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Aspects of Quaternary relief evolution of Miocene volcanic areas in Hungary: A review

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Quaternary relief evolution of various volcanic areas in Hungary has been determined by (a) the original volcanic succession and related, primary landforms and (b) the subsequent postvolcanic tectonism and erosion. This overview presents some details of these processes through selected relief types from the Miocene volcanic mountains of Hungary: the High Börzsöny erosional caldera rim, the Rocks of Vadálló-kövek, the Dobogókõ Ridge, the Danube Bend area, and the badlands and fairy chimneys of the southern foreland of the Bükk Mts, by showing different volcanic relief types, and postvolcanic tectonic, paleogeographic and erosional history. In the Quaternary, the tectonic transformation of these and other volcanic areas has been highly variable; in contrast, erosional processes of the Quaternary, i.e. pedimentation, loess and other eolian sedimentation, derasion, periglacial relief formation, and channel erosion, have affected almost all areas in Hungary; hence types and rates of erosion can be well constrained.

Key words: Miocene, Quaternary, relief evolution, volcanism, Börzsöny Mts, Danube Bend

Introduction

Of the present surface of Hungary, approximately 15 000 km^2 belong to the low-mountain relief type. About half of this is volcanic in origin. Most of the volcanic fields (ca. 90% in area) were formed in the Miocene Epoch (Börzsöny–Visegrád Mountains, central and eastern Cserhát, Karancs Hill, Mátra Mountains, Tokaj Mountains, the southern Bükk Foreland and most of the northern foothills of the Bükk and Mátra Mts). Some scattered volcanic occurrences (the basalt buttes of the Tapolca and Marcal Basins and a portion of the Balaton Uplands) are

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of Mio-Pliocene age, whereas others (the Nógrád–Gömör Basalt Field) are of Plio-Pleistocene age.

During the several million year-long erosion following volcanic activity, the Quaternary period (1.8 Ma, but generally it is considered longer in the Pannonian Basin: 2.4 Ma, Krolopp 1990; Jámbor 1998) played a very important role in degrading the original volcanic landforms. It has long been accepted that this is due to the combined effect of tectonic activity (e.g. normal and strike-slip faulting, and base level drop: Horváth 1997; Fodor et al. 1999; Karátson et al. 2006) as well as accelerated erosion in the Ice Ages (van Husen 1978; Cederbom et al. 2004). However, the total Quaternary denudation, especially when compared to the Miocene surface evolution, was far from the 10–15 Ma-old period characterized by a humid, subtropical environment (e.g. Karátson et al. 2006).

A fundamental problem of the Quaternary relief evolution is that most of the dominant surface processes have not left a significant amount of material, because fluvial erosion and other areal slope processes transported most of the sediment into subsiding peripheral areas (i.e. the Pannonian Basin). Yet some typical accumulation forms and remnant landforms (e.g. felsenmeer, talus slopes, and rock towers, steep stream gorges) serve as evidence of how those processes operated.

Another problem is that the original volcanic landforms are still debated in many cases. Although there are a number of specific works on this issue (e.g. Balla 1978; Székely 1987; Bokor 1990; Karátson et al. 2000; Székely and Karátson 2004; Karátson et al. 2006), type, size and exact locality of individual eruptive centers are sometimes uncertain or not clarified. This is a very important question because in addition to rock type and lithologic properties, the type and size of the original volcanic edifice greatly contributed to the subsequent erosional processes.

Reviewing the development of Hungarian thinking about original volcanic landforms, one can see that the first “reconstructional” concept was applied by L. Lóczy Sen. (1913, mostly to basalt volcanoes) and J. Cholnoky (e.g. 1937, mostly to the Miocene volcanic mountains). Especially Cholnoky started from the direct identification of original volcanic landforms, actually taking no account of the role of subsequent erosional transformation. Mistakes and exaggerations resulting from Cholnoky's work were logical consequences of his defining the original landforms merely on the basis of geomorphological analogies. For instance, he reconstructed the Sátor Hills in the Tokaj Mts as a Somma–Vesuvius-type caldera complex; the subsequent, detailed petrological work identified exhumed subvolcanic bodies there (Gyarmati 1977). In a similar manner, along the partly arcuated Dobogóko Ridge in the Visegrád Mts, he envisaged a “caldera rim” merely by a morphological analogy, without studying the exposed deposits and facies relationships (see below). The one-sided viewpoint of those times could have been a principal reason for the fact that most authors went in the other direction and “destroyed” the primary volcanic landforms all over

Hungary when the concept of peneplanation emerged in the 1950s. For example, according to Láng (1955), “in the Mátra Mountains, there are no primary volcanic landforms”, whereas in the Börzsöny Mts, “the presence of volcano flanks produced by primary accumulation can be traced in only a few cases”. This evaluation was later adopted by Bulla (1962), who stated explicitly: “in the Börzsöny Mts, original (primary) volcanic accumulational landforms are lacking”.

In subsequent research, the next positive step was due to geologists. It was among others Szádeczy-Kardoss (e.g. Szádeczky-Kardoss et al. 1959), introducing the hypothesis of the caldera of the Mátra Mts, and Balla (1978), reconstructing the High Börzsöny paleovolcano (see Fig. 3), who “re-established” the original volcanic landforms. Although there are a number of debated points in their reconstructions (e.g. in the Mátra Mts, where the present author and his colleagues see no evidence for a caldera; Karátson et al. 2001), it is evident that thanks to these and other workers (e.g. Balla and Korpás 1980; Nemerkényi 1986; Székely 1987; Korpás and Lang 1993; Kiss et al. 1996), research on volcanic landforms was given a new stimulus, especially in the 1970s and 1980s. The acceptance of the volcano reconstructional concept also appeared in the National Atlas of Hungary (1989), where the volcanic relief was marked again by 'craters', 'calderas' and 'volcanic cones', although the role of peneplanation, in another light, should not have been withdrawn.

Today, according to origin, the volcanic mountains and volcanic occurrences of Hungary can be grouped tentatively as follows (Fig. 1): 1. Andesite–dacite volcanic mountains: a) extrusive products and volcanic edifices: small stratovolcanoes, lava dome groups and remnants of lava flow successions (e.g. most parts of the Börzsöny–Visegrád Mts, Tokaj Mts, and some parts of the High (central) Mátra Mts and Cserhát Mts) b) intrusive/subvolcanic products: subvolcanic bodies and exhumed dykes/sills (e.g. those of the Börzsöny–Visegrád and Tokaj Mts, Karancs Hill, and some portions of the Cserhát Mts). 2. Rhyolite–dacite ignimbrite sheets/plateau remnants (e.g. Bükkalja [=the southern foreland of the Bükk Mts], some parts of the Cserhát Mts, and the northern foothill of the Bükk and Mátra Mts). 3. Basalt lava flow fields (e.g. sheets of Medves Plateau, Bondoró Hill), 4. Basalt nested maar – scoria/lava cone – pyroclastic cone complexes (eruptive centers, mostly basalt buttes, most typically in the Tapolca and Marcal Basins: Badacsony, Somló, Ság, Szigliget Hills, Tihany Peninsula, etc).

