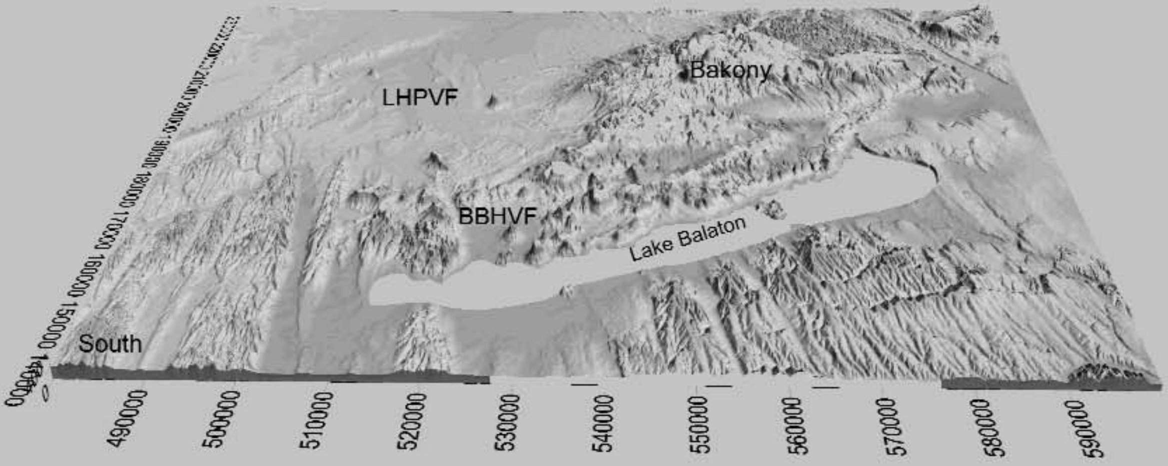
geologica hungarica
SERIES GEOLOGICA, TOMUS 26, pp. 57–72

Chapter 2

Second International Maar Conference — Hungary–Slovakia–Germany

Late Miocene to Pliocene palaeogeomorphology of the western Pannonian Basin based on studies of volcanic erosion remnants of small-volume intraplate volcanoes



Contents

Abstract 58
Introduction 58
Calculation method of erosion on the basis of eroded monogenetic volcanoes 59
Post-volcanic erosion 60
Erosion rate between end of Pannonian sedimentation and start of volcanism – pre-volcanic erosion 63
Conclusion 63
References 67
Colour plates 69

Abstract

Neogene volcanic fields in the western Pannonian Basin are eroded clusters of predominantly phreatomagmatic volcanoes that erupted from the Late Miocene (~8 My) and repeatedly became active until the Pliocene (~2.3 My). The volumetrically largest accumulation of volcanic erosion remnants is located in the Bakony – Balaton Highland Volcanic Field (BBHVF). In contrast more randomly distributed vent remnants occur in the Little Hungarian Plain Volcanic Field (LHPVF), and are aligned along major faults. The alkaline basaltic eruptive centres are eroded scoria cones, tuff rings, maar volcanic complexes and shield volcanoes. The amount of erosion has been calculated using volcanic lithofacies-distribution of these volcanic erosional remnants. Erosion remnants of the BBHVF are considered as being diatremes that undercut the syn-volcanic palaeosurfaces and therefore their present elevation represents various exposure levels below the syn-volcanic palaeosurface. At the LHPVF, volcanism is inferred to have developed on a flat lying land dominated by alluvial sedimentation, and volcanic landforms that very likely have been buried under younger (Late Pliocene to Quaternary) sediments. Volcanic remnants of the LHPVF are inferred to have been exhumed recently. Preserved tuff ring structures are still recognisable on old landforms. Erosion rates from the BBHVF are calculated based on estimation of the depth of exposure level of the preserved diatreme facies. Considering a phreatomagmatic origin of the studied volcanoes and a characteristic north–south lineament of the remnants of the volcanic edifices, it is inferred that they erupted in hydrogeologically active zones (valleys), which are likely to be controlled by faults. The calculated amount of 100–300 m erosion since volcanism ceased is interpreted as minimum value for the erosion of the predominantly Neogene siliciclastic sedimentary units. Erosion between the end of the Neogene shallow marine to fluvio-lacustrine sedimentation and the start of volcanism (~8 My) is calculated in two ways; 1. using the same erosion rates before volcanism, which was calculated from the time since the volcanism terminated, or 2. using a uniform average erosion rate for the pre-volcanic time based on field evidences (e.g. 10 to 100 m/My). These calculations result in a total thickness of Neogene sedimentary cover in the BBHVF region of 250 m up to 900 m before erosion. The erosion calculations based on volcanological evidences and the estimation of the total thickness of the immediate pre-volcanic Neogene sedimentary cover at ~8 My support the conclusion that Neogene sedimentary cover buried most of the western Pannonian Basin including the Transdanubian Range. The erosion rate of the BBHVF is estimated to vary between 100 m/My and 20 m/My.

Keywords: maar, diatreme, monogenetic, erosion, alluvial, fluvial, basalt, exhumation, erosion rate

Introduction

The alkaline basaltic, intracontinental, monogenetic volcanic fields in the western Pannonian Basin such as the Bakony – Balaton Highland Volcanic Field (BBHVF) and the Little Hungarian Plain Volcanic Fields (LHPVF) had been active during the Mio/Pliocene (~8 to 2.3 My – BALOGH et al. 1982, 1986, BORSY et al. 1986, BALOGH and PÉCSKAY 2001, BALOGH and NÉMETH 2004, WIJBRANS et al. 2004 – Plate 2.1). They largely comprise variably eroded tuff rings, maars, scoria cones and lava flows. The basement of the volcanic fields consists of two major groups of rocks,

1. a deeper seated hard rock succession including major karst aquifers, and
2. topmost unconsolidated "soft" sedimentary succession of Neogene shallow marine to fluvio-lacustrine silt, sand, and gravel units deposited either from the Pannonian Lake or fluvio-lacustrine systems that occupied the region after this lake disappeared (KÁZMÉR 1990, MÜLLER 1998, MAGYAR et al. 1999). The erosion style and rate after the end of the Neogene shallow marine to fluvio-lacustrine sedimentation as well as the initial thickness and the maximum extent of the sediments from this depositional cycle have been the key issues of the geological research in Western Hungary for a long time (JÁMBOR 1989, MÜLLER and MAGYAR 1992, JUHÁSZ 1994, JUHÁSZ et al. 1997, MÜLLER 1998, BUDAI and CSILLAG 1998, 1999, BUDAI et al. 1999, MAGYAR et al. 1999). With the results of volcanic facies analysis of the eroded remnants of the western Pannonian Basin an estimation of the erosional level of the volcanoes and the thickness of the eroded Neogene siliciclastic units of the small-volume intraplate volcanoes was possible. The level of exposure of pyroclastic rocks of the diatreme facies and the location of crater rim deposits and their relationship with lava flows and/or pre-volcanic rock units show that the erosion rate since the end of volcanism has not exceeded a few tens of metres per million years. This suggests that the total thickness of the Neogene sedimentary cover in the BBHVF region did not exceed 450 m. The preserved intact volcanic landforms in the LHPVF suggest that those volcanic landforms might have been buried, and were therefore well-preserved against erosion. Such an interpretation is supported by geophysical data that indicate the existence of volcanic structures below Quaternary sediments in the LHPVF region (TÓTH 1994). There are clear evidences that intrusive processes also were taking place resulted in form of sill and dyke intrusion into the Neogene sediments (e.g. Sümegprága). Because gravimetry and geomagnetic methods are not able to distinguish intrusive and extrusive bodies that are covered by younger sedimentary units, the reconstruction of the palaeosurfaces defined by coherent lava flow units are predominantly based on the surface exposures of coherent lava bodies that are inferred to be extrusive. However, Pliocene volcanic rocks in the western Pannonian region that are covered by younger siliciclastic (e.g. not related to deposition in volcanic depressions) sediments are only known from the LHPVF and the hills north of the Keszthely Mts. It is inferred that very recent fluvial processes played a role in the exhumation of tuff rings in the LHPVF. The palaeogeomorphological reconstruction that is made predominantly for the BBHVF is an attempt to calculate the relative pre-volcanic surface elevations for each volcanic centres on the basis of identified volcanic lithofacies relationships (NÉMETH et al. 2003b). Identified pyroclastic rocks in respect to their acci-

dental lithic fragment contents and types, the texture of the volcanic glass shards, the micro and macro texture of the preserved pyroclastic rocks as well as the presence or lack of coherent lava facies helped to establish negative and positive landforms such as maars and scoria cones with lava lakes. According to their original morphology the position of the pre-volcanic surface of a certain age was established (NÉMETH and MARTIN 1999b, NÉMETH et al. 2003b). Here a brief summary is given to present a few results that show the usefulness of such studies in respect to the estimation of the morphology during syn-volcanic time and the estimation of the thickness of eroded rock units.

