, 1992; De Rosa et al., 1992; Capaccioni & Coniglio, 1995; Colella & Hiscott, 1997).

In the central and eastern part of the BBHVF the initial volcaniclastic sequences are built up by dominantly wet base surges and in contrast in the western side of the volcanic field dry base surges are more common in this initial

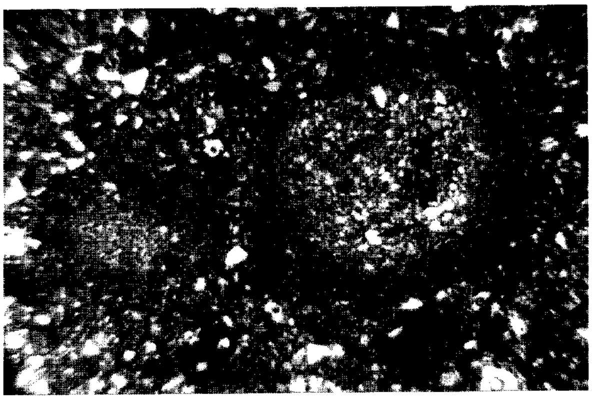

Fig. 7 – Photomicrograph of primary phreatomagmatic deposit with accretionary lapilli. The shiny, angular fragments are quartz derived from the Pannonian Sandstone beds (arrow). A few quartz fragments have metamorphic origin, most likely derived from Silurian schist fromations (shorter side of the picture is 2 mm).

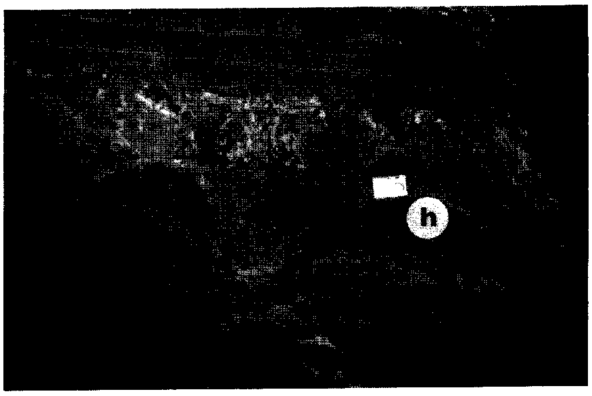

Fig. 8 – Permian Red Sandstone fragment caused an impact sag (arrow) from phreatomagmatic sequence at Tihany Peninsula (Barátlakások). The block has already fallen out from the bed, just few small debris is left in the bed. Note the dark colour undulating bed in the middle of the picture. This bed represents an impact surface, where large ballistic blocks were impacted. The continuous pressure due to the impacts resulted in sudden water loss and lithification of the unconsolidated, fine-grained tephra (h). The scale bar is 5 cm long.

sequence. The dominantly base surge deposited initial volcaniclastic sequences suggest that the eruption columns of the eruptive centers were relatively low in the central and eastern region (e.g. Tihany), and just slightly higher in the eruptive centers of western side of the BBHVF (e.g. Szigliget).

The high wetness and indurated characters of hydrovolcanic deposits are more characteristic for the Tihany Peninsula and the Kali Basin (north) eruptive centers. Especially in the Tihany Peninsula, the eruptive centers show a paradox with the occurrence of highly indurated wet surge beds and large amount of deeply excavated country rocks in these beds (Németh, 1997). This type of maar volcanic center named as a Tihany-type of maar volcano and is related to the occurrence of relatively thick porous media aquifer (Pannonian Sandstone) overlying fracture controlled aquifer (Mesozoic dolomites, limestones, Paleozoic schist)(Németh et al., in prep.). The products of this kind of eruptive centers are highly «indurated tuff cone kind» of beds which contain large quantities of deep excavated xenoliths, representing strong involvement of karst water to fuel phreatomagmatic explosion. The Tihany-type of maar volcanic centers is probably very important all over in the BBHVF. They are identified in the Fekete-hegy volcanic complex, Tihany Volcano, Kõ-hegy, Pula, Bondoró-hegy.

