Late Miocene paleo-geomorphology
of the Bakony-Balaton Highland Volcanic Field (Hungary)
using physical volcanology data

by

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with 10 figures and 3 tables

Summary. A new view is presented of the Bakony-Balaton Highland Volcanic Field (BBHVF), Hungary, active in late Miocene and built up of ca. 100 mostly alkaline basaltic eruptive centers, scoria cones, tuff rings, maar volcanic complexes and shield volcanoes. A detailed map shows the physical volcanology of the monogenetic volcanic field. In areas where thick Pannonian Sandstone beds build up the pre-volcanic strata normal maar volcanic centers have formed with usually thick late magmatic infill in the maar basins. In areas, where relatively thin Pannonian Sandstone beds resting on thick Mesozoic or Paleozoic fracture-controlled, karstwater-bearing aquifer, large unusual maar volcanic sequences appear (Tihany type maar volcanoes). In the northern part of the field large former scoria cones and shield volcanoes give evidence for a smaller impact of the ground and surface water causing phreatomagmatic explosive activity. The Tihany type maar volcanic centers are usually filled by thick maar lake deposits, building up Gilbert type gravelly, scoria rich deltas in the northern side of the maar basins, suggesting a mostly north to south fluvial system in the pre-volcanic surface. Calculating paleosurface elevation for the eruptive centers, two paleo-geomorphology maps are drawn for a younger (4–2.8 Ma) and an older (7.54–4 Ma) scenario. The erosion rate of the volcanic field is estimated to vary between 96 m/Ma and 18 m/Ma. In the western site of BBHVF the erosion rate is higher (more than 60 m/Ma, Tapolca Basin), and an average 50 m/Ma in the center and eastern side.

Zusammenfassung. *Palaeographie des vulkanischen Gebietes im Bakony-Balaton-Hügelland (Ungarn, Obermiozän), belegt durch physikalisch-vulkanologische Daten.* – Das vulkanische Gebiet im Bakony-Balaton-Hügelland in Ungarn war im Oberen Miozaen aktiv und umfaßt ca. 100, vor allem alkalin-basaltische, eruptive Zentren, Schlackenkegel, Tuffringe, Maar-Komplexe und Schildvulkane. Neue Ergebnisse erlaubten die Erstellung einer detaillierten physisch-vulkanologischen Karte, die ein monogenetisch vulkanologisches Gebiet zeigt. Wo Pannonische Sandsteine die pre-vulkanische Stratigraphie bilden, haben sich normale vulkanische Zentren gebildet, mit gewöhnlich mächtigen spätmagmatischen Ablagerungen in Maar-Kratern. In Gebieten, die weniger mächtige Panonische Sandsteinschichten über mächtigen Mesozoischen oder Palaeozoischen Karstwasser-führenden Aquiferen aufweisen, erscheinen ungewöhnliche vulkaniklastische Sequenzen (Tihany-Typ Maar-Vulkane). Im nördlichen Teil des Gebietes findet man große Schlackenkegel und Schildvulkane, die darauf hin deuten, daß der Einfluß von Grund- und Oberflächenwasser nicht gegeben war, der phreatomagmatische Explosionen ausgelöst haben könnte. Tihany-Typ Maar-Krater sind gewöhnlich gefüllt mit mächtigen Seeablagerungen, die im nördlichen Teil oft Gilbert-Typ-Deltas bil-

den und reich an Schlacken sind, was darauf hindeutet, daß das ehemalige pre-vulkanische Gebiet geprägt war durch ein nord-südliches Fluß-System. Die Berechnung der Palaeohöhe ermöglichte es, zwei palaeo-geomorphologische Karten zu erstellen, die einerseits ein jüngeres (4–2.8 MA) und andererseits ein älteres (7.54–4 MA) Ereignungsbild darstellen. Die Erosionsrate wurde geschätzt und liegt wahrscheinlich zwischen 96 m/MA und 18 m/MA. Im Westen des Arbeitgebietes liegt die Erosionsrate höher (mehr als 60 m/MA), im Zentrum und Osten liegt der Durchschnitt bei ca. 50 m/MA.

Résumé. *Paléo-géomorphologie de la zone volcanique haute Bakony-Balaton (Hongrie), en utilisant des données de volcanologie physique.* – Un nouveau regard est porté sur la zone volcanique haute Bakony-Balaton (Bakony-Balaton Highland Volcanic Field – BBHVF), Hongrie, active au miocène tardif et composée d'une centaine de centres éruptifs en majorité basaltiques alcalins, cônes de scories, anneaux de tuff, complexes volcaniques de maar et volcans boucliers. Une carte détaillée montre la volcanologie physique du terrain volcanique monogénétique. Dans les zones ou la couche pré-volcanique se compose d'épais lits de grès Pannoniens, des centres volcaniques normaux de type maar se sont formés avec des remplissages magmatiques tardifs généralement épais dans les bassins de maars. Dans les zones ou des lits de grès Pannoniens relativement fins reposent sur d'épais aquifères Mésozoiques ou Paléozoiques controlés par les fractures et contenant des eaux karstiques, apparaissent des séquences volcaniques de maars, inhabituelles et étendues (maar de type Tihany). Dans la partie Nord du terrain, d'anciens grands cônes de scories et des volcans boucliers impliquent un moindre impact des nappes phréatiques et eaux de surface causant une activité phréatomagmatique explosive. Les maars de type Tihany sont en général remplis par d'épais dépôts de lacs de maars, édifiant des deltas de type Gilbert, caillouteux, riches en scories, du côté Nord des bassins de maars, suggérant un système fluvial principalement Nord-Sud au niveau de la surface pré-volcanique. En calculant l'élévation de la paléosurface pour les centres éruptifs, deux cartes paléo-géomorphologiques sont tracées pour un scénario jeune (4–2.8 Ma) et un scénario ancien (7.54–4 Ma). Le taux d'érosion du terrain volcanique varie, selon estimation, entre 96 m/Ma et 18 m/Ma. Au niveau du site ouest du BBHVF, le taux d'érosion est plus important (plus de 60 m/Ma, Bassin Tapolca), et est d'une moyenne de 50 m/Ma au centre et sur le côté est.

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 is right next to the north shore of Lake Balaton. 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 produced mostly alkaline basalt (e. g., SZABÓ et al. 1992). The volcanism was related to the post-extensional tectonic processes in the central Pannonian Basin (SZABÓ et al. 1992). They most likely represent a continuous facies between shallow water, emergent and subaerial hydrovolcanic processes in a large lacustrine-fluvial basin. The general paleo-environment and its hydrogeology caused a special kind of eruptive mechanism mainly in the explosive volcanic activity.