Derived from the above variegated volcano types, the present-day volcanic areas of Hungary differ radically from one other. Sometimes the subsequent erosion resulted in a convergence of landscape physiognomy (e.g. eroded lava domes and exhumed laccoliths), but most areas reflect the properties of the main original volcanic processes. Low-viscosity lava flows (Medves Plateau: Horváth et al. 1997; certain parts of the Mátra Mts: Varga et al. 1975), extrusion of smaller/larger lava domes (Galla, Sas, Só and Karancs Hills: Karátson et al. 2000) or lava dome groups (High Börzsöny: Karátson 1995; Karátson et al. 2000; Tokaj

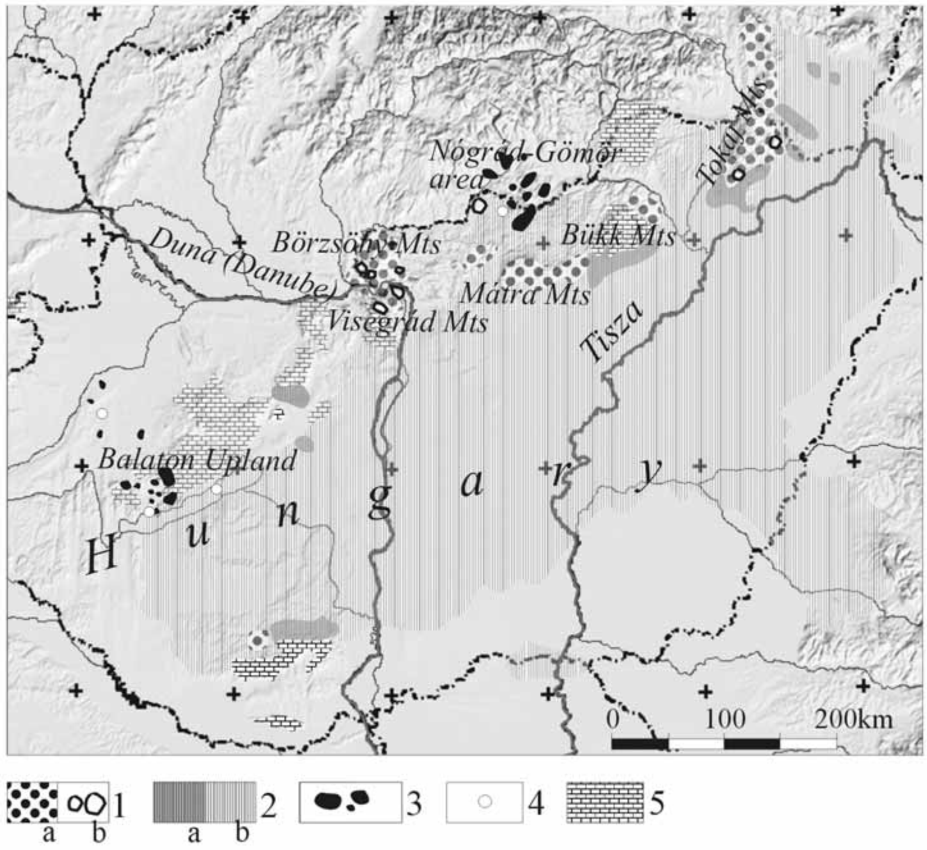

Fig. 1
Tentative grouping of volcanic relief types in Hungary (modified from Karátson 1999). 1. Andesite-dacite volcanic mountains: a) extrusive products and volcanic edifices: small stratovolcanoes, lava dome groups and remnants of lava flow successions, b) intrusive/subvolcanic products: subvolcanic bodies and exhumed dykes/sills (only some typical ones are shown); 2. Rhyolite-dacite ignimbrite sheets/plateau remnants: a) on the surface, b) buried; 3. Basalt lava flow fields; 4. Basalt nested maar – scoria/lava cone – pyroclastic cone complexes (only some typical ones are shown); 5. Paleo-Mesozoic, mostly carbonate, mountains of the Inner Carpathians

Nagy Hill: Gyarmati 1977), large-volume pyroclastic flows (Bükkalja: Capaccioni et al. 1995; Szakács et al. 1998) are among the main processes that determined the physiognomy of the areas in question.

Postvolcanic relief evolution – and especially the Quaternary tectonic and erosional processes – has not been uniform, making it more difficult to decipher the role of erosion. There are already a number of case studies proving that the preservation and rate of degradation of primary landforms have not necessarily correlated with the age of a given volcanic area (Karátson et al. 2000; Karátson et al. 2001). For example, the Börzsöny, Visegrád and Mátra Mts, all belonging to the (1) genetic category, exhibit progressively less preserved volcanic landforms; the differences, taking the roughly same (Mid-Miocene) age into account (Karátson et al. 2000; Karátson et al., in print), are mostly due to the diverging postvolcanic (mostly Quaternary) tectonic evolution. Obviously the erosive processes were similar for all, depending mostly on elevation.

As a result of the complex, long-term degradation histories, there is no question that the primary landforms have been moderately or strongly modified. This is a matter or fact in the light of the early studies mentioned above. On the other hand, apart from qualitative categories used by some authors (e.g. Székely 1987), it is better to speak generally of secondary or modified/transformed relief types in every case. The meaning of this term is as follows. The surface of a young volcano, e.g. the youngest, Late Pleistocene lava domes of the Csomád (Ciomadul) Volcano in the East Carpathians, as well as the inner slopes of its craters, are the slightly eroded remnant of the primary relief (degraded by no more than some tens of meters: Karátson 1996). In contrast, in the case of the volcanic cone of the Tokaj Nagy Hill or the High Börzsöny in the North Hungarian Mts, the primary landform is preserved – or indicated – only by the relicts of the radial (sometimes tectonically distorted) ridge pattern (for the Börzsöny Mts, see Balla 1978; Székely and Karátson 2004). The tectonic transformation – especially in the Hungarian andesite volcanic mountains of larger size – is mostly connected to the NW–SE and NE–SW lineament pattern, typical in the North Hungarian Mts and well defined throughout the Pannonian Basin (see below, e.g. Gerner et al. 1995; Fodor et al. 1999).

In the present overview, after presenting some examples (brief case studies) of the Miocene andesite/dacite volcanic mountains, I attempt to characterize the role and rate of postvolcanic, especially Quaternary, degradation of the volcanic areas. Although Quaternary relief evolution in the Hungarian volcanic mountains has long been studied (e.g. Székely 1969, 1987; Pinczés 1977), its connection to the primary landforms and pre-Quaternary evolution has not been adequately addressed. Therefore, another important aim of this paper is to emphasize the differences of original volcanic constructs and the resulting differences in erosion.

