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# Shallow-seated controls on the evolution of the Upper Pliocene Kopasz-hegy nested monogenetic volcanic chain in the Western Pannonian Basin (Hungary)

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**Abstract:** Monogenetic, nested volcanic complexes (e.g. Tihany) are common landforms in the Bakony–Balaton Highland Volcanic Field (BBHVF, Hungary), which was active during the Late Miocene up to the Early Pleistocene. These types of monogenetic volcanoes are usually evolved in a slightly different way than their "simple" counterparts. The Kopasz-hegy Volcanic Complex (KVC) is inferred to be a vent complex, which evolved in a relatively complex way as compared to a classical "*sensu stricto*" monogenetic volcano. The KVC is located in the central part of the BBHVF and is one of the youngest (2.8–2.5 Ma) volcanic erosion remnants of the field. In this study, we carried out volcanic facies analysis of the eruptive products of the KVC in order to determine the possible role of changing magma fragmentation styles and/or vent migration responsible for the formation of this volcano. The evolution of the KVC started with interaction of water-saturated Late Miocene (Pannonian) mud, sand, sandstone with rising basaltic magma triggering phreatomagmatic explosive maar-diatreme forming eruptions. These explosive eruptions in the northern part of the volcanic complex took place in a N–S aligned paleovalley. As groundwater supply was depleted during volcanic activity the eruption style became dominated by more magmatic explosive-fragmentation leading to the formation of a mostly spatter-dominated scoria cone that is capping the basal maar-diatreme deposits. Subsequent vent migration along a few hundred meters long fissure still within the paleovalley caused the opening of the younger phreatomagmatic southern vent adjacent to the already established northern maar. This paper describes how change in eruption styles together with lateral migration of the volcanism forms an amalgamated vent complex.

**Key words:** volcanic hazard, phreatomagmatic, scoria cone, maar, vent migration, magma fragmentation, pyroclastic density current.

## Introduction

With respect to magma fragmentation two "end-members" can be recognized. In a "dry" magmatic eruption the expansion of magmatic volatiles in an overpressured environment is responsible for fragmenting the magma explosively. In small-volume mafic magmatic systems scoria cones and spatter cones are the typical volcanoes produced by the magmatic fragmentation style (Vespermann & Schmincke 2000). On the other end of the magma fragmentation spectrum is the "wet" explosive interaction of magma with water resulting in phreatomagmatic eruptions that form maars, tuff rings and tuff cones (Lorenz 1973, 1986; Wohletz & Sheridan 1983; Lorenz & Kurszlaukis 2007). Maar and tuff ring volcanoes form when the rising magma interacts either with ground or surface water respectively (Lorenz 1986; Németh et al. 2010; White & Ross 2011). The evolution of a phreatomagmatic volcano is commonly related to 1) syn-eruptive valley systems where water is readily available below the surface along hydrologically active faults and fractures such as in the West Eifel Volcanic Field in western Germany (Lorenz 1984; Lorenz & Zimanowski 2000), or 2) in low lying, well-drained siliciclastic sedimentary basins such as the Pannonian Basin in Central Europe in which the Bakony–Balaton Highland and Little Hungarian Plain Volcanic Fields (BBHVF and LHPVF respectively) are located (Martin & Németh 2004).

A "s*ensu stricto*" monogenetic volcano is defined as: "*a volcano that was active for a relatively short period of time, days to years, and that erupted in many small-volume eruptions*" (Lorenz 2007; Németh et al. 2010). However, a large number of volcanoes traditionally viewed as monogenetic seem to be actually complex volcanic edifices and their eruption histories are defined by multiple eruptive phases or is even polycyclic and/or polymagmatic in nature (Brenna et al. 2010; Kereszturi et al. 2010; Needham et al. 2011). Volcanoes of this subtype can form well-distinguished volcanic units generated by distinct eruptive phases or even by several eruptive episodes (Németh et al. 2010). Fragmentation styles (e.g. phreatomagmatic vs. magmatic) can change dramatically during complex monogenetic volcano-forming eruptions and are commonly associated with lateral and/or vertical vent migrations (Auer et al. 2007; Ort & Carrasco-Núñez 2009). In addition eye-witness accounts and geological records of recent maar-forming eruptions support such vent migrations (Németh & Cronin 2011). The variability of these processes can significantly control the architecture and the shape of the resulting volcanic edifice.

The primary goal of the present research is to reveal the fundamental role of eruption-related processes, such as changing fragmentation styles and vertical/horizontal movements of the explosion locus in the course of the evolution of a monogenetic volcano referred to here as the Kopasz-hegy Volcanic Complex (KVC; Fig. 1) in the central part of the BBHVF. The main characteristic of the KVC is the significantly different shape that makes it unique within the BBHVF. The KVC edifice closely resembles a volcanic chain or a large phreatomagmatic volcano formed through a complex eruption series from several eruptive vents.

Inspite of the young age of the KVC (around 2.8–2.5 Ma; Balogh K. pers. comm.), its inner volcanic architecture and diverse pyroclastic successions are relatively well-exposed along erosional escarpments in a circular array that provides an excellent insight into the volcanic evolution of a complex, "chain-like" eruption center.

## Geological background

The KVC is located at the western boundary of the Kál Basin (Fig. 1). The basement of this part of the Bakony Mts and Balaton Highland mostly consists of Devonian schist (e.g. Lovasi Schist Formation), Permian red sandstone (e.g. Balaton Highland Sandstone Formation) and Triassic marl, dolomite (Budai & Csillag 1998; Budai et al. 1999; Csillag 1999, 2003; Fodor et al. 2002). The Kál Basin is character-