The BBHVF has more than 50 basaltic volcanoes (LÓCZY 1913, JUGOVICS 1968, JÁMBOR et al. 1981), but this number seems to be strongly underestimated as several very complex eruptive centers are composed of a number of individual vents. The real number of eruptive centers could reach 150–200 in this relatively small (ca. 3500 km^2)
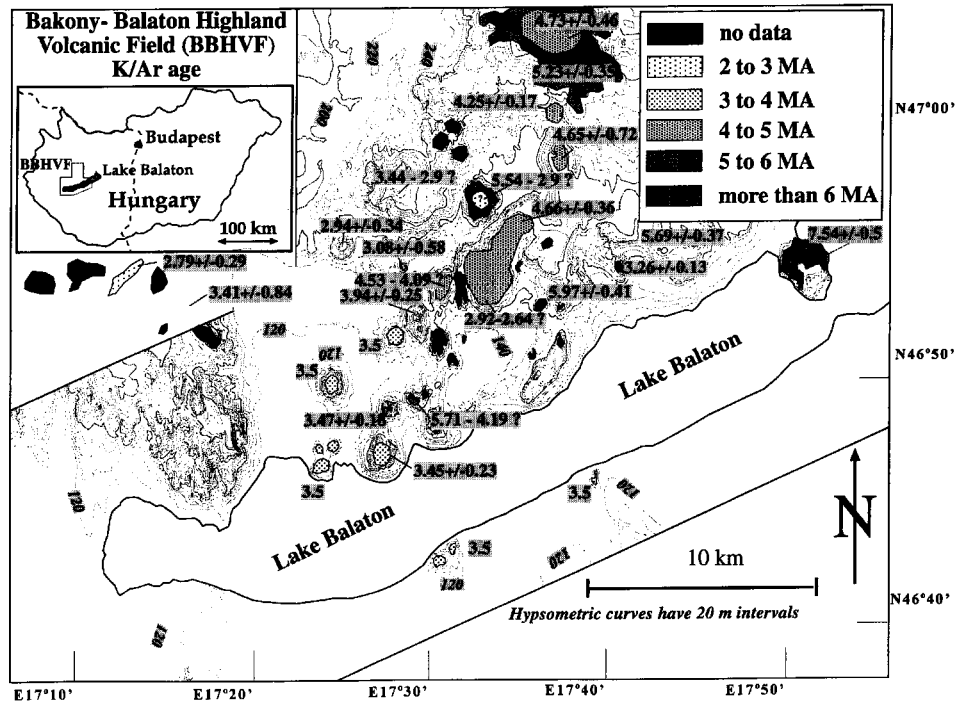
Fig. 1.   Map with the K/Ar age (data from BALOGH et al. 1986, BORSY et al. 1986).

area (fig. 2.). 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 1994). The underlying basement of the volcanic field consists of thick Silurian schist, Permian Red Sandstone and Mesozoic carbonate beds. This unit basically forms a large scale anticline structure, which is locally covered by Tertiary sediments in local basins. The Silurian schist formation is a 400–600 m thick unit which contains alternating, very low-grade metamorphosed psammitic and pelitic beds (LELKES-FELVÁRI 1978). The Permian Red Sandstone Formation is a thick (400–600 m) continental alluvial formation (MAJOROS 1980). The Mesozoic formations are represented by Triassic limestone and dolomites, which have a direct relation to the Triassic Eastern Alps. 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, with diverse sedimentary environments adjusted to the irregular basin morphology (KÁZMÉR 1990). The lacustrine sandstones, mudstones, marl of the brackish Pannonian Lake are widespread in the Pannonian Basin (KÁZMÉR 1990). These are usually fine-grained clastic quartzofeldspathic sediments showing gradual transition into fine grained sandstones which were deposited in a shallower water environment. Just before volcanism started the area was most likely characterized by an alluvial plain with quick depositional changes within short distances (KÁZMÉR 1990). The volcanism was mainly subaerial but there is evidence of local subaqueous to emergent con-
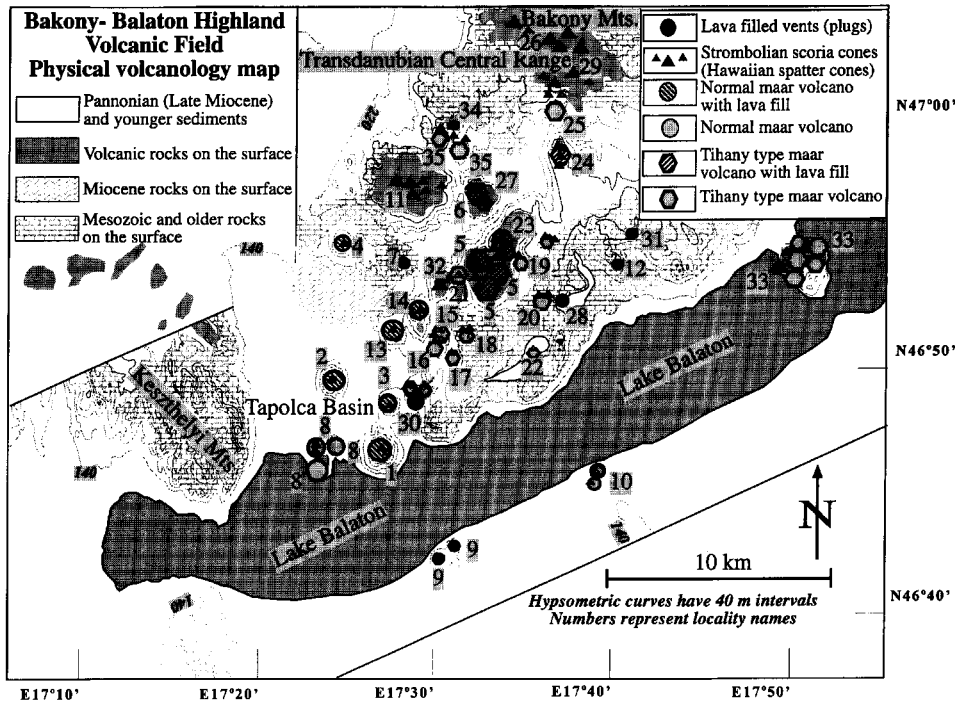
Fig. 2.   Map with the classification of eruptive centres (with locality numbers shown on table 1–2–3).

ditions (term by KOKELAAR 1986) of volcanic evolution of individual volcanic edifices. The volcanism was related to the distribution of paleovalleys developed along ancient, probably rejuvenated pre-Neogene tectonic lines, similarly to processes in the West Eifel, Germany (BÜCHEL 1993). After the volcanism, fluvial sedimentation was general in the area, but the recent Lake Balaton basin was filled just later, in the Quaternary (CSERNYI & BODOR-NAGY 1997).

The explosive volcanic centers of the BBHVF show characteristics similar to the monogenetic basaltic volcanic fields in Arizona (Hopi Buttes) (WHITE 1991a, 1991b), Western Snake River, Idaho (GODCHAUX et al. 1992), Massif Central, France (JUVIGNÉ et al. 1993), Newer Volcanics, Victoria (JOYCE 1975, JOHNSON 1989), Eifel, Germany (SCHMINCKE 1977), Anatolia, Turkey (KELLER 1973). The most widespread landforms are the circular, mostly lava capped buttes and hills of eroded maar crater fill sediment (fig. 3). These centers are usually related to underlying maar structures and occasionally eroded tuff ring rim remnants in areas where lavaflows preserved them. Individual maar structures without lava infill are less common, and hard to identify in the field. Their remnants consist of maar crater lake filling volcaniclastics. In the northern part of the BBHVF, Strombolian scoria cone remnants and Hawaiian spatter cone deposits are common, but usually individual Strombolian scoria beds, interbedded in hydrovolcanic setting, are also common everywhere in the field. There are large lava flows in the recently higher elevated areas in the Bakony Mountains. They

are usually eroded pahoehoe type of flows with widespread columnar jointed structures. Small lavaflows in valley filling situation often occur (Hajagos-hegy). The largest lava covered areas in the Bakony Mountains are shield volcanoes (Kab-hegy; Agártető). Large lava plugs as eroded vent-filling lava forms occur together with adjacent vent-filling volcaniclastic sediments (Hegyestű).

