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ORIGINAL PAPER

D. Karátson · K. Németh · B. Székely
Zs. Ruszkiczay-Rüdiger · Z. Pécskay

Incision of a river curvature due to exhumed Miocene volcanic landforms: Danube Bend, Hungary

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Abstract A new model for the formation and relief evolution of the Danube Bend, northern Hungary, is discussed on geomorphological and volcanological grounds. We propose that the present-day U-shaped loop of the Danube Bend was partly inherited from the horseshoe caldera morphology of Keserűs Hill volcano, a mid-Miocene (ca 15 Ma) lava dome complex with an eroded central depression open to the north. According to combined palaeogeographical data and erosion rate calculations, the drainage pattern in the Danube Bend region was formed when Pleistocene tectonic movements resulted in river incision and sedimentary cover removal. Formation of the present curvature of the river was due to the exhumation of the horseshoe-shaped caldera as well as the surrounding resistant volcaniclastic successions (i.e. Visegrád Castle Hill) and a hilltop lava dome (Szent Mihály Hill). The process accelerated and the present narrow gorge of the Danube Bend was formed by very rapid, as young as late Quaternary differential tectonic uplift, also enhancing the original volcanic morphology. On the basis of comparative long-term erosion-rate calculations, we estimated successive elevation changes of the volcanic edifice, including partial burial in late Miocene time. In comparison with various order-of-magnitude changes, the mid-to-late Quaternary vertical movements show increased rates and/or base level drop in the Pannonian Basin.

Keywords Miocene volcanism · Horseshoe-shaped caldera · Differential uplift · River incision · Pannonian basin

D. Karátson (✉) · Zs. Ruszkiczay-Rüdiger
Department of Physical Geography, Eötvös University,
Pázmány P. sétány 1/c, 1117, Budapest, Hungary
E-mail: dkarat@ludens.elte.hu

K. Németh
Hungarian Geological Institute, Stefánia út 14,
1143, Budapest, Hungary

B. Székely
Institut für Geowissenschaften, Universität Tübingen,
Sigwartstr. 10, 72076, Tübingen, Germany

B. Székely
Space Research Group, Department of Geophysics,
Eötvös University, Pázmány P. sétány 1/b,
1117, Budapest, Hungary

Zs. Ruszkiczay-Rüdiger
Netherlands Research Centre for Integrated Solid Earth Science
(ISES), de Boelelaan 1085, HV 1081, Amsterdam, The Netherlands

Z. Pécskay
Institute of Nuclear Research, Hungarian Academy of Sciences,
Bem József tér 18/c, 4001, Debrecen, Hungary

Present address: K. Németh
Soil and Earth Sciences, Institute of Natural Resources,
College of Sciences, Massey University, PO Box 11 222,
Palmerston North, New Zealand

Introduction: the problem of Danube Bend

The arcuate rocky "Visegrád Gorge" of the Danube Bend in Northern Hungary (Fig. 1), conspicuous on satellite images, separates two mid-Miocene volcanic areas: the Börzsöny and Visegrád Mountains (Fig. 2). These are among the oldest members of the Inner Carpathian Volcanic Chain (e.g. Pécskay et al. 1995). It is widely accepted that the Danube river found its place between these mountains in Plio-Pleistocene times (e.g. Bulla 1941; Pécsi 1959; Gábris 1994). However, the fundamental questions: (1) how and why the 12-km long horseshoe-shaped section of the gorge was formed and (2) what the relationship is, if any, between its two sides: the northern Visegrád Mountains to the south and the Szent Mihály Hill to the north, have not adequately been addressed so far. Láng (1955) proposed an epigenetic origin of a previous meander of a "large palaeoriver", but evidence and field data were not presented.

Our main objective is twofold. Firstly, the possible contribution of the original volcanic landforms to the present fluvial landform has never been investigated.

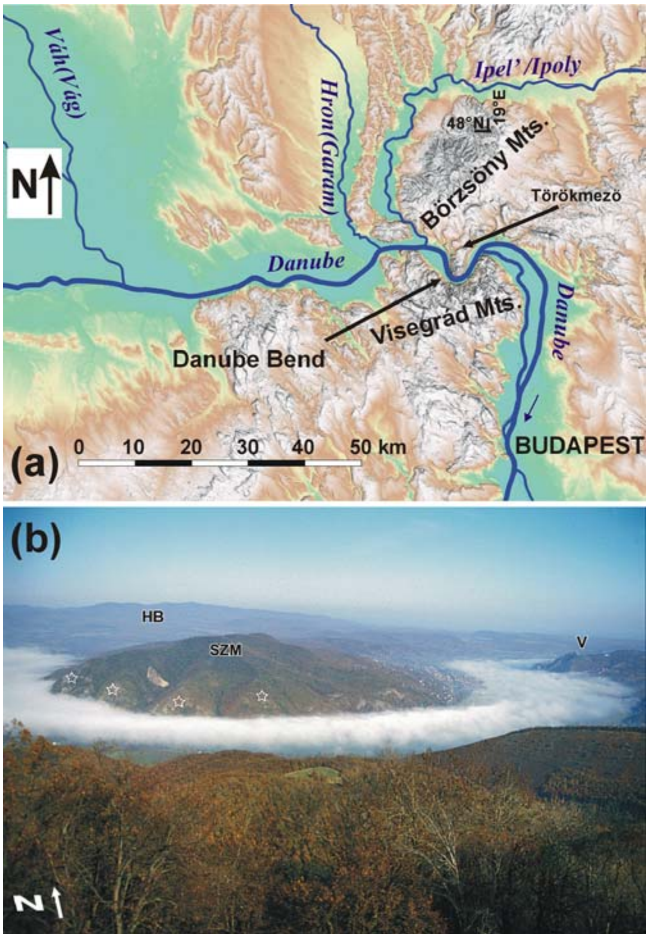

Fig. 1 **a** Position and key locations of the river curvature Danube Bend in North Hungary. The river, together with its present-day tributaries on the northern side, forms a water gap between the mid-Miocene Visegrád and Börzsöny volcanic mountains. This drainage pattern may be as young as mid-to-late Pleistocene. **b** Panoramic view of the Danube Bend as seen from the highest point of the mid-Miocene Keserűs Hill volcano. Layer of fog situated ca 80 m above the Danube corresponds to an earlier position of the river bed. *SZM* Szent Mihály Hill (see stratigraphic log of its left side in Fig. 4d). *Stars on the lower flank* indicate steep, triangular hillslope surfaces (flatirons) formed since mid/late Pleistocene, rapid river incision. *V* Visegrád Castle Hill, located 8 km far from the rim, consists of top of resistant block-and-ash flow and debris-avalanche breccias, and has topographically constrained the course of the river. *HB* Remnants of the High Börzsöny lava dome complex similar to Keserűs Hill volcano

We present new results on the Miocene volcanism of the Visegrád Mountains, and show that the preserved volcanic landforms served as an important geomorphological background for the fluvial relief evolution. Secondly, subsidence and sedimentation in the Pannonian Basin and recent evidence of subsequent differential uplift and erosion, which is of broader interest, are discussed. We point out that the Danube Bend is a key element to check the applicability of new ideas to the relief evolution of the Pannonian Basin (e.g. Dunkl and Frisch 2002). Moreover, we think that the proposed evolutionary scenario may serve as a useful model for other segments of peri-Alpine evolution of large river channels.

Landforms and volcanic successions

Geographical and geological setting

The northern part of the Visegrád Mountains (700 m asl) is situated along the southern side of the Danube Bend (ca 100 m asl). It has long been considered a uniform volcanic field together with the well exposed, steep Szent Mihály Hill on the northern side (Cholnoky 1937; Korpás 1998), which is swept round by the river in a 5×6 km large loop (Fig. 1). Both sides consist of andesitic lava and volcaniclastic rocks (Fig. 2) but a detailed mapping has not yet been carried out. To the south, the Danube River is surrounded by 500–700 m tall, steep ridges and tributaries in between that are more or less perpendicular to the course of the river (Figs. 2, 3). A single location, the Visegrád Castle Hill (333 m) at the eastern edge of the river curvature, has very steep ($>35^{\circ}$) slopes. After passing the Castle Hill, the river turns southward, and reaches the Great Hungarian Plain, forming islands of gravelly alluvium (e.g. Szentendre Island: Fig. 2). The Szent Mihály Hill also has very steep ($>40^{\circ}$) lower flanks and slight breaks midslope (Figs. 1, 3).

Due to deep erosion, in some areas of the mountains the underlying Oligocene–Lower Miocene sedimentary formations crop out. In other places the sedimentary cover deposits are exposed. In Table 1, a brief summary of the preserved mid-Miocene volcanic pile is given. Field data indicate that the majority of the volcanic rocks belong to the main amphibole andesite unit, making up both sides of the Danube Bend. In order to clarify the type and age of volcanic processes, field volcanological and K/Ar geochronological studies have been made.

