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An Overview of the Monogenetic Volcanic Fields of the Western Pannonian Basin: Their Field Characteristics and Outlook for Future Research from a Global Perspective

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1. Introduction

Miocene to Pleistocene basaltic volcanic fields are common in the Pannonian Basin in Central Europe (Figs 1 & 2). Included in these fields are the here described monogenetic volcanic fields of western Hungary. These volcanic fields provide excellent exposures to explore the volcanic facies architecture of monogenetic volcanoes that formed during a period of intra-continental volcanism that lasted over 6 million years (Fig. 2). Over this 6 millions of years eruptive history (Wijbrans et al., 2007), volcanic fields such as the Bakony-Balaton Highland (BBHVF) or the Little Hungarian Plain Volcanic Field (LHPVF) formed (Fig. 1) as typical low magma-flux, time-predicted fields that were largely tectonically-controlled rather than magmatically-controlled (Martin & Németh, 2004; Kereszturi et al., 2011). The preserved volcanic eruptive products of the BBHVF, including pyroclastic, effusive and intrusive rocks, have been estimated to be about 3 km^3, significantly larger than those erupted through the LHPVF (Martin & Németh, 2004; Kereszturi et al., 2011). Considering the potential erosion of distal air fall tephras and the common juvenile pyroclast-poor nature of the majority of the preserved pyroclastic rocks, a recalculation of eruptive volumes to dense rock equivalent (DRE) values would likely yield a total erupted volume of less than 5 km^3 for the western Hungarian Miocene to Pleistocene volcanic fields. Here we provide a short review of the current research on these monogenetic volcanic fields in western Hungary with an aim to characterise their pyroclastic successions and infer the eruptive environment where they erupted and accumulated. Furthermore, we define key research subjects for future study on these fields on the basis of our current knowledge. Such future research directions for the western Hungarian monogenetic volcanic fields could significantly contribute to our understanding of the volcanic evolution, eruption styles, and preservation potential of monogenetic volcanic fields in general. A "sister" volcanic field approach is also proposed to link these volcanic fields to other, similar volcanic fields worldwide (Németh et al., 2010).

2. Monogenetic volcanic fields of the Western Pannonian Basin (WPB)

The volcanic fields of the Western Pannonian Basin (WPB) are erosional remnants forming buttes and mesas (Fig. 3A) that are commonly composed of gently inward dipping primary

pyroclastic rocks (Fig. 3B) and capping lavas (Martin & Németh, 2004). The centre parts of the volcanic buttes are composed of tuff breccias commonly rich in accidental lithic fragments from the underlying basement rocks (Fig. 3C). The majority of the preserved pyroclastic rocks are lapilli tuffs that are rich in volcanic glass shards (Fig. 3D) and accidental lithic fragments (Martin & Németh, 2004; Németh, 2010b). These volcanic fields are commonly referred to as monogenetic volcanic fields (White, 1991a; Valentine & Gregg, 2008; Manville et al., 2009; Németh, 2010a), attesting to the small-volume of the individual volcanoes that make up the field. The small volume of the individual volcanoes and the generally simple volcanic architecture of the volcanoes are the key features that define these volcanoes as monogenetic. In spite of the small volume nature of the preserved and inferred original volcanic landforms of these volcanic fields, there are volcanic complexes that were clearly erupted in various eruptive episodes, commonly through laterally shifted vents that produced nested volcanic complexes (Auer et al., 2007; Kereszturi & Németh, 2011). These volcanic fields can also be classified as typical phreatomagmatic volcanic fields (Németh, 2010a) on the basis of the overwhelming evidence of magma – water interaction driven explosive eruptions, at least in the initial stage of the eruptive history of the majority of the volcanoes of western Hungary. The phreatomagmatic explosive eruption style has been interpreted due to the abundance of preserved pyroclastic rock units in volcanic glass shards with macro- and micro-textural features characteristic of sudden chilling of the rising basaltic melt upon contact with external water, as demonstrated by comparison of experimental volcanology results (Büttner et al., 2002; Büttner et al., 2006) with natural glass shards (Dellino & LaVolpe, 1996; Büttner et al., 1999; Dellino & Liotino, 2002). Textural features, such as the low vesicularity and angular and rugged shape, evident in volcanic glass shards from the western Hungarian volcanic fields are generally accepted to support magma and water explosive interaction in other locations (Heiken & Wohletz, 1986; Büttner et al., 1999; Dellino, 2000; Morrissey et al., 2000; Dellino & Kyriakopoulos, 2003) (Fig. 4). The volcanic rocks of the western Hungarian Mio/Pleistocene volcanic fields are preserved in a very diverse type of volcanic landforms such as erosional remnants of maar-diatremes, tuff rings, scoria cones, lava shields and lava fields (Németh & Martin, 1999).

The original volcanic landforms of the western Hungarian volcanic fields have been reconstructed on the basis of the 3D facies architecture of the preserved pyroclastic and coherent lava rock units, the volcanic stratigraphy and the associated volcanic facies relationship with syn-eruptive country rock units. This method has been widely used in older, erosion-advanced volcanic fields such as Hopi Butte in Arizona (White, 1989; White, 1990; White, 1991b; Vazquez & Ort, 2006), Chubut in Argentina (Németh et al., 2007), Waipiata in New Zealand (Németh & White, 2003), Western Snake River Plain in Idaho (Godchaux et al., 1992; Godchaux & Bonnichsen, 2002; Brand & White, 2007) or the east Oregon volcanic fields (Heiken, 1971; Brand & Clarke, 2009), among many known fields.

In addition, the micro- and macro textural analysis of the juvenile particles of the preserved pyroclastic rocks of the WPB volcanic erosion remnants, and the component analysis of the same rocks, demonstrated clearly the abundance of country rock fragments from the known basement and Neogene basin-filling sediments which indicated a significant excavation of country rocks in the course of the eruptions (Martin & Németh, 2004). The abundance of country rocks in the pyroclastic successions is also a sign that magma fragmentation must have taken place in those strata and the released kinetic energy fragmented and excavated the rocks in situ (Lorenz & Kurszlaukis, 2007). Such a process can take place when hot magma and ground-water interact explosively below the surface and the generated shock

wave fragments the wall rock (Lorenz, 1986; Wohletz, 1986; Zimanowski et al., 1986; Morrissey et al., 2000; White & Ross, 2011), allowing accidental lithic-dominated debris to exit the vent (Lorenz, 1986; Lorenz & Kurszlaukis, 2007; White & Ross, 2011). The result of this is a significant volume of excavated country rocks, the formation of mass deficit that eventually leads to a gradual collapse, and the formation of volcanic debris-filled volcanic conduit, or diatreme (White & Ross, 2011). The mechanism of the formation of a diatreme is far from well-known, and there is still argument about whether it is magmatic gas (Stoppa, 1996; Stoppa & Principe, 1997; Sparks et al., 2006; Walters et al., 2006; Suiting & Schmincke, 2009; 2010) or magma and water explosive interaction (Lorenz, 1973; 1986; Zimanowski et al., 1986; Wohletz & Heiken, 1992; Mastrolorenzo, 1994; Zimanowski et al., 1995; Zimanowski et al., 1997; Calvari & Tanner, 2011) that drives the energy release that fragments the country rocks. However, there is agreement that the resulting subsurface pipe is a volcanic and non-volcanic debris dominated zone with collapsed blocks of wall rock and complex arrays of juvenile particle enriched sub-vertical regions (Lorenz & Kurszlaukis, 2007; White & Ross, 2011).
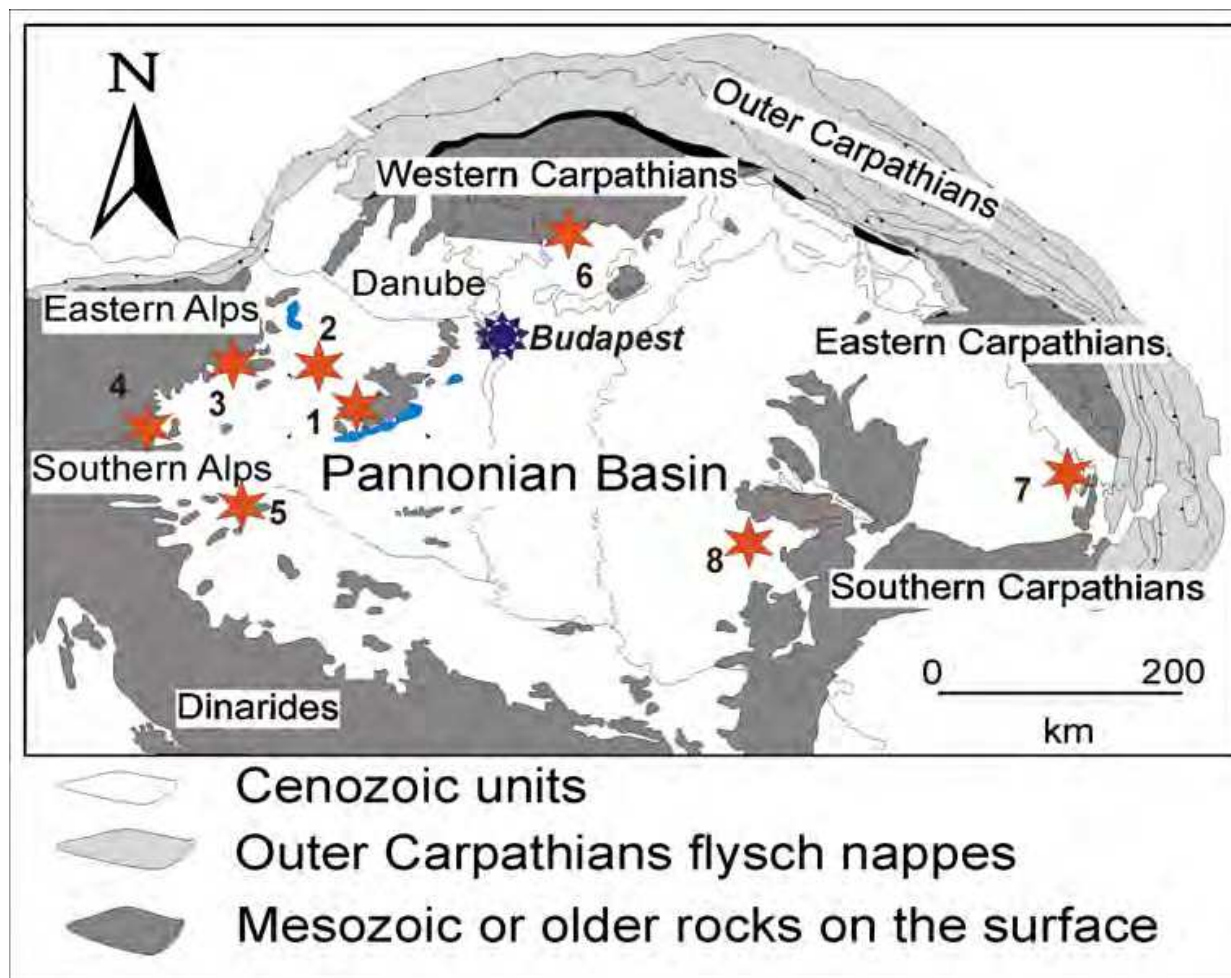