Drier surge beds and normal porous media aquifer controlled maar volcanic characteristics are more widespread in the Tapolca Basin eruptive centers. In that area the beds show less indurated characteristics, more baking of the large Pannonian Sandstone fragments, and significantly less deep seated Mesozoic and Paleozoic fragments. There are strongly eroded remnants of this kind of center from Szigliget, Balatonboglár, probably Szentgyörgy-hegy and Csobánc (Fig. 1).

During the eruption not all of the magma can be simultaneously in contact with the water, therefore one part of the eruption column can be phreatomagmatic and another part be purely magmatic (Ort et al., 1998). Strombolian magmatic and phreatomagmatic volcaniclastics can be intercalated if two or more vents with different explosion mechanism are operating simultaneously next to each other (Houghton & Schmincke, 1985; Houghton & Hackett, 1984; Houghton & Smith, 1993). In the BBHVF both situations most likely occurred. In the Tihany Peninsula there is clear evidence of simultaneously operating Strombolian and phreatomagmatic vents.

Phreatic explosions are steam generated and do not involve the ejection of fresh magma (Fisher & Schmincke, 1984; Cas & Wright, 1987). Clear phreatic explosion centers and their products are not described yet from the BBHVF, but samples of several beds from the Tihany Peninsula represent extremely high proportion of accidental lithic fragments from the basement rocks and just a few percent of juvenile ejecta.

Phreatomagmatic explosions involve dynamic explosive interaction between magma and external water source as groundwater, or a surface body of water such as lake or sea, and the ejection of a significant juvenile magmatic component (Fisher & Schmincke, 1984; Cas & Wright, 1987; Schmincke, 1977; White, 1991, 1996). White (1996) showed that most likely the recycling processes in the vent are the most important to form different landforms by phreatomagmatic processes.

Phreatomagmatic explosion in subaerial conditions usually produced low rimmed tuff rings (Moore, 1967; Keller, 1973; Heiken, 1971; Lorenz, 1970, 1986; Wohletz & Sheridan, 1983; Waters & Fisher, 1971; Sohn & Chough, 1989; Chough & Sohn, 1990; White, 1989; 1990; Ort et al., 1997). In subaqueous to emergent condition tuff cones form (Wohletz & Sheridan, 1983; White, 1991; Verwoerd & Chevalier, 1987; Sohn & Chough, 1992, 1993; Kokelar, 1983, 1986). The water source for the phreatomagmatic centers in the BBHVF was underground water. The eruptions produced deep excavated maar\diatreme structures, which were filled by maar lake volcaniclastics and later fresh water carbonate beds and magmatic products as Strombolian scoria cones or lavaflows.

5. Maar crater-fill sediments, Gilbert type deltas

In the BBHVF there are eroded remnants of maar crater filling volcaniclastic deposits. Usually they represent the higher stratigraphic position in the hydromagmatic eruptive center's volcaniclastic units. They are steep bedded volcaniclastic hills and are characteristic with their asymmetric hills and highly scoria rich volcaniclastics. High-level deposits of steeply dipping (30-35°) beds of reworked tuff, lapilli tuff represent the former maar crater edge. These steep dipping, reworked tuff cliffs are interpreted as erosion remnants of former Gilbert type of deltaic rim deposits (Németh, 1998). The dip of the beds shows the original slope of the former maar craters, from which the unconsolidated tephra was mobilized and moved down to the maar crater basin. In several well preserved outcrops in the Tihany peninsula this steep beds can be related to flat-bedded former rim beds. Usually there are two major lithofacies associations which are characteristic of these deltaic sequences. One of them is a coarse grained, juvenile, scoriaceous lapilli-rich lithofacies association with inverse to normal graded beds (Fig. 9). The lapilli are rounded, black and contain tachylitic glass. These lapilli tuff beds also contain small amount of accidental lithics (Fig. 10). There is usually a relatively high amount (5 vol%) of large broken crystals of pyroxene,

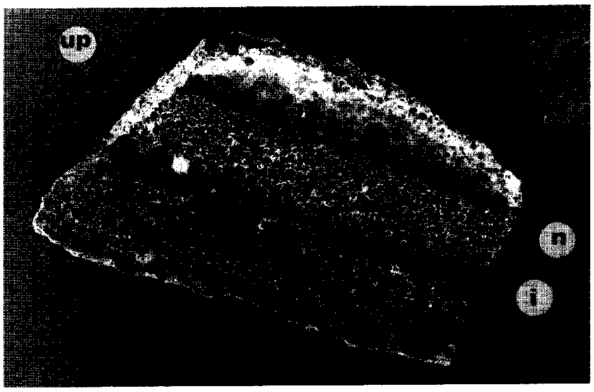

Fig. 9 – Coarse grained, scoriaceous lapilli tuff beds from Tihany interpreted as coarse grained density current deposit from Gilbert-type delta front. The individual beds are inverse to normal graded (arrows; i – inverse; n – normal grading). Note the roundness of the lapilli and the white calcite cement between them.