Examples of Quaternary degradation of Miocene volcanic landforms

The erosional caldera rim of the High Börzsöny lava dome group

Located at 750–930 m a.s.l., this highest part of the High Börzsöny is the caldera rim (Balla 1978; Karátson 1995) of the original, Mid-Miocene (14 Ma) lava dome group, ca. 1,300 m high (Karátson et al. 2000; Fig. 2). The present-day ridge was formed by the significant retreat and enlargement of the small caldera (formed probably by several craters: Karátson et al. 2000). Long-term erosion may have gone deeper than the present absolute elevation: the “High Börzsöny” may have been 400–500 m-high rolling hills by the Pliocene. Subsequently, the summit region was affected by an uneven uplift of ca. 100–300 m: the southern and

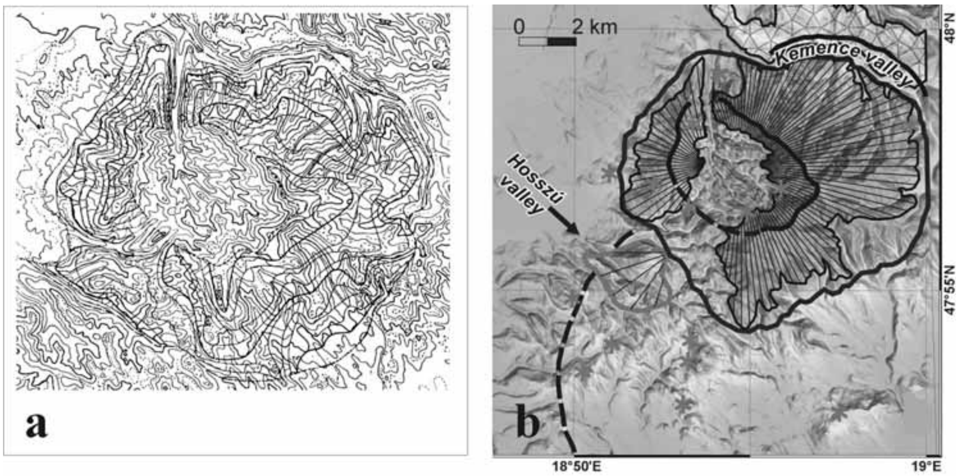

Fig. 2
Reconstruction of the High Börzsöny Volcano (a: Balla 1978; b: Székely and Karátson 2004; scale is the same)

eastern rim of the caldera (e.g. Csóványos–Nagy-Hideg Hill) emerged higher relative to the northwestern portion (Hollókõ Ridge; Székely and Karátson 2004).

Tectonic transformation. The erosional caldera rim is not roundish but has a rectangular, elongated shape (Fig. 2). This was attributed to tectonic movements (tilting: Balla 1978 and differential uplift: Karátson et al. 2000), and was studied in detail by Székely and Karátson (2004). The actual elevation of the rim is not uniform; it is considerably higher to the SE and S, and lower to the NW. There is an extremely low section in the west, attributed to a deeply truncating sector collapse (Karátson 1995; Karátson et al. 2000), while the outlet drains the central depression toward the NNW. The present drainage as well as the elongated, rectangular shape of the caldera is found to be of tectonic origin. In the DEM-derived polar coordinate image of the Börzsöny Mts (Székely and Karátson 2004), the paleocone morphology is overprinted by caldera rim irregularities, implying tectonic influence. These irregularities – i.e. non-parallel caldera rims and contrasting drainage patterns outside – suggest a displacement within the original cone. In Fig. 3 is shown a striking SW–NE trending lineament (termed the Piliscsaba–Bernecebaráti Line) which seems to be a normal fault that affected other, nonvolcanic structures to the S as well. It is notable that similar SW–NE faults of Quaternary age have also been identified in the neighboring Gödöllõ Hills (Fodor et al. 2005). When it crossed the High Börzsöny Caldera, the Piliscsaba–Bernecebaráti Fault may have caused a downthrow of the western part toward the NW, in turn causing a NW–SE elongation of the caldera area. Up to the time of this faulting, the inner drainage (within the depression) may have been directed westward, then deflected to the present N-oriented outlet valley.

Fig. 3
Selected main Miocene to Pleistocene (?) faults in the Börzsöny–Visegrád Mts (Karátson 2005; Karátson et al. 2006; Székely and Karátson, unpublished data). 1. Eastern main fault (Balla 1977); 2. Nagy Valley (Czakó and Nagy 1976); 3. Piliscsaba–Bernecebaráti Fault (Székely and Karátson 2004); 4. Hosszú Valley – Gödöllõ Fault (after many authors, Székely et al. in prep.)

The narrow, steep-sided valley is in accordance with its young age.

Postvolcanic, possibly Quaternary erosion. The southern rim and its vicinity (Szabó-kövek, Vilma-pihenõ, Katalin-szikla, Oltárkõ rocks and other unnamed rock formations) is one of the best exposed areas in the volcanic mountains of Hungary. The rocks are typical products of the youngest andesitic activity of effusive and slightly explosive character. The lava-outpouring activity is represented by platy-jointed lava rocks, and the explosive one by coarse-grained, unsorted, unstratified pyroclastic breccia: block-and-ash flow deposits of lava dome collapses (Karátson 1995). In the latter case, radially cracked blocks frequently occur in the breccia. The material of the breccia rushed down the original flanks of the High Börzsöny volcano along small canyons and gullies. As a result these valley-filling deposits should have been emplaced perpendicularly to the crater/caldera rim, and thus also to the present, erosional rim. The breccia is highly resistant to erosion: the fine-grained, cemented matrix (tuff) has tolerated the thermal fracturing, dilatation and shrinking of clasts that subsequently occurred especially in the glacial stages of the Pleistocene.

Due to the good preservation, the present-day rocky outcrops of the breccia occurrences partly reflect the original position (or at least the orientation) of the valleys. Located more or less perpendicularly to the strike of the southern caldera rim (as well as to the northeastern Miklós-tetõ and northwestern Hollókõ Ridges), a number of small sections of eroded rock formations, or rock towers, can be found. Consequently, the present position of the pyroclastic breccia occurrences can be considered as a geomorphic inversion, for two reasons (Karátson 1997). First, the original valley-filling deposits have been exposed and become a positive landform. Notably, this occurred in many cases throughout the

Relief evolution of the Danube Bend

The above-mentioned caldera rim of the Keserûs Hill Volcano has a U-shaped morphology, open toward the Danube, and may have formed by sector collapse (Karátson et al. 2002, 2006: Fig. 5). In the Early to Middle Miocene the northern foreland of the caldera, i.e. site of the Pleistocene Danube Bend, could have been a shallow submarine depression or, rather, an archipelago, which was rapidly filled by coarse-grained volcaniclastic successions during the eruptive phases. This environment is proved by the coeval Leitha (reef) Limestone as well.