Fig. 1. Mio/Pleistocene monogenetic volcanic fields of the Pannonian Basin and their relationship with major stratigraphic units of the Carpathian – Pannon region. 1 – Bakony-Balaton Highland Volcanic Field; 2 - Little Hungarian Plain Volcanic Field; 3 – Burgenland; 4 - Styria Basin; 5 - Northern Slovenian Volcanic Field; 6 – Nógrád – Gemer Volcanic Field; 7- Persanyi Mts; and 8 - Bánát.

The Mio/Pleistocene eroded volcanoes visible in western Hungary today are inferred to represent the preserved part of the original volcanic edifices with only the crater to upper conduit-filling deposits of the former volcanoes exposed (Németh & Martin, 1999; Németh et al., 2003). This provides the opportunity to understand the 3D architecture of the proximal volcanic facies of such small-volume intra-continental volcanoes. Due to the eroded state of the Western Pannonian Basin (WPB) volcanic fields in general, these sites are not suitable for the systematic volcanic facies analysis commonly performed on young volcanoes (Vazquez & Ort, 2006) where the aim is to identify proximal to distal facies variations and understand pyroclast transportation by pyroclastic fall and density currents. Nearly each of the known individual volcanoes of the WPB volcanic fields have at least in their base pyroclastic units a record of an initial stage magma-water interaction triggered explosive eruption that formed basal phreatomagmatic tephra ring deposits around the active vents (Martin & Németh, 2004). However, gradual eruption style changes have been recognized in sites where proximal crater rim deposits are preserved, indicating a complex interplay between internal and external governing parameters on mafic explosive volcanic eruptions of western Hungary (Martin & Németh, 2004).
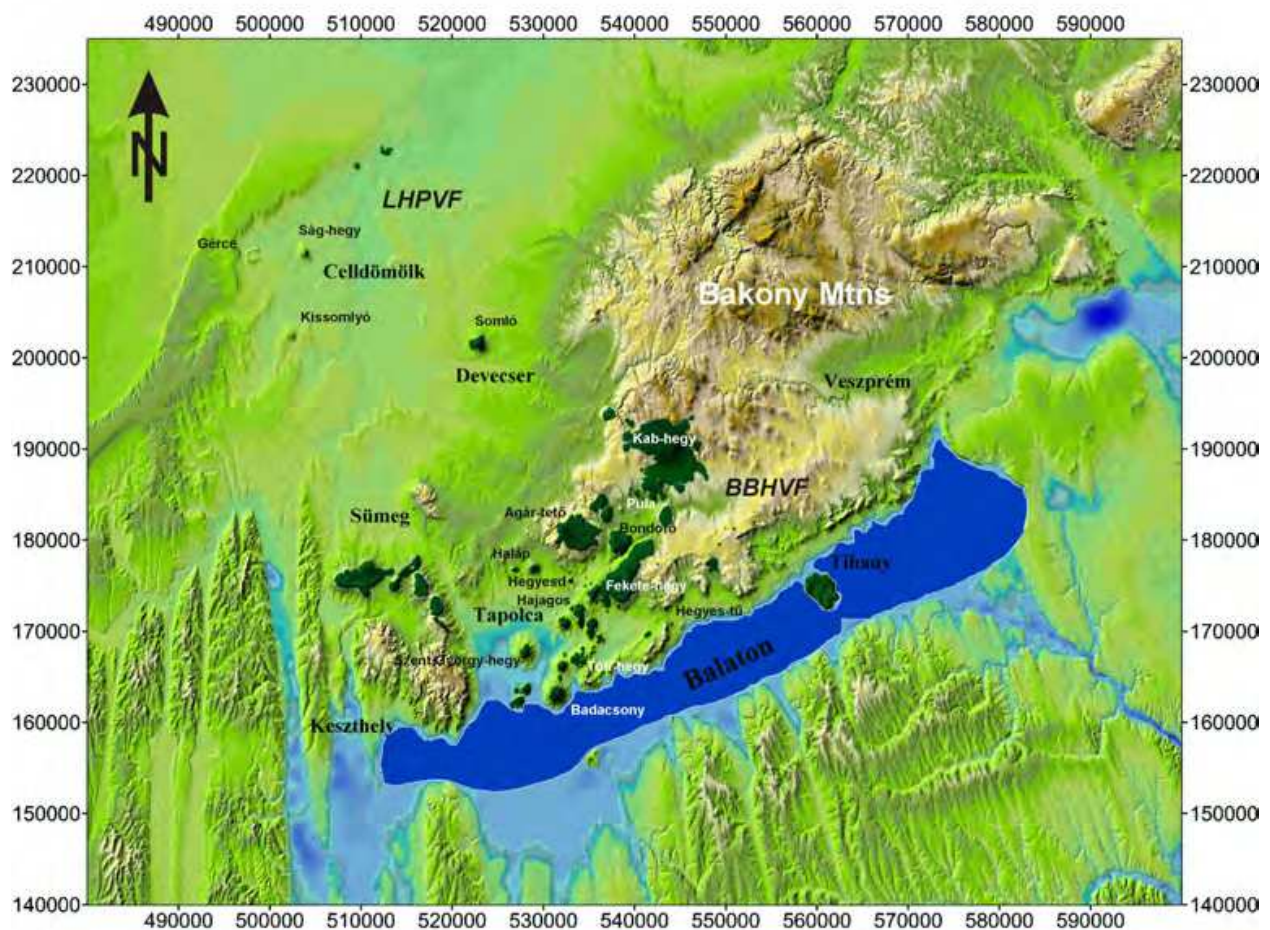

Fig. 2. Mio/Pleistocene monogenetic volcanic fields in western Hungary: BBHVF – Bakony-Balaton Highland Volcanic Field, and LHPVF - Little Hungarian Plain Volcanic Field. Distribution of volcanic rocks on the surface is marked by dark green. Hungarian Grid Reference shown in the margin with 10 km rectangular spacing.

The WPB is of particular interest in volcanic research, due to the strong correlation recently recognized between gradually changing environmental elements over millions of years and volcanic eruptions that were produced by changing eruption styles from phreatomagmatic to magmatic explosive over about 6 million years of evolution (Kereszturi et al., 2011). In addition to the long-term eruption style changes, abrupt to gradual changes in eruption styles have been recognized in a short time-scale comparable to the lifetime of an individual monogenetic volcano. The past two decades the volcanology research in the WPB confirmed the overwhelming dominance of magma-water interaction driven explosive eruption styles during the eruption history of nearly each individual volcano which is the basis of the definition of these volcanic fields as externally dominated (Martin & Németh, 2004; Németh et al., 2010; Kereszturi et al., 2011). In addition, these volcanic fields also show a marked link between the syn-volcanic country rock hydrology, the surface water abundance and the resulting volcanic eruption styles (Martin & Németh, 2004).

Fig. 3. Volcanic features preserved in typical monogenetic basaltic volcanoes of the WPB. A) Volcanic buttes of the western margin of the Kál basin of the Bakony- Balaton Highland Volcanic Field. Badacsony has an extensive lava cap, a former lava lake and associated scoria cone, while Szigliget is dominantly a pyroclastic rock dominated erosional remnant; B) Well-bedded juvenile ash- and lapilli-rich pyroclastic succession of the Gérce tuff ring in the Little Hungarian plain Volcanic Field with interbedded tuff breccia horizon (arrow) abundant in lapilli-sized Neogene sediments as country rocks; C) Peperitic domain from the Hajagos-hegy maar-diatreme from the BBHVF (lt –lapilli tuff host, fl – fluidized zone, b – basanite fragments from coherent intrusive body; D) Glassy pyroclasts from the Hegyesd diatreme core zone (BBHVF). Sideromelane glass shards (s) are blocky, moderately vesicular and their microlite content varies greatly.