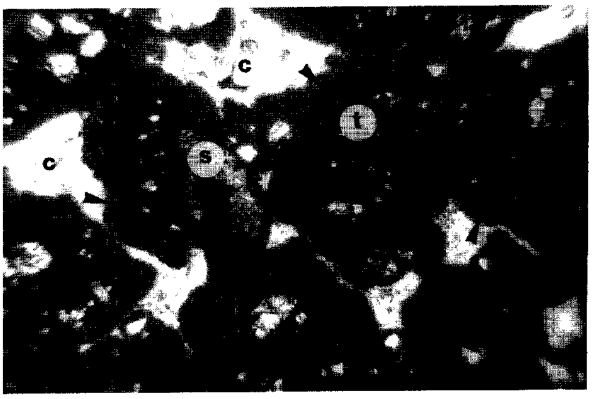

Fig. 10 – Photomicrograph about maar lake reworked volcaniclastic deposits from Tihany. Note the dark grey, algee rim around the lapilli (arrow). t – tachylit; s – sideromelane; c – calcite).

olivine, or amphibole in lapillus grain size. The grains are often algae coated and calcite cemented (Fig. 10). Between the large grains there is micritic calcite, and occasionally fine grained muddy sediment (altered glass or sediment?). This lithofacies association is usually 0.5 to 1 m thick and contains several individual lithofacies. It is usually interrupted by a fine grained, cross bedded, channeled tuff lithofacies association, which varies in thickness. Often it is just a few cm thick or it is even missing (Kali Basin center hill). In the Tihany Peninsula on the Kiserdő-tető hill (Fig. 1) the lower part of the deltaic deposits contains well developed beds of this lithofacies association.

An important fact is that the tephra was not predominantly remobilized from the individual hydromagmatic eruptive center's own ejecta. The deltaic deposits contain a high amount of scoriaceous lapilli, mostly Strombolian type, mixed with different composition of sideromelane glass. Therefore the deltas have been interpreted to have been fed by small streams (either run off or creeks from hills of the Late Miocene Bakony Mts.) which carried ejecta from the nearby vents, basically from close Strombolian scoria cones. A similar situation was describe from the Hopi Buttes (Teshim Butte Maar) by White (1989, 1992).

According to White's (1988, 1989, 1991) description of reworked tephra beds from the Hopi Buttes, these steep bedded, reworked characteristics beds can be interpreted as foreset sequence of Gilbert type deltas. The bedding structures of these sequences are results of basically grain flow and turbulent sediment gravity flows on the steep inner slopes of the maar craters.

The widespread Gilbert type delta structures on the BBHVF accompanied with negative Bouguer anomaly strongly suggest an intensive maar-diatreme volcanism, with post-eruptive depositional processes. The extremely high amount of scoriaceous lapilli in the deltaic lithofacies shows that the Strombolian type of explosive volcanism was widespread and important after the first hydromagmatic activity in the BBHVF.

6. Maar lake carbonates

In several places widespread maar lake carbonate sedimentation followed the maar volcanism and the later redeposition process of the tephra. At two localities there is a thick sequence of fresh water carbonates, at least 15 m at the Tihany Peninsula and probably around 20 m at the Tálodi-erdő (Fig. 1). There is also thick fresh water limestone, dolomite sequences in the Pula region (Fig. 1). Smaller beds, or rip up clasts from maar crater fill deposits are also known from Szigliget, Balatonboglár, Fekete-hegy (Fig. 1). At the Tihany Peninsula the fresh water limestone laminae show often soft sediment deformation structures, which are related to hot spring activity or earthquakes, caused by nearby explosive volcanism. From the total thickness of 15 m of fresh water limestone beds at Tihany and the 0.2 – 0.7 mm thick single laminae a quite lacustrine sedimentation over 50 000 years has been calculated. This long, undisturbed period in the lake life suggest that the general relief of the area shortly after the erosion of scoria cones and hydrovolcanic rim deposits was low. The fresh water limestone sequences, especially in Tihany are now in the highest elevated areas. They must represent the former lake bottom thus they are useful for calculating local erosion rates.

