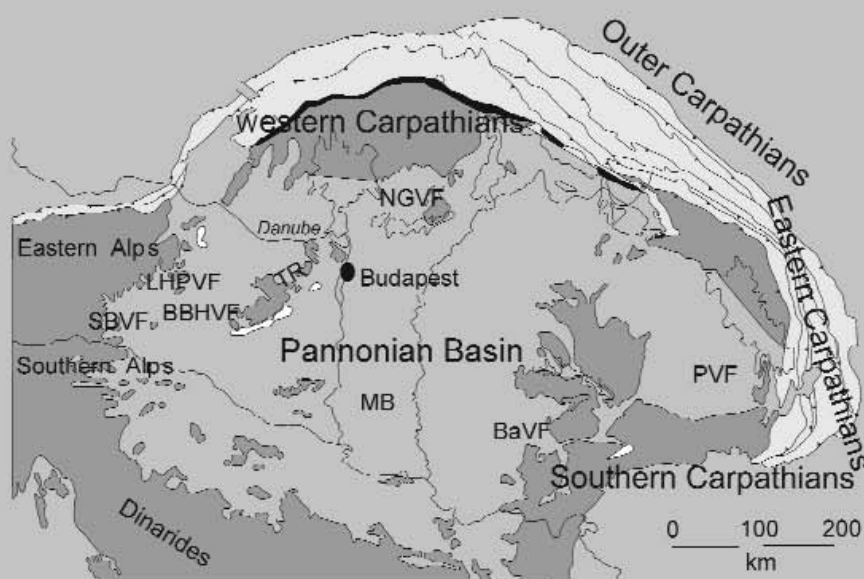


Phreatomagmatic volcanic fields in a Mio/Pliocene fluvio-lacustrine basin,
western Pannonian Basin, Hungary: a review



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Abstract

The volcanic erosion remnants in the western Pannonian Basin are grouped into volcanic fields such as the Bakony – Balaton Highland Volcanic Field (BBHVF), Little Hungarian Plain Volcanic Field (LHPVF), and Styrian Basin Volcanic Field (SBVF). These volcanic fields were active in Late Miocene to Late Pliocene times and are located in the territories of Hungary, Austria and Slovenia. They are formed by at least 100 alkaline basaltic eruptive centres such as variably eroded scoria cones, tuff rings, maars, maar volcanic complexes, shield volcanoes, mesa flows and shallow subsurface intrusive complexes (dykes and sills). In this paper the basic volcanologic characteristics of the volcanic fields in the western Pannonian Basin are presented as a review of past research activities as well as the result of ongoing physical volcanological research in the region. It is demonstrated that the distribution of volcanoes in the western Pannonian Basin is structurally controlled by old structural elements in the pre-volcanic rock units. The geographical distribution of different vent types, such as phreatomagmatic versus magmatic vents, are in relationship with the general hydrogeological characteristics of the pre-volcanic rock units. In areas where thick Pannonian sandstone beds build up the underlying strata the so called “normal maar volcanic centres” have usually a thick late magmatic infill in the maar basins. The eruptive mechanism of these volcanoes was controlled by the unconsolidated, water-saturated porous media aquifer, that lead to the formation of “champagne glass” shaped volcanoes and flat tuff rings. In areas where relatively thin Pannonian sandstone beds cover the thick Mesozoic or Palaeozoic fracture controlled karstwater bearing aquifer, large maar volcanic sequences are common, classified as Tihany-type maar volcanoes. These maar volcanic centres are commonly filled with thick maar lake deposits, building up Gilbert-type gravely, scoria rich deltas in the northern side of the maar basins, suggesting mostly north to south oriented palaeo-fluvial systems. In the elevated, northern part of the field erosional remnants of scoria cones and associated shield volcanoes indicate a minor impact of the ground and surface water that may have led to phreatic and phreatomagmatic explosive activity.

Keywords: phreatomagmatic, volcanic glass, maar, tuff ring, scoria, hydrogeology, erosion, Pannonian Basin, vent, aquifer, dyke, sill, monogenetic

Introduction

The Bakony – Balaton Highland (BBHVF), the Little Hungarian Plain (LHPVF) and the Styrian Basin Volcanic Fields (SBVF) are located in the western Pannonian Basin, Hungary (Figure 1.1). The largest number of Neogene volcanic erosional remnants is in the BBHVF, which includes the Keszthely Mts., where shallow subsurface sills and dykes associated with monogenetic volcanoes are exposed (Plate 1.1). The BBHVF is close to the Lake Balaton north shore. The volcanic centres of the BBHVF were active between 7.54 My and 2.8 My (BALOGH et al. 1982, BORSY et al. 1986, BALOGH and PÉCSKAY 2001, BALOGH and NÉMETH 2004 – Figure 1.2) and produced mostly alkaline basaltic volcanic products (SZABÓ et al. 1992, EMBEY-ISZTIN 1993). The volcanoes in the LHPVF are in the same age and compositional range as the BBHVF (BALOGH, et al. 1982, 1983, 1986, HARANGI et al. 1994, 1995, PÉCSKAY et al. 1995, SZABÓ et al. 1995, BALOGH and PÉCSKAY 2001). The eruptive centres of the BBHVF have a close relationship with the eruption centres of the LHPVF eruptive centres according to their composition, age and general eruption mechanisms (JUGOVICS 1969b, 1972, HARANGI et al. 1994, NÉMETH and MARTIN 1999c, MARTIN et al. 2003). The two volcanic fields operated simultaneously (BALOGH and PÉCSKAY 2001, WJBRANS et al. 2004) but the general palaeoenvironment (KÁZMÉR 1990) and their hydrogeology could have caused different styles of eruptive mechanism mainly in the explosive volcanic activity (NÉMETH and MARTIN 1999c).

The BBHVF itself alone has approximately 50 basaltic volcanoes in a relatively small (around 3500 km²) area (JUGOVICS 1969a), however, the number of vents maybe far more than 50 due to the existence of volcanic complexes and nested volcanoes (MARTIN et al. 2003). The volcanic erosional remnants form a more scattered distribution in the LHPVF, and the number of volcanoes is less (~10) than in the BBHVF (JUGOVICS 1915, 1916, 1972), however, volcanic erosional remnants buried under thick Quaternary deposits are known from the region (TÓTH 1994). Individual Neogene alkaline basaltic volcanic erosional remnants are located close to the triple border of Hungary, Austria and Slovenia as well as close to the eastern metamorphic core complexes in the Eastern Alps (JUGOVICS 1916, 1939, KRALJ 2000) together often referred as SBVF.

The volumetrically largest field of all is the BBHVF, often mentioned together with the LHPVF due to similarities in the age, timing and eruption mechanism. The BBHVF belongs to the Transdanubian Range unit, which is correlated with the Upper Austroalpine nappes of the east Alpine orogen (MAJOROS 1983, KÁZMÉR and KOVÁCS 1985, TARI 1991). The underlying basement of the volcanic fields consists of Palaeozoic rocks (Silurian schist, Permian red sandstone – CSÁSZÁR and LELKESNÉ-FELVÁRI 1999) and a thick Mesozoic carbonate sequence (BUDAI and VÖRÖS 1992, BUDAI and HAAS 1997, HAAS and BUDAI 1999, HAAS et al. 1999). This basement forms a large-scale anticline structure of Eoalpine origin (Figure 1.3) in the Transdanubian Range area and is locally covered by Tertiary sediments (TARI et al. 1992, 1999, HORVÁTH 1993, SACCHI and HORVÁTH 2002).

Tertiary sediments were deposited in local sedimentary basins on a regional erosional unconformity (MÜLLER and MAGYAR 1992, MÜLLER 1998, TARI and PAMIC 1998, JUHÁSZ et al. 1999, MÜLLER et al. 1999). In the Neogene, just shortly before the volcanism started, a large lake, the Pannonian Lake, occupied main parts of the Pannonian Basin (Figure 1.4.), which had a very colourful sedimentary environment as reflected in the irregular basin morphology

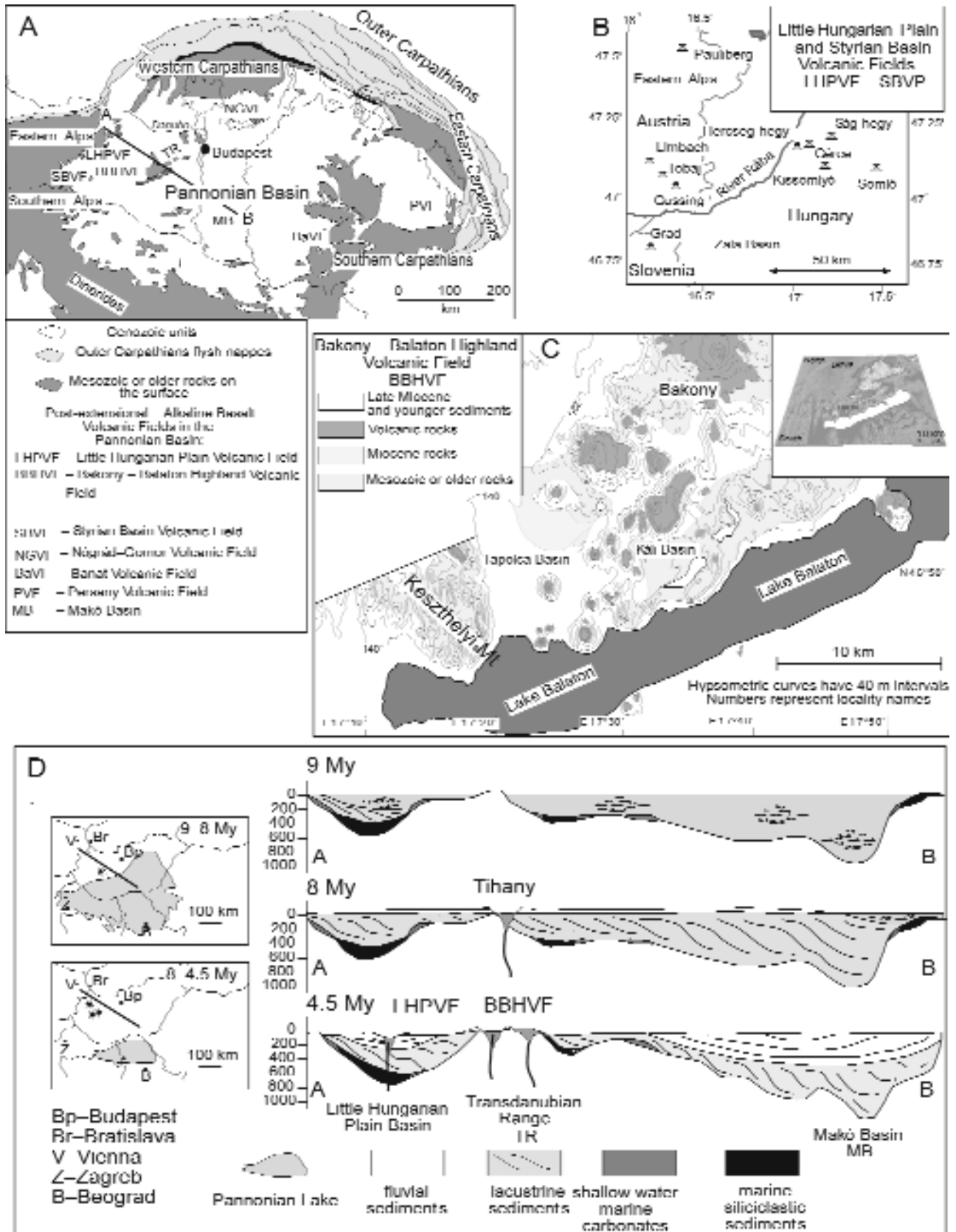


Figure 1.1. Structural elements of the Carpatho-Pannon region (A) with respect to the Mio/Pliocene alkaline basaltic volcanic fields. The location of the volcanic erosional remnants of the Little Hungarian Plain and Styrian Basin Volcanic Fields (B) and the Bakony – Balaton Highland Volcanic Field (C) are shown in relevance to other rock units. The western Pannonian Basin was occupied by the Pannonian Lake around 9 My (D); that lake gradually vanished and had only small basins in the southern part of the Pannonian Basin 4.5 My ago (D). During onset of the volcanism, the region was occupied by an alluvial plain with a flat morphology, and potentially with large, but shallow water masses (D). Please note: The model on "D" is modified after MAGYAR et al. (1999)

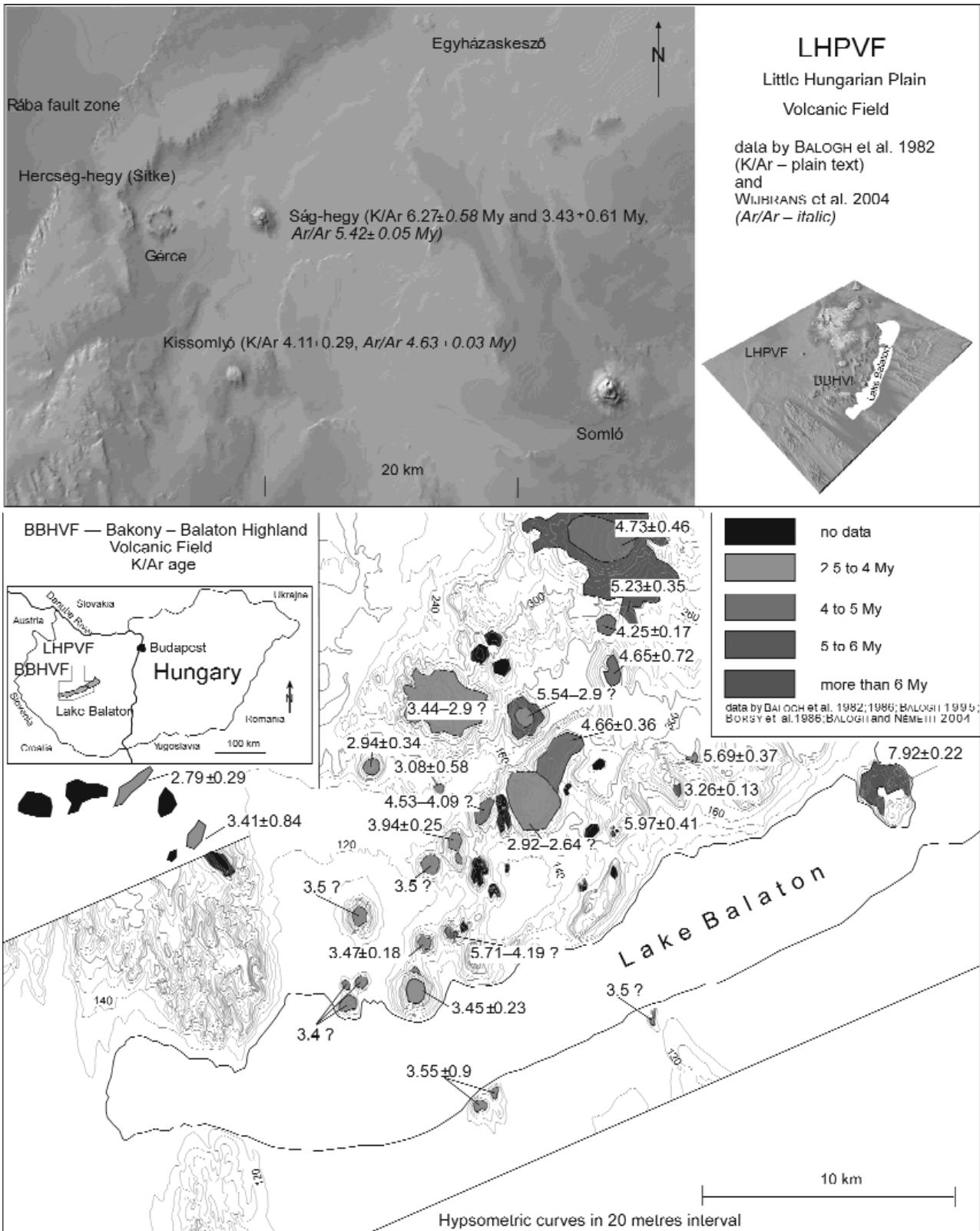


Figure 1.2. K/Ar age distribution map of the Little Hungarian Plain (A) and the Bakony – Balaton Highland (B) Volcanic Fields (after BALOGH et al. 1982, 1986, BORSY et al. 1986, and BALOGH and NÉMETH 2004)

(KÁZMÉR 1990). The lacustrine sandstones, mudstones, marls of the brackish Pannonian Lake are widespread in the Pannonian Basin (JÁMBOR 1980, 1989, KÁZMÉR 1990, MÜLLER and MAGYAR 1992, MÜLLER 1998, GULYÁS 2001). Just before volcanism started the area in the western Pannonian Basin formed an alluvial plain with unconsolidated water-saturated sediments in significant spatial and temporal variation (KÁZMÉR 1990).

The alkaline basaltic volcanism in the western Pannonian Basin was of a predominantly subaerial, intracontinental type. However, large shallow water bodies may have been present during eruptions, which most likely led to the formation of emergent volcanoes (KOKELAAR 1983, 1986, WHITE 1996a, 2001, WHITE and HOUGHTON 2000). These volcanoes quickly breached the water table of these lakes (MARTIN and NÉMETH 2002a, 2004b). The distribution of volcanoes in the western Pannonian Basin is related to the distribution of palaeo-valleys, which formerly were occupied by streams with good water supply (MARTIN et al. 2003). These "wet" valleys are most likely related to the reactivation of pre-Neogene fracture zones similar to the zones of structural weakness in the Eifel Volcanic Fields, Germany (LORENZ and BÜCHEL 1980a, b, BÜCHEL and LORENZ 1982, HUCKENHOLZ and BÜCHEL 1988, 1993, BÜCHEL et al. 2000).

After volcanism ceased, fluvial/alluvial sedimentation was widespread in the western Pannonian Basin. Major erosion affected the region well after volcanism ceased (CSILLAG et al. 1994, JORDÁN et al. 2003, NÉMETH et al. 2003b). Lake Balaton, as one of the major landmarks of western Pannonia, is a recent landform and its history dates back only 17,000 to 15,000 years (CSERNY and CORRADA 1989, CSERNY 1993, CSERNY and NAGY-BODOR 2000, TULLNER and CSERNY 2003). However, pre-Lake Balaton lacustrine systems very likely existed in the region also throughout the Quaternary (TULLNER and CSERNY 2003).

All types of eroded volcanoes can be found in the western Pannonian Basin (Plate 1.2) which show similar characteristics as most other monogenetic intracontinental volcanic fields such as Hopi Buttes, Arizona (WHITE 1991b, ORT et al. 1998), Western Snake River, Idaho (GREELEY 1982, GODCHAUX et al. 1992, BRAND 2004, WOODS and CLEMENS 2004), Waipiata Volcanic Field, New Zealand (NÉMETH and WHITE 2003), or West Eifel, Germany (LORENZ 1984). The most prominent geomorphologic formations are the circular, lava capped buttes. These centres are usually related to underlying phreatomagmatic volcanoes such as maar structures and tuff rings. Individual maar structures without lava infill are less common and difficult to identify. Such volcanic structures are locally filled by post-maar lava flows that subsequently have been buried under thick lacustrine units. In the northern part of the BBHVF Strombolian scoria cone remnants and Hawaiian spatter cone deposits are common. However, they commonly consist of scoria beds, which are inter-bedded with phreatomagmatic tuffs and lapilli tuffs, suggesting simultaneous Strombolian and phreatomagmatic activity. Large lava flow fields in the western Pannonian Basin only exist

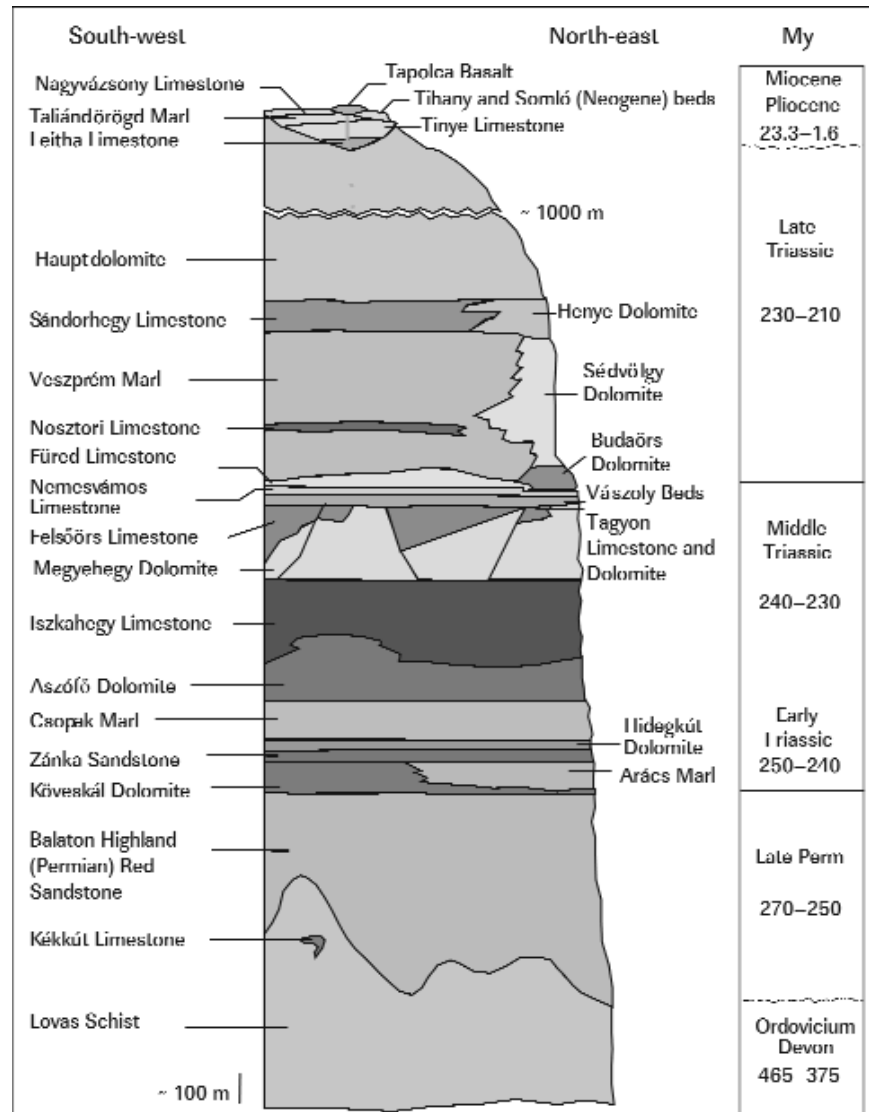


Figure 1.3. A general stratigraphy of the southern part of the Transdanubian Range (after BUDAI et al. 1999). The section shows all the identified rock formations and also gives a hint of the approximate location of certain rock formations

in the northern part of the BBHVF and they form the areas of highest elevation today (Plate 1.1). The lava flows are eroded and their type is often hard to reconstruct due to the advanced erosion. Smaller lava flows are inferred to have filled valleys. The largest lava fields are in the Bakony Mountains and consist of eroded shield volcanoes such as Kab-hegy and Agár-tető (Plate 1.1). Lava plugs intruded into small vents and are preserved to their higher resistance to erosion (Hegyes-tű).

The BBHVF is of great volcanological and palaeo-geomorphological interest. The relatively long volcanic history of the area (7.54–2.8 My – BALOGH and PÉCSKAY 2001) and the adjacent lacustrine to fluvial environment make the western Pannonian Basin an ideal area for studying phreatomagmatic volcanoes in relation to a changing lacustrine environment and the palaeogeomorphological evolution of the Late Miocene to Pliocene landscape. There is a great potential in developing our knowledge about:

1. eruption mechanisms resulting from magma/water interactions with different magma/water-ratio,
2. the relationship of volcanic activity and the confining palaeo-environment,
3. the related palaeohydrology and petrophysical characteristics of the pre-volcanic units, and
4. interrelationships between tectonics and lithospheric rheology that control the magma ascent in various tectonic regimes.

Tectonic framework of the western Pannonian Basin and its relevance to the Neogene intraplate volcanism

The Pannonian region has been considered to be part of the Alpine belt, and it reveals the complexity of orogenic evolution (HORVÁTH and TARI 1999). Continental to oceanic rifting of the Tethyan realm followed the Variscan convergence, subduction and continental collision, all shaping the Palaeozoic to Mesozoic substrata of the region. Subsequently, two periods of basin formation and development occurred in a compressional-transpressional regime during the Late Cretaceous and Palaeogene (TARI et al. 1993, TARI 1994). From the earliest Miocene large-scale lateral displacement and block rotation took place in the internal domain of the orogen, simultaneously with the formation of the Pannonian Basin (HORVÁTH 1993, CSONTOS 1995, FODOR et al. 1999, BADA and HORVÁTH 2001). This has been characterised by lithospheric extension, interrupted by compressional events (HORVÁTH 1995). Gravitational collapse of the Intra-Carpathian domain, combined with subduction zone roll-back are thought to have been the driving mechanism of the Neogene back-arc extension (RATSCHBACHER et al. 1991, FODOR et al. 1999, BADA and HORVÁTH 2001, HORVÁTH et al. 2004), which gave way to widespread volcanism in the basin. The modern Pannonian Basin is in an initial phase of positive structural inversion, the related structural features are not yet fully developed (HORVÁTH and CLOETINGH 1996, GERNER et al. 1999, BADA et al. 2001). The structure of the basin system is the result of distinct modes of Miocene through Pliocene extension exerting a profound effect on the lithospheric configuration. In summary, the Miocene through Quaternary evolution of the Pannonian Basin was characterised by considerable depth-dependent lithospheric stretching (TARI et al. 1999) as a consequence of the collapse of former orogenic terrains and the subduction rollback of the Carpathian arc (CSONTOS et al. 1992, KOVAČ et al. 1994, FODOR et al. 1999, BADA and HORVÁTH 2001, HORVÁTH et al. 2004). Therefore, the Pannonian basin was classified as a typical Neogene back-arc basin in the Mediterranean system (HORVÁTH and BERCKHEMER 1982). These plate-scale processes led to the formation of the early Inner Carpathian and the late East Carpathian volcanic arcs (SZABÓ et al. 1992, LEXA 1999).

There is a large number of models describing the evolution of the Pannonian Basin which is summarized in BADA and HORVÁTH (2001), such as:

1. asthenospheric dome-triggered active rifting (STEGENA 1967),
2. active rifting that has been initiated by a subduction generated mantle updoming (HORVÁTH et al. 1975, STEGENA et al. 1975),
3. a hinge retreat of the subduction of the European margin driven by the negative buoyancy of the slab that induces trench suction forces and hence, passive rifting in the overriding plate (ROYDEN et al. 1983a, 1983b, ROYDEN and KARNER 1984), and
4. a similar hinge retreat is inferred to be sustained by an eastward mantle flow pushing against the downgoing slab (DOGLIONI et al. 1999) similarly to the inferred present situation in the Etna region (DOGLIONI et al. 2001).

In summary, these basin evolution models generally reflect two major views, i.e. active versus passive rifting.

The volcanism in the Pannonian Basin is marked by submarine pyroclastic and coherent trachyandesitic lava of Karpathian age (~17.5–16.2 My), Badenian (~16.2–3 My) pyroclastic and coherent basaltic, andesitic, dacitic and rhyolitic, and Late Miocene to Pliocene (~12–2 My in the western Pannonian Basin) alkali basaltic rocks, which are inter-layered with coeval sedimentary rocks (SZABÓ et al. 1992). Structural interpretation of reflection seismic profiles reveals distinct modes of upper crustal extension in the Middle Miocene – Recent Pannonian Basin (TARI et al. 1992).

