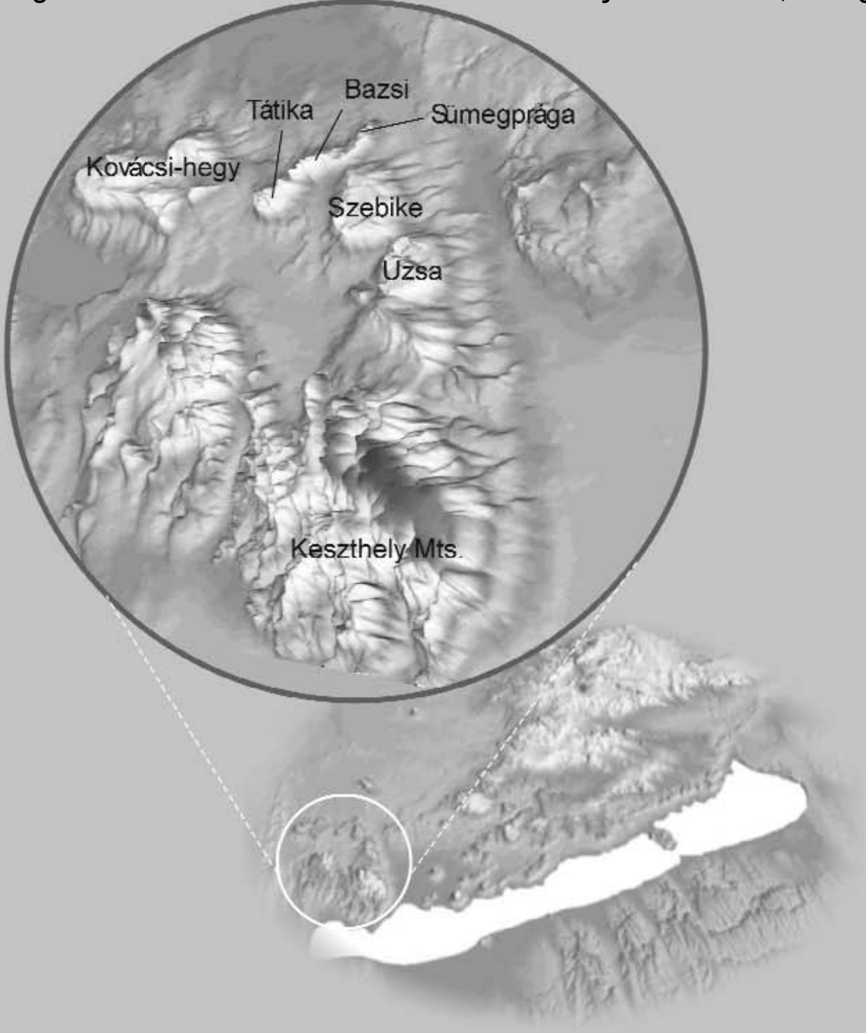
geologica hungarica
SERIES GEOLOGICA, TOMUS 26, pp. 133–152

Shallow sub-surface intrusive processes associated with phreatomagmatic volcanism north of the Keszthely Mountains, Hungary



Contents

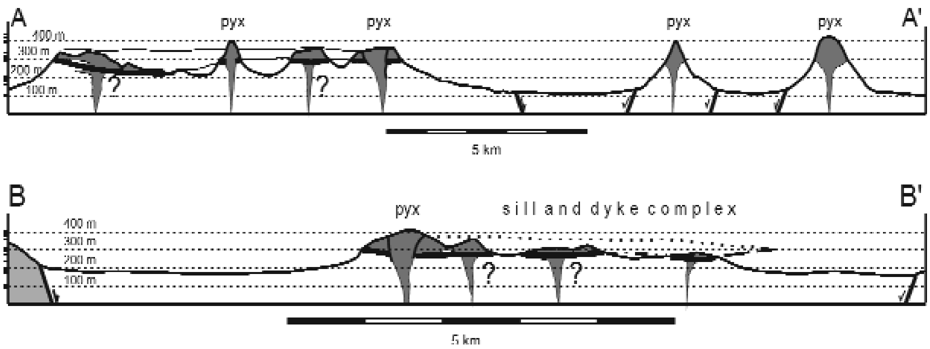
Abstract

Neogene alkaline basaltic rocks in the western Pannonian Basin are eroded remnants of former maars, tuff rings, tuff cones, scoria cones and lava fields. The erosion level of these volcanoes is deep enough locally to expose diatreme zones associated with the phreatomagmatic volcanoes. West of the Bakony – Balaton Highland Volcanic Field the erosion level is deeper yet, exposing shallow subsurface dyke and sill swarms related to former intra-plate volcanoes. The basanitic sills are irregular in shape and their lateral extent is highly variable. Individual sills reach a thickness of a few tens of metres and they commonly form dome-like structures with rosette-like radial columnar joint patterns. The largest sill system identified in this region is traceable over kilometres, and forms a characteristic ridge running north-east to south-west. Elevation differences in the position of the basanitic sills within an otherwise undisturbed "layer cake-like" siliciclastic succession indicate emplacement of the basanite magma at multiple levels over kilometre-scale distances. The margins of sills in the system are irregular at a dm-to-mm-scale. Undulating contacts of the sills together with gentle thermal alteration in the host sediment over cm-to-dm distances, indicate the soft, but not necessarily wet state of the host deposits at the time sills were intruded. Parts of the sill complex show a complicated relationship with the host sediment in form of peperitic zones and irregularly shaped, disrupted, peperite textures. This is interpreted to reflect inhomogenenities in water content and rheology of the siliciclastic deposits during intrusion. The current summit of this ridge preserves a small diatreme that seems to cut through an otherwise disk-like sill indicating to some degree of relationship between sill emplacement and phreatomagmatic explosive eruptions. A complex pyroclastic-to-lava succession is exposed in a large, still active quarry in the eastern part of an area inferred to represent a maar basin that was filled by post-maar lava flows, volcanic debris avalanche deposits, and by scoria cones.