Calculation method of erosion on the basis of eroded monogenetic volcanoes

The calculation of erosion rates can be separated into two steps;

1. estimation of erosion since the start of volcanism, and
2. estimation of erosion between the end of the Neogene shallow marine to fluvio-lacustrine sedimentation and the start of volcanism (Plate 2.2). This calculation is based on the assumption that the created volcanic landforms have not been covered by young sediments after their formation, and they have been stand against subaerial erosion following their eruption. This assumption is well-constrained in most of the locations in the BBHVF. However, the fact that some covered volcanic rocks (pyroclastic and coherent lava flows) exist in the LHPVF indicates that syn- and post-volcanic lacustrine sedimentation took place there and therefore these proposed two step erosion calculation model cannot be fully applied for the LHPVF.

It is generally accepted based on lithofacies and field relationships of lacustrine beds, seismic sections, and palaeontological evidence (MAGYAR et al. 1999, SACCHI et al. 1999, SACCHI and HORVÁTH 2002) that sedimentation in the Pannonian Lake terminated at 8 My ago in the BBHVF region. On the basis of seismic sections as well as facies relationships of Pliocene siliciclastic sediments it is inferred that local shallow lakes and wide fluvial systems existed well after the Pannonian Lake vanished in the LHPVF. There is also a general agreement that the water depth of the Pannonian Lake in western Pannonian region prior the volcanism was not more than 50 m (MÜLLER 1998, MÜLLER et al. 1999). There is evidence that tuff rings in the LHPVF were filled by thick lacustrine sediments (BENCE et al. 1978, SOLTI 1986, FISCHER and HABLY 1991, BRUKNER-WEIN et al. 2000), indicating a general availability of water through porous media aquifers and suggesting some extent of surface water involvement in their crater-lake formation. Moreover, pyroclastic successions of the Kis-Somlyó tuff ring (Plates 2.1 and 2.2) exhibit features suggesting that they were deposited in shallow water (MARTIN and NÉMETH 2002, 2004). Volcanic remnants of the LHPVF are generally flat, lensoid in plan view (pyroclastic mound like) with low angle bedding dip directions of the juvenile clast-rich lapilli tuffs. The dip direction of the pyroclastic beds commonly point to a former centre of the respective volcano suggesting a very broad volcanic edifice with low rims that easily have been flooded by water from a braided river system or from a shallow (e.g. few m) lake (Plate 2.1). This process could have been responsible for a short burial time and preservation of volcanic edifices under younger deposits. Such buried tuff rings are well known from the region (TÓTH 1994) and suggest, that volcanic landforms of the LHPVF are exhumed rather recently as can be seen by the relatively intact tuff rings such as the Gérce–Sitke system (Plates 2.1 and 2.2 and Figures 2.1 and 2.2). The implication of this observation of the LHPVF is that the LHPVF is rather erosion than an accumulation surface, which developed due to inversion from accumulation to sudden erosion very recently.

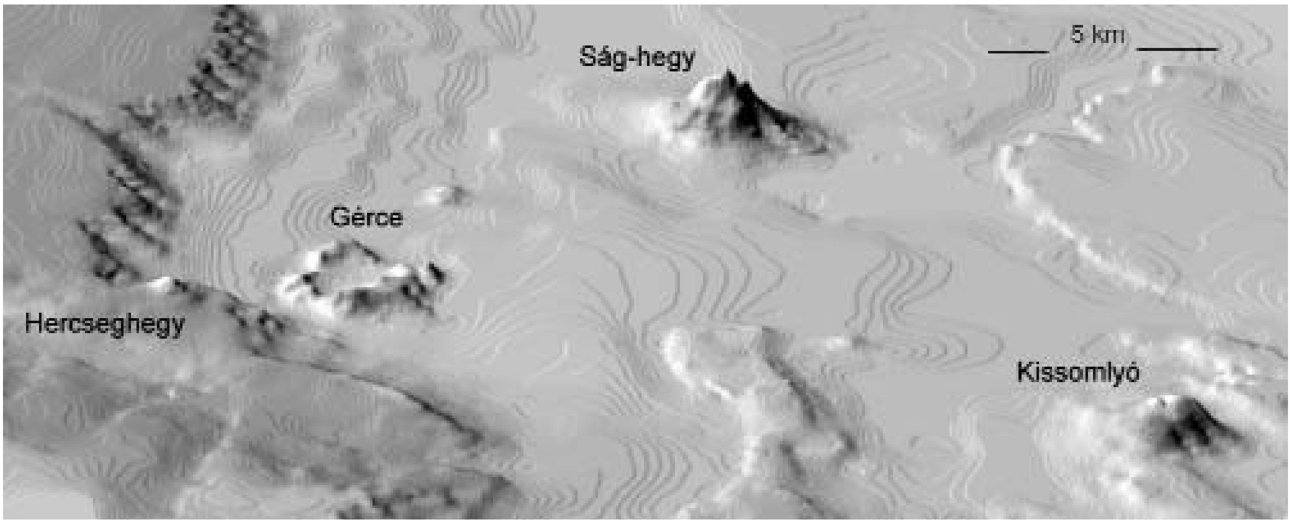


Figure 2.1. Digital terrain model for the LHPVF showing exhumed, intact tuff rings (such as the Gérce) that have been excavated recently

K/Ar as well as the recent ^{39}Ar/^{40}Ar ages of volcanic rocks in the BBHVF and LHPVF suggest a long-lasting activity (~8 to 2.3 My – BALOGH et al. 1982, 1986, BORSY et al. 1986, BALOGH and PÉCSKAY 2001, BALOGH and NÉMETH 2004, WIJBRANS et al. 2004). The age distribution of the measured eruptive centres strongly varies. The position of the eruptive centres in the different age groups from the BBHVF shows a slight westward shift of eruptive centres along a NE–SW line through time. The dominant part of the eruptive centres is grouped into the 4 to 2.8 My age group and show a more pronounced westward shift of the NE–SW trending line vents (Plate 2.1). A shield volcano in the north (Plate 2.1) was formed under "dry" eruptive conditions, suggesting little surface and groundwater availability during its eruption. The Hajagos-hegy, Gulács and Badacsony (Plate 2.1) represent large wide tuff ring with maar depressions, which were filled by thick (up to 50 m) lava flows or lava lakes. The eruptive centres show a slightly N–S elongated form. Clearly visible, especially in the Hajagos-hegy (Plate 2.1), is a lava flow, which cut through the former crater rim and flowed onto the pre-volcanic swampy area. These, N–S and NE–SW aligned centres suggest that explosion occurred in a N–S; NE–SW streams valley system. The ellipsoid shape of the volcanic centres may reflect an influence of the syn-volcanic stress field in the area as suggested from many volcanic fields (NAKAMURA 1977, CONNOR et al. 1992, 2000, CONNOR and CONWAY 2000).

Post-volcanic erosion

To estimate post-volcanic erosion, volcanic lithofacies were studied at each erosional remnant of the BBHVF (NÉMETH and MARTIN 1999b, NÉMETH et al. 2003a). Identification of different volcanic facies allowed the establishment of the exhumation level of the crater-filling deposits, vent zones or deep subsurface structures of individual volcanoes such as maars, tuff rings or scoria cones (Plate 2.3). With the relative proportions of different pyroclastic facies as well as the dip direction of the bedding planes, the position of the present exposures below the syn-volcanic palaeosurface was estimated (NÉMETH and MARTIN 1999b). As indicated by the presence of angular sideromelane glass shards and a large proportion of accidental lithic clasts in the pyroclastic rocks, most of the volcanic remnants were produced by subsurface phreatomagmatic explosive eruptions (NÉMETH and MARTIN 1999a, b, MARTIN et al. 2003). Most of the original landforms are interpreted as negative forms such as maars and/or near syn-volcanic palaeo-surface forms such as tuff ring craters; however, most of these landforms were subsequently filled by Strombolian scoria cones and/or lava flows (MARTIN et al. 2003). Using geometrical relationships between crater depth and width as well as thickness of crater rim deposit (LORENZ 1985, 1986), the size of the original volcanic landform and the present level of erosion was estimated (NÉMETH and MARTIN 1999b). According to the physical volcanological observations based on detailed mapping around the individual volcanic erosional remnant the total erosion was estimated for each volcano (NÉMETH and MARTIN 1999b). The major eruptive centres of the BBHVF with large negative Bouguer-anomalies, strong positive geomagnetic anomalies and occurrence of primary phreatomagmatic (and occasional reworked maar crater fill sediments) products suggest that these are maar structures that undercut the syn-volcanic palaeo-surface and often were filled with coherent lava bodies. In areas where mostly scoriaceous pyroclastic rocks were found with no negative Bouguer-anomaly the original landforms are interpreted as having been formed on a syn-volcanic palaeo-surface which is represented by the contact elevation between the volcanic and pre-volcanic rock units (NÉMETH and MARTIN 1999b). Where lava capped buttes are located above areas with significant negative Bouguer-anomalies and phreato-magmatic deposits are common in the pyroclastic succession, the original eruptive centres were maars (NÉMETH and MARTIN 1999b). The measured diameter of the remnant of the lava filled maar basin is inferred being almost equal in

Figure 2.2. Detail of an aerial photograph (Hungarian Military Collection) from the tuff ring east of Gérce village showing a more or less perfectly preserved crater rim, which very likely was buried similarly to other still covered volcanic edifices in the LHPVF

size as the original maar basin diameter (d – Figures 2.2 and 2.3). The maximum crater depth (D) was calculated according to LORENZ (1986);

$$D = d/5$$

wherein d = measured/estimated crater diameter, which is based on statistical studies of relatively young maars (Figure 2.4). Three basic type of erosional remnants have been identified and dealt with separately (NÉMETH and MARTIN 1999b):

1. maar basin filled by late magmatic scoria cones, lava lakes, which were then eroded to different levels;
2. maar basins developed and filled by late reworked tephra deposits, fresh water carbonates, which were then eroded to different levels;
3. scoria cones, shield volcanoes, commonly in association with lava lakes, spatter cones, which were then eroded.