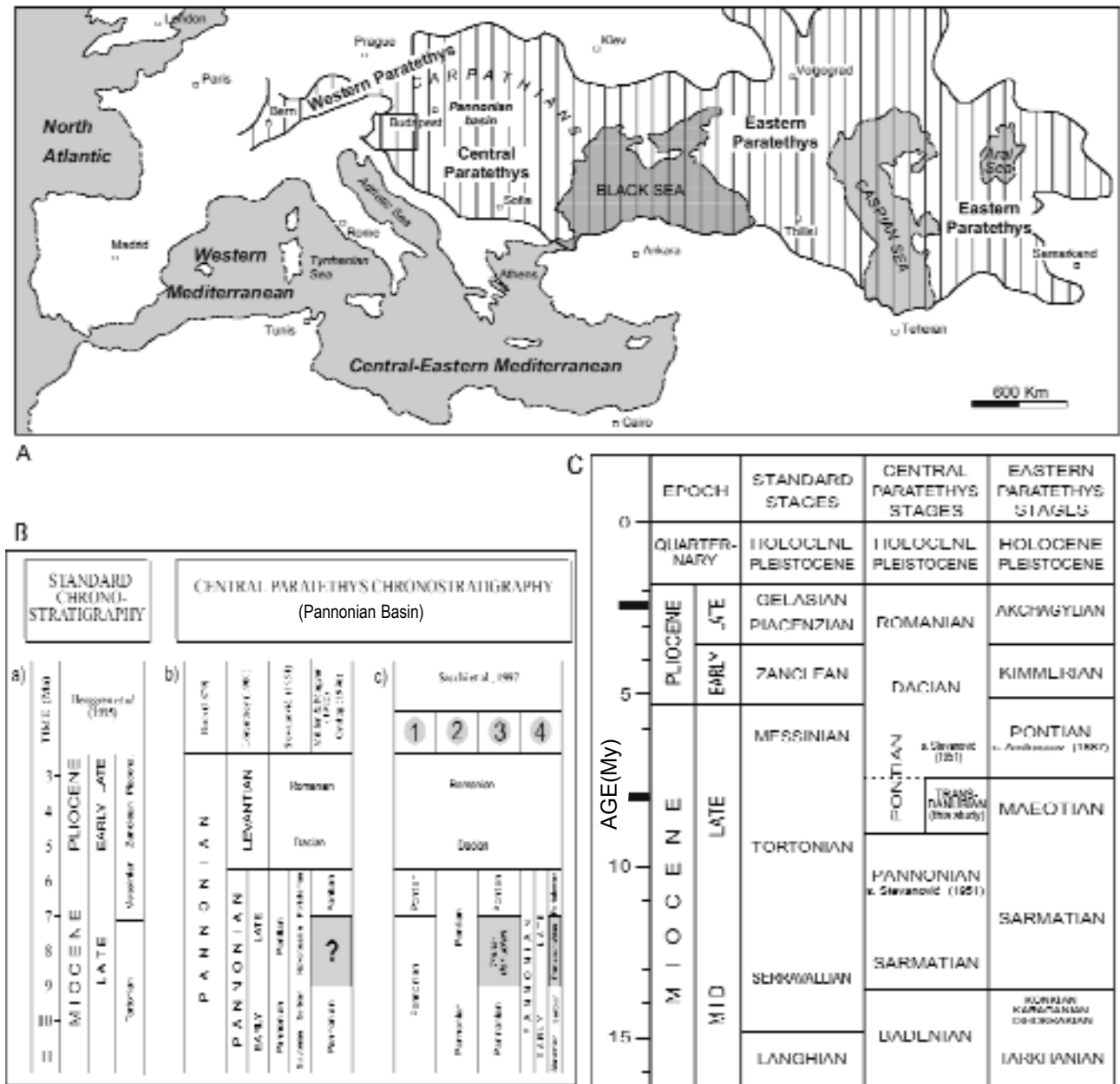


Figure 1.4. (A) Outline of the Paratethys–Mediterranean region during Late Miocene (after MÜLLER et al. 1999). Diagram is by the authors' permission. (B) Correlation between the Late Neogene (a) Mediterranean and (b) Central Paratethys stages. Column (c) illustrates four possible redrawings of the Late Miocene chrono-stratigraphic framework of the Pannonian Basin (Central Paratethys – from SACCHI et al. 1997). Numbers on "c" represent possible solutions of correlation. Diagram is after SACCHI and HORVÁTH 2002 with the authors' permission. (C) Mediterranean and Paratethys stages for the last 15 Myr (after RÖGL 1998, and MAGYAR et al. (1999). Transdanubian is referred after (SACCHI et al. 1999a) as an intermediate stage (or substage) between the Pannonian s.str. (s. STEVANOVIC 1951) and the Pontian s.str. (ANDRUSOV 1887). The Transdanubian substitutes the lower part of Pontian s. STEVANOVIC (1951). The interval of Neogene volcanism in the western Pannonian Basin is marked by two thick black lines on the left side of the diagram. The diagram is after SACCHI and HORVÁTH 2002, with the authors' permission

While some sub-basins in the system show little extension (planar rotational normal faults), others are characterised by a large magnitude of extension (detachment faults, metamorphic core complexes – TARI et al. 1992). Seismic stratigraphic interpretations indicate that the non-marine post-rift sedimentary fill of the Pannonian Basin can be described in terms of sequence stratigraphy (VAKARCS et al. 1994).

Starting in the latest Miocene (Figure 1.4.), a considerable amount of basaltic magma erupted in the Transdanubian Range (TR) and Balaton Highland area in the Pliocene (SZABÓ et al. 1992, NÉMETH and MARTIN 1999c, NÉMETH et al. 2000). A total magma output has been estimated for the BBHVF on the basis of volume estimates of coherent lavas and dense rock equivalents of juvenile pyroclasts from phreatomagmatic and magmatic explosive eruptive products. This gave a minimum estimate of ~2.7 km³ and a maximum estimate of ~6.5 km³ total magma output (NÉMETH et al. 2000). A realistic estimate of 4±0.5 km³ of total magma output (NÉMETH et al. 2000)

over ca. 5.7 My time indicates that the BBHVF rather belongs to a volcanic field with low magma output ratio, which is typical for a strike-slip tectonic regime, or regions of moderate lithospheric extension such as the San Francisco Volcanic Field, Arizona. Approximately 90% of the total magma output is estimated to be basanitic in composition, leaving 10% for more differentiated rock types such as tephrite, phonotephrite, that are the major constituents of the phreatomagmatic pyroclastic deposits (NÉMETH et al. 2000). Estimating of the erupted volume of juvenile material from pyroclasts is more complicated due to the uncertainty of the eroded volumes. The tectonic role and style of magmatism is still under debate (SZABÓ et al. 1992, EMBEY-ISZTIN et al. 1993, HARANGI et al. 1995, KEMPTON et al. 1997). In general most of the workers agree that the Neogene alkali basalts from western and central Europe dominantly derived from asthenospheric partial melting (EMBEY-ISZTIN et al. 1993). However, there are growing evidences that in most cases they were modified by melt components from the enriched lithospheric mantle through which they have ascended (EMBEY-ISZTIN et al. 1993). A debate on the role of crustal contamination of the magmas still exists. Most of the models deal with some contamination from a subducted slab from former subduction in the region and/or some degree of metasomatism (BALI et al. 2002). In general, the incompatible-element patterns of the lavas of the volcanic fields of the western Pannonian Basin show that these lavas are relatively homogeneous (EMBEY-ISZTIN et al. 1993) and are enriched in K, Rb, Ba, Sr, and Pb with respect to average ocean island basalt such as Hawaii, and resemble alkali basalts of Gough Island.

Heat flow values in the Pannonian Basin greatly vary (DÖVÉNYI and HORVÁTH 1988), and are up to 300 mW/m² in areas of volcanic fields that are inferred to be located above shallow magma chambers (SACHSENHOFER et al. 1997, 1998, 2001). Elevated heat flow values from the Austrian basins were obtained from areas related to the Eastern Alps, a consequence of rapid uplift of the whole orogen (SACHSENHOFER et al. 1997, 2001, SACHSENHOFER 2001).

In spite of the large number of data available from tectonic and geochemical studies, the question of the relationship between volcanism and the Neogene tectonic processes in the Pannonian Basin has not been addressed adequately yet. One possible explanation, which is in agreement with other field-based observations such as geomorphological evolution and facies relationships, could be that magmatism is related to the latest stage of post-rift faulting (FODOR et al. 1999). In this course, basaltic volcanism may have occurred after the cessation of post-rift sedimentation and preserved incipient denudation surfaces (NÉMETH and MARTIN 1999d, NÉMETH, et al. 2003b). The Pliocene basaltic volcanism may also belong to the late-stage inversion of the Pannonian Basin, which was generally associated with uplift and denudation (HORVÁTH 1995, HORVÁTH and CLOETINGH 1996).

Lithospheric structure and magma ascent of Neogene alkaline basaltic volcanic fields

Continental monogenetic volcanic fields are subject to the same physical constraints as other volcanic systems. Dense mantle-derived magmas are prone to pond near their levels of neutral buoyancy, at depths of 25–30 km, in the upper mantle/continental crust boundary and/or in rheological and density contrast zones between the brittle/ductile transition in mid-crustal levels (RYAN 1987a, b, WALKER 1989, LISTER 1991, LISTER and KERR 1991, WATANABE et al. 1999, 2002). Eruption of such magmas in small volumes requires substantial injected volumes of which only a small proportion reaches the surface, and/or specific stress conditions within the transected lithosphere (LISTER 1991, WATANABE et al. 1999).

Various mechanical considerations of fluid-filled crack propagation (e.g. LISTER 1991) through a lithosphere that is under tectonic stress conclude that either **extension** (e.g. ascend of mantle material and then upflow of magma along “open” (extensional) fractures) or **tectonic inversion** (e.g. mantle material ponds at the Moho and other density and/or rheology contrast zones in the lithosphere and then magma is expelled by tectonic forces) seem to be a viable mechanism for volcanic activity of the Neogene alkaline basaltic volcanism in the western Pannonian Basin.

During pure extension, when the vector of the maximum compressional stress is vertical and the minimum compressional stress is in horizontal position (predominantly normal faulting) vertical dyke propagation is favoured (LISTER 1991, WATANABE et al. 1999). Magma can reach the surface and predominantly form monogenetic, deep-rooted volcanoes (WATANABE et al. 1999). When the maximum compressional stress is in horizontal and the minimum is in vertical position, melt intrusion is only possible when this configuration temporarily switches into either pure extension or to a period when the maximum and minimum compressional stress orientation change place (WATANABE et al. 1999). If the switching period is short, magma can be trapped and form sill-like reservoirs. Further movement toward the surface is possible during a new switching period, which process must lead to a multiple level magma “pocket” build up through a series of so called “failed eruptions”. When the maximum compressional stress is in vertical and the minimum in horizontal position, but their differential stress is small (e.g. strike slip system) magma gradually can reach the

surface through multiple “failed eruptions” (WATANABE et al. 1999). In this situation a large magma supply rate is necessary in general for the magma to reach the surface. In this condition the generation of polygenetic volcanic systems is favoured if the differential stress is generally small in absolute value and does not change significantly with depth. In conditions when the differential stress is variable according to the depth (e.g. depending on the changeable physical conditions of the crust – temperature, lithology distribution etc.) both polygenetic volcanoes and monogenetic volcanic fields can form.

Locations of highly differentiated silicic igneous bodies such as in the axis of the Little Hungarian Plain sub-basin, which is filled by about 3000 m thick low density Miocene to recent siliciclastic sediments (TARI 1994) and cap a metamorphic complex, suggest that these thick, low-density rock-filled basins may have functioned as a density trap (WALKER 1989) and led to magma chamber formation where alkaline basaltic magma fractionated to trachyte, trachyandesite in the otherwise predominantly alkaline basaltic volcanic products. Similar density traps have been reported in the Yucca Mts area (Nevada, USA), where low density thick (up to 6 km) ignimbrites that filled a basin functioned as density trap against the ascent of the otherwise buoyant, hot basaltic melt (CONNOR et al. 2000). The inferred timing (~12–9 My) of the formation of such otherwise bimodal (trachyte – basalt – SCHLEDER and HARANGI 2000) polygenetic volcano in the axis Little Hungarian Plain region is in good concert with the predominantly strike-slip controlled tectonic regime in the region in this time (TARI et al. 1992, TARI 1994). Perhaps the alkaline basaltic volcanism in the western Pannonian Basin post-dates this complex volcano and is coincident with the general tectonic inversion that most of the workers accept but the reason of this volcanism is not fully understood. From a tectonic point of view, magma may reach the surface in the general compressional regime when it may switch for various time length to be pure extensional or strike-slip dominated. The general complexity of the Neogene “so called” monogenetic volcanoes of the western Pannonian Basin from both a geochemical (see later) and volcanological point of view, and the newly identified dyke and sill complexes associated with these volcanoes suggest that a temporal switch from a compressional tectonic regime to a more strike-slip dominated regime may be a sensible reason for the melt to reach the surface. However, the general agreement on fast uprise of the basaltoid melt that carry large mantle nodules somehow indicate more pure extensional periods temporally during the general compressional regime. Because up to now there is no clear sign of temporal and/or spatial distribution of volcanic features indicative for these two major scenarios, we suggest that in a generally “unstable” compressional regime, the tectonic stress field may have switched to either pure extension or strike-slip regimes according to other controlling factors such as changes of heat flow or position of the mantle anomaly. For a working hypothesis, if there is any temporal change in tectonic regime (e.g. gradual transition from pure extension to pure compression as a result of the tectonic inversion),

1. monogenetic volcanoes (e.g. short-lived volcanoes with simple architecture) that issued lavas and/or pyroclastic rocks carried large mantle nodules are expected to be older and

2. younger volcanic edifices may be more complex, often associated with sill complexes. There are sill and dyke complexes that are relatively young (~3 My) and volcanoes erupted large mantle nodules that are old, but it is too early to draw any broader conclusion on the basis of the very limited research that has been carried out in this respect.

In summary, it can be concluded that the lithosphere in the Pannonian Basin has a very complex structure. The crust as well as the lithosphere is strongly attenuated and high heat flow prevails (hottest basin in continental Europe). Rock units with variable density, rheology and heat conductivity could have facilitated magma ponding that might have led to further magma evolution via fractionation in these magma storage places (chambers). Such lithospheric architecture could temporarily trap otherwise “fast” uprising basaltoid melt of mantle origin when the regional stress field is switching to a more compressive regime for a short time interval. Such a scenario is very likely during basin evolution dominated by strike slip faulting, such as is inferred for the western Pannonian Basin during the onset of volcanism in the Late Miocene through Pliocene.

Geochemistry and petrogenesis of eruptive products of the Miocene to Pliocene volcanism in the western Pannonian Basin

Alkaline basaltic volcanism throughout the Neogene was widespread in the Pannonian Basin, leading to the formation of distinct volcanic fields. Volcanism, in general, since the Miocene is associated with the tectonic development of the Carpatho-Pannonian region and is connected with the formation of the Pannonian Basin (SZABÓ et al. 1992). Volcanic activity has previously been divided into three main genetic types (SZABÓ et al. 1992) according to the common composition, eruption style, and location of the volcanic centres:

1. Early Miocene mainly acidic explosive volcanism that led to the accumulation of extensive ignimbrite sheets (welded and non-welded type, predominantly rhyolitic in composition), block-and-ash flow deposits as well as their

reworked volcano-sedimentary units, often intercalated with normal marine to terrestrial sediments (LIFFA 1940, PANTÓ 1963, 1966, HÁMOR et al. 1980, SZÉKY-FUX and KOZÁK 1984, PÓKA 1988, CAPACCIONI et al. 1995, SZAKÁCS et al. 1998, LEXA 1999). The recent spatial distribution of this volcanic province exhibits a great separation which is inferred to be the result of a large right lateral displacement along the Mid-Hungarian shear zone (Figure 1.1) during the Early Miocene (STEGENA et al. 1975, BALLA 1980, 1981, ROYDEN et al. 1983a).

2. Middle Miocene – Pliocene calc-alkaline, mainly intermediate stratovolcanic complexes in the Inner Western Carpathians and in the East Carpathians, related to a subducted oceanic slab (KONEČNÝ et al. 1999b). Their geochemical compositions show a transitional character between active continental margin and island arc type magmatic rocks (DOWNES et al. 1995a, b). The thickness of the crust increased with time and from west to east beneath this volcanic arc. The small-to-medium sized block-and-ash flow dominated lava dome fields (ZELENKA 1960, BALLA and KÖRPÁS 1980, KÖRPÁS and LANG 1993, KARÁTSON et al. 2000) and their associated reworked volcanoclastic successions often formed thick accumulations of volcanoclastic mass flows (KARÁTSON and NÉMETH 2001). Such volcanoclastic successions can be traced in the entire Carpathian Volcanic Chain and often bear significant information on basin evolution.

3. Pliocene–Pleistocene alkali basaltic volcanism in the Pannonian Basin is considered to have been related to an up-welled, then cooled asthenospheric dome (SZABÓ et al. 1992). This is thought to have induced the thermal regime from which magmatic melts ascended (SZABÓ et al. 1992). Various geochemical studies of the alkaline basalts suggest mantle up-welling as a major driving force of the alkaline basaltic Neogene volcanism (SZABÓ et al. 1992). The compositional difference in space and time are inferred to reflect the existence of local individual small-sized diapiric bodies as well as several processes (e.g. fractional crystallisation, mixing), which modified the original magma (SZABÓ et al. 1992). Such diapiric bodies are often referred to as common Central European mantle up-welling feeding volcanic fields across Europe in the Neogene (DUDA and SCHMINCKE 1978, WILSON and BIANCHINI 1999). The eruption of basaltic melts was temporally associated with the final phase of the development of the Pannonian Basin, however, it often has been considered to post-date the cessation of the post-rift sedimentation. The accumulation of volcanic debris on an erosional surface and the volcanism itself is coeval with the start of the basin inversion as was pointed out earlier (HORVÁTH 1995, FODOR et al. 1999, NÉMETH and MARTIN 1999d, MARTIN et al. 2003).

There is a general agreement regarding the petrogenesis of Neogene alkali basaltic rocks in the Pannonian Basin. The basaltic rocks were formed during the Late Cenozoic post-orogenic phase and their eruption was related to the evolution of the extensional Pannonian Basin following Eocene–Miocene subduction and its related calc-alkaline volcanism (SZABÓ et al. 1992, EMBEY-ISZTIN et al. 1993). The alkaline volcanic centres, dated by K/Ar methods are between ~12 and 1 My in age (PÉCSKAY et al. 1995), forming well-distinguishable volcanic fields. Some fields are near the western (Graz Basin, Burgenland, Slovenia), northern (Nógrád–Gömör/Gemer), and eastern (Eastern Transylvanian Volcanic Field) margins of the basin, but the majority are concentrated near the Transdanubian Range (Bakony – Balaton Highland and Little Hungarian Plain Volcanic Field). Coherent lavas range from slightly hy-normative transitional basalts through alkali basalts and basanites to olivine nephelinites. No highly evolved coherent lava (extrusive nor intrusive) compositions have been identified from any of the locations yet (SZABÓ et al. 1992, EMBEY-ISZTIN et al. 1993, HARANGI et al. 1995). This makes the Pannonian Neogene basaltic volcanic fields different from other European volcanic fields such as the Eifel, where e.g. phonolitic lava flows as well as ignimbrites are common (BOGAARD and SCHMINCKE 1985, FREUNDT and SCHMINCKE 1986, BEDNARZ and SCHMINCKE 1990, HARMS and SCHMINCKE 2000). The presence of mantle peridotite xenoliths, xenocrysts, and high-pressure megacrysts in coherent lavas, even in the slightly more evolved ones and in pyroclastic rocks, is inferred to indicate that differentiation took place within the upper mantle (DOWNES et al. 1992). However, the mantle source often is referred to be heterogeneous (DOBOSI 1989, DOBOSI et al. 1991, DOBOSI and FODOR 1992, SZABÓ and BODNAR 1995, 1998, DOBOSI et al. 2003). The study of peridotite xenoliths revealed a strong relationship between deformation and temperatures of peridotites, in as much as coarse-grained protogranular and poikilitic xenoliths had high temperatures (up to 1175 °C), whereas fine-grained equigranular and mosaic xenoliths had low temperatures (800–900 °C – EMBEY-ISZTIN et al. 2001). This picture suggests that diapiric uplift of hot mantle material into a cooler uppermost mantle has probably taken place (EMBEY-ISZTIN et al. 2001).

Isotope geochemistry

The Sr and Nd isotope ratios from the Neogene coherent lava flows of the Pannonian Basin span the range of Neogene alkali basalts from Western and Central Europe (DUDA and SCHMINCKE 1978, 1985, MERTES and SCHMINCKE 1985, BEDNARZ and SCHMINCKE 1990), and suggest that the magmas of the Pannonian Basin dominantly derived from asthenospheric partial melting. Pb isotope studies, however, indicate that in most cases the asthenospheric melt composition was modified by melt components from the enriched lithospheric mantle through which the magma ascended (EMBEY-ISZTIN et al. 1993). Various metasomatic processes may have interacted with the uprising melts (BALI et al. 2002), similarly to other alkaline volcanic provinces in Central Europe (WITTEICKSCHEN et al. 1993, SHAW 1997, SACHS

and HANSTEEN 2000, SHAW and EYZAGUIRRE 2000). Delta ^{18}O values indicate that the magmas have not been significantly contaminated with crustal material during ascent and isotopic and trace-element ratios therefore reflect mantle source characteristics (EMBEY-ISZTIN et al. 1993). The uniform oxygen isotope ratio in the phenocrysts suggests that the mantle source of the alkali basalts was also homogeneous with respect to its oxygen isotope composition, which is in contrast to the relatively wide variation of Sr, Nd and Pb isotope ratios in the source (DOBOSI et al. 1998). Variations in radiogenic isotope compositions in the basalts have been interpreted as result of the interaction of subduction-related fluids with the mantle source of the basalts. If this was the case, then the fluids, which caused significant changes in the Sr and Pb isotope ratios of the mantle source, did not noticeably modify its oxygen isotope composition. Incompatible-element patterns show that the basic lavas, which erupted in the Balaton area and Little Hungarian Plain, are relatively homogeneous and are enriched in K, Rb, Ba, Sr, and Pb with respect to average ocean island basalt, and resemble alkali basalts of Gough Island type (EMBEY-ISZTIN et al. 1993). In addition, $^{207}\text{Pb}/^{204}\text{Pb}$ is enriched relative to $^{206}\text{Pb}/^{204}\text{Pb}$. In these respects, the lavas of the Balaton area and the Little Hungarian Plain differ from those of other regions of Neogene alkaline magmatism of Europe (EMBEY-ISZTIN et al. 1993). This may be due to the introduction of marine sediments into the mantle during the earlier period of subduction and metasomatism of the lithosphere by slab-derived fluids rich in K, Rb, Ba, Pb, and Sr. Lavas erupted in the peripheral areas have incompatible-element patterns and isotopic characteristics different from those of the central areas of the basin, and more closely resemble Neogene alkaline lavas from areas of western Europe where recent subduction has not occurred (EMBEY-ISZTIN et al. 1993). However, in this respect there is no agreement yet. The alkaline volcanic activity that occurred in the Persani Mountains (eastern Transylvanian Basin) and Banat (eastern Pannonian Basin) regions of Romania between 2.5 My and 0.7 My (DOWNES et al. 1995b) produced coherent alkaline basaltic lavas that are primitive, silica-undersaturated alkali basalts and trachybasalts (7.8–12.3 wt.% MgO; 119–207 ppm Ni; 210–488 ppm Cr), which are LREE-enriched (DOWNES et al. 1995b). Mantle-normalised trace-element diagrams revealed an overall similarity to continental intraplate alkali basalts, but when compared to a global average of ocean island basalts (OIB), the Banat lavas are similar to average OIB, whereas the Persani Mts. basalts have higher Rb, Ba, K and Pb and lower Nb, Zr and Ti. These features slightly resemble those of subduction-related magmas, particularly those of a basaltic andesite related to the nearby older arc magmas (DOWNES et al. 1995b). With $^{87}\text{Sr}/^{86}\text{Sr}$ varying from 0.7035–0.7045 and $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.51273–0.51289, the Romanian alkali basalts are indistinguishable (DOWNES et al. 1995b) from those of the western Pannonian Basin (Hungary and Austria – HARANGI et al. 1994, 1995, EMBEY-ISZTIN and KURAT 1997) and Neogene alkali basalts throughout Europe. It is inferred that, although the Romanian alkali basalts have a strong asthenospheric (i.e. OIB-type mantle source) component, their Pb isotopic characteristics were derived from mantle, which was affected by the earlier subduction (DOWNES et al. 1995b). It is in general agreement that Neogene alkaline basaltic rocks in the Pannonian Basin have some characteristics that represent some influence by former subduction in the region and associated metasomatic processes in the mantle.

Petrography of pyroclastic rocks

The western Pannonian volcanic fields also consistently comprise basal vitric pyroclastic units overlain by lavas (NÉMETH and MARTIN 1999c, MARTIN et al. 2003). The pyroclastic rocks of the volcanic fields contain various proportions of country rock clasts, which apparently represent vent-filling assemblages. Locally there are well-bedded tuff ring deposits preserved (Figure 1.5). Dykes and lava flows have sub-planar to highly irregular, locally peperitic (MARTIN and NÉMETH 2000), contacts with pyroclastic rocks, suggesting intrusion shortly after emplacement of the tuffs and tuff breccias while they were still unconsolidated. The pyroclastic rocks typically have aphyric or sparsely feldspar-phyric juvenile clasts (sideromelane glass shards), whereas the slightly younger dykes and lavas are characterized by abundant pyroxene±kaersutite phenocrysts. The volcanic glass shards are variously shaped from blocky to strongly stretched being microvesicular and/or containing abundant microlites and/or microphenocryst (Plate 1.3). The vesicle morphology of the glass shards exhibits features characteristic for both magmatic degassing and sudden collapse due to cooling of the melt by magma

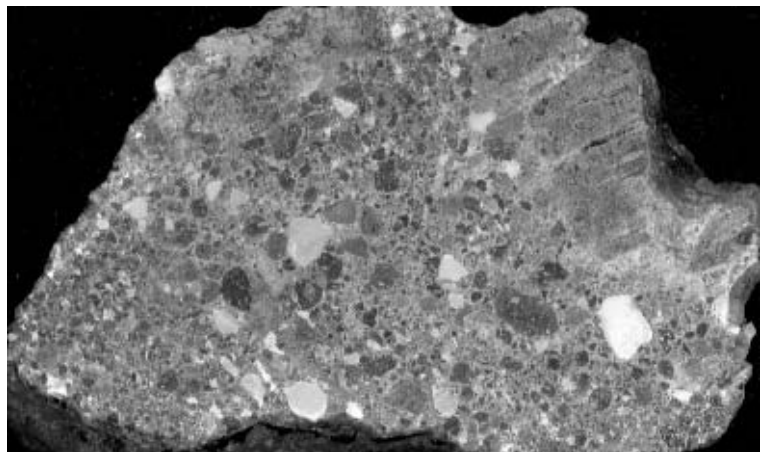


Figure 1.5. Typical phreatomagmatic accidental lithic rich (white angular clasts from the Triassic carbonates) lapilli tuff from Pula, BBHVF
The shorter side of the photo is 10 cm

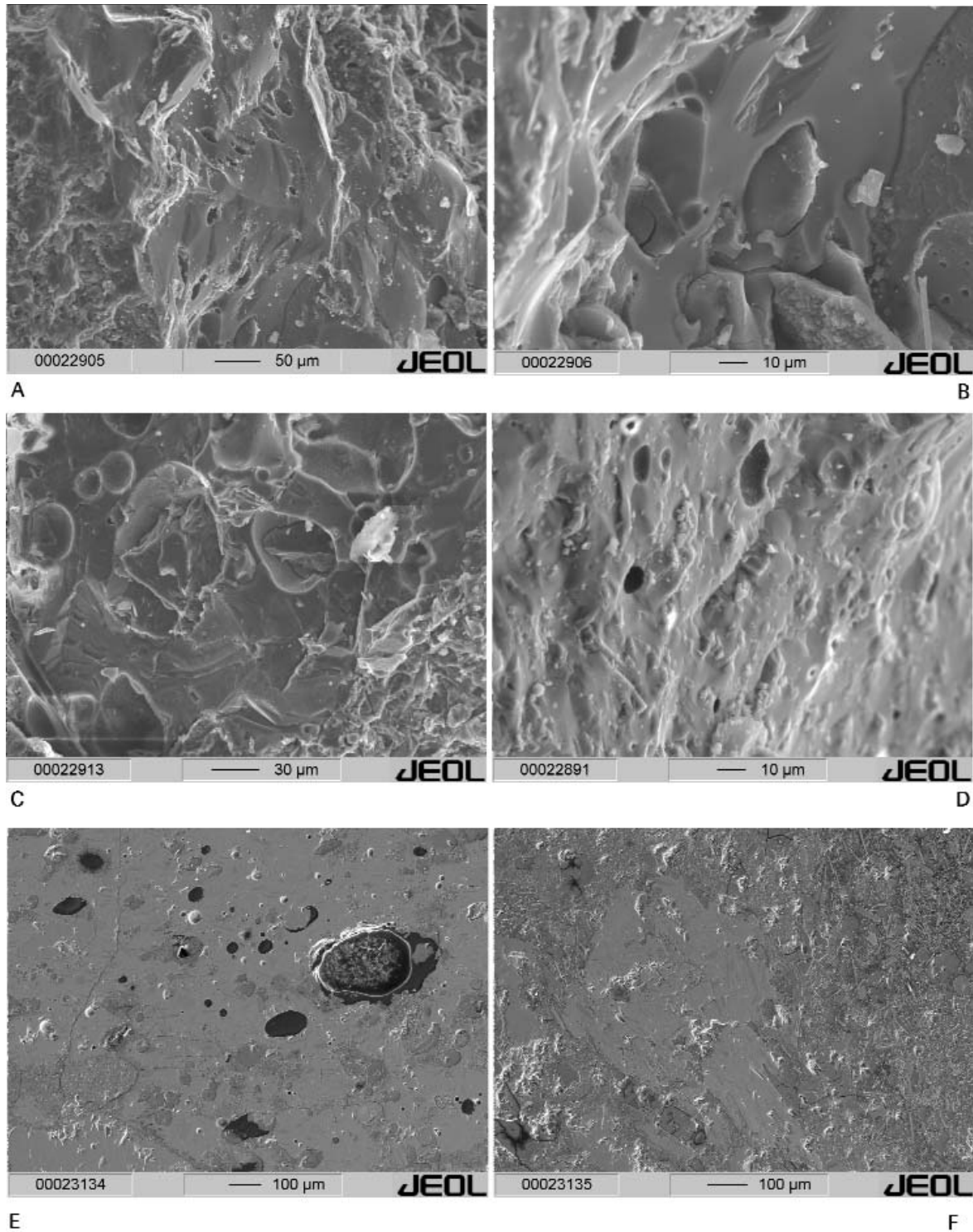


Figure 1.6. Scanning Electron Microscope photos of volcanic glass shards from the western Pannonian Basin made on JEOL 6740 Superprobe housed at the Geological Institute, TU-Bergakademie, Freiberg, Germany

- A – Ság-hegy; phreatomagmatic lapilli tuff. Note the smooth surface and blocky shape of the glass shard. [on rock fragment]
 B – Ság-hegy; phreatomagmatic lapilli tuff, a close-up of a vesicle. Note the angular limit of the vesicle, as well as the fracture, blocky shape of the shard. [on rock fragment]
 C – Hajagos; phreatomagmatic lapilli tuff. Glass shards are moderately vesicular, with angular shape vesicles. [on rock fragment]
 D – Pula; phreatomagmatic lapilli tuff with moderately vesicular phonotephritic lapilli. [on rock fragment]
 E – Kis-Hegyes-tű; tephritic glass shard with low vesicularity of a phreatomagmatic lapilli tuff. [on polished thin section]
 F – Kis-Hegyes-tű; phreatomagmatic lapilli tuff with blocky, non-vesicular tephritic glass shards. Microlites shown on this image are slightly darker. [on polished thin section]

water interaction (Figure 1.6). There are abundant deep-seated xenoliths, 1 to 15 cm in size, in the uppermost beds of pyroclastic deposits at some of the volcanoes (Plate 1.4).