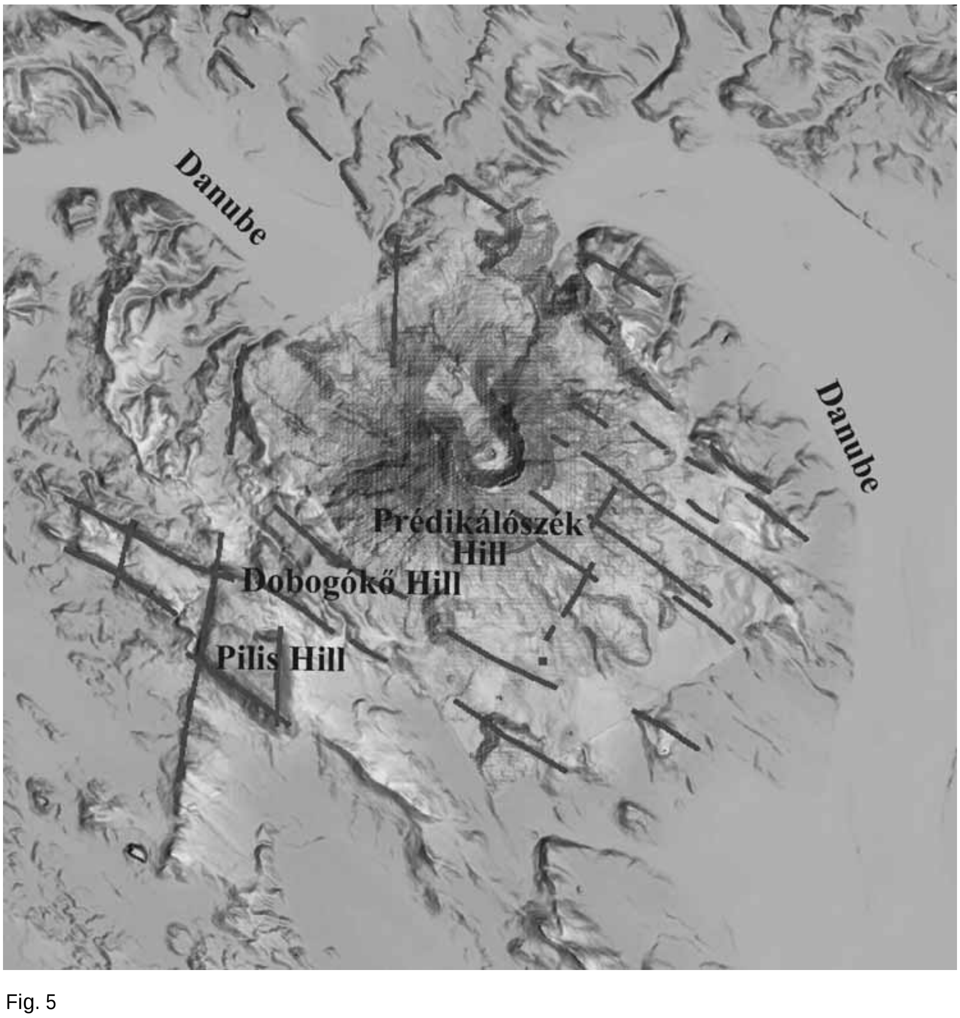

Fig. 5
Shaded relief map of Mt. St. Helens Volcano inserted into the Keserûs Hill horseshoe-caldera. Denudation during the past 15 Ma resulted in an erosional enlargement and retreat of the rim (Karátson et al. 2006)

Subsequent to its extinction, the emergent, 1,200–1,300 m-high Keserûs Hill Volcano, and part of the hummocky terrain in its foreland, had been significantly eroded under the Late Miocene subtropical climatic conditions. The submarine (Badenian, Sarmatian? and mostly Pannonian) upfill produced an up to 300–400 m-thick sedimentary cover; however, the summit region of the volcano, as well as those of the highest hummocks (possibly the Visegrád Castle Hill and the lava-capped Szent Mihály Hill) may have remained emergent (Karátson et al. 2006).

Following the eventual disappearance and upfill of the Pannonian Lake, new rivers, possibly meandering eastward on a gently sloping surface, appeared from the W (i.e. Paleo-Danube, Paleo-Ipoly; Fig. 6). In other words the low-relief original ring plain, filled with a few hundred meters of sediment, may have been the predecessor of the subsequent alluvial plain, which itself may have existed up to the Pleistocene. Then, due to enhanced tectonic movement (e.g. base level drop of the Pannonian Basin: Karátson et al. 2006), the Paleo-Danube cut into the alluvial plain and also the underlying sediments. Eventually, after eroding the soft marine sequence, the river reached the hard volcanic rocks. Due to accelerated uplift (Ruszkiczay-Rüdiger et al. 2005) and/or base level drop (Karátson et al. 2006), the Danube has cut down a further ca. 200–250 m into the volcaniclastic pile and maintained its bed. This process has exhumed the paleovolcanic geomorphology: the formation of the U-shaped river curvature (i.e. the Danube Bend) was due to the most resistant volcanic successions and landforms. Thus the curvature was formed by flowing around a post-caldera lava

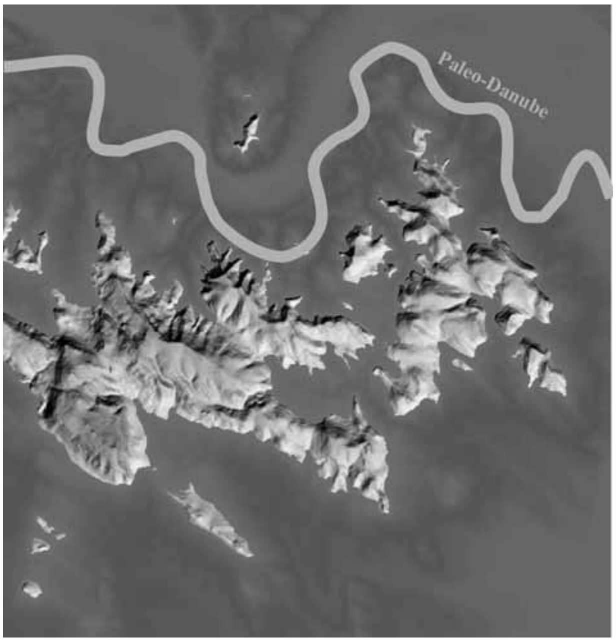

Fig. 6
Paleo-Danube (or Paleo-Ipoly) may have appeared on a flat plain in front of the Keserûs Hill Volcano during early Pleistocene times. Image was constructed by filling the present-day base with 350 m of sediment. Subsequently, the paleo-rivers (or their meanders) may have followed the exhuming volcanic morphology (Karátson et al. 2006)

dome (Szent Mihály Hill) opposite the significantly eroded, retreated, enlarged U-shaped caldera, and further downstream it also enhanced the morphology of an exposed hummock (Visegrád Castle Hill: Karátson et al. 2006). These resistant landforms were capable of establishing the river bed and perhaps one of its meanders (Karátson et al. 2006). In other places, where such paleovolcanic geomorphology and deposits were absent (e.g., Szentendre Island toward the S), the river may have eroded its sediments (and previous meanders, if any).

During this process, the Mid/Late Pleistocene downcut of the Danube has left a number of river terraces in and around the Danube Bend (Kéz 1934; Bulla 1941; Pécsi 1959). The actual relative height of the Keserûs Hill Volcano (500–600 m) is the result of the aforementioned long-term denudation and Quaternary uplift. The present steep slopes are formed by intense mass movements (slumping, soil creep, etc.) in response to the rapid vertical movements.