It is claimed that the large volcanic centers always represent longer periods of volcanic activity with complex eruptive processes where mostly phreatomagmatic and magmatic phases alternated. Apparently there is little evidence of phreatic explosion processes. Usually late magmatic explosive and effusive processes followed the early phreatomagmatic processes.
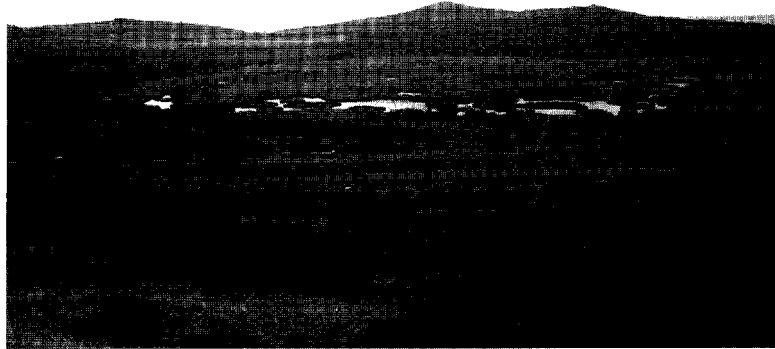

Fig. 3. General landscape of the BBHVF. View from east to west at Tihany.

Fig. 4. Reworked tephra bed from maar lake deposit sequence (Tihany). Shorter side of the picture is 20 cm.

The recent geomorphology of the area shows intensive erosion and a geomorphic inversion during the last 7.54 Ma. The recent high elevated areas are usually lava capped steep sloped hills that represent former lava-filled maar craters. Former maar craters were often filled by reworked volcaniclastics (fig. 4) (tephra debris flow deposits, Gilbert-type deltaic rim deposits) and in the later stage by fine laminated freshwater carbonates which were strongly cemented by hot spring fluids (NÉMETH 1997, NÉMETH et al. in prep). These sequences also conserved the maar crater fill deposits to form butte structures. The remnants of the original Strombolian scoria cones usually are near vent agglutinates and spatter deposits. The original volcanic landform is strongly modified in the BBHVF by late erosional processes and only the crater fill or near vent sediments are traceable in recent time. In this paper a paleo-geomorphology reconstruction for the BBHVF is attemted at, calculating the relative pre-volcanic surface elevations to each volcanic centers according to their volcaniclastic sediments. Using the different type of volcaniclastic deposits so called negative and positive landforms as maar and scoria cones with lava lakes were identified and the position of the pre-volcanic surface to a certain age was recalculated.

Finally, two paleogeographic maps for the two possible age groups are shown.

2   The hydromagmatic-magmatic spectrum from tuff cones to cinder cones

Maar volcanoes which developed directly on fracture-controlled aquifer basement rocks (Mesozoic carbonate, Permian Red Sandstone, Silurian schist) or on thin Pannonian clastic sediments are excavated deeply in the underlying sequences, and produced mostly wet surge beds (term after e. g.: LORENZ 1974, FRAZZETTA et al. 1983, 1989, DELLINO et al. 1990, DE ROSA et al. 1992) with a large amount of accidental lithics from depth. The other type of maar volcanic structures is developed, where the old fracture-controlled aquifers are covered by thick (~ 600 m) Pannonian clastic sedimentary rocks (porous media aquifer). These maar volcanic structures produced dry surge deposits and almost in all cases the maar basins were filled by late magmatic explosive product as scoria and spatter beds with lava infill. Therefore, the relationship between the maar-related pyroclastic sequence and the nature of the underlying aquifer seems to be a very important factor to develop a different style of eruption and eruption products of the maar volcanoes on the BBHVF. Maars surrounded by "tuff-cone kind" (term by WOHLETZ & SHERIDAN 1983) sequences of wet-surge deposits may be preferentially located in areas with underlying fracture controlled aquifers, covered by relatively thin (not more than 300 m) porous media aquifers (Pannonian clastic sediments), that produce relatively high water yields to the explosion focus. Maars surrounded by "tuff-ring kind" sequences of dry-surge deposits, in contrast, correlate with underlying porous-media aquifers that produce relatively low water yields to the explosion focus. This situation is also possible in those areas where the fracture controlled aquifer is in a too deep position, thus the ongoing phreatomagmatic explosions are not able to excavate the maar basin deep enough to involve the fracture controlled aquifer to the phreatomagmatic explosions (Badacsony, Szentgyörgyhegy, Szigliget). In areas where tuff-cone kind of deposits developed on top of porous-media aquifer, it is indicated that in some porous-media aquifers the flow rate of water into the vent may be as great

as in fracture-controlled systems. Another possibility is that fracture-controlled aquifers may not be able to supply large amounts of water to the volcanic vent. This situation could happen if magma intrudes into an area of reduced permeability and hydraulic conductivity. Thus maar surrounded by a tuff ring may form, even if the explosion took place on fracture-controlled aquifer, which is virtually "empty" during the dry season, or if the magma fails to intercept a hydrologicaly important fracture within the rock mass. Therefore a cinder cone may form like in the BBHVF in regions where the fracture-controlled aquifer is relatively close to the surface. The fracture-controlled aquifer as pointed out could have a very strong seasonality due to the wide range of water supply by rainfall or spring run off. Thus it is possible that in areas where fracture-controlled aquifer was cut by rising magma produced large unusual type of maar volcanoes like Joya Honda in Mexico (ARANDA-GOMEZ & LUHR 1996) or in Tihany in the BBHVF (NÉMETH et al. in prep) in the wet season (spring vents), and few month later when the fracture-controlled aquifer is theoretically empty during the dry season, scoria cones developed due to lack of groundwater (summer vents).

3 Complex volcaniclastic sedimentation in a fluvio-lacustrine basin

The age distribution of the measured eruptive centers strongly varies (BALOGH et al. 1986) (fig. 1). There were two major problems with previous K/Ar age determination, sampling and loss of Ar. The samples for the age determination were collected from lavaflows that cover the previous volcaniclastic sequences. Therefore the age of the lavaflow not necessarly represents the age of the hydrovolcanic eruptive center. On the other hand close maar volcanic centers are able to collect lavaflows from different sources, thus the age determination from single samples can cause confusion. Weathering causes a significant Ar loss, a source of error in dating. The eruptive centers were grouped into different age groups to establish a geomorphic evolution. The ages from earlier database and the interpretations of the eruptive centers are shown on Table 1-2-3.

The position of the eruptive centers in the different age groups shows a slight westward shift of eruptive centers along a NE-SW line. The eruptive centers are situated in a gentle southward dipping paleosurface.

1st age group

The now higher elevated areas, covered by mostly magmatic explosive and effusive volcanic products suggest that the magma/water interaction in those areas was probably limited during the volcanism. Thus the Kab-hegy, and Agárteto were already elevated hillside since 5.23 Ma, where the paleokarst surface was well below the paleosurface. In the lowlands the final Pannonian lacustrine sedimentation became of more fluvial character. Probably large flat alluvial plain formed in the early period of the volcanism, with small streams incised, swampy, small pond covered landscape. The oldest eruptive center in Tihany shows that in that time the hydrogeological conditions were good for maar forming, subaerial explosive activity. Tihany, a special type of maar volcanic complex formed (Tihany type maar volcano, by NÉMETH et al. in prep), where the thick karstwater bearing Mesozoic and Permian

Table 1   Classification of the younger eruptive centres (4-2.8 Ma) (M – maar; S – Strombolian scoria cone).