Age of the Neogene intraplate volcanoes in the western Pannonian Basin and their relationship to the immediate pre- and syn-volcanic sedimentation in the region

Intracontinental Mio/Pliocene volcanic fields of the western Pannonian Basin developed between 7.56 and 2.3 My (BALOGH et al. 1986, PÉCSKAY et al. 1995, BALOGH and NÉMETH 2004) across an area in size of about 50,000 km² (Figure 1.1). In the western Pannonian Basin, there are two closely related volcanic fields, that contain the largest number of volcanoes,

1. Bakony – Balaton Highland Volcanic Field (BBHVF) and
2. Little Hungarian Plain Volcanic Field (LHPVF – Plate 1.5).

Phreatomagmatic volcanoes in the northern LHPVF tend to comprise broader, lensoid landforms and in their crater/vent volcanic facies peperites are common (MARTIN and NÉMETH 2004a, c). The depth of magma-water interaction in these volcanoes is inferred to have been shallow (MARTIN and NÉMETH 2004b). The presence of peperites indicates that the host sediment (both siliciclastic and pyroclastic) into which the magma intruded or on which the lava erupted was water saturated (MARTIN and NÉMETH 2000). In the BBHVF, especially in the central and eastern part, a large number of volcanic remnants exhibit features that are characteristic for magma-water interaction in deeper zones (e.g. karst water) of the pre-volcanic sedimentary sequence (NÉMETH et al. 2001).

Shallow lakes may have existed in an alluvial plain during onset of volcanism (MAGYAR et al. 1999), which may have led to shallow subaqueous-to-emergent volcanism (Figures 1.1 and 1.4). Textures of pyroclastic rock units as well as the common occurrence of peperites prove this (MARTIN and NÉMETH 2004b). Shallow lacustrine siliciclastic sedimentary units that deposited in these shallow lakes represent the immediate pre-volcanic rock units of the volcanic facies in the western Pannonian Basin. On the basis of unconformity-bounded sedimentary units in the Neogene sequence of the continental sedimentary record of the western Pannonian Basin, three major maximum flooding surfaces have been identified and dated by magnetostratigraphic correlation to be 9.0 My, 7.3 My and around 5.8 My (LANTOS et al. 1992, SACCHI et al. 1999, SACCHI and HORVÁTH 2002). The first maximum flooding event correlates with the *Congeria czjzeki* open lacustrine beds (LÖRENTHEY 1900, MÜLLER and MAGYAR 1992, MAGYAR 1995, MAGYAR et al. 1999), which marks the Lower Pannonian stage of LÖRENTHEY (1900). After the flooding event, a significant base level drop and subaerial erosion took place around 8.7 My (MÜLLER and MAGYAR 1992, SACCHI et al. 1999). The second maximum flooding event took place around 7.3 My ago and is represented by the appearance of *Congeria rhomboidea* beds (MÜLLER and MAGYAR 1992, MAGYAR et al. 1999, SACCHI et al. 1999). General low-stand and subaerial conditions in the marginal areas are estimated to have occurred around 6 My ago (SACCHI et al. 1999), which was followed by the last known flooding around 5.3 My ago. However, this flooding event has not affected the region of the western Pannonian volcanic fields. It has reached only the southern margin of the basin (MAGYAR et al. 1999).

The intensive geochronological research carried out in the past decades on young alkaline basaltic rocks from the Pannonian Basin has confirmed that K/Ar data on these rocks give the reasonable geological ages and the most frequent error is caused by the presence of excess Ar (BALOGH et al. 1996). In spite of the presence of excess Ar detected from the Neogene basaltic rocks of the Pannonian Basin the geological age of these rocks has been obtained by applying the isochron methods (McDOUGALL et al. 1969, HARPER 1970, McDOUGALL and COOMBS 1973, SHAFIQULLAH and DAMON 1974, HAYATSU and CARMICHAEL 1977, McDOUGALL and DUNCAN 1980, McDOUGALL et al. 2001).

Although there are analytical and sampling difficulties a great number of K/Ar age data are available from the Neogene basaltic volcanic rocks from the western Pannonian Basin. There is no apparent spatial distribution pattern among major age groups of volcanic rocks (Figure 1.2). The age



Figure 1.8. Aerial photograph of the Füzes-tó region, a 2.64 My (³⁹Ar/⁴⁰Ar – WJBRANS et al. 2004) old erosion remnant of a scoria cone

Note the tuff ring (line) in which the scoria cone formed and which is still well-preserved, (crater rim marked with dashed line). Note that the scoria cone must have been either open, or subsequently partly collapsed toward the north-east

dates between 8 to 2.3 My seem to be randomly scattered in the area (Figure 1.2). There is a general centre point of ages at around 3.5–4 My BP, derived from volcanic remnants in the western part of the BBHVF (Figure 1.2). On the basis of new, laser induced step heating $^{39}\text{Ar}/^{40}\text{Ar}$ high precision ages, it seems, that one of the major part of the alkaline basaltic volcanism in the region, falls into the 3.8–4 My old period, which is in good concert with the previous K/Ar dates (Halom-hegy/3.78, 3.82, Hajagos/3.81, Hegyesd/3.9, Fekete-hegy lava field/3.81, Szigliget diatreme Várhegy pyroclastic sequence/4.08 – BALOGH et al. 1986, BORSY et al. 1986, WIJBRANS et al. 2004). An older age group of volcanoes can be identified on the basis of the $^{39}\text{Ar}/^{40}\text{Ar}$ ages at around 4.2 to 4.8 My (Szent György-hegy/4.22, Szigliget lava/4.53, Kis-Somlyó/4.63 and Tóti-hegy/4.74), however dates from Szigliget is likely to be in error, and they rather belong to the previous age group (WIJBRANS et al. 2004). These numbers also represent similar values than previous K/Ar dates from the same volcanoes (BALOGH et al. 1986, BORSY et al. 1986). The oldest known volcanic remnants are in Tihany, and their ages are fixed at around 8 My by repeated attempt to obtain isochron dates by the K/Ar method (BALOGH and NÉMETH 2004). The youngest volcanic edifices are erosion remnants of scoria cones topping the Haláp (3.08 $^{39}\text{Ar}/^{40}\text{Ar}$ – WIJBRANS et al. 2004), Agár-tető (2.9 K/Ar – BALOGH et al. 1986), Fűzes-tó (2.64 $^{39}\text{Ar}/^{40}\text{Ar}$ – WIJBRANS et al. 2004) and Bondoró (2.3 K/Ar – BALOGH and PÉCSKAY 2001). Among these locations are the most well-preserved scoria cones in the western Pannonian Basin, which are still holding some primary morphology as well-defined crater rim (Figure 1.8).

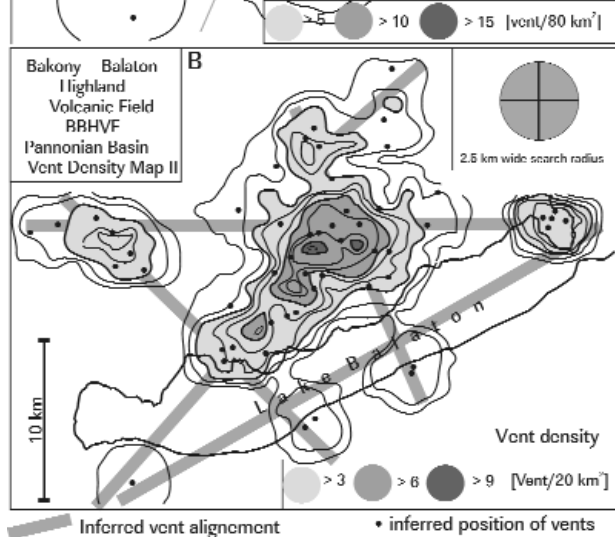
Overall it can be summarised that the Neogene basaltic volcanism was active in the western Pannonian Basin between ~ 8 and 2.3 My, having a total duration of 5.3 My.

Distribution of volcanic erosion remnants

Studies of vent distribution in a volcanic field are very useful to establish the relationship between volcanism and tectonism and give some conclusions on the relationship between structural elements and the location of volcanic edifices (CONNOR and CONWAY 2000). Such studies have been successfully applied on various volcanic fields. Major tendencies of vent migration and tectonic events have been found elsewhere (CONNOR 1990, TOPRAK 1998, CONNOR et al. 2000, ROWLAND and SIBSON 2001).

Volcanic erosion remnants in the western Pannonian Basin are clustered into three major well-distinguished volcanic fields. The Styrian area (in Austria and Slovenia) is well-separated from the Bakony – Balaton Highland and Little Hungarian Plain Volcanic Fields (both are in Hungary), and features only largely separated vents. Volcanic erosional remnants from the BBHVF and LHPVF are not clearly separated from each other and the transition between these two fields is more continuous (Plate 1.5). The significant difference between these two fields is that the apparent vent density in the BBHVF is larger, and vent clustering is more prominent. Vent alignment is more characteristic in the LHPVF, where vents seemingly follow the Rába Fault Zone (Plate 1.5).

The distribution of identified volcanic erosion remnants in the BBHVF is represented by contouring vent density on the basis of a rectangular grid with uniform spacing of 2 km and a search radius of 5 km (Figure 1.9, A). On this map, the BBHVF is characterised by one major vent cluster in the geometrical centre of the field and by two additional clusters, one in the east and one in the west, all together forming a more or less east–west-trending alignment (Figure 1.9, A). The highest vent density reaches 20 vents in an area of 80 km² (0.25 vents/km²), centred around a nested



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Figure 1.9. Vent density maps of the Bakony – Balaton Highland Volcanic Field (BBHVF – MARTIN et al. 2003)

The distribution of vents is analysed by the density contours drawn manually on the basis of rectangular grids with the spacing of 2 km and search radius of 5 km on figure A, and with a spacing of 1 km and search radius of 2.5 km on figure B

maar system (Fekete-hegy – MARTIN et al. 2003). This location represents mafic volcanoclastic flow deposits (referred also as hydroclastic flow – NÉMETH and MARTIN 1999b), with large amounts of dm-size lherzolite xenoliths, mantle and/or deep crustal nodules (TÖRÖK and DE VIVO 1995, TÖRÖK et al. 2003), and pyroclastic deposits indicative of high-energy phreatomagmatic explosive eruptions (MARTIN et al. 2003). Further individual vent clusters are shown on a vent density map on the basis of a 1-km rectangular grid and 2.5 km search radius (Figure 1.9, B), mimicking major known crustal structural zones orientated mainly NE–SW and NW–SE (TARI 1991, BUDAI et al. 1999, BUDAI and CSILLAG 1999, DUDKO 1999). In general, using larger search radius and larger steps on grid, it is inferred that vent-distribution features are related to deep subsurface features such as the geometry of the melting anomaly (CONNOR 1990). In contrast, smaller search radius and steps on the grid give information on the surface structure of the pre-volcanic system (CONNOR 1990). It has been thus inferred that the Mio-Pliocene volcanism in the BBHVF was related to a characteristic melting anomaly from where the magma intruded into shallow subsurface crustal inhomogeneities, such as fault lines. Along with the vent clustering and alignments the north–south elongation of individual vents is likely to be related to valley pattern and inherited structural elements of the basement rocks (Figure 1.10). Analysis of the present morphology of the central part of BBHVF has revealed that north-south oriented textural pattern exist in this region, either representing palaeo-valleys and/or surface expressions of old structural elements (JORDÁN et al. 2003). In the LHPVF, however, the vents are scattered. It is also noteworthy that major volcanic complexes such as Ság-hegy, Somló, Kab-hegy and Tihany (Plate 1.5) fall on a straight line that has no obvious surface expression in the form of faults or other structural elements (JUGOVICS 1969b, JÁMBOR et al. 1981).

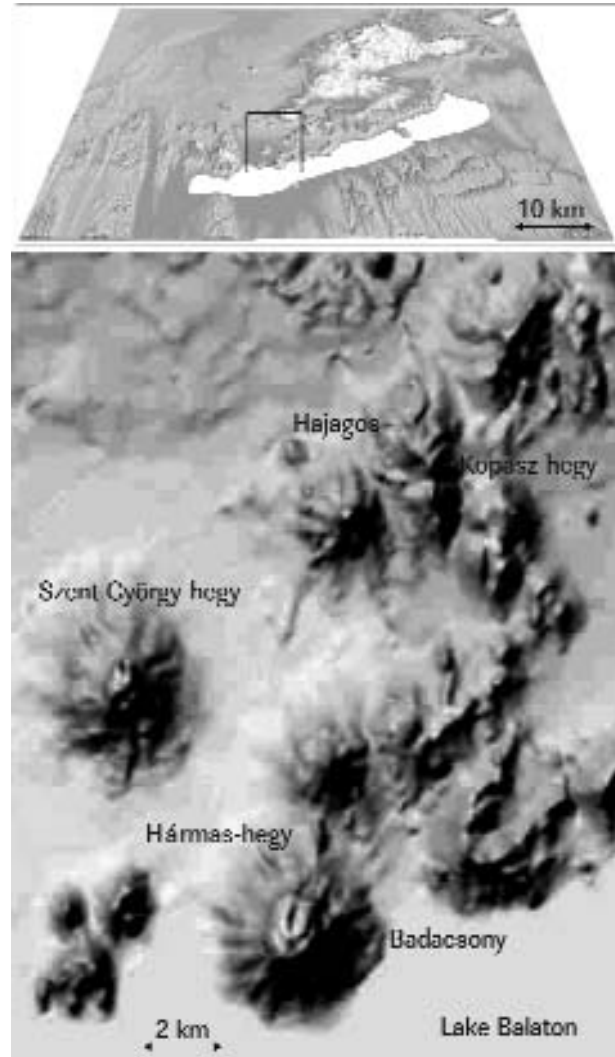


Figure 1.10. North-south elongated volcanic erosion remnants from the BBHVF on digital terrain model
The elongated volcanic remnants are named on the map

Lavaflows, scoria and spatter cones

There is a clear evidence for the presence of preserved fissure-vent systems in the western Pannonian Basin. In a small area around the northern part of the Keszthely Mts (e.g. Sümeprága – Plates 1.1 and 1.5) NE/EW elongated coherent lava rock outcrops occur. The extent of the lava rocks is strongly related to shallow subsurface intrusions such as sill and dyke systems and adjacent small lava flows, plugs. The linear alignment, of the lava rock outcrops suggests a fissure related origin, however, their surface exposures either have been eroded already, or never existed. The age distribution of the different eruptive centres also shows an alignment which probably is related to older structural zones in the basement, probably performed by the fluvial systems during the volcanism. Elongated structures of individual centres, or eruption complexes, especially in the middle part of the BBHVF (Hajagos-hegy, Sátorma-hegy, Fekete-hegy) also suggest longitudinal orientation of individual vents (Figure 1.10). The principal source of the lava flows appears to have been elongated, north to south, north-east to south-west trending former lava lakes. The best example for this is the Hajagos-hegy with a north to south trending lava lake, which overflowed southwards (Kő-hegy – Plate 1.6). The original lava lake was probably 700–1000 m long and 800 m wide. The buttes of Badacsony, Szent György-hegy, Csobánc, Haláp (Plate 1.1) show slightly elongated north–south shape. In the middle part of the BBHVF, there is a large volcanic complex, called Fekete-hegy volcano (Plates 1.1 and 1.5), which consists of smaller eruptive centres with different intercalated lava layers (MARTIN et al. 2002). The lava filled individual centres that also show a NE–SW-trend. The Fekete-hegy is interpreted as a complex lava channel, spatter cone and scoria cone system with several large intercalated lava lakes as well as lava flows fed by scoria cones in the surrounding phreatomagmatic tuff

ring(s – MARTIN et al. 2002). The southernmost outcrops clearly show irregular shapes of the former lava lake and pyroclastic beds of a former tuff ring (MARTIN et al. 2002).

Shield volcanoes are common and give the major sources of lavas in intraplate provinces (WALKER 1993, 2000, CONNOR and CONWAY 2000). Eruptions of large Hawaiian-type volcanic centres are commonly related to fissure-vent systems, but in a small plain-basalt province eruptions are related to central vent systems. However, there are several examples where shield volcanoes developed along basement fissure systems (JOHNSON 1989). In the BBHVF there are two shield volcanic complexes probably associated with a large number of eruption vents (KORPÁS 1983, NÉMETH and MARTIN 1999d). The larger one (Kab-hegy – Plate 1.1) represents the highest topographic point in the Transdanubian Range. Individual lava flows tend to be around 5 to 8 km long and cover around 50 km² in area (JUGOVICS 1971, KORPÁS 1983, KORPÁS and SZALAY MÁRTON 1985). The total thickness of the lava cover reaches several tens of metres (JUGOVICS 1971, KORPÁS 1983, KORPÁS and SZALAY MÁRTON 1985). The lava field around Kab-hegy is a thick accumulation of various lavas that have been recognised already in the year 1934 by VITÁLIS. The lava flow units are often separated by thick palaeosoil layers as well as intensive alteration horizons of the basalt itself, indicating time gaps between effusion of lava flows and suggesting a complex eruptive history of this region (VITÁLIS 1934, VÖRÖS 1962, 1966, 1967). The top of the lava field is inferred to be an eroded scoria cone preserved as a plug. Adjacent to the lava fields of Kab-hegy small Strombolian scoria cone remnants and Hawaiian spatter deposits are common. The other large shield volcanic complex is the Agár-tető south-west of the Kab-hegy with a present elevation of 499 m. There is a small remnant of a scoria cone sitting over the lava plateau of the Agár-tető. The wide range of measured K\Ar age (5.25–2.8 My – BALOGH et al. 1986), the different lava flow units, the slightly different petrographic characteristics of the lava flow(s) and the lava inter-beds on the flank of the topping scoria cone suggest a long-lived volcanic activity, which might be related to stable melt sources over structural weakness zone. Such time sequence is well known from several small to medium size shield volcanoes such as the Rangitoto Island (Auckland Volcanic Field, New Zealand – JOHNSON 1989, ENDBROOKE 2001) or large scoria cone examples from the Eifel (Germany) region (HOUGHTON and SCHMINCKE 1989). Moreover, Rangitoto (New Zealand) has a well-developed capping scoria cone as well as eroded satellite vents on the flank of the main edifice of the shield. The small spatter deposits on the top zone of the Agár-tető represent former summit craters of small (50–100 m) scoria and associated spatter cones. The preserved deposits represent small vent zones of this former explosion centres. Small remnants of lava cone structures are traceable everywhere where large lava lakes preserved. These areas usually are small (few tens of metres) irregularities in the large lava fields. They are inter-bedded with lava, and consist of spatter deposits (Badacsony, Szent György-hegy, Fekete-hegy, Sátorma-hegy – Figure 1.10).



Figure 1.11. Welded lava spatter-rich deposit from Ság-hegy

The magmatic explosive and effusive volcanic activity which produced large volumes of eruptive products as well as the presence of the elevated Mesozoic basement under this volcanic zone suggest that there was no magma-water interaction during the eruptive history, thus this area is inferred to have been already a higher elevated area in the Pliocene. These shield volcanoes in comparison with eastern-Australian examples, are relatively small with less than 1 km³ volume of lava products (7 km³ in eastern-Australia, JOHNSON 1989).

Large spatter and scoria cones (Figure 1.11) are strongly eroded in the BBHVF. They remained only as erosional remnants. Only the summit craters of the Agár-tető, Bondoró and Fűzes-tó (Plate 1.5) are preserved in a recognisable morphology. Strombolian scoria cone remnants are however often preserved only as scoria mounds on top of larger volcanic erosion remnants such as the Boncsos-tető on top of the Fekete-hegy (MARTIN et al. 2002). Highly vesicular scoriaceous deposits often accumulated between lapilli tuffs rich in accidental lithic clasts indicating that eruption styles may have changed especially in the late stage of the eruptions of individual vents according to the available water to sustain magma-water interaction (HOUGHTON and HACKETT 1984, HOUGHTON and SCHMINCKE 1986, HOUGHTON et al. 1999). Scoriaceous deposits are often rich in irregular shaped mud chunks which are preserved between scoriaceous lava spatters often in significant thickness (tens of metres: e.g. Ság-hegy – Plate 1.1), indicating an active quarrying of an unstable volcanic conduit and/or presence of

water-rich slurry in the vent zones during more magmatic fragmentation of magma (KOKELAAR 1986, WHITE 1991b, ORT et al. 1998, MCCLINTOCK and WHITE 2000). Scoria cone remnants are usually preserved in western Pannonian Basin as near vent strongly baked, red, slightly bedded sequences with large spindle or highly vesicular fluidal bombs. Welding of scoriaceous lapilli is common (Plate 1.6). Strombolian scoria and spatter deposits are common in relation with maar volcanoes. Such beds often reflect irregularities in the magma/water interaction having clear magmatic and phreatomagmatic fragmentation styles such as it was observed during the eruption of the Ukinrek Maar, Alaska (KIENLE et al. 1980, SELF et al. 1980, ORT et al. 2000). Scoria cones often develop in maar basins such as the La Breña Maar in Mexico (Plate 1.7, A), which is a recent analogy how e.g. the Pula maar (Plate 1.1) may have looked like prior to the water filled its basin. Scoria cones are inferred to have grown in maar basins in the BBHVF such as inferred for Uzsa maar (Plates 1.1 and 1.5). Such scoria cones (e.g. Uzsa) may have collapsed into the maar basin, feeding extensive volcanic debris avalanches and associated debris flows, which tend to accumulate in the maar basin. A remnant of a Strombolian scoria cone in the Fűzes-tó region preserves near vent scoriaceous volcanoclastic breccia with muddy matrix that is inferred to represent remnants of the water saturated slurry in the vent during the Strombolian activity. The uprise of magma at Fűzes-tó is inferred to have involved turbulent jets that did not generate shockwaves as suggested in theoretical considerations (MASTIN 2004).

Pyroclastic cone growth modelling focuses on the role of ballistic (no-drag) ejection that often are referred as Strombolian activity as a result of weak-intensity, strongly intermittent activity observed to be associated with bursting of large gas bubbles extending across much of the vent, and producing ballistic emplacement of clasts larger than 10 cm (e.g. MCGETCHIN et al. 1974, JAUPART and VERGNOLLE 1997, VERGNOLLE and MANGAN 2000). Particles with a size less than 10 cm are normally unable to follow ballistic trajectories instead depositing from eruption clouds with characteristic jet dynamics (e.g. subplinian – e.g. SPARKS et al. 1997). The grain size pattern observed from scoria cone remnants of western Hungary suggests other than the classic ballistic (no-drag) model of cone growth (e.g. subplinian) and indicates not only Strombolian dynamics of the eruptions as it suggested on the basis of experimental studies (e.g. RIEDEL et al. 2003).

No pahoehoe or aa lava formations in the western Pannonian volcanic fields have been preserved. The blocky appearance of the preserved lava flow remnants indicate that they were originally predominantly aa type flows. Direct surface remnants of tumuli, hornitos, pressure ridges, lava tubes, caves or channels are not known from the BBHVF, but several surface irregularities from the Kab-hegy lava field suggest their existence, however, further research needs to constrain this conclusion. On the top of the Fekete-hegy, micro-pahoehoe surfaces on red, rugged lava flows, which are covered by vegetation, are inferred to be the youngest lava flow surfaces in the western Pannonian Basin.

Columnar jointing, that is a product of the progressive cooling of lavas or intrusions (SPRY 1962, DEGRAFF and AYDIN 1987, BUDKEWITSCH and ROBIN 1994, LYLE 2000), is widespread in the coherent lavas from the western Pannonian Region. Usually the simple thin sheet-like lava bodies produce simple, upright joints. Thicker lava bodies have two or multiple-tiered layering with lower, well developed upright joints (colonnade) and irregular, semi or wholly radial small joint systems in the top (entablature – LYLE 2000), among which the best exposed is in the Hajagos (Plate 1.7, B). In thick (~10 m) lava flow remnants in the BBHVF. The joint package reaches several metre thicknesses. Other examples comprise Badacsony and Hegyes-tű. Radiating, rosette-like joints in thick lava flows may represent former individual lava channels or feeder dykes that are especially common in the Sűmegprága shallow subsurface sill and dyke complex (Plate 1.7, C). Rosette-like joints related to lava tubes are present in the upper level of the Hajagos-hegy basalt quarry, and the Badacsony basalt quarry (MARTIN and NÉMETH 2002b).

Hyaloclastite and peperite

Hyaloclastite forms by quench fragmentation of magma in contact with water. It can form when lava flows erupt into water or flow from land into water, or where magma intrudes wet unconsolidated sediments (RITTMANN 1958, 1962, 1973, MCPHIE et al. 1993). Such hyaloclastite deposits were found in several places in the western Pannonian region and are inferred to represent lava flows entering a maar lake such as the Uzsa maar. At Hajagos, there are volcanoclastic breccias from in situ debris flanks that consist of large, strongly chilled, micro-vesicular, black, angular basaltic fragments in micro-crystalline carbonate cemented matrix. The fragments in several places contain fine-grained, brown, silty, muddy fragments in the vesicles. Another locality close to the Hegyes-tű columnar jointed basalt outcrop shows hyaloclastitic volcanoclastic sediment that contains large pillowed lava fragments indicating lava and water interaction in a water-rich vent.

Peperite forms when lava intrudes into wet, unconsolidated sediment. Peperite can be described on the basis of juvenile clast morphology being blocky or fluidal (globular – BUSBY-SPERA and WHITE 1987) but other shapes occur and mixtures of different clast shapes are also found (SKILLING et al. 2002). Magma is dominantly fragmented by quenching, phreatomagmatic explosions, magma-sediment density contrasts, and mechanical stress as a consequence of inflation

or movement of magma or lava (DOYLE 2000, SKILLING et al. 2002, ZIMANOWSKI and BÜTTNER 2002, WOHLETZ 2002). According to the observations of BUSBY-SPERA and WHITE (1987) blocky peperite forms usually during interaction of coarse grained, water saturated sediment and melt. In contrast globular peperite forms when melt intrudes into fine grained sediment (BUSBY-SPERA and WHITE 1987). This tight relationship between host sediment grain size distribution and the peperite type seems not always to be the case (DOYLE 2000, DADD and VAN WAGONER 2002, HOOTEN and ORT 2002, MARTIN 2002). Variations are clearly demonstrated from the western Pannonian Basin (MARTIN and NÉMETH 2000). Peperites are common in the western part of the BBHVF and on the LHPVF. Blocky peperite identified from the Hajagos-hegy (Plate 1.1) basalt quarry (lower level – MARTIN and NÉMETH 2000) is related to the feeder dykes that invaded fine grained host sediment and lava lake margin that developed in the volcanic depression caused by the phreatomagmatic eruptions (MARTIN and NÉMETH 2000). In near vent position of the lower part of the lava flow at Hajagos there is a lava foot breccia, where small, pillowed lava fragments mix with yellowish sandstone fragments. The peperite formed when a lava flow entered water-saturated sediment, probably in a swampy area. In several localities large (2–3 m wide, 3–4 m high) peperitic bubble structures formed in the lava flow units. Inside the bubbles highly vesicular, closely packed pillowed lava formed in sandy matrix. The lava flows are inferred to have formed as tumuli by the vaporisation of the swamp water, during the flow movement. This kind of tumuli structure is common in the lower level of the Badacsony (Plate 1.1) lava flows and in the Hajagos-hegy southern region. Peperites are also described from Balatonboglár, Temető-domb (Plate 1.1 – NÉMETH et al. 1999b). Large black, red scoria fragments in a fluidised sandy matrix represent magma and water-saturated sediment interaction in near vent position. Peperitic lava lake margins have been described from the Ság-hegy, where a lava lake fed small sills (Plate 1.7, E) that intruded into the wet irregular shape tuff ring (MARTIN and NÉMETH 2004c). A crater lake of a small tuff ring at Kis-Somlyó has been flooded by a basanite lava flow and developed pillow lava, as well as delicate mixture of basanite melt and silt forming peperite (MARTIN and NÉMETH 2004b).