Keywords: maar, diatreme, monogenetic, erosion, sill, dyke, dome, basalt, peperite

Introduction

Pliocene volcanic rocks crop out north of the Keszthely Mts and form an elevated ridge reaching more or less the same elevation (>300 m) as the southern Triassic limestone and dolomite blocks (Plate 4.1 and Figure 4.1). The volcanic rocks are somehow separated from the main volcanic zone of the Balaton Highland and form a distinctive cluster (Plate 4.1). The volcanic rocks in this area form a north-west to south-east trending zone, but the ridge alignments are different from this direction. The erosional remnants in the central part of the area form a very characteristic north-east to south-west ridge like feature (Plate 4.1). Volcanic rocks form mesa-like hills west (Kovácsi-hegy) and south-east (Szebike) of this ridge (Plate 4.1). The immediate pre-volcanic rocks are Neogene siliciclastic siltstones, sandstones, silt and sand. The southern margin of the area is fault bounded against Triassic limestone with a dolomite ridge that reaches an elevation of over 400 metres. Lava capped mesas (e.g. Tátika – 413 m, Uzsa lava plateau – 340 m) are more or less at the same elevation. The volcanic rocks are situated in a graben-like zone bounded by faults, a north-westward continuation of the Tapolca Basin (Plate 4.1 and Figure 4.1).



Figures 4.1. Simplified cross sections through the volcanic hills north of the Keszthely Mts. Thick line shows the possible lower margin of the coherent lava inferred to be a sill complex
Dashed line projects the possible upper contact of the sill complexes (pyx = pyroclastic rocks). Cross section lines are shown on Plate 4.1

Pyroclastic rocks crop out in large volumes only at the Uzsa locality (Plate 4.1). Small outcrops of pyroclastic rocks have been identified high up on Tátika (at about 380 m). The other localities show only coherent basanite. The basanite ridge of the Tátika–Sümegprága (Sarvaly) is a chain of irregularly shaped, commonly rosette-like columnar jointed basanites that are in intrusive contact with the host Neogene siliciclastic rock units. In contrast, the Kovácsi-hegy is a tabular basanite flow with multiple flow units forming vertically oriented columnar joints. A basanite ridge formed by dissected bud-like basanite intrusions forms a north-west to south-east ridge just south of Uzsa (Kő-orra).

The ages of the lava flows are among the youngest of the Pliocene intraplate volcanic rocks in the western Pannonian Basin and range between 3.4 to 2.7 My (BALOGH and PÉCSKAY 2001, BALOGH et al. 1986). This age range is similar to that of volcanic rocks of the Tapolca Basin (BALOGH et al. 1986, BORSY et al. 1986). This similarity also highlights the genetic relationship between these volcanic rocks and those of the Tapolca Basin.

Uzsa

Uzsa is the most voluminous Pliocene volcanic remnant north of the Keszthely Mts. It is diverse in type of preserved pyroclastic and effusive/intrusive rocks and their origin not yet fully understood. One of the largest still-active basalt quarries is located here. The intensive quarrying, which began in the fifties, has removed a significant part of the coherent basaltic lava, and gives access to the inner architecture of the lava capped mesa (Plate 4.2).

The lava flow units inferred to locate on horizontally bedded Neogene siliciclastic units. The contact zone, which is not exposed, is estimated to be at an elevation of about 300 m. The lava flows in the quarry wall expose multiple flow units. The basanitic rock is in general vertically jointed (Plate 4.3, A, B) with a few dm-wide columns which may reach heights up to 20 m. The basanite unit base to the pre-volcanic sedimentary rock units is not exposed anywhere in the quarry.

Between lava flow units large irregular zones of highly vesicular lava domains in a whitish, sandy, silty matrix are common (Plate 4.3, C). A few dm-sized pillow-like, vesicular lava bodies in the foot wall form a well-packed structure with preferred orientation of the individual pillow lobes. The transition to the coherent lava body is continuous, and a drop-like texture and gradual increase of vesicularity of the lava flow unit toward the pillowed zone can be identified (Plate 4.3, C). Such pillowed lava foot zones are present in different levels of the quarry and indicate that lava effusion may have been discontinuous. The silt and sand forming part of the matrix of these pillowed zones suggests that following a lava effusion stage, a short period of sedimentation took place on the surface of the older lava flows. The lava flows immediately above the pillowed lava foot zone are platy jointed (Plate 4.3, C). This joint pattern changes gradually to more-vertical jointing patterns up-section. In several parts of the quarry an onion-like joint pattern is prominent near the known and/or inferred margin of the lava flow (Plate 4.4, A, B), which suggests that the lava may be close to the margin towards the sediment.

Pyroclastic successions

The largest volume of pyroclastic rocks is preserved at Uzsa just north of the Keszthely Mts. The pyroclastic rocks are grouped in two distinct units:

1. In the central and western part of the quarry massive, weakly bedded, matrix-supported, grey to brown, accidental lithic-rich lapilli tuff and tuff breccia (Plate 4.4, C) crop out, and form a few tens of metres thick succession truncated by coherent basanite lava flows.

2. Red, weakly bedded, scoriaceous lapilli tuff and tuff breccia (Plate 4.5) crop out on the top of the major succession of coherent lava flows in the southern side of the quarry.

The first unit is rich in sideromelane glass shards that are moderately to weakly vesicular and blocky in shape (Plate 4.6), which suggests phreatomagmatic fragmentation (BÜTTNER et al. 1999, 2002, DELLINO and LIOTINO 2002). The glass shards are tephritic in composition and often show well-developed gel palagonitic rims (Plate 4.6). The pyroclastic rocks are characteristically rich in large, angular, non-vesicular blocky volcanic lithic fragments up to a metre in size (Plate 4.6, C). These blocks are porphyritic in texture and commonly fractured.

The weakly bedded, ill-sorted lapilli tuff unit dips approximately 15 degrees more steeply outward than the pyroclastic rocks of the same unit in the centre of the Uzsa volcanic complex, which may indicate the presence of a tuff ring (or pyroclastic mound) that was part of a former phreatomagmatic volcano. However, an alternative possibility is that basalt intrusion resulted in tilting of originally more shallow-dipping beds. Moderate amounts of non-volcanic accidental lithic fragments have been identified as predominantly abraded fragments of siltstone and sandstone. These clasts are characteristically derived from the immediate pre-volcanic Neogene units. The basal massive part of the pyroclastic rocks of unit 1, however, contains white, smooth surfaced, carbonate-rich silt fragments interpreted to have been derived from lacustrine units which are however unknown in the local strata (Plate 4.7, C).