The volcanic fields studied in detail in the WPB are among those that could be looked as type localities for the characterization of low-land volcanic fields that were erupted through a combined aquifer that has laterally changeable thickness and hydrological characteristics similar to those described in low-lying alluvial plains (Németh et al., 2010; Ross et al., 2011). A combined aquifer is defined to be a country rock pile beneath the volcano (especially the upper 500 metres below surface) that consists of a layer-cake-like strata of rocks with very great diversity of hydraulic conductivity, porosity, permeability and tortuosity, as defined by the state of diagenesis, grain size, bedding, and abundance of fractures and fissures in the rocks. A porous-media aquifer is defined as a rock-sediment pile with moderate hydraulic conductivity, storage capacity, and a typical but complex relationship between water-recharge and water-withdraw (i.e. the system needs time to recharge after withdrawal).
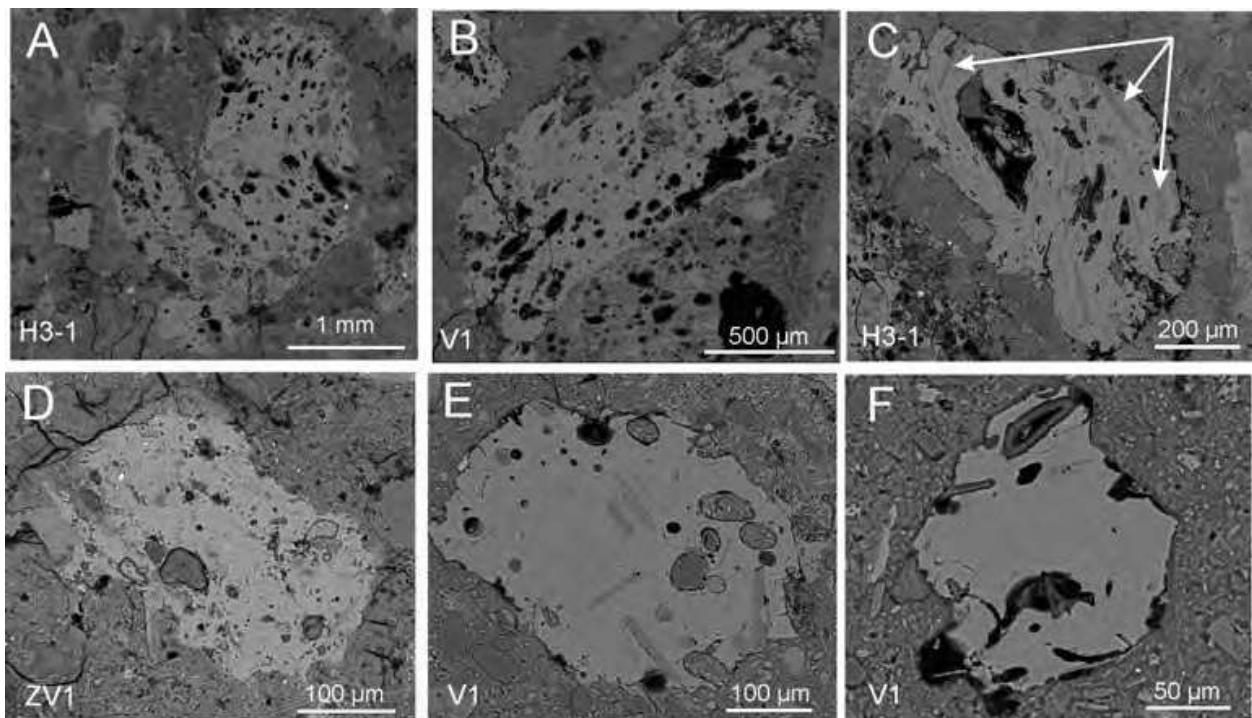

Fig. 4. Volcanic glass shards on back-scattered electron-microscopy (BSE) images from the BBHVF exhibit blocky shapes and complex particle outlines typical for brittle fragmented, and therefore fast cooled (chilled) melt upon contact with coolant (water or water-saturated sediment). The upper row (A, B & C) shows glass shards of coarse ash that are glassy in texture, bulky in shape, but carry textural features characteristic of chilling in the time the melt was still deforming in a ductile fashion. The coarser particles are considered to represent pyroclasts that were not directly derived from the interaction zone of magma and external water, but fragmented by the release of explosion energy from the main body of quickly cooling magma around the interaction zone (non-interactive particles). The lower row (D, E, & F) are fine ash particles that are more angular, blocky, with large patches of glassy areas with no microlite or vesicles indicating sudden chilling of the magma and its brittle fragmentation. These fine ash particles are considered to represent pyrolcasts directly derived from the interaction zone between hot magma and external water. Note on "C" the trachytic texture defined by microlites (arrows).

A fracture-controlled aquifer is dominated by rocks that store water in fractures (cavities) that can supply an infinite volume of water upon withdrawal if water-filled zones were encountered, but can behave as a complete aquitard in areas of no fractures or cavities. While these type of aquifers are end-members, in nature some sort of combination of these basic types form the zone that magma encounters in the upper few hundreds of metres of its to the surface. We can express the type of aquifers beneath a volcanic field to define the dominant behaviour type, such as soft-substrate versus hard-substrate aquifers (Lorenz, 2003; Sohn & Park, 2005; Auer et al., 2007; Németh et al., 2010; Ross et al., 2011). For a global comparison, the WPB's volcanic fields are compared with other localities that are erupted through an aquifer defined as a combined substrate type (e.g. soft substrate covered hard substrate) which highlights the rheology, and therefore the hydrology, of the country rocks the magma encounters (Németh et al., 2010). The WPB's volcanic fields are relatively well-described from a physical volcanology point of view. However, new globally significant research has recently identified the following as the critical parameters that strongly influencing the basic characteristics of the resulting volcanic fields: the interplay between the external and internal forcing of the eruption styles of small-volume mafic volcanoes; the influence of long term environmental changes on the variations of the dominant eruption styles in the evolution of the volcanic field; and the long term fluctuation of magmatic flux and output rates (Valentine & Perry, 2006; Valentine & Keating, 2007; Valentine & Perry, 2007; Keating et al., 2008; Brenna et al., 2010; Genareau et al., 2010; Valentine & Hirano, 2010; Brenna et al., 2011). An application of these new results for WPB volcanism could lead to a better understanding of the eruption history of the individual monogenetic volcanoes of WPB and could allow them to be comparedto similar volcanoes worldwide. In addition, new research is needed to understand the magmatic evolution over shorter time-scales that may produce complex monogenetic volcanoes closely resembling polygenetic volcanoes. Overall the current knowledge on the volcanic field evolution of the WPB is substantial enough to be able to provide a good volcanic reconstruction, applying the "sister volcanic field" approach to understand the overall volcanic field and individual volcano eruption history (Németh et al., 2010).

3. Geological setting

Volcanic fields in the western Pannonian Basin are Late Miocene to Pleistocene alkaline basaltic intracontinental fields (Szabó et al., 1992; Balogh & Németh, 2005; Wijbrans et al., 2007; Lexa et al., 2010). They consist of erosional remnants of maars, tuff rings, scoria cones, lava flows and lava fields (Martin & Németh, 2004). Four individual fields have been separated in the WPB on the basis of their location (Fig. 1): Bakony-Balaton Highland Volcanic Field (BBHVF) in Hungary (Fig. 5), Little Hungarian Plain Volcanic Field (LHPVF) in Hungary, Burgenland - Styria Volcanic Fields (BSVF) in Austria, and Northern Slovenian Volcanic Field (NSVF) in Slovenia. Research on the volcanic history of the BBHVF and LHPVF has concluded their extensively phreatomagmatic origin (Martin & Németh, 2004). In contrast we know very little about the volcanic eruption mechanism, eruptive environment and style in the case of the Austrian and Slovenian volcanic fields. Preliminary research, however, indicates their similarity to those volcanic fields located in western Hungary (Martin & Németh, 2004; Kralj, 2011). Time and space distribution of monogenetic volcanism in the western Pannonian Basin seems to show a random pattern (Pécskay et al., 1995). The earliest known alkaline basaltic rocks are located in the NSVF marking an onset of volcanism about 10-13 million years ago (Pécskay et al., 1995; Lexa et al., 2010). The date of the onset of volcanism in the BBHVF is well established at about 8 million years ago