Phreatic and phreatomagmatic eruptive centres

Explosive volcanic eruption could be a result of elevated heat of pore water due to dyke (phreatic explosion) or cryptodome emplacement or direct contact between hot magma and various aquifers or standing water body (phreatomagmatic explosion – CAS and WRIGHT 1988).

Phreatic explosions are steam generated and do not involve the ejection of fresh magma (CAS and WRIGHT 1988). Phreatic explosions resulting in steep, deep and often wide craters such as formed by the USU 2000 (Hokkaido) eruption due to the heat of emplaced shallow subsurface magma body (OHBA et al. 2002). Clear phreatic explosion centres and their products are not described yet from the western Pannonian Basin, however, a large amount of the pyroclastic beds associated with volcanic remnants of the region is commonly very rich (90 vol.%) in accidental lithic rock fragments derived from various pre-volcanic rock units (Plate 1.8, A). This very high percentage of non-volcanic country rock fragments in the accumulated deposits around vents led to the conclusion that volcanism in the western Pannonian region might be synsedimentary with the siliciclastic sedimentation in the Pannonian Lake (JUGOVICS 1937, KULCSÁR and GUCYZNÉ SOMOGYI 1962, JÁMBOR and SOLTÍ 1975, JÁMBOR et al. 1981).

Phreatomagmatic activity

Phreatomagmatic explosions involve dynamic explosive interaction between magma and external water source such as groundwater, or a surface body of water such as a lake or the sea, and the ejection of a significant juvenile magmatic component (WOHLETZ 1983, FISHER and SCHMINCKE 1984, WOHLETZ and MCQUEEN 1984, WOHLETZ 1986, CAS and WRIGHT 1988, ZIMANOWSKI et al. 1991, WHITE and HOUGHTON 2000). The term “phreatomagmatic eruption” is predominantly used for terrestrial magma-water interaction driven processes. Eruptions initiated in standing water bodies are often referred to as Surtseyan style eruptions (KOKELAAR 1983, KOKELAAR and DURANT 1983, KOKELAAR 1986, WHITE and HOUGHTON 2000). They are characterised by eruption cloud that breach the water surface in advance of the eruption (emergent volcanism). In case the eruption is fully subaqueous with no subsequent water surface breach, the magma water interaction lead to explosive eruption which fed subaqueous pyroclastic density currents mantling the sea/lake floor and move radially, leading to an accumulation of a pyroclastic mound (WHITE 1996a, 2000, 2001, WHITE and HOUGHTON 2000, MARTIN and WHITE 2001). Volcanic edifices resulted from both of these volcanic eruptions (emergent and fully subaqueous) often have a similar basal setting, exhibiting pyroclastic rocks rich in juvenile chilled fragments and only a few accidental lithics or minerals derived from the synsedimentary non-volcanic units (e.g. sea floor sediments – WHITE 1996a, BELOUSOV and BELOUSOVA 2001, MARTIN and WHITE 2001). In case of emergence, the vent temporally could be blocked from the open water, and more or less subaerial conditions may be reached, resulting in similar eruption styles than in other terrestrial

phreatomagmatic explosions or even lava fountaining as it has been reported from Surtsey (KOKELAAR 1983, HOUGHTON and NAIRN 1991). During emergent volcanism, tuff cones often build up to levels above the water surface, which consists of steeply dipping juvenile clast-rich pyroclastic units (SOHN and CHOUGH 1992, 1993). In case of magma-water interaction in terrestrial setting, the volcanic landform and the erupted products largely depend on the depth of explosion locus and the type of bed rocks (hard rock versus soft rock – LORENZ 1986, 2002, 2003). In case of an unstable volcanic conduit wall, the recycling of erupted pyroclasts as well as the sediment laden slurry in the vent could play an important role in the course of the eruption and determine the type of deposit that may accumulate around the vent (HOUGHTON and SMITH 1993, WHITE 1996b).

The majority of the eruptive centres of the volcanic fields in the western Pannonian Basin have a phreatomagmatic history. Subaerial phreatomagmatic explosions usually produce low rimmed tuff rings (WATERS and FISHER 1970, HEIKEN 1971, KELLER 1973, WOHLTZ and SHERIDAN 1983, SOHN and CHOUGH 1989, GODCHAUX et al. 1992, ALLEN et al. 1996, MASTROLORENZO 1994, SOHN 1996, VESPERMANN and SCHMINCKE 2000). The water source of the phreatomagmatic centres in the Western Pannonian region is predominantly a combination of ground water and some water from shallow lakes and/or fluvial systems (NÉMETH and MARTIN 1999c, NÉMETH et al. 1999b, 2001, MARTIN et al. 2003). The identification of magma-water interaction is based on the common presence of

1. chilled juvenile lithic clasts,
2. the angular, blocky, moderately vesicular volcanic glass shards and the
3. variable amount of fragments from the disrupted pre-volcanic rock units.

The blocky shape of the volcanic glass shards and a low vesicularity attest to the sudden chilling, as well as the high confining pressure during the magma-water interaction (NÉMETH and MARTIN 1999a) as it has been concluded from other similar volcanic fields (HEIKEN 1972, 1974, HEIKEN and WOHLTZ 1986, ZIMANOWSKI 1986, 1997, 1995, 1998, DELLINO and LAVOLPE 1995, BÜTTNER and ZIMANOWSKI 1998, DELLINO 2000, DELLINO et al. 2001, DELLINO and LIOTINO 2002). Generally the phreatomagmatic products from the western Pannonian Basin are rich in chilled semi-angular juvenile volcanic lithic fragments and fresh to moderately palagonitized volcanic glass shards typical for fragmentation driven by magma/water interaction (e.g. FRÖCHLICH et al. 1993, BÜTTNER et al. 1999, 2002 – Plate 1.3). The sideromelane glass shards are light brown to yellow (Plate 1.3). The glass shards are slightly to strongly palagonitized, having a palagonite rim and/or palagonite bands along microfractures (Plate 1.8). The glass shards commonly contain a few elongated microvesicles, which are filled with secondary minerals, especially if the glass shard itself shows advanced stage of palagonitization (Plate 1.3 and 1.8). The vesicles are slightly stretched (Plate 1.3 and 1.8). The phreatomagmatic rock units are characteristically rich in mud, silt and sand derived from the immediate pre-volcanic Neogene shallow marine to fluvio-lacustrine sedimentary sequences (NÉMETH and CSILLAG 1999, NÉMETH and MARTIN 1999c). Two major types of pyroclastic rock could be defined,

1. juvenile clast and siliciclastic sediment grain (from Neogene units) rich and
2. which are more enriched in accidental lithic clasts from deep seated pre-volcanic rock units (NÉMETH and MARTIN 1999c, NÉMETH et al. 2001).

Pyroclastic rocks from the LHPVF and the western part of the BBHVF are like the first type. In contrast pyroclastic rocks from vent remnants in the eastern BBHVF are more like the second type. This relationship is inferred to be related with the explosion locus, and the sub-surface architecture of the different regions, which is likely to determine the palaeo-hydrogeology of the regions (MARTIN and NÉMETH 2003). The depth of the phreatomagmatic fragmentation at the volcanoes of the western Pannonian Basin varies greatly according to the accidental lithic clast population of the phreatomagmatic pyroclastic rocks (NÉMETH and MARTIN 1999c). In the central part of the BBHVF a few locations preserve pyroclastic rocks, which are rich in accidental lithic fragments from every known lithology from the upper crust, and therefore the fragmentation level could have been in a range of kilometers from the syn-volcanic palaeosurface. Because aquifer pore pressure increases with depth, many researchers have assumed that once pressure exceeds water's critical pressure, magma/water interaction ceases to be explosive because steam is not formed (e.g. CAS and WRIGHT 1988). This assumption is suggested to be incorrect according to the latest results of theoretical experimental work, which show the potential for dynamic interaction at confining pressures up to and perhaps exceeding 100 MPa (WOHLTZ 2004). These results suggest that interaction can initiate at maximum depth >4 km, reaching depth perhaps exceeding 10 km as suggested by WOHLTZ (2004). Indeed, there is evidence of fluid (H₂O) inclusion study on volcanic glass from pyroclastic rocks associated with phreatomagmatic successions of the BBHVF (e.g. Szigliget), that their entrapment may have occurred at around a few km (~10 km) depth. This fluids could have been responsible for the magma/water interaction (e.g. BALI et al. 2002, TÖRÖK et al. 2003).

The eruptions inferred to produce deeply excavated maar/diatreme structures occur in areas with commonly karst water bearing, fracture controlled aquifers and which are covered by relatively thin Neogene soft rocks (NÉMETH et al. 2001, MARTIN and NÉMETH 2003). This scenario is equivalent to LORENZ (2002) "hard rock" model, where the conduit wall is able to be stable during the eruption. With the substantial water supply from the fracture controlled aquifer (e.g. karst water) the eruption could continue for a longer time, however, the eruptive products may only accumulate near-

by the vent (NÉMETH et al. 2001). These deep maar basins later functioned as sedimentary traps and give way to accumulation of thick maar lake deposits (e.g. alginite) and intercalated debris flow and turbidity current deposits (NÉMETH 2001) similarly to other deep maars (WHITE 1992, DROHMANN and NEGENDANK 1993, FISHER et al. 2000, VASS et al. 2000, BULLWINKEL and RIEGEL 2001, PIRRUNG et al. 2003).

During phreatomagmatic eruptions not all of the volume of the magma can be simultaneously in interaction with water, therefore parts of the eruption column can be phreatomagmatic and other parts can purely be magmatic as it has been observed and documented from the Ukinrek maar eruption (SELF et al. 1980, BÜCHEL and LORENZ 1993, ORT et al. 2000). Similar involvement of different types of fragmentation history in the same vent zone is well known from Surtseyan eruptions and the study of the deposits of this type of eruptions revealed a complex intercalation between deposits derived from strikingly different fragmentation histories (THORARINSSON et al. 1964, THORARINSSON 1965, 1967, LORENZ 1974, KOKELAAR 1983, WHITE and HOUGHTON 2000, COLE et al. 2001). Moreover, in case of nearby active vents (maybe in the same crater), intercalation of deposits from magmatic and phreatomagmatic fragmentation history are reported to be very common, such as reported from the White Island (New Zealand – HOUGHTON and NAIRN 1991), Eifel (Germany – HOUGHTON and SCHMINCKE 1986), Crater Hill (New Zealand – HOUGHTON et al. 1996) or Ohakune Crater (New Zealand – HOUGHTON and HACKETT 1984). Pyroclastic deposits with Strombolian magmatic and phreatomagmatic fragmentation histories in intercalated settings have been documented from the Tihany Peninsula and are inferred to be the result of the instability of magma/water ratio during the late stage of the eruption of the Tihany Maar Volcanic Complex (NÉMETH et al. 2001).

Maars and tuff rings

The common high amount of accidental lithics in the phreatomagmatic pyroclastic rocks from the western Pannonian Basin, the systematic gravity and geomagnetic anomaly associated with the location of such pyroclastic rock units suggest the presence of low density clastic material filled “holes” in the pre-volcanic rocks such as excavated maar/diatreme structures. In general, maar volcanoes (*sensu lato*) are low volcanic cones with bowl shaped craters that are wide relative to rim height (FISHER and SCHMINCKE 1984, LORENZ 1986). They range from craters cut into country rock below ground level (*maar sensu stricto*), to craters with low rims composed of phreatic, phreatomagmatic, and magmatic debris (tuff ring – FISHER and SCHMINCKE 1984). During the eruptive process the explosion locus migrates down, (LORENZ 1973, FISHER and SCHMINCKE 1984, LORENZ 1986) excavating deeper and deeper seated accidental lithics in time and resulting in an enrichment of such deeper fragments upwards in the stratigraphic tephra column (LORENZ 1986). This model has been tested in several locations worldwide, however, there are field evidences that in special cases magmatic fragmentation history of the magma may predate the phreatomagmatic fragmentation such as it has been documented from the Pinacate in Mexico (GUTMANN 2002). Systematic sampling and testing to determine the explosion locus migration has not been performed yet from the Neogene volcanics of the western Pannonian Basin and it is a subject of current research. However, in most of the studied places from the western Pannonian region, an abundance of shallow seated accidental lithics in the initial phreatomagmatic pyroclastic units, are results of vent opening eruptions, which has been documented from many places (NÉMETH and CSILLAG 1999, NÉMETH et al. 1999a, 2001, MARTIN et al. 2002, 2003). In spite of this initial enrichment of the pyroclastic successions in clast derived from the uppermost immediate pre-volcanic units, the majority of the volcanic successions do not show systematic clast population trends.

In the pyroclastic successions of the Neogene western Pannonian Basin base surge and fall out beds form the basal units in most of the places. A general trend shows that most of the surge beds of the eruptive centres are wet surge beds, however, subsequent accumulation of dry surges are characteristic. The textural characteristics that are more prominent in wet surge deposits are more common in locations in the eastern part of the BBHVF such as the Tihany Peninsula and the Kál Basin (north – NÉMETH et al. 2001). In the Tihany Peninsula (Plate 1.1), the pyroclastic succession has a thick (tens of metres) accumulation of wet surge beds that are rich in large (dm-scale), deeply excavated country rocks (NÉMETH et al. 2001). The formation of the phreatomagmatic volcanoes at Tihany is inferred to be related with magma and karst water interaction from fracture controlled aquifers combined with water from the porous media aquifer on the near surface region (NÉMETH et al. 2001). The products of this kind of eruptions, which had two very different type of water source to fuel the magma-water interaction, are highly “indurated” beds of pyroclastic breccias interbedded with tuffs and lapilli tuffs originated from wet base surges and phreatomagmatic fall out, combined with ballistic bomb and block shower during major conduit collapsing phases (NÉMETH et al. 2001). The deposits of this type of eruptions are thick and carry evidences of high water/magma ratio during the eruption and accumulation of deposits from high concentration and water charged pyroclastic mass flows (NÉMETH et al. 2001). This type of phreatomagmatic eruption termed as Tihany-type maar volcanic eruption, highlights the speciality of such events due to the interaction between two different water sources during the eruption (NÉMETH et al. 2001). Similar type of eruptions likely occurred in the centre part of the BBHVF, where fracture

filling water bearing units are covered by Neogene soft rocks that have likely been water saturated during the volcanism (MARTIN et al. 2002).

Dry surge beds in pyroclastic successions and evidence of the major role in controlling the magma-water interaction by the porous media aquifer are more common in the western part of the BBHVF and in few sites from the LHPVF. In these sites the pyroclastic beds show less indurated characteristics, baking of silt and mud as well as scoria are more prominent, and the relative amount of deep seated Mesozoic and Palaeozoic fragments is significantly less (Plate 2.8, D). There are strongly eroded remnants of this kind of centres from Szigliget, Balatonboglár, probably Szent György-hegy and Csobánc (Plate 1.5).

Types of phreatomagmatic volcanoes

The wide range of types of magma-water interaction led to the formation of different types of volcanic edifices, including maars, tuff rings and scoria cones with a great variety of depositional features as preserved in their pyroclastic units in the western Pannonian Basin (MARTIN et al. 2003). Different types of volcanoes were identified on the basis of volcanic textures, shape and composition of their pyroclasts, sedimentary structures, and the presence of pillow basalts and peperites. Base surge and fallout tephra were deposited around maars and tuff rings by phreatomagmatic explosions, caused by interactions between water-saturated sediments and alkali basalt magma locally carrying peridotite and pyroxenite xenoliths as well as pyroxene megacrysts, which are well exposed in **nested maar complexes** (Figure 1.12) such as Tihany (NÉMETH et al. 2001) and Fekete-hegy (MARTIN et al. 2002). Fekete-hegy is volumetrically one of the largest in the BBHVF (MARTIN et al. 2002), it is a representative example demonstrating the architecture of complex multivent systems with chains and/or groups of predominantly phreatomagmatic vents. It forms a lava-capped butte in the central part of the BBHVF with basaltic lava flows overlying ~50 m of pyroclastic unit (MARTIN et al. 2002).

Complex multiple volcanoes (Figure 1.12 – MARTIN et al. 2003) with solidified large volume lava lakes are characteristic volcanic remnants especially in the western part of the BBHVF, such as Badacsony (Plate 1.5), one of the largest lava-capped buttes in the BBHVF (Figure 1.13). Thick (>50 m), black, strongly chilled, aphanitic basanitic lava overlies a coarse-grained, unsorted yellow lapilli tuff (MARTIN and NÉMETH 2002b). The lapilli tuff consists of finely dispersed accidental lithic fragments of quartz or quartzofeldspathic sandstone, and blocky, weakly to highly vesicular microlite-poor sideromelane (tephrite, phonotephrite), indicative of phreatomagmatic origin, near-surface vesiculation and possible excavation of pre-volcanic country rocks (MARTIN and NÉMETH 2002b). In addition, xenocrysts of olivine and pyroxene may reach 5 vol.%. The lava lake at Badacsony exhibits irregular lower contacts with the pyroclastic units, often displaying peperite structures (MARTIN and NÉMETH 2002b). The peperite encloses highly vesicular scoriaceous lava spatter clasts, with vesicles filled by clay, calcite or quartzofeldspathic assemblage suggesting rejuvenation or longevity of volcanic vents at the same site (MARTIN and NÉMETH 2002b).

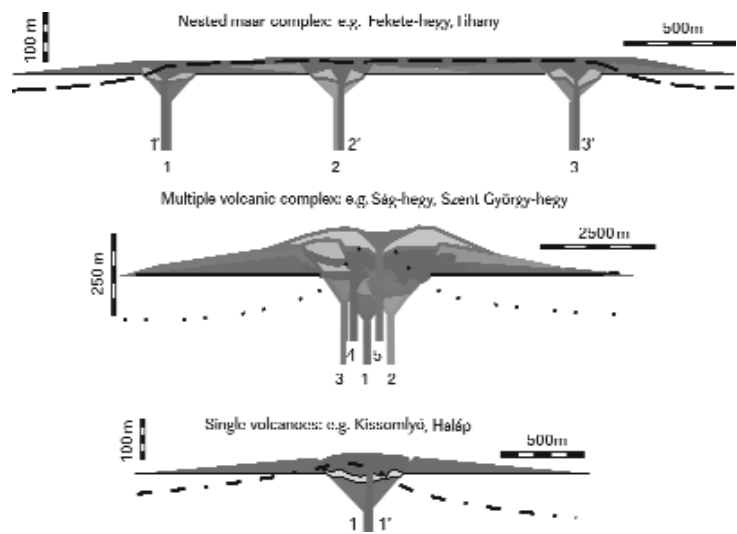


Figure 1.12. Volcanic types have been identified from the western Pannonian Basin, according to the preserved type of pyroclastic rocks, the relative ratios of juvenile versus accidental lithic clasts, the 3D architecture of the preserved volcanoes in relevance to the reconstructed craters, and the amount of effusive products associated with such volcanoes. Numbers represent time sequence of eruptions. Dashed lines show present surface



Figure 1.13. Panoramic view to Badacsony from north



Figure 1.14. Small diatreme remnant of the Kereki-domb in the central part of the Kál Basin

Single phreatomagmatic volcanoes (Figure 1.12 — MARTIN et al. 2003) are also widespread, such as Kis-Somlyó, (MARTIN and NÉMETH 2002a, 2004b) Kereki-domb (Figure 1.14) or Vár-hegy of Zánka (NÉMETH et al. 2003a). They consist of moderately to strongly eroded pyroclastic mounds, forming small hills and exposing phreatomagmatic lapilli tuff beds, often in chaotic setting, which are commonly covered by lava flows. The presence of chilled, angular, moderately vesicular sideromelane fragments and the predominantly Neogene sediment-derived accidental lithic clast population in the exposed pyroclastic rocks allow to infer that these volcanic remnants represent near vent to vent-fill pyroclastic units of former phreatomagmatic volcanoes, such as maars surrounded by tuff rings, which were topped by lava flows in the last stage of volcanic activity.

Maar crater-fill sediments, Gilbert-type deltas

In the BBHVF there are eroded remnants of maar crater fill volcanoclastic deposits (NÉMETH 2001). Commonly they represent the higher stratigraphic position in the phreatomagmatic eruptive centres. They are steeply bedded volcanoclastic units forming a radial dip pattern around a former crater (NÉMETH 2001). Their volcanoclastic successions are commonly rich in scoriaceous lapilli and broken pyrogenic minerals and/or xenocrysts. These high-level deposits that have been identified from the Tihany Peninsula are steeply dipping (about 30-35°) beds of reworked tuff and lapilli tuff on the former maar crater edge and interpreted to be erosional remnants of Gilbert-type of deltaic rim deposits (NÉMETH 2001). The dip of the beds mostly shows the original slope of the former maar craters, where the unconsolidated tephra were mobilised and moved down into the maar crater basin. Similar delta sequences have been identified from well exposed settings from the Hopi Buttes, (WHITE 1989, 1990, 1991b, 1992) where such deposits occur in dry maar settings after disappearance of water and moderate erosion. Similarly, steeply inward dipping pyroclastic units on the crater floor of the Crater Elegante maar (Mexico) forming ramp like structures have been interpreted to be result of delta building into the former maar lake, which is exposed today, due to the disappearance of the lake (GUTMANN 1976). The bedding structures of these sequences at Tihany are inferred to be the result of grain flow and turbulent sediment gravity flows on the steep inner slopes of the maar craters (NÉMETH 2001). Two major lithofacies association have been identified,

1. A coarse-grained, 0.5 to 1 m thick, juvenile, scoriaceous lapilli-rich lithofacies association with inverse to normal graded beds. The lapilli are rounded, black, tachylitic glass with small amount of accidental lithics. There is commonly a relatively high amount (5 vol.%) of large broken crystals of pyroxene, olivine, or amphibole with lapillus grain size. The grains in several places are algae-coated, spatic calcite cemented. Between the large grains there are micritic calcite, and occasionally fine grained muddy sediment (altered glass and/or sediment).

2. A fine grained, cross bedded, channelized tuff lithofacies association interbedded with the coarse grained units. This lithofacies association varies in thickness and in several places represents just a few cm thick unit or is even missing.

At Tihany, the large proportion of scoriaceous lapilli in these units indicates that the source region of the delta must have consisted of eroded scoria cones, or scoria-rich pyroclastic units topping the basal phreatomagmatic successions (NÉMETH 2001). It is therefore inferred that the deltas were fed either by small streams (either run off or creeks from the elevated hills of former Bakony Mts) or by passive collapse of such scoria lapilli rich tephra blocks into the maar lakes of Tihany (NÉMETH 2001). In other part of the western Pannonian Basin, pyroclastic rocks with textures characteristic for reworking indicate that destructive events into maar crater lakes may have been important events, and the resulting pyroclastic rock units could be identified.

Maar lake carbonates

In several areas widespread carbonate sedimentation is inferred to have followed the maar volcanism and to have formed sedimentary basins and trapped reworked tephra from the former crater rims (NÉMETH and MARTIN 1999c). At the Tihany Peninsula at least 15 m thick fresh water carbonate unit is preserved capping the pyroclastic and crater lake successions. Fresh water, carbonate-rich interbeds are also known from Pula and from in situ debris from Balatonboglár and Fekete-hegy (Plate 1.1). At the Tihany Peninsula the carbonate succession contains a high amount of soft sediment deformation structures that are located nearly vertical pipe-like structures inferred to be hot spring pipes. Therefore, these deformations are inferred to be related to hot spring activity and/or earthquakes caused by nearby explosive volcanism. From the thickness of 0.2–0.7 mm of single lamina built sequence with 15 m of total thickness at Tihany, a quite lacustrine sedimentation of 50 000 years has been calculated. This long term undisturbed period in the lake life suggest that the general relief of the area was smooth shortly after the erosion of scoria cones and phreatomagmatic rim deposits.

Today, the carbonate sequences, especially in Tihany case, are in the highest elevated areas. They must represent the former lake bottom thus they are useful for calculating local erosion rates.

Recent studies of seismic profiles through the Lake Balaton, east of the Tihany Peninsula (Figure 1.15) revealed hard surfaces, which may be correlates with the fresh water carbonate units topping the pyroclastic succession of Tihany (SACCHI et al. 1999, SACCHI and HORVÁTH 2002). These units have been interpreted as silicified travertine mounds developed at warm/hot springs and correlated with the PAN2 regional unconformity surface representing a maximum flooding event (9 My) of the Lake Pannon as a result of significant base level lowering as well as the volcanism in the region (SACCHI and HORVÁTH 2002). From a volcanological point of view, these travertine deposits clearly overly unconformably the pyroclastic successions of Tihany (NÉMETH et al. 2001) that have been dated to be about 8 My in age (BALOGH and NÉMETH 2004). These travertines at Tihany are seemingly correlated with the mound structures identified on the seismic profiles (SACCHI et al. 1999). There is a disagreement between timing of events that suggests that the origin of these rocks and their relationship with the volcanism and the general stratigraphy is far from resolved. Today these travertine bed remnants can be traced in a uniform elevation and cover the immediate Neogene siliclastic units in the southern part of the peninsula, indicating that if they have been associated with the maar basins of Tihany, those basins must have been open towards the south (NÉMETH et al. 1999a) and probably have been part of a larger standing water body system (Figure 1.16). Such cases are described from maar fields near sea level, or large lakes (HAYWARD et al. 2002).

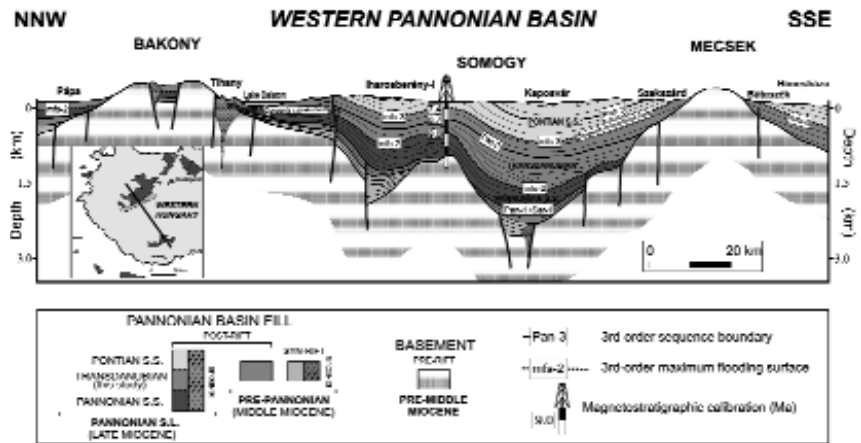


Figure 1.15. Correlation of units identified by seismic sections through the Lake Balaton (SACCHI et al. 1999, SACCHI and HORVÁTH 2002)

The stratigraphic unit between maximum flooding surfaces mfs-2 and mfs-3 (ca. 9.0–7.4 My) represent the newly introduced stage called Transdanubian (SACCHI and HORVÁTH 2002). The new K/Ar dating of the Tihany Maar Volcanic Complex give ~ 8 My for the eruption of the maars at Tihany, which correlates well with the regional stratigraphic situation of the Neogene sediments nearby (BALOGH and NÉMETH 2004). Figure used with permission of the authors of original figure

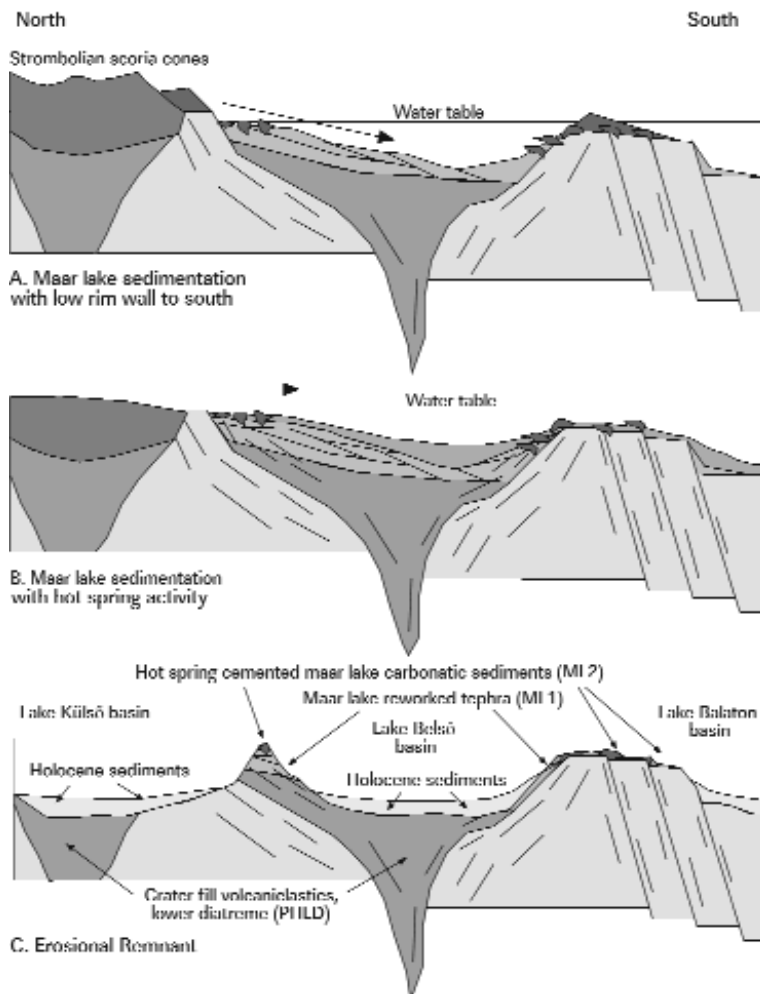


Figure 1.16. Model of the evolution of the Tihany Maar Volcanic Complex, with open maar basins, which may have been connected with normal lacustrine basins nearby (NÉMETH et al. 1999a)

General features of the western Pannonian Basin

The Neogene alkaline basaltic volcanic erosional remnants of the western Pannonian Basin are exposed from former subsurface to surface levels but they are commonly covered by the Quaternary erosional talus flanks. 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 most strongly eroded

regions are those where no subsequent lava caps sheltered the volcanoclastic sequences. The Balatonboglár, Szigliget, Tihany Peninsula allow the study of the deepest level of the volcanic centres, exposing diatreme facies (Plates 2.1 and 2.5). Probably the eruptive centres of Balatonboglár (Boglár Volcano), Kereki-domb, Vár-hegy of Zánka, Hármashegy and Véndek-hegy (Plates 2.1 and 2.5) represent the deepest exposed level of the phreatomagmatic eruptive centres (NÉMETH and MARTIN 1999c, NÉMETH et al. 2003a) and are inferred to be exposed zones of lower diatremes (terminology after WHITE 1991b). Apart from this deep level of exposures, there are no exposed irregular shapes, fragmented wall rock rich dykes, like those are widely reported from other monogenetic maar-diatreme volcanic fields as e.g. Hopi Buttes or southern Africa (WHITE 1991a, b, KURSZAUKIS and LORENZ 1997, LORENZ and KURSZAUKIS 1997, LORENZ 2000). Such levels of exposures and preserved outcrops are more common in the northern part of the Pannonian Basin, in southern Slovakia and northern Hungary (KONEČNÝ et al. 1999a, KONEČNÝ and LEXA 2000). In the BBHVF, the Tóti-hegy and Hegyesd are the good examples where such relationship between feeder dyke and host diatreme filling pyroclastic rocks may exist, however, their contact is not exposed (Plates 2.1 and 2.5). The best example for individual plugs as an exposed sub-volcanic feeder dyke is Hegyes-tű 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 (Plates 2.1 and 2.5).