In the upper level of the Uzsa quarry, reddish, moderately bedded, scoriaeous lapilli tuff and tuff breccia units (unit 2) form at least a few tens of metres thick succession capping the hills. The pyroclastic rocks of this unit contain a large number of fluidally shaped, dense to highly vesicular lava fragments (Plate 4.8, A, B). The size and the packing of vesicular lava clasts change gradually from south to north. Ambiguously, the succession also bears textural characteristics of a lava delta foot zone (SCHMINCKE et al. 1997, SKILLING 2002). There is a gradual decrease in dip from 20–25 degrees in the pyroclastic beds toward a shallow-dipping platy jointed, undulating coherent basanite flow.

In the upper section of the quarry, the contact zone between coherent lava and phreatomagmatic lapilli tuff units (unit 1) is exposed (Plate 4.7, A). The contact zone is sharp but irregular (Plate 4.7). It is obvious that the lava flow, now quarried away to leave behind a castle-like structure, post-dates the deposition of the pyroclastic units, and it is inferred to have rather had a shallow intrusive contact (e.g. lava lake emplacement) with the pyroclastic succession similarly to that at Ság-hegy (MARTIN and NÉMETH 2002, 2004).

Interpretation

The predominantly chaotic textural characteristics and the thickness of the tuff breccia and lapilli tuff beds of unit 1 suggest that the fragments of this unit were transported and deposited from volcanic debris flows associated with phreatomagmatic volcanoes similar to those of the Iblean Mts, Sicily (SCHMINCKE et al. 1997). However, ongoing research highlights that not all "massive" beds associated with phreatomagmatic volcanoes result from secondary remobilization of tephra (e.g.

Ferrar, Antarctica – HANSON and ELLIOT 1996) but that some may represent primary products of a phreatomagmatic eruption (e.g. Ferrar, Antarctica – WHITE and MCCLINTOCK 2001). To distinguish these sediments of different origin are not easy as it is known from the Ferrar province (ELLIOT and HANSON 2001), and it is a subject of ongoing research in the western Pannonian Basin, as well. The deposits may represent crater and/or vent filling units that accumulated in the crater and/or conduit of a phreatomagmatic volcano, e.g. a maar. The presence of oriented vesicles in some of the otherwise dense volcanic blocks of the pyroclastic rocks of unit 1 suggests that the vesicle elongation reflect stretching or shear of the magma either in the vent (e.g. dyke – BÜCHEL and LORENZ 1993) or afterwards, e.g. that they were parts of lava foot breccias (FISHER and SCHMINCKE 1984). The common presence of these dense volcanic lithic fragments in the massive to weakly-bedded lapilli tuff and tuff breccias, especially in the basal part of the unit 1 indicates that

1. coherent lava bodies must have existed prior to the phreatomagmatic eruptions, similarly to other fields such as the Crater Elegante (Pinacate, Sonora, Mexico – GUTMANN 1976), and/or

2. they have been derived rather from dykes than from previous lavas (HOUGHTON and SMITH 1993, VESPERMANN and SCHMINCKE 2000).

Fluid-form vesicular lava fragments in unit 2 are inferred to be small lava bombs and lapilli that rolled down-slope on the flanks of a former volcanic edifice (HEAD and WILSON 1989, THORDARSON and SELF 1993, ELLIOT and HANSON 2001). The gradual change of packing from south to north suggests a rapid change in volcanic facies architecture reflecting a nearby source. The bedding and the clast distribution pattern within this unit suggest that it originated by piling up of volcanic material in conjunction with ongoing remobilization on the flank of a volcano (HOUGHTON and SCHMINCKE 1989, VESPERMANN and SCHMINCKE 2000), rather than by successive deposition from spatter-rich pyroclastic density currents (VALENTINE et al. 2000). The gradual transition in bedding dips could alternatively suggest that the deposit represents a lava delta (SKILLING 2002), though no pillow lava nor pillow-fragment breccias that would add support for this interpretation have been identified. The abundance of fine-grained, lithic-derived clasts in the matrix of the succession is also suggestive of a scoria cone origin.

In summary, the Uzsa quarry (Láz-hegy) provides an excellent view into the inside of a lava capped mesa. Such mesas are very common in Western Hungary, but the rocks forming them are often poorly exposed, with only coherent lava flows traceable at the surface. The great thickness of the massive to weakly-bedded pyroclastic rocks at the basal zone of the Uzsa volcanic succession are inferred to have phreatomagmatic origin and indicate that magma/water interaction played an important role in the formation of the Uzsa volcanic complex. The relatively low proportion of non-volcanic accidental lithic fragments in these pyroclastic rocks indicates that the magma/water interaction that triggered explosive fragmentation occurred near the surface and/or there was not very much water available to fuel magma/water interaction. However, the large proportion of volcanic lithic fragments may be interpreted as fragments from a thick pile of coherent flows that formed the immediate pre-volcanic succession, and through which the explosive eruptions quarried. The topmost scoriaceous pyroclastic succession could be interpreted as either part of a scoria cone or as a lava delta. The hill south of the southern limit of the Uzsa quarry is interpreted to be a remnant of a scoria cone. Thus both lava deltas and scoria cones (which may have been the source of the lava flows) may have coexisted in Uzsa.

Sümegprága

Sümegprága is the northernmost part of a ~5 km long ridge exposing volcanic rocks and trending from north-east to south-west (Plate 4.9, A–E), with the ridge at Sümegprága reaching an elevation of about 260 m. Coherent lava flows appear at elevations around 220 metres and above (Plate 4.9, A–E). At this site basanitic lava has been quarried in the past, exposing the three dimensional architecture of the coherent lava unit. The lava flows form a small, flat hill, that has been opened up during the quarrying (Plate 4.9, A–E). The basanite is in intrusive contact with the host Neogene siliciclastic units. There are tabular and rosette-like coherent basanite that are in sharp but irregular contact with the host sediment (Plate 4.10, A, B). The contact zones of the coherent basanite are thermally affected (Plate 4.10, C), with sand and silt slightly hydrothermally altered at the contact zone of up to a metre near the intrusive bodies (Plate 4.10, C). Small protrusions from the master sills commonly form irregularly shaped dm-to-metre thick dykes with chilled margins (Plate 4.10, D). Peperitic margins are rare, and only exposed in small, dm-scale zones where slightly baked sand/silt is in contact with coherent flows. The textural characteristics of the host sediment are the same as for other Neogene siliciclastic units forming the immediate pre-volcanic successions elsewhere in the region. Small outcrops around Sümegprága show intrusive contacts between coherent lava bodies and host sediments, indicating that the ridge is consist of a sill and dyke complex.