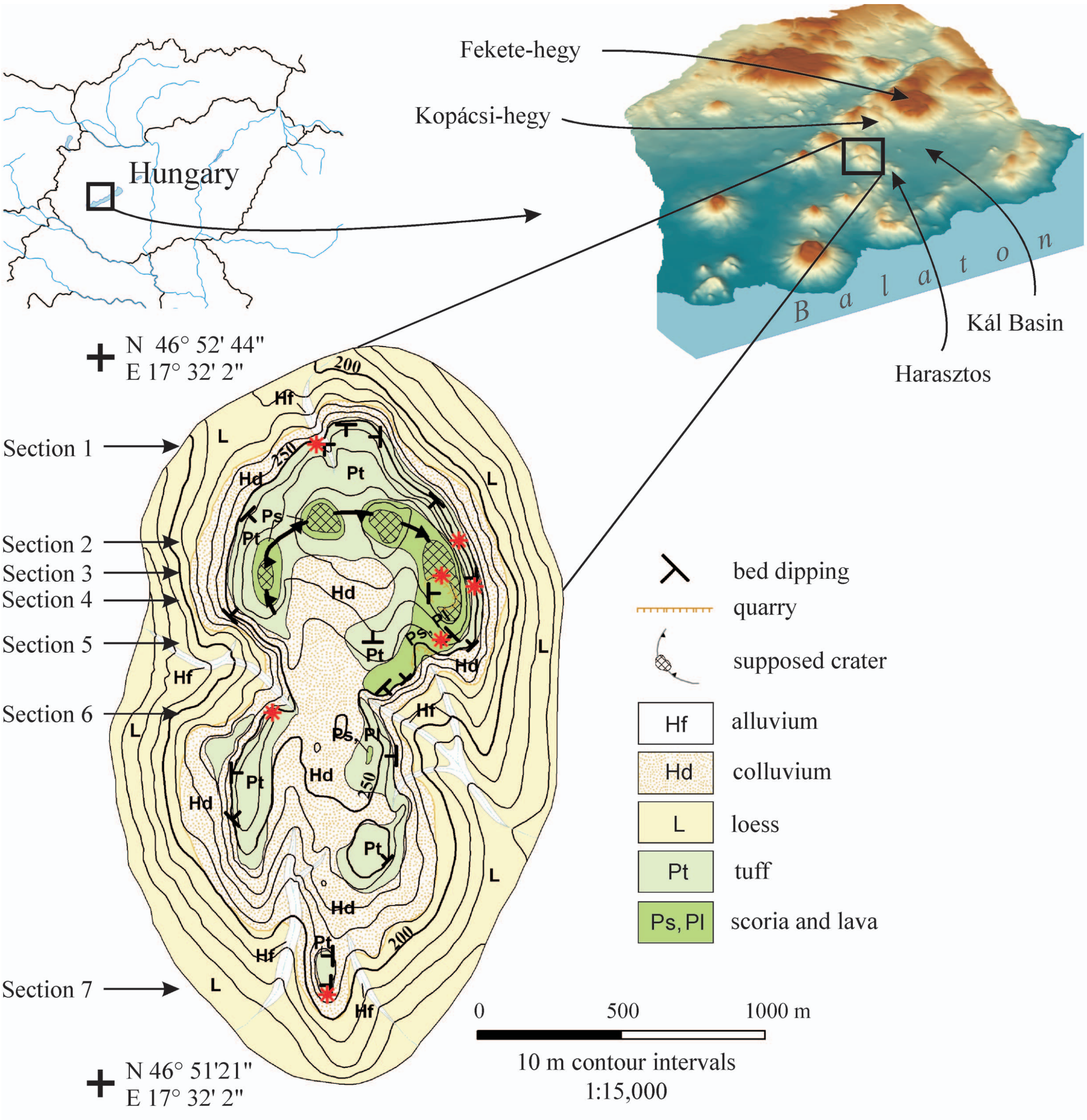

**Fig. 1.** The location of the Kopasz-hegy Volcanic Complex in the BBHVF and its simplified geological map. Note: the stars are the measured sections.

ized by highly degraded syncline and anticline structures comprised of the aforementioned rocks (Csillag 2003). According to Csillag (2003), an anticline structure that formed during early Alpine structural movements from the Cretaceous to Middle Eocene is located directly below the volcanic remnant of the KVC. Overlying these old structures unconsolidated and porous Upper Miocene (Pannonian stage) siliciclastic sediments from Lake Pannon can be found (Budai et al. 1999; Csillag 2003). Their sedimentation ended around 8 Ma ago in the study area (Magyar et al. 1999). Southward progradation of rivers gradually filled the shallow basin of the late stage Lake Pannon and transformed the area into a broad coastal plain with rolling hills and streams contained in longitudinal valleys. This environment provided abundant ground and surface water along N-S-trending stream valleys for the small-volume intracontinental basaltic volcanism (Martin & Németh 2004).

According to K-Ar and Ar-Ar radiometric dating (Balogh et al. 1986; Balogh & Pécskay 2001; Balogh & Németh 2005; Pécskay et al. 2006; Wijbrans et al. 2007; Balogh et al. 2010), the alkali basaltic volcanism was active over a period of nearly 6 Myr (Szabó et al. 2004). The onset of volcanism was about ~7.94 Ma at the Tihany Peninsula (Balogh & Németh 2005; Wijbrans et al. 2007) while its last activity occurred about ~2.29 Ma at Bondoró (Balogh & Pécskay 2001; Kereszturi et al. 2010). Volcanism in the BBHVF is characterized by a low magma output rate, around 0.5 km$^3$/Myr, combined with tectonically controlled behaviour (Kereszturi et al. 2011).

Recent studies revealed that the volcanism of the BBHVF was typical of monogenetic volcanic fields that erupted in environments with high external water availability and which were producing various types of phreatomagmatic volcanic landforms such as maars and tuff rings that are commonly associated with scoria cone forming events in their late stage evolution (Németh et al. 2001; Martin & Németh 2004; Auer et al. 2007; Csillag et al. 2008).

According to new K-Ar age determinations by Kadosa Balogh (pers. comm.), the KVC was emplaced during the late phase of volcanic activity of the BBHVF between 2.82 ± 0.36 and 2.59 ± 0.12 Ma ago. The KVC is composed of the erosional remnants of two N-S aligned, oval-shaped (in map view) and closely spaced eruption centers (northern and southern). The alignment of the volcanic vents correlates well with the surface and sub-surface extent of the pre-volcanic siliciclastic sediments (e.g. unconsolidated sand and silica cemented sandstone lenses) of the Kálla Gravel Formation that formed within a N-S elongated paleovalley system during the Miocene and/or Pliocene (Bence et al. 1999). Furthermore, the nearby Kopácsi-hegy (about 1 km toward the NE; Fig. 1) with its basal maar with intra-crater scoria cone and valley filling pyroclastics flow deposits inferred to be initiated from this phreatomagmatic volcano also show a similar, N–S-trending elongation (Németh & Martin 1999). Two other, previously identified nearby eruptive centers (Kopasz-hegy north and south; Fig. 1 and Fig. 10) and a third vent called Harasztos just south of the KVC may also be part of the aligned vents of the KVC. On the basis of scattered surface deposits of unsorted accidental lithic fragment and chilled volcanic juvenile particle dominated lapilli tuffs of Harasztos it is inferred to be a deeply eroded phreatomagmatic volcano, where diatreme facies deposits are exposed and cross-cut by N-S trending basalt dykes (Bence et al. 1987; Németh et al. 2003). In this study, we focus only on the two northern, amalgamated maar structures forming the KVC and do not elaborate on the volcanic relationship between the KVC and the southern vents.

## Volcanic architecture

The KVC is an elongated volcanic chain composed of two erosional volcanic edifices each about 800–1000 m in diameter (Fig. 1). The highest point of the edifice is 300 m a.s.l. at the northern part of KVC with its elevation systematically decreasing towards the south. Along the present erosional remnant of the KVC, we examined seven outcrops in detail (Fig. 1). The eruption sequences of KVC are represented by 14 sedimentary facies that are separated on the basis of bedding characteristics, structures, grain-size, and composition. The terminology of pyroclastic deposits such as ash, lapilli and blocks is based on Fisher & Schmincke (1984) and White & Houghton (2006). According to Ingram (1954) the bed thickness is defined: thinly laminated < 0.3 cm; thickly laminated 0.3–1 cm; very thinly bedded 1–3 cm; thinly bedded 3–10 cm; medium bedded 10–30 cm; thickly bedded 30–100 cm and very thickly bedded > 100 cm.