The first are those centres, which have a thick lava cap overlying maar basins. The syn-volcanic palaeo-surface in relation to the present morphology is calculated by

$$Hp = Hc - w$$

where Hc = the recent plateau surface on the top of the buttes and w = thickness of the crater rim of the tuff ring.

The thickness of the crater rim deposits (w) is estimated to range from a few tens of metres to up to 200 metres according to observations of different types of maars (CAS and WRIGHT 1988). However, the crater rim thickness (w) is strongly controlled by the geometrical size of the maar crater.

The calculation of the erosion on the basis of erosion remnants without lava caps is strongly dependent on the calculated crater depth (D). The crater depth has been calculated after LORENZ (1986). 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 the pyroclastic rock units (±10; 1/3D; 1/2D; 2/3D – NÉMETH and MARTIN 1999b).

On the basis of this very simple but systematic study an estimate is given for each location, which represents the possible syn-volcanic palaeosurface elevation (Table 2.1). The formula from LORENZ (1986) is based on empirical description of geometrical parameters of maar volcanoes, and it is generalised. It is evident, that in areas where maar volcanoes developed in "soft rock" environment

Figure 2.3. View of the tuff ring east of Gérce exhibiting primary morphological features of its crater rim

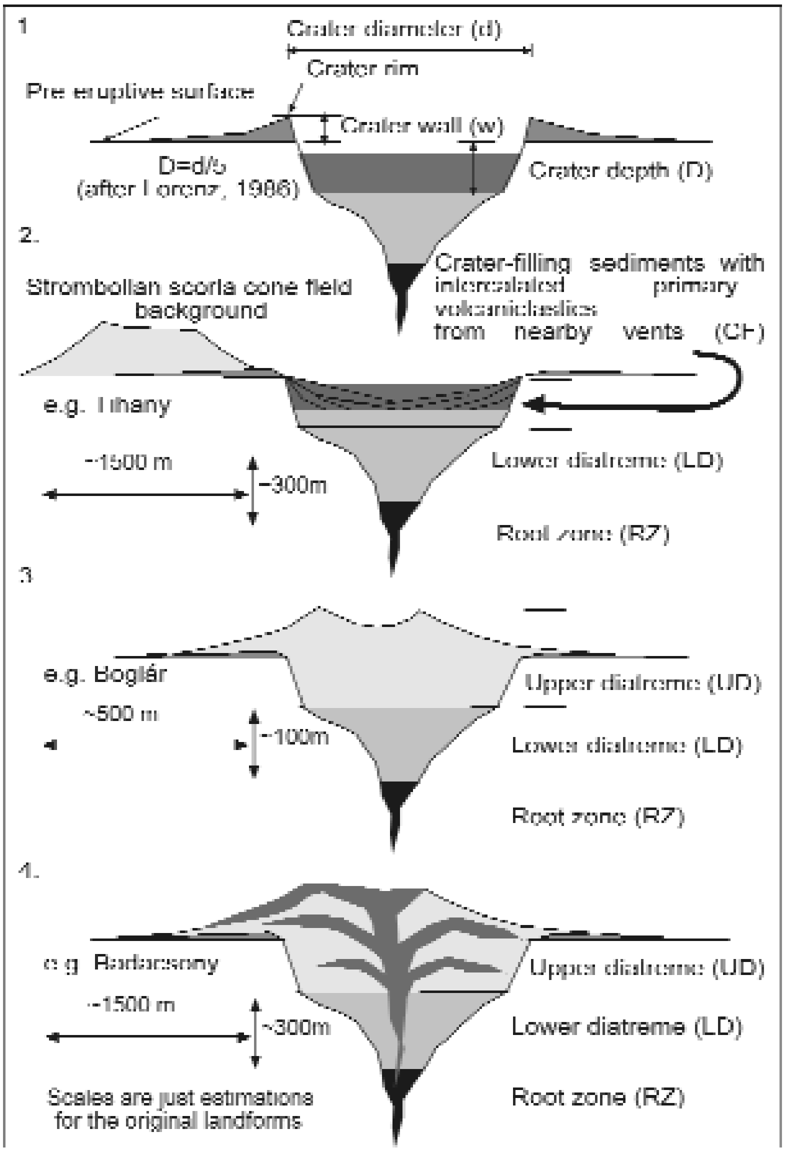


Figure 2.4. Calculation method to estimate the erosion of a monogenetic volcanic landform (NÉMETH and MARTIN 1999b)

Table 2.1. Volcanic erosional remnants of the BBHVF

Locality	Age [My]	Ev [m]	EvR [m/My]	T [My]	Ep1 [m]	Et1 [m]	Ep2 [m]	Et2 [m]	C [m]	P [m]
1. Badacsony	3.45	**270**	78	4.55	**355**	*625*	**46**	*316*	+100	725/416
2. Szt.György-hegy	2.80	**270**	96	5.2	**499**	*769*	**52**	*322*	+100	869/422
3. Gulács	3.47	**260**	75	4.53	**340**	*600*	**45**	*305*	+100	700/405
4. Haláp	2.94	**208**	71	5.06	**359**	*567*	**51**	*259*	-50	517/209
5. Fekete-hegy	2.92	**210**	72	5.08	**367**	*577*	**51**	*261*	-100	477/161
6. Bondoró-hegy	3.00	**180**	60	5.00	**300**	*480*	**50**	*230*	-50	430/180
7. Hegyesd	3.08	**180**	58	4.92	**285**	*465*	**49**	*229*	-100	365/129
8. Szigliget	3.4	**222**	65	4.6	**299**	*521*	**46**	*268*	+150	671/418
9. Fonyód	3.55	**142**	40	4.45	**178**	*320*	**45**	*187*	+150	470/327
10. Boglár	3.5	**130**	37	4.5	**166**	*296*	**45**	*175*	+150	446/225
11. Agártető	3.44	**150**	44	4.56	**201**	*351*	**46**	*196*	-100	251/96
12. Tagyon	3.26	**?**	?	4.74	**?**	*?*	**?**	*?*	?	?
13. Csobánc	3.5	**225**	64	4.5	**288**	*513*	**45**	*270*	+50	563/320
14. Hajagos-hegy	3.94	**180**	46	4.06	**187**	*367*	**41**	*221*	+100	467/321
15. Kopasz-hegy	3.5 ?	**160**	46	4.5	**207**	*367*	**45**	*205*	- 50	317/165
16. Pipa-hegy	3.5 ?	**160**	46	4.5	**207**	*367*	**45**	*205*	- 50	317/165
17. Kékkút	3.5 ?	**160**	46	4.5	**207**	*367*	**45**	*205*	- 100	267/105
18. Kerekimajor	3.5 ?	**80**	23	4.5	**104**	*184*	**45**	*125*	- 50	134/75
19. Öreg-hegy	3.5 ?	**90**	26	4.5	**117**	*207*	**45**	*135*	+ 100	307/235
20. Horog-hegy	3.5 ?	**192**	55	4.5	**248**	*440*	**45**	*235*	- 100	340/135
21. Füzes-tó	3.5 ?	**160**	46	4.5	**207**	*367*	**45**	*205*	- 50	317/165
22. Kishegyestű	3.5 ?	**178**	51	4.5	**230**	*408*	**45**	*226*	+ 50	458/276
23. Fekete-hegy N	4.66	**180**	39	3.34	**130**	*310*	**33**	*213*	- 100	210/113
24. Tálodi-erdő	4.65	**82**	18	3.35	**60**	*142*	**34**	*116*	+150	292/266
25. Pula	4.25	**120**	28	3.75	**105**	*225*	**36**	*156*	+100	325/256
26. Kabhegy	4.93	**200**	41	3.07	**126**	*326*	**31**	*231*	- 100	226/131
27. Bondoró	5.54	**180**	32	2.46	**79**	*259*	**25**	*205*	- 50	209/165
28. Hegyestű	5.97	**166**	28	2.03	**57**	*223*	**20**	*186*	- 100	123/86
29. Kabhegy (old)	5.23	**-**	-	2.77	**-**	-	**-**	-	-	-
30. Tóti-hegy	5.71	**256**	45	2.29	**104**	*360*	**23**	*279*	+ 100	460/379
31. Tagyon2	5.69	**229**	40	2.31	**92**	*321*	**23**	*252*	- 100	221/152
32. Sátorma	4.53	**184**	41	3.47	**142**	*326*	**35**	*219*	- 50	276/169
33. Tihany	7.54	**232**	31	0.46	**14**	*246*	**5**	*237*	+ 150	396/287
34. T.dörögd	4.5	**-**	-	3.5	**?**	*?*	**?**	*?*	?	?
35. T.dörögd	4.5	**-**	-	3.5	**?**	*?*	**?**	*?*	?	?
36. Zánka/Várhegy	6 ?	**160**	27	2	**54**	*214*	**20**	*180*	-100	114/80
37. Véndeg-hegy	3 ?	**140**	47	5	**235**	*375*	**50**	*190*	-50	325/140
38. Hármashegy	3.5 ?	**220**	63	4.5	**284**	*504*	**45**	*265*	+100	604/365