Name and locality number	Age (K/Ar) in Ma	Recent highest elevation, and calculated Hc in meter	Type	Crater diameter (d) in meter (estimated)	Crater depth (D) in meter (using LORENZ 1986)	Ejecta wall (w) in meter (using LORENZ 1986)	Total ejecta in X10⁶ m³ (using MERTES 1983)	Calculation of relative elevation	Relative elevation in meter	Erosion in meter	Erosion rate in m/Ma
1. Badacsony	3.45	437/420	M/S	1500	300	50	225	Hc−w	370	270	78
2. Szentgyörgy-hegy	2.80	415/400	M/S	1000	200	30	75	Hc−w	370	270	96
3. Gulács	3.47	398/400	M/S	800	160	20	50	Hc−w	380	260	75
4. Haláp	2.94	358/358	M/S	1000	200	30	75	Hc−w	328	208	71
5. Fekete-hegy	2.92	448/369	2 M and 1 M/S	2X1500 –and 1X1000	200 and 160	30 and 20	2X225 + 1X75=575	Hc−20	350	210	72
6. Bondoró-hegy	3.00	380/370	M/S	1000	200	30	75	Hc−w	340	180	60
7. Hegyesd	3.08	281/280	Plug?	200?	–	–	?	Hc+20	300	180	58
8. Szigliget	3.4	242/242	3 M (one with S)	2X800 and 1X1200	160 and 240	20 and 40 1X150=250	2X50 +	Hc+1/3D	322	222	65
9. Fonyód	3.55	232/232	2 plugs?	300 and 100	–	–	?	Hc + 10?	242	142	40
10. Boglár	3.5	164/164	2 M/S	500	100	10	2X20 = 40	Hc + 2/3D	230	130	37
11. Agártető	3.44	511/511	Shield volcano and scoria cone field	On 20 km² area, minimum few tens of scoria cones	–	–	?	Pre-volcanic and volcanic sequence border elevation	Min. 400	511+nX10−400=150	44
12. Tagyon	3.26	310/310	Plug ?	200	–	–	?	Hc+20	330	?	?
13. Csobánc	3.5	375/375	M/S	1000	200	30	75	Hc−w	345	225	64
14. Hajagos-hegy	3.94	334/330	M/S	1000	200	30	75	Hc−w	300	180	46

Table 2   Classification of the younger assumed eruptive centres (age data ara not available or not sure).

Name and locality number	Age (K/Ar) in Ma	Recent highest elevation, and calculated Hc in meter	Type	Crater diameter (d) in meter (estimated)	Crater depth (D) in meter (using LORENZ 1986)	Ejecta wall (w) in meter (using LORENZ 1986)	Total ejecta in X10^6 m^3 (using MERTES 1983)	Calculation of relative elevation	Relative elevation in meter	Erosion in meter	Erosion rate in m/Ma
15. Mindszentkálla (Kopasz-hegy)	3.5 ??	301/300	M/S	1000	200	30	75	Hc	300	160	46
16. Mindszentkálla (Pipa-hegy)	3.5 ??	240/200	M	1000	200	30	75	Hc+1/2D	300	160	46
17. Kékkúti-hegy	3.5 ??	220/220	M	800	160	20	50	Hc+1/2D	300	160	46
18. Kerekimajor	3.5 ??	171/171	M	800	160	20	50	Hc+2/3D	280	80	23
19. öreg-hegy	3.5 ??	250/250	M	300	60	8	10	Hc+2/3D	290	90	26
20. Horog-hegy	3.5 ??	266/266	M	500	100	10	20	Hc+2/3D	332	192	55
21. Füzes-tó	3.5 ??	301/300	M/S	1000	200	30	75	Hc	300	160	46
22. Kishegyestü	3.5 ??	238/238	M	800	160	20	50	Hc+1/2D	318	178	51

Table 3   Classification of the older eruptive centres (7.54–4 Ma).

Name and locality number	Age (K/Ar) in Ma	Recent highest elevation, and calculated Hc in meter	Type	Crater diameter (d) in meter (estimated)	Crater depth (D) in meter (using LORENZ 1986)	Ejecta wall (w) in meter (using LORENZ 1986)	Total ejecta in X10^6 m^3 (using MERTES 1983)	Calculation of relative elevation	Relative elevation in meter	Erosion in meter	Erosion rate in m/Ma
23. Fekete-hegy North	4.66	373/370	M/S	1500	300	50	225	Hc – w	320	180	39
24. Tálodi-erdő	4.65	312/312	M/S	1500	300	50	225	Hc – w	262	82	18
25. Pula	4.25	200/0200	M	1000	200	30	75	Hc + 1/2D	300	120	28
26. Kabhegy	4.93	599/599	Shield volcano and scoria cone field	On 50 km^2 area	–	–	–	Pre-volcanic and volcanic border elevation	Min. 400	599 +nX10 –400=200 (250)	41 (51)
27. Bondoró-hegy	5.54	380/380	M/S	1000	200	30	75	Hc – w	340	180	32
28. Hegyestű	5.97	336/336	Plug?	200	–	–	–	Hc + erosion of basalt?	366	166	28
29. Kabhegy (old)	5.23	599/599	Shield volcano and scoria cone field	On 50 km^2 area	–	–	–	As 26.	As 26	As 26	As 26
30. Tóti-hegy	5.71	346/346	Plug ?	200	–	–	–	Hc + erosion of basalt?	376	256	45
31. Tagyon2	5.69	399/399	Plug ?	200	–	–	–	Hc + erosion of basalt?	429	229	40
32. Sátorma-hegy	4.53	354/354	M/S/H	1000	200	30	75	Hc – w	324	184	41
33. Tihany	7.54	232	4 M	1500	300	50	4X225 =1000	Hc + 1/3D	332	232	31
34. T.dörögd	4.5 – 5.0??		Plug ?	200	–	–	–	Hc + erosion of basalt			
35. T.dörögd	4.5 – 5.0??		2 M	1000	200	30–	2X75=150	Hc + 1/2D			

formations were covered by relatively thick Pannonian sand, which were intruded by uprising basaltic magma. In this case the individual eruptions were controlled by the water content of the wet Pannonian sand and the karstwater rich, fracture-controlled aquifers. The formed maar craters were filled by debris transported by streams from the surrounding scoria cone fields. The individual maar craters functioned as local erosion bases (e.g. WHITE 1991a model). Gilbert-type deltaic fronts show NW to SE, N to S and NE to SW transportation direction. After the erosion of surrounding scoria field into the local erosion bases relatively quiet freshwater carbonate sedimentation started. The measured sedimentation rate in Tihany allowed 50 000 year quiet undisturbed sedimentation in the maar lakes which were probably open to south.

2nd age group

The eruption centers of the second age group (6–5 Ma) show a westward shift from Tihany (fig. 1, fig. 2, Table 3). Kab-hegy represents "dry" conditions during volcanism (low water availability to fuel hydromagmatism), producing both explosive and effusive products and landforms. The other 3 localities (Tóti-hegy, Hegyestű, Mencshely) in the same age group probably represent feeder dykes. The Mencshely locality's stratigraphy is uncertain. Hegyestű contains a small amount of hyaloclastitic volcaniclastic adjacent to the main feeder system, suggesting that local water supply was available during the emplacement of the igneous body, but probably this was not enough to cause phreatomagmatic explosions. Tóti-hegy is a local feeder dyke. There are few samples from Holocene debris flanks from the nearby hills, which show hydromagmatic characteristics, but their relation to the plug (age and stratigraphy) is unknown. In this case there is a possibility that Tóti-hegy is a strongly eroded maar structure. The most complex center in this age group is Bondoró, with a hydromagmatic base, which suggests that the subsurface water supply was substantial in this lowland region. The distribution of eruptive centers of this age group shows a wide NE-SW zone, suggesting a wide alluvial fan area with relatively low relief.