7. General features of the Bakony- Balaton Highland Volcanic Field as a conclusion

The volcanoes of the BBHVF are exposed from the subsurface to surface levels but the Quaternary erosional talus flanks usually cover them. Thus the outcrop availability strongly controls the facies relationship in the individual localities. The deepest levels of exposures are located in the western and the southern part of the area. The most strongly eroded regions are where no subsequent lava caps sheltered the volcaniclastic sequences. Thus Balatonboglár, Szigliget, Tihany Peninsula (Fig. 1) provide an opportunity to study the deepest region of the volcanic centers. Probably the eruptive centers of Balatonboglár (Boglár Volcano) (Fig. 1) represent the deepest visible level of the eruptive centers. Small lava rock, plug outcrops surrounded by prevolcanic sediments are known from the BBHVF, but their origin is not clear because of the poor outcrop (e.g. Kali Basin west, Fig. 1). The best examples for individual plugs, subvolcanic feeder dykes are the Tóti-hegy, Hegyestû, Hegyesd (Fig. 1). They represent hills, covered by columnar jointed basalt. There is no information (no outcrop) about occurrence of adjacent volcaniclastic deposits around these lavarocks. Only in the Hegyestû (Fig. 1), there is an adjacent hyaloclastitic, pillowbreccia bearing volcaniclastics formation right next to the columnar jointed plug which probably represents fluidized crater fill volcaniclastic sediment. Unusual volcaniclastic breccia fragments from the eastern part of the Kali Basin represent deeply eroded root zones, diatremes. The lack of outcrops make it difficult to say more about the origin of these hills (Horoghegy, Balatonhenye, Várhegy-Zánka). Lower diatremes (terminology by White, 1991) (Fig. 2) are relatively rare due to the Quaternary debris talus. There are examples from Balatonboglár (Várdomb) (Fig. 1) which probably represent lower diatreme zones with strongly reworked tephra deposit mixed with altered pre-volcanic sedimentary, accidental lithics (in the Boglár case, baked Pannonian Sandstone fragments). Upper diatremes occur below the positive relief volcanic centers, such as scoria cones, and contain interbedded, phreatomagmatic tuffs and scoria beds. Most of the BBHVF buttes represent upper diatreme structures, similarly to the Hopi Buttes or Western Snake river subaerial volcanic centers (White, 1991; Godchaux et al., 1992). Surface volcanic edifice are preserved in areas of low erosion, and include volcanoes produced by both hydromagmatic and magmatic eruptions. The vents characterized by magmatic explosivity are concentrated in the northern part of the area (Kab-hegy, Agártetö, Haláp, Hegyesd). The BBHVF maars are filled by reworked volcaniclastic deposits forming Gilbert type deltas. These deposits are often interbedded with primary base surge and fall out beds from nearby vents. The general dip of the deltaic rim deposits show a southward trend, suggesting a north to south stream system during the volcanism. Often there is evidence of nearby maars which were active simultaneously producing interbedded pyroclastics from different sources (Tihany Peninsula). The maar diameters of the BBHVF range from few hundreds of meter up to 5 km in diameter (Fekete-hegy - 5 km; Tihany - 4 km; Bondoró - 2.5 km; Badacsony - 2.5 km), but the largest centers probably represents maar volcanic complexes with connected large basins. The average maar basins are 1 - 1.5 km wide, which is within the range of most maars (Schmincke, 1977; Fisher & Schmincke, 1984; Cas &

Wright, 1987; Lorenz, 1986; White, 1991; Ort et al.,1997). The maar vents are hybrids of hydromagmatic and magmatic activity, formed by initial maars or tuff rings. Their deposits became progressively «drier» due to reduced magma\water interaction (Heiken, 1971; Wohletz & Sheridan, 1983; Lorenz, 1986; Houghton & Schmincke, 1989; Godchaux et al., 1992; Ort et al., 1997). The typical type of hybrid volcanoes are located in the south western site of the field (Badacsony, Szentgyörgy-hegy, Hajagos-hegy, Fekete-hegy) (Fig. 1). Hydromagmatic explosive activity, dominantly base surge and fall out, produced the pyroclastic deposits. Most of the late lavas covered the initially phreatomagmatic pyroclastic deposits.