Numbers correspond to locations on Plate 1.1, B. Age data from BALOGH et al. (1982), BORSY et al. (1986) and BALOGH (1995). Abbreviations: Ev = post-volcanic erosion, EvR = post-volcanic erosion rate, T = time between end of Pannonian sedimentation and start of volcanism, Ep1 = erosion between end of Pannonian sedimentation and start of volcanism calculated with the same erosion rate estimated in post-volcanic time, Et1 = total erosion using Ep1 and Ev, Ep2 erosion between end of Pannonian sedimentation and start of volcanism calculated with low erosion rates (10 m/My), Et2 = total erosion using Ep2 and Ev, C = correction value, P = total thickness of Pannonian sediments

the maar basin will be rather broad, and shallow, in contrast to "hard rock" environment, where the maars could be very deep (LORENZ 2000, 2003a, b). Maar volcanoes often show transition toward tuff ring, and their geometrical parameters could differ from LORENZ (1986) empirical formula, such as it is known from maar and tuff ring volcanoes from Oregon where ratio of crater depth to diameter often is 1 to 10 (HEIKEN 1971). Deep maar volcanoes very likely need hard rock environment such as the Crater Elegante, Mexico (cut in lava flow succession – d, 270 – D, 1650 – GUTMANN 1976) or Joya Honda, Mexico (cut into limestone units – d, 300, – D,1200 – ARANDA-GOMEZ and LUHR 1996) to maintain the LORENZ (1986) average 1 to 5 ratio between crater depth to diameter. This implies that the calculations from the western part of the BBHVF where the phreatomagmatic volcanoes cut into soft rock (Figure 2.3), is in overestimate (e.g. few tens of metres), and the calculated erosion values should be viewed as maximum values (Table 2.1).

Detailed analyses on thin-sections and hand specimens from the pyroclastic rock units revealed quartz, quartzo-feldspatic aggregates, plastically deformed mud chunks (mm to cm scale), and muscovite from all of the studied pyroclastic outcrops from the BBHVF (NÉMETH et al. 2003a). All of these components are characteristic for the Neogene siliciclastic sediments. The presence of lithic fragments or exotic minerals derived from these units in the phreatomagmatic pyroclastic rocks attest that these clasts must have been disrupted by the phreatomagmatic explosions, recycled in the phreatomagmatic vents to become part of various lithofacies in and around the vents (NÉMETH et al. 2003b). It can be concluded that post-volcanic (Pliocene) erosion rates vary between 18 and 96 m/My; however, mostly 50 m/My has been calculated (NÉMETH and MARTIN 1999b, NÉMETH et al. 2003b). Re-establishing the syn-volcanic palaeosurfaces in the region, a uniform surface below 100 m with relative elevation variation may be visible (Plate 2.4).

Erosion rate between end of Pannonian sedimentation and start of volcanism — pre-volcanic erosion

Calculation of the pre-volcanic erosion rate in the area is problematic. Few direct field evidence is available to help reconstructing palaeosurfaces for times prior to 8 My. The use of the same erosion rates for pre-volcanic times as for post-volcanic times would imply that the erosional potential was the same ever since the end of Pannonian Lake sedimentation. Based on this simplification, the amount of erosion since the end of the Pannonian Lake sedimentation would be more than twice as large as the amount of erosion since the end of volcanic activity. The total thickness of accumulated sediments in the area would have exceeded 800 m in basins with an estimated erosion of more than 600 m. However, field evidence such as lava flows over weakly dissected morphology and the general uniform elevation of lava flow contact to pre-volcanic rock units indicates that erosion rates must have been lower before the volcanism than after the end of volcanic activity (NÉMETH et al. 2003b). The youngest deposits of Pannonian age in the BBHVF are lacustrine limestones (Nagyvázsony Mésző Formation — NMF). These are intercalated with strongly altered basaltic tuffs (BUDAI and CSILLAG 1998, 1999, BUDAI et al. 1999) that are inferred to have been deposited from phreatomagmatic eruptions of the oldest volcanoes in the region (Tihany, 8 My). The limestone tends to form an extensive plateau, outlining the extent of a closed laguna that developed in the final stage of Pannonian Lake sedimentation (BUDAI et al. 1999). Extensive lava flows derived from the volumetrically largest volcano of the BBHVF (Kab-hegy, shield volcano) were observed to overlie the youngest units inferred to have been deposited from the Pannonian Lake (NMF) at uniform elevation (~300 m a.s.l. — BUDAI et al. 1999). As indicated by the results of K/Ar age determinations, textural and compositional similarities, mineral orientation and drill core data, lava sheets of the major shield volcano (Kab-hegy) can be correlated with dissected lava sheets located south of this centre (Tálodi-erdő — JÁMBOR et al. 1981). The large (10 km-scale) extent of lava on a uniform elevation and the undisturbed contact between lava and limestone suggest that the palaeosurface on which the lava erupted was that with insignificant fluvial incision and poorly developed valleys. The age difference between these lavas (~5 My) and the cessation of Pannonian sedimentation (~8 My) suggests that the interval of ~3 My was not long enough to develop a significant valley system. A low erosion rate of e.g. ~10 m/My was inferred for the region in pre-volcanic times. Based on these calculations, the total erosion after the end of the Pannonian Lake sedimentation can be maximalized to ~300 m, while the total thickness of the Pannonian sediments accumulated in the region was about at ~450 m (NÉMETH et al. 2003b).

Conclusion

Based on the analyses of the erosional remnants of monogenetic volcanoes from the BBHVF, the following conclusions can be drawn:

— the post-Pannonian erosion must be separated into two stages;

— prior to the start of Mio/Pliocene volcanism, and

— between the Mio/Pliocene volcanism and present;

— post-volcanic erosion rates vary between ~20 and 100 m/My, resulting in a total erosion of 80 to 270 m of predominantly Pannonian sediments;

— in reconstructing the Pliocene syn-volcanic palaeosurface, a remarkable flat landscape can be constructed with a total geomorphic relief of less than ~100 m;

— considering that most of the volcanoes had at least an initial phreatomagmatic eruptive phase, their position marks local lowlands;

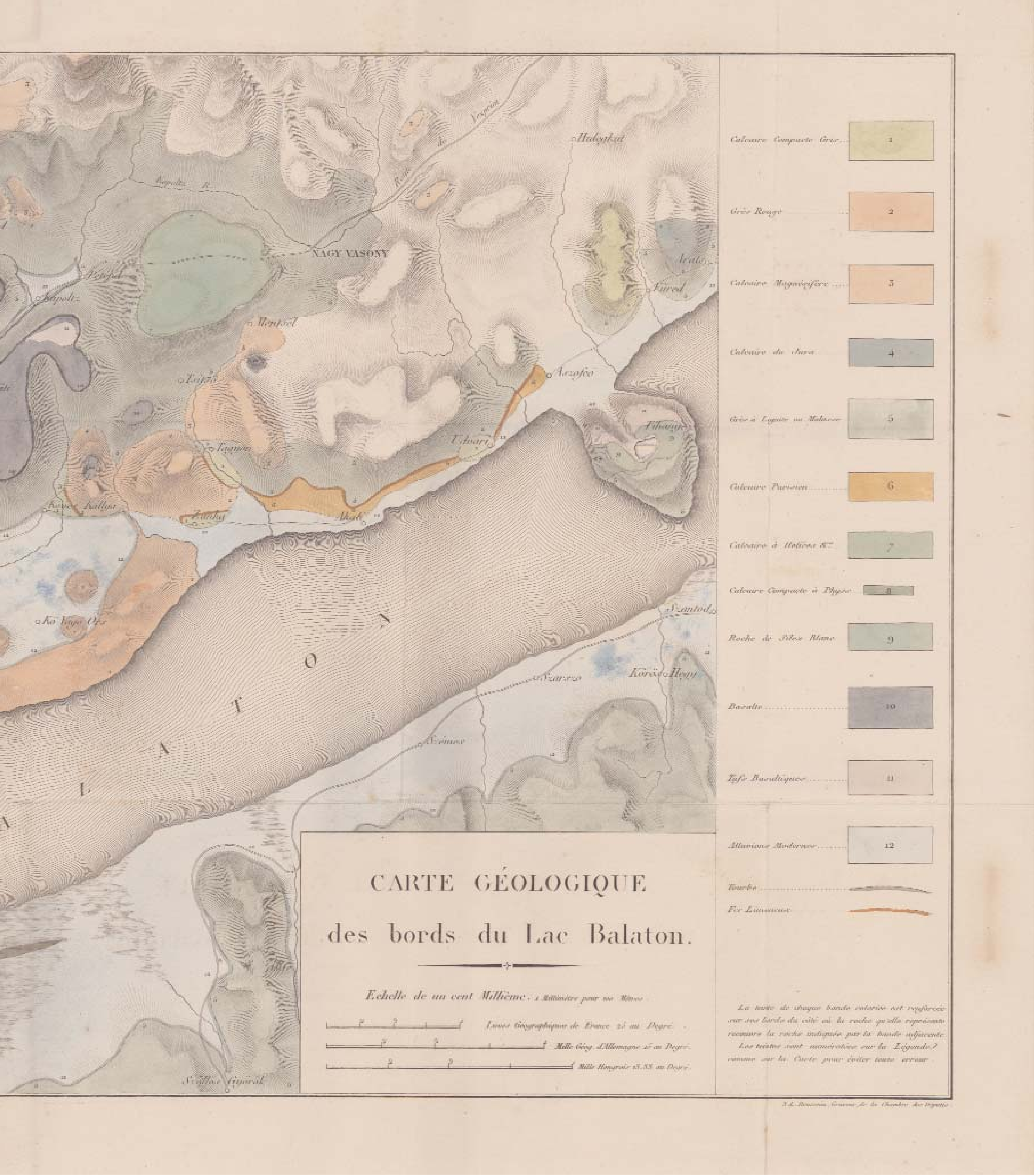
— the total thickness of the Pannonian sedimentary cover is estimated to have been 250 to 900 metres prior to erosion starting at ~8 My, most realistically being not more than 450 m;