### *Northern edifice*

#### *Medium bedded lapilli tuff (LT1)*

**Description:** This facies LT1 is widespread in the outcrops of the KVC, mostly in proximal position just about 300 m from the eruptive center. However, this facies type can be occasionally identified in more distal position up to 800 m away from the eruptive center (Fig. 1). These layers are a few dm thick and mostly composed of grey to brownish lapilli tuff (Figs. 2 and 3). The massive lapilli tuff shows a high abundance of angular to sub-angular, accidental lithic clasts (cm to dm sized) sourced from the underlying country rocks, especially of sandstone fragments from the Pannonian sediments. Some of them have a mm-wide chilled margin. The upper parts of the outcrops comprise more Permian sandstone fragments than the lower parts. Below the larger lithic blocks, there are no impact sags in these beds. Individual layers are parallel bedded and normal graded. Cauliflower bombs occur, but they are rare.

**Interpretation:** The location at the base of the succession, bedding structures and the abundance of accidental lithics indicate that these beds were formed during a vent clearing event that were triggered by phreatomagmatic eruptions (Lorenz 1986).

The contact zone between the pre-eruptive sediment and the pyroclastic rocks of the KVC has not been exposed, but Pannonian sand and sandstone outcrops can be found near the base of the KVC about 200–210 m a.s.l. (Budai et al. 1999). This evidence implies that the bottom of the outcrop (~220–230 m a.s.l.) is close to the very basal part of pyroclastic succession. The abundance of Pannonian sandstone

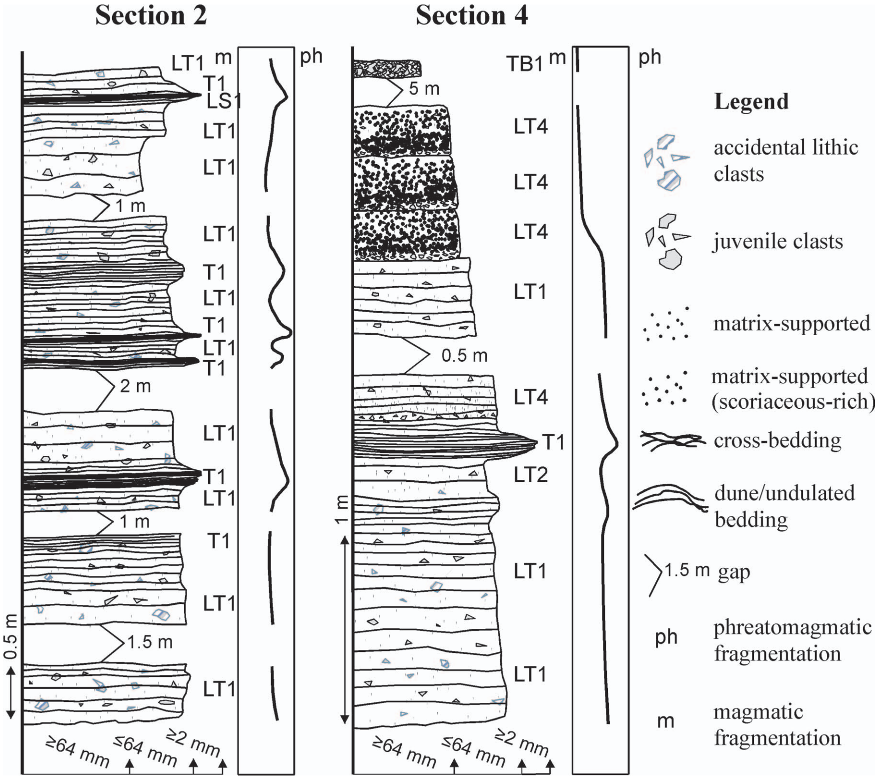

**Fig. 2.** Log of Section 2 (GPS coordinates: N 46°52′25″ and E 17°32′51″) and Section 4 (GPS coordinates: N 46°52′21″ and E 17°32′52″) exposed on the eastern slope of the KVC.

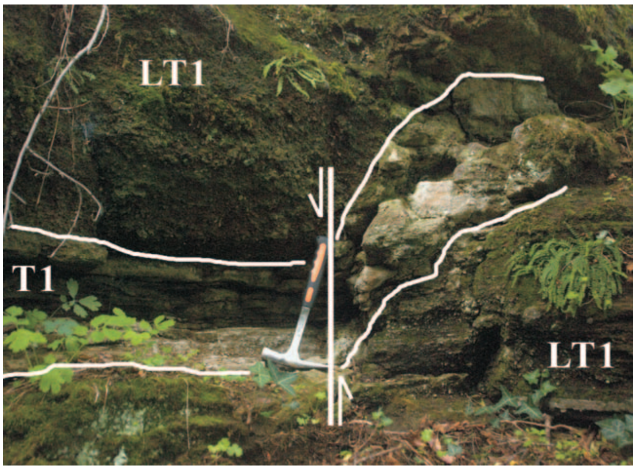

**Fig. 3.** Lithofacies T1 intercalation between LT1 in the Section 2 in the northern part of KVC. The arrows indicate small displacement along a possibly syn-eruptive fault.

lithic fragments suggest that these explosions occurred in this rock unit along a hydraulically active fault system. The increasing amount of fragments from deep seated rocks in higher sections in the pyroclastic sequence indicates the downward migration of the explosion chambers in time (Lorenz 1986; Lorenz & Kurszlaukis 2007). Lack of impact sags beneath larger clasts and the bedding characteristics of the pyroclastic rock units suggest that larger blocks were transported by relatively dry, pyroclastic density current in a lateral direction (Sohn & Chough 1989).

### *Thinly laminated tuff (T1) and lapilli stone (LS1)*

**Description:** This facies (T1) is exposed in the eastern slope of the KVC (mostly in the Section 2 in the Fig. 1). It consists of white to grey, thinly laminated coarse- and fine-ash beds (Figs. 2, 3 and 4). It is commonly parallel bedded and sometimes cross-laminated without any larger blocks, impact sags or any eye-visible accidental lithic clasts. However, the matrix comprises abundant particles derived from siliciclastic sediments. The maximum thickness is about 20–30 cm. This facies is mostly intercalated by medium and very thinly bedded (LT1 and LT2) and undulating bedded lapilli tuffs (LT3). Upward in the section (Fig. 2), the facies T1 gradually becomes a more lapilli-dominated, but still relatively well-sorted bed (facies LS1).