The base surge deposits of the BBHVF vary depending on proximity to their vents. Proximal beds usually contain abundant accidental lithics. In the eastern side (Tihany maar volcanic complex) the major and largest accidental fragments are Permian Red Sandstone, Silurian Schist (Lovas Schist Formation), with smaller fragments of Mesozoic carbonatic rocks (dolomites, marls, limestones), and Pannonian Sandstone. The matrix of the surge beds contains a high proportion of sand from the Pannonian Sandstone beds. In the western side of the BBHVF the main accidental lithic fragments are from the Pannonian Sandstone Formation. Both the large fragments (up to 25 cm in diameter) and the matrix are rich in sandstone fragments. In smaller proportion (less than 20 vol% of total accidental lithics) there are schist fragments and small carbonate fragments. In the middle part of the area (Fekete-hegy, Bondoró-hegy, Pipa-hegy) the Mesozoic carbonates are the major part of the accidental lithics (min 85 vol% of total accidental lithics). In the distal facies the base surge beds become finer-grained. Clear distal facies of surge beds are example from the Tihany Peninsula. Characteristic surge features such as sandwaves, dunes, impact sags, erosional U-shaped valleys are common (Tihany Peninsula, Fekete-hegy, Bondoró-hegy, Szigliget)(Fig. 1). Fall deposits associated with surge beds are also common (Fekete-hegy) (Fig. 1).

The general features of the Bakony-Balaton Highland Volcanic Field are very similar to others which erupted into wet environments such as Fort Rock Christmas Valley, Oregon (Heiken, 1972); Snake River Plain, Idaho (Godchaux et al., 1992), Hopi Buttes, Arizona (White, 1989, 1991), Newer Volcanics, Victoria and South Australia, (Joyce, 1975, Johnson, 1989), Auckland Volcanic Field, New Zealand (Allen et al., 1996); Durango, St. Potosi, Mexico (Aranda-Gomez & Luhr, 1996). The Eifel Volcanic Field, Germany shows similarity with the BBHVF, especially the influence of the fracture controlled aquifer in the phreatomagmatic activity and the composition of the magma (Schmincke, 1977; Duda & Schmincke, 1978; Schmincke et al., 1983; Büchel, 1993).

8. Summary: intracontinental volcaniclastic deposition in a fluvio-lacustrine basin

To summarize the geomorphological evolution of the BBHVF, we suggest that the volcanism was formed in a fluvio-lacustrine basin (Fig. 11). The early eruptions formed in the southeastern side of the field, where the former lacustrine sedimentation turned into fluvial environment. In this region the former lacustrine sediments were still water saturated and unconsolidated. The thin porous media aquifer and the thick fracture controlled aquifer gave substantial water supply to fuel hydromagmatic explosive volcanism producing unusual maar structures (Fig. 11). During the next stage alluvial fans developed by the sedimentation of streams coming from the slightly higher background, the former Bakony Mts. Finally volcanism occurred in the swamps, streams and small ponds with different explosive and effusive mechanism. The largest volcanic complexes (Fekete-hegy, Bondoró-hegy) erupted large, long lavaflows which probably blocked the slightly higher elevated areas around the Tálodi-erdõ, Pula region, thus the run off water from the background (Bakony Mts.) formed a large freshwater lake in post-volcanic time. Finally the volcanism shifted westward, following the same NE-SW line. These volcanic centers show slightly emergent characters, and surface water availability, but the major part of them is tuff ring, maar type of subaerial volcanic center.