— Pannonian sedimentary cover must have been still widespread in the region before volcanism started. Pannonian sediments were only stripped away from elevated ridges.

For the geomorphologic development of the BBHVF two major models have been considered on the basis of the erosion remnants of the Neogene basaltic volcanoes. Originally, the first observations suggested that volcanic erosional remnants represent volcanoes that gradually developed on an erosion surface (Lóczy 1913, 1920, Cholnoky 1918). This would imply that the younger a volcano the deeper was its position in comparison to the elevation of stratigraphy markers (Figure 2.5). The other model postulates that the volcanoes evolved in a sedimentary basin with a fast accumulation rate, and they were buried quickly. Therefore the erosion gradually excavated older volcanic structures creating a "layer-cake" age relationship, having the older volcanic remnants in deeper level (which is represented by their present

Figure 2.5. One of the first geological map from the BBHVF made by a French geologists Beudant F.S. in 1822 shows in a very graphic way the uniform top level of the volcanic erosion remnants
This map was one of the first in Hungary where they used the metric system during mapping

topographic elevation – JÁMBOR and SOLTI 1976, JÁMBOR 1980, 1989, JÁMBOR et al. 1981). This conclusion is supported by some apparent intercalation of Neogene siliciclastic and pyroclastic sediments on the basis of drill core data (JÁMBOR and SOLTI 1975, JÁMBOR 1989). However, recent studies confirmed that most of the sequences intercalated between volcanic and siliciclastic units are near continuous accumulation of accidental lithic rich primary pyroclastic rocks (NÉMETH et al. 2001). Moreover, the pyroclastic rocks in the BBHVF are interpreted to represent often diatreme



filling rocks that cut into a syn-volcanic surface, thus their stratigraphy position is hard to establish (NÉMETH et al. 2003a). The present morphology however is remarkably uniform (Figures 2.6 and 2.7) in spite of the apparent age differences among volcanic erosion remnants. This means that volcanoes erupted in a very gentle morphology with no or underdeveloped drainage systems. Pyroclastic rocks that form erosional remnants of small intraplate volcanoes have been interpreted to be exposed diatreme rocks long time ago from the Styrian Basin in Austria (e.g. WINKLER 1925, STRAUSZ1943). This interpretation is based entirely on the stratigraphic and spatial relationships between volcanic, pre-volcanic and post-volcanic rock units (e.g. WINKLER 1925). Regardless of these preliminary interpretations the general geomorphological view of the erosional remants as they are exposed diatreme rocks is new and recently supported and presented here in this summary by textural data of the volcanic rocks.

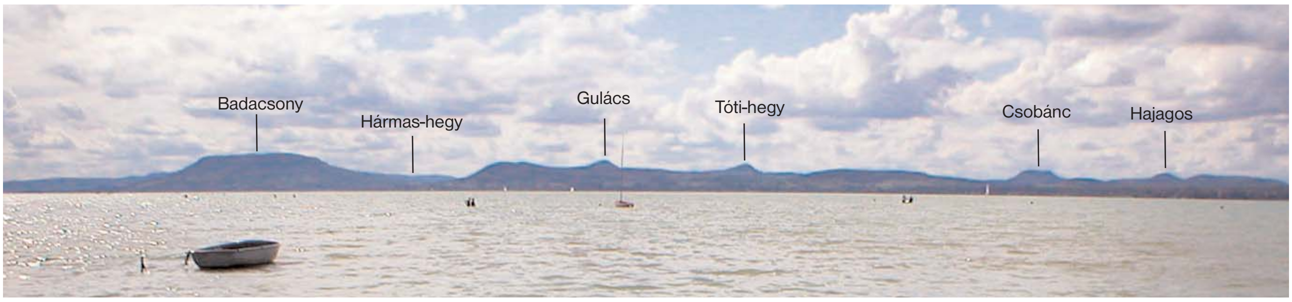


Figure 2.6. Uniform top level of the volcanic erosion remnants (named hills) of the central part of the BBHVF as it looks like from the southern shore of the Lake Balaton

Figure 2.7. Uniform top level of the volcanic erosion remnants (named hills) of the Tapolca Basin from the southern shore of the Lake Balaton. Note the more or less same elevation of the large volcanic butte (Badacsony) in the left hand side of the picture and the Palaeozoic ridge in the right hand side suggesting a very gentle relief in syn-volcanic time on that the volcanoes developed

On the basis of the textural characteristics, as well as the sedimentological features of the preserved pyroclastic rocks of the BBHVF, it is more realistic, that these volcanoes erupted through the pre-volcanic Neogene siliciclastic units in terrestrial conditions, where their erosion immediately modified their shape giving way to develop younger volcanoes on an already eroded landscape. The picture on the LHPVF might be somehow different, however, more detailed studies need to establish temporal and spatial relationships among volcanoes and sedimentation versus erosion across these two volcanic fields.

The estimated erosion rates are in the range of few tens of metres per millions of years. This value is in good agreement with calculations based on other methods from Central Europe (BULLA 1965, MOLNÁR and ZELENKA 1995, KARÁTSON 1996, BAJNÓCZI et al. 2000).

***

Acknowledgements: This review is a result of the past ten years research of the authors embedded in a framework of the general knowledge of the tectonic and magmatic development of the Neogene volcanism in the western Pannonian Basin. During this time various organisations supported this research such as, the Hungarian Science Foundation OTKA F 043346, OTKA T 032866, Magyary Zoltán Post-doctorate Fellowship 2003–2004, DAAD German Hungarian Academic Exchange Program 2002/2003 and the DFG (Ma 2440), many thanks to all of these organisations. Constructive suggestions and review by Ferenc Molnár (Eötvös University, Budapest) lifted significantly the quality of this summary and are greatfully acknowledged. General review by Volker Lorenz (Würzburg University, Germany and Tamás Budai (MÁFI, Budapest) helped to find a reader-friendly presentation style of this work. Great consultations about geomorphological processes in the western Pannonian region with Gábor Csillag (MÁFI, Budapest) are gratefully acknowledged.

References

Aranda-Gomez, J. J. and Luhr, J. F. 1996: Origin of the Joya Honda maar, San Luis Potosi, Mexico. – *Journal of Volcanology and Geothermal Research* 74 (1–2), pp. 1–18.

Bajnóczi, B., Molnár, F., Maeda, K. and Izawa, E. 2000: Shallow level low-sulphidation type epithermal systems in the Regec caldera, Central Tokaj Mts., NE Hungary. – *Geologica Carpathica* 51 (4), pp. 217–227.

Balogh, K. and Pécskay, Z. 2001: K/Ar and Ar/Ar geochronological studies in the Pannonian–Carpathians–Dinarides (PANCARDI) region. – *Acta Geologica Hungarica* 44 (2–3), pp. 281–301.

Balogh, K. and Németh, K. 2004: Evidences of the Neogene small-volume intracontinental volcanism in Western Hungary: K/Ar geochronology of the Tihany Maar Volcanic Complex. – *Geologica Carpathica* [in press]

Balogh, K., Jámbor, A., Partényi, Z., Ravaszné Baranyai, L. and Solti, G. 1982: A dunántúli bazaltok K/Ar radiometrikus kora (K/Ar radigenic age of Transdanubian basalts). [in Hungarian with English summary]. – *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 1980,* pp. 243–259.