Holdvilág Gorge

This is a spectacular, short gorge (ca. 250–300 m a.s.l.) formed by Quaternary channel erosion in the early deposits of the Miocene volcanic activity of the Visegrád Mountains. The base of the gorge is cut into prevolcanic, partly shallow marine fossiliferous silty-sandy deposits; the middle and upper portion expose moderate to fine-grained volcaniclastic successions of variable origin (Bendõ et al. 2000, Karátson et al., in print).

The gorge was formed by Late Pleistocene–Holocene fluvial erosion. The backward erosion of Holdvilág Creek may have been due to a late stage of the subsidence of the neighboring Pilisvörösvár tectonic graben (Fodor et al. 1999). At first the channel could have created a narrow, deep gully cut into the erodible sedimentary layers; then, a series of related slides and rockfalls would have widened it to a gorge. Whilst the fine-grained (mostly phreatomagmatic) lower strata were rapidly eroded, the backward erosion significantly slowed down in the resistant, overlying block-and-ash and debris-flow deposits (indicated by the steep-sided "ladder" section). It is important to note that other small gullies or gorges in the vicinity (e.g. Salabasina Gorge), as well as farther away at Kõ Hill at Pomáz, expose deposits of similar origin but characterized by various successions, thickness and even lithology.

Facies relations and geometry reflect a Miocene paleogeography similar to that of the present day. At that time there may have been a number of small valleys pointing toward the seashore, which progressively became filled by various mass movements (mostly lahars). Subsequent to this volcanically-controlled morphology and followed by long-term erosion, intense channel erosion dissected the volcanic relief in the Quaternary, and geomorphological inversion occurred numerous times due to the variable resistance of volcanic strata. As for the Holdvilág Gorge itself, its steep sides consist of (valley-filling) volcaniclastic flow-deposits, i.e. the present-day gorge is an inversion of the original morphology.

Mátrabérc Ridge

The Mátrabérc Ridge (Fig. 7) is the main, slightly arcuate ridge of the Mátra Mts running from the village of Mátrakeresztes to that of Mátraszentlászló, and has been interpreted by most authors as a caldera rim, first proposed by Szádeczky-Kardoss et al. (1959), although they did not definitely indicate the rim contours.

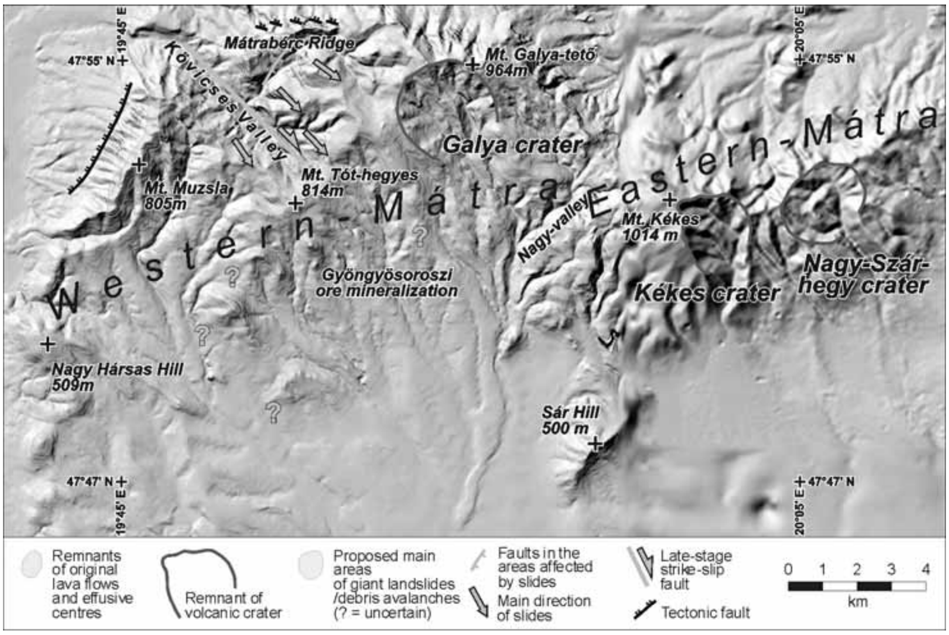

Fig. 7
Postvolcanic (Pannonian? to Pleistocene) tectonic modifications in the Mátra Mts: both the Eastern and Western Mátra have been uplifted significantly, resulting in fundamental transformation (sliding, degradation) of the western part but leaving effusive craters morphologically recognizable in the eastern part (Karátson et al. 2002)

According to our study (Karátson et al. 2002), the ridge is rather a tectonically uplifted structural landform, which has been steepened by giant landslides and tectonic collapses toward the S (possibly in Miocene/Pliocene times), then by enhanced Quaternary erosion and mass movements to the S and, more significantly, to the N. The basal part of the ridge consists of various successions of the “Middle Rhyolite Tuff” (Varga et al. 1975) and overlying volcano-sedimentary layers (Karátson et al. 2002). In the latter a number of fractures and fault planes connected to the aforementioned giant slides can be observed. Since the volcano-sedimentary strata are cut by dykes (fused tuffs also occur), the Mátrabérc Ridge could be the basal or “root” zone of the faulting as well as of slide movements (Karátson et al. 2002). In geomorphological terms, the slightly arcuated rim of the ridge (Óvár–Ágasvár–Büdös-kút Hills) is the Mio/Pliocene slide scarp zone, which was further eroded in the Quaternary. Due to the slides and subsequent erosion, the uplifted root zone could have lost its overlying volcanic cover, mostly andesite lava flows, the remaining thickness of which is no more than 100–200 m. The transported andesitic slide masses may now be located among the “cover” andesites in other places to the SE (e.g. Havas, Világos or Tót-hegyes Hills). The striking NW–SE directions of some geomorphic elements in the N, especially the Kövicses Valley, are the result of NW–SE faulting, as suggested already by Noszky (1927) and Czakó and Zelenka (1981). Because these faults seem to cut the proposed slide areas, they must be younger: their age is possibly Plio-Pleistocene.

The Mátrabérc Ridge, as well as the Galya Ridge to the E, are slightly undulating and have very steep north flanks. This feature was already interpreted by Noszky (1927) and later by many others (most recently Szabó 1996) as smaller-scale Pleistocene–Holocene slumping. The cause for this process could have been the effective weathering of parallel-jointed andesite lava rocks at the highest level of the ridge, in addition to the underlying volcano-sedimentary layers and the dacite tuff that may have served as natural sliding planes. Therefore the present undulating morphology of the ridge is due to these youngest, small-scale slide events.