The phreatomagmatic volcanic centers show fine, linear distribution, suggesting that the surface water supply derived from elongated and longitudinal stream occupied valleys at this time. The elongated structure also suggest deep fracture system in the fracture controlled aquifer, which allowed free water movement of the subsurface karst water, thus able to fuel phreatomagmatic explosions. The fractures were also able to control the path of the uprising basaltic melt. This two major control operated together in the same time. The changing of former lacustrine environment (Pannonian Lake) with the development of separate lake basins controlled the water content of the porous media aquifer. The most long-lived sub-basins are responsible for hydromagmatic explosions in later time. The centre of volcanism later shifted to the western Tapolca Basin (Fig. 1), where large thick water-saturated, mostly lacustrine sediments occurred, even thought the lacustrine sedimentation has already turned into fluvial system during the volcanism. Fig. 12 shows the general facies relationship between volcaniclastic facies of individual eruptive centers and their erosional remnants from the BBHVF.

The calculated erosion rate of the individual centers varies between 96 m\Ma (Szentgyörgy-hegy) to 18 m\Ma (Tálodi-erdõ)(Németh & Martin, in prep). In the highlands the erosion rate of the shield volcanoes is not more than 51 m\Ma. The erosion rate in the BBHVF is relatively high in comparison to other basaltic monogenetic volcanic fields. In southern Australia, a relatively low elevated volcanic field (the prevolcanic surface is 100-200 m above sea level), in a mild climate, showed 8 m\Ma erosion rate (Bishop, 1985; Wellman, 1979). Walker (1984) calculated downcutting rates of 58m\Ma in the elevated basaltic highlands of Iceland in the region where the mean elevation is 400 m. The erosion rate in the BBHVF probably was affected by the later developed fluvial systems, which cut through the region, eroded the uncovered volcanics and the erodable Pannonian lacustrine and fluvial beds.

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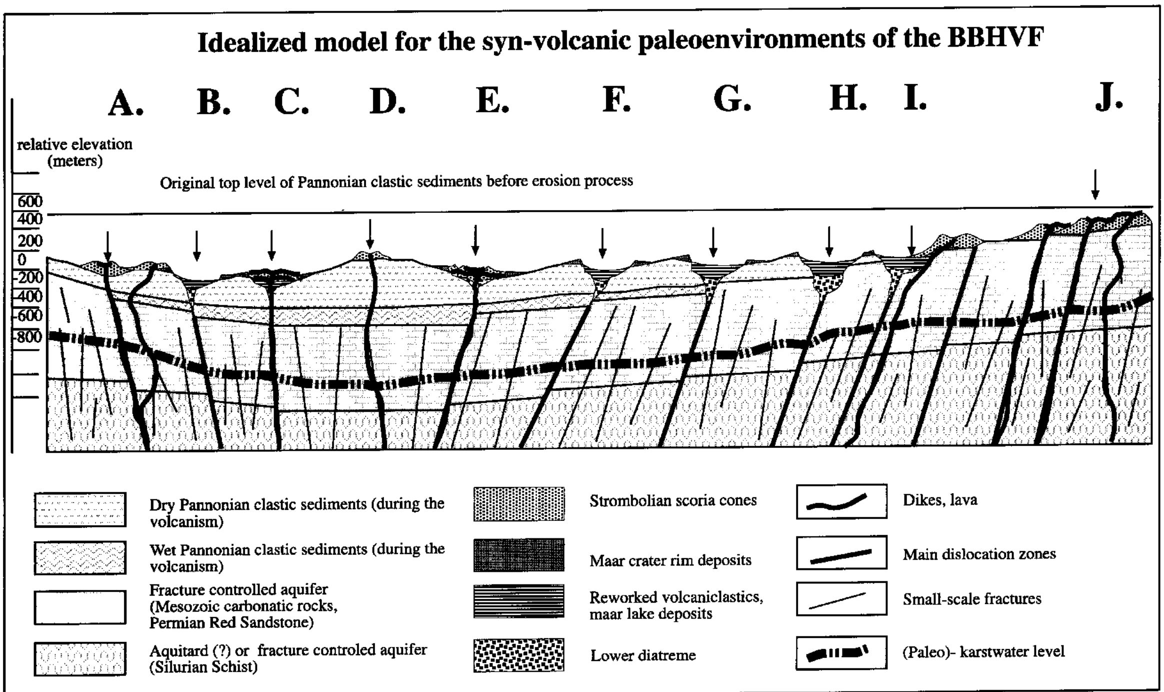