(Balogh & Németh, 2005; Wijbrans et al., 2007; Balogh et al., 2010). The main phase of volcanism in the BBHVF falls in the 4 to 3 million years ago time period; while in the LHPVF the peak of activity took place slightly earlier, about 5 million years ago (Wijbrans et al., 2007). The volcanism ceased in the western Pannonian Basin in the Pleistocene around 2.3 Ma (Kereszturi et al., 2010; Kereszturi et al., 2011).
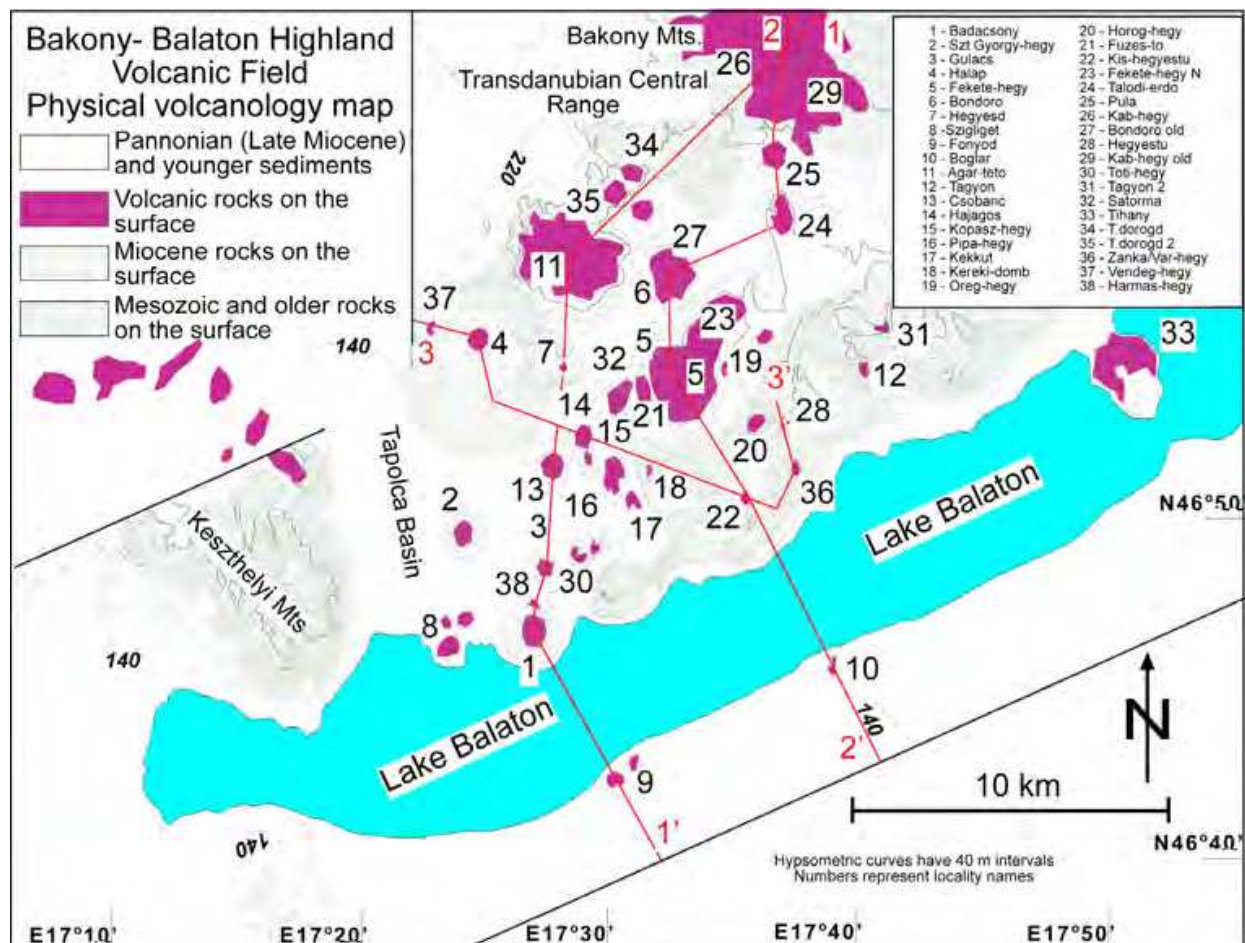

Fig. 5. Simplified geological map of the Bakony- Balaton Highland Volcanic Field marking Miocene to Pleistocene volcanic rocks on the surface. Numbers correspond to identified volcanic centres (some cases with multiple vents reconstructed). Cross sections along section lines (1-1'; 2-2', 3-3') are shown on Fig. 9.

4. Eruptive environment of the WPB

At the onset of the eruption of monogenetic volcanoes in the WPB in western Hungary (Fig. 2), magma began to interact with a moderate amount of groundwater in the water-saturated Neogene fluvio-lacustrine sand, silt and gravel beds (Martin & Németh, 2004). As the eruptions continued, the craters grew both vertically and laterally and the repeated phreatomagmatic blasts fragmented the deeper fractured hard rock substrate around the explosion locus, commonly giving the karst water (or any fracture controlled aquifer-store) direct access to the rising hot basaltic magma (Németh et al., 2001).

Evidence to support magma and water interaction between rising basalt magma and ground water are recorded in the lapilli tuff and tuff units abundant in glassy pyroclasts (Németh,

2010b). The micro-texture of volcanic glass shards are dominantly angular, bulky, low in vesicularity and rich in surface features typical of brittle fragmentation. This points to the fast cooling rate of these pyroclasts as they formed (Fig. 4). Microlite-rich glassy pyroclasts with micro-vesicles indicate active degassing and crystallisation of the magma upon contact with external water that freeze and lock these textures (Fig. 4).

The complex shape of pyroclasts identified from fine grained, accidental lithic fragment-rich rock units indicate complex shape parameters and fractal values typical for bulky particles with complex boundaries (Németh, 2010b), as compared to glass particles studied elsewhere (Dellino & LaVolpe, 1996; Büttner et al., 1999; Zimanowski et al., 2003). These rock types are exclusively rich in accidental rock fragments derived from the underlying pre-volcanic strata. In areas where the basement rocks of Mesozoic carbonate, Paleozoic sandstones or schist rocks are covered by thick Neogene siliciclastic semi-consolidated deposits, the preserved pyroclastic rocks contain abundant volumes of rock fragments derived from this cover bed (Fig. 6A). Pyroclastic rocks identified from regions located in areas with thin Neogene siliciclastic cover are abundant in accidental lithic rocks fragments derived from various basement rocks (Fig. 6B). On the basis of the abundance of country rocks in the majority of the preserved pyroclastic rocks of the volcanic fields in western Hungary, it can be inferred that the eruptions excavated a significant portion of the underlying pre-volcanic substrates and incorporated the material in the accumulating pyroclastic debris. The abundant volume of excavated country rocks attests to the formation of a volcanic depression, commonly referred to as a maar-diatreme volcano (Lorenz, 1986; White & Ross, 2011). While original maar volcanic landforms are rarely preserved in the WPB, the textural characteristics of the preserved pyroclastic rocks allow us to reconstruct their shape, size and volcanic facies architecture.

Fig. 6. Pyroclastic rocks of the monogenetic volcanic erosion remnants of the WPB are rich in accidental lithic fragments. Pyroclastic rocks of the Ság-hegy (A) in the LHPVF are dominated by various glassy pyroclasts (g) and abundant fragments from the Neogene siliciclastic underlying sedimentary successions such as mud aggregates (m), abundant quartz (arrows) or just mud in the matrix (yellowish homogeneous background). The view on "A" is about 2 mm across. In areas where the Neogene siliciclastic sedimentary cover was thin during the volcanism such as in Pula in the BBHVF (B), the accidental lithic fragments are dominated by clasts derived from the basement, such as Mesozoic limestone and dolomite fragments (arrows). Fragments from the Neogene sedimentary successions are commonly milled and hydrothermally altered (circle). Lens cap is about 5 cm across.

The appearance of maar volcanoes and their deposits in the Western Pannonian Basin are inferred to be strongly dependent on the paleo-hydrological conditions of the near-surface porous media, as well as the deep fracture-controlled aquifer (Martin & Németh, 2004). The seasonal variability of water-saturation of the karstic systems, as well as the climatic influence on surface and/or near sub-surface water, are considered to be potential controlling parameters of the style of explosive volcanism that took place over the evolution of an individual volcanic field (Németh et al., 2001).

Shallow but broad maar volcanoes are inferred to have been formed due to phreatomagmatic explosions of mixing magma with water-saturated siliciclastic sediments in areas where thick Neogene silicilcastic units build up the immediate pre-volcanic strata, such as in the LHPVF (Martin & Németh, 2005). Such volcanoes have often formed late magmatic infill in their maar basins, such as scoria cones and lava lakes. Today these volcanoes are preserved as lensoid shaped volcanic successions, usually capped by solidified lava lakes forming low aspect ratio mounds (Martin & Németh, 2005). The pyroclastic successions of this type of phreatomagmatic volcano are rich in sand, silt and mud from the Neogene siliciclastic basin filling sediments (Martin & Németh, 2005). Deep seated xenoliths are rare. In areas where the Neogene sedimentary cover was thin, deep maar crater formation has been inferred on the basis of the present day steep and abrupt 3D architecture of phreatomagmatic pyroclastic rock facies. The abundance of sand and silt in the matrix of lapilli tuff and tuff breccia units with a high proportion of angular accidental lithic fragments from deep-seated hard rock units suggests that these volcanoes must have had deeper fragmentation sites that allowed excavation country rocks from deeper regions. The presence of abundant deep seated xenoliths in such volcanic erosional remnants suggests that water must have been available in those zones in fractures. This type of maar volcanoes is interpreted to develop in areas, where relatively thin Neogene fluvio-lacustrine units rested on the Mesozoic or Paleozoic fracture-controlled, e.g. karst water-bearing, aquifer (Németh et al., 2001). Nemeth et al. posed the idea that the seasonal variation of karst water aquifers and their fracture and cavity controlled hydrogeological nature (e.g. fast recharge rate, zero or unlimited hydraulic conductivity across such rock units) would vary the available water that magma could meet so that magma could pass a karst water aquifer at a time when it is nearly dry or completely filled with water. This could result strikingly different volcanic landforms forming in "spring" (maximum water capacity - phreatomagmatic) and "summer" (minimum water capacity - magmatic) (Németh et al., 2001).