Balogh, K., Árva-Sós, E., Pécskay, Z. and Ravasz-Baranyai, L. 1986: K/Ar dating of post-Sarmatian alkali basaltic rocks in Hungary. – *Acta Mineralogica et Petrographica, Szeged* 28, pp. 75–94.

Bence, G., Jámbor, A. and Partényi, Z. 1978: A Várkesző és Malomsok környéki alginit (olajpala) és bentonit kutatások eredményei.[New results of exploration of alginite (oil-shale) and bentonite around Várkesző and Malomsok]. – *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 1977,* pp. 257–267.

Beudant F. S. 1822: Voyage minéralogique et géologique en Hongrie, pendant 1, année 1818. I–III. Paris.

Borsy, Z., Balogh, K., Kozák, M. and Pécskay, Z. 1986: Újabb adatok a Tapolcai-medence fejlődéstörténetéhez. (Contributions to the evolution of the Tapolca-basin, Hungary.) [in Hungarian with English abstract]. – *Acta Geographica Debrecina* 23, pp. 79–104.

Brukner-Wein, A., Sajgó, C. and Hetényi, M. 2000: Comparison of Pliocene organic-rich lacustrine sediments in twin craters – *Organic Geochemistry* 31 (5), pp. 453–461.

Budai, T. and Csillag, G. 1998: A Balaton-felvidék középső részének földtana. (Geology of the middle part of the Balaton Highland.) [in Hungarian]. – *A Bakony természettudományi kutatásának eredményei (Results of the Scientific Research on the Bakony Mts)* 118 p.

Budai, T. and Csillag, G. (Editors) 1999: *A Balaton-felvidék földtana: magyarázó a Balaton-felvidék földtani térképéhez, 1:50 000.* [Geology of the Balaton Highland: explanatory booklet for the geology map of the Balaton Highland, scale 1:50 000.] – *Occasional Papers of the Geological Institute of Hungary* 197. Geological Institute of Hungary, Budapest, 257 p.

Budai, T., Csillag, G., Dudko, A. and Koloszár, L., 1999: A Balaton-felvidék földtani térképe. [Geological map of the Balaton Highland.] – Magyar Állami Földtani Intézet, Budapest.

Bulla, B. 1965: Tertiary levelled surfaces (peneplanes) in Hungary. – In: Mazur, E. and Stehlk, O. (Eds): *Geomorphological problems of Carpathians,* pp. 181–197.

Cas, R. A. F. and Wright, J. V. 1988: *Volcanic succesions, modern and ancient*. – Chapman & Hall, London, 528 p.

Cholnoky, J. 1918: *A Balaton hidrográfiája*. – Magyar Földrajzi Társaság Balaton-bizottsága, Budapest, 316 p.

Connor, C. B. and Conway, F. M. 2000: Basaltic volcanic fields. – In: Sigurdsson, H. (Ed.): *Encyclopedia of Volcanoes,* Academic Press, San Diego, pp. 331–343.

Connor, C. B., Condit, C. D., Crumpler, L. S. and Aubele, J. C. 1992: Evidence of Regional Structural Controls on Vent Distribution – Springerville Volcanic Field, Arizona. – *Journal of Geophysical Research-Solid Earth* 97 (B9), pp. 12349–12359.

Connor, C. B., Stamatakos, J. A., Ferril, D. A., Hill, B. E., Ofoegbu, G. I., Conway, F. M., Sagar, B. and Trapp, J. 2000: Geologic factors controlling patterns of small-volume basaltic volcanism: Application to a volcanic hazard assesment at Yucca Mountain, Nevada. – *Journal of Geophysical Research* 105 (1), pp. 417–432.

Fischer, O. and Hably, L. 1991: Pliocene flora from the alginite at Gérce. – *Ann. Hist.-Nat. Mus. Nat. Hungary* 83, pp. 25–47.

Gutmann, J. T. 1976: Geology of Crater Elegante, Sonora, Mexico. – *Geological Society of America Bulletin* 87, pp. 1718–1729.

Heiken, G. H. 1971: Tuff rings: examples from the Fort Rock-Christmas Lake Valley Basin, South-Central Oregon – *Journal of Geophysical Research* 76 (23), pp. 5615–5626.

Jámbor, Á. 1980: A Dunántúli-középhegység pannóniai képződményei (Pannonian in the Transdanubian Central Mountains). – *A Magyar Állami Földtani Intézet Évkönyve* 65, pp. 1–259.

Jámbor, Á. 1989: Review of the geology of the s.l. Pannonian Formations of Hungary. – *Acta Geologica Hungarica* 32 (3–4), pp. 269–324.

Jámbor, Á. and Solti, G. 1975: Geological conditions of the Upper Pannonian oil-shale deposit recovered in the Balaton Highland and at Kemeneshát. – *Acta Mineralogica-Petrographica, Szeged* 22 (1), pp. 9–28.

Jámbor, Á. and Solti, G. 1976: Geological conditions of the Upper Pannonian oil-shale deposit recovered in the Balaton Highland and at Kemeneshát. [in Hungarian with English abstract]. – *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 1974,* pp. 193–219.

Jámbor, Á., Partényi, Z. and Solti, G. 1981: A dunántúli bazaltvulkanitok földtani jellegei. (Geological characteristics of the Transdanubian basaltic volcanic rocks.) [in Hungarian]. – *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 1979,* pp. 225–239.

Juhász, E., Kovács, L. O., Müller, P., Tóth-Makk, A., Phillips, L. and Lantos, M. 1997: Climatically driven sedimentary cycles in the Late Miocene sediments of the Pannonian Basin, Hungary. – *Tectonophysics* 282 (1–4), pp. 257–276.

Juhász, Gy. 1994: Sedimentological and stratigraphical evidences of water-level fluctuations in the Pannonian Lake. – *Földtani Közlöny* 123, pp. 379–398.

Karátson, D. 1996: Rates and factors of stratovolcano degradation in a continental climate; a complex morphometric analysis for nineteen Neogene Quaternary crater remnants in the Carpathians. – *Journal of Volcanology and Geothermal Research* 73 (1–2), pp. 65–78.

Kázmér, M. 1990: Birth, life, and death of the Pannonian Lake. – *Palaeogeography Palaeoclimatology Palaeoecology* 79, pp. 171–188.

Lóczy, L. sen. 1913: A Balaton környékének geológiai képződményei és ezeknek vidékek szerinti telepedése. [Geological units of the Balaton area and their stratigraphy.] [in Hungarian]. – In: Lóczy, L. sen. (Ed): *A Balaton tudományos tanulmányozásának* *eredményei [New results of the scientific research of the Balaton][in Hungarian],* Magyar Királyi Földtani Intézet [Royal Hungarian Geological Institute], Budapest, 617 p.

LÓCZY, L. SEN. 1920: *A Balaton-tó környékének részletes geológiai térképe. M = 1:75 000. [Detailed geological map of the Lake Balaton area. 1: 75 000].* — Magyar Királyi Földtani Intézet [Royal Hungarian Geological Institute], Budapest

LORENZ, V. 1985: Maars and diatremes of phreatomagmatic origin: a review. — *Transactions of the Geological Society of South Africa* 88, pp. 459–470.

LORENZ, V. 1986: On the growth of maars and diatremes and its relevance to the formation of tuff rings. — *Bulletin of Volcanology* 48, pp. 265–274.

LORENZ, V. 2000: Formation of maar-diatreme volcanoes. — *Terra Nostra* 2000 (6), pp. 284–291.

LORENZ, V. 2003a: Syn- and post-eruptive processes of maar-diatreme volcanoes and their relevance to the accumulation of post-eruptive maar crater sediments. [Maar-diatréma vulkánok szín-és poszt-eruptív folyamatai, azok kapcsolata a poszt-eruptív maar kráter-tavi üledékekkel.] [in English with Hungarian abstract]. — *Földtani Kutatás [Quaterly Journals of the Geological Survey of Hungary], Budapest* XL (2003/2–3), pp. 13–22.

LORENZ, V. 2003b: Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. — *Geolines — Journal of the Geological Institute of AS Czech Republic* 15, pp. 72–83.

MAGYAR, I., GEARY, D. H. and MÜLLER, P. 1999: Palaeogeographic evolution of the Late Miocene Lake Pannon in Central Europe. — *Palaeogeography Palaeoclimatology Palaeoecology* 147 (3–4), pp. 151–167.

MARTIN, U. and NÉMETH, K. 2004: Eruptive and depositional history of a Pliocene intracontinental tuff ring developed in a fluvio-lacustrine basin: Kissomlyó volcano (western Hungary). — *Journal of Volcanology and Geothermal Research* [in review]

MARTIN, U., AUER, A., NÉMETH, K. and BREITKREUZ, C. 2003: Mio/Pliocene phreatomagmatic volcanism in a fluvio-lacustrine basin in western Hungary. — *Geolines — Journal of the Geological Institute of AS Czech Republic* 15, pp. 75–81.