Role of volcanic successions in palaeo-geomorphology

Selected stratigraphic logs (Figs. 4, 5) represent various facies associations from bottom to top of the volcanic pile and are arranged approximately along a N–S section (locations in Figs. 2, 3a, 7b).

At the southern periphery, the section from the ravine of Holdvilág Creek to the rocky Csikóvár Hill (V-15: Fig. 4a) reveals a complex succession of dacitic to andesitic, shallow subaqueous to emergent volcanic activity. Small-volume ignimbrites, abundant block-and-ash flow and debris-flow deposits were related to lava dome eruptions (Gméling et al. 2000; Höfer 2003).

In the central part, the elevated Rocks of Zsiványsziklák (V-14: Fig. 4b) exhibit a somewhat similar succession to Holdvilág Creek, except that the lower phreatomagmatic deposits are absent. A great number of pyroclastic and reworked volcaniclastic flow units

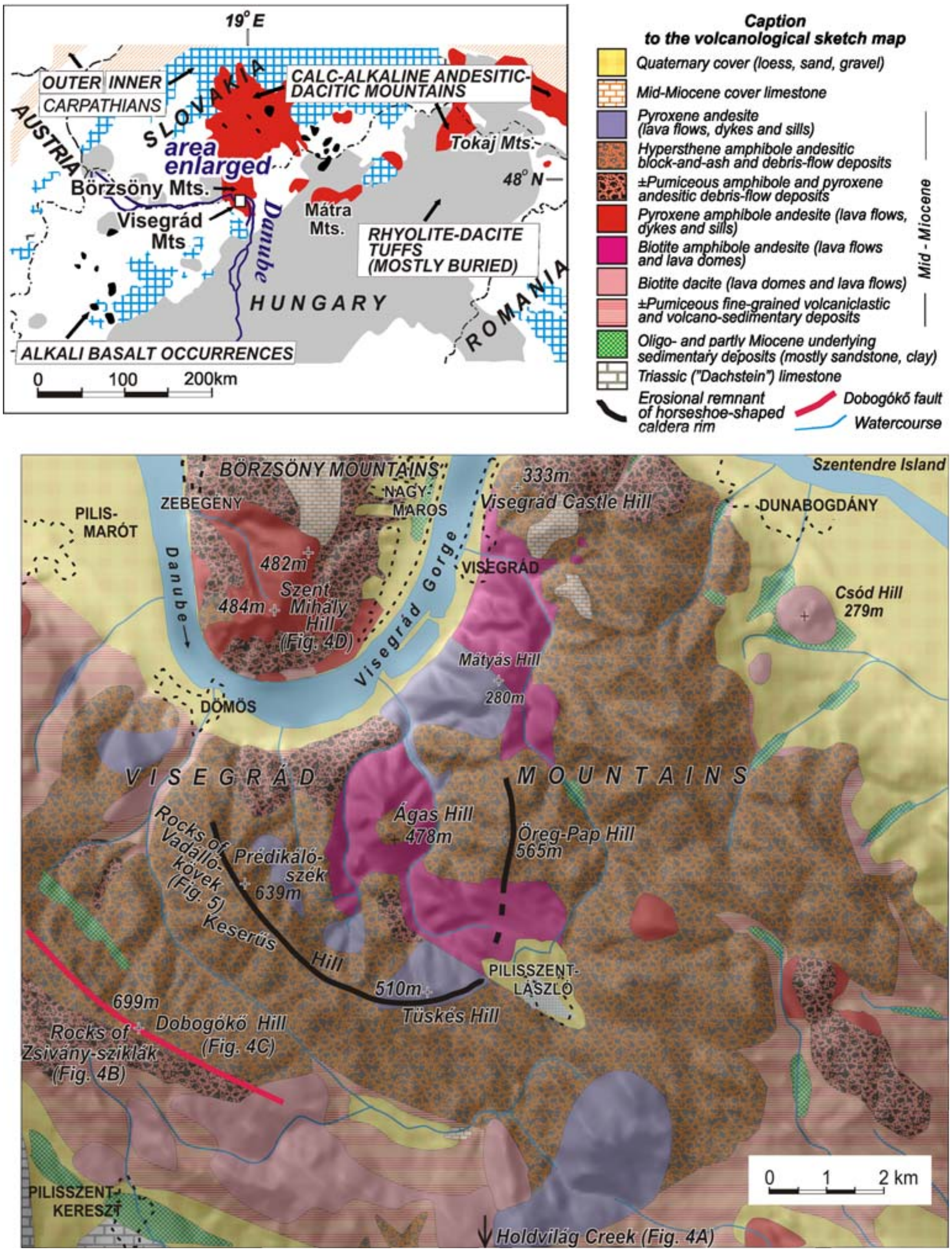

Fig. 2 Setting and volcanological sketch map of the Visegrád Mountains**.** Geology based on Schafarzik and Vendl (1929), Zelenka (1960), Korpás et al. (1977) and Korpás (1998), modified by our data

indicate distal deposition on a ring plain. Similar successions are present at V-52 to 55 and V-118 (see Fig. 3a).

The Rocks of Vadálló-kövek (V-11, hereafter referred to as VK; Fig. 5) are a series of well-exposed rock towers made up by proximal, coarse-grained, andesitic block-and-ash flow deposits (Karátson et al. 2001) with thin, interbedded fluvial and hyperconcentrated streamflow deposits. The unsorted, unstratified, monolithologic (amphibole andesite) breccia sequences, composed of up to 10 m thick flow units, as well as the presence of interbedded epiclastic deposits with moderate (15–25°) dips (Fig. 5), imply the preservation of the lower flanks of an explosive lava dome complex.

The Dobogókő Hill breccias (Rocks of Thirring-sziklák, V-13: Fig. 4c) exhibit identical lithology and similar sedimentological features to VK. More developed stratification and grading, thinner flow units, as well as overall finer grain sizes than at VK, argue for a more distal deposition of the same deposit type. Orientation of elongated rock towers (originally as valley-filling, now exhumed deposits) along the southwestward dip of strata, locate the possible source of both deposits (V-11 and V-13) to the northeast.

The Visegrád Castle Hill (hereafter referred to as VCH: Fig. 2) exposes a more than 200 m succession on its western, very steep side facing the Danube. It consists

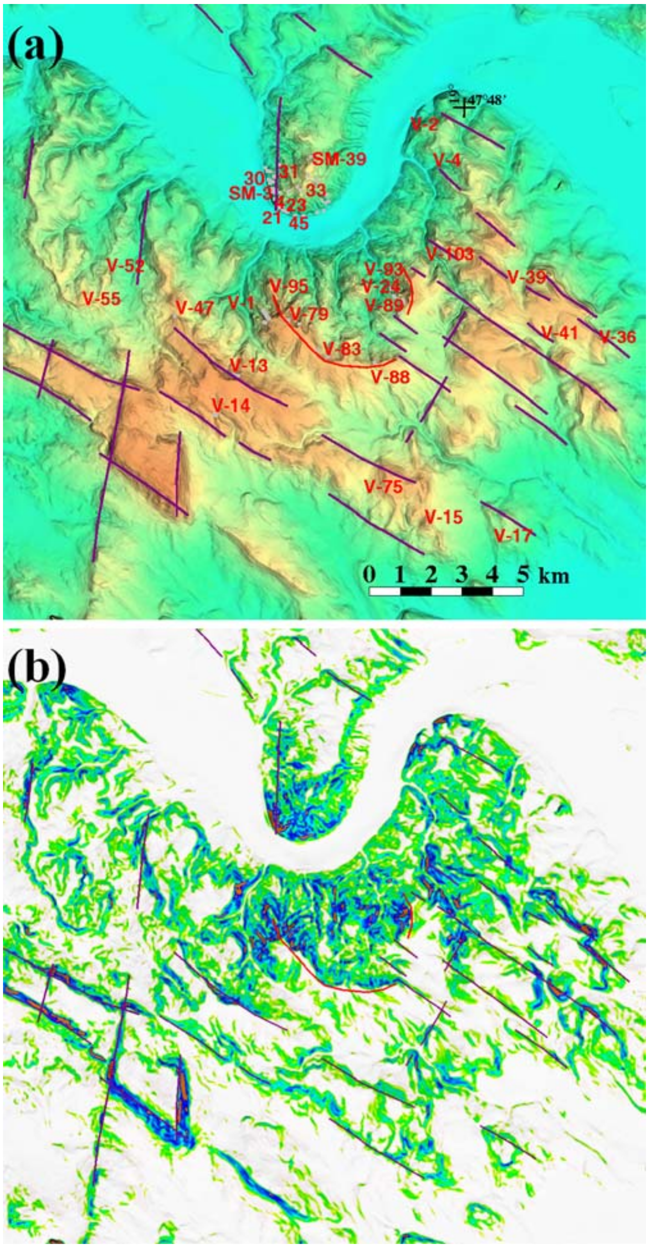

Fig. 3 DEM-derived images of the Visegrád Mts. **a** Shaded and coloured relief map with the eroded, tectonically dismembered and displaced rim of the Keserűs Hill horseshoe-shaped caldera (*red outlines*) and inferred major faults (*violet lines*). Red numbers refer to mapped outcrops mentioned in the text. Spatial integration of data is according to Molnár and Timár (2002) and Timár et al. (2002). **b** Average slope angle map calculated with 150 m rectangular window excluding slope angles below 3°. The steepest slopes (increasingly coloured from white through green to deep blue) characterize first of all the Keserűs Hill horseshoe-caldera, especially along the inner side of its eroded rim, the outer slopes being much more gentle. This contrast suggests that the original slope characteristics have been inherited. Note the steep slope pattern of the S part of Szent Mihály Hill similar to the main structure, resulting from the late Pleistocene incision of the Danube

of a lower andesite autoclastic breccia and an upper andesite breccia of identical lithology to VK and its vicinity. The upper part shows the characteristics of block-and-ash-flows similar to VK. However, shear zones, plastic deformation of embedded, fine-grained strata and jigsaw-fit of oversized (>5 m) blocks imply additional debris-avalanche transport mechanism, possibly from the volcanic centre of VK.

The Szent Mihály Hill (hereafter referred to as SM) composite section (SM-3, 4, 31, 32, 33: Fig. 4d) displays even more complex sequences. At the base, highly fractured lava rock (the possible subvolcanic level, found also in boreholes) is overlain, among others, by very coarse-grained debris-flow as well as small-volume debris-avalanche deposits. Lithological similarities to VK (i.e., VK-type amphibole andesite and a basic pyroxene andesite (SM-3) that occurs near VK (V-66), as well as the general, gentle northward dip of strata, indicate that these volcaniclastic successions were deposited on a ring plain (term after Palmer and Neall 1991), extending from the south. The topmost, 150–200 m thick blocky andesite lava unit may have originated from a local vent that erupted subsequent to the volcaniclastic sedimentation on the ring plain.

In order to infer the source and the geometric centre of the amphibole andesitic volcanism, dips of the above and other relevant deposits have been measured (Table 2, Fig. 6). Azimuth and inclination data have been determined for (a) flat surfaces of individual, oversized clasts in block-and-ash and debris-flow deposits, (b) layered matrix or laminated, fluvial/hyperconcentrated streamflow deposits, and (c) strike of elongated, originally valley-filling rock formations such as described with the Dobogókő Hill breccias.

K/Ar datings

The exact timing of the mid-Miocene volcanism of the Visegrád Mountains is thought to lie within an interval of 16.5–13.5 Ma (Pécskay et al. 1995; Korpás 1998). In our study, we selected identical or similar amphibole andesite rock types from both sides of the Danube. For methods used, see Balogh (1985) and Pécskay et al. (1995).

The obtained data show identical ages within the analytical error. The age of the amphibole andesite of VK (V-11: 15.43 ± 0.60 Ma) is the same either for the Dobogókő Hill breccia (V-13) of distal block-and-ash flow origin, or the VCH upper breccia (V-2b) of possibly debris-avalanche origin. At SM, amphibole andesite lava similar in age to VK (15.50 ± 0.66 Ma) is overlain by the topmost andesite lava unit of slightly younger age (14.55 ± 0.64 to 14.03 ± 0.80 Ma); moreover, all rocks of SM have identical paleomagnetic characteristics with those of VK (E. Márton-Szalay, personal communication).

We note that, due to analytical (~0.7 Ma) as well as geological errors, a single eruptive stage cannot be proven. However, the good fit of the available volcanological, petrographical and K/Ar isotopic data indicate that the andesite sequence was the result of a

Table 1 Major geologic features of prevolcanic rocks to mid-Miocene volcanic successions in the Visegrád Mountains

Age	Lithology	Facies, palaeogeography	Surface outcrops	Reference
Mid-Miocene	Leitha Limestone	Reef limestone	Visegrád Castle Hill, Szent Mihály Hill	Müller (1984), Dulai (1996)
Mid-Miocene	Predominant amphibole andesite volcaniclastic and minor lava rocks	Lava domes and related block-and-ash flow deposits with interbedded volcanic-sedimentary rocks; subaerial volcanism	Central and N part	Schafarzik and Vendl (1929), Zelenka (1960), Korpás et al. (1977), Harangi et al. (1999) and this paper
Mid-Miocene	± Garnet-bearing (rhyo)dacitic lava and volcaniclastic rocks	Lava domes, subvolcanic bodies and related pyroclastics and resedimented volcaniclastic deposits; shallow submarine to emergent volcanism	S to SE part	Schafarzik and Vendl (1929), Zelenka (1960), Korpás et al. (1977), Harangi et al. (1999) and this paper
Lower Miocene	Sandstone	Shallow submarine (littoral) deposit	A narrow belt in the E periphery	Bohn-Havas and Korecz-Laky (1980)
Eocene-Oligocene	Clay, sandstone and gravel	Shallow submarine deposits	A few Oligocene localities mostly in the W part	Korpás (1998) and references therein
Upper Triassic	Limestone	Platform carbonates	S to SW of the Visegrád Mts.	Korpás (1998) and references therein

well-defined eruptive stage ca 14.5–15 Ma ago, determined by the amphibole andesitic block-and-ash flow activity of Keserűs Hill volcano.

Interpretation of the volcanic structure

For the amphibole andesitic series, an early "caldera hypothesis" about the volcanic structure of the Northern Visegrád Mountains (Schafarzik and Vendl 1929; Cholnoky 1937) is still maintained in recent literature (Korpás 1998). These authors proposed a double, nested caldera (the Dobogókő and Keserűs Hill "Somma-type" volcanoes). This interpretation was based on arcuate ridge sections, drainage patterns, and the Somma-Vesuvius geomorphological analogy, but with little field-based information and detailed discussion. Morphologically, both "calderas" are open to the north encircling the U-shaped loop of the Danube Bend (Figs. 2, 3a). The outer "caldera" rim, which is much less clear in the

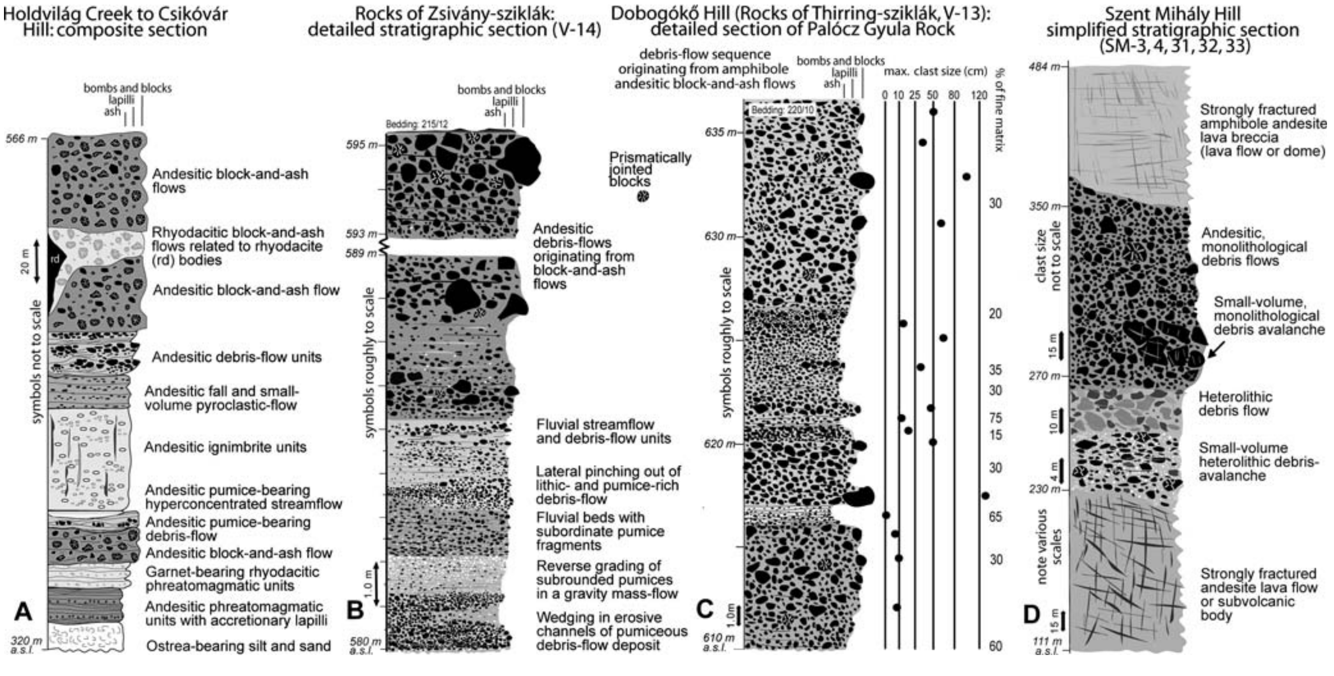

Fig. 4 Representative volcanological sections of the Visegrád Mountains. For localities, see Figs. 2 and 3a. **a** Holdvilág Creek and Csikóvár Hill, **b** Rocks of Zsivány-sziklák (V-14), **c** Dobogókő Hill northern slope (V-13), **d** Szent Mihály Hill western slope (for discussion, see text). Figure 4a has been compiled in part using data of Gméling et al. (2000) and Höfer (2003)

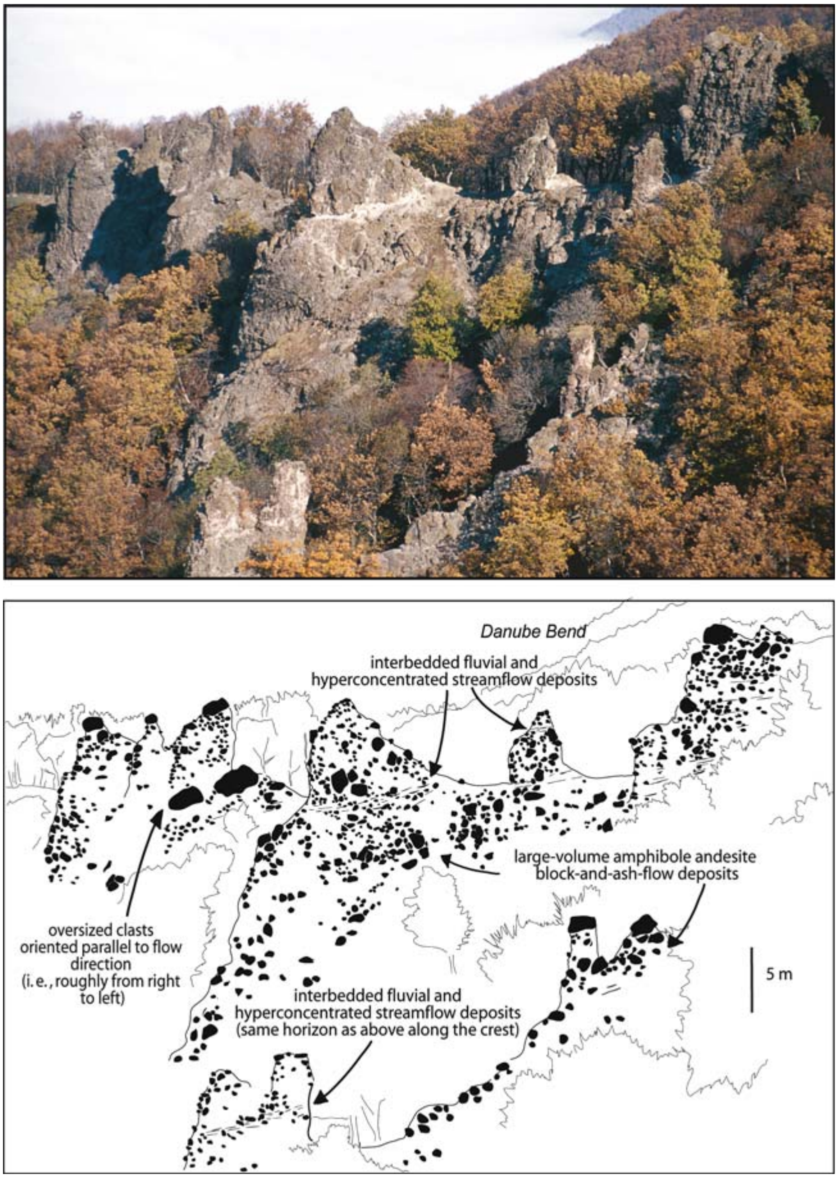

Fig. 5 View and interpretation of the Rocks of Vadálló-kövek (V-11). Outcrop series located on the southwestern flank of Keserűs Hill volcano, close to the eroded rim of the horseshoe-caldera (to the right)

morphology, was proposed to be 10 km and the inner one 4 km in diameter. However, no caldera-related deposits such as ignimbrites, and no explanations as to how the ‘‘calderas’’ were formed, have been presented.

On the basis of our data, neither volcanological nor geomorphological evidence support large caldera-forming eruptions in the study area. This negative evidence includes (1) the general lack of ignimbrites; (2) dominance of resedimented volcaniclastic deposits, implying small-scale eruptions and effective reworking in quiescent periods; (3) centimetre-sized pumice and typically subrounded pumice and subangular andesite clasts which also imply small-scale eruptions and considerable reworking; (4) no clear caldera morphology along the outer, larger ‘‘caldera’’ (i.e. linear instead of arcuate ridges, and missing ridge sections, see Fig. 3a); (5) slope category distribution (Fig. 3b) shows no indication of a double caldera structure; (6) the outer ‘‘caldera rim’’ successions (e.g. V-13, 14, 39) reveal stratified, 5–15° dipping layers of various debris-flow deposits, typical of a ring plain; (7) those successions (e.g. at Dobogókő Hill, V-13) exhibit the same lithologic and volcanic-sedimentary features as the central area (e.g. VK); (8) the inferred small- to medium-scale eruptions fit with those concluded in the coeval, neighbouring Börzsöny Mountains (Karátson and Németh 2001) to the north, and the Burda (Helemba) Mountains (Konečny and Lexa 1994) to the northwest.

In contrast, for the inner (Keserűs Hill) proposed caldera, the existence of a deeply eroded volcanic structure can be verified. The edifice has an easily recognizable, arcuate ‘‘caldera rim’’ (Figs. 2, 3). Along the rim, at the area of VK and Öreg Pap Hill (V-24, etc.), monolithologic, coarse-grained sequences of block-and-ash flow deposits are exposed, characteristic of lava dome complexes (Fig. 5). At the southeastern rim of the

Table 2 Dip data and K/Ar ages of selected deposits of the widespread amphibole andesite volcanism of the Visegrád Mts

Locality (Fig. 3a) and no. K/Ar laboratory	Dip or strike$^{(*)}$ of rock azimuth or orientation (°) /inclination (°)	Analytical results of K/Ar dating			
		K (%)	$^{40}Ar_{rad}$ (%)	$^{40}Ar_{rad}$ (ccSTP/g)	K/Ar age (Ma)
Rocks of Vadálló-kövek (VK) V-11 (no.5771)	[2] 234/20, [3] 245/30, [7] 265/18, 270/20, 250*, [9] 250*, [10] 240*, [11] 260*, [12] 225-250/20, [13] 240/16	1.563	74.4	9.418×10^{-7}	15.43 ± 0.60
Dobogókő Hill (Rocks of Thirring-sziklák) V-13 (no.5772)	[2] 220/10, 225*, [3] 225*, [4] 220*	1.532	45.5	9.183×10^{-7}	15.35 ± 0.67
Zsivány-sziklák V-14	220/38, 238/15				
Öreg Pap Hill V-24	Upper part: 100, 90* , middle part: 85*, lower part: 80/20 (matrix)				
Öreg Pap Hill V-90	125/23 (average of four similar dips)				
Öreg Pap Hill V-91	70−150/20				
Öreg Pap Hill V-92	80-90/20, 85*				
Öreg Pap Hill V-93	42/20, 48/5 (matrix)				
Öreg Pap Hill V-103	30/10				
Tost-sziklák V-47	248/5, 280/5, 264/10, 262/12				
Prédikálószék Hill (N) V-95	265/20				
Prédikálószék Hill (S) V-79	290/40				
Prédikálószék Hill (SE) V-80	242/18				
Prédikálószék Hill (E) V-66 (no.6155)		1.421	35.5	8.435×10^{-7}	15.21 ± 0.74
Keserűs Hill rim (SSW) V-82	180–250* (six measurements)				
Keserűs Hill rim (SSW) V-83	176*				
Tüskés Hill V-88 lava flow	175/22 (average of eight similar dips)				
Visegrád Castle Hill (VCH) V-2a (lower) (no.5505)		1.124	51.8	6.339×10^{-7}	14.45 ± 0.61
Visegrád Castle Hill (VCH) 2b (upper) (no.5504)		1.172	62.0	6.995×10^{-7}	15.29 ± 0.61
Visegrád Castle Hill (VCH) 2b (upper) (no.5769)		1.460	26.6	8.701×10^{-7}	15.28 ± 0.96
Prépost Hill V-7b lava flow (no.5515)		1.206	19.5	7.213×10^{-7}	15.32 ± 1.14
Bagó-kő Hill VH-50 (no.5775)		0.974	41.4	5.535×10^{-7}	14.56 ± 0.66
Bodzás Valley SM-36 lava flow (no.5774)		1.214	47.8	7.348×10^{-7}	15.50 ± 0.66
Szent Mihály Hill SM-40 (no.5768)		1.290	27.7	7.060×10^{-7}	14.03 ± 0.80
Szent Mihály Hill SM-38 (no.6159)		2.126	44.7	1.207×10^{-6}	14.55 ± 0.64

Most localities are pyroclastic breccia, except some lava flow occurrences. Dip data, measured at localities of block-and-ash and debris-flow deposits around the Keserűs Hill volcano, refer to (a) flat surfaces of individual clasts, (b) strike of rock formations inferred to be parallel to flow (*), and (c) layered, laminated matrix ("matrix"). Numbers in [brackets] within the first two groups, i.e. V-11 and V-13, indicate individual rock towers (see the example of the Rocks of Vadálló-kövek in Fig. 5). All K/Ar datings were made on whole rock, except SM-38 (volcanic glass fraction)

"caldera" (Tüskés Hill: V-88), platy jointed, outward-dipping lava flows also occur. In addition, the VK and Öreg Pap Hill breccia successions are characterized by interbedded, low-angle (15–20° dipping) hyperconcentrated streamflow and fluvial deposits. These indicate that the lower flanks of the original lava dome have been preserved: undulations and varying thickness of the interbedded deposits point to temporary gullies cut into the volcano flanks. Dip data of the described breccias, lava flows and volcanic-sedimentary deposits at Keserűs, Prédikálószék, Tüskés and Öreg Pap hills, as well as those of reworked block-and-ash flow and other debris-flow deposits at distal localities (Table 2, Fig. 6), show a systematic quaquaversal orientation. This is a compelling evidence for the existence of a volcanic cone surface, displaying radial pathways of gravity mass flows. Hence, we interpret the Keserűs Hill volcano as a lava dome complex exhibiting a truncated cone shape.

To the north of Keserűs Hill, at several localities of VCH and SM, debris-flow to small debris-avalanche deposits (with oversized blocks 5–8 m in diameter) crop out. The steep morphology of the VCH upper part, which has the same age as Keserűs Hill volcano, may be due to the exposure of a hummock rather than an edifice vent (cf. Korpás 1998; Harangi et al. 1999). Interpretation of the SM sequence is more complex. Its basal successions may correspond to the proximal part of the ring-plain series around Keserűs Hill volcano. The short distance of the ring-plain from the calculated geometrical centre of the volcano (3–4 km) as well as the high proportion of high-energy mass-flow deposits (Fig. 3) fit in with such an assumption.

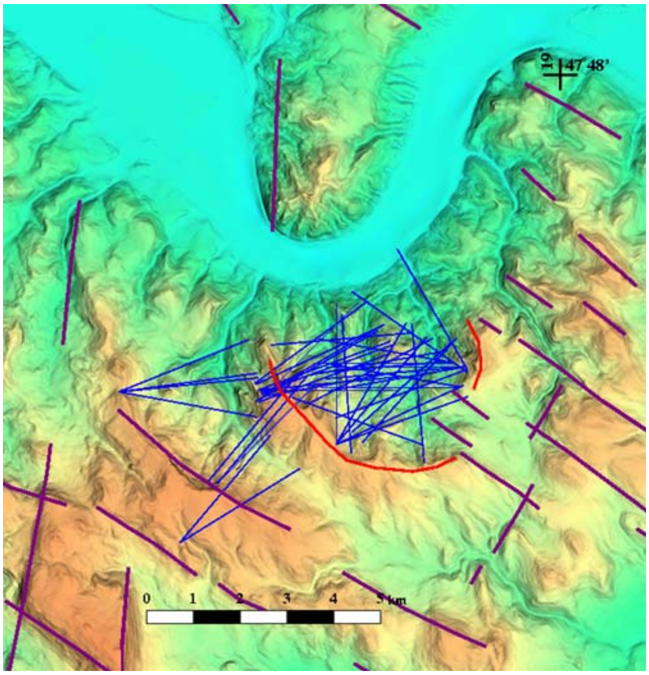

Fig. 6 Derivation of the projection centre of Keserűs Hill volcano on the basis of dipping data reported in Table 2. *Blue lines* correspond to individual dips measured. *Quadrangle* shows the approximate position of the inferred summit vents

The fact that the VCH top sequence and much of the SM successions are related to destructive, voluminous mass-flows has important implications for the original volcanic landform. Because they are located opposite the U-shaped Keserűs Hill depression, its open scar can be explained as remnant of a horseshoe-shaped caldera related to a series of sector collapses, similar to that which occurred e.g. on Mt. St. Helens (Lipman and Mullineaux 1981). Accordingly, we use the term Keserűs Hill "caldera" in this sense hereafter. To illustrate the size and character of the original relief, a real example, the DEM of Mt. St. Helens (2,500 m after the 1980 eruption) has been combined with the DEM of the northern Visegrád Mountains (Fig. 7a upper image). The Mt. St. Helens data have been rotated 30° counterclockwise and lowered by 1,000 m to compensate for the topographic differences.

That the present landform is inherited from the original one is also suggested by the DEM-derived slope angle map (see Fig. 3b) which shows similar steep slopes in the depression, especially along its inner rim. This spatial arrangement of slope distributions is common all over the Carpathian Miocene to Pliocene volcanic depressions (Karátson 1996). Other exceptionally high average slopes occur typically along fault planes. The reconstruction of the original Keserűs Hill cone by dip data (Fig. 6) shows that its centre should have been located near the southern tip of the present-day Danube Bend.

In the following section, in order to link the original geomorphic situation to the formation of the Danube Bend, we give a step-by-step evolutionary scheme of Keserűs Hill volcano, deciphering successive palaeogeographic changes since mid-Miocene time. Inferred topographic profiles, tentatively connected to changing erosion rates, are displayed in Fig. 7b. In order to make erosion history more quantitative, we applied erosion rates (a) mostly adopted from the literature for specific climate conditions, (b) estimated as the ratio of eroded thickness and elapsed time, and (c) cited numerical values from publications. All the data and relevant methods are comprised in Table 4, whereas calculated elevation decrease, erosion base level changes, and denudation rates are summarized in Fig. 8 and Table 3.

Evolution of the Danube Bend region: palaeogeographic reconstruction

Badenian—early Pannonian (15–8 Ma)

Stratigraphic data indicate a widespread, littoral shallow submarine basin all over the Börzsöny-Visegrád Mountains prior to and coeval with the mid-Miocene volcanism (e.g. Karátson et al. 2000). In the so-called Central Slovakian Volcanic Field 5 km northward as well as the Burda (Helemba) Mts. 10 km northwestward, closely related in time and character of volcanic activity (Pécskay et al. 1995), a shallow-water initial palaeogeography has also been pointed out (Konečny and Lexa 1994). Consequently, the erosional base level corresponded to the sea level for a long time.

The Keserűs Hill lava-dome complex, with similar dimensions to Unzen, Merapi or Mont Pelée, might have originally been 1,300–1,500 m high (Fig. 7b). The environment was subtropical, having a mild climate (17–18°C mean annual temperature) and heavy rainfall (ca 1,500 mm: Kordos 1979; Bruch et al. 2004) similar to the present Philippines and Lesser Antilles arcs. It was characterized by intense mass wasting and short, steep valleys. Therefore, erosion rate may have been much higher than during the last 10 Ma in the Carpatho-Alpine region (i.e. 30–50 m/Ma: Einsele 1992; Karátson 1996; Németh and Martin 1999; Németh et al. 2003). However, the amount of sediment removal by erosive processes should have been reduced by the (1) very near position of erosion base level fed by short water courses, (2) heavy vegetation, and (3) rapid infill of surrounding shallow basins due to the neighbouring, ongoing volcanic activity (for geochronological details, see Pécskay et al. 1995). The reconstructed subtropical environment, on the basis of these considerations and relevant data of Ahnert (1970), Meybeck (1976), Summerfield (1991) and Hinderer and Einsele (2001), implies a 80–100 m/Ma erosion rate. Such a rate might have slowly decreased in time in response to the termination of volcanism, subsequent afforestation, and the onset of subsidence in the Pannonian Basin (see below). By mid-Pannonian time (~8 Ma ago), ca 600–700 m denudation is calculated (Table 3, Fig. 8) and hence the Keserűs Hill volcano

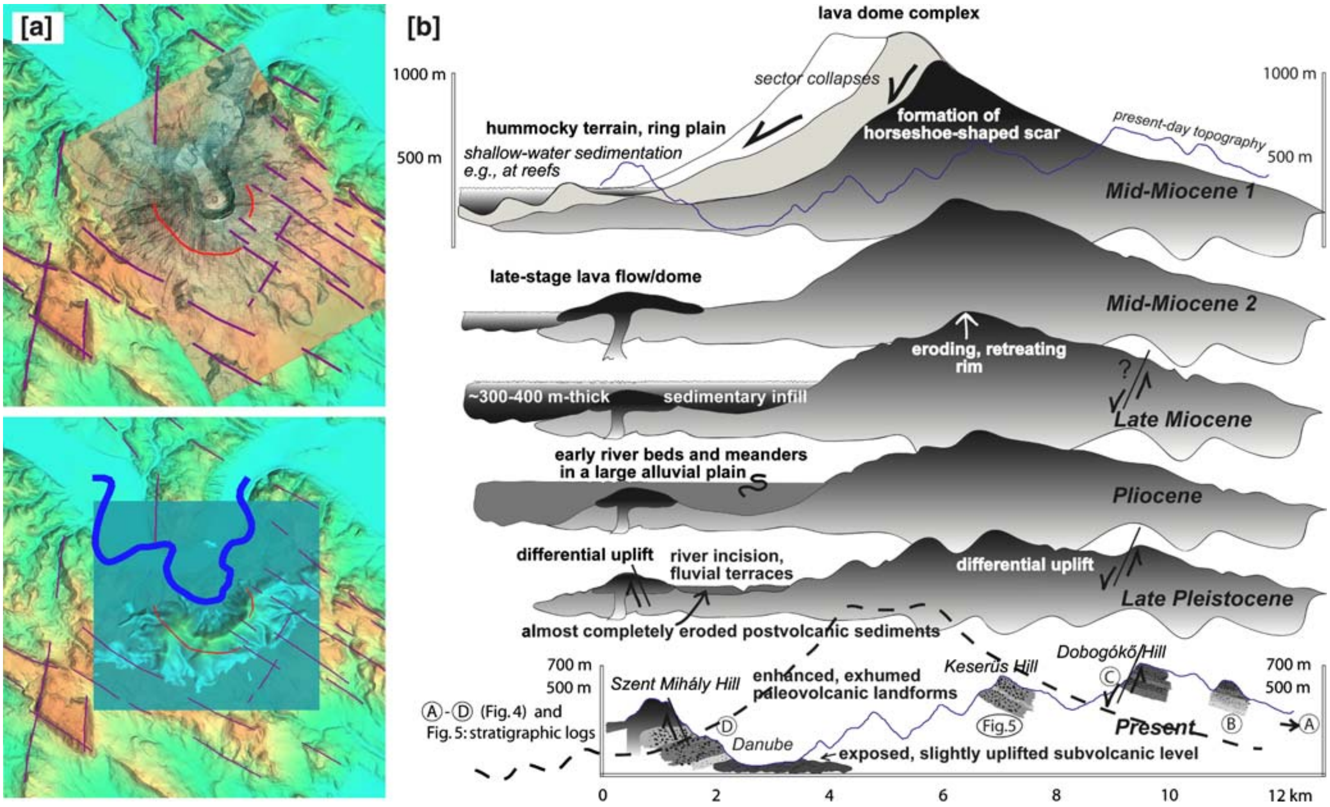

Fig. 7 Evolutionary scheme of Keserűs Hill volcano: a proposed volcano-geomorphic reconstruction in relation to Danube Bend. **a** Tentative DEM-reconstruction of Keserűs Hill volcano after the extinction of volcanic activity. On top, the unmodified DEM of Mt. St. Helens volcano (after the 1980 eruption) as a real example has been combined with the Visegrád Mountains. On bottom, tentative DEM-reconstruction of Keserűs Hill volcano in the Pliocene-Pleistocene boundary (end of alluvial regime). In order to visualize the possible topographic control of a U-shaped volcanic depression in deflecting the Palaeo-Danube, we inserted the present-day, moderately eroded Carpathian Makovica volcano as an example (also to scale). **b** Main geomorphic changes displayed in roughly N–S-oriented topographic profiles from the mid-Miocene to present

Table 3 Estimated erosion rates and elevation changes of the originally 1,300–1,500 m high Keserűs Hill volcano (also see Fig. 7)

Period (Ma)	Erosion rate (m/Ma)	Total vertical erosion (m)	Volcano height (m asl) at the end of period	Relative height (m) above erosion base level
15–8	80–100	600–700	700–800	700–800
8–5.5	30–50	100	600–700	300–400 or less
5.5–1.8	≤ 30	100	500–600	400–500
1.8–present	50–80	> 100	600–700[a]	500–600

For discussion, see text

[a] Value computed by adding ~200 m Quaternary uplift

may have been lowered to 700–800 m asl. In the surroundings, ≤ 200 m thick coeval marine sedimentary deposits (Korpás 1998) can be found. This limited figure indicates that most of the material eroded from the Visegrád-Börzsöny Mountains deposited in the farther, deeper depressions of the mid-Miocene Pannonian basin. However, identification of correlative deposits from more distant boreholes is still an open question.

Mid–late Pannonian (8–5.5 Ma)

This time interval is characterized by the overall subsidence of the Pannonian Basin and related rapid infill by prograding river deltas. Most of the sediments originated from the emerging hinterland of the Carpatho-Alpine orogen, but volcanic areas that were located 100–200 km farther inside the basin have also contributed to the terrestrial sediment influx. Several hundred metres burial by soft Pannonian sediments have been inferred for large areas of the NW part of the basin (e.g. Dunkl and Frisch 2002), i.e. near the Börzsöny-Visegrád Mts. In our study area, no Pannonian deposits have been reported. However, it is very likely that the ring plain sequences including SM and VCH became progressively buried beneath siliciclastic sediments (see Fig. 7b), except the summit level and upper flanks of the still emergent Keserűs Hill volcano.

Table 4 Incision, denudation, exhumation and uplift rates of, or related to, the Danube Bend (DB) area, calculated from various types of source data for different time scales

Indicator type (horizon, etc.)	Dating method	Rate type	Rate (mm/a)	Scope (ka)	References
Volcanic structure	K/Ar ages, volcanic geomorphology, morphometry	Denudation rate	0.03	11,000–0	Karátson (1996)
Travertine horizons	Geomorphology, palaeontology, Sedimentology	Base level drop/incision rate	0.02–0.06*	8,500–360	Mottl (1942), Schréter (1953), Pécsi (1973), Jánossy 1979, Kretzoi and Pécsi (1982), Schweitzer and Scheuer (1995)
Volcanic structure, Pannonian sediments	K/Ar ages, volcanic geomorphology, volcanology, sedimentology	Denudation rate	0.05 (0.02–0.09)	7,500–0	Németh et al. (2003)
Average exhumation	Thermochronology, fission track data	Exhumation rate	0.2–0.26	5,000–0	Dunkl and Frisch (2002)
Terrace levels of DB and Gerecse Hills (upstream DB)	Geomorphology, palaeontology, sedimentology	Incision rate	0.06*	2,500–360	Noszky (1935), Mottl (1942), Pécsi (1959), Jánossy (1979), Kretzoi and Pécsi (1982), Gábris (1994), Schweitzer and Scheuer (1995)
Travertine horizons	Geomorphology, palaeontology, sedimentology, Th/U dating	Base level Drop/incision rate	0.18–0.22*	360–0	Mottl (1942), Schréter (1953), Pécsi (1973), Jánossy (1979), Kretzoi and Pécsi (1982), (1982) Schweitzer and Scheuer (1995)
Cave minerals	Th/U dating, mineralogy	Base level drop/incision rate	0.23*	360–0	Leél-Őssy and Surányi (2003)
Terrace levels of the Gerecse Hills and Buda Hills (upstream and downstream DB)	Geomorphology, palaeontology, sedimentology	Incision rate	0.14–0.19*	360–0	Mottl (1942), Pécsi (1959), Jánossy (1979), Kretzoi and Pécsi (1982), Gábris (1994), Schweitzer and Scheuer (1995)
Terrace levels of DB	Geomorphology	Incision rate	0.41*	350–0	Noszky (1935), Pécsi (1959), Kretzoi and Pécsi (1982), Gábris (1994)
Terrace levels of DB	Exposure age dating	Incision rate	1.6*	270–0	Ruszkiczay-Rüdiger et al. (2005b)
Present surface	Repeated precise levelling	Uplift rate	1.0	0.005–0	Mike (1969), Joó (1992)

Data of incision rate, marked with asterisk, have been compiled by Ruszkiczay-Rüdiger et al. (2005a)

The erosion rate during the second half of the Pannonian (ca 8–5 Ma: Kázmér 1990) may have decreased relative to the previous period for a number of interrelated processes. The overall, post-rift basin subsidence coupled with high rate of sediment accumulation resulted in the rise of erosion base level, which in turn decreased the erosive capacity of channels. The less warm but still humid continental climate (with 15–17°C mean annual temperature: Bruch et al. 2004) may also have decreased the intensity of erosion processes. For the unburied part of the volcanic edifice, we calculated with the intermediate 30–50 m/Ma erosion rate mentioned above (Table 3). On this basis, the elevation of the volcano is estimated 600–700 m asl by the end of Pannonian time, but a significant part became progressively buried in the periphery. Thus, relative elevation (above the increased erosion base) may have been as low as 300–400 m (Table 3).

Pliocene (5.5–1.8 Ma)

Little geological record exists from the period between 5 and 2 Ma. That time interval is considered to be transitional from the archipelagic to the terrestrial environment. The most significant palaeogeographic changes were (1) the disappearance of the Pannonian Lake, giving place to a lacustrine–palustrine environment (Szádeczky-Kardoss 1938; Kázmér 1990), and (2) significant cooling and aridification of climate (Kordos 1979; Hably and Kvacek 1998), with instabilities toward Pleistocene time (e.g. Willis et al. 1999). Lack of well-developed, large rivers as well as temporarily dry, cool climate periods imply a moderate-low erosion rate. On the basis of a quantitative approach, we have used 30 m/Ma erosion rate as a bulk value, from a comparative study on the late Miocene to Pliocene segment of the Eastern Carpathian volcanic chain (Karátson 1996).

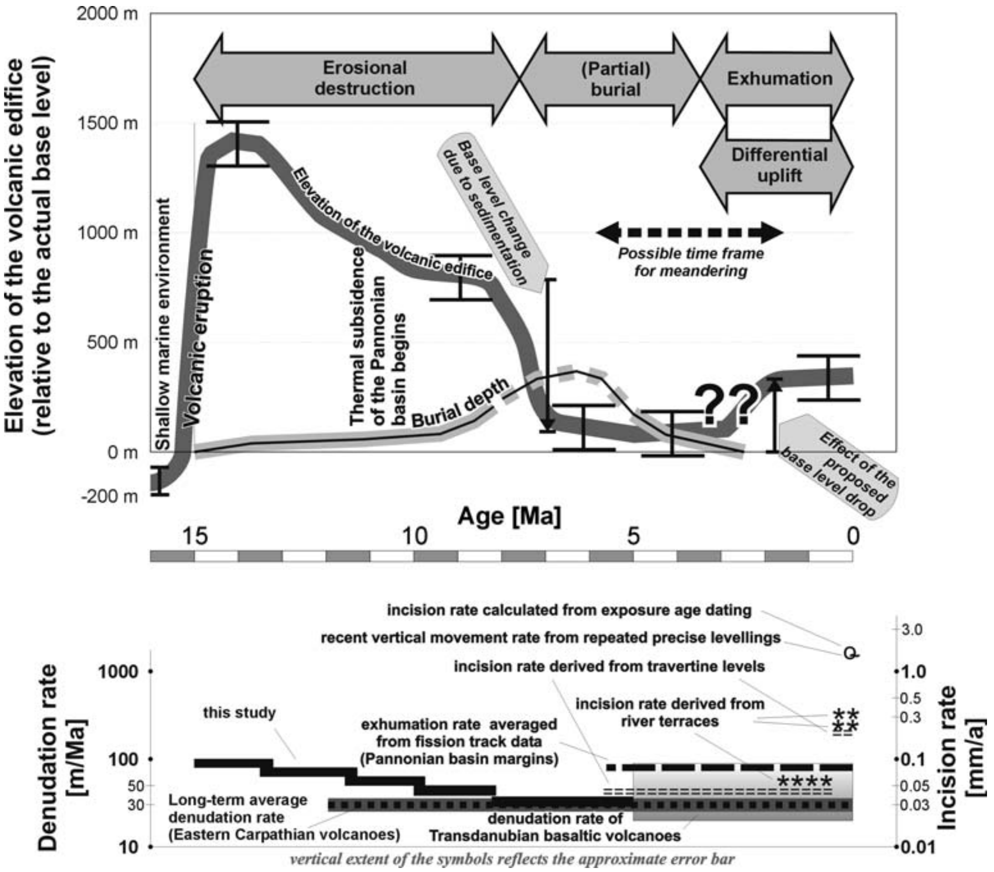

Fig. 8 Denudation history of the Danube Bend region and Keserűs Hill volcanic complex. *Top*: *Thick dark gray line* shows the proposed elevation changes (topmost part) of Keserűs Hill volcano relative to the actual base level and without tectonic modifications. Tentative *error bars* indicate the time slices for which direct or implied evidence exists. Considerable burial in Pannonian times causes a drop in relative elevation. *Light gray line* indicates the depth of partial burial during the subsiding regime. *Bottom*: Temporal variation of estimated denudation rates, in comparison to the incision/uplift rates of the Danube in the Quaternary inferred from travertine levels (*double line*) and river terraces *(asterisks*; both derived from data of Ruszkiczay-Rüdiger et al. 2005a), exposure age dating of strath terraces of the Visegrád Gorge (oval; Ruszkiczay-Rüdiger et al. 2005b), and recent vertical movements (differential uplift; see Table 4). *Dotted gray line*: long-term average denudation rate of the Eastern Carpathian volcanic edifices (Karátson 1996); *shaded box*: the range of denudation rates for Transdanubian basalt volcanoes (Németh et al. 2003); *thick dashed line*: average value calculated from fission track data of Dunkl and Frisch (2002). Note logarithmic vertical axis and different scales (m/Ma on the left for long-term denudation, and mm/a on the right for the Quaternary incision; 100 m/Ma = 0.1 mm/a)

As a consequence, during Pliocene times, a further 100 m of vertical erosion may have occurred (Table 3). Therefore, the resulting height of the volcano could be no more than 500–600 m asl. On the other hand, because of the more intense denudation of surrounding Pannonian deposits, the relative height should have been slightly increased (Table 3). Relief evolution under the prevailing mild continental climates (Hably and Kvacek 1998), affected by wind erosion under arid climatic periods, might have resulted in a more gentle relief than today, with significant pedimentation in the mountain periphery (e.g. Láng 1955).

An important implication of the inferred morphology to the relief evolution of the area comes from the formation of the extended, flat-lying, Pannonian sedimentary plain at the northern foot of Keserűs Hill caldera (see Fig. 7a, b). Because the area of SM and VCH was probably buried, the relatively large plain, whenever it was eventually drained in Pliocene times, yielded the only opportunity for the development of meandering palaeorivers.

Quaternary (1.8 Ma–present)

During the Pleistocene epoch, the morphology of the study area, as part of the Alpine-Carpathian system, has seen considerable, interrelated effects of neotectonic movements (e.g. Cloetingh et al. 2002) and climatic changes. In the eastern Alps and northwestern Carpathians, the glacial stages with strong frost action and intense mass movements resulted in an accelerated denudation, whereas interglacial periods were characterized by moderate areal erosion in the elevated areas, and increased discharge in major rivers (van Husen 1987; Gábris 1994). In particular, drainage patterns, precursors of the present ones, have been established during the interglacial stages, when melting of Alpine glaciers resulted in greater discharges (e.g. Hinderer 2001). We calculated with an erosion rate of 50–80 m/Ma on the average, based on Alpine data (Hinderer 2001; Hinderer and Einsele 2001). Total Quaternary relative denudation has been estimated >100 m (Table 3).

In many places of the northern Hungarian Mountains, as part of the northwest Carpathians, erosion was enhanced by differential neotectonic uplift (e.g. Dunkl and Frisch 2002). In the study area, Oligocene sedimentary deposits underlying the mid-Miocene volcanic series crop out at the northern foot of Dobogókő Hill as high as 420 m asl (Fig. 2); submarine to subaerial volcaniclastic sequences can be found at the base of SM or VCH as low as 120 m asl. In the vicinity of SM there are Leitha limestone beds, which were deposited as reef debris in the volcanic archipelago at same heights, but now are found in elevations from 150 m (western foreground) to 400 m asl (northern hillslopes: Fig. 2). At the bottom of the Danube (ca 100 m asl), strongly fractured subvolcanic rocks crop out (see Fig. 2: Nagymaros Engineering Geological Map 1989). From these data, a 200 m Plio/Pleistocene uplift for the SM–Dobogókő Hill area is a reasonable estimate (see volcano height corrected by this value in Table 3).

In relation to these differential tectonic movements (e.g. Noszky 1935; Gábris 1994; Ruszkiczay-Rüdiger et al. 2005a; see Table 4), five to eight river terraces, located in various elevations, have been described in the Danube Bend (Kéz 1934; Bulla 1941; Pécsi 1959). For instance, the terraces interpreted by Pécsi (1959) as of Günz, Mindel or Riss glacials exhibit 30–100 m vertical differences, respectively, and they reach the maximum elevation in the Visegrád Gorge. Even the Postglacial terrace levels (Gábris 1994) imply very young differential uplift of at least 0.4 mm/a. In fact, repeated precise levelling has shown 1–1.5 mm/a recent uplift in the Danube Bend area (Mike 1969; Joó 1992). In accordance, new exposure age dating by in situ produced cosmogenic ^{3}He (Ruszkiczay-Rüdiger et al. 2005b) have yielded 1.6 mm/a river incision for the last ~270 ka. The incision of the Danube River was triggered by the uplift of the Hungarian Mountain Range (e.g. Gábris 1994). Accordingly, the observed ≤400 m incision can be taken as good approximation for the uplift of the Danube Bend. The new incision/uplift data significantly exceed rates based on earlier works for the whole or the late Pleistocene (Pécsi 1959; Kretzoi and Pécsi 1982; Gábris 1994; Ruszkiczay-Rüdiger et al. 2005a; Table 4, Fig. 8). Although incision rates are not directly comparable to denudation rates, in Fig. 8 (bottom) we summarized both types of rates. The increasing Quaternary rates, which are apparent even on a logarithmic scale, imply increased tectonic uplift, and/or a considerable base level drop downstream in the Danube valley.

In the area, the calculated Quaternary erosion rate totals in a 900–1,000 m lowering (Table 3). This would result in a 400–500 m absolute height of Keserűs Hill volcano at present. Therefore the vertical difference to the current 600–700 m altitude conforms to the young tectonic uplift. Keeping this in mind, and adding the facies interpretation of the exposed highest-level outcrops of the lava dome (e.g. V-11, see above), the remaining part should represent only the lower flanks, originally at some 200–300 m asl. The Dobogókő Hill area to the south (V-13, V-14), which is reconstructed as the distal facies, might have experienced even more intense uplift through normal faulting (indicated in Figs. 3, 7b). North of the Dobogókő Hill ridge, the preserved thickness of the volcanic pile overlying the uplifted Oligocene sediments (Fig. 2) is only 200–250 m.

Discussion: evolution of the Danube Bend

A number of constraining factors emerging from the above scenario helps to draw important conclusions for the relief evolution of the Danube Bend area.

Due to the lack of geological record, precise age of the beginning of fluvial regime in the Danube Bend is unknown. The Danube River itself might have arrived at the western border of the Pannonian Basin in early Pliocene times (Sümeghy 1938), and flowed southward for a long time. Toward the end of the Pliocene, in response to uplift in southwestern Hungary (Szádeczky-Kardoss 1938), it turned eastward. The late Pliocene appearance of the river in the Danube Bend was suggested first by Schafarzik (1918). Until that time, most likely the Hron(Garam)-Váh(Vág)-Ipoly(Ipel') river system drained most of the northwestern Carpathians through or near the Danube Bend area (Prinz 1936; Szentes 1943). At the Pliocene/Pleistocene boundary, the volcanic relief of the northern Visegrád Mountains should have been rolling hills (≤ 400–500 m asl), consisting of the remnants of the significantly eroded Keserűs Hill lava dome complex, with its horseshoe-shaped caldera open to the north. In the northern foreground of the volcano, the original mid-Miocene volcaniclastic ring plain successions were covered by thick Pannonian sediments, forming a 5–8 km wide alluvial plain. The lowland morphology enabled the originally alluvial palaeoriver system, the ancestor of Danube, to find its course in the most erodible deposits.

The first stage: characteristics of early river channels

A tentative reconstruction of Keserűs Hill caldera ca 2 Ma ago, at the end of the alluvial regime, is given in Fig. 7a (bottom). The image draws attention to the deflecting effect of the horseshoe-shaped landform, along with the late-stage SM summit lava dome opposite side, and the VCH hummocky morphology to the northeast. To show the effect of such a morphology, we inserted the present-day, less eroded, U-shaped Makovica volcanic crater (east Slovakia) as an example in the following way: the original DEM data were rotated 90° CCW and lowered by 700 m (in order to model the burial of the periphery of the volcanic edifice by ca 300-m thick Pannonian sediments). Prior to the stage depicted in the image, the Palaeo-Danube or its forerunner may have been located in a somewhat different position: for instance, Láng (1955) reported fluvial gravel beds of an ancient river in Törökmező area (Fig. 1), some 7 km to the north of SM (i.e. opposite side). This suggests that the present Danube Bend is a subsequent feature. Today, the area north of SM (220 m asl) is considerably higher than the Danube Bend (101 m asl), which is in accordance with the subsequent, rapid incision of the present river.

A possible pathway of the early main river (Palaeo-Danube or -Ipoly) is also indicated in Fig. 7a. Increased discharge during interglacial stages may have resulted in the formation of large river beds and meanders as proposed by Láng (1955). We calculate that, according to the river curvature radius versus discharge relationship (Dury 1976; Gábris 2001; Timár 2003), a possible palaeoriver here should have had ca 6,500 m^3/s bankfull discharge to form the present-day 4.5 km large "meander". The calculated value is considerably higher than the present-time average of annual floods at the Nagymaros gage station (4,000 m^3/s: VITUKI 2002). The erosional capacity of such a large river (or its direct tributaries) should have resulted in a high-rate removal of the postvolcanic sedimentary deposits. However, we note that such high discharges may have occurred for only limited times.

This fluvial scenario resembles to that in front of the eastern Alps (Székely et al. 2002). Namely, in the area of the Bohemian massif, the Danube actually incises antecedently some 200–250 m in two water gaps, in morphologically similar gorges to the Visegrád one. Moreover, as well as the eroded Pannonian cover in the Danube Bend, the overlying molasse sequence has also been removed and the river has found its course in the resistant, crystalline bedrock.

Recent uplift: incision of the river curvature by exhumation of the volcanic relief

An early, more flexible drainage of meandering palaeorivers could be changed and long-term river channels formed when a very young (< < 1 Ma; Ruszkiczay-Rüdiger et al. 2005b) uplift/incision has occurred. Apart from exposure age data mentioned above, the present-day geomorphology of the Danube Bend clearly indicates this change. Namely, there are well-developed, steep (30°–40°) triangular hillsides (flatirons) on both sides of the Visegrád Gorge (see Fig. 1), indicating fast incision of the river. The alluvial plain of the Ipoly river (now a direct tributary of the Danube: Fig. 1) is also bordered by flatirons on the eastern (Börzsöny) side, although showing more gentle, 10° slopes. The tips of such flatirons along the Danube Bend (both at SM and opposite side), located ca 150–200 m above the present bed, constrain the net vertical movement of the youngest uplift phase and point to the much larger width of the original river valley: ca 2.5–3 km compared to the present-day 0.5–0.6 km.

In our model, the most important prerequisite for the formation of the U-shaped Danube Bend is the exhumation of the original volcanic relief. This may have occurred when the Pannonian sedimentary cover was completely removed. The horseshoe-shaped scar as a natural depression hosted the southward-deflected river bed, including its possible meander. The formation of the peculiar river loop was further facilitated by the exhumation of other steep landforms (e.g. SM summit lava dome and VCH debris-avalanche deposit). When the resistant material of these hills was better exposed, they served as topographic controls for the loop shape of the river. This process, i.e. the beginning of the exhumation of the resistant volcanic rock, changed the alluvial regime of the ancient Danube Bend to a bedrock channel. Tectonic faults, e.g. the one at the western side of SM (Figs. 3, 7a: Láng 1955; Czakó and Nagy 1977) as well as less resistant, altered subvolcanic rocks cropping out in the present-day river bed of Danube (Nagymaros Engineering Geological Map 1989) could be additional factors contributing to the conservation of the loop shape.

The meandering/alluvial style considerably predates (i.e. Pliocene/early Pleistocene) the acceleration of vertical movements, when the shape of the river curvature was fixed between exhumed volcanic landforms. As mentioned above, the initiation of the present morphology of the Visegrád Gorge should be a young (mid-to-late Pleistocene?) phenomenon. Until that time, the Danube may have had different pathways (e.g. north of SM).

Conclusion

The Pleistocene evolution of the Danube Bend is proposed to be governed by the exhumation of the original Miocene volcanic relief. In the Northern Visegrád Mountains, the main Keserűs Hill volcanic edifice was a lava dome complex, characterized by a horseshoe-shaped scar open to the north. Reconstruction of the original volcanic cone, that was made up mostly of resistant block-and-ash flow breccias, is supported by plotting detailed dip measurements against present topography. The lava-capped Szent Mihály Hill to the north and the resistant Visegrád Castle Hill breccias to the east were also among the least erodible features.

Postvolcanic relief evolution of the volcanic edifice has been constrained by subsequent, mostly Pannonian sedimentation, various climates and, especially since the Plio-Pleistocene, tectonic movements. A fluvial regime replaced the initial marine and subsequent lacustrine environments during Pliocene times, when an alluvial plain may have formed on the Pannonian sediments in the northern foreground of Keserűs Hill volcano.

Early rivers dewatering large north Carpathian catchment areas should have appeared in that plain. As a result of occasional high discharges as well as tectonic movements, intense fluvial erosion of the trunk channel and short bedrock tributaries led to the ultimate removal of postvolcanic sedimentary cover.

More recent differential uplift and erosion base level drop had fundamental effects on the drainage pattern. After the sedimentary cover was removed, the reappearance of the horseshoe caldera determined the shape of the river pathway. As the incision of the Danube has continued, the caldera morphology has been progressively exhumed and morphologically enhanced. In addition, the exposed, resistant volcanic formations to the north (Szent Mihály Hill) and east (Visegrád Castle Hill) were also capable of topographically controlling the river curvature. Eventually, the present-day Danube Bend has been fixed in between. Position of river terraces combined with uplift/river incision rates shows that most of the inferred process should have occurred during mid-to-late Quaternary times.

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