**Interpretation:** The size of the pyroclasts (mostly ash and lapilli-dominated LS1 facies) and its cross-laminated nature suggest that this facies may have been produced by base surge rather than fallout (Sohn & Chough 1989). The fine grain size (i.e. lack of visible lithics) may represent highly efficient explosive, phreatomagmatic fragmentation of the ascending magma under relatively 'optimal' magma to water ratio to gain maximum explosive energy release (Wohletz & Sheridan 1983). The source of external water is inferred to be the slightly water-saturated Pannonian sediments close to the surface as the deposit contains a large number of fine-grained particles from the pre-volcanic succession (Martin & Németh 2004). This could also be a result of the relatively shallow level of magma fragmentation where magma interacted with "soft substrate" hosted aquifer. Both, the lack of impact sags and any deformation of the beds as well as the sharp bedding contact suggest that the depositional system was relatively dry (i.e. no excess water/moist in the system to cause plastic bed deformations). The lack of impact sags demonstrates that the country rocks were easy to fragment, friable and/or poorly consolidated.

### *Very thinly bedded tuff (T2) and lapilli tuff (LT2)*

**Description:** These two facies occur in the most distal position only on the northern slope of the KVC (Section 1 in the Fig. 1). The very thinly bedded lapilli tuff (LT2) displays alternating layers of coarse ash and lapilli tuff with mostly normal grading (Figs. 2 and 4). The thickness of individual layers is about several cm to few dm. The very thinly bedded tuff (T2) comprises more ash than the LT2 (Fig. 4). Both facies LT2 and T2 are grain-supported.

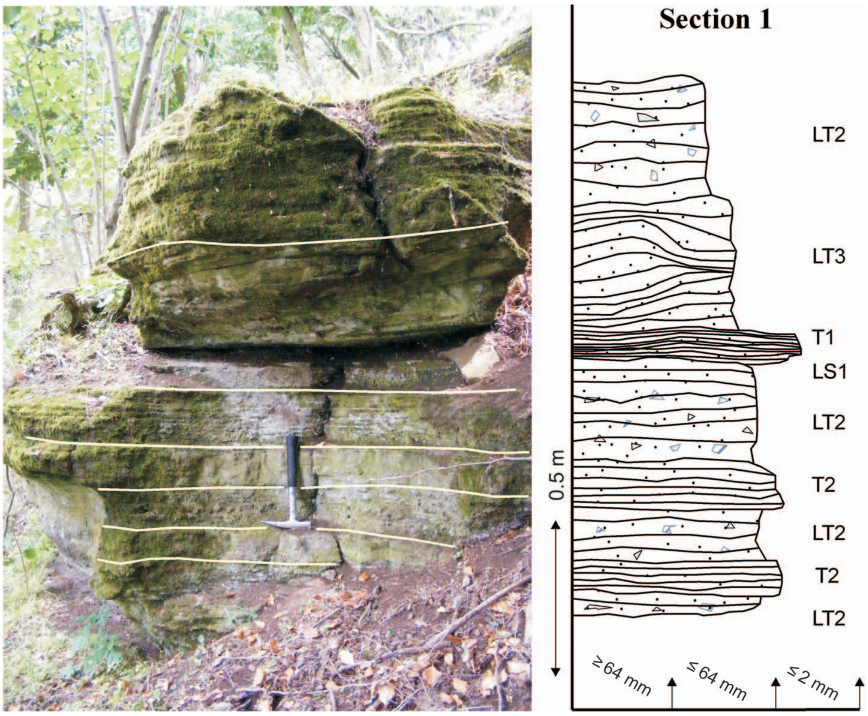

**Fig. 4.** Field photo and simplified sedimentary log of distal phreatomagmatic units of the KVC in the Section 1 (GPS coordinates: N 46°52′34″ and E 17°32′30″). Legend is in the Fig. 2.

**Interpretation:** Facies LT2 is interpreted as the result of a low concentration, dry base surge based on the grading and the segregation of lapilli and coarse ash (Sohn & Chough 1989). Facies T2 may represent the subsequent fall-out from an elutriation ash-cloud related to this turbulent and low concentration base surge (Sohn & Chough 1989).

*Undulating bedded lapilli tuff (LT3)*

**Description:** Undulating bedded lapilli tuffs (LT3), in general, occur in distal positions in the northern slopes of the KVC (Fig. 3). Facies LT3 is situated on the top of the phreatomagmatic rock units exposed at the base of the outcrop. These layers are characterized by slightly undulating and normal graded bedding structures and rare block-sized fragments. LT3 is comprised of homogeneous, grey to brownish tuffs and lapilli tuffs. Individual layers are a few cm to dm thick.

**Interpretation:** This facies may be interpreted as a lateral equivalent of the LT1, and inferred to be generated by relatively 'dry' base surges on the basis of its sharp, stratified and normal graded style of bedding. In addition, the undulating appearance of facies LT3 is also in agreement with a pyroclastic density current depositional origin (Crowe & Fisher 1973). This facies is inferred to have been deposited within the N–S paleovalley but at a significantly different distance from the source vent and in a different position within the paleovalley than facies LT1. The undulated bedding characteristics indicate that the pyroclastic density current was low in particle concentration (Vazquez & Ort 2006). Such conditions are expected along the shoulder of a valley thus LT3 most likely represents the pyroclastic deposits accumulated in an 'overbank' location in medial or distal position from the vent, similarly to the phreatomagmatic pyroclastic flow deposits of Kopácsi-hegy nearby (Németh & Martin 1999).

*Medium bedded, scoria-rich lapilli tuff (LT4)*

**Description:** This facies mostly crops out in the upper part of the northern volcanic remnant. Facies LT4 is richer in juvenile fragments than LT1. In general, these juvenile fragments vary in vesicularity (from poor to moderate), and they are mostly grey to black or reddish in colour (Figs. 2 and 5). Individual layers of facies LT4 are a few dm in thickness and show normal grading.

**Interpretation:** The stratigraphic position indicates that this facies was deposited during the late stage of the eruptive sequence and is the result of explosive eruptions with transition from phreatomagmatic to magmatic fragmentation of the rising magma. Such fragmentation style changes are inferred to be controlled by near surface geological conditions such as the water supply fluctuations or a variable magma supply rate into the root zone (Lorenz & Kurszlaukis 2007). The magma fragmentation responsible for the formation of LT4 is interpreted as the result of dryer but still phreatomagmatic eruptions. This facies is a precursory facies followed by subsequent deposition of more magmatically fragmented pyroclastic deposits higher in the rock sequence (Fig. 2).

**Fig. 5.** Closer view of an increased scoriaceous-rich lapilli bed (A) and the overview photo of the transitional layers exposed in the Section 4 (B).