MOLNÁR, F. and ZELENKA, T. 1995: Fluid Inclusion Characteristics and Paleothermal Structure of the Adularia–Sericite Type Epithermal Deposit at Telkibánya, Tokaj Mts, Northeast Hungary. — *Geologica Carpathica* 46 (4), pp. 205–215.

MÜLLER, P. 1998: A pannóniai képződmények rétegtana. (Stratigraphy of the Pannonian sediments.) [in Hungarian]. — In: BÉRCZI, I. and JÁMBOR, Á. (Eds): *Magyaroszág geológiai képződményeinek rétegtana (Stratigraphy of geological units of Hungary),* Budapest, pp. 485–493.

MÜLLER, P. and MAGYAR, I. 1992: A Prosodacnomyak rétegtani jelentősége a Kötcse környéki pannóniai s.l. üledékekben (Stratigraphycal importance of Prosodacnomy bearing pannonian s.l. sediments from Kötcse) [in Hungarian with English abstract]. — *Földtani Közlöny, Budapest* 122 (1), pp. 1–38.

MÜLLER, P., GEARY, D. H. and MAGYAR, I. 1999: The endemic molluscs of the Late Miocene Lake Pannon: their origin, evolution, and family-level taxonomy. — *Lethaia* 32 (1), pp. 47–60.

NAKAMURA, K. 1977: Volcanoes as possible indicators of tectonic stress orientation — principal and proposal. — *Journal of Volcanology and Geothermal Research* 2, pp. 1–16.

NÉMETH, K. and MARTIN, U. 1999a: Large hydrovolcanic field in the Pannonian Basin: general characteristics of the Bakony – Balaton Highland Volcanic Field, Hungary. — *Acta Vulcanologica* 11 (2), pp. 271–282.

NÉMETH, K. and MARTIN, U. 1999b: Late Miocene paleo-geomorphology of the Bakony – Balaton Highland Volcanic Field (Hungary) using physical volcanology data. — *Zeitschrift für Geomorphologie* 43 (4), pp. 417–438.

NÉMETH, K., MARTIN, U. and HARANGI, SZ. 2001: Miocene phreatomagmatic volcanism at Tihany (Pannonian Basin, Hungary). — *Journal of Volcanology and Geothermal Research* 111 (1–4), pp. 111–135.

NÉMETH, K., MARTIN, U. and CSILLAG, G. 2003a: Lepusztult maar/diatrema szerkezetek a Bakony – Balaton Felvidék Vulkáni Területről. (Eroded maar/diatrema structures from the Bakony – Balaton Highland Volcanic Field.) [in Hungarian with English abstract]. — *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 2000,* pp. 83–99.

NÉMETH, K., MARTIN, U. and CSILLAG, G. 2003b: Calculation of erosion rates based on remnants of monogenetic alkaline basaltic volcanoes in the Bakony–Balaton Highland Volcanic Field (Western Hungary) of Mio/Pliocene age. — *Geolines — Journal of the Geological Institute of AS Czech Republic* 15, pp. 102–106.

SACCHI, M. and HORVÁTH, F. 2002: Towards a new time scale for the Upper Miocene continental series of the Pannonian basin (Central Paratethys). — *Stephan Mueller Special Publication Series* 3 (Neotectonics and surface processes: the Pannonian Basin and Alpine/Carpathian System), pp. 79–94.

SACCHI, M., HORVÁTH, F. and MAGYARI, O. 1999: Role of unconformity-bounded units in the stratigraphy of the continental record; a case study from the late Miocene of the western Pannonian Basin, Hungary. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen.,* Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 357–390.

SOLTI, G. 1986: Az egyházaskeszői tufakráterben települő bentonit és alginit telep. [Bentonite and alginite in the Egyházaskeszõ tuff crater]. — *A Magyar Állami Földtani Intézet Évi Jelentése = Annual Report of the Hungarian Geological Institute 1986,* pp. 379–397.

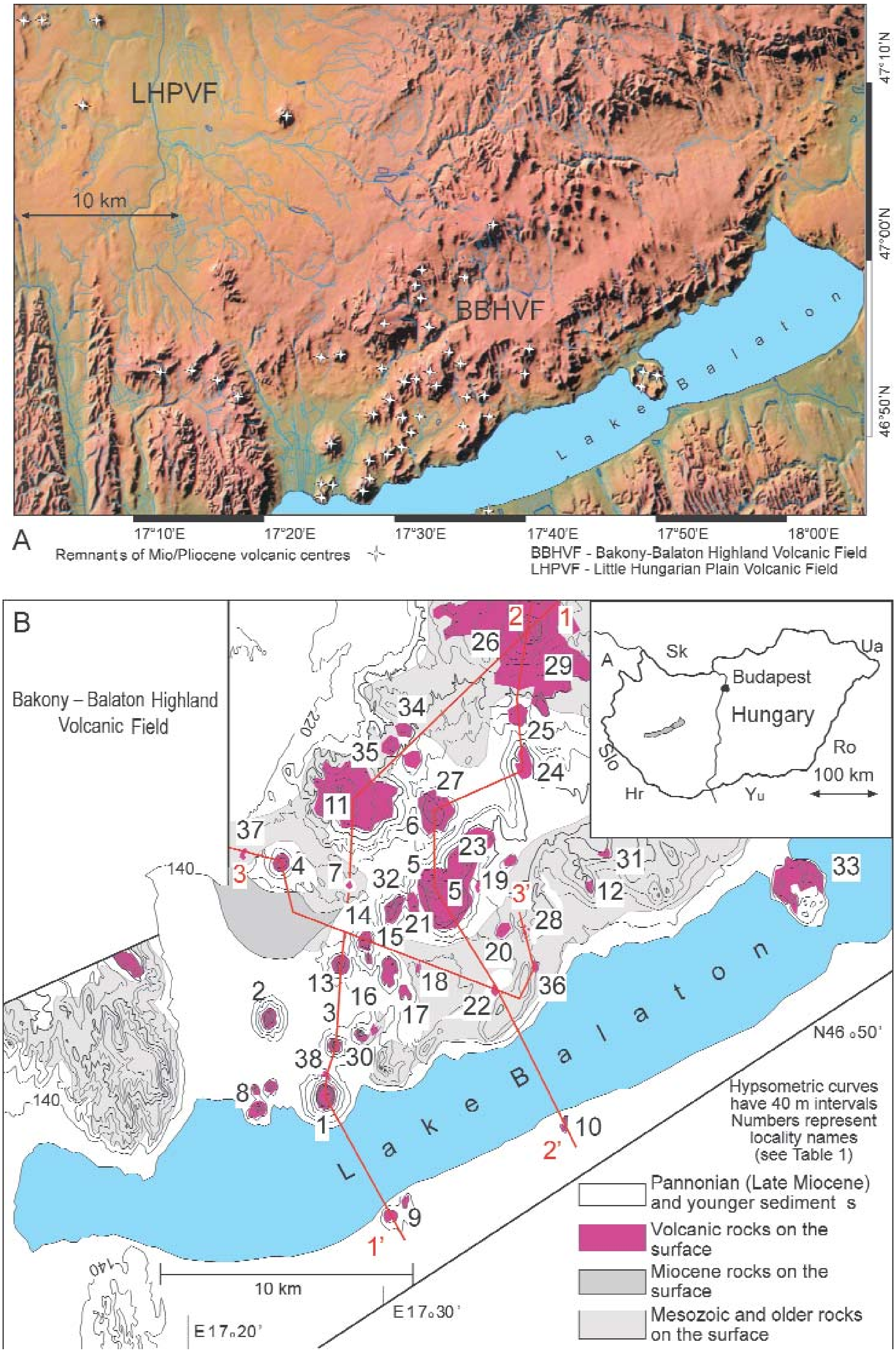
STRAUSZ, L. 1943: Adatok a Vend-vidék és Zala geológiájához. (Data for the geology of the Vend-region and Zala). — *Földtani Közlöny* 73. pp. 38–53. [in Hungarian]

TÓTH, CS. 1994: A Kemenesháti tufagyűrűk geofizikai kutatása. [Geophysical investigation of tuff rings in the Kemeneshát]. — *Geophysical Transactions = Geofizikai Közlemények = Geofizicheskiy Byulletin'* 39 (2–3), pp. 161–191.