Bazsi to Tátika

In the continuation of the ridge from Sümegprága to the south-west a sill/dyke complex is exposed in another, smaller, quarry (Plate 4.11, A–C). The sills are very irregular in shape and have chilled margins (Plate 4.12, A). Along the margin of the coherent lava body the host sediment is thermally affected in a dm-to-metre wide zone. In places, irregular margins and globular peperites can be identified (Plate 4.12, B). In these zones, the lava showed fluidal behavior and blobs which are mixed with the host sediment. Because there is no obvious evidence of high temperature alteration of the silt/sand along the coherent magmatic bodies (e.g. hornfels) we can only state that at least some hydrothermal effect on the host sediment (Plate 4.12, B) took place along the intrusive bodies.

In the upper quarry small finger-like lava intrusions into the host sediment can be observed, and terminate into an irregularly shaped zone of volcaniclastic rock (Plate 4.12, C). The clasts in this unit are angular, non-to-moderately vesicular, black and basanitic in composition, and are hosted by a fine, homogenised silt/sand (Plate 4.12, C). The basanitic clasts are generally finely crystalline or tachylitic in texture, but have cm-thick palagonite rims (Plate 4.12, C).

The 3D relationships of the coherent basanite with the host rock indicate that at Bazsi a sill and dyke complex is exposed. The location of this quarry is close to the Sümegprága quarry, and the elongation of the basanite body along the length of the ridge indicate that Bazsi is part of the same major sill and dyke system that runs from north-east to south-west. Similar dyke and sill complexes in poorly exposed settings have been mapped out to the south-west. Other major ridges, south-west of Bazsi, each represent bud-like basanite bodies that have rosette-like columnar jointing.

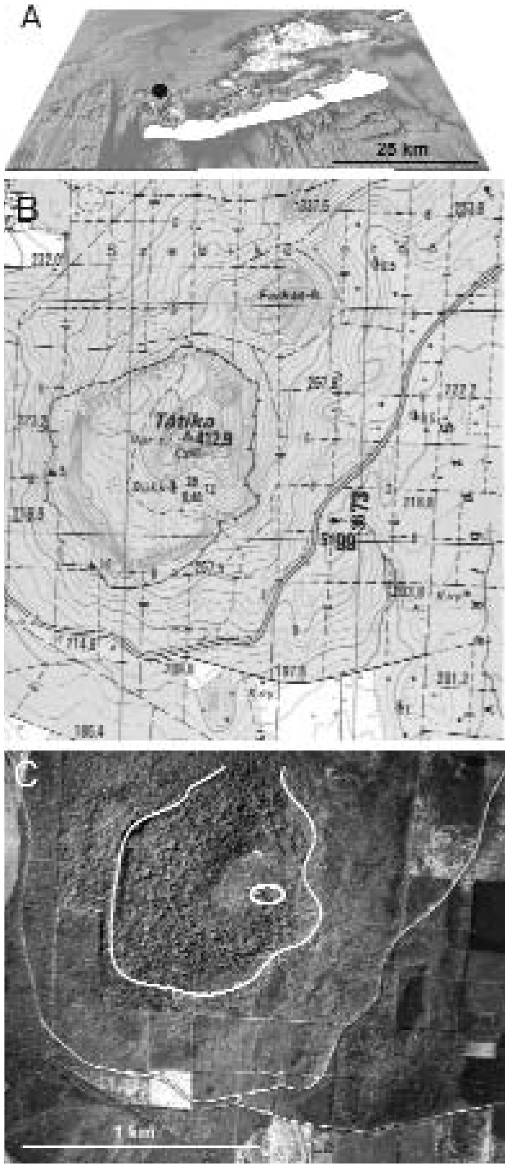
The most south-western hill of the ridge terminates in a circular shaped plateau-like lava region forming the plateau of the hill Tátika (Figure 4.2). The quarry of Bazsi exposes basanitic sills up to the level of 300 metres, and is covered by the same sand as it is exposed in the quarry itself. The plateau at Tátika reaches 350 metres (Figure 4.2). This plateau is cut through by few basanite buds that are characterized by rosette-like columnar jointing. In the basal zone pyroclastic rocks are exposed.

Pyroclastic rocks, collected from poor outcrops away from the quarry, are rich in fine sand, silt, quartz grains, and mud chunks (mm-to-cm size), derived from rock types characteristic of the immediate pre-volcanic Neogene rock units (Plate 4.12, D). The pyroclastic rocks of Tátika contain sideromelane glass shards that are blocky in shape and moderately vesicular, typical products of phreatomagmatic fragmentation (Heiken and Wohletz 1986, 1991, Wohletz 1986). The glass shards are tephritic in composition, similar to glass shards from Neogene phreatomagmatic lapilli tuff and tuff units elsewhere in the western Pannonian Basin (Martin et al. 2003).

The general spatial relationship between coherent lava units of Bazsi and Tátika, and the Neogene siliciclastic succession indicate that the basanite is in intrusive contact with the sedimentary rocks, and is part of an elongated sill and dyke system in this region. The only location where pyroclastic rocks are exposed is Tátika, indicating that explosive eruption took place in that site. The textural characteristics of the recovered pyroclastic rocks indicate that the explosive eruptions of Tátika were driven by magma/water interaction. The pyroclastic succession seems to be cut by basanitic sills and dykes, which suggests sill/dyke intrusion after the phreatomagmatic eruption of Tátika. The erosion levels at these locations are deep. The minimum level of the syn-volcanic palaeosurface is at the top of the Tátika, assuming that

1. there has been no uplift nor tectonic dissection of the volcanic rock-capped ridges between Tátika and Sümegprága, and

2. Tátika pyroclastic rocks represent the top, rather than lower parts, of a diatreme. Even if the present hill top of Tátika really is the top of a diatreme, its position therefore should represent a level below the syn-volcanic palaeosurface using general considerations for the 3D architecture of a diatreme (Lorenz 1987, 2000a, b, White 1991a, b). It is hence a conservative estimate that the immediate pre-volcanic Neogene siliciclastic units were all present at the time of eruption in this region, and that the sill complex hence intruded at depths of at least 50-100 metres below the palaeosurface. It is very likely, however, that this depth is an underestimate, and that the Neogene sedimentary cover has suffered some 200–300 metres of erosion in this region, as has been calculated for the Bakony – Balaton Highland Volcanic Field (Németh and Martin 1999).