*Thickly bedded, scoriaceous pyroclastic breccias (PB1)*

**Description:** Scoriaceous pyroclastic breccias are widespread in the upper section of the edifice (Figs. 1, 2 and 6). Layers of these facies are poorly defined. It is generally a succession of a light grey to black, highly to moderately vesicular basaltic breccias and rarely lapilli which are intercalated with thin lava layers (Facies LR1; Fig. 6). These deposits are highly to moderate welded and agglutinated and form four mound-shaped hills on the top of the northern eruption center that breached toward the south (above ~285 m a.s.l.; Fig. 1).

**Interpretation:** On the basis of textural (e.g. high vesicularity) and bedding characteristics, we interpret these pyroclastic rocks to be eruptive products from weakly Hawaiian to Strombolian-style eruptions (Vespermann & Schmincke 2000; Agustín-Flores et al. 2011) in the final stage of the activity of the KVC. The distribution of facies PB1 reveals that these eruptions produced a scoria cone over the basal shallow maar crater that was surrounded by a low tephra ring. In spite of its young age, the scoria cone itself is characterized by poor preservation (i.e. almost invisible morphology in the field, breaching of the crater), which can indicate some degree of truncation during syn- or post-eruptive time.

*Lava rocks (LR1 and LR2)*

**Description:** Two types of lava rocks have been identified at the KVC (LR1 and LR2). Facies LR1 comprises a coherent texture but shows still recognizable few cm- to dm-sized clast outlines suggesting that the rock was originally fragmented. Most of these facies dip toward the center of the preserved volcanic edifice (Fig. 1). Vesicles are rare. This facies occurs only in the Section 5 in the SE part of the KVC. Facies LR2 is characterized by a grey to black colour, and a moderately vesicular coherent texture with rare bomb and block-rich horizons (Fig. 7). Generally these rocks form an outward dipping (about 5–10 degree) layered rock unit. A small quarry exposes LR2 in the eastern edge of KVC (Fig. 1).

**Interpretation:** Facies LR1 and LR2 are inferred to have resulted from short-lived Hawaiian-type lava fountain eruptions (Head & Wilson 1987). According to the stratigraphical position, facies LR1 accumulated between the foot of the scoria cone and the inner crater wall of the tephra ring surrounding the shallow maar crater. The ballistically ejected spatter was large and the magma output rate was high enough to retain the heat of lava clots upon landing and for quick accumulation to form thin rootless lava flow(s). In contrast, the gently outward dipping of the facies LR2 indicates that this facies was accumulated on the outer flank of the scoria cone as a small-scale spatter-fed lava flow.

### Southern edifice

*Disorganized lapilli tuff (LT5) and tuff breccias (TB1)*

**Description:** This facies (LT5) is widespread around the southern vent (Section 6 in the Fig. 1). This facies is mostly massive, but sometimes weakly bedded, poorly-sorted, normal graded and matrix-supported. The rock contains grey to brownish and yellowish lapilli with common block of basaltic cognate xenoliths (LT5; Fig. 8). The accidental lithic clasts are heterogeneous in composition and in size (up to a few dm in diameter) and include minor portions of Permian red

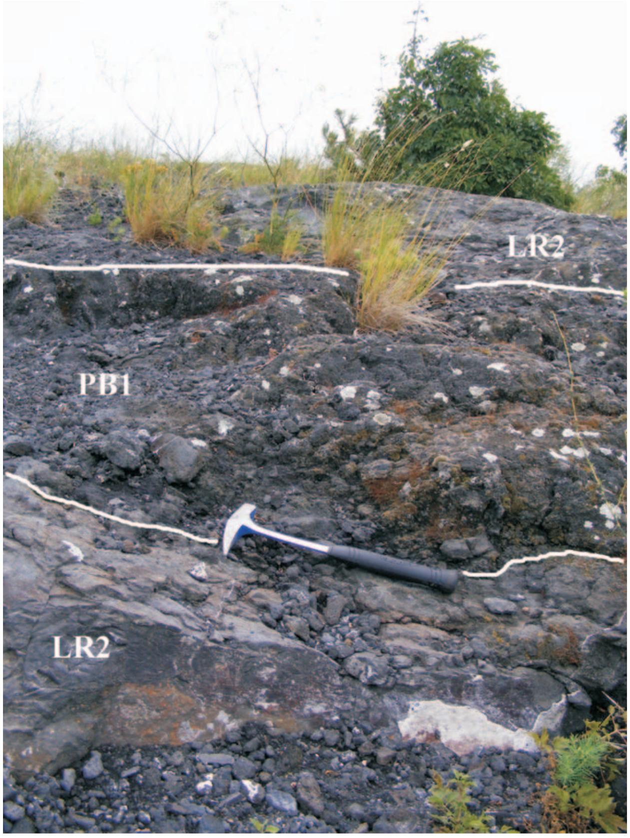

**Fig. 6.** Capping scoria cone units with dominant highly vesicular, black tuff breccias (PB1) intercalated with small lava horizons (LR2) in Section 3 (GPS coordinates: N 46°52′18″ and E 17°32′48″).

**Fig. 7.** Field photo of a small-scale rootless lava flow (in the Section 5; GPS coordinates: N 46°52′10″ and E 17°32′48″) generated by an intermittent Hawaiian-stage in the eruption history of the KVC.

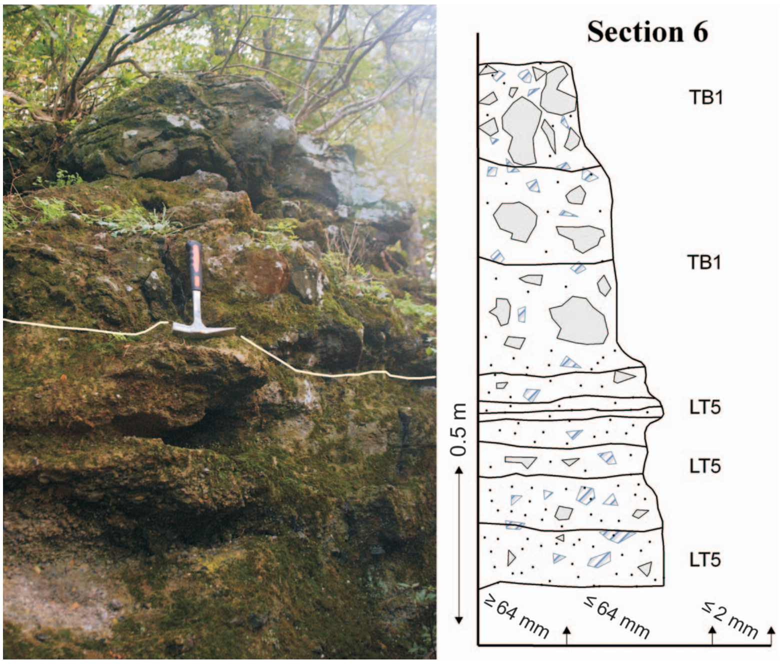

**Fig. 8.** Section 6 (GPS coordinates: N 46°52′00″ and E 17°32′18″) exposed near the "overlapping" part of the KVC and expose weakly to massively bedded LT5 and TB1 with high proportions of Devonian schist from the underlaying strata and basaltic fragments from the simultaneously active scoria cone forming eruptions of the northern eruption vent, respectively. Legend is in the Fig. 2.

sandstone, Pannonian sandstone, sub-rounded pebbles of quartz and angular basaltic clasts. This outcrop contains a large proportion of basaltic and Devonian schist fragments (Fig. 8). On occasions these accidental lithics are enclosed by a thin, chilled basaltic rim. The largest fragments of the lava clots reach a diameter of up to 60–80 cm. In addition, few mantle-derived xenoliths (lherzolit) and amphibole xenocrysts a few mm in size have been recognized.