A - Strombolian scoria cones in dry season, when karst water level drops; B, F, G - Normal maar volcanoes in stream valleys; C - Normal maar volcano with initial maar lake sedimentation, then late large magma supply with scoria cone building period. Peperite forming in maar basin; D - Strombolian scoria cones on high Pannonian clastic sediment ridges; E - Normal maar volcanoes with large magma supply in the final stage (scoria cone building); H - Tihany type maar volcano; I - Tihany type maar volcano with scoria cone background building phase when karst water level drops; J - shield volcanoes and scoria cones in the high areas

Fig. 11 – Different types of eruptive centers from the BBHVF and their relation to the paleo-geomorphology.

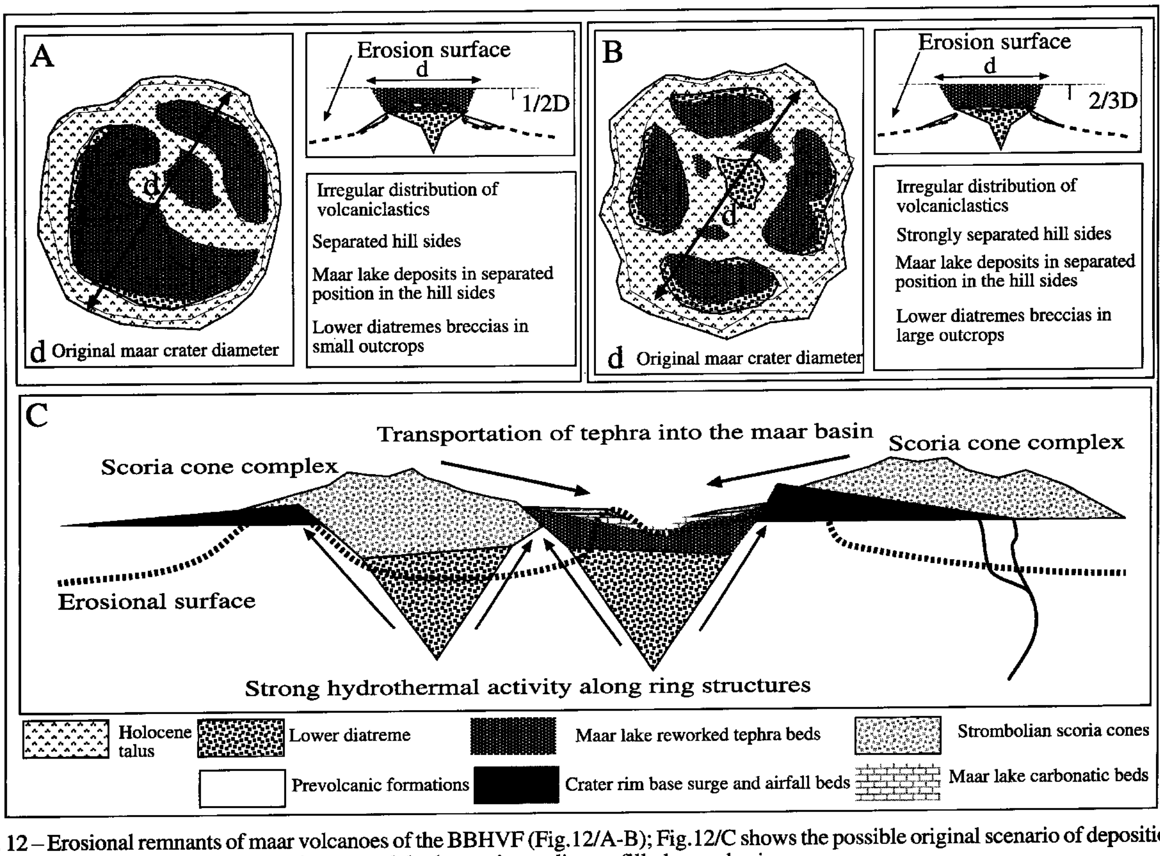

Fig. 12 – Erosional remnants of maar volcanoes of the BBHVF (Fig.12/A-B); Fig.12/C shows the possible original scenario of depositional environments of scoria cone and/or late maar lake lacustrine sediment filled maar basins.

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