5. Pyroclastic architecture of typical monogenetic volcano of the WPB

In the western Hungarian monogenetic volcanic fields, each of the identified volcanic eruptive centres represents a proximal zone of a former volcano. Nearly all of the known volcanoes had at least a short period of phreatomagmatic activity in their vent opening stage. This is recorded in the preserved fine grained, accretionary lapilli bearing (Figs 7A & B), massive to mega-ripple bedded pyroclastic rocks (Fig. 7C) formed by pyroclasts deposited by pyroclastic density currents and phreatomagmatic falls associated with intermittent initial vent breccias. These deposits are known from proximal pyroclastic successions that are commonly deposited on inward dipping inner crater walls and are represented by large blocks that collapsed in the growing volcanic crater. Erosional talus commonly covers key outcrops around the preserved volcanic buttes; however, steep cliff

faces can expose pyroclastic rock facies which are typically accumulated beneath the syn-eruptive paleosurface and considered to be rock types forming diatremes. Such rocks are typically chaotic in texture, abundant in accidental lithic rock fragments from fine to coarse grained sizes. Volcaniclastic deposits accumulated in the maar craters are also known (e.g. Pula) that are typically deposited from volcaniclastic debris flows that transported volcanic debris from the tephra rings surrounding the maar basin (Németh et al., 2008). In few places (e.g. in Pula, Gérce), thick laminated rhythmic lacustrine deposits are preserved in maar craters, occasionally disturbed by ash falls from distal volcanic eruptions (Fig. 7D) or contorted the accumulated deposits by paleoseismicity (Németh et al., 2008).
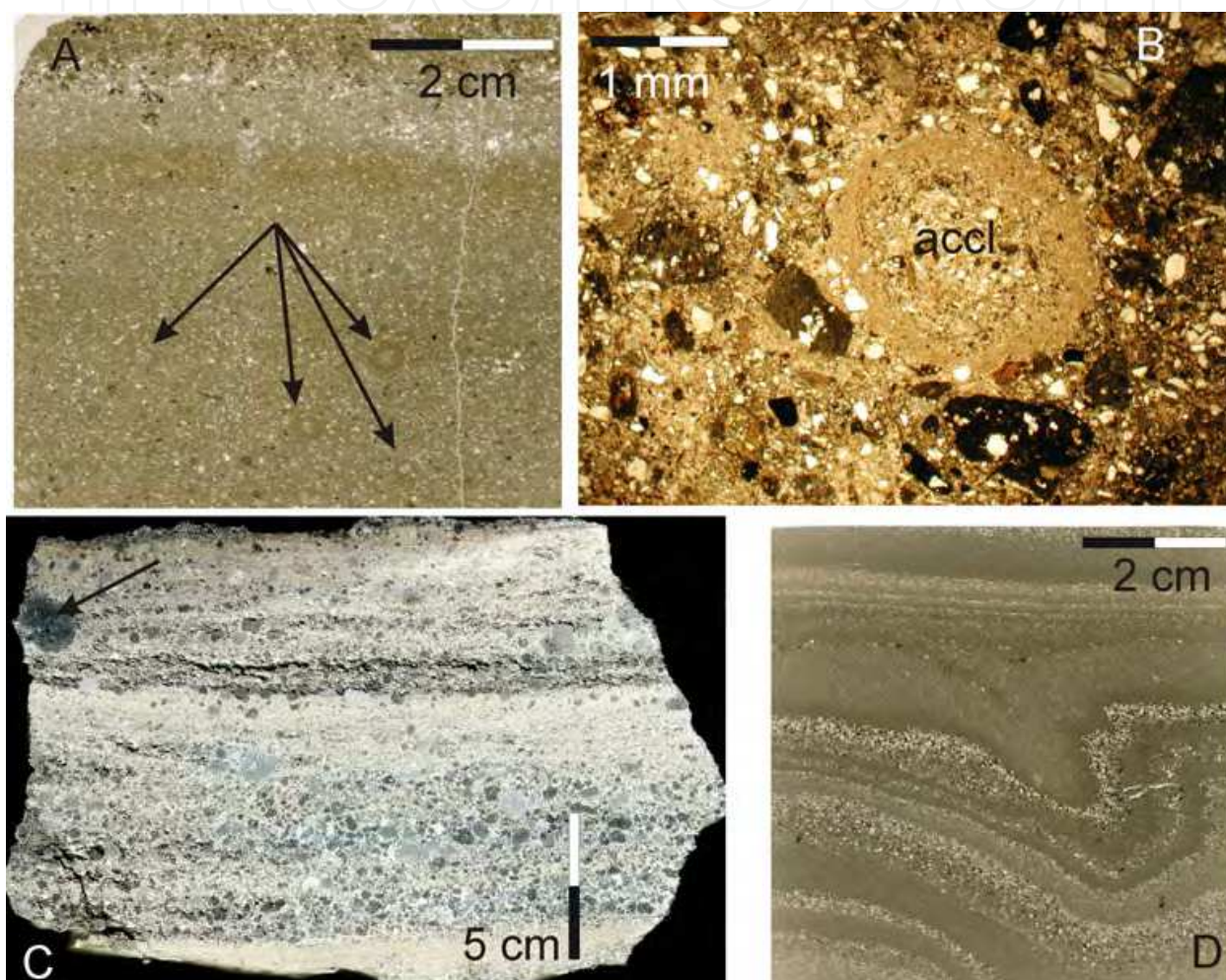

Fig. 7. Accretionary lapilli-bearing fine ash beds from the BBHVF. Accretionary lapilli are rim type (from Tihany on "A", marked by arrows and Szentbékkálla on "B" signed as "accl"). Typical lapilli tuff and tuff succession in proximal setting form pyroclastic units such as the sample shown from Kissomlyó ("C"). Fine ash accumulation in maar lakes has been recorded from the Pula maar lake deposits (dark grains).

Exposed diatreme-filling rocks in the erosion remnants in the western Pannonian Basin are rich in sedimentary grains, as well as mineral phases, from Neogene shallow marine to fluvio-lacustrine sedimentary units. These units are not preserved anymore, but their existence suggests a near intact sedimentary cover over the basement in syn-volcanic time (Németh et al., 2003). The general abundance of such clasts in the pyroclastic rocks also

indicates the importance of soft substrate environment for phreatomagmatic volcanoes. Such volcanoes are commonly interpreted to form "champagne-glass" shaped maar/diatremes that are suspected to underlie the eruptive centres of the LHPVF (Lorenz, 2003). However, recent studies showed evidence that steep-walled diatremes can equally form in hard as well as soft-substrate (White & Ross, 2011). The link between substrate type and the resulting maar-diatreme volcano is so far not well understood (White & Ross, 2011). The WPB volcanic erosion remnants are abundant in rock textures which indicate interaction between magmatic bodies confined between the limit of crater walls and tephra rings and water-saturated sediments to form a great variety of peperite textures (Martin & Németh, 2007). The identification of these intra-crater peperites, accompanied with lava domes and shallow intrusions, indicates that maar/tuff ring volcanoes were likely to have been quickly flooded by ground and/or surface water, suggesting that they were excavating their craters into the region close to the level of the syn-eruptive ground-water table.

Fig. 8. Typical butte of the Tapolca Basin in the Bakony- Balaton Highland Volcanic Field with a thick lava cap sitting over pyroclastic rocks abundant in accidental lithic fragments and angular volcanic glass shards typical for pyroclastic rocks with phreatomagmatic origin.

The Neogene alkaline basaltic volcanic erosional remnants of the western Pannonian Basin are exposed from former subsurface to surface levels of the maar-diatreme volcanoes (Fig. 8). Today the lower parts of the exhumed diatremes are commonly covered by Quaternary talus flanks (Fig. 8). The outcrop availability strongly controls the identification of the facies relationships. The deepest levels of exposures are located in the western and the southern part of the area. The level of exposure of the diatreme facies reflects the ability to remove the