The TB1 is often normally graded and contains fine, matrix-poor tuff breccias (Fig. 8). The main characteristics of LT5 and TB1 are the presence of lapilli and block-sized coherent basalt fragments up to ~60–80 cm in diameter. These blocks are mostly black, angular, many of them with significant surface cracks and rarely welded and vesiculated in textures. The geographical distribution of these basalt lithics is limited to the rim of the southern eruption center. Nevertheless, in a more distal position (800–900 m from the inferred source vent) only a few cm-sized particles can be seen in the pyroclastic units. The facies LT5 occasionally contains rounded boulders of Permian red sandstone. A few meters below the Section 6 a small dyke with a thickness of about 30–50 cm is exposed (Fig. 8). This dyke intruded into the previously described pyroclastic rock unit and has a sharp margin with the fragmented host rocks. The dyke dips steeply toward the interior of the southern eruption center.

**Interpretation:** Like the northern eruption center, the southern vent was also formed by phreatomagmatic eruptions, which produced the LT5 and TB1. Evidence for this type of eruptions includes the fine, matrix-supported domains and the weakly bedded appearance of the pyroclastic successions rich in glassy juvenile pyroclasts and abundant accidental lithic fragments. Due to differences in the facies architecture of the pre-volcanic country rock assemblages the volcanic processes were inferred to be slightly different from the northern vent as it is indicated by the great variety of accidental clasts including the dominant basaltic and schist fragments. This abundance of accidental lithic clasts from various country rock sources supports the model of subsurface explosive eruptions that excavated and mixed these lithologies. These lithics such as Permian red sandstone are sometimes rounded to subrounded, and are inferred to have originated from a N-S aligned active stream valley in which both the northern and southern vents erupted. In contrast, large basaltic blocks were formed by magmatic fragmentation without interaction with external water.

The coarse fragmentation of magma, the matrix-poor texture of the preserved pyroclastic rocks and the high abundance of magmatic clots exposed around the southern vent suggest that the available water supply in the capping Pannonian sediments was limited (i.e. it had a variably low groundwater reflux into the root zone). In addition, a significant proportion of those basaltic fragments show a well-developed crack system on the surface suggesting that the fragments suffered rapid cooling during the eruption. The origin of large basalt fragments could originate from a simultaneously active nearby northern vent.

### *Massive bedded (LT6) and slightly undulating lapilli tuff (LT7)*

**Description:** Both of these facies are exposed only in the southern edge of the KVC and comprise massive, poorly bedded (LT6) and undulating, thinly stratified (LT7), normal graded, matrix-supported, grey to yellow lapilli tuff with rare large blocks (Fig. 9). This part of the pyroclastic succession of the KVC contains accidental lithic clasts (i.e. basalt and Triassic marl fragments), significantly smaller in size (only a few cm) and better sorted compared to the LT5. Some ash laminas show "mud cracks".

**Interpretation:** LT6 and LT7 are inferred to be the same layers of pyroclastic units that were observed in the Section 6, but in probably more medial to distal positions from the vent. Their matrix-supported appearance and their slightly undulate and sometimes thinly stratified bedding suggest deposition from pyroclastic density currents (Vazquez & Ort 2006). But this pyroclastic rock unit is located in the southern extremity of the KVC, and has no cross- or dune-bedded layers, so therefore its depositional environment is probably situated closer to the rim of the maar crater of the southern vent system. The presence of mud cracks in the fine-grained tuff beds suggests short (minutes to hours or even days) pauses in the volcanic activity.

**Fig. 9.** Example of distal outcrops (Section 7; GPS coordinates: N 46°51′73″ and E 17°32′30″) of highly concentrated pyroclastic density current deposits.

## 3D distribution of facies associations

The KVC consists of two, relatively small (600–800 m in diameter) nearly circular shaped (in map view) volcanic edifices, the northern and southern eruption centers (Fig. 1). The fundamental problem with respect to the evolution of the KVC is the proximity of these two eruption centers to each other both from a temporal (shown by K-Ar ages range in a narrow time-frame from 2.82 ± 0.36 Ma and 2.59 ± 0.12 Ma) and a spatial point of view (the two edifices are coalescing and form a narrow volcanic chain from N to S). This chain-like arrangement is not as common in the case of maar diatreme volcanoes, as they are among monogenetic scoria cones that form narrow volcanic chains commonly along fissures with several, relatively small volcanic edifices, for example the Mt Amarilla chain in Tenerife, Canary Islands (Clarke et al. 2009). Chain-like phreatomagmatic volcanoes, however, are known from regions where structurally strongly controlled and fractured deep rock units are covered by unconsolidated water-saturated porous media (sand, silt, tillite) such as is the case in the Pali Aike Volcanic Field in Argentina (Ross et al. 2011) or the Hverfjall eruptive fissure in Iceland (Mattsson & Höskuldsson 2011).

On the basis of our study, we present the distribution of the major types of deposits including basal phreatomagmatic, transitional as well as capping Hawaiian/Strombolian-type pyroclastic rocks in the KVC. Both the northern and the southern eruption centers are characterized by basal pyroclastic rocks representing pyroclastic deposits originally derived from pyroclastic density currents and subsequent ash-falls that are preserved mostly in proximal and rarely medial/distal positions. The proportion of scoriaceous fragments is increasing upward. The basal pyroclastic rocks on the southern side of the edifice are mostly built up by unbedded or weakly bedded pyroclastic units with a great variety of accidental lithics including Devonian schist, Permian sandstone, Pannonian sand/sandstone and Triassic marl. The most significant feature of the southern eruption center's pyroclastic successions (mostly in proximal positions to the vent) is the abundance of basaltic fragments from a few cm up to 1 m in diameter (Fig. 8). The origin of these fragments cannot be explained by applying a purely transitional eruption (as the case of the northern edifice), because in the case of the southern eruptive center, we have not found any sign of gradual changing of textural characteristics (increasing number of vesicle-rich lapilli) similar to those in structures such as are preserved in the northern eruption center. In the lithofacies LT3 and LT4 the increased proportions of scoriaceous lapilli and blocks/bombs can be found as a sign of a change in the style of eruptions. The northern side of the KVC hosts a deeply truncated and degraded scoria cone remnant which is only preserved in the form of four small mounds (Fig. 1). The inferred location of the crater is probably in the center of the northern edifice surrounded by the abovementioned small mounds (Fig. 1). The crater is significantly breached towards the south.