Badlands and 'beehive rocks' (fairy chimneys)

In the Bükkalja (=the southern foreland of the Bükk Mts) the fairy chimneys (Fig. 8a) are the most spectacular features from the physical geographical viewpoint (Borsos 1991). In some cases as high as 25–30 m, these conical landforms are termed 'beehive rocks' in Hungary for their small hollows excavated into their

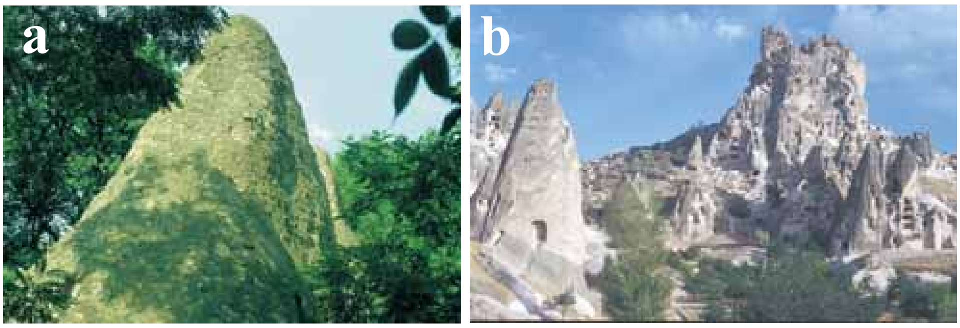

Fig. 8
a) Fairy chimney ("beehive rock") near Cserépváralja in the Bükkalja (Bükk Mts southern foreland); b) fairy chimneys near Göreme, Turkey

sides for apicultural or ritual purposes in prehistoric times (and/or later, during the early kingdoms of the Árpád dynasty). The material of the fairy chimneys is always massive, resistant, unwelded ignimbrite of rhyolitic to dacitic composition (Capaccioni et al. 1995; Harangi et al. 2000).

The badland formation could be analogous to that of Cappadocia, one of the best known volcanic badland morphologies formed in ignimbrite. There, under a typical semiarid climate, among other chimneys and cones similar in size to those in the Bükkalja area occur (e.g. Zelve, Göreme: Fig. 8b). On this basis the original plateaus of the Bükkalja may have undergone rapid erosion by temporary gullies, dissecting and fragmenting the edges of the plateaus during and after the volcanic activity, similarly to extended ignimbrite sheet reliefs worldwide. Typically, as a result of this process, the ridges and by-ridges between the gullies become high and steep, and eventually their tips become emergent and disconnected from the main ridge (i.e. formation of fairy chimneys: Bada et al. 2005). Fairy chimney formation may have occurred in the Bükkalja first on the unforested ignimbrite surfaces during the Miocene volcanism, but it could have also occurred (i.e. rejuvenated) under semiarid climates in subsequent epochs (Late Miocene through Pliocene to Pleistocene). Whilst in the more humid periods forestation diminished the dense dissection by gullies, the more arid periods (especially the occasional semi-desert conditions in the Pliocene) favored badland and fairy chimney formation.

The present-day exposure of the chimneys, i.e. their occurrence under a semi-humid climate, may be the result of young, rapid Quaternary uplift and related short-term erosion. This erosion acts mostly on the asymmetrically tilted plateau remnants of the original ignimbrite sheets. In places where the commonly northern rim of the tilted, southward- or southeastward-dipping plateau consists of welded ignimbrite, fairy chimneys are not found; in other places where the plateau rim consists of unwelded ignimbrite, fairy chimney morphology could have been formed (or preserved) in the northern, northwestern and western periphery. At present, the number of individual fairy chimneys is approximately 80 (Borsos 1991). Obviously, this is the oversized or accidentally exhumed “relict” portion of a much larger number of cones that had been eroded during previous times.

The question arises when the last exhumation (or even creation) of the fairy chimneys took place. It is very likely that some badland formation could occur even in the Pleistocene or Holocene (cf. similar badland morphology in the 7 ka-old Mazama Ignimbrite at Crater Lake Caldera, Oregon, BAcon et al. 2002). However, it is also probable that aa big portion of the present fairy chimneys are exhumed landforms. Apart from the typical (a few cm thick) weathering crust that covers their surface, this is suggested by the fact that most of the Bükk Mts, and thus the entire Bükkalja area, was buried by a Pannonian cover some hundred meters thick, prior to the rapid Quaternary uplift (Dunkl et al. 1994; Dunkl and Frisch 2002). The role of the weathering crust is obvious: where it is disintegrated or destroyed (e.g. around the natural or artificial hollows), the surface of the cone begins to be eroded.

The rapid succession of temporary burial and exhumation is interestingly proved by the position of beehive holes occurring in many chimneys. These can be found in different levels (sometimes on the same cone); in some places, they occur at ground level or beneath; in other places at 2–3 m relative height, which implies that after their excavation, alternating erosion processes could have produced partial burial, e.g. by soil creep or flow, and partial exhumation.

The fairy chimney landforms also comprise short-lived "artificial" badlands, i.e. highly dissected surfaces of volcaniclastic deposits formed in historical times. The best example is the badland near the village of Kazár (north of the Mátra Mts: Fig. 9), and similar small-size erosion surfaces can be found in the Mátra, Cserhát, Börzsöny and Tokaj Mts as well. In these cases, a special factor (slide, forest-fire, exploiting, exhaustive grazing) was responsible for the rapid deforestation that, in turn, generated badland formation. This process, under the present semi-humid climate, can never lead to typical fairy chimney formation, because reforestation occurs after a few hundred years. For instance, the ^{14}C age of the Kazár badland (obtained on a buried tree-trunk) is 250 yrs (Table 1), proving the very young age of such landforms. However, spectacular, small-sized badland morphology can be studied in the mentioned places, which are sometimes nature conservation areas.

Fig. 9
The Kazár badland nature conservation area

Table 1
Radiocarbon dating of a buried tree-trunk at Kazár badland (performed by †E. Hertelendy, Institute of Nuclear Research of the Hungarian Academy of Sciences

Radiocarbon age	Sample No.: deb-6348 **250 ± 30** $\delta^{13}C$ = –26.02‰(PBD)	
Calibrated age cal AD 1656 Cal AD ranges obtained from intercecpts		
	One σ	cal AD 1647–1665
	Two σ	cal AD 1636–1772, 1944–1952
Minimum of cal age ranges	(cal ages)	Maximum of cal age ranges
1 σ cal AD 1647	(1656)	1665
2 σ cal AD 1636	(1656)	1952

Postvolcanic (Quaternary) surface evolution: role of tectonic activity, rates and types of erosion

Conclusions drawn from volcanological and geomorphological research in the Börzsöny–Visegrád and Mátra Mts show that postvolcanic tectonic movements and erosion played a different role but took equal part in forming the present-day relief. The basic difference is that the tectonic movements (uplift, subsidence/burial, tilting, faulting, rotation, etc.) have affected the volcanic relief to variable extent, whereas the rates of erosion have been more uniform and, although they vary through time, they can be estimated with precision.

Role of postvolcanic (mostly Quaternary) tectonism

In the North Hungarian mountains, where volcanic relief in Hungary is the most significant, a long known structural pattern, i.e. NW–SE and NE–SW lineaments and related displacements, are characteristic. Some of these directions (typically the NE–SW one) are commonly older (Oligocene to Mid-Miocene), others (typically the NW–SE one) tend to be younger, i.e. Quaternary (e.g. Czakó and Zelenka 1981; Fodor et al. 1999), although older directions may also have been rejuvenated (L. Csontos, pers. commun.); see Fig. 3. The intense Quaternary tectonic activity is due to the "neotectonic" compressive stage of the evolution of the Pannonian Basin (Horváth et al. 1995).