host sediments. In the western part of the BBHVF for instance, the Neogene sedimentary cover was easily eroded and, once penetrated, allowed the diatremes to be exhumed (Fig. 9). The most strongly eroded regions are those where no subsequent lava caps sheltered the volcaniclastic sequences. Probably the eruptive centres of Balatonboglár (Boglár Volcano), Kereki-domb, Vár-hegy of Zánka, Hármas-hegy and Véndek-hegy (Fig. 9) represent the deepest exposed level of the phreatomagmatic eruptive centers (Martin & Németh, 2004) and are inferred to be exposed zones of lower diatremes, a term used for the Hopi Buttes' diatreme field by (White, 1991b). Interestingly, the diatremes and plugs located in the eastern part of the BBHVF are among the oldest volcanic features known from the western Hungarian monogenetic volcanic fields, and represent the eruptive products of the onset of the volcanism about 8 million years ago (Balogh et al., 2010).
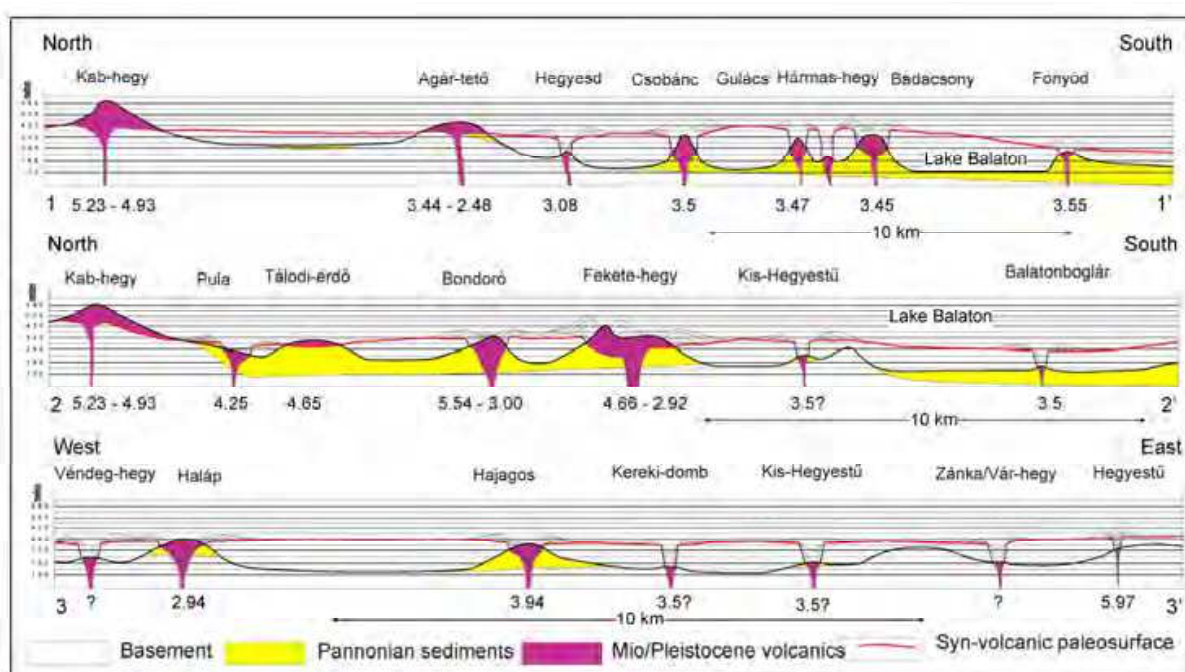

Fig. 9. Cross-section across the BBHVF with erosional remnants of monogenetic volcanoes as reconstructed by Németh et al 2003. Cross section lines are shown on Fig. 5. Numbers below each cross section represent age ranges of the volcanic erosion remnants determined from numerous K-Ar radiometric age datings (Balogh et al., 1986; Balogh & Pécskay, 2001).

Apart from this deep level of exposure, there are no exposed irregular shaped, fragmented wall rock rich dykes (Lorenz & Kurszlaukis, 2007), like those that are widely reported from other monogenetic maar-diatreme volcanic fields, including Hopi Buttes (White, 1991b). Such levels of exposures and preserved outcrops are more common in the northern part of the Pannonian Basin, in southern Slovakia and northern Hungary (Fig. 1) (Lexa et al., 2010). The best example of an individual plugs as an exposed base of a volcanic lava filled crater is at Hegyes-tű (Figs 2 & 5) where a small remnant of vent filling mixture of volcanic and siliciclastic debris is preserved and intruded by the plug, indicating that explosive fragmentation preceded the formation of the basanite plug (Balogh et al., 2010).
Upper diatremes (White & Ross, 2011) represent scoria cones and associated lava plugs built on the basal phreatomagmatic volcano. However, they do not necessarily represent volcanic landforms grown over the syn-volcanic landscape. After erosion, a significant part of the
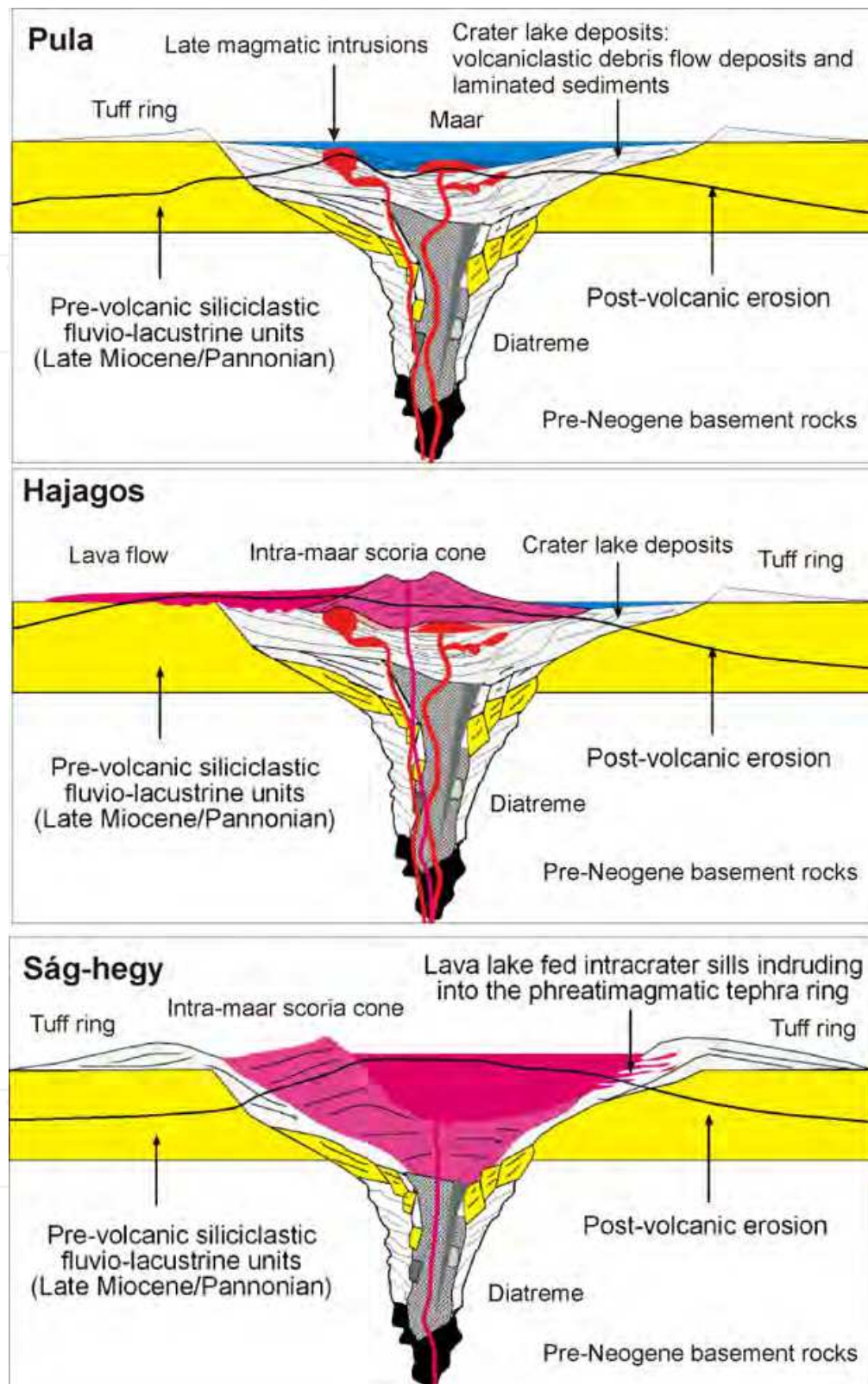
Fig. 10. Theoretical cross-sections of complex maar volcanoes reconstructed on the basis of preserved pyroclastic rocks, their texture and distribution patterns. A combination of crater lake sedimentation and/or magmatic crater filling successions are reconstructed on the basis of preserved 3D facies architecture of volcanic rocks and their textural characteristics.

volcanic edifice could be eliminated, and in the eroded phreatomagmatic volcanic field the identification of such remnants should be undertaken with precaution to establish the syn-volcanic paleo-surface, to estimate the erosion. Surface volcanic edifices are preserved in areas of low erosion, and include volcanoes produced by both phreatomagmatic and magmatic eruptions. These vents are characterized by magmatic fragmentation triggered explosive eruptions. Vent remnants of these volcanoes are concentrated in the northern and central part of the BBHVF, such as Kab-hegy, Agár-tető, Haláp and Hegyesd (Fig. 2 & 5).

The preserved phreatomagmatic pyroclastic successions and their distributional pattern suggests that the original maar diameters of the western Pannonian region ranges from few hundreds of meters up to 5 km in diameter (Fekete-hegy – 5 km; Tihany – 4 km; Bondoró - 2.5 km; Badacsony - 2.5 km), however, the largest centres probably represent maar volcanic complexes with inter-connected large basins similar to those maars known from South-Australia and Victoria (Jones et al., 2001). The average maar basins are inferred to have been 1-1.5 km wide originally, which is within the range of most maars worldwide (Lorenz, 1986; Ross et al., 2011).