Briefly, this proximal location of the eruption centers may have caused several anomalies in the architecture of both phreatomagmatic volcanoes and in the architecture of the northern capping scoria cone.

## Discussion

### *Shallow-seated geological structure beneath the Kopasz-hegy Volcanic Complex*

The pyroclastic successions exposed in the examined outcrops contain a high abundance of accidental lithic fragments that were derived directly from the underlying pre-eruptive formations. A similar diversity of country rock xenoliths was documented by Auer et al. (2007) from the adjacent volcanic complex of Fekete-hegy, but the Fekete-hegy covers a significantly larger area and is located on a large fault system.

In the case of the KVC, these accidental lithic fragments are comprised of Devonian schist, Permian red sandstone, Triassic marl and Pannonian sandstone. They vary gradually from the northern eruption center to the southern one (i.e. lack of Triassic marl in the northern edifice). In addition, a recent detailed volcano-sedimentary study of a further eruption center, Harasztos (Fig. 10) also found a high proportion of Triassic marl lithics and only a low abundance of Pannonian sandstone (Németh et al. 2003).

However, the distribution and type of dominant lithic fragments show a high variability within a small area (4 km$^2$).

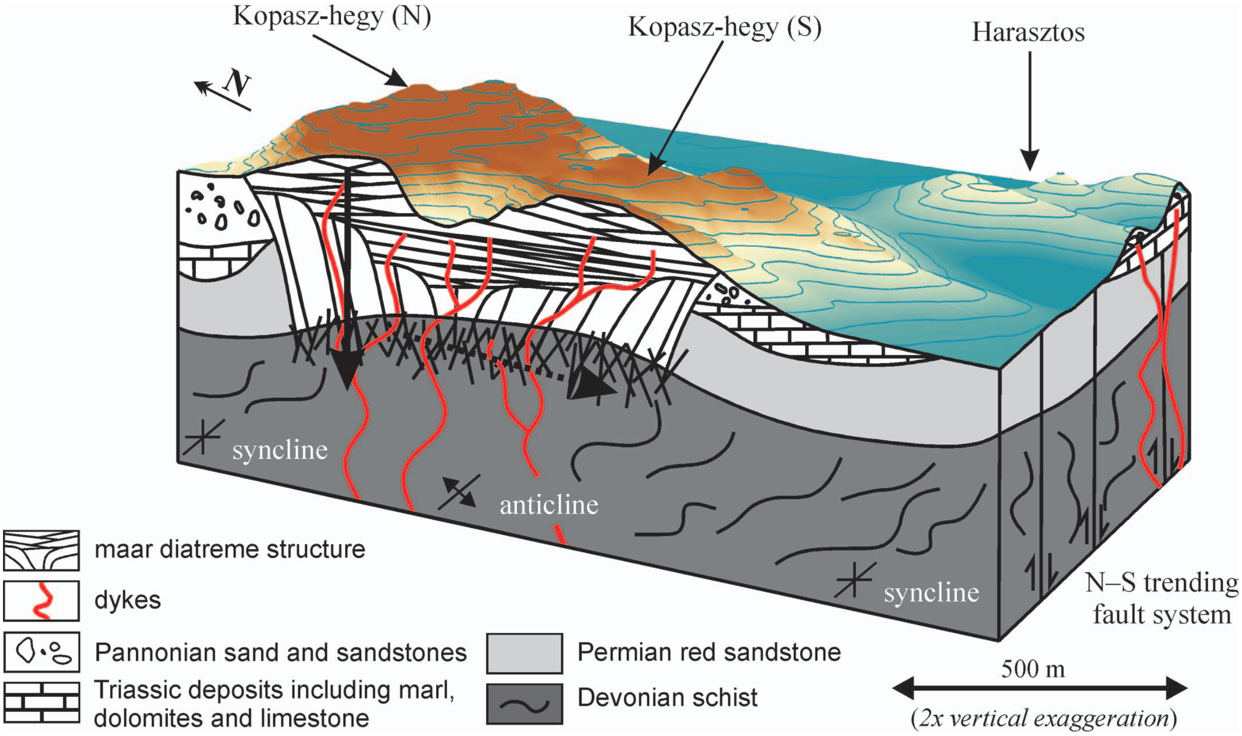

**Fig. 10.** General model for the formation of a chain-like, nested monogenetic volcano, the KVC in the BBHVF. Older basement rocks formed small, anticline and syncline structures capped by thin siliciclastic sediments and rocks of Pannonian age (sand/silt/mud and their diagenized varieties). The formation of the KVC was characterized by the initial downward movement of the explosion loci (black arrow) as well as the subsequent lateral migration of the volcanism (dashed arrow) along the boundary of the water-rich, unconsolidated sediment and the water-poor, older schist and sandstones rocks beneath the KVC and the along the N-S aligned fracture system. The thickness of underlying rocks is not to scale. Source of geological data: Budai et al. (1999), Csillag (2003, 2004), Csillag, G. (pers. comm.).

For example, the pyroclastic units of the northern edifice mostly contain Permian and Pannonian sandstone lithics while the southern edifice mostly exposes basalt fragments and older Devonian schist fragments (up to a few dm in diameter). Based on the distribution, type, dominance and relationship to the local and regional country rock structural architecture, we can draw a model shown on Figure 10 to characterize the hosting geological structures beneath the KVC. In general, the Kál Basin as well as the whole region of the BBHVF is characterized by small-sized anticline and syncline structures of mostly Devonian schist, Permian red sandstone and Mesozoic carbonates (Csillag et al. 1998; Budai et al. 1999; Csillag 2003, 2004; Németh et al. 2003). Based on the distinct spatial distribution of accidental lithic fragments, we suggest a small-sized (1×1 km) anticline structure beneath the KVC. This hypothesis coincides with other regional geological observations (Csillag et al. 1998; Budai et al. 1999; Csillag 2003, 2004).

### *Changing fragmentation styles*

In the evolution of the KVC a gradual change can be seen in the nature of volcaniclastic deposits, which suggests a transition from phreatomagmatic to subsequent magmatic fragmentation styles. However, this change in fragmentation style can only be seen in the pyroclastic successions of the northern edifice. In this case, the deepening of the conduit system resulted in a slight inverse distribution of accidental lithic fragments in the preserved phreatomagmatic rock units, which indicates a classical movement of the explosion-locus to a deeper position during the course of the volcanic activity (Lorenz 1986; Lorenz & Kurszlaukis 2007).