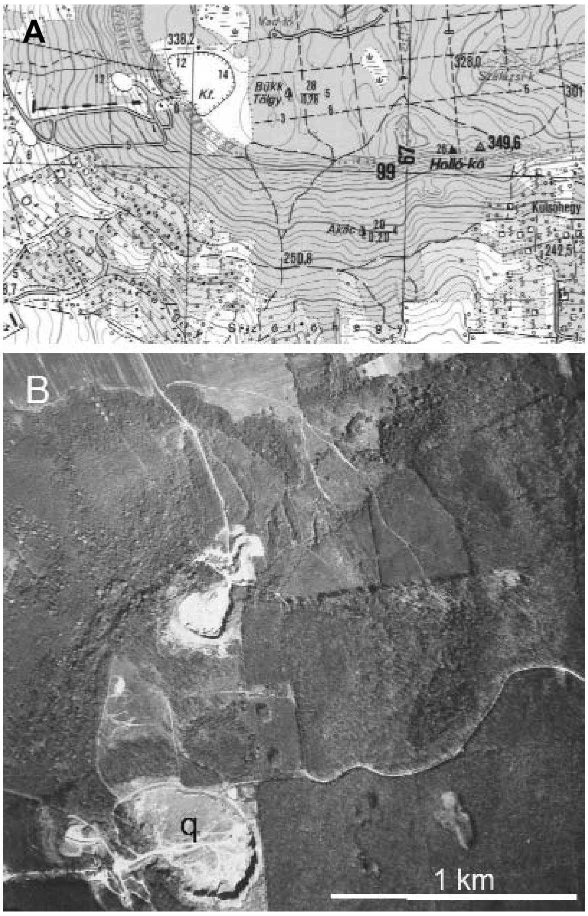


Figures 4.2. Location map of Tátika (A), which marks the termination of the volcanic rock ridge between Sümegprága and Tátika

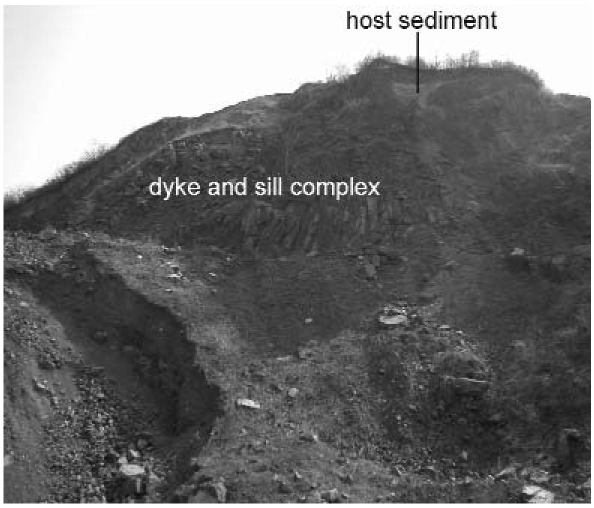
Note the plateau forms a circular zone at Tátika (B, C) that corresponds well with the extent of coherent basanite units (white line). On this plateau a cliff is well visible on aerial photo (C). This cliff preserves a massive, lapilli tuff succession (white circle), however, in poorly preserved condition

Kovácsi-hegy

The Kovácsi-hegy comprises the westernmost Neogene alkaline basaltoid volcanic hills north of the Keszthely Mts. (Figure 4.3). The Kovácsi-hegy forms a circular plateau about 300 m in elevation marking the extent of the lava flows over the Neogene sands and silts. East of this lava plateau, the morphology is more rugged, and consists of north-east to south-west, and north-west to south-east, trending ridges, similar to the ridge between Sümegprága and Tátika (Figure 4.3). These ridges consist of coherent basanite buds having intrusive contacts with Neogene siliciclastic host units similar to those exposed in east (Figure 4.4). The contact between the pre-volcanic rocks and coherent basanite is not exposed at the Kovácsi-hegy. In a large quarry system along the western margin of the Kovácsi-hegy a basanite unit at least 50 m thick and comprises at least two cooling units. The basanite body is columnar jointed with perpendicular, very regular columns that are 20 to 40 cm in diameter. In the area there are no pyroclastic rocks exposed.



Figures 4.3.
Location map of the Kovácsi-hegy (A). On the airphoto it is clearly visible, that the Kovácsi-hegy forms a circular plateau around 300 m elevation (B). East of this plateau, the morphology is more rugged, and consists of north-east to south-west as well as north-west to south-east trending ridges, similar to the ridge between Sümegprága and Tátika. These ridges consist of basanite buds with intrusive contact to a host Neogene siliciclastic units similar to those exposed in east, q = quarry



Figures 4.4. Intrusive basanitic lava bud – similar to the lava buds at Bazsi – in a host Neogene sand and silt from a small quarry east of the Kovácsi-hegy

Conclusion

The volcanic rocks mapped north of the Keszthely Mts have long been a subject of geological research in the region (LÓCZY 1913, 1920, JUGOVICS 1948). Each researcher noted the general lack of pyroclastic rocks in these locations in comparison to other Neogene alkaline basaltic regions in the western Pannonian Basin. Current research confirms that there is a general lack of pyroclastic rocks in this region, and this may be of some significance in analysis of the volcanic evolution of the Neogene alkaline basaltic systems in the western Pannonian Basin. The volumetrically largest known pyroclastic succession is at Uzsa, which had a significant phreatomagmatic explosive eruptive history, and may have formed a maar and/or tuff ring. The Uzsa phreatomagmatic succession subsequently was covered by effusive and eruption products generated by magmatic fragmentation. The topmost volcanic succession at Uzsa has been interpreted as the erosional remnant of scoria cones or possibly of lava deltas. The circular distribution of the lava fields at Uzsa suggests some form of control on the extent of the lava, such as a tuff ring and/or maar crater wall. Inferring accumulation of the volcanic material in a confined maar basin with its base below surrounding ground level, the present highest level of scoriaceous pyroclastic rocks in a mound-like hill south of the Uzsa quarry therefore is inferred to represent the syn-volcanic palaeosurface. Clarification of this interpretation is a subject of future research.