3rd age group

The third age group (5–4 Ma) represents a more characteristic rows of eruptive centers from NE to SW (fig. 1, fig. 2, Table 3). Kab-hegy was probably active over a longer period, thus built up a large shield volcanic edifice on the locally elevated Mesozoic block. The other three localities represent intensive hydromagmatic eruptive centers. The Pula eruptive center is a clear maar eroded remnant with alginite maar lake beds. Tálodi-erdő is a maar complex with a thick lava cap. Fekete-hegy is a maar volcanic complex with several vents. All vents erupted thick lava flows, which filled the former maar basins. A lava flow closed the former stream valley between Fekete-hegy and Bondoró. This closed system could have caused overfilled maar lake development and local freshwater basin development in the Pula region. Boncsos-hegy represents a "drier" eruptive environment. The water content of the thinner Pannonian sand formation or the disrupted karstwater supply was able to change the eruptive style from phreatomagmatic to magmatic.

4ᵗʰ age group

The eruptive centers of the fourth age group (4–2.8 Ma) show a more pronounced westward shift of the NE-SW trending line (fig. 1, fig. 2, Table 2–3). A shield volcano in the north was formed under "dry" eruptive conditions, representing little surface, subsurface water availability during its eruption. The Hajagos-hegy Gulács, Badacsony represent a large wide tuff ring structure with probably deep maar depression (according to the geophysical data), which were filled by thick (up to 50 m) lava flows or lava lakes. The eruptive centers show a slightly N-S elongated form. Clearly visible, especially in the Hajagos-hegy, is a lavaflow which cuts through the former crater rim and flowed onto the pre-volcanic swampy area. These kinds of N-S, NE-SW elongated shape of individual centers strongly suggest that the volcanic center were exploded in an N-S; NE-SW streams valley system, where the original valley geometry controlled the morphology of the explosion craters. The N-S, NE-SW stream system occurrence is supported with presence of the widespread N to S Gilbert type deltaic systems in the area. These systems are clearly developed in the middle and western part of the BBHVF.

Clear subaqueous volcanic centers do not exist on the BBHVF. There is some evidence of emergent type of volcanism in the western-central part of the BBHVF. This is supported by samples of chilled, sideromelane rich lapilli, hyaloclastite from Holocene talus deposits around Hajagos-hegy and Kő-hegy. The strongly vitric character suggests a phreatomagmatic explosive activity. The initial volcaniclastic apron was built into a very shallow water mass (probably pond with less than 10 m depth), than the explosion focus downmigrated, causing normal maar forming explosions. The occurrence of relatively water rich surface in this regions is supported by the presents of the peperitic lava foot breccia, gas bubbles (tumuli) in the lower level of lava flows (Hajagos-hegy, Kő-hegy, Gulács, Badacsony, Szigliget, Csobánc and Szentgyörgyhegy). In the Tapolca basin, the fracture-controlled aquifer was probably too deep during the volcanism thus normal tuff ring, maar forming volcanism developed. In the central part of the volcanic field the porous media aquifer was thinner, thus unusual type of maar volcanic centers, Tihany type maar volcanoes were built.

4   Conclusion: paleogeographical reconstruction from physical volcanology data

The age distribution and classification of different eruptive centres is shown on tables 1, 2 and 3. The eruptive centres are referred into two major age groups. The older one contains the centres, which are older than 4 million years. The younger group consist of centres with an age between 2.8 and 4 Ma. Figs. 8 and 9 show the two paleo-geomorphological maps.

According to the physical volcanology observations with detailed mapping around the individual centers total erosion was estimated for each point. By identification of the volcaniclastic rocks and classification of each eruptive center according to their eruptive style, a geomorphological map could be drawn by age groups (fig. 6 and fig. 7). The relative elevation term (Hp) was introduced which represents an elevation calculated on the base of physical volcanology data (fig. 7). We calculated relative elevation data for the previously separated two age groups to create a paleo-

geomorphological map. Fig. 6 summarizes the basic terminology to separate different volcaniclastic units related to maar/diatreme volcanism. The terminology is based on WHITE (1991b), elaborated to describe different levels of eruptive center erosion remnants from the Hopi Buttes (fig. 6).

The major eruptive centers with large Bouguer anomaly, geomagnetic anomaly and occurrence of primary phreatomagmatic and reworked maar crater fill sediments reconstructed as large maar structures which were depressions. In areas where mostly magmatic volcaniclastics were found and no Bouguer anomaly was reported, elevations were reconstructed compare to the pre-volcanic surface.

Where large lava capped buttes are above large Bouguer anomaly areas and phreatomagmatic deposits are found, the eruptive centers have a deep excavated maar basement. The measured diameter of the recent remnant of the lava filled maar basin is almost equal to the real maar basin diameter (d) since the crater wall of the maar basin is very steep (fig. 6 and fig. 7). From the measured/estimated crater diameter (d) we calculate the maximum crater depth (D) according to LORENZ (1986) empirical form (D = d/5), based on statistical studies of relatively young maars. The total ejecta from individual centers was calculated using the empirical diagram of MERTES (1983). Tables 1–2–3 show the calculated values for each studied eruptive centers. Fig. 7 shows the 3 main basic situation to calculate the relative elevation of the pre-eruptive surface. The three basic type are:

1 – maar basin filled by late magmatic upper diatreme structure (scoria cones, lava lakes) then eroded to different levels;

2 – maar basins developed and filled by late reworked tephra deposits, fresh water carbonates, then eroded to different levels;

3 – scoria cones, shield volcanoes, commonly with lava lakes, spatter cones developed then eroded.
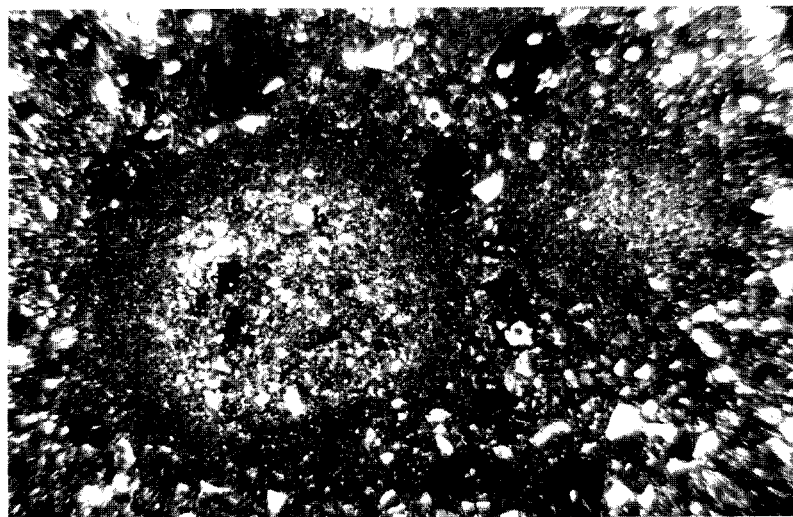