In the basal parts of these phreatomagmatic units, fine tuff and lapilli-dominated layers are common and reflect a higher degree of fragmentation of the ascending magma. These fine ash and lapilli intercalations are deposited at variable stratigraphic levels, indicating a complex history of magma–water interaction over time (Fig. 2). The presence of fine Pannonian siliciclast particle-rich laminated tuff (T1) suggests that the possible source of phreatomagmatic explosions was well-localized (probably not thicker than 100 m), but water-saturated during the eruptions. However, the diversity and complexity of the phreatomagmatic deposits suggest that the water supply varied over time. This intermittent and limited supply of groundwater is altogether responsible for the formation of the capping scoriaceous breccias (e.g. PB1), intercalated with spatter-dominated units (e.g. LR1 and 2). These conditions allowed the construction of a spatter-dominated scoria cone within the previously built maar crater (Fig. 1). Such changes in the fragmentation and eruptive style, with no significant time break, can be explained due to the gradual drying of the capping water-saturated Pannonian deposits and the underlying aquitard Permian and Devonian basement. Such situation is common in phreatomagmatic volcanic eruptions and has even been documented during the historic maar eruption of Nilahue maar, Chile (Müller & Veyl 1957). Alternatively, the groundwater ejected during a phreatomagmatic eruption was more than the recharge rate of the porous aquifers, especially if the volcanic activity was short-lived only (possibly days to weeks). The deep geological setting may locally also have controlled the fragmentation style, because the karst water-rich carbonates were partly missing beneath the KVC that otherwise could have been able to provide substantial and quickly rechargeable water to fuel sustained phreatomagmatism during the entire time span of the eruption (Csillag et al. 1994; Budai et al. 1999). Instead of carbonates the water-poor and aquitard Permian sandstone and Devonian schist can be found beneath the KVC (Budai et al. 1999).

### *Shallow-seated geological control on vent migration of the Kopasz-hegy Volcanic Complex*

In the KVC, two types of eruption loci migration took place on the basis of sedimentary evidence (Fig. 10). In the northern eruption center, the most general eruption loci movement can be interpreted as **downward migration** of the root zone of the diatreme as a commonly referred mode inferred for many maar-diatreme volcanoes worldwide (Lorenz 1986; Németh et al. 2001; Lorenz & Kurszlaukis 2007). Conditions that favour downward migration may have existed until the explosion loci reached the (physically as well as hydrologically different) older basement rocks (i.e. Permian red sandstone; Fig. 10).

For the **lateral vent migration**, the Quaternary Tecuitlapa maar complex (Trans-Mexican Volcanic Belt) is probably the best recently recognized example (Ort & Carrasco-Núñez 2009). In the crater wall sequence of the Tecuitlapa maar abundant accidental lithic fragments document explosive events that "sampled" various levels of the substrata (Ort & Carrasco-Núñez 2009). The lateral vent migration process at the Tecuitlapa maar has been explained by the high physical and hydrological contrast between the underlying unconsolidated and fractured bedrocks providing irregularities of water-saturation level as well as mechanical character changes of the country rocks (Ort & Carrasco-Núñez 2009). This explanation can be partly adopted to interpret the lateral migration of the volcanism documented in the KVC due the very similar geological conditions (Fig. 10). In the KVC, the upper pre-volcanic deposits were loose, unconsolidated Pannonian sand and silt and coherent sandstone lenses (Csillag et al. 1998; Budai et al. 1999; Csillag 2004). In contrast, the deeper seated hard-rocks such as the Permian red sandstone and Devonian schist have different hydrological and mechanical properties (Gondár & Gondárné Sőregi 1999; Németh et al. 2001) similar to the country rocks at the Tecuitlapa maar. Additionally, the N-S aligned fault-system beneath the KVC (Fig. 10) has also helped the propagation of magma towards the south producing a complex, closely spaced phreatomagmatic chain.

### *Scoria cone breaching caused by vent migration*

The shape of a typical scoria cone is commonly characterized by some breaching. For example, the shape of 27 % of the monogenetic flank cones of Mt Etna is disturbed by breaching (Corazzato & Tibaldi 2006). However, breaching of a scoria cone is frequently a consequence of the effusion activity and/or tectonic settings during and in the late stage of the course of an eruption (Corazzato & Tibaldi 2006) causing rafting events that can remove large sections of the cone flank (Németh et al. 2011). Breaching observed at the KVC does not relate to any lava flows, but may have been associated with the closely spaced additional eruptions and lateral migration of the volcanism from N to S. This newly formed vent has likely effected the growth of subsequent adjacent scoria cones as well as the stability of existing landforms in the northern side of the capping, intra-maar scoria cone.

## Conclusion

(1) The eruption history of the Kopasz-hegy Volcanic Complex is characterized by phreatomagmatic eruption periods, which built up two intercalating maar structures and a capping intra-maar scoria cone (Figs. 1 and 10). The eruption took place between 2.82 and 2.59 Ma ago according to K-Ar radiometric datings by Kadosa Balogh.

(2) The evolution of the KVC was predominantly phreatomagmatic in origin, but the late stage eruptions formed a small scoria cone on the top of the northern part of the complex (Fig. 10). This scoria cone was a result of the changing fragmentation style from phreatomagmatic to more magmatic in a relatively short time frame. The probable reason for the formation of a scoria cone was most likely the local exhaustion of water supply from the Pannonian siliciclastic deposits.

(3) The formation of the younger phreatomagmatic volcano in the southern edge of KVC was inferred to be a result of phreatomagmatic eruption triggered by newly intruded magma (Fig. 10) and the motion of the explosive loci towards south within the small paleo-valley cut into the thin Pannonian sediments. The reason for the lateral migration of the volcanism was probably (i) the various hydrological properties of the underlying basement rocks of the BBHVF that were unable to support magma/water interactions due to their limited discharge rate (e.g. the Pannonian sediments) and aquitard behaviour (e.g. Permian red sandstone) and (ii) extended N-S aligned fault system beneath the complex.

(4) In the case of the KVC, the travel path of small-volume pyroclastic flow and surges as well as the direction of the lateral migration of the volcanism are significantly governed by the alignment of a N-S trending paleo-valley, which hosted and controlled the entire formation of the eruptive vents.

(5) The scoria cone breaching was closely related to eruptions of the southern edifice. The magmatic fragments in the pyroclastics succession were probably derived from the coeval erupting scoria cone vent of the northern edge of the KVC. These simultaneous magmatic explosions of the northern scoria cone may have partly fuelled with large lava clots and basalt blocks the concentrated pyroclastic density current associated with the phreatomagmatism of the southern vent. Due to the load from the northern vent, these density currents were more concentrated in particles than pyroclastic surges in general.

(6) Magma fragmentation style changes and lateral migration with phreatomagmatic phases have a significant volcanic hazard aspects (Lorenz 2007). A change in fragmentation style can lead to the formation of intra-crater scoria and spatter cones that can be destabilized by a newly opened gradually or abruptly shifted phreatomagmatic vent in its vicinity posing extra and unexpected hazards during a volcanic eruption.

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