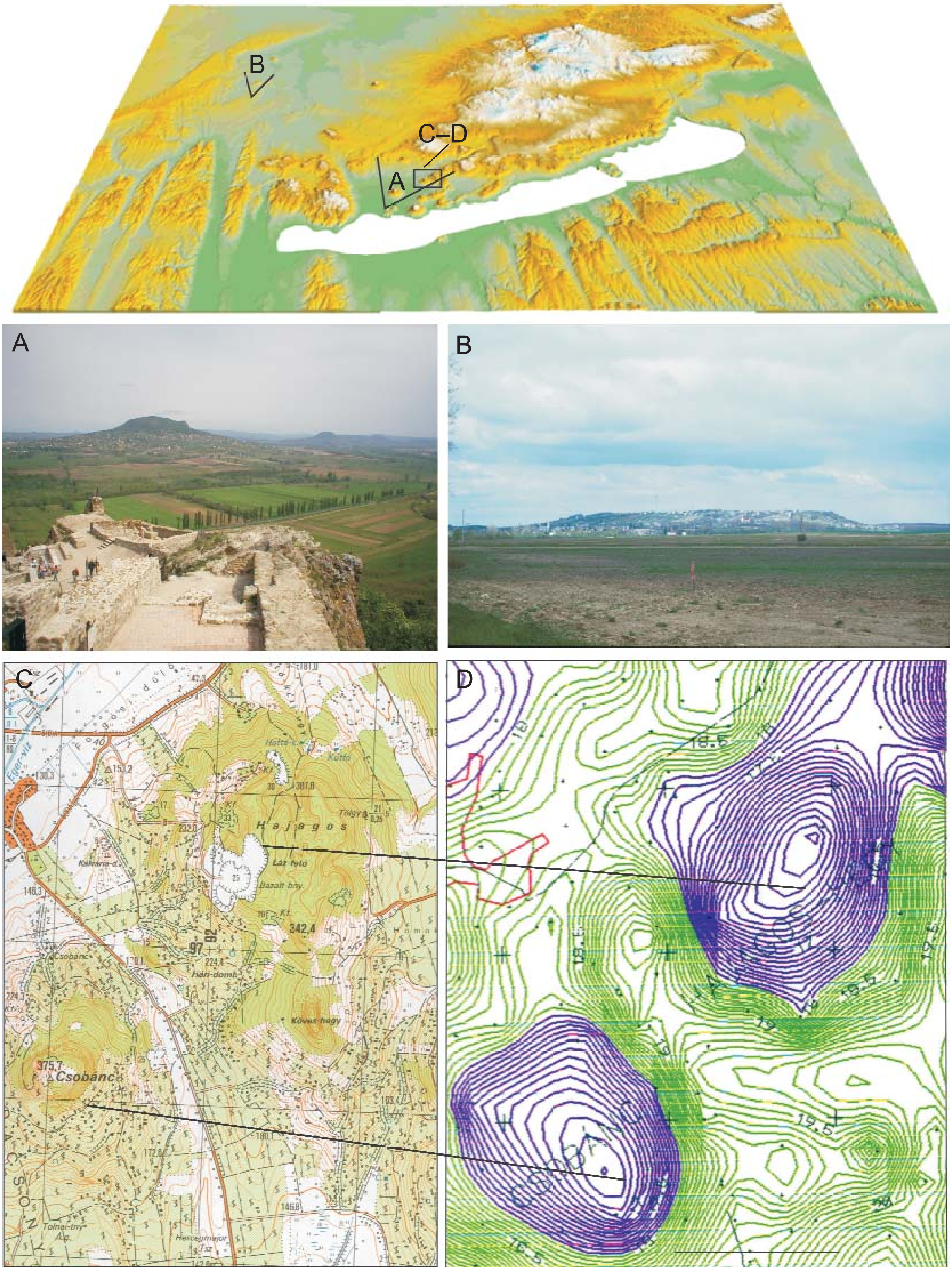
WIJBRANS, J., NÉMETH, K., MARTIN, U. and BALOGH, K. 2004: ^{40}Ar/^{39}Ar geochronology of a Mio/Pliocene phreatomagmatic volcanic field in the western Pannonian Basin, Hungary. — *Earth Planetary Science Letters* [in review]

WINKLER, A. 1925: A Kis-Magyar-Alföld szegélyén a Kelet-Stájer medencében fellépő bazaltkitörések kora és keletkezése. (The age and origin of the basalt volcanism in the margin of the Little Hungarian Plain, in the Eastern Styrian Basin.) — *Földtani Közlöny 55.* pp. 227–231. [in Hungarian]

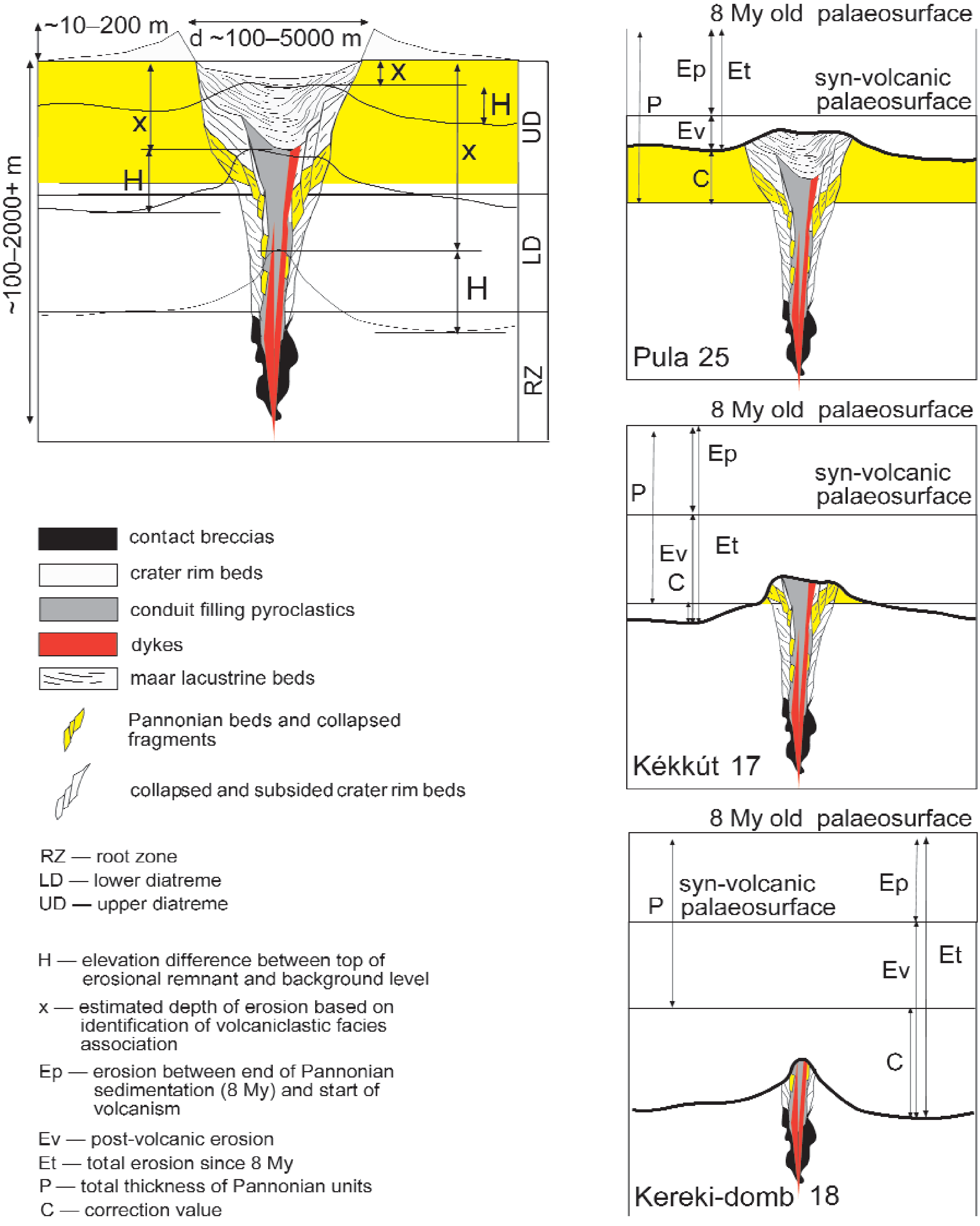
Digital terrain model (A) of the western Pannonian Basin with erosional remnants of small-volume intraplate volcanoes (stars). A simplified geological map of the Bakony – Balaton Highland Volcanic Field (B) gives an overview of the relationship between distribution of volcanoes and type of exposed units. The lines on this map correspond to the cross sections shown on Plate. 2.4. Numbers refer to the identified volcanic erosion remnants and the names are shown on Table 2.1



General landscape features of eroded monogenetic volcanoes, A) Szent György-hegy, BBHVF, B) Kis-Somlyó (LHPVF). The general negative Bouguer anomalies where lava capped buttes are located suggests a significant mass deficit below these erosional remnants. On figure D an example is shown from the Hajagos in comaprison to the topography of the hill itself (C). The values on the gravity map are in milligalls and recovered from unpublished data of Kovácsvölgyi (Eötvös Lorand Geophysical Institute, Budapest)



Estimation of the erosion level on the basis of identified volcanic lithofacies from the BBHVF (Németh et al., 2003b). Model of a monogenetic phreatomagmatic volcano and its erosion through time. Note the 3 different stages of erosion can be established by the identification of different volcanic lithofacies from different examples from the field. Abbreviations correspond to Table 2.1



Reconstructed syn-volcanic palaeosurfaces through the BBHVF showing a very uniform, flat landscape (Németh et al. 2003b). Cross-section lines are shown on Plate 2.1, B