The ridge between Sümegprága and Tátika is clearly a shallow subsurface sill and dyke complex. This system, at least in one place, has been cut through by a diatreme (near Tátika). This implies that the emplacement of sills and dykes pre-dates formation of the phreatomagmatic volcanoes.

At the Kovácsi-hegy, a sill and dyke system similar to the Sümegprága and Tátika system has been identified. The Kovácsi-hegy rocks are inferred to have formed as a basanitic sill on the basis of its general recent elevation and its 3D relationship with the neighbouring coherent flow units, which are clearly intrusive in origin.

The intrusive origin of the majority of the basanitic rocks north of the Keszthely Mts suggests that significant erosion took place since their emplacement around 3 My. A conservative estimate would reconstruct the level of the palaeosurface at the level of the present top of the Tátika, where pyroclastic rocks crop out. However, if the Tátika is the remnant of an exhumed diatreme, it would imply that its present top section represents a level well below the syn-volcanic palaeosurface. A realistic estimate would add a minimum of 50 metres above the peak of the present Tátika to establish the reference elevation for the syn-volcanic palaeosurface. With this calculation, the minimum missing Neogene sedimentary cover would be in the range of 250–350 metres in comparison to the presently preserved average of ~150 metres of strata. This would imply that the sill and dyke complex in the region developed around 100 to 250 metres below the syn-volcanic palaeosurface. The present day high altitude of the intrusive rocks at this region in comparison to other effusive coherent lava rock locations in the BBHVF in a more or less similar elevation suggests some sort of differential base level changes through the Neogene which process needs further study (MARTIN and NÉMETH 2003).

The recognition that a majority of the coherent igneous rocks exposed north of the Keszthely Mts. originated as intrusive sill and dyke complexes also highlights the complexity of magma emplacement and feeding systems for small-volume intracontinental alkaline basaltic volcanic systems. There are growing examples worldwide that demonstrate that maar/diatreme volcanism is often associated with complex effusive (extensive lava flows) and intrusive (dykes, sills and laccoliths) processes such i.e. as it has been reported from the Saar-Nahe Basin, Germany (LORENZ and HANEKE 2004). Both recent and preceding seismic studies have identified several mound-like, high velocity zones within Neogene strata a few tens to a hundred metres below the surface in the Lake Balaton basin (CSERNY and CORRADA 1989, SACCHI et al. 1999, SACCHI and HORVÁTH 2002). These structures are best interpreted to represent similar structures as the Sümegprága–Tátika sill and dyke systems that never made it to the syn-volcanic surface, and which are not yet exhumed.

***

Acknowledgements: This review gives a short summary about the recent research on the Pliocene intraplate alkaline basaltic volcanic rocks north of the Keszthely Mountains. This research is a subject of Károly Németh's Magyary Zoltán Post-doctoral Fellowship. The authors are grateful for funds such as from the Hungarian Science Foundation OTKA F 043346, DFG (Ma 2440) and the DAAD German Hungarian Academic Exchange Program 2002/2003 that helped to carry out this research, many thanks to these organisations. Constructive suggestions and reviews by James D. L. White (Otago University, New Zealand) and Volker Lorenz (University of Würzburg, Germany) helped to sharpen the manuscript. Suggestions from the Series Editor (Tamás Budai, MÁFI, Budapest) made the manuscript more reader friendly, and are greatfully acknowledged.

References

BALOGH, K. and PÉCSKAY, Z. 2001: K/Ar and Ar/Ar geochronological studies in the Pannonian–Carpathians–Dinarides (PANCARDI) region. – *Acta Geologica Hungarica* 44 (2–3), pp. 281–301.

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.

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.

BÜTTNER, R., DELLINO, P. and ZIMANOWSKI, B. 1999: Identifying magma-water interaction from the surface features of ash particles. – *Nature* 401(6754), 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.

CSERNY, T. and CORRADA, R. 1989: A Balaton medencéje és holocén üledékei részletes geofizikai-földtani vizsgálatának újabb eredményei. [New results of teh 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.

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.

ELLIOT, D. H. and HANSON, R. E. 2001: Origin of widespread, exceptionally thick basaltic phreatomagmatic tuff breccia in the Middle Jurassic Prebble and Mawson Formations, Antarctica. – *Journal of Volcanology and Geothermal Research* 111 (1–4), pp. 183–201.

FISHER, R. V. and SCHMINCKE, H.-U. 1984: *Pyroclastic Rocks*. – Springer, Heidelberg, 474 p.

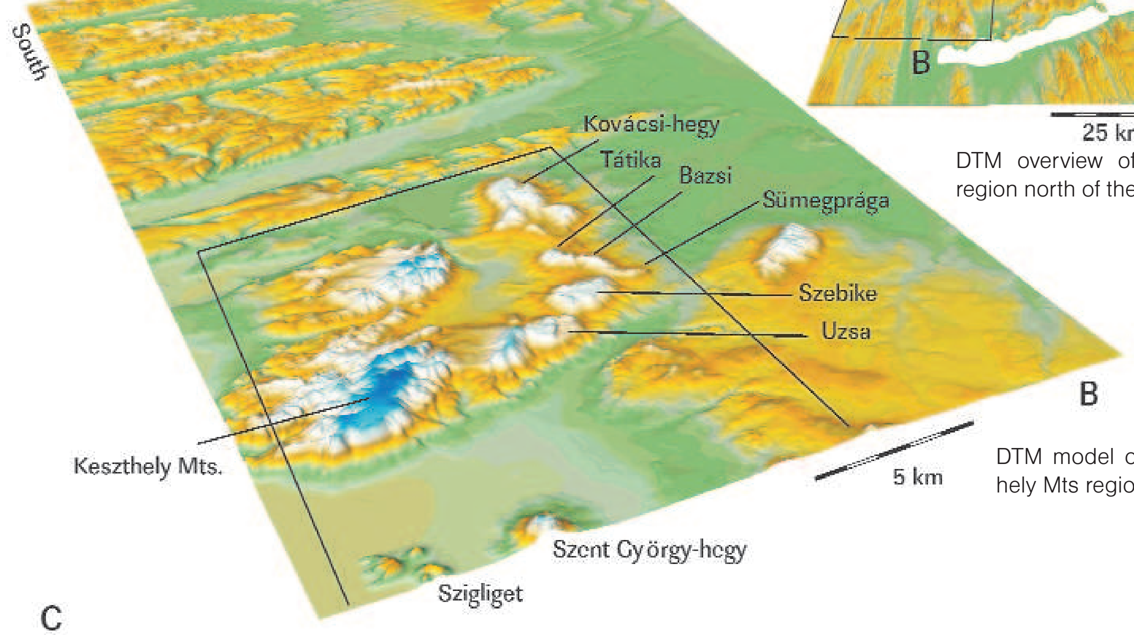
GUTMANN, J. T. 1976: Geology of Crater Elegante, Sonora, Mexico. – *Geological Society of America Bulletin* 87, pp. 1718–1729.