Fig. 5. Primary volcaniclastic sediment in thin section with rim-type accretionary lapilli (Bondoró). Shorter side of the picture is 2 mm.
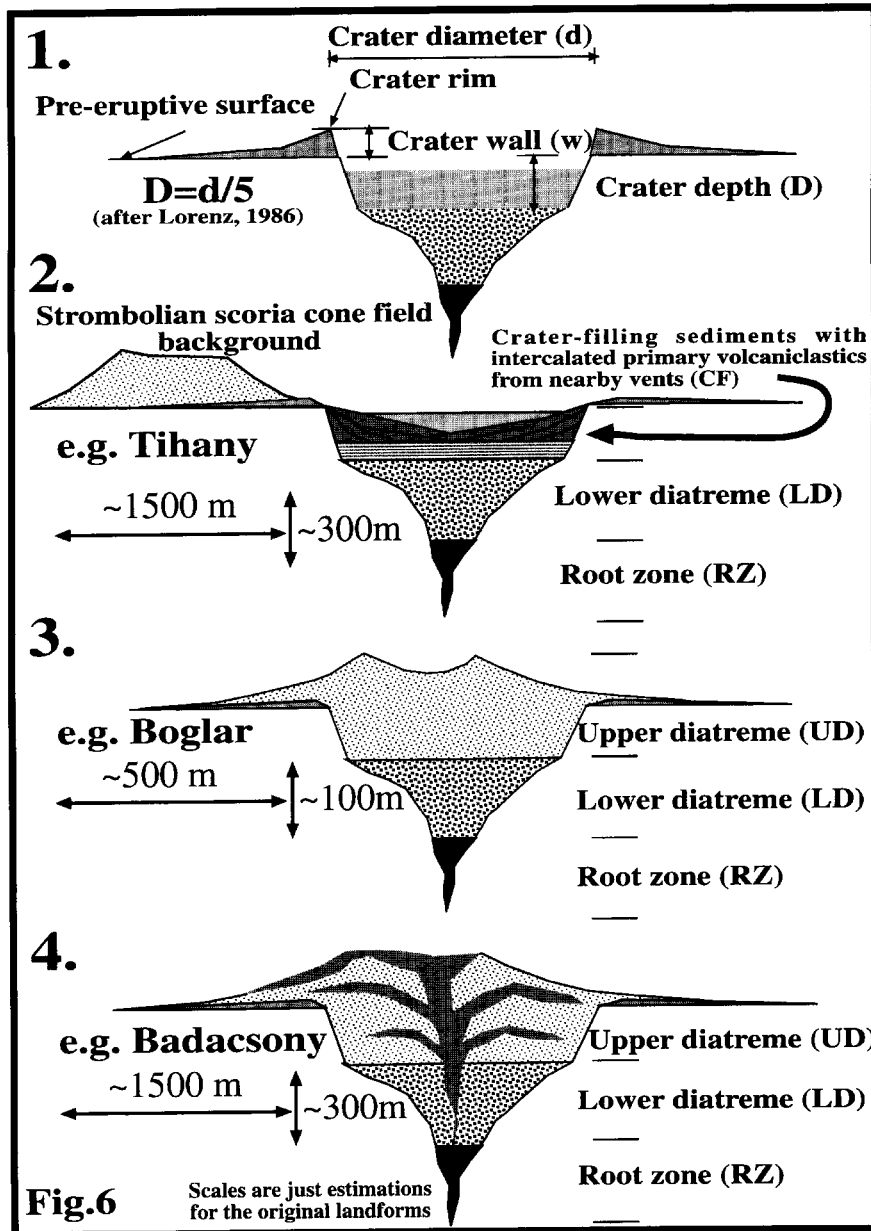
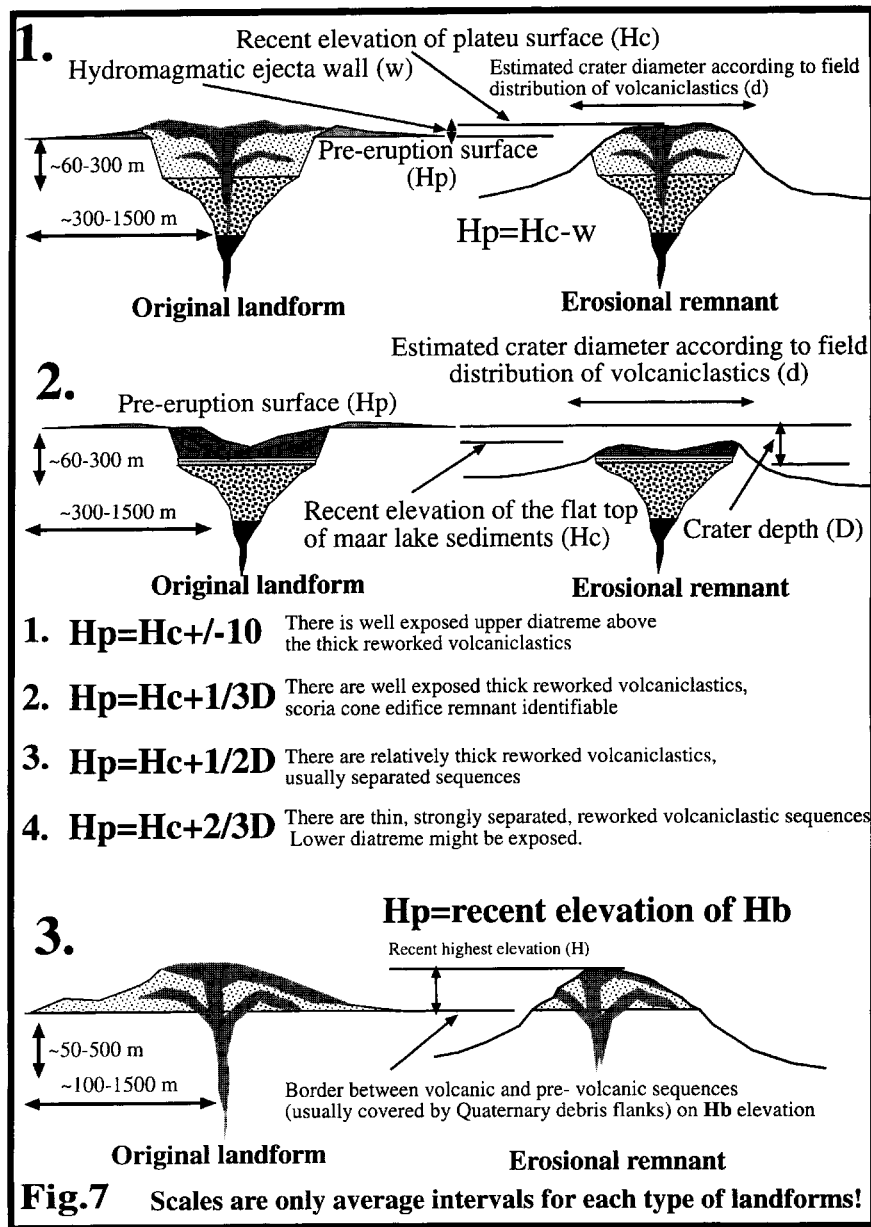Fig. 6.   Terminology of maar/diatreme landforms, sedimentary units.

Fig. 7. Calculation of relative elevation (pre-volcanic surface elevation), for explanation see the text.

The first situation (fig. 7/1) shows those centers with a thick lava cap with underlying maar basin. The lava cap is above Strombolian scoria beds. The symmetric shape of the buttes allowed us to estimate that the upper diatreme were built into a former maar basin, thus the size and shape of the lava lake were controlled by the ejecta wall (w). Therefore Hp = Hc – w. Hc is the recent plateau surface on the top of the buttes. Introducing Hc is important because several irregularities on the top of the buttes are related with former vent filled zones, even plugs, thus they were probably positive forms compare to the top of the ejecta walls. For the ejecta wall estimation observations and descriptions by e.g. WOHLETZ & SHERIDAN (1983), FISHER & SCHMINCKE (1984), LORENZ (1986), WHITE (1991), BÜCHEL (1993) were used for the geometrical parameter of thickness of crater rim deposits, which range from a few tens of meters to 200 meters. Basically the crater rim deposit thickness is strongly controlled by the geometrical size of the maar crater, thus estimated to ca 50–100 m.