In the volcanic mountains the change of tectonic style in the Quaternary caused several 100 m to 1–2 km lateral displacements (Varga et al. 1975; Czakó and Zelenka 1981; Székely and Karátson 2004) and vertical movements of a few 100 m (Balla 1978; Karátson 1995; Karátson et al. 2006). The effect of these was significant not only on the further modification of secondary (erosional) landforms, but also that they might have fundamentally transformed and masked the primary landforms (see above). The horizontal displacements (i.e., faults) resulted in the pre-formation of new valleys (e.g. Kövicses Valley in the Mátra

Mts: Czakó and Zelenka 1981; the valley system of the South Börzsöny Mts: Karátson et al. 2000), whereas tectonic uplift led to accelerated erosion (examples see above).

Rates of erosion

There are only few studies dealing with the quantitative rates of denudation in the Hungarian (and Carpathian) volcanic mountains. In an earlier work of the author, K/Ar radiometric dating and morphometric correlation of reconstructed landforms (e.g. craters) of the East–Northeast Carpathians made it possible to obtain data on the changes of selected morphometric variables per time unit (for instance, enlargement of craters or development of intra-craterial valley network: Karátson 1996). Also, a general denudation rate, 260 m + 31.5 m/Ma, for the last 11 Ma (i.e. a time frame since the Late Miocene), was obtained (Karátson 1996) (the constant 260 m value is an average figure resulting from the initial, rapid erosion that took place on unforested, initial surfaces). Obviously, this average rate may show a high variability through time, but can be accepted as a minimum value in the long term.

Excellent occurrences for erosion rate calculations are the basalt buttes of the Balaton Uplands, which have normally preserved the pre-volcanic (mostly Pannonian) paleosurface. Németh and Martin (1999) and Németh et al. (2003), correlating the thickness of underlying deposits, the actual and reconstructed elevation of the volcanoes, as well as available K/Ar data, have obtained an average of 50 m/Ma denudation rate, although the range is high (20–90 m/Ma). The extreme rates (especially in the western part of the Tapolca Basin) can be explained by local, rapid Plio/Pleistocene uplift (Németh et al. 2003).

At present, erosion data derived from other than the above methods do not exist for the Hungarian volcanic mountains, although exposure age or fission track dating (cf. Dunkl and Frisch 2002) are promising tools for such calculations. Recently, Ruszkiczay-Rüdiger et al. (2005) presented an incision rate for the late Pleistocene evolution of the Danube obtained by exposure age dating, and Karátson et al. (2006) summarized related results (denudation and incision rates) of volcanic successions, travertine horizons, cave minerals and terrace levels obtained by geomorphology, sedimentology, Th/U dating, paleontology, and precise leveling. These authors pointed out that for the Danube Bend a very young (late Pleistocene) uplift and erosion had occurred, much more intense than the long-term average denudation.

Using a 30 m/Ma average erosion rate the denudation of the Tokaj Mts, the youngest among the calc-alkaline volcanic mountains in Hungary, is 500–600 m, whereas in the oldest landscapes, the Börzsöny–Visegrád Mts, it is 700–800 m [among the few authors who gave numerical values for erosion, Láng (1955) proposed only 300–500 m for the Börzsöny, but, at the same time, he considered the primary landforms as being totally degraded]. However, when investigating erosion rates in greater detail, there are a number of factors that may modify the above generalized calculation. Especially Early or Middle Miocene subtropical erosion had higher rates (up to 80–100 m from peri-Alpine studies: Einsele 1992; Hinderer and Einsele 2001); also, the periglacial surface processes in the glacial stages showed accelerated erosion (50–80 m: van Husen 1978; Hinderer 2001; Hinderer and Einsele 2001). On the other hand, the Middle to Late Miocene partial burial and the relatively arid climatic Pliocene stages may have preserved or only subordinately affected the paleosurfaces. For instance, the 1,300–1,500 m-high High Börzsöny and Keserûs Hill volcanoes (Börzsöny–Visegrád Mts) were eroded by 700–800 m in the Miocene, 100 m in the Pliocene and another 100 m in the Quaternary (Karátson et al. 2006). Meanwhile, an at least 200 m (Quaternary) uplift has been postulated, compensating for the total vertical lowering. Nevertheless, 900–1000 m total denudation, exceeding the above general calculation, has been suggested.

One of the most significant postvolcanic uplift as well as erosion histories may have occurred in the Western Mátra Mts. There, along the Mátrabérc Ridge, the volcanic-sedimentary layers – namely, those considered formerly as the “Middle Rhyolite Tuff” but that are probably younger (13–14 Ma) – crop out as high as 700 m, and the overlying volcanic pile, as mentioned before, is only in the order of 100 m thick.

In the vicinity of the Tapolca Basin, due to the reconstructed rapid uplift and erosion (Németh et al. 2003), the total denudation of Pannonian deposits ranges between 80 and 270 m, which, if extrapolated to the aforementioned 30 m/Ma average erosion rates in m/Ma, fits well with the mountainous areas.

Types and processes of Quaternary erosion

The Quaternary relief evolution of the volcanic mountains of Hungary has been determined by the aforementioned enhanced tectonic activity (within this, a significant uplift) as well as the effect of successive glacial stages. The generally well-studied erosion processes and related landforms are summarized here with regard to the volcanic landscapes. Channel erosion specifically is not discussed here, but general statements arisen from the case studies shown earlier are included.

1. *Pedimentation.* In general, the slightly dipping foothills of the Börzsöny, Mátra, Bükk and Tokaj Mts, surrounding them from the S, are considered as pediment surfaces formed up to the Pliocene Epoch. Their formation should have occurred under semiarid climatic conditions (and/or alternating drier and wetter periods) by the retreating erosion of torrents as well as intense mass movements. Subsequent (i.e. Quaternary) differential uplift could have enhanced these processes, resulting in multiplied and disintegrated, dissected pediments (Pécsi 1964; Székely 1969). According to the present author, however, the generalization of pedimentation in the volcanic mountains, or their

connection to uniform levels (cf. Székely 1969) is not informative, because morphometrically uniform levels or landforms can only be found within a given volcanic mountain or structure. In other words, the pedimentation always occurred specifically, in accordance with the primary (volcanic) landforms and local tectonism. What can be said in general is that along the southern periphery of the volcanic mountains, the marginal subsidence of the Great Hungarian Plain possibly affected large pediment areas which have become buried. Simultaneously, the uplift of the mountains and hence the increase of their elevation relative to the erosion base (i.e. the plains) may have favored pedimentation processes, especially in the semiarid periods.

In the Börzsöny Mts, its southern foreland (South Börzsöny) is a dissected region with some remnant of primary volcanic landforms and their tectonically disintegrated parts, without significant pediments. To the N, the ridges of the Börzsönyháta foothill area is a remnant surface of the base of the volcanic cone of the Kemence Valley Caldera; there the flat surfaces of the uniform, slightly north-dipping ridges can be considered as a pediment.

In the Mátra Mts, the uplift in the northern part resulted in slightly dipping slopes of the southern part. On these slopes as well as the connected, Pannonian sediments, a relatively large belt of pediment and glacis surfaces were formed (e.g. Székely 1969). To the N the young uplift resulted in a steep escarpment and, in its foreland, typical pediments are missing both in the Western and Eastern Mátra (Karátson et al. 2001); the situation is similar along the downfaulted edge of the Western Mátra, where the young (Pleistocene) trench of the Zagyva River was formed.