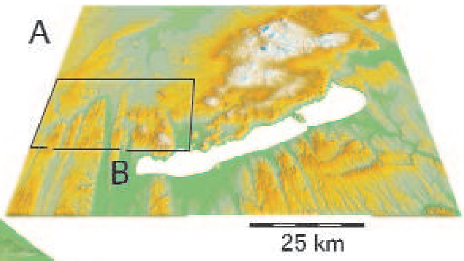
HANSON, R. E. and ELLIOT, D. H. 1996: Rift-related Jurassic basaltic phreatomagmatic volcanism in the central transantarctic mountains: Precursory stage to flood- basalt effusion. – *Bulletin of Volcanology* 58 (5), pp. 327–347.

HEAD, J. W. and WILSON, L. 1989: Basaltic pyroclastic eruptions: influence of gas release patterns and volume fluxes on fountain structure and the formation of cinder cones, spatter cones, rootless flows, lava ponds and lava flows. – *Journal of Volcanology and Geothermal Research* 37, pp. 261–271.

HEIKEN, G. H. and WOHLETZ, K. H. 1986: *Volcanic ash*. – University of California Press, Berkeley, 246 p.

HEIKEN, G. H. and WOHLETZ, K. 1991: Fragmentation processes in explosive volcanic eruptions. — In: *Sedimentation in Volcanic Settings,* SEMP Special Publications 45, pp. 19–26.
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 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.
JUGOVICS, L. 1948: Adatok Tátika–Prága–Sarvaly-hegyek vulkanológiai felépítéséhez; [Beitraege zum vulkanologischen Aufbau der Berge Tátika–Prága–Sarvaly]. — *Földtani Közlöny* 78, pp. 196-205.
LORENZ, V. 1987: Phreatomagmatism and Its Relevance. — *Chemical Geology* 62 (1–2), pp. 149–156.
LORENZ, V. 2000a: Formation of the root zones of maar-diatreme volcanoes. — *Terra Nostra* 2000 (6), pp. 279–284.
LORENZ, V. 2000b: Formation of maar-diatreme volcanoes. — *Terra Nostra* 2000 (6), pp. 284–291.
LORENZ, V and HANEKE J. 2004: On the relationship between diatremes, dykes, sills, laccoliths, intrusive-extrusive domes, lava flows and tephra deposits with unconsolidated, water-saturated sediments of the late-Variscan intermontan Saar-Nahe Basin, Germany. — In: BREITKREUZ, C. and PETFORD, N. (Eds): *Physical Geology of Subvolcanic Systems — Laccoliths, Sills, and Dykes,* Geological Society Special Publications, London, 234 [in press].
LÓCZY, L. SEN. 1913: A Balaton környékének geológiai képződményei és ezeknek vidékek szerinti telepedése. [Geological units of the Balaton area and their stratigraphy.] [in Hungarian]. — In: LÓCZY, L. SEN. (Ed.): *A Balaton tudományos tanulmányozásának eredményei. [New results of the scientific research of the Balaton.] [in Hungarian].* Magyar Királyi Földtani Intézet [Royal Hungarian Geological Institute], Budapest, pp. 617.
LÓCZY, L. SEN. 1920: *A Balaton-tó környékének részletes geológiai térképe* M = 1:75 000. [Detailed geological map of the Lake Balaton area. 1: 75 000.] — Magyar Királyi Földtani Intézet [Royal Hungarian Geological Institute], Budapest
MARTIN, U. and NÉMETH, K 2003: Erosion, base level change and palaeogeomorphology of a Mio/Pliocene maar pitted fluvio-lacustrine basin in western Hungary. [Joint meeting of the Deutsche Mineralogische Gesellschaft, the Geologische Vereinigung and the Deutsche Geophysikalische Gesellschaft. Ruhr University, Bochum, 22–25. September 2003, Bochum, Germany] — *Beih. z. European Journal of Mineralogy* 15 (1), pp. 126.
MARTIN, U. and NÉMETH, K. 2004: 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, London, 234 [in press].
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.
NÉMETH, K. and MARTIN, U. 1999: Late Miocene palaeo-geomorphology of the Bakony – Balaton Highland Volcanic Field (Hungary) using physical volcanology data. — *Zeitschrift für Geomorphologie* 43 (4), pp. 417–438.
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. 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.
SCHMINCKE, H. U., BEHNCKE, B., GRASSO, M. and RAFFI, S. 1997: Evolution of the northwestern Iblean Mountains, Sicily: uplift, Plicocene/Pleistocene sea-level changes, palaeoenvironment, and volcanism. — *Geologische Rundschau* 86 (3), pp. 637–669.
SKILLING, I. P. 2002: Basaltic pahoehoe lava-fed deltas; large-scale characteristics, clast neration, emplacement processes and environmental discrimination. — In: SMELLIE, J. L. and CHAPMAN, M. G. (Eds): *Volcano-ice interaction on Earth and Mars.,* Geological Society of London. London, United Kingdom, Geological Society Special Publications 202, pp. 91–113.
THORDARSON, T. and SELF, S. 1993: The Laki (Skaftar-Fires) and Grimsvotn Eruptions in 1783–1785. — *Bulletin of Volcanology* 55 (4), pp. 233–263.
VALENTINE, G. A., PERRY, F. V. and WOLDEGABRIEL, G. 2000: Field characteristics of deposits from spatter-rich pyroclastic density currents at Summer Coon volcano, Colorado. — *Journal of Volcanology and Geothermal Research* 104, pp. 187–199.
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.
WHITE, J. D. L. 1991a: The depositional record of small, monogenetic volcanoes within terrestrial basins. — In: FISHER R.V., SMITH, G. A., *Sedimentation in Volcanic Settings,* SEMP 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. and MCCLINTOCK, M. K. 2001: Immense vent complex marks flood-basalt eruption in a wet, failed rift: Coombs Hills, Antarctica. — *Geology* 29 (10), pp. 935–938.
WOHLETZ, K. H. 1986: Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies. — *Bulletin of Volcanology* 48, pp. 245–264.