The volcanoes of the western Pannonian region have been reconstructed to be hybrids of phreatomagmatic and magmatic volcanic edifices and formed by initial maar or tuff ring forming events especially those erupted in an area with thick Neogene siliciclastic sedimentary cover (Fig. 10). The gradual exhaustion of water source to fuel the magma/water interaction led to "drier" phreatomagmatic, then pure magmatic, fragmentation of the uprising melt, often building large scoria cones inside the phreatomagmatic volcanoes, as witnessed at Vulkaneifel in Germany (Houghton & Schmincke, 1986) or Auckland Volcanic Field in New Zealand (Houghton et al., 1999). The typical types of such volcanoes are located in the southwestern site of the BBHVF in the Tapolca Basin (Badacsony, Szent György-hegy, Hajagos-hegy, Fekete-hegy).

6. "Dry" volcanoes

In the central part of the BBHVF erosion remnants of scoria cones and shield volcanoes give evidence for a smaller impact of the ground and surface water in control of the volcanic eruptions. The age distribution of erosional remnants of scoria cones suggest a peak in their formation about 3 million years ago, which coincides well with a dryer period of the environmental history of the region, suggesting a potential link between the large scale climatic changes and eruption style variations over long time periods in this region (Kereszturi et al., 2011).

Erosion remnants of scoria cones are commonly strongly modified after erosion, and their original volcanic landforms can be hardly recognized (Fig. 11A). In spite of the general assumption of the fast erosion of scoria cones, there are remarkable well-preserved scoria cones known from the central part of the BBHVF (Kereszturi et al., 2011). These scoria cone remnants are about 3 – 2.3 million years old and still have retained their original crater morphology and some part of their constructional edifice (Kereszturi et al., 2011). Many of the late magmatic capping units over basal tuff rings are abundant in welded lava spatter and or lava spindle bombs commonly cored with mantle origin xenoliths (Fig. 11B).

Fig. 11. One of the youngest, relatively intact scoria cone of Agár-tető of the BBHVF with a still recognisable cone morphology and breached crater (A) and a collection of spindle bombs (commonly filled with mantle-derived xenoliths such as peridotite lherzolite) from capping pyroclastic units of one of the best preserved scoria cone, Kopácsi-hegy, just west of the Fekete-hegy maar volcanic complex in the Bakony- Balaton Highland Volcanic Field (B).

7. Discussion on future research

Intense research over the past 10 years allowed characterisation of the WPB volcanic fields as phreatomagmatic monogenetic volcanic fields. Alongside this recognition, substantial research has been done to describe in detail the eruption scenarios these volcanoes may have provided during their activity. In spite of the huge step forward in knowledge of Miocene to Pleistocene volcanism in the Pannonian Basin, there are major questions that can be formulated and need to be answered in the near future. The recent volcanic research highlighted the need to formulate our research effort along 4 major lines of enquiry (Fig. 12): to understand 1) how monogenetic these monogenetic volcanoes are; 2) what the relative role is of the external and internal forces that may have controlled the formation of individual volcanoes; 3) how the long term environmental changes may effect the overall manifestation of volcanism over the nearly 6 million years of volcanic field evolution; and 4) what the syn-eruptive landscape and the volcanic landform looked like, and how these can be connected with the preserved pyroclastic rock units.

7.1 The "monogenetic enigma"

Current research in the Western Pannonian Basin's phreatomagmatic volcanoes has documented clear field and textural evidence of volcanism that accumulated multiple pyroclastic units separated by volcaniclastic successions indicating some break in the eruption. Locations (on Figs 2 & 5), such as Fekete-hegy (Auer et al., 2007), Bondoró (Kereszturi et al., 2010) and Tihany (Németh et al., 2001), are prime suspects to demonstrate a multiphase nature of the eruption of these volcanoes commonly accompanied by vent shifting in the course of their eruption. These volcanoes are complex phreatomagmatic to magmatic volcanic edifices, inferred to have been erupted over a long time, leaving behind pyroclastic successions separated by well-marked discordance horizons. Newly initiated research intends to identify any signatures of the chemical zoning or polymagmatic nature of these volcanoes, similar to those recently identified in pyroclastic units of Jeju Island in

Korea. A combined effort of sedimentology and geochemical research from complex volcanic erosion remnants can provide answers to identify small chemical changes that may be related to magma plumbing systems, volcanic conduit complexity and volcanic conduit dynamics and their changes over short time (Fig. 13A). Such chemical signatures are likely to be reflected in the type and texture of pyroclastic rocks preserved. Such research has not been completed yet from the WPB, and potentially could provide significant new views on monogenetic volcanism, that could be linked to research in New Zealand, Korea, Argentina or the western USA.
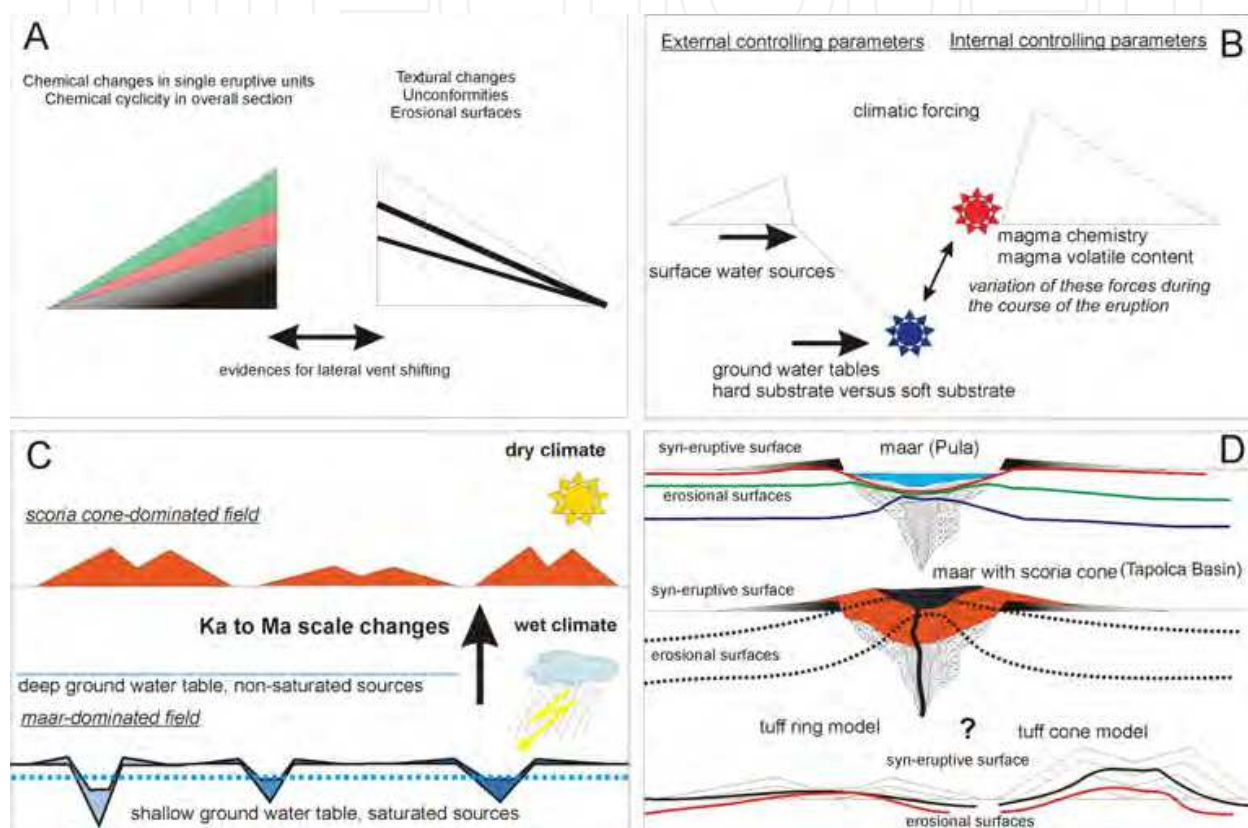