Upper diatremes (WHITE 1991b) 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 volcanic edifice could be eliminated, and in the eroded phreatomagmatic volcanic field the identification of such remnants should be dealt with precaution to establish the syn-volcanic palaeo-surface, to estimate the erosion. Most of the BBHVF buttes represent upper diatremes, similarly to the Hopi Buttes (WHITE 1991b) or Western Snake river subaerial volcanic centres (GODCHAUX et al. 1992). Surface volcanic edifices are preserved in areas of low erosion, and include volcanoes produced by both phreatomagmatic and magmatic eruptions. The vents characterized by magmatic explosivity are concentrated in the northern part of the area of the BBHVF (Kab-hegy, Agár-tető, Haláp, Hegyesd). The preserved maar diameters of the western Pannonian region ranges from few hundreds of metres 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 connected large basins (MARTIN et al. 2002). 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 et al. 1970, HEIKEN 1971, LORENZ 1973, SCHMINCKE et al. 1983, FISHER and SCHMINCKE 1984, LORENZ 1986, CAS and WRIGHT 1988). The maar vents from the western Pannonian region are reconstructed as hybrids of phreatomagmatic and magmatic volcanic edifices, formed by initial maar or tuff ring forming events. 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 of the phreatomagmatic volcanoes similarly to several examples from Eifel (HOUGHTON and SCHMINCKE 1986, 1989) or from Mexico (ARANDA-GOMEZ et al. 1992). 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 – Plate 1.1).

Proximal base surge beds commonly contain abundant accidental lithics. In the eastern side (Tihany maar volcanic complex) the major accidental fragments are permian red sandstone, silurian schist (e.g. Lovas Schist Formation) mesozoic carbonates (dolomites, marls, limestones), and pannonian sandstone. Commonly the large (up to 75 cm in diameter) fragments are silurian schist or permian red sandstone. The matrix of the surge beds contains a high proportion of sand from the Pannonian sandstone beds. In the western side of the BBHVF and in the LHPVF the main accidental lithic fragments are from the Pannonian siliciclastic units. Both the large fragments (up to 25 cm in diameter) and the matrix are rich in sandstone fragments. In smaller proportion (less than 20 vol.% of total accidental lithics), there are schist fragments and small carbonate fragments. In the middle part of the area (Fekete-hegy, Bondoró, Pipa-hegy – Plate 1.1) the Mesozoic carbonates are the major part of the accidental lithics (min. 85 vol.% of total accidental lithics). In distal facies the base surge beds become finer-grained. Clear distal facies of surge beds are visible from the Tihany Peninsula. Characteristic surge features such as sandwaves, dunes, impact sags, U-shaped valleys are common (Tihany Peninsula, Fekete-hegy, Bondoró, Szigliget – Figure 1.2). Fall deposits associated with surge beds are also common (Fekete-hegy).

At the onset of the eruption, magma began to interact with a moderate amount of groundwater in the water-saturated Neogene fluvio-lacustrine sand beds. As the eruptions continued, the craters grew and the phreatomagmatic blasts fractured the deeper (harder, consolidated) rock facies around the downward migrating explosion locus, giving the karst (or any fracture controlled aquifer-stored) water free access to the explosion chamber. The appearance of maar volcanoes and their deposits of western Hungary are strongly dependent on the palaeo-hydrological conditions of the fracture-controlled aquifer, which vary seasonally due to the wide range of water supply from rainfall or spring runoff. Maar volcanoes formed due to phreatomagmatic explosions of mixing magma with water saturated clastic sediments in areas where thick Neogene siliciclastic units build up the immediate pre-volcanic strata. Such volcanoes have often formed late magmatic infill in their maar basins. These vents, named summer vents, represent low water input from the

lower karst level. Unusual maars (Tihany-type maar) had a special combination of water source from both the porous media aquifer and fracture-controlled aquifer, with the latter probably have been the dominant supplier. Such maars developed in areas, where relatively thin Neogene fluvio-lacustrine units rested on the Mesozoic or Palaeozoic fracture-controlled, e.g. karst water-bearing aquifer. These maars most likely were generated during springtime, thus the vents are named spring vents. In the northern part of the volcanic field former scoria cones and shield volcanoes give evidence for a smaller impact of the ground and surface water in control of the volcanic eruptions. Exposed diatreme-filling rocks with sedimentary grains as well as mineral phases that derived from already eroded Neogene shallow marine to fluvio-lacustrine sedimentary units are the evidence that such a sedimentary cover was intact in syn-volcanic time. The general abundance of such clasts in the pyroclastic rocks also indicates the importance of soft rock environment to where phreatomagmatic volcanoes were erupted forming “champagne-glass” shaped maar/diatremes. The presence of intravent peperite, subaqueous dome and/or cryptodome, shallow intrusions as well as hyaloclastite facies in craters indicate that maar/tuff ring volcanoes have been quickly flooded by ground and/or surface water, suggesting that they were erupted close to the level of palaeoground water table.

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 (GODCHAUX et al. 1992), Hopi Buttes, Arizona (WHITE 1989, 1990, 1991b), Saar-Nahe, Germany (LORENZ 1971).

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References

- ALLEN, S.R., BRYNER, V. F., SMITH, I. E. M. and BALLANCE, P. F. 1996: Facies analysis of pyroclastic deposits within basaltic tuff-rings of the Auckland volcanic field, New Zealand. — *New Zealand Journal of Geology and Geophysics* 39, pp. 309–327.
- ANDRUSSOV, N. 1887: Geogische Untersuchungen in der westlichen Hälfte der Halbinsel Kertsch. — *Bull. D. Société d. natur. D. I. Nouv. Russie* 2, 69–147
- ARANDA-GOMEZ, J. J., LUHR, J. F. and PIER, J. G. 1992: The La-Breña-El-Jaguey-Maar Complex, Durango, Mexico .1. Geological evolution. — *Bulletin of Volcanology* 54 (5), pp. 393–404.
- BADA, G. and HORVÁTH, F. 2001: On the structure and tectonic evolution of the Pannonian basin and surrounding orogens. — *Acta Geologica Hungarica* 44 (2–3), pp. 301–327.
- BADA, G., HORVÁTH, F., CLOETINGH, S., COBLENTZ, D. D. and TÓTH, T. 2001: Role of topography-induced gravitational stresses in basin inversion: The case study of the Pannonian basin. — *Tectonics* 20 (3), pp. 343–363.
- BALI, E., SZABÓ, Cs., VASELLI, O. and TÖRÖK, K. 2002: Significance of silicate melt pockets in upper mantle xenoliths from the Bakony – Balaton Highland Volcanic Field, Western Hungary. — *Lithos* 61 (1–2), pp. 79–102.
- BALLA, Z. 1980: Neogene volcanites in the geodynamic reconstruction of the Carpathian region. — *Geophysical Transactions = Geofizikai Közlemények = Geofizicheskij Byulletin'* 26, pp. 5–41.
- BALLA, Z. and KÖRÖPÁS, L. 1980: A Börzsöny-hegység vulkáni szerkezete és fejlődéstörténete. [Volcano-tectonics and its evolution in the Börzsöny Mountains]. — *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute, 1978*, pp. 75–101.
- BALLA, Z. 1981: Neogene volcanic rocks and their significance in geodynamic reconstructions in the Carpathian region. — *Geotectonics* 15 (3), pp. 255–265.
- BALOGH, K., JÁMBOR, A., PARTÉNYI, Z., RAVASZNÉ BARANYAI, L. and SOLTI, G. 1982: A dunántúli bazaltok K/Ar radiometrikus kora (K/Ar radiogenic age of Transdanubian basalts). [in Hungarian with English summary] — *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute, 1980*, pp. 243–259.
- BALOGH, K., JÁMBOR, A., PARTÉNYI, Z., RAVASZ-BARANYAI, L., SOLTI, G., NUSSZER, A. and ANONYMOUS 1983: Petrography and K/Ar dating of Tertiary and Quaternary basaltic rocks in Hungary. — *Anuarul Institutului de Geologie si Geofizica = Annuaire de l'Institut de Geologie et de Geophysique* 61, pp. 365–373.
- BALOGH, K., ÁRVA-SÓS, E., PÉCSKAY, Z. and RAVASZ-BARANYAI, L. 1986: K/Ar dating of post-Sarmatian alkali basaltic rocks in Hungary. — *Acta Mineralogica et Petrographica, Szeged* 28, pp. 75–94.
- BALOGH, K., KONEČNÝ, V., ORLICKÝ, O., LEXA, J. and VASS, D. 1996: Method, experiences and results of K-Ar dating of alkali basalt volcanism in central and southern Slovakia (West Carpathians). — *Acta Geologica Hungarica* 39 (Suppl.), pp. 8–11.

- BALOGH, K. and PÉCSKAY, Z. 2001: K/Ar and Ar/Ar geochronological studies in the Pannonian–Carpathians–Dinarides (PANCAR-DI) region. — *Acta Geologica Hungarica* 44 (2–3), pp. 281–301.
- BALOGH, K. and NÉMETH, K. 2004: Evidences of the Neogene small-volume intracontinental volcanism in Western Hungary: K/Ar geochronology of the Tihany Maar Volcanic Complex. — *Geologica Carpathica* [in press]
- BARBERI, F. and VARET, J. 1970: The Erta Ale volcanic range (Danakil Depression, Northern Afar, Ethiopia). — *Bulletin Volcanologique* 34, pp. 848–917.
- BEDNARZ, U. and SCHMINCKE, H.-U. 1990: Evolution of the Quaternary melilite-nephelinite Herchenberg volcano (East Eifel). — *Bulletin of Volcanology* 52, pp. 426–444.
- BELOUSOV, A. and BELOUSOVA, M. 2001: Eruptive process, effects and deposits of the 1996 and the ancient basaltic phreatomagmatic eruptions in Karymskoye lake, Kamchatka, Russia. — In: WHITE, J. D. L. and RIGGS, N. R. (Eds): *Volcaniclastic sedimentation in lacustrine settings*, Blackwell Sciences, Oxford, UK, Special Publication of the International Association of Sedimentologists 30, pp. 35–60.
- BOGAARD, V. D. P. and SCHMINCKE, H. U. 1985: Laacher See tephra — a widespread isochronous Late Quaternary ash layer in central and Northern Europe. — *Geological Society of America Bulletin* 96, pp. 1554–1571.
- BORSY, Z., BALOGH, K., KOZÁK, M. and PÉCSKAY, Z. 1986: Újabb adatok a Tapolcai-medence fejlődéstörténetéhez (Contributions to the evolution of the Tapolca-basin, Hungary) [in Hungarian with English abstract]. — *Acta Geographica Debrecina* 23, pp. 79–104.
- BRAND, B. 2004: Basalt emergent volcanoes and maars, Sinker Butte - Snake River Canyon, Idaho. In: HALLER, K.M. and WOOD, S. H. (Eds): *Geological field trips in southern Idaho, eastern Oregon, and northern Nevada*. Boise State University, Boise, Idaho, pp. 106–116.
- BUDAI, T. and VÖRÖS, A. 1992: Middle Triassic history of the Balaton Highland: extensional tectonics and basin evolution. — *Acta Geologica Hungarica* 35 (3), pp. 237–250.
- BUDAI, T. and HAAS, J. 1997: Triassic sequence stratigraphy of the Balaton Highland, Hungary. — *Acta Geologica Hungarica, Budapest* 40 (3), pp. 307–335.
- BUDAI, T., CSILLAG, G., DUDKO, A. and KOLOSZÁR, L. 1999: *A Balaton-felvidék földtani térképe [Geological map of the Balaton Highland]*. — Magyar Állami Földtani Intézet, Budapest.
- BUDAI, T. and CSILLAG, G. (Editors), 1999: *A Balaton-felvidék földtana: magyarázó a Balaton-felvidék földtani térképéhez, 1:50 000* [Geology of the Balaton Highland: explanatory booklet for the geology map of the Balaton Highland, scale 1:50 000]. — *Occasional Papers of the Geological Institute of Hungary* 197, Geological Institute of Hungary, Budapest, p. 257
- BUDKEWITSCH, P. and ROBIN, P.-Y. 1994: Modelling the evolution of columnar joints. — *Journal of Volcanology and Geothermal Research* 59, pp. 219–239.
- BULLWINKEL, V. and RIEGEL, W. 2001: The laminated lake sediments of the Eckfeld maar (Middle Eocene, Germany): Types of stratification and role of organic matter. — *Facies* 45, pp. 165–176.
- BUSBY-SPERA, C. J. and WHITE, J. D. L. 1987: Variation in peperite textures associated with differing host-sediment properties. — *Bulletin of Volcanology* 49, pp. 765–775.
- BÜCHEL, G. and LORENZ, V. 1982: Zum Alter des Maarvulkanismus der Westeifel. — *Neues Jahrbuch für Geologie, Paleontologie, Mineralogie* 163 (1), pp. 1–22.
- BÜCHEL, G. 1993: Maars of the Westeifel, Germany. — In: NEGENDANK, J. F. W. and ZOLITSCHKA, B. (Eds): *Paleolimnology of European Maar Lakes*, Springer-Verlag, Berlin, Heidelberg, pp. 1–13.
- BÜCHEL, G. and LORENZ, V. 1993: Syn- and post-eruptive mechanism of the Alaskan Ukinrek maars in 1977. — In: NEGENDANK, J. F. W. and ZOLITSCHKA, B. (Eds): *Paleolimnology of European Maar Lakes*, Springer-Verlag, Berlin, Heidelberg, pp. 15–60.
- BÜCHEL, G., NEGENDANK, J. F. W., WUTTKE, M. and VIERECK, L. 2000: Quaternary and Tertiary Eifel maars, Enspel (Westerwald) and Laacher See: Volcanology, sedimentology and hydrogeology. — In: NEUFFER, F. O. and LUTZ, H. (Eds): *Field trip guidebook. International Maar Conference, Daun/Vulkaneifel (Germany) August 17–27, 2000*, Mainzer Naturwissenschaftliches Archiv, Mainz, pp. 85–125.
- BÜTTNER, R. and ZIMANOWSKI, B. 1998: Physics of thermohydraulic explosions. — *Physical Review E* 57(5), pp. 5726–5729.
- BÜTTNER, R., DELLINO, P. and ZIMANOWSKI, B. 1999: Identifying magma-water interaction from the surface features of ash particles. — *Nature* 401(6754), pp. 688–690.
- BÜTTNER, R., DELLINO, P., LA VOLPE, L., LORENZ, V. and ZIMANOWSKI, B. 2002: Thermohydraulic explosions in phreatomagmatic eruptions as evidenced by the comparison between pyroclasts and products from Molten Fuel Coolant Interaction experiments. — *Journal of Geophysical Research-Solid Earth* 107(B11), art. no. 2277.
- CAPACCIONI, B., CORRADOSSI, N., HARANGI, R., HARANGI, SZ., KARÁTON, D., SAROCCHI, D. and VALENTINI, L. 1995: Early Miocene pyroclastic rocks of the Bükkalja Ignimbrite Field (North Hungary) — A preliminary stratigraphic report. — *Acta Vulcanologica* 7 (2), pp. 119–124.
- CAS, R. A. F. and WRIGHT, J. V. 1988: *Volcanic succesions, modern and ancient*. — Chapman & Hall, London, 528 p.
- COLE, P. D., GUEST, J. E., DUNCAN, A. M. and PACHECO, J. M. 2001: Capelinhos 1957–1958, Faial, Azores: deposits formed by an emergent surtseyan eruption. — *Bulletin of Volcanology* 63 (2–3), pp. 204–220.
- CONNOR, C. B. 1990: Cinder cone clustering in the TransMexican Volcanic Belt: Implications for structural and petrologic models. — *Journal of Geophysical Research* 95 (B12), pp. 19,395–19,405.
- CONNOR, C. B. and CONWAY, F. M. 2000: Basaltic volcanic fields. — In: SIGURDSSON, H. (Ed.): *Encyclopedia of Volcanoes*, Academic Press, San Diego, pp. 331–343.
- CONNOR, C. B., STAMATAKOS, J. A., FERRILL, D. A., HILL, B. E., OFOEGBU, G. I., CONWAY, F. M., SAGAR, B. and TRAPP, J. 2000: Geologic factors controlling patterns of small-volume basaltic volcanism: Application to a volcanic hazards assessment at Yucca Mountain, Nevada. — *Journal of Geophysical Research-Solid Earth* 105 (B1), pp. 417–432.
- CONWAY, F. M., FERRILL, D. A., HALL, C. M., MORRIS, A. P., STAMATAKOS, J. A., CONNOR, C. B., HALLIDAY, A. N. and CONNOR, C. B. 1997: Timing of basaltic volcanism along the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona, from Ar-40/Ar-39 dates: Implications for longevity of cinder cone alignments. — *Journal of Geophysical Research-Solid Earth* 102 (B1), pp. 815–824.
- CONWAY, F. M., CONNOR, C. B., HILL, B. E., CONNOR, C. D., MULLANEY, K. and HALL, C. M. 1998: Recurrence rates of basaltic volcanism in SP Cluster, San Francisco volcanic field, Arizona. — *Geology* 26, pp. 655–658.

- CSÁSZÁR, G. and LELKESNÉ-FELVÁRI, G. 1999: Balatoni Fillit Formációcsoport (Balaton Phyllite Formation group). — In: BUDAI, T. and CSILLAG, G. (Eds): *A Balaton-felvidék földtana (Geology of the Balaton Highland)[in Hungarian and English]*, Geological Institute of Hungary, Budapest, pp. 15–21.
- CSERNY, T. and CORRADA, R. 1989: A Balaton medencéje és holocén üledékei részletes geofizikai-földtani vizsgálatának újabb eredményei [New results of the detailed geophysical-geological investigation of Holocen sediments and basins of Lake Balaton]. — *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute 1987 (2)*, pp. 341–347.
- CSERNY, T. 1993: Lake Balaton, Hungary. — In: GIERLOWSKI-KORDESCH, E. and KELTS, K. (Eds): *A Global Geological Record of Lake Basins*, Cambridge University Press, Cambridge, pp. 397–401.
- CSERNY, T. and NAGY-BODOR, E. 2000: Limnogeology of Lake Balaton. — In: GIERLOWSKI-KORDESCH, E. H. and KELTS, K. R. (Eds): *Lake basins through space and time AAPG Studies in Geology 46*, pp. 605–615.
- CSILLAG, G., GONDÁRNÉ, S. and KOLOSZÁR, L. 1994: *A földtani felépítés meghatározó szerepe a Káli-medence felszín alatti vízrendszerében* (The key role of the basement geology in the ground-water systems in the Kali-basin) [in Hungarian], "Water resources and water conservation management of the Carpathian basin" Conference, Eger, Hungary, pp. 136–156.
- CSONTOS, L., NAGYMAROSY, A., HORVÁTH, F. and KOVAČ, M. 1992: Tertiary evolution of the Intra-Carpathian area: a model. — *Tectonophysics 208*, pp. 221–241.
- CSONTOS, L. 1995: Tertiary tectonic evolution of the Intra-Carpathian area; a review. — *Acta Vulcanologica 7 (2)*, pp. 1–13.
- DADD, K. A. and VAN WAGONER, N. A. 2002: Magma composition and viscosity as controls on peperite texture: an example from Passamaquoddy Bay, southeastern Canada. — *Journal of Volcanology and Geothermal Research 114 (1–2)*, pp. 63–80.
- DEGRAFF, J. M. and AYDIN, A. 1987: Surface morphology of columnar joints and its significance to mechanics and direction of joint growth. — *Geological Society of America Bulletin 99*, pp. 605–617.
- DELLINO, P. and LAVOLPE, L. 1995: Fragmentation versus transportation mechanisms in the pyroclastic sequence of Monte-Pilato Rocche-Rosse (Lipari, Italy). — *Journal of Volcanology and Geothermal Research 64 (3–4)*, pp. 211–231.
- DELLINO, P. 2000: Phreatomagmatic deposits: fragmentation, transportation and deposition mechanisms. — *Terra Nostra 2000 (6)*, pp. 99–105.
- DELLINO, P., ISAILA, R., LA VOLPE, L. and ORSI, G. 2001: Statistical analysis of textural data from complex pyroclastic sequences: implications for fragmentation processes of the Agnano-Monte Spina Tephra (4.1 ka), Phlegraean Fields, southern Italy. — *Bulletin of Volcanology 63 (7)*, pp. 443–461.
- DELLINO, P. and LIOTINO, G. 2002: The fractal and multifractal dimension of volcanic ash particles contour: a test study on the utility and volcanological relevance. — *Journal of Volcanology and Geothermal Research 113 (1–2)*, pp. 1–18.
- DOBOSI, G. 1989: Clinopyroxene zoning patterns in the young alkali basalts of Hungary and their petrogenetic significance. — *Contribution to Mineralogy and Petrology 101*, pp. 112–121.
- DOBOSI, G. and FODOR, R. V. 1992: Magma fractionation, replenishment, and mixing as inferred from green-core clinopyroxene in Pliocene basanite, southern Slovakia. — *Lithos 28 (2)*, pp. 133–150.
- DOBOSI, G., SCHULTZ, G. R., KURAT, G. and KRACHER, A. 1991: Pyroxene chemistry and evolution of alkali basaltic rocks from Burgenland and Styria, Austria. — *Mineralogy and Petrology 43 (4)*, pp. 275–292.
- DOBOSI, G., DOWNES, H., MATTEY, D. and EMBEY-ISZTIN, A. 1998: Oxygen isotope ratios of phenocrysts from alkali basalts of the Pannonian Basin; evidence for an O-isotopically homogeneous upper mantle beneath a subduction-influenced area. — *Lithos 42 (3–4)*, pp. 213–223.
- DOBOSI, G., DOWNES, H., EMBEY-ISZTIN, A. and JENNER, G. A. 2003: Origin of megacrysts and pyroxenite xenoliths from the Pliocene alkali basalts of the Pannonian Basin (Hungary). — *Neues Jahrbuch für Mineralogie-Abhandlungen 178 (3)*, pp. 217–237.
- DOGLIONI, C., GUEGUEN, E., HARABAGLIA, P. and MONGELLI, F. 1999: On the origin of west-directed subduction zones and applications to the stern Mediterranean. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen.*, Geological Society of London, London, United Kingdom, Geological Society Special Publication 156, pp. 541–561.
- DOGLIONI, C., INNOCENTI, F. and MARIOTTI, G. 2001: Why Mt Etna? — *Terra Nova 13 (1)*, pp. 25–31.
- DOUBIK, P. and HILL, B. E. 1999: Magmatic and hydromagmatic conduit development during the 1975 Tolbachik Eruption, Kamchatka, with implications for hazards assessment at Yucca Mountain, NV. — *Journal of Volcanology and Geothermal Research 91 (1)*, pp. 43–64.
- DOWNES, H., EMBEYISZTIN, A. and THIRLWALL, M. F. 1992: Petrology and geochemistry of spinel peridotite xenoliths from the western Pannonian Basin (Hungary) — Evidence for an association between enrichment and texture in the upper mantle. — *Contributions to Mineralogy and Petrology 109 (3)*, pp. 340–354.
- DOWNES, H., PANTÓ, G., PÓKA, T., MATTY, D. P. and GREENWOOD, P. B. 1995a: Calc-alkaline volcanics of the Inner Carpathian Arc, northern Hungary; new geochemical and oxygen isotopic results. — *Acta Vulcanologica 7 (2)*, pp. 29–41.
- DOWNES, H., SEGHEDI, I., SZAKÁCS, A., DOBOSI, G., JAMES, D. E., VASELLI, O., RIGBY, I. J., INGRAM, G. A., REX, D. and PÉCSKAY, Z. 1995b: Petrology and geochemistry of late Tertiary/Quaternary mafic alkaline volcanism in Romania. — *Lithos 35 (1–2)*, pp. 65–81.
- DOYLE, M. G. 2000: Clast shape and textural associations in peperite as a guide to hydromagmatic interactions: Upper Permian basaltic and basaltic andesite examples from Kiama, Australia. — *Australian Journal of Earth Sciences 47 (1)*, pp. 167–177.
- DÖVÉNYI, P. and HORVÁTH, F. 1988: A review of temperature, thermal conductivity and heat flow data from the Pannonian basin. — In: ROYDEN, L. H. and HORVÁTH, F. (Eds): *The Pannonian Basin, AAPG Bulletin 45*, pp. 195–233.
- DROHMANN, D. and NEGENDANK, J. F. W. 1993: Turbidites in the sediments of lake Meerfelder maar (Germany) and the explanation of suspension sediments. — In: NEGENDANK, J. F. W. and ZOLITSCHKA, B. (Eds): *Paleolimnology of European Maar Lakes*, Springer-Verlag, Berlin, Heidelberg, Lecture Notes in Earth Sciences 49, pp. 195–208.
- DUDA, A. and SCHMINCKE, H. U. 1978: Quaternary basanites, melillite nephelinites and tephrites from the Laacher See area (Germany). — *Neues Jahrbuch für Mineralogie, Abhandlungen 132 (1)*, pp. 1–33.
- DUDA, A. and SCHMINCKE, H.-U. 1985: Polybaric differentiation of alkali basalt magmas: Evidence from green-core clinopyroxenes (Eifel, FRG). — *Contribution to Mineralogy and Petrology 91*, pp. 340–353.