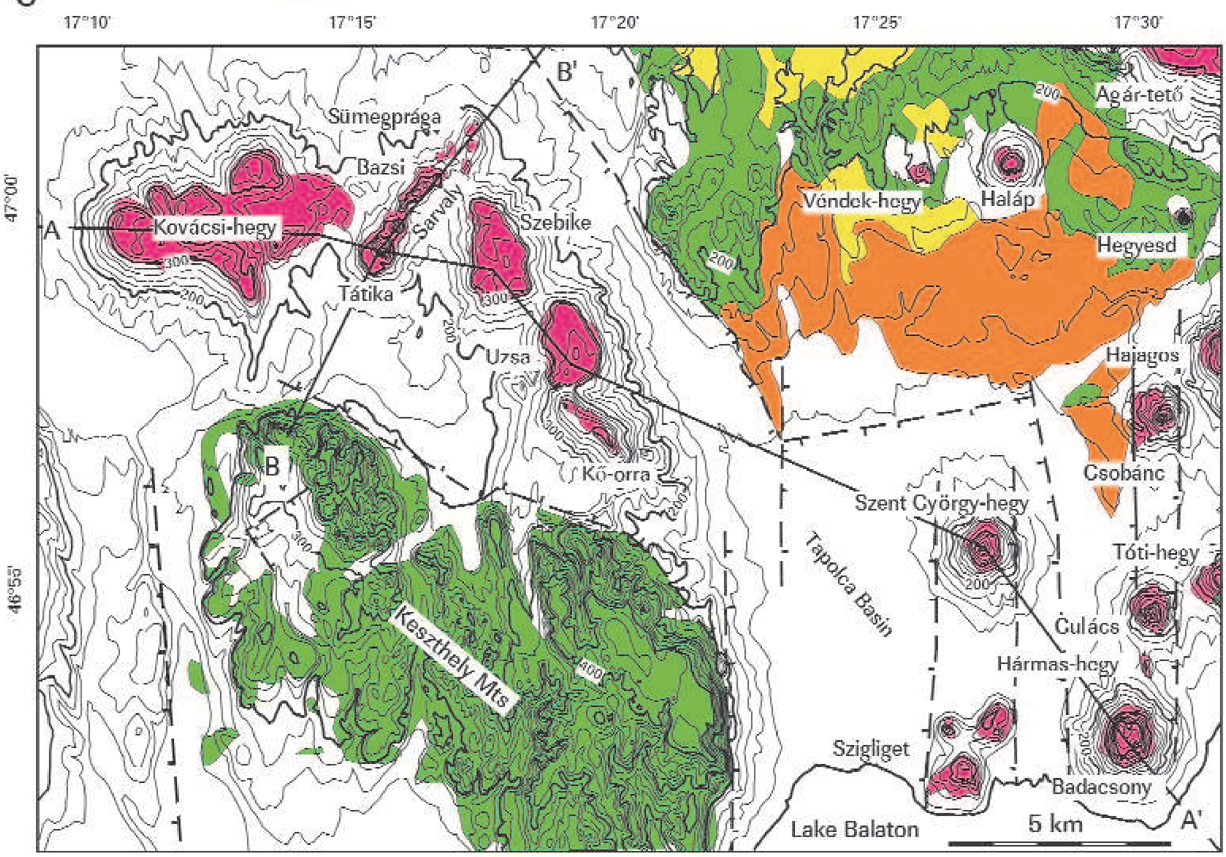


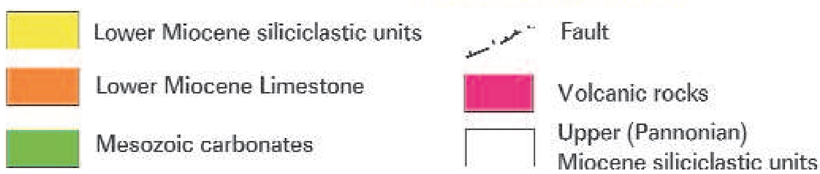


DTM overview of the volcanic region north of the Keszthely Mts

DTM model of the Keszthely Mts region

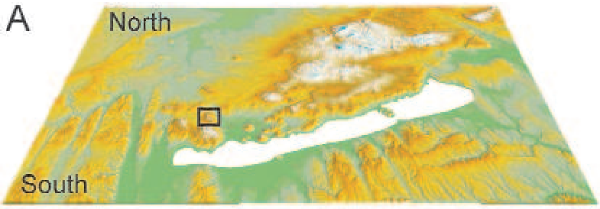
C



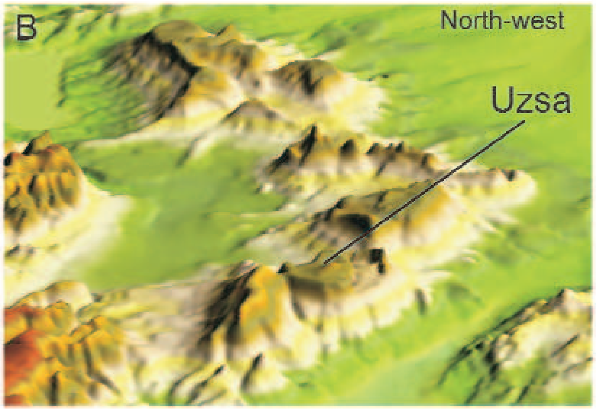


Simplified geological map of the area north of the Keszthely Mts. Lines shown position of the simplified cross sections on Figure 4.1

Plate 2 / Chapter 4 — Second International Maar Conference — Hungary–Slovakia–Germany