Fig. 12. Graphic expressions of basic research questions and orientations for future work on the WPB's volcanic fields: A) Question on the complexity of the eruption history of a single volcano of WPB such as 1) simple monogenetic versus complex monogenetic volcanism, 2) monomagmatic versus polymagmatic activity, 3) distinct eruptive episodes versus eruption cycles, and 4) recognition of potential lateral vent migration. B) Role of internal versus external controlling parameters – or the balance between phreatomagmatic and magmatic fragmentation styles. Recognition of shallow and deep water sources to fuel phreatomagmatism and the hydrogeology of such water sources. Definition of the role of the magma composition, source and volatile content to define the magma potential for the style of magmatic fragmentation. C) Recognition of how long term environmental changes may have influenced the eruption styles of the volcanism of the volcanic fields such as dry climate (scoria cone-dominated) versus wet climate (phreatomagmatism-dominated). D)To reconstruct primary volcanic landforms (negative landforms – e.g. maars - versus positive landforms – e.g. tuff rings, tuff cones and scoria cones) to establish landscape evolution.
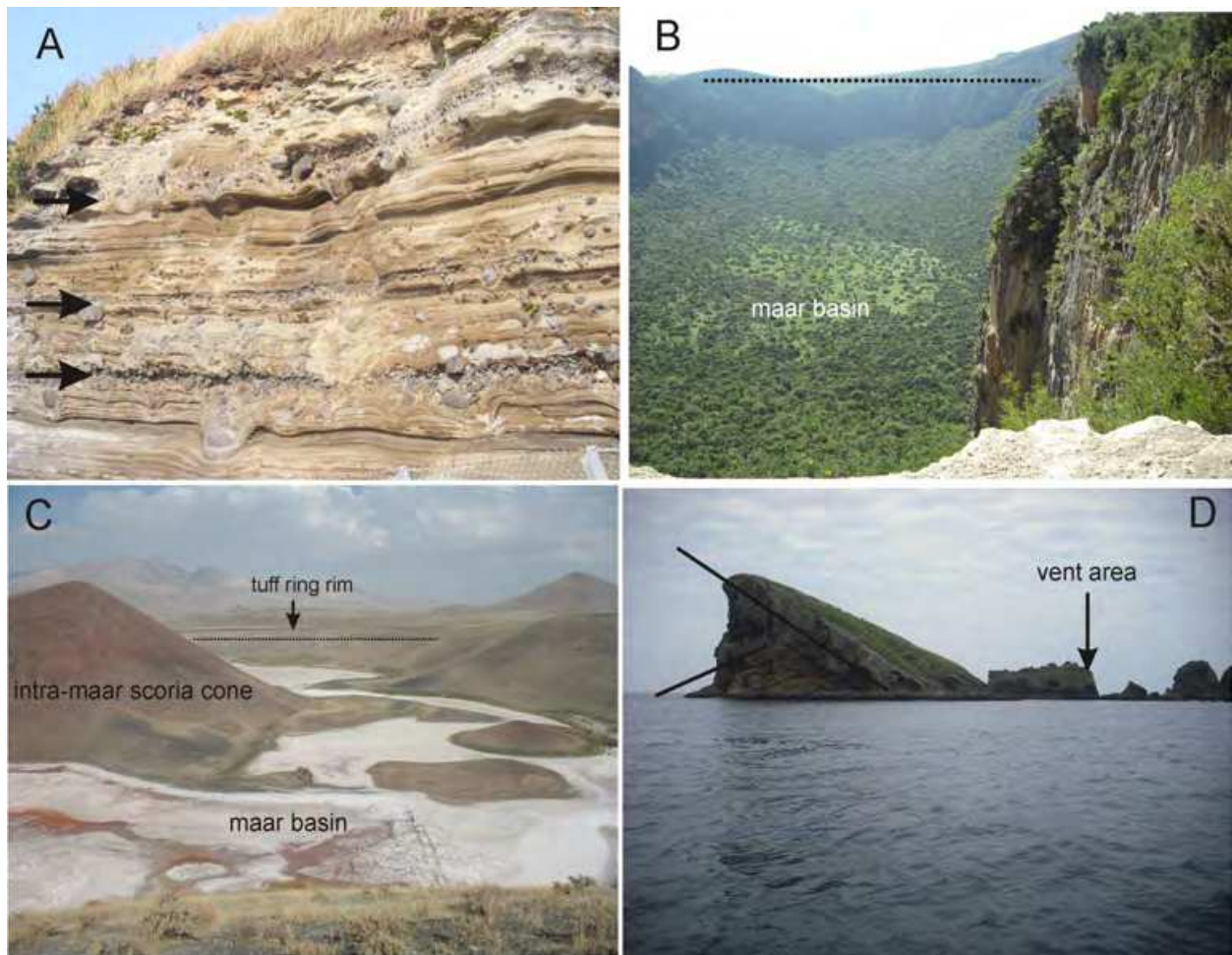
Fig. 13. A) Explosion breccia horizons (arrows) from Suwolbong tuff ring in Jeju Island, Korea represents not only textural changes but also chemical breaks in the small-volume volcanic edifice's history; B) Joya Honda maar in San Luis Potosi, Mexico with its nearly 300 metres deep maar crater is a fine example to question how external and internal forces control the final result of monogenetic volcanism. The crater rim tuff ring-forming deposit is about 50 m thick in the view above dashed line; C) Maar volcanoes can form in areas that are located currently in arid climate due to the availability of ground-water in their recent past (such as Mekegölü in central Turkey), and collect aeolian deposits. Climatic changes can influence the eruptive styles a monogenetic volcanic field can be dominated by; D) Recognition of constructional monogenetic edifices and their facies architecture can help us to delineate the erosional history of the area where the monogenetic volcano erupted. This tuff cone in the figure in a small off shore island of Chagui-do (Jeju, South Korea) exposes its inner, crater filling deeply inward dipping crater facies that is strikingly similar to upper diatreme facies of a maar volcano.

7.2 External versus internal control on eruption styles

It has been recently recognized in few volcanic fields, that the volcanic landform and its eruption styles are controlled by the changes of internal and external parameters (Valentine & Gregg, 2008). Internal parameters that considered to be controlling the magma fragmentation and therefore the eruption style can be defined as those that reflect the type of source of the magma, its degassing, vesiculation, crystallisation and the style of its road to

the surface. The magma flux and output rates are the key parameters that seem to play an important role in volcanic eruptions (Houghton et al., 1999; Houghton & Gonnermann, 2008; Valentine & Gregg, 2008). However, volcanic fields that erupted through broad areas with variable country rocks and underlying sedimentary sequences with diverse water saturation, permeability and hydraulic conductivity levels (Fig. 13B). These external parameters strongly affect the style of volcanism such as magmatic effusive, explosive versus phreatomagmatic.

In a simple way, small magma supply (rate and flux) can create a situation where the external parameters overrun the system providing the development of phreatomagmatic volcanoes with substantial volume. On the other hand, if the magma supply is continuous, the external water sources can be exhausted quickly and the magmatic (internal) controlling parameters take over the control of the eruption style (Fig. 13C). The resulting pyroclastic successions, therefore, will provide evidence for gradual volcanic facies changes in a single eruption sequence of a single volcano.

The WPB seems to be a perfect site which has volcanoes clearly dominated by internal parameters and also those that were run over by the external parameters. As a result, the WPB is a perfect and complex amalgamation of complex volcanoes.

7.3 Understanding long-term environmental evolution and its influence on eruption styles

It is a logical assumption if external factors can play a significant role in the style of eruptions, and the overall landform evolution of a monogenetic volcano, such parameters can change over a long time (e.g. thousands to millions of years). As a result one can expect that climatic changes maybe reflected in the overall attitude of a volcanic field in certain time periods (e.g. phreatomagmatic versus magmatic dominated fields vary over time) (Fig 13C).

Recent research attempted to understand the climatic evolution of the WPB, and confirmed the potential of such an approach as it seems that some changes could be related to volcanic field wide environmental changes (Kereszturi et al., 2011). While this idea is new, and not too easy to test, the first results are promising, and it certainly merits further investigation.

7.4 Landscape evolution models

Landscape evolution models can be separated into two major approaches: 1) understanding and reconstructing the original volcanic landforms and 2) on the basis of the type and style of the volcanic eruptions, reconstruct the syn-eruptive volcanic landscapes and model the long-term erosion of the volcanic field.

Currently it is accepted that the majority of the volcanic erosion remnants of the WPB are maar-diatreme volcanoes, many of them preserving exposed diatreme facies forming butte-like hills. While this model seems to be consistent with volcanic textures recognized in the preserved volcanic successions, there are large numbers of sites where the original volcanic landforms need to be reconstructed in a far more detailed manner. It is a critical to know whether a certain volcanic erosion remnant represents "something" which was beneath or on the syn-eruptive surface (Fig. 13D). To answer this fundamental question is especially important in areas such as the Tapolca Basin (Figs 2 & 5), where clear evidence indicates that the eruptions were in their late stage when scoria and lava spatter cones were built that are constructional landforms.

To reconstruct precisely the volcanic landforms will provide vital information on the syn-eruptive environment and its potential landforms. A concentrated research effort, systematically targeting these questions, would provide a more united and more precise syn-eruptive landscape model to the WPB than the currently existing ones.

8. Conclusion

The general features of the volcanic fields of the Western Pannonian Basin are very similar to other eroded volcanic fields which erupted into wet environments such as Fort Rock Christmas Valley, Oregon (Heiken, 1971), Snake River Plain, Idaho (Brand and White, 2007; Godchaux et al., 1992; Németh and White, 2009), Hopi Buttes, Arizona (Vazquez and Ort, 2006; White, 1989; White, 1990; White, 1991), and Saar-Nahe (Germany) (Lorenz and Haneke, 2004). It seems that the WPB phreatomagmatic volcanoes evolved at a time when climatic and environmental changes were dramatic, and that is likely reflected in the overall eruptive styles of the newly formed volcanoes. It is generally accepted that the WPB phreatomagmatic volcanoes are eroded maar-diatreme type volcanoes, many with a complex history commonly forming nested volcanic complexes. While this idea is generally plausible, it is time to pursue future research to refine our understanding of the WPB phreatomagmatism, and utilise this knowledge to contribute to our general model on monogenetic volcanism, landscape evolution and eruption style changes over time. It is suggested that cooperative work with an intention to identify volcanic field analogies on a global scale can help to develop more accurate models to understand the Mio-Pleistocene basaltic volcanism in the Pannonian Basin.

9. Acknowledgment

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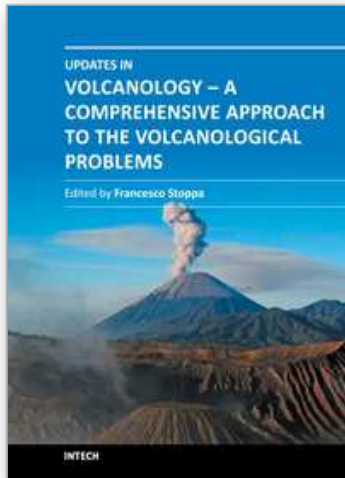
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