In the Bükkalja, as was summarized earlier, the young erosion has produced strongly disintegrated ignimbrite plateau remnants. The high-rate uplift of the Bükk Mts (Dunkl et al. 1994) has favored pediment formation, and considering the normally southward-oriented tilting of the plateau fragments, pediment and glacis were formed as belted-outcrop plain surfaces (Pinczés 1977).

Finally, in the Tokaj Mts, its southern foreland (=Tokaj–Hegyalja) is one of the most typical pediments formed partly on ignimbrite sheets.

2. Formation of loess and other eolian deposits. Formation of loess occurred in the cold, dry periods of the Pleistocene, when the surfaces of alluvial fans became exposed to wind erosion. The loess cover can be found in the southern Börzsöny, along the Danube Bend, sporadically in the northern foothills of the Mátra and Bükk Mts, in the western and southern pediments of the Tokaj Mts, and the basalt buttes of the Tapolca and Marcal Basins. Its thickness ranges from a few to 15–20 m. In the Cserhát Mts the formation and preservation of the loess cover was subordinate for lithological reasons (dominance of clayey sediments), whereas in the southern forelands of Mátra and Bükk the lack of neighboring alluvial fans reduced loess formation. To the E, due to the decreasing annual rainfall in the Pleistocene, the elevation boundary of loess preservation was progressively higher (in Tokaj Nagy-Hill at Tokaj, loess is found at ca. 400 m a.s.l.) Above this level, and in other areas where local climatic or lithological conditions did not favor loess formation and preservation, loam soils were formed in the volcanic mountains. The mantle-bedding loess and loam cover, in lower elevations, smoothed the relief and reduced channel erosion.

3. Derasion. Derasion processes (s.s.) include low-rate mass movements normally occurring on moderate slopes, which, especially in the glacial stages of the Pleistocene, typified the lower foothill (in part pediment) areas of the volcanic mountains of Hungary (e.g. Pécsi 1964). In relatively broader areas, derasion was effective above all in the less humid periods, when channel erosion was subordinate relative to soil creep, soil flow and slow-rate slumping. Among others, derasion valleys and ridges as well as hummocky terrains are relict landforms of those periods, being naturally further modified in subsequent times. At present, derasion acts in only special (even unusual) conditions, e.g. on clayey deposits, surfaces without forest, etc., but is normally associated with normal erosion processes.

4. Periglacial relief formation. The periglacial processes (s.s.), including typical, high-rate mass movements, have long been studied in the volcanic mountains, among others by Noszky (1927), Székely (e.g. 1969), Pinczés (e.g. 1977), Borsy (e.g. Borsy et al. 1987) and Szabó (e.g. 1996).

Frost-weathering/frost-shattering induced slope processes: formation of blockmeers (Felsenmeere), talus slopes, cryoplanation steps, gelisolifluction, etc. These processes were characteristic in the higher levels of the Börzsöny, Mátra and Tokaj Mts, connected to climatic and lithological conditions. The blockmeers were formed from debris of lava rocks (especially lava flow infaces, exposed small escarpments that have steep, erodible surfaces): e.g. High Börzsöny summit region (Fig. 10), Galya-tetõ, Kékes, Nagy-Milic Hills. In the Visegrád Mts, due to the insignificance of lava flows, these landforms are missing. The Pleistocene frost weathering "used" the pre-formed planes of flow orientation originally formed in homogeneous, widespread andesite lava flows (less frequently basaltic andesite, basalt, dacite and rhyolite as well); subsequently, along the planes, parallel jointing (from a mm to dm scale) was formed. In a similar manner, in basalt lava flows, the original columnar jointing (formed perpendicularly to the cooling lava bodies) was further exhumed and eroded by Pleistocene frost weathering. Along the retreated, eroded edges of the basalt buttes, the famous basalt "organs" were formed: from the exposed, originally closely-spaced prismatic columns a loose arrangement of round-cornered, cylindrical forms has been created. Many times, the exposed columns have also developed "normal" parallel jointing (e.g. the "roll-of-coins" at Szent György and the Badacsony basalt organs in the Tapolca Basin, or at Szilváskõ Hill in the Nógrád Basalt Field).

In contrast to lava rocks, the poorly sorted volcaniclastic rocks in general, and especially the coarsest grained breccia were, thanks to their fine matrix, more resistant to intense periglacial frost action and related volumetric changes (thermal fracturing). Moreover, the oversized clasts could preserve the underlying successions from disintegration (formation of pedestals, mushroom rocks;

Fig. 10
Parallel-jointed amphibole pyroxene andesite lava rock and blockmeer in the High Börzsöny

see above). The Pleistocene talus slopes and blockmeers are rarely active today, commonly fossilized/inactivated by the cover crust of moss and lichen. Cryoplanation characterized mostly the moderate slopes, where the downhill gravitational moving of weathered debris was slow. In contrast, the mixed deposits of gelisolifluction as well as those of the sandy-gravelly grèzes litées could be accumulated mostly on the gentle, lower hill slopes/pediment areas.

High-rate slope processes: slumps, slides, topples, rock falls, etc. A large number of smaller or greater rock outcrops (dozens of occurrences in a single volcanic mountain) has been exposed due to these processes. Hummocky terrains, small ponds, swampy depressions are also among the resulting landforms. According to Szabó (1996), mostly the relatively humid and mild postglacial periods allowed these types of high-rate mass movements to occur (in his studies, the reliably reconstructed movements are mostly of Late Pleistocene – Holocene age).

In the volcanic mountains, among the geomorphologic preconditions of slide processes proposed by Szabó (1996) – i.e. caldera rims, dissected volcano flanks, tectonically modified mountain escarpments – the latter seems to be the most prominent factor, at least in those cases investigated by the present author. In other words, structural pre-formation may have been predominant. The erosional caldera rims of the High Börzsöny, Kemence Valley and Keserûs Hill volcanic edifices are poor in slide forms. Some other prominent rims proposed as "caldera rims" by earlier workers, the Mátrabérc and Dobogókõ Ridges, can be interpreted as structural escarpments formed along normal faults (for details, see above). There is no question that the richness of slumps and slides along these rims/escarpments has been due to young tectonic uplifts (in addition to lithological and structural preconditions). A large number of slide and slump forms characterize the northern rim of the Mátra Mts (Noszky 1927; Szabó 1996), as well as the northeastern (in part southeastern) slopes of the Visegrád Mts that face the Danube River. It is very interesting that the young (neotectonic) movements, i.e. uplift or extensional forces, could have resulted in sliding and cracking of massive rocks even in places where slope angle values are moderate or low (e.g. at Rocks of Zsivány Sziklák or Vasas-szakadék Gorge: Kósik 2005). In addition to these, among the "abnormal" cases are also the relatively scarce slides and subsidences of artificial origin, e.g. those due to coal mining at Szilváskõ Hill (Horváth et al. 1997).

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