Fig. 7/2 provides a model for maar basin development, later filled by reworked tephra deposits. The calculation of the erosion in this case is strongly dependent on the calculated crater depth (D). The crater depth has been calculated after Lorenz (1986) measuring and estimating the crater diameter (d). Depending on the facies distribution around the maar complexes, erosion has been calculated by adding the relative amount of eroded material to the measured recent plateau elevation of volcaniclastics (±10; 1/3D; 1/2D; 2/3D). Most of the BBHVF this type of eruptive centers are remnants of the case of fig. 7/2–2 and fig. 7/2–3. Each case is demonstrated in fig. 8.

The calculation of the prevolcanic surface elevation of landforms like spatter cones, scoria cones and shield volcanoes without maar base are shown in fig. 7/3.

The two paleogeomorphology maps (fig. 9 and fig. 10) indicate that volcanism was strongly controlled by the distribution of Pannonian sediments, the general geomorphology of the area, deep structures in the basement, and the syn-volcanic karst water level.

To summarize the geomorphological evolution of the BBHVF, volcanism was found to occur in a fluvio-lacustrine basin. The early eruptions formed in the south eastern side of the field, where the former lacustrine sedimentation turned into a 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 ensured a substantial water supply to fuel hydromagmatic explosive volcanism producing unusual maar structures. During the next stage alluvial fans developed by streams coming from the slightly higher background, the Late Miocene hills of Bakony Mts. Finally explosive and effusive volcanism occurred in the swamps, streams and small ponds. The largest volcanic complexes (Fekete-hegy, Bondoró-hegy) erupted large, long lavaflows which probably blocked the slightly higher elevated areas around the Tálodi-erdő, Pula region, thus the run off waters from the background (Bakony Mts.) formed a large post-volcanic freshwater lake. Finally volcanism shifted westward, following the same NE-SW line. These volcanic centers are of slightly emergent character, but the major part of them are tuff ring, maar type of subaeral volcanic center.