- DUDKÓ, A. 1999: A Balaton-felvidék szerkezete (Structural geology of the Balaton Highland) [in Hungarian and English]. — In: BUDAI, T. and CSILLAG, G. (Eds): *A Balaton-felvidék földtana (Geology of the Balaton Highland)*, Geological Institute of Hungary, Budapest, pp. 133–145.
- EDBROOKE, S.W. (Compiler) 2001: Geology of the Auckland area— *Institute of Geological and Nuclear Sciences 1:250 000 geological map 3.*, Lower Hutt, New Zealand Institute of Geological and Nuclear Sciences Limited 1 sheet + 74 p.
- EMBEY-ISZTIN, A. 1993: A compilation of new major, trace element and isotope geochemical analyses of the young alkali basalts from the Pannonian Basin. — *Fragmenta Geologica et Petrographica* 16, pp. 5–26.
- EMBEY-ISZTIN, A., DOWNES, H., JAMES, D. E., UPTON, B. G. J., DOBOSI, G., INGRAM, G. A., HARMON, R. S. and SCHARBERT, H. G. 1993: The petrogenesis of Pliocene alkaline volcanic-rocks from the Pannonian Basin, eastern Central-Europe. — *Journal of Petrology* 34 (2), pp. 317–343.
- EMBEY-ISZTIN, A. and KURAT, G. 1997: Young alkali basalt volcanism from the Graz Basin to the Eastern Carpathians. — In: DUDICH, E. and LOBITZER H. (Eds): *Advances in Austrian-Hungarian joint geological research*. MÁFI (Geological Institute of Hungary), pp. 159–175.
- EMBEY-ISZTIN, A., DOBOSI, G., ALTHERR, R. and MEYER, H. P. 2001: Thermal evolution of the lithosphere beneath the western Pannonian Basin; evidence from deep-seated xenoliths. — *Tectonophysics* 331 (3), pp. 285–306.
- FISHER, C., GAUPP, R. and PIRRUNG, M. 2000: Coarse-grained sediments from the Eckfeld Maar (Middle Eocene, Eifel, Germany): Development of sedimentary facies. — *Terra Nostra Terra Nostra* 2000 (6), pp. 118–122.
- FISHER, R. V. and SCHMINCKE, H.-U. 1984: *Pyroclastic Rocks*. — Springer, Heidelberg, 474. pp.
- FLEROV, G. B. and BOGOYAVLENSKAYA, G. Y. 1983: Geology and petrochemistry of the Tolbachik regional zone of cinder cones. — In: FEDOTOV, S. A. and MARKHININ, Y. K. (Eds): *The Great Tolbachik Fissure Eruption*, Cambridge University Press, Cambridge, pp. 96–115.
- FODOR, L., CSONTOS, L., BADA, G., GYÖRFI, I. and BENKOVICS, L. 1999: Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens; a new synthesis of palaeostress data. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen.*, Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 295–334.
- FREUNDT, A. and SCHMINCKE, H. U. 1986: Emplacement of small-volume pyroclastic flows at Laacher Sea (East-Eifel, Germany). — *Bulletin of Volcanology* 48 (1), pp. 39–59.
- FRÖHLICH, G., ZIMANOWSKI, B. and LORENZ, V. 1993: Explosive thermal interactions between molten lava and water. — *Experimental Thermal and Fluid Science* 7(4), 319–332.
- GERNER, P., BADA, G., DÖVÉNYI, P., MUELLER, B., ONCESCU, M. C., CLOETINGH, S. P. L. and HORVÁTH, F. 1999: Recent tectonic stress and crustal deformation in and around the Pannonian Basin; data and models. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen.*, Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 269–294.
- GODCHAUX, M. M., BONNICHSEN, B. and JENKS, M. D. 1992: Types of phreatomagmatic volcanoes in the Western Snake River Plain, Idaho, USA. — *Journal of Volcanology and Geothermal Research* 52 (1–3), pp. 1–25.
- GREELEY, R., 1982. The Snake River Plain, Idaho: Representative of a new category of volcanism. — *Journal of Geophysical Research* 87(B4), pp. 2705–2712.
- GULYÁS, S. 2001: The palaeogeography of Lake Pannon during deposition of the *Congeria rhomboidea* beds. — *Geologica Croatia* 54 (1), pp. 15–26.
- GUTMANN, J. T. 1976: Geology of Crater Elegante, Sonora, Mexico. — *Geological Society of America Bulletin* 87, pp. 1718–1729.
- GUTMANN, J. T. 2002: Strombolian and effusive activity as precursors to phreatomagmatism: eruptive sequence at maars of the Pinacate volcanic field, Sonora, Mexico. — *Journal of Volcanology and Geothermal Research* 113 (1–2), pp. 345–356.
- HAAS, J. and BUDAI, T. 1999: Triassic sequence stratigraphy of the Transdanubian Range (Hungary). — *Geologica Carpathica* 50 (6), pp. 459–475.
- HAAS, J., HÁMOR, G. and KÖRÖSI, L. 1999: Geological setting and tectonic evolution of Hungary. — *Geologica Hungarica series Geologica* 24, pp. 179–196.
- HARANGI, SZ., VASELLI, O., KOVÁCS, R., TONARINI, S., CORADOSSI, N. and FERRARO, D. 1994: Volcanological and magmatological studies on the Neogene basaltic volcanoes of the Southern Little Hungarian Plain, Pannonian Basin (Western Hungary). — *Mineralogica et Petrographica Acta* 37, pp. 183–197.
- HARANGI, SZ., VASELLI, O., TONARINI, S., SZABÓ, CS., HARANGI, R. and CORADOSSI, N. 1995: Petrogenesis of Neogene extension-related alkaline volcanic rocks of the Little Hungarian Plain volcanic field (western Hungary). — *Acta Vulcanologica* 7 (2), pp. 173–187.
- HARMS, E. and SCHMINCKE, H. U. 2000: Volatile composition of the phonolitic Laacher See magma (12,900 yr BP): implications for syn-eruptive degassing of S, F, Cl and H₂O. — *Contributions to Mineralogy and Petrology* 138 (1), pp. 84–98.
- HARPER, C. T. 1970: Graphical solution to the problem of radiogenic argon-40 loss from metamorphic minerals. — *Ecl. Geol. Helv.* 63, pp. 119–140.
- HASENAKA, T. and CARMICHAEL, I. S. E. 1985: The cinder cones of Michoacán-Guanajuato, central Mexico: their age, volume and distribution, and magma discharge rate. — *Journal of Volcanology and Geothermal Research* 25, pp. 105–124.
- HASENAKA, T. and CARMICHAEL, I. S. E. 1987: The cinder cones of Michoacán-Guanajuato, central Mexico: Petrology and chemistry. — *Journal of Petrology* 28, pp. 241–269.
- HASENAKA, T. 1994: Size, distribution, and magma output rate for shield volcanoes of the Michoacán-Guanajuato Volcanic Field, Central Mexico. — *Journal of Volcanology and Geothermal Research* 63 (1–2), pp. 13–31.
- HAYATSU, A. and CARMICHAEL, C. M. 1977: Removal of atmospheric argon contamination and the use and misuse of the K-Ar isochron methods. — *Canadian Journal of Earth Sciences* 14, pp. 337–345.
- HAYWARD, B. W., GRENFELL, H. R., SANDIFORD, A., SHANE, P. R., MORLEY, M. S. and ALLOWAY, B. V. 2002: Foraminiferal and molluscan evidence for the Holocene marine history of two breached maar lakes, Auckland, New Zealand. — *New Zealand Journal of Geology and Geophysics* 45 (4), pp. 467–479.

- HÁMOR, G., RAVASZNÉ BARANYAI, L., BALOGH, K. and ÁRVÁNE SÓS, E. 1980: A magyarországi miocén riolituffa-szintek radiometrikus kora. [Radiometric age of the Miocene rhyolite tuffs in Hungary]. — *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute 1978*, pp. 65–73.
- HEIKEN, G. H. 1971: Tuff rings: examples from the Fort Rock-Christmas Lake Valley Basin, South-Central Oregon. — *Journal of Geophysical Research* 76 (23), pp. 5615–5626.
- HEIKEN, G. H. 1972: Morphology and petrography of volcanic ashes. — *Geological Society of America Bulletin* 83, pp. 1961–1988.
- HEIKEN, G. H. 1974: An atlas of volcanic ash. — *Smithsonian Earth Science Contributions* 12, pp. 1–101.
- HEIKEN, G. H. and WOHLITZ, K. H. 1986: *Volcanic ash*. — University of California Press, Berkeley, 246 p.
- HOOTEN, J. A. and ORT, M. H. 2002: Peperite as a record of early-stage phreatomagmatic fragmentation processes: an example from the Hopi Buttes volcanic field, Navajo Nation, Arizona, USA. — *Journal of Volcanology and Geothermal Research* 114 (1–2), pp. 95–106.
- HORVÁTH, F., STEGENA, L. and GÉCZY, B. 1975: Ensimatic and ensialic interarc basins. — *Journal of Geophysical Research* 80, pp. 281–283.
- HORVÁTH, F. and BERCKHEMER, H. 1982: Mediterranean backarc basins. — In: BERCKHEMER, H. and HSÜ, K. (Eds): *Alpine-Mediterranean geodynamics*, American Geophysical Union 7, pp. 141–173.
- HORVÁTH, F. 1993: Towards a mechanical model for the formation of the Pannonian basin. — *Tectonophysics* 226 (1–4), pp. 333–357.
- HORVÁTH, F. 1995: Phases of compression during the evolution of the Pannonian Basin and its bearing on hydrocarbon exploration. — *Marine and Petroleum Geology* 12, pp. 837–844.
- HORVÁTH, F. and CLOETINGH, S. 1996: Stress-induced late-stage subsidence anomalies in the Pannonian basin. — *Tectonophysics* 266 (1–4), pp. 287–300.
- HORVÁTH, F. and TARI, G. 1999: IBS Pannonian Basin project; a review of the main results and their bearings hydrocarbon exploration. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen*. Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 195–213.
- HORVÁTH, F., BADA, G., SZAFIÁN, P., TARI, G., ÁDÁM, A. and CLOETINGH, S. 2004: Formation and deformation of the Pannonian Basin: constraints from observational data. — In: GEE, D. G. and STEPHENSON, R. (Eds): *European Lithosphere Dynamics*, Geological Society of London, London, United Kingdom, Geological Society Special Publications [in press]
- HOUGHTON, B. F. and HACKETT, W. R. 1984: Strombolian and phreatomagmatic deposits of Ohakune Craters, Ruapehu, New Zealand; a complex interaction between external water and rising basaltic magma. — *Journal of Volcanology and Geothermal Research* 21 (3–4), pp. 207–231.
- HOUGHTON, B. F. and SCHMINCKE, H. U. 1986: Mixed deposits of simultaneous strombolian and phreatomagmatic volcanism; Rothenberg Volcano, East Eifel volcanic field. — *Journal of Volcanology and Geothermal Research* 30 (1–2), pp. 117–130.
- HOUGHTON, B. F. and SCHMINCKE, H. U. 1989: Rothenberg scoria cone, East Eifel; a complex strombolian and phreatomagmatic volcano. — *Bulletin of Volcanology* 52 (1), pp. 28–48.
- HOUGHTON, B. F. and NAIRN, I. A. 1991: The 1976–1982 Strombolian and phreatomagmatic eruptions of White Island, New-Zealand — Eruptive and depositional mechanisms at a wet volcano. — *Bulletin of Volcanology* 54 (1), pp. 25–49.
- HOUGHTON, B. F. and SMITH, R. T. 1993: Recycling of magmatic clasts during explosive eruptions — estimating the true juvenile content of phreatomagmatic volcanic deposits. — *Bulletin of Volcanology* 55 (6), pp. 414–420.
- HOUGHTON, B. F., WILSON, C. J. N., ROSENBERG, M. D., SMITH, I. E. M. and PARKER, R. J. 1996: Mixed deposits of complex magmatic and phreatomagmatic volcanism: An example from Crater Hill, Auckland, New Zealand. — *Bulletin of Volcanology* 58 (1), pp. 59–66.
- HOUGHTON, B. F., WILSON, C. J. N. and SMITH, I. E. M. 1999: Shallow-seated controls on styles of explosive basaltic volcanism: a case study from New Zealand. — *Journal of Volcanology and Geothermal Research* 91 (1), pp. 97–120.
- HUCKENHOLZ, H. G. and BÜCHEL, G. 1988: Tertiärer Vulkanismus der Hocheifel. — *Fortschritte des Mineralogie Stuttgart* 66 (2), pp. 43–82.
- JAUPART, C. and VERGNOLLE, S. 1997: Laboratory models of Hawaiian and Strombolian eruptions. — *Nature* 331, pp. 518–520.
- JÁMBOR, Á. 1980: A Dunántúli-középhegység pannóniai képződményei (Pannonian in the Transdanubian Range). — *A Magyar Állami Földtani Intézet Évkönyve* 65, pp. 1–259.
- JÁMBOR, Á. 1989: Review of the geology of the s.l. Pannonian Formations of Hungary. — *Acta Geologica Hungarica* 32 (3–4), pp. 269–324.
- JÁMBOR, A. and SOLTI, G. 1975: Geological conditions of the Upper Pannonian oil-shale deposit recovered in the Balaton Highland and at Kemeneshát. — *Acta Mineralogica-Petrographica, Szeged* 22 (1), pp. 9–28.
- JÁMBOR, A., PARTÉNYI, Z. and SOLTI, G. 1981: A dunántúli bazaltvulkanitok földtani jellegei. (Geological characteristics of the Transdanubian basaltic volcanic rocks) [in Hungarian]. — *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute 1979*, pp. 225–239.
- JOHNSON, R. W. 1989: *Intraplate volcanism in Eastern Australia and New Zealand*. — Cambridge University Press, Cambridge, 408 p.
- JORDÁN, G., CSILLAG, G., SZÜCS, A. and QVARFORT, U. 2003: Application of digital terrain modelling and GIS methods for the morphotectonic investigation of the Káli Basin, Hungary. — *Zeitschrift für Geomorphologie* 47 (2), pp. 145–169.
- JUGOVICS, L. 1915: Az Alpok keleti végződése alján és a Vas vármegyei Kis Magyar Alföldön felbukkanó bazaltok és bazalttufák, I. rész. (Basalts and basalt tuffs near the eastern Alps, in the Little Hungarian Plain, Vas County. Part 1) [In Hungarian]. — *A Földtani Intézet Évi Jelentése 1915*, pp. 49–73.
- JUGOVICS, L. 1916: Az Alpok keleti végződése alján és a Vas vármegyei Kis Magyar Alföldön felbukkanó bazaltok és bazalttufák, II. rész. (Basalts and basalt tuffs near the eastern Alps, in the Little Hungarian Plain, Vas County. Part 2) [In Hungarian]. — *A Földtani Intézet Évi Jelentése 1916*, pp. 63–76.
- JUGOVICS, L. 1937: A Sághegy felépítése és vulkanológiai viszonyai; [Der Aufbau und die vulkanologischen Verhältnisse des Ságberges]. — *Mat. u. Naturw. Anz. (Ung. Akad. Wiss.)* 56 (3), pp. 1214–1235.

- JUGOVICS, L. 1939: Die Basalte des Paulibergeres im Burgenland (Gau Niederdonau). – *Chemie der Erde* 12 (2), pp. 158–207.
- JUGOVICS, L. 1969a: A Balatonfelvidék és a Tapolcai medence bazaltvidékének földtani jellegei. (Geological characteristics of the basalt lands at the Balaton Highland and in the Tapolca Basin) [in Hungarian with English and Russian summary]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute* 1968, pp. 223–243.
- JUGOVICS, L. 1969b: A dunantúli bazalt és bazalttufa területek. (Basalt and basaltic tuff regions of Transdanubia) [in Hungarian with English and Russian summary]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute* 1967, pp. 75–82.
- JUGOVICS, L. 1971: Kabhegy és a körülötte települő bazaltterületek (kabhegyi bazaltcsoport). (Geologic features of the basalt in the Kab mountain area, Kab mountain basalt group) [in Hungarian with English and Russian summary]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute* 1968, pp. 245–255.
- JUGOVICS, L. 1972: A Kisalföld bazalt és bazalttufa előfordulásai. [Basalt and basaltic tuff deposits in the Little Alfold]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute*, 1970, pp. 79–101.
- JUHÁSZ, E., PHILLIPS, L., MÜLLER, P., RICKETTS, B., TÓTH, M. A., LANTOS, M. and KOVÁCS, L. 1999: Late Neogene sedimentary facies and sequences in the Pannonian Basin, Hungary. – In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen*. Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 335–356.
- KARÁTSÓN, D. and NÉMETH, K. 2001: Lithofacies associations of an emerging volcanoclastic apron in a Miocene volcanic complex: an example from the Börzsöny Mountains, Hungary. – *International Journal of Earth Sciences* 90 (4), pp. 776–794.
- KARÁTSÓN, D., MÁRTON, E., HARANGI, SZ., JÓZSA, S., BALOGH, K., PÉCSKAY, Z., KOVÁCSVÖLGYI, S., SZAKMÁNY, G. and DULAI, A. 2000: Volcanic evolution and stratigraphy of the Miocene Börzsöny Mountains, Hungary: An integrated study. – *Geologica Carpathica* 51 (5), pp. 325–343.
- KÁZMÉR, M. 1990: Birth, life, and death of the Pannonian Lake. – *Palaeogeography Palaeoclimatology Palaeoecology* 79, pp. 171–188.
- KÁZMÉR, M. and KOVÁCS, S. 1985: Permian–Palaeogene palaeogeography along the eastern part of the Insubric–Periadriatic Lineament system: evidence for continental escape of the Bakony–Drauzug Unit. – *Acta Geologica Hungarica, Budapest* 28, pp. 71–84.
- KEMPTON, P. D., DOWNES, H. and EMBEY-ISZTIN, A. 1997: Mafic granulite xenoliths in neogene alkali basalts from the Western Pannonian Basin: Insights into the lower crust of a collapsed orogen. – *Journal of Petrology* 38 (7), pp. 941–970.
- KIENLE, J., KYLE, P. R., SELF, S., MOTYKA, R. J. and LORENZ, V. 1980: Ukinrek Maars, Alaska, 1. April 1977 eruption sequence, petrology, and tectonic settings. – *Journal of Volcanology and Geothermal Research* 7, pp. 11–37.
- KLÜGEL, A., SCHMINCKE, H. U., WHITE, J. D. L. and HOERNLE, K. A. 1999: Chronology and volcanology of the 1949 multi-vent rift-zone eruption on La Palma (Canary Islands). – *Journal of Volcanology and Geothermal Research* 94 (1–4), pp. 267–282.
- KLÜGEL, A., HOERNLE, K., SCHMINCKE, H.-U. and WHITE, J. D. L. 2000: The chemically zoned 1949 eruption on La Palma (Canary Islands): Petrologic evolution and magma supply dynamics of a rift zone eruption. – *Journal of Geophysical Research* 105 (B3), pp. 5997–6016.
- KOKELAAR, B. P. 1983: The mechanism of Surtseyan volcanism. – *Journal of the Geological Society of London* 140, pp. 939–944.
- KOKELAAR, P. 1986: Magma-water interactions in subaqueous and emergent basaltic volcanism. – *Bulletin of Volcanology* 48, pp. 275–289.
- KOKELAAR, B. P. and DURANT, G. P. 1983: The submarine eruption of Surtla (Surtsey, Iceland). – *Journal of Volcanology and Geothermal Research* 19, pp. 239–246.
- KONEČNÝ, V., LEXA, J., BALOGH, K. and BROSKA, I. 1999a: Neogene–Quaternary alkali basalt volcanism of Slovakia; review of volcanic forms and evolution. – *Geologica Carpathica* 50 (Special Issue), pp. 112–114.
- KONEČNÝ, V., LEXA, J. and HOJSTRICOVA, V. 1999b: The central Slovakia Neogene volcanic field; a review. – *Guidebook Series – Society of Economic Geologists* 31, pp. 181–196.
- KONEČNÝ, V. and LEXA, J. 2000: Pliocene to Pleistocene alkali basalt diatremes and maars of Southern Slovakia: a common model for their evolution. – *Terra Nostra* 2000 (6), pp. 220–232.
- KORPÁS, L., 1983: *A Kab-hegy és környékének vulkanológia vázlata* (Volcanological framework of Kabhegy) [in Hungarian with English summary]. – Országos Földtani és Geofizikai Adattár [Open Files], Budapest, 49 p.
- KORPÁS, L. and SZALAY MÁRTON, E. 1985: Basaltvolcanological reconstruction in the Transdanubian Range of Hungary. – *Memórias. – Congreso Latinoamericano de Geología* 6 (2), pp. 153–162.
- KORPÁS, L. and LÁNG, B. 1993: Timing of volcanism and metallogenesis in the Börzsöny Mountains, northern Hungary. – *Ore Geology Reviews* 8 (6), pp. 477–501.
- KOVAČ, M., KRÁL, J., MÁRTON, E., PLASIENKA, D. and UHER, P. 1994: Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. – *Geologica Carpathica* 45, pp. 83–96.
- KRALJ, P. 2000: Upper Pliocene alkali basalt at Grad, northeastern Slovenia. – *Geologija* 43 (2), pp. 213–218.
- KULCSÁR, L. and GUCYZNÉ SOMOGYI, A. 1962: A celldömölki Sághegy vulkánja. [The Sághegy volcano near Celldömölk, Hungary]. – *Acta Geographica Debrecina* VIII/1 (27), pp. 33–83.
- KURSZLAUKIS, S. and LORENZ, V. 1997: Volcanological features of a low-viscosity melt: The carbonatitic gross Brukkaros Volcanic Field, Namibia. – *Bulletin of Volcanology* 58 (6), pp. 421–431.
- LANTOS, M., HÁMOR, T. and POGÁCSÁS, G. 1992: Magneto- and seismostratigraphic correlations of Pannonian s.l. (late Miocene and Pliocene) deposits in Hungary. – *Paleontologia i Evolucio* 24–25, pp. 35–46.
- LEXA, J. 1999: Outline of the Alpine geology and metallogeny of the Carpatho-Pannonian region. – *Guidebook Series – Society of Economic Geologists* 31, pp. 65–108.
- LIFFA, A. 1940: Boldogkőváralja és környékének geológiai viszonyai; [Die geologischen Verhältnisse von Boldogkőváralja und dessen Umgebung]. – *K. Ung. Geol. Anst. (Magyar K. Földt. Int.), Jber. 1933–1935* (4), pp. 1337–1411.

- LISTER, J. R. 1991: Steady Solutions for Feeder Dykes in a Density-Stratified Lithosphere. — *Earth and Planetary Science Letters* 107 (2), pp. 233–242.
- LISTER, J. R. and KERR, B. C. 1991: Fluid-mechanical models of crack propagation and their application to magma transport. — *Journal of Geophysical Research* 96 (B6), pp. 10,049–10,077.
- LORENZ, V. 1971: Collapse structures in the Permian of the Saar-Nahe area, Southwest Germany. — *Geologische Rundschau* 60, pp. 924–948.
- LORENZ, V. 1973: On the formation of Maars. — *Bulletin of Volcanology* 37 (2), pp. 183–204.
- LORENZ, V. 1974: Studies of the Surtsey tephra deposits. — *Surtsey Research Program Report* 7, pp. 72–79.
- LORENZ, V. 1984: Explosive volcanism of the West Eifel volcanic field, Germany. — In: KORNPROBAT, J. (Ed.): *Kimberlites I.: Kimberlites and related rocks*, Elsevier, Amsterdam, pp. 299–307.
- LORENZ, V. 1986: On the growth of maars and diatremes and its relevance to the formation of tuff rings. — *Bulletin of Volcanology* 48, pp. 265–274.
- LORENZ, V. 2000: Formation of the root zones of maar-diatreme volcanoes. — *Terra Nostra* 2000 (6), pp. 279–284.
- LORENZ, V. 2003: Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. — *Geolines — Journal of the Geological Institute of AS Czech Republic* 15, pp. 72–83.
- LORENZ, V. and BÜCHEL, G. 1980a: Zur Vulkanologie der Maare und Schlackenkegel der Westeifel. — *Mitteilung Pollichia* 68, pp. 29–100.
- LORENZ, V. and BÜCHEL, G. 1980b: Die Kesseltaeler der vulkanischen Westeifel; Nachweis ihrer Genese. — *Mainzer geowissenschaftliche Mitteilungen* 8, pp. 173–191.
- LORENZ, V. and KURSZAUKIS, S. 1997: On the last explosions of carbonatite pipe G3b, Gross Brukkaros, Namibia. — *Bulletin of Volcanology* 59, pp. 1–9.
- LORENZ, V., MCBIRNEY, A. R. and WILLIAMS, H. 1970: *An investigation of volcanic depressions. Part III. Maars, tuff-rings, tuff-cones and diatremes*. — Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., Houston, Texas, 196 p.
- LÖRENTHEY, I. 1900: Foraminifera der pannonischen Stufe Ungarns. — *Neues Jahrbuch für Mineralogie, Geologie und Paläontologie* 2, pp. 99–107.
- LYLE, P. 2000: The eruption environment of multi-tiered columnar basalt lava flows. — *Journal of the Geological Society* 157, pp. 715–722.
- MAGYAR, I. 1995: Late Miocene Mollusk Biostratigraphy in the Eastern Part of the Pannonian Basin (Tisza-tulaj, Hungary). — *Geologica Carpathica* 46 (1), pp. 29–36.
- MAGYAR, I., GEARY, D. H. and MULLER, P. 1999: Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. — *Palaeogeography Palaeoclimatology Palaeoecology* 147 (3–4), pp. 151–167.
- MAJOROS, G. 1983: Lithostratigraphy of the Permian formations of the Transdanubian Central Mountains. — *Acta Geologica Hungarica* 26, pp. 7–20.
- MARTIN, U. 2002: The Miocene eruption of a small emergent volcano at the Otago Peninsula, New Zealand. — *Neues Jahrbuch für Geologie P-A*, 225 (3), pp. 373–400
- MARTIN, U. and NÉMETH, K. 2000: Peperite structures from the Bakony – Balaton Highland Volcanic Field (Pannonian Basin, Hungary): Examples from the Hajagos-hegy. — *Terra Nostra* 2000 (6), pp. 318–329.
- MARTIN, U. and WHITE, J. D. L. 2001: Depositional mechanisms of density current deposits from a submarine vent at the Otago Peninsula, New Zealand. — In: KNELLER, B. and PEAKALL, J. (Eds): *Sediment transport and deposition by particulate gravity currents*, Special Publication of the International Association of Sedimentologists, Blackwell Sciences, Oxford 31, pp. 245–261.
- MARTIN, U. and NÉMETH, K. 2002a: Magma-wet sediment interaction in a crater lake of a tuff ring, developed in a pyroclastic mound dammed valley: Kissomlyó volcano (Western Hungary). — In: WHITE J. D. L. (Ed.), *American Geophysical Union Chapman Conference on Explosive Subaqueous Volcanism*, 21–25 January 2002. University of Otago, Dunedin, 37 p.
- MARTIN, U. and NÉMETH, K. 2002b: Interaction between lava lakes and pyroclastic sequences in phreatomagmatic volcanoes: Haláp and Badacsony, western Hungary. — *Geologica Carpathica* 53 (CD-version [ISSN 1335-0552])
- MARTIN, U. and NÉMETH, K. 2004a: Blocky versus fluidal peperite textures developed in crater lakes and vent fills of phreatomagmatic volcanoes in Mio/Pliocene volcanic fields of Western Hungary. — *Journal of Volcanology and Geothermal Research* [in review]
- MARTIN, U. and NÉMETH, K. 2004b: Eruptive and depositional history of a Pliocene intracontinental tuff ring developed in a fluvio-lacustrine basin: Kissomlyó volcano (western Hungary). — *Journal of Volcanology and Geothermal Research* [in review]
- MARTIN, U. and NÉMETH, K. 2004c: Peperitic lava lake-fed sills at Ság-hegy, western Hungary: a complex interaction of wet tephra ring and lava. — In: BREITKREUZ, C. and PETFORD, N. (Eds): *Physical Geology of Subvolcanic Systems — Laccoliths, Sills, and Dykes*, Geological Society Special Publications 234, Blackwell Sciences, Oxford [in press].
- MARTIN, U., NÉMETH, K., AUER, A., BREITKREUZ, C. and CSILLAG, G. 2002: Depositional record of a Pliocene nested multivalent maar complex at Fekete-hegy, Pannonian Basin, Hungary. — *Geologica Carpathica* 53 (CD-version [ISSN 1335-0552])
- MARTIN, U., AUER, A., NÉMETH, K. and BREITKREUZ, C. 2003: Mio/Pliocene phreatomagmatic volcanism in a fluvio-lacustrine basin in western Hungary. — *Geolines — Journal of the Geological Institute of AS Czech Republic* 15, pp. 75–81.
- MASTIN, L. 2004: Beyond explosive MFCI: the hydrodynamics of magma-water mixing and its effect on fragmentation and eruptive violence. — *Geological Society of America, 56th Annual Meeting Rocky Mountain Section — 100th Annual Meeting Cordilleran Section, 2004 Abstracts with Program* 36 (4) [April 2004], May 3–5, 2004, Boise, Idaho, p. 84.
- MASTROLORENZO, G. 1994: Averno tuff ring in Campi-Flegrei (South Italy). — *Bulletin of Volcanology* 56 (6–7), pp. 561–572.
- MCCLINTOCK, M. K. and WHITE, J. D. L. 2000: Phreatomagmatism at Coombs Hills, Antarctica: Large-scale laterally quarrying eruptions as a precursor to flood basalt volcanism. — *Terra Nostra* 2000 (6), pp. 336–341.
- MCDUGALL, I. and COOMBS, D. S. 1973: Potassium-Argon ages for the Dunedin Volcano and outlying volcanics. — *New Zealand Journal of Geology and Geophysics* 16 (2), pp. 179–188.

- MCDUGALL, I. and DUNCAN, R. A. 1980: Linear volcanic chains recording plate motions? – *Tectonophysics* 63, pp. 275–295.
- MCDUGALL, I., POLLACK, H. A. and STIPP, J. J. 1969: Excess radiogenic argon in young subareal basalts from Auckland volcanic field, New Zealand. – *Geochimica et Cosmochimica Acta* 33, pp. 1485–1520.
- MCDUGALL, I., VERWOERD, W. and CHEVALLIER, L. 2001: K-Ar geochronology of Marion Island, Southern Ocean. – *Geological Magazine* 138 (1), pp. 1–17.
- MCGETCHIN, T.R., SETTLE, M. and CHOUET, B.A. 1974: Cinder cone growth modelled after North East crater, Mt Etna, Sicily. – *Journal of Geophysical Research* 79, pp. 3257–3272.
- MCKNIGHT, S. B. and WILLIAMS, S. N. 1997: Old cinder cone or young composite volcano? The nature of Cerro Negro, Nicaragua. – *Geology* 25 (4), pp. 339–342.
- MCPHIE, J., DOYLE, M. and ALLEN, R. 1993: *Volcanic Textures. A guide to the interpretation of textures in volcanic rocks.* – Tasmanian Government Printing Office, Tasmania, 196 p.
- MERTES, H. and SCHMINCKE, H. U. 1985: Mafic potassic lavas of the Quaternary West Eifel volcanic field; 1, Major and trace elements. – *Contributions to Mineralogy and Petrology* 89 (4), pp. 330–345.
- MÜLLER, P. 1998: A pannóniai képződmények rétegtana (Stratigraphy of the Pannonian sediments) [in Hungarian]. – In: BÉRCZI, I. and JÁMBOR, Á. (Eds): *Magyarország geológiai képződményeinek rétegtana (Stratigraphy of geological units of Hungary)*, Budapest, pp. 485–493.
- MÜLLER, P. and MAGYAR, I. 1992: A Prosodacnomyak rétegtani jelentősége a Kötöcse környéki pannóniai s.l. üledékekben (Stratigraphical importance of Prosodacnomy bearing pannonian s.l. sediments from Kötöcse) [in Hungarian with English abstract]. – *Földtani Közöny* 122 (1), pp. 1–38.
- MÜLLER, P., GEARY, D. H. and MAGYAR, I. 1999: The endemic molluscs of the Late Miocene Lake Pannon: their origin, evolution, and family-level taxonomy. – *Lethaia* 32 (1), pp. 47–60.
- NÉMETH, K. 2001: Deltaic density currents and turbidity deposits related to maar crater rims and their importance for paleogeographic reconstruction of the Bakony – Balaton Highland Volcanic Field (BBHVF), Hungary. – In: KNELLER, B., MCCAFFREY, B., PEAKALL, J. and DRUITT, T. (Eds): *Sediment transport and deposition by particulate gravity currents*, Special Publication of the International Association of Sedimentologists, Blackwell Sciences, Oxford 31, pp. 261–277.
- NÉMETH, K. and CSILLAG, G. 1999: Tapolcai Bazalt Formáció [Tapolca Basalt Formation]. – In: BUDAI, T. and CSILLAG, G. (Eds): *Balaton-felvidék földtana [Geology of the Balaton Highland]*, Geological Institute of Hungary, Budapest, 197, pp. 114–122.
- NÉMETH, K. and MARTIN, U. 1999a: Volcanic glass study of volcanoclastic deposits of Tihany-type and normal maar volcanoes from the Bakony – Balaton Highland Volcanic Field (BBHVF), Hungary. – *IUGG - IAVCEI, Birmingham, UK Abstract Volume* p. B171.
- NÉMETH, K. and MARTIN, U. 1999b: Small-volume volcanoclastic flow deposits related to phreatomagmatic explosive eruptive centres near Szentbékállá, Bakony – Balaton Highland Volcanic Field, Hungary: Pyroclastic flow or hydroclastic flow? – *Földtani Közöny* 129 (3), pp. 393–417.
- NÉMETH, K. and MARTIN, U. 1999c: Large hydrovolcanic field in the Pannonian Basin: general characteristics of the Bakony – Balaton Highland Volcanic Field, Hungary. – *Acta Vulcanologica* 11 (2), pp. 271–282.
- NÉMETH, K. and MARTIN, U. 1999d: Late Miocene paleo-geomorphology of the Bakony – Balaton Highland Volcanic Field (Hungary) using physical volcanology data. – *Zeitschrift für Geomorphologie* 43 (4), pp. 417–438.
- NÉMETH, K. and WHITE, J. D. L. 2003: Reconstructing eruption processes of a Miocene monogenetic volcanic field from vent remnants: Waipiata Volcanic Field, South Island, New Zealand. – *Journal of Volcanology and Geothermal Research* 124 (1–2), pp. 1–21.
- NÉMETH, K., MARTIN, U. and HARANGI, SZ. 1999a: Miocene maar/diatreme volcanism at the Tihany Peninsula (Pannonian Basin): The Tihany Volcano. – *Acta Geologica Hungarica* 42 (4), pp. 349–377.
- NÉMETH, K., MARTIN, U. and PHILIPPE, M. 1999b: Eroded porous-media aquifer controlled hydrovolcanic centers in the South Lake Balaton region, Hungary; the Boglár Volcano. – *Acta Geologica Hungarica* 42 (3), pp. 251–266.
- NÉMETH, K., MARTIN, U. and HARANGI, SZ. 2000: On the calculation of the geometry of the diatreme pipe from a deposits of an “accidental lithic clast rich” maar, Tihany East Maar, (Hungary). – *Terra Nostra* 2000 (6), pp. 383–391.
- NÉMETH, K., MARTIN, U. and HARANGI, SZ. 2001: Miocene phreatomagmatic volcanism at Tihany (Pannonian Basin, Hungary). – *Journal of Volcanology and Geothermal Research* 111 (1–4), pp. 111–135.
- NÉMETH, K., MARTIN, U. and CSILLAG, G. 2003a: Lepusztult maar/diatrema szerkezetek a Bakony – Balaton Felvidék Vulkáni Területről (Eroded maar/diatrema structures from the Bakony – Balaton Highland Volcanic Field). [in Hungarian with English abstract]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute 2000*, pp. 83–99.
- NÉMETH, K., MARTIN, U. and CSILLAG, G. 2003b: Erosion rate calculation based on eroded monogenetic alkaline basaltic volcanoes of the Mio/Pliocene Bakony – Balaton Highland Volcanic Field, Hungary. – *Geolines – Journal of the Geological Institute of AS Czech Republic* 15, pp. 93–97.
- NÉMETH, K., WHITE, J. D. L., REAY, A. and MARTIN, U. 2003c: Compositional variation during monogenetic volcano growth and its implications for magma supply to continental volcanic fields. – *Journal of the Geological Society of London* 160 (4), pp. 523–530.
- OHBA, T., TANIGUCHI, H., OSHIMA, H., YOSHIDA, M. and GOTO, A. 2002: Effect of explosion energy and depth on the nature of explosion cloud – A field experimental study. – *Journal of Volcanology and Geothermal Research* 115 (1–2), pp. 33–42.
- ORT, M. H., DALLEGE, T. A., VAZQUEZ, J. A. and WHITE, J. D. L. 1998: Volcanism and sedimentation in the Mio-Pliocene Bidahochi Formation, Navajo Nation, NE AZ. – In: DUEBENDORFER, E. (Ed.): *Geologic Excursions in northern and Central Arizona. Field trip Guidebook for Geological Society of America Rocky Mountain Section Meeting, Arizona*, Geological Society of America, Flagstaff, Arizona, pp. 35–57.
- ORT, M. H., WOHLLETZ, K., HOOTEN, J. A., NEAL, C. A. and MCCONNEL, V. S. 2000: The Ukinrek maars eruption, Alaska, 1977: a natural laboratory for the study of phreatomagmatic processes at maars. – *Terra Nostra* 2000 (6), pp. 396–400.
- PANTÓ, G. 1963: Ignimbrites of Hungary with regard to their genetics and classification. – *Bulletin Volcanologique* 25, pp. 175–181.
- PANTÓ, G. 1966: A Tokaji-hegység földtani vizsgálatának 1964. évi eredményei. [Results of geologic investigations in 1964 in the Tokaj mountains]. – *A Magyar Állami Földtani Intézet Évi jelentése = Annual Report of the Hungarian Geological Institute 1964*, pp. 439–442.

- PÉCSKAY, Z., LEXA, J., SZAKÁCS, A., BALOGH, K., SEGHEDI, I., KONECNY, V., KOVÁCS, M., MÁRTON, E., KALICIAK, M., SZÉKY-FUX, V., PÓKA, T., GYARMATI, P., EDELSTEIN, O., ROSU, E. and ZEC, B. 1995: Space and time distribution of Neogene–Quaternary volcanism in the Carpatho-Pannonian region. — *Acta Vulcanologica* 7 (2), pp. 15–28.
- PIRRUNG, M., FISCHER, C., BUCHEL, G., GAUPP, R., LUTZ, H. and NEUFFER, F. O. 2003: Lithofacies succession of maar crater deposits in the Eifel area (Germany). — *Terra Nova* 15 (2), pp. 125–132.
- PÓKA, T. 1988: Neogene and Quaternary volcanism of the Carpathian-Pannonian region; changes chemical composition and its relationship to basin formation. — In: ROYDEN LEIGH, H. and HORVÁTH, F. (Eds): *The Pannonian Basin; a study in basin evolution*, pp. 257–277.
- RATSCHBACHER, L., FRISCH, W., LINZER, H. G. and MERLE, O. 1991: Lateral Extrusion in the Eastern Alps. 2. Structural-Analysis — *Tectonics* 10 (2), pp. 257–271.
- RIEDEL, C., ERNST, C. G. J. and RILEY, M. 2003: Controls on the growth and geometry of pyroclastic constructs. — *Journal of Volcanology and Geothermal Research* 127, pp. 121–152.
- RITTMANN, A. 1958: Il meccanismo di formazione delle lave a pillows e dei cosiddetti tufi palagonitici. — *Boll. Accad Gioenia Sci Nat Catania Ser IV* 4, pp. 311–318.
- RITTMANN, A. 1962: Volcanoes and their activity. — John Wiley and Sons, New York, 305 p.
- RITTMANN, A. 1973: Lave a pillow ed ialoclastiti. — *Rend. Soc. Ital. Mineral. Petrol.* 29, pp. 397–412.
- ROWLAND, J. V. and SIBSON, R. H. 2001: Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: soft-linked segmentation of a continental rift system. — *New Zealand Journal of Geology and Geophysics* 44 (2), pp. 271–283.
- ROYDEN, L. H. and KARNER, G. D. 1984: Flexure of lithosphere beneath the Appennine and Carpathian foredeep basins: evidence for an insufficient topographic load. — *AAPG Bulletin* 68, pp. 704–712.
- ROYDEN, L., HORVÁTH, F., NAGYMAROSY, A. and STEGANA, L. 1983a: Evolution of the Pannonian Basin System. 2. Subsidence and Thermal History. — *Tectonics* 2 (1), pp. 91–137.
- ROYDEN, L., HORVÁTH, F. and RUMPLER, J. 1983b: Evolution of the Pannonian Basin System 1. Tectonics. — *Tectonics* 2 (1), pp. 63–90.
- RÖGL, F. 1998: Paleogeographic considerations for Mediterranean and Paratethys seaways (Oligocene and Miocene). — *Ann. Naturhist. Mus. Wien* 99 A, pp. 279–310.
- RYAN, M. P. 1987a: Neutral buoyancy and the mechanical evolution of magmatic systems. — In: MYSEN, B. O. (Ed): *Magmatic processes: Physico-chemical principles*, The Geochemical Society, University Park, Pennsylvania, pp. 259–287.
- RYAN, M. P. 1987b: Elasticity and contractancy of Hawaiian olivine tholeiite and its role in the stability and structural evolution of sub-caldera magma reservoirs and rift systems. — In: *Volcanism in Hawaii. U.S. Geological Survey Professional Papers*, USGS, pp. 1395–1447.
- SACCHI, M. and HORVÁTH, F. 2002: Towards a new time scale for the Upper Miocene continental series of the Pannonian basin (Central Paratethys). — *Stephan Mueller Special Publication Series* 3 (Neotectonics and surface processes: the Pannonian Basin and Alpine/Carpathian System), pp. 79–94.
- SACCHI, M., HORVÁTH, F., MAGYAR, I., and MÜLLER, P. 1997: Problems and progress in establishing a Late Neogene Chronostratigraphy for the Central Paratethys. — *Neogene Newsletter, Padova* 4, pp. 37–46.
- SACCHI, M., HORVÁTH, F. and MAGYARI, O. 1999: Role of unconformity-bounded units in the stratigraphy of the continental cord; a case study from the late Miocene of the western Pannonian Basin, Hungary. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen*, Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 357–390.
- SACHS, P. M. and HANSTEEN, T. H. 2000: Pleistocene underplating and metasomatism of the lower continental crust: a xenolith study. — *Journal of Petrology* 41 (3), pp. 331–356.
- SACHSENHOFER, R. F. 2001: Syn- and post-collisional heat flow in the Cenozoic Eastern Alps. — *International Journal of Earth Sciences* 90 (3), pp. 579–592.
- SACHSENHOFER, R. F., LANKREIJER, A., CLOETINGH, S. and EBNER, F. 1997: Subsidence analysis and quantitative basin modelling in the Styrian basin (Pannonian basin system, Austria). — *Tectonophysics* 272 (2–4), pp. 175–196.
- SACHSENHOFER, R. F., DUNKL, I., HASENHUTTL, C. and JELEN, B. 1998: Miocene thermal history of the southwestern margin of the Styrian basin: vitrinite reflectance and fission-track data from the Pohorje/Kozjak area (Slovenia). — *Tectonophysics* 297 (1–4), pp. 17–29.
- SACHSENHOFER, R. F., JELEN, B., HASENHUTTL, C., DUNKL, I. and RAINER, T. 2001: Thermal history of Tertiary basins in Slovenia (Alpine–Dinaride–Pannonian junction). — *Tectonophysics* 334 (2), pp. 77–99.
- SCHLEDER, Z. and HARANGI, SZ. 2000: A buried late Miocene alkaline trachyte volcano at the axis of the Little Hungarian Plain, NW Hungary. — *Acta Mineralogica–Petrographica (Szeged)* 41 (Suppl. 6), p. 96.
- SCHMINCKE, H.-U., LORENZ, V. and SECK, H. A. 1983: The Quaternary Eifel Volcanic Fields. — In: FUCHS, K. (Ed.): *Plateau Uplift*, Springer-Verlag, Berlin, Heidelberg, pp. 139–151.
- SELF, S., KIENLE, J. and HUOT, J.-P. 1980: Ukinrek Maars, Alaska, II. Deposits and formation of the 1977 Crater. — *Journal of Volcanology and Geothermal Research* 7, pp. 39–65.
- SHAFIQUILLAH, M. and DAMON, P. E. 1974: Evaluation of K-Ar isochron methods. — *Geochimica et Cosmochimica Acta* 38, pp. 1341–1358.
- SHAW, C. S. J. 1997: Origin of sulfide blebs in variably metasomatized mantle xenoliths, quaternary West Eifel volcanic field, Germany. — *Canadian Mineralogist* 35, pp. 1453–1463.
- SHAW, C. S. J. and EYZAGUIRRE, J. 2000: Origin of megacrysts in the mafic alkaline lavas of the West Eifel volcanic field, Germany. — *Lithos* 50 (1–3), pp. 75–95.
- SIEBE, C., RODRIGUEZ-LARA, V., SCHAAF, P. and ABRAMS, M. 2004: Geochemistry, Sr-Nd isotope composition, and tectonic setting of Holocene Pelado, Guespalapa and Chichinautzin scoria cones, south of Mexico city. — *Journal of Volcanology and Geothermal Research* 130 (3–4), pp. 197–226.
- SKILLING, I. P., WHITE, J. D. L. and MCPHIE, J. 2002: Peperite: a review of magma-sediment mingling. — *Journal of Volcanology and Geothermal Research* 114 (1–2), pp. 1–17.

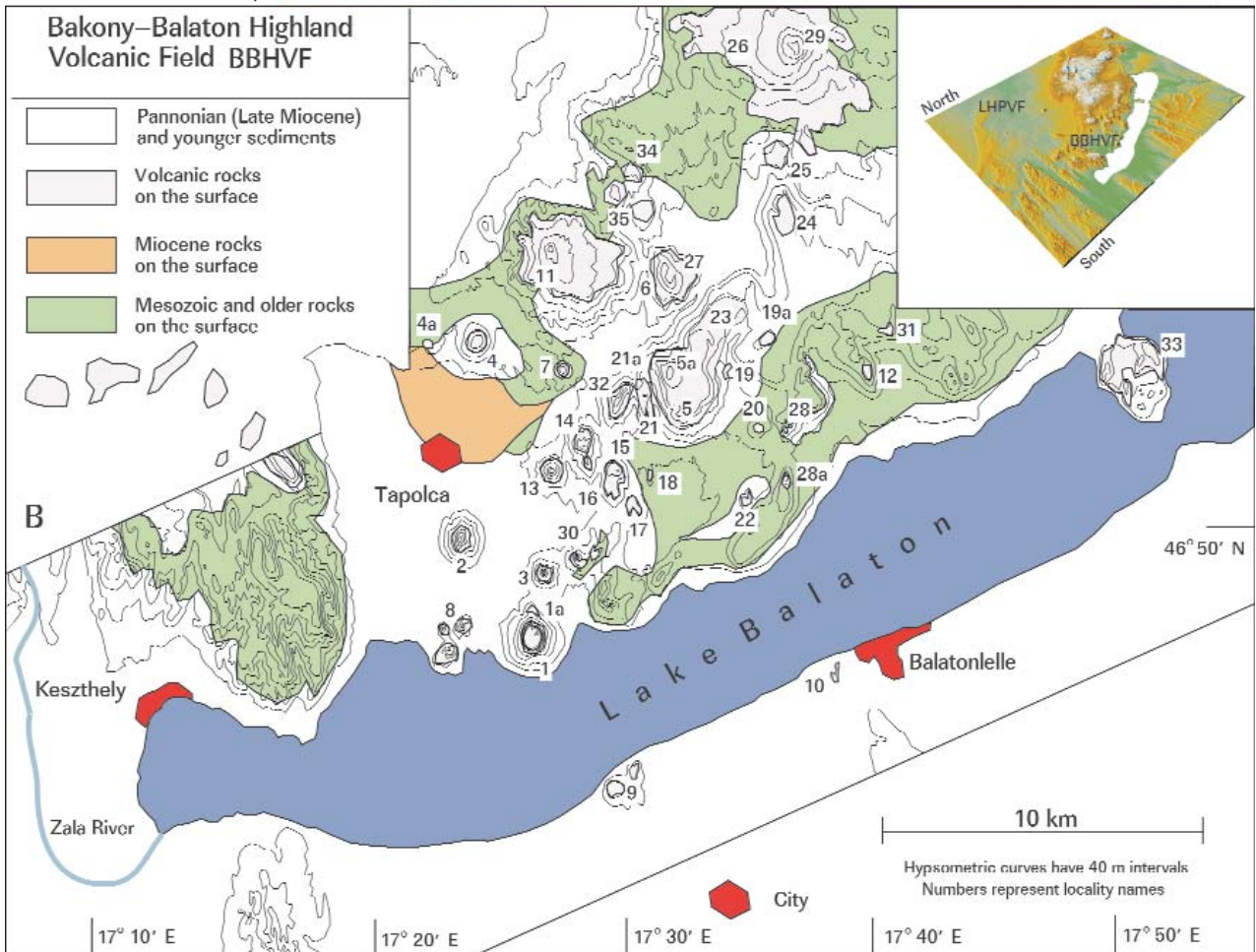
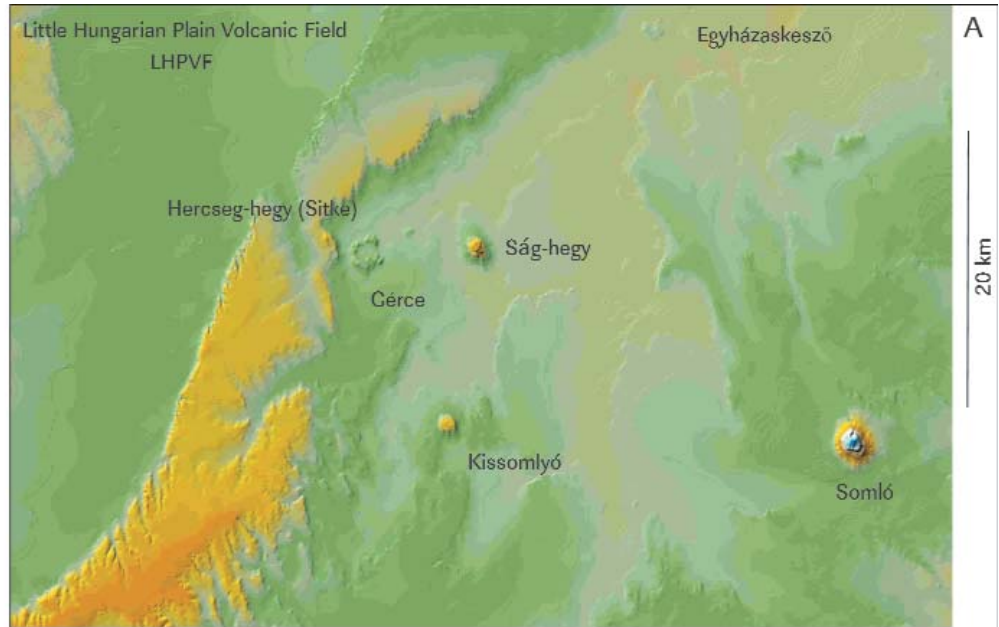
- SOHN, Y. K. 1996: Hydrovolcanic processes forming basaltic tuff rings and cones on Cheju Island, Korea. — *Geological Society of America Bulletin* 108 (10), pp. 1199–1211.
- SOHN, Y. K. and CHOUGH, S. K. 1989: Depositional Processes of the Suwolbong Tuff Ring, Cheju Island (Korea). — *Sedimentology* 36 (5), pp. 837–855.
- SOHN, Y. K. and CHOUGH, S. K. 1992: The Ilchulbong Tuff Cone, Cheju Island, South-Korea — Depositional Processes and Evolution of an Emergent, Surtseyan-Type Tuff Cone. — *Sedimentology* 39 (4), pp. 523–544.
- SOHN, Y. K. and CHOUGH, S. K. 1993: The Udo Tuff Cone, Cheju Island, South-Korea - Transformation of pyroclastic fall into debris fall and grain flow on a steep volcanic cone slope. — *Sedimentology* 40 (4), pp. 769–786.
- SPARKS, R. S. J., BURSİK, M. I., CAREY, S. N., GILBERT, J. S., GLAZE, L. S., SIGURDSSON, H. and WOODS, A. W. 1997: *Volcanic plumes*. — Wiley, New York, 574 p.
- SPEERA, F. J. 1984: Carbon dioxide in petrogenesis III: role of volatiles in the ascent of alkaline magma with special reference to xenolith-bearing mafic lavas. — *Contribution to Mineralogy and Petrology* 88, pp. 217–232.
- SPRY, A. H. 1962: The origin of columnar jointing particularly in basalt flows. — *Journal of the Geological Society of Australia* 8, pp. 191–216.
- STEGENA, L. 1967: A Magyar-medence kialakulása. — *Földtani Közlemény* 97, pp. 278–285.
- STEGENA, L., GÉCZY, B. and HORVÁTH, F. 1975: Late Cenozoic Evolution of Pannonian Basin. — *Tectonophysics* 26 (1–2), pp. 71–90.
- STEVANOVIĆ, P. M. 1951: Pontische Stufe im engeren Sinne — Obere Congerienschichten Serbiens und der angrenzenden Gebiete. — *Serbische Akademie der Wissenschaften, Sonderausgabe, Mathematisch-Naturwissenschaftliche Klasse, 2, Beograd* 187, pp. 1–351
- STRONG, M. and WOLF, J. 2003: Compositional variations within scoria cones. — *Geology* 31 (2), pp. 143–146.
- SZABÓ, Cs. and BODNAR, R. J. 1995: Chemistry and origin of mantle sulfides in spinel peridotite xenoliths from alkaline basaltic lavas, Nógrád–Gömör volcanic field, northern Hungary and southern Slovakia. — *Geochimica et Cosmochimica Acta* 59 (19), pp. 3917–3927.
- SZABÓ, Cs. and BODNAR, R. J. 1998: Fluid-inclusion evidence for an upper-mantle origin for green clinopyroxenes in late Cenozoic basanites from the Nograd-Gomor volcanic field, northern Hungary/southern Slovakia. — *International Geology Review* 40 (9), pp. 765–773.
- SZABÓ, Cs., HARANGI, Sz. and CSONTOS, L. 1992: Review of Neogene and Quaternary Volcanism of the Carpathian Pannonian Region. — *Tectonophysics* 208 (1–3), pp. 243–256.
- SZABÓ, Cs., VASELLI, O., VANNUCCI, R., BOTTAZZI, P., OTTOLINI, L., CORADOSSI, N. and KUBOVICS, I. 1995: Ultramafic xenoliths from the Little Hungarian Plain (western Hungary); a petrologic and geochemical study. — *Acta Vulcanologica* 7 (2), pp. 249–263.
- SZAKÁCS, A., ZELENKA, T., MÁRTON, E., PÉCSKAY, Z., PÓKA, T. and SEGHEDI, I. 1998: Miocene acidic explosive volcanism in the Bükk Foreland, Hungary; identifying eruptive sequences and searching for source locations. — *Acta Geologica Hungarica* 41 (4), pp. 413–435.
- SZÉKY FUX, V. and KOZÁK, M. 1984: A Nyírség mélyszinti neogén vulkanizmusa. [Deep-seated Neogene volcanism in the Nyirseg, northeastern Hungary]. — *Földtani Közlemény* 114, (2), pp. 147–159.
- TARI, G. 1991: Multiple Miocene block rotation in the Bakony Mountains, Transdanubian Central Range, Hungary. — *Tectonophysics* 199 (1), pp. 93–108.
- TARI, G. 1994: *Alpine tectonics of the Pannonian basin*. — *Manuscript*, [PhD], Geology Department, Rice University, Houston, 501 p.
- TARI, G. and PAMIC, J. 1998: Geodynamic evolution of the northern Dinarides and the southern part of the Pannonian basin. — *Tectonophysics* 297 (1–4), pp. 269–281.
- TARI, G., HORVÁTH, F. and RUMPLER, J. 1992: Styles of Extension in the Pannonian Basin. — *Tectonophysics* 208 (1–3), pp. 203–219.
- TARI, G., BÁLDI, T. and BÁLDI-BEKE, M. 1993: Paleogene Retroarc Flexural Basin beneath the Neogene Pannonian Basin — a Geodynamic Model. — *Tectonophysics* 226 (1–4), pp. 433–455.
- TARI, G., DÖVÉNYI, P., DUNKL, I., HORVÁTH, F., LENKEY, L., STEFANESCU, M., SZAFIÁN, P. and TÓTH, T. 1999: Lithospheric structure of the Pannonian Basin derived from seismic, gravity and geothermal data. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen*. Geological Society of London, London, United Kingdom, Geological Society Special Publications 156, pp. 215–250.
- THORARINSSON, S., EINARSSON, T., SIGVALDASON, G. and ELISSON, G. 1964: The submarine eruption of the Vestmann Islands 1963–64. A preliminary report. — *Bulletin Volcanologique* 27, pp. 435–445.
- THORARINSSON, S. 1965: The Surtsey eruption: Course of events and development of Surtsey and other new islands. — *Surtsey Research Progress Report* II pp. 113–135.
- THORARINSSON, S. 1967: *Surtsey. The New Island in the North Atlantic*. — The Viking Press, New York, 47 p.
- TOPRAK, V. 1998: Vent distribution and its relation to regional tectonics, Cappadocian Volcanics, Turkey. — *Journal of Volcanology and Geothermal Research* 85 (1–4), pp. 55–67.
- TÖRÖK, K. and DE VIVO, B. 1995: Fluid inclusions in upper mantle xenoliths from the Balaton Highland, Western Hungary. — *Acta Vulcanologica* 7 (2), pp. 277–284.
- TÖRÖK, K., BALI, E., SZABÓ, Cs. and SZAKÁLL, J. A. 2003: Sr-barite droplets associated with sulfide blebs in clinopyroxene megacrysts from basaltic tuff (Szentbékáll, western Hungary). — *Lithos* 66 (3–4), pp. 275–289.
- TÓTH, Cs. 1994: A Kemenesháti tufagyűrűk geofizikai kutatása. [Geophysical investigation of tuff rings in the Kemeneshát]. — *Geophysical Transactions = Geofizikai Közlemények = Geofizicheskij Byulletin'* 39 (2–3), pp. 161–191.
- TULLNER, T. and CSERNY, T. 2003: New aspects of lake-level changes: Lake Balaton, Hungary. — *Acta Geologica Hungarica* 46 (2), pp. 215–238.
- VAKARCS, G., VAIL, P. R., TARI, G., POGÁCSÁS, G., MATTICK, R. E. and SZABÓ, A. 1994: 3rd-Order Middle Miocene Early Pliocene Depositional Sequences in the Prograding Delta-Complex of the Pannonian Basin. — *Tectonophysics* 240 (1–4), pp. 81–106.

- VASS, D., KONEČNÝ, V., TUNYI, I., DOLINSKY, P., BALOGH, K., HUDÁČKOVÁ, N., KOVAČOVÁ-SLAMKOVÁ, M. and BELACEK, B. 2000: Origin of the Pliocene vertebrate bone accumulation at Hajnačka, southern Slovakia. — *Geologica Carpathica* 51 (2), pp. 69–82.
- VERGNIOLLE, S. and MANGAN, M. 2000: Hawaiian and Strombolian eruptions. — In: SIGURDSSON, H., HOUGHTON, B., MCNUTT, S., RYMER, H. and STIX, J. (Eds): *Encyclopedia of Volcanoes*, Academic Press, New York, pp. 447–461.
- VESPERMANN, D. and SCHMINCKE, H.-U. 2000: Scoria cones and tuff rings. — In: SIGURDSSON, H., HOUGHTON, B. F., MCNUTT, S. R., RYMER, H. and STIX, J. (Eds): *Encyclopedia of Volcanoes*, Academic Press, San Diego, pp. 683–694.
- VITÁLIS, I. 1934: Adatok a Kab-hegy bazaltlávaömlésének a megismétlődéséhez (Zur Wiederholung des Basaltergusses des Kabhegy). — *Mat. u. Naturw. Anz. (Ung. Akad. Wiss.)* 50, pp. 520–529.
- VÖRÖS, I. 1962: Iddingsitesedés a kabhegyi bazaltban. — *Földtani Közlemény* 92 (2), pp. 174–184.
- VÖRÖS, I. 1966: A Kab-hegyi terület vulkanológiai és hegység szerkezeti viszonyai. — *Földtani Közlemény* 96 (3), pp. 292–300.
- VÖRÖS, I. 1967: Fe-Ti oxide minerals in Transdanubian (western Hungary) basalts. — *Annales Universitatis Scientiarum Budapestinensis de Rolando Eoetvoes Nominatae. Sectio Geologica* 10, pp. 99–108.
- WALKER, G. P. L. 1989: Gravitational (density) controls on volcanism, magma chambers and intrusions. — *Australian Journal of Earth Sciences* 36, pp. 149–165.
- WALKER, G. P. L. 1993: Basaltic-volcano systems. — In: PRICHARD, H. M., ALABASTER, T., HARRIS, N. B. W. and NEARLY, C. R. (Eds): *Magmatic Processes and Plate Tectonics*, pp. 3–38.
- WALKER, G. P. L. 2000: Basaltic volcanoes and volcanic systems. — In: SIGURDSSON, H., HOUGHTON, B. F., MCNUTT, S. R., RYMER, H. and STIX, J. (Eds): *Encyclopedia of Volcanoes*, Academic Press, San Diego, pp. 283–290.
- WATANABE, T., KOYAGUCHI, T. and SENO, T. 1999: Tectonic stress controls on ascent and emplacement of magmas. — *Journal of Volcanology and Geothermal Research* 91, pp. 65–78.
- WATANABE, T., MASUYAMA, T., NAGAOKA, K. and TAHARA, T. 2002: Analog experiments on magma-filled cracks: Competition between external stresses and internal pressure. — *Earth Planets and Space* 54 (12), pp. 1247–1261.
- WATERS, A. C. and FISHER, R. V. 1970: Maar volcanoes. — In: *Proceedings of the 2nd Columbia River Basalt Symposium, 1969*, Eastern Washington State College Press, Cheney Washington, pp. 157–170.
- WHITE, J. D. L. 1989: Basic elements of maar-crater deposits in the Hopi Buttes volcanic field, Northeastern Arizona, USA. — *Journal of Geology* 97, pp. 117–125.
- WHITE, J. D. L. 1990: Depositional architecture of a maar-pitted playa — sedimentation in the Hopi Buttes Volcanic Field, Northeastern Arizona, USA. — *Sedimentary Geology* 67 (1–2), pp. 55–84.
- WHITE, J. D. L. 1991a: The depositional record of small, monogenetic volcanoes within terrestrial basins. — In: FISHER, R. V. and SMITH, G. A. *Sedimentation in Volcanic Settings*, SEPM Special Publications 45, pp. 155–171.
- WHITE, J. D. L. 1991b: Maar-diatreme phreatomagmatism at Hopi Buttes, Navajo Nation (Arizona), USA. — *Bulletin of Volcanology* 53, pp. 239–258.
- WHITE, J. D. L. 1992: Pliocene subaqueous fans and Gilbert-type deltas in maar crater lakes, Hopi Buttes, Navajo Nation (Arizona), USA. — *Sedimentology* 39, pp. 931–946.
- WHITE, J. D. L. 1996a: Pre-emergent construction of a lacustrine basaltic volcano, Pahvant Butte, Utah (USA). — *Bulletin of Volcanology* 58, pp. 249–262.
- WHITE, J. D. L. 1996b: Impure coolants and interaction dynamics of phreatomagmatic eruptions. — *Journal of Volcanology and Geothermal Research* 65, pp. 1–17.
- WHITE, J. D. L. 2000: Subaqueous eruption-fed density currents and their deposits. — In: MUELLER, W., CHOWN, E. H. and THURSTON, P. C. (Eds): *Processes in physical volcanology and volcanoclastic sedimentation: modern and ancient*, *Precambrian Research* 101, pp. 87–109.
- WHITE, J. D. L. 2001: Eruption and reshaping of Pahvant Butte volcano in Pleistocene Lake Bonneville. — In: WHITE, J. D. L. and RIGGS, N. R. (Eds): *Volcanoclastic sedimentation in lacustrine settings*, Blackwell Sciences, Oxford, UK, Special Publication of the International Association of Sedimentologists 30, pp. 61–80.
- WHITE, J. D. L. and HOUGHTON, B. F. 2000: Surtseyan and related eruptions. — In: SIGURDSSON, H., HOUGHTON, B., MCNUTT, S., RYMER, H. and STIX, J. (Eds): *Encyclopedia of Volcanoes*, Academic Press, New York, pp. 495–512.
- WIJBRANS, J., NÉMETH, K., MARTIN, U. and BALOGH, K. 2004: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of a Mio/Pliocene phreatomagmatic volcanic field in the western Pannonian Basin, Hungary. — *Earth and Planetary Science Letters* [in review]
- WILSON, M. and BIANCHINI, G. 1999: Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions. — In: DURAND, B., JOLIVET, L., HORVÁTH, F. and SÉRANNE, M. (Eds): *The Mediterranean basins; Tertiary extension within the Alpine Orogen*, Geological Society of London, United Kingdom, Geological Society Special Publications 156, pp. 141–168.
- WITTECKSCHEN, G., SECK, H. A. and REYS, C. H. 1993: Multiple Enrichment Processes and Their Relationships in the Subcrustal Lithosphere beneath the Eifel (Germany). — *Journal of Petrology* 34 (1), pp. 1–22.
- WOHLETTZ, K. H. 1983: Mechanisms of hydrovolcanic pyroclast formation: grain-size, scanning electron microscopy, and experimental studies. — *Journal of Volcanology and Geothermal Research* 17, pp. 31–63.
- WOHLETTZ, K. H. 1986: Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies. — *Bulletin of Volcanology* 48, pp. 245–264.
- WOHLETTZ, K. H. 2002: Water/magma interaction: some theory and experiments on peperite formation. — *Journal of Volcanology and Geothermal Research* 114 (1–2), pp. 19–35.
- WOHLETTZ, K. 2004: Depth controls of water/magma interaction in maar volcanism. — *Geological Society of America, 56th Annual Meeting Rocky Mountain Section — 100th Annual Meeting Cordilleran Section, 2004 Abstracts with Program* 36 (4) [April 2004], May 3–5, 2004, Boise, Idaho, p. 84.
- WOHLETTZ, K. H. and SHERIDAN, M. F. 1983: Hydrovolcanic Explosions II. Evolution of Basaltic Tuff Rings and Tuff Cones. — *American Journal of Science* 283 (1983), pp. 385–413.
- WOHLETTZ, K. H. and MCQUEEN, R. G. 1984: Experimental studies in hydromagmatic volcanism. — In: *Studies in Geophysics: Explosive volcanism: Inception, evolution and hazards*, National Academy Press, Washington, pp. 158–169.

- WOOD, S. H. and CLEMENS, D. M. 2004: Tectonic and magmatic evolution of the Snake River Plain volcanic province. In: BONNICHSEN, B., McCURRY, M. and WHITE, C. (Eds): *Tectonic and magmatic evolution of the Snake River Plain volcanic province*. Idaho Geological Survey, Moscow, pp. 69–103
- ZELENKA, T. 1960: Kőzettani és földtani vizsgálatok a Dunazug-hegység DNy-i részén. — *Földtani Közöny* 90 (1), pp. 83–102.
- ZIMANOWSKI, B. 1998: Phreatomagmatic explosions. — In: FREUNDT, A and ROSI, M. (Eds): *From magma to tephra*. Elsevier, Amsterdam, pp. 25–53.
- ZIMANOWSKI, B. and BÜTTNER, R. 2002: Dynamic mingling of magma and liquefied sediments. — *Journal of Volcanology and Geothermal Research* 114(1–2), 37–44.
- ZIMANOWSKI, B., LORENZ, V. and FRÖHLICH, G. 1986: Experiments on phreatomagmatic explosions with silicate and carbonatitic melts. — *Journal of Volcanology and Geothermal Research* 30, pp. 149–153.
- ZIMANOWSKI, B., FRÖHLICH, G. and LORENZ, V. 1991: Quantitative Experiments on Phreatomagmatic Explosions. — *Journal of Volcanology and Geothermal Research* 48 (3–4), pp. 341–358.
- ZIMANOWSKI, B., FRÖHLICH, G. and LORENZ, V. 1995: Experiments on steam explosion by interaction of water with silicate melts. — *Nuclear Engineering and Design* 155 (1–2), pp. 335–343.
- ZIMANOWSKI, B., BÜTTNER, R., LORENZ, V. and HAFELE, H. G. 1997: Fragmentation of basaltic melt in the course of explosive volcanism. — *Journal of Geophysical Research-Solid Earth* 102 (B1), pp. 803–814

**Shaded relief model of the Little Hungarian Plain Volcanic Field (excluding the Styrian Basin Volcanic Field) (A).
Simplified geological map of the Bakony – Balaton Highland Volcanic Field (B) with the localities of volcanic erosion remnants**

1. Badacsony, 1a. Hármashegy, 2. Szent György-hegy, 3. Gulács, 4. Haláp, 4a. Véndek-hegy, 5. Fekete-hegy south, 5a. Boncsos-tető, 6. Bondoró west, 7. Hegyesd, 8. Szigliget, 9. Fonyód, 10. Boglár, 11. Agár-tető, 12. Tagyon, 13. Csobánc, 14. Hajagos, 15. Kopasz-hegy, 16. Pipa-hegy, 17. Kékkút (Harasztos-hegy), 18. Kerekidomb, 19. Öreg-hegy, 19a. Balatonhenye, 20. Horog-hegy, 21. Szentbékálló, 21a. Füzestő (Kopácsi-hegy), 22. Kis-Hegyes-tű/Lapos-Hegyes-tű, 23. Kapolcs, 24. Tálodi-erdő, 25. Pula, 26. Kab-hegy west, 27. Bondoró east, 28. Hegyes-tű, 29. Kab-hegy peak, 30. Tóti-hegy group, 31. Halom-hegy, 32. Sátorma, 33. Tihany, 34. Taliándörögd hills, 35. Öcs hill



Typical volcanic landforms associated with phreatomagmatic volcanic fields



Crater Elegante (Mexico), maar

Diatremes of Hopi Butte, Arizona

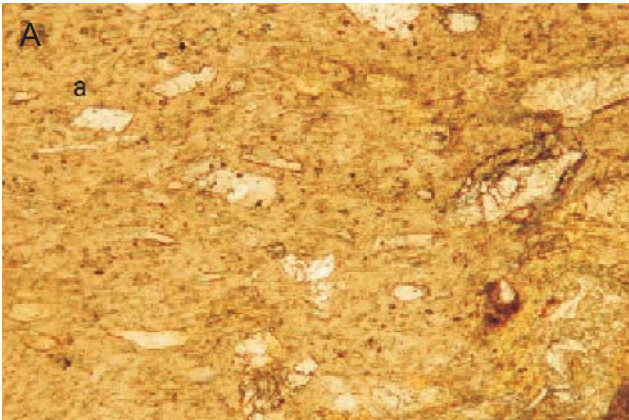


Cerro Colorado (Mexico), tuff ring

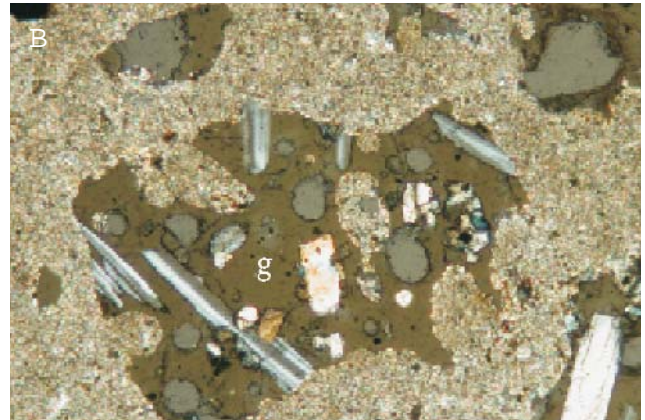
Cinder (scoria) cones of the Durango Volcanic Field (Mexico)



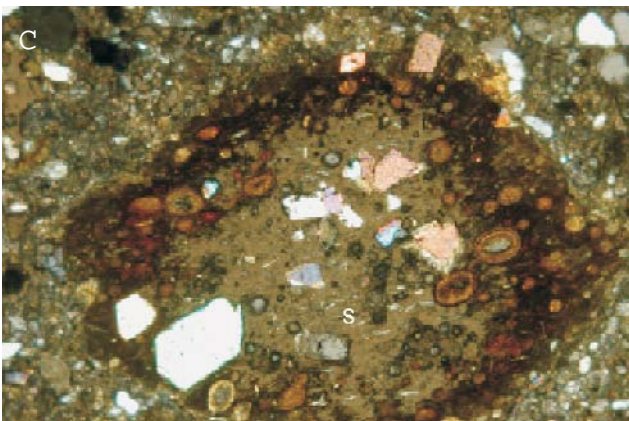
Volcanic glass shards on photomicrographs from the western Pannonian Basin



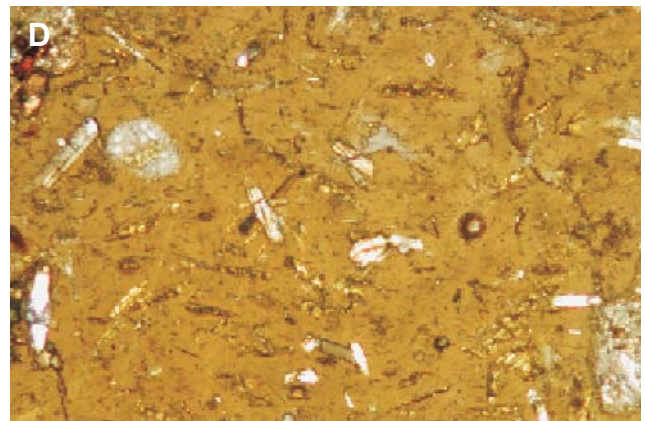
Boglár diatreme; oriented microlite-rich glass shard. The shards often contain amphybole crystals (a). The shorter side of the photo is 1 mm [parallel plane light]



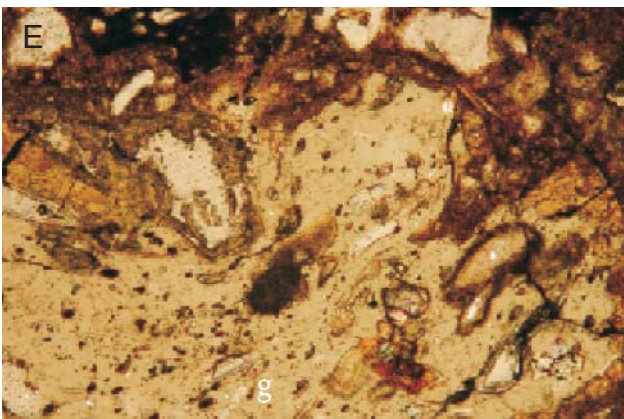
Pula; moderately vesicular, blocky volcanic glass shard (g) from a glass shard rich layer in the maar lake lacustrine succession. The short side of the photo is 1 mm [parallel plane light]



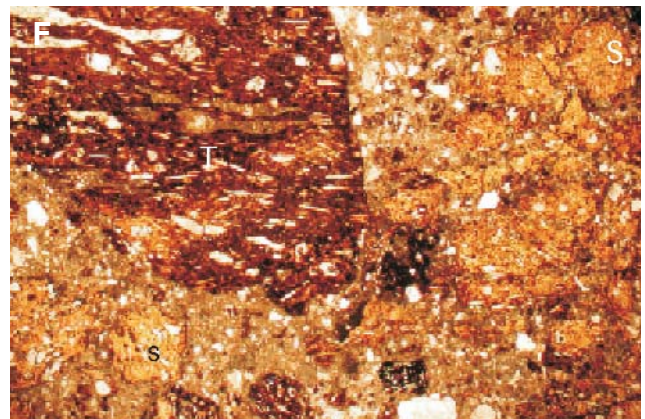
Egyházaskesző; blocky, moderately vesicular sideromelane glass shard (s) with palagonite rim (dark rim) from a lapilli tuff. Note the non-oriented, microphenocryst bearing texture of the glass shard. The short side of the photo is 1 mm [parallel plane light]



Uzsza; vesicle-free, non-oriented microphenocryst bearing glass shard. The short side of the view is 0.5 mm [parallel plane light]



Hármashegy; moderately vesicular, microlite-poor tephritic glass shard (g) from a diatreme. The short side of the photo is 0.5 mm [parallel plane light]



Kékkút diatreme; glass shard with trachytic texture (T). Note the smaller, lighter coloured sideromelane glass shards (s). The short side of the photo is 1 mm [parallel plane light]

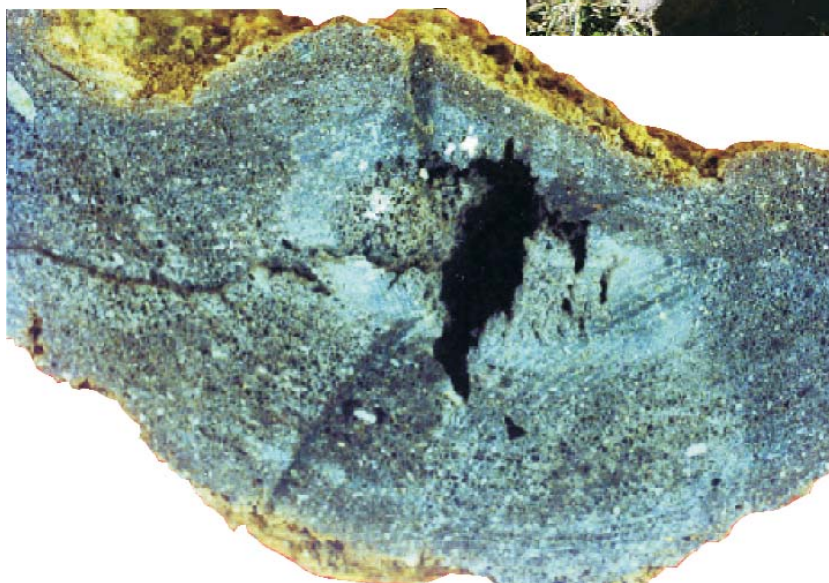
*Plate 4 | Chapter 1**Second International Maar Conference — Hungary–Slovakia–Germany*

Lherzolite xenolith (s) from a spindle bomb ~30 cm across (A) from the Füzes-tó. A great variety of mantle nodules can be found in dense (B) as well as highly vesicular spindle bombs (C – bomb is 40 cm across) from this region



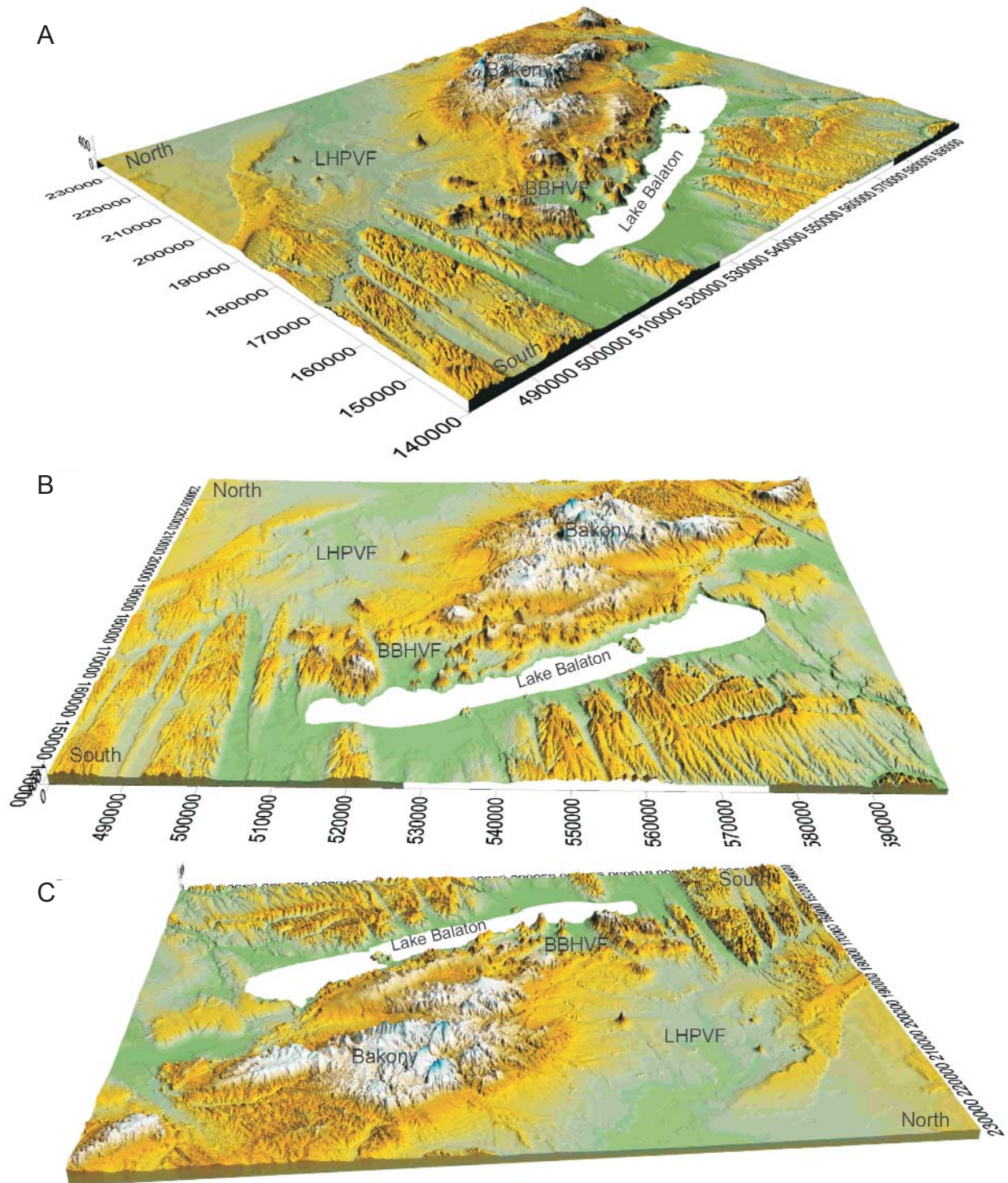
A

B



C

Oblique 3D views of the Bakony – Balaton Highland and the Little Hungarian Plain Volcanic Fields



North-south elongated hill of Hajagos, looking from the Csobánc (from west). The lines mark the limit of volcanic rocks mapped.

Lava flow — l, Pyroclastic rock units — px, Neogene siliciclastic units — Ns, Quarry — Q





A Scoria cone and adjacent lava flow field in the La Breña Maar, Mexico. This maar is in good analogy with maar remnants of the BBHVF such as the Pula Maar prior to flooding by water



B Columnar jointed basanitic lava exposing variable oriented jointing pattern (Haláp)



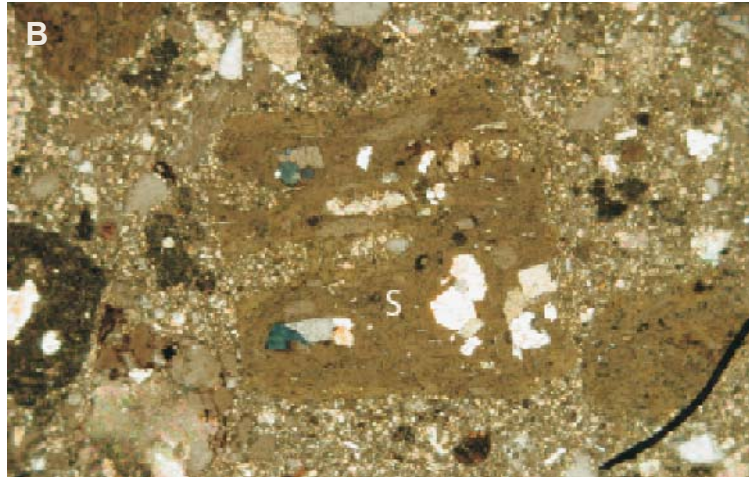
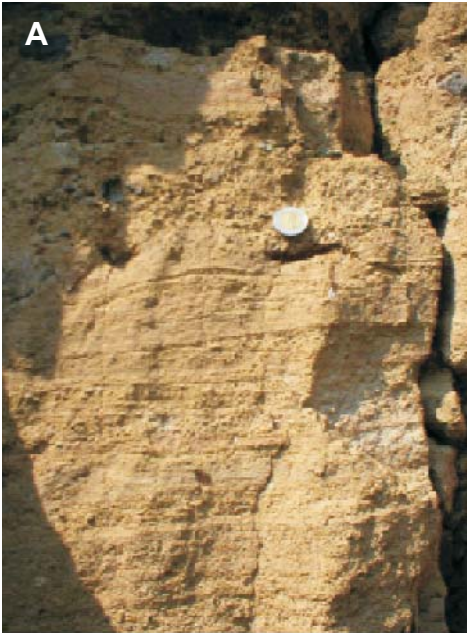
C Rosette-like joints in the Sümegprága shallow sill and dyke complex



D Blocky peperite from Hajagos developed due to interaction of basanite melt and fine grained, wet, siliciclastic sediment

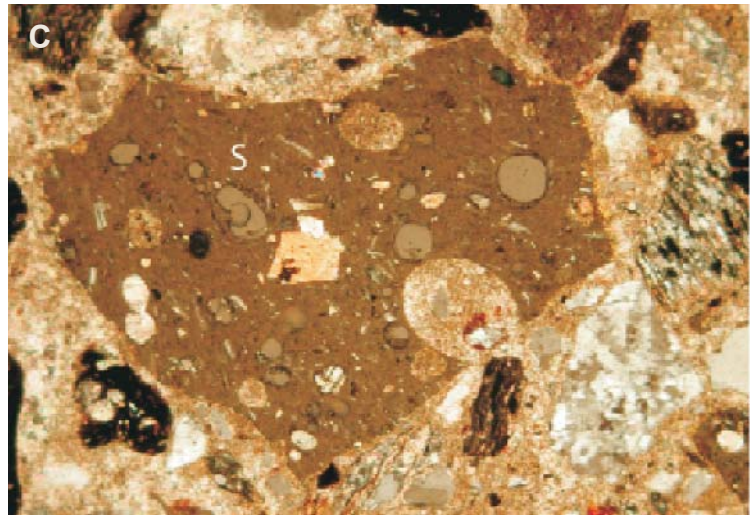


E Peperitic sill that intruded into the tuff ring sequence of the Ság-hegy

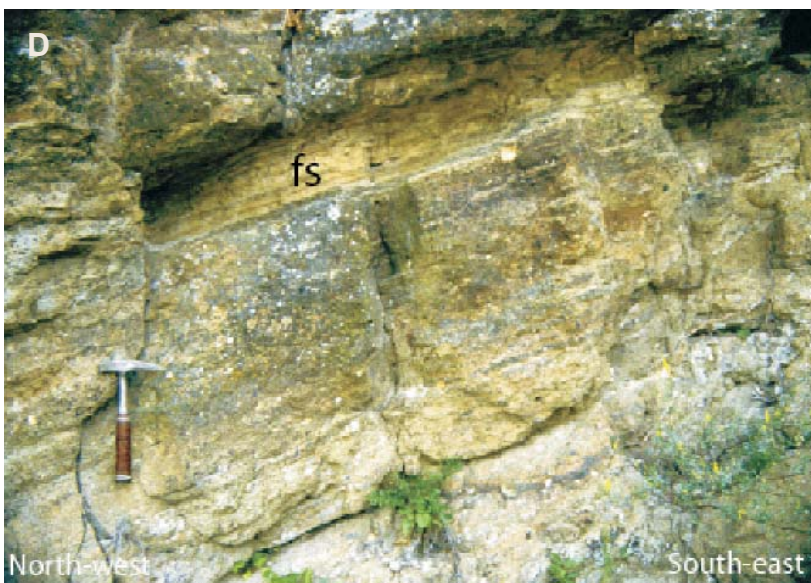


Photomicrograph of blocky volcanic glass shard (S) from Fekete-hegy, BBHVF (half cross polarized light). The shorter side of the picture is about 2 mm

Accidental lithic rich tuff from Ság-hegy. The dominant proportion of the clasts are sand or quartz derived from Neogene clastic succession, all suggested earlier that the deposit is rather a siliciclastic deposit, and therefore volcanism and siliciclastic deposition from the Pannonian Lake is coeval. After careful studies it is concluded that most of these samples are base surge deposits from energetic explosions in the unconsolidated sand beds



Photomicrograph of blocky moderately vesicular glass shard (S) from Tihany, BBHVF (half cross polarized light). The shorter side of the picture is about 2 mm



Dry surge bed from Szigliget, exhibiting a larger amount of glassy shards as well as thermally affected clasts and minerals from the immediate pre-volcanic siliciclastic rock units