The phreatomagmatic volcanic centers show fine, linear distribution, suggesting that longitudinal stream occupied valleys occurred at this time. The elongated structure also suggests a deep fracture system in the fracture-controlled aquifer, which
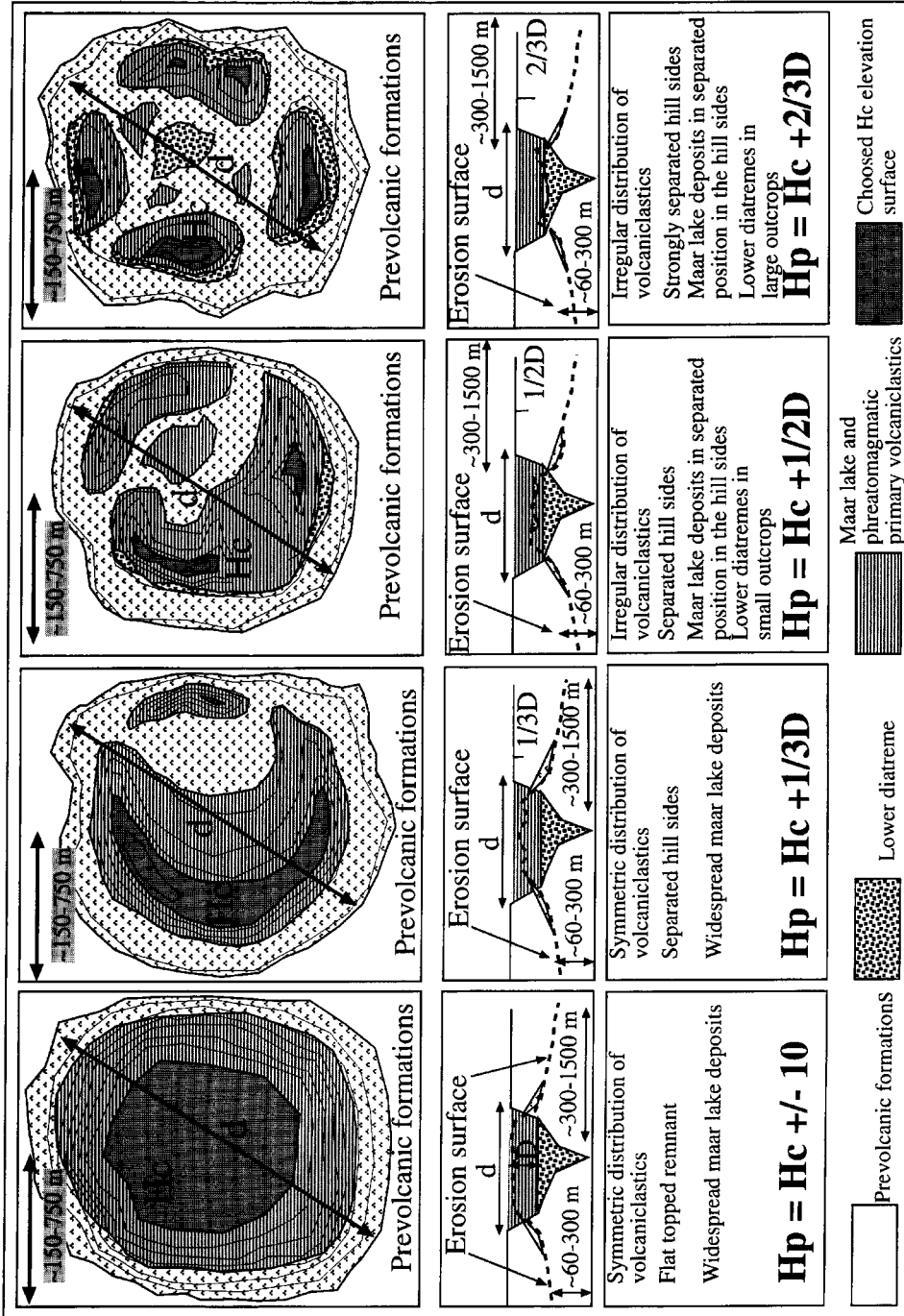
Fig. 8. Calculation of pre-eruptive surface elevation for maar basins without lava caps.
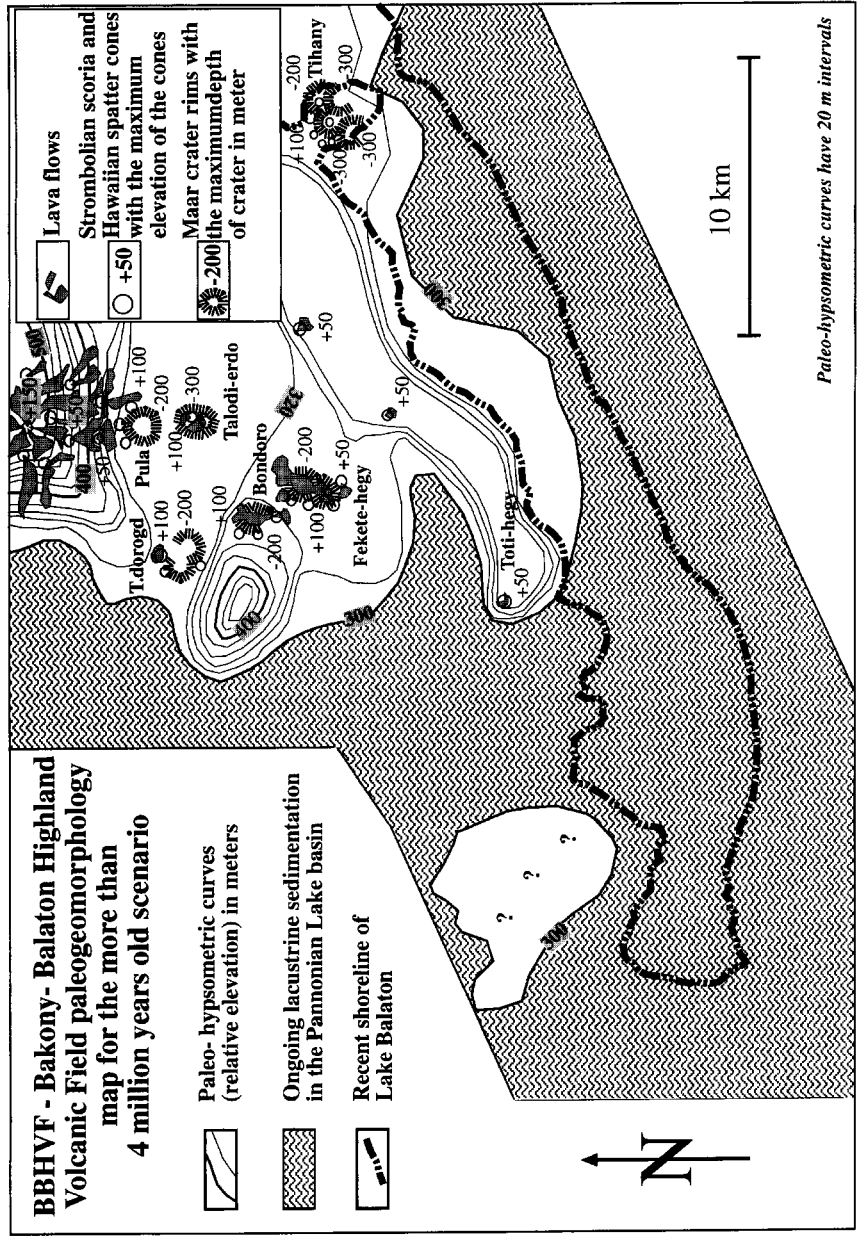
Fig. 9.   Paleogeography map for the more than 4 million years scenario (7.54–4 Ma).
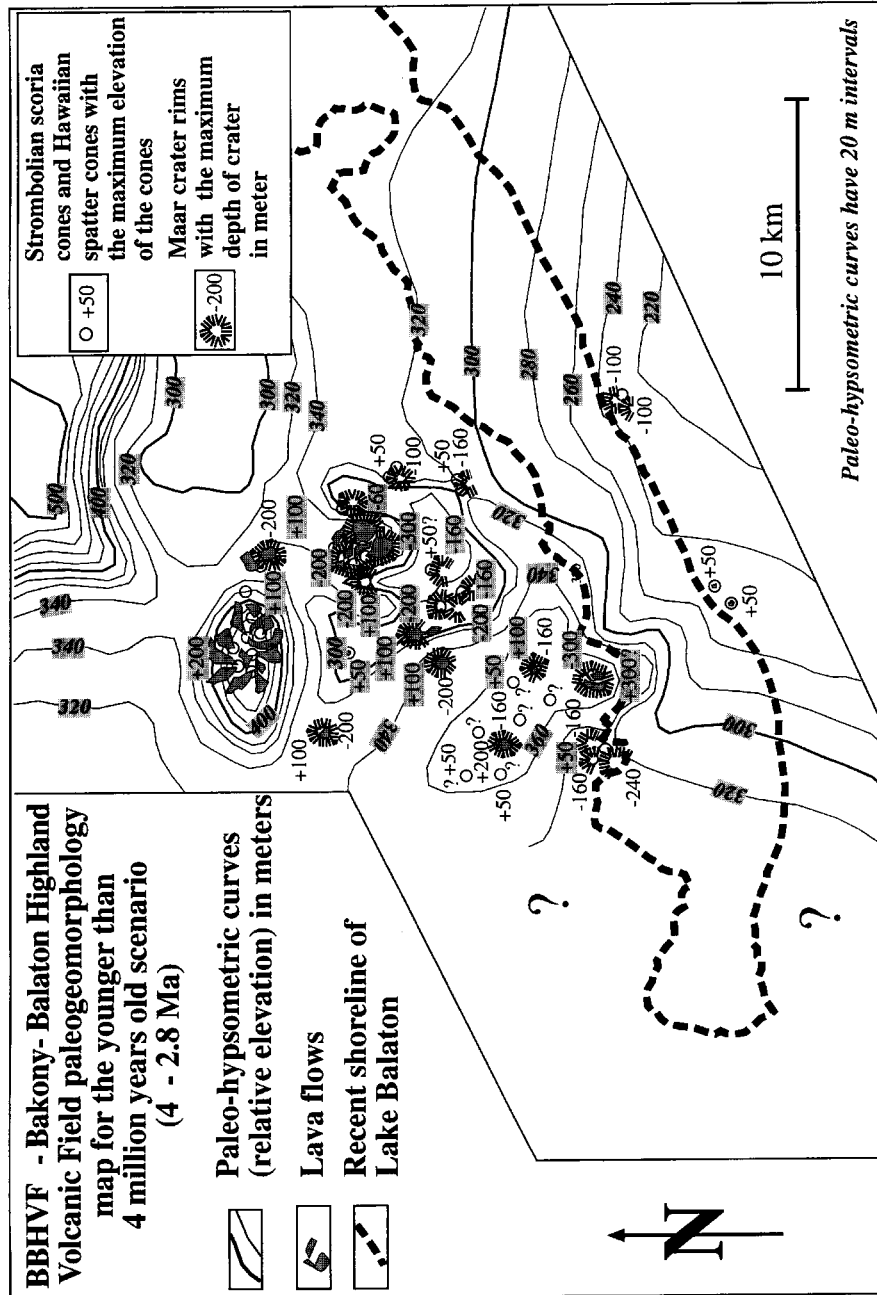
Fig. 10.   Paleogeography map for the 4–2.8 million years scenario.

allowed free water movement of the subsurface karst water, thus able to fuel phrea-
tomagmatic explosions. The fractures were also able to control the path of the upris-
ing basaltic melt. These two major controls operated together parallelly. The lacus-
trine environment (Pannonian Lake) was replaced by separate lake basins controlled
the water content of the porous media aquifer. The most enduring sub-basins are
responsible for hydromagmatic explosions in later time. The focus of volcanism
shifted to the western Tapolca Basin, where thick water-saturated, mostly lacustrine
sediments occurred.

The calculated erosion rate of the individual centers varies between 96 m/Ma
(Szentgyörgy-hegy) to 18 m/Ma (Tálodi-erdő). 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 but is in
the same range (~ 30 m/Ma) as the Miocene to Quaternary andesite/dacite strato-
volcanoes in the Carpathians in Romania, Slovakia and Hungary (KARÁTSON 1996,
1999, KARÁTSON et al. 1999). In southern Australia, a relatively low elevated vol-
canic field (the prevolcanic surface is 100–200 m above sea level), on a mild climate
showed 8 m/Ma erosion rate (WELLMAN 1979, BISHOP 1985). WALKER (1984) calcu-
lated downcutting rates of 58 m/Ma in the elevated basaltic highlands of Iceland in
the region where the mean elevation is 400 m. According to authors' calculation a
strong uplift process is assumed for the last few million of years accompanied with
a cold, sub-arctic weather. Probably the uplift was penecontemporaneous with the
volcanism. The erosion rate was probably effected 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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Late miocene paleo-geomorphology of the bakony-balaton highland volcanic field (Hungary) using physical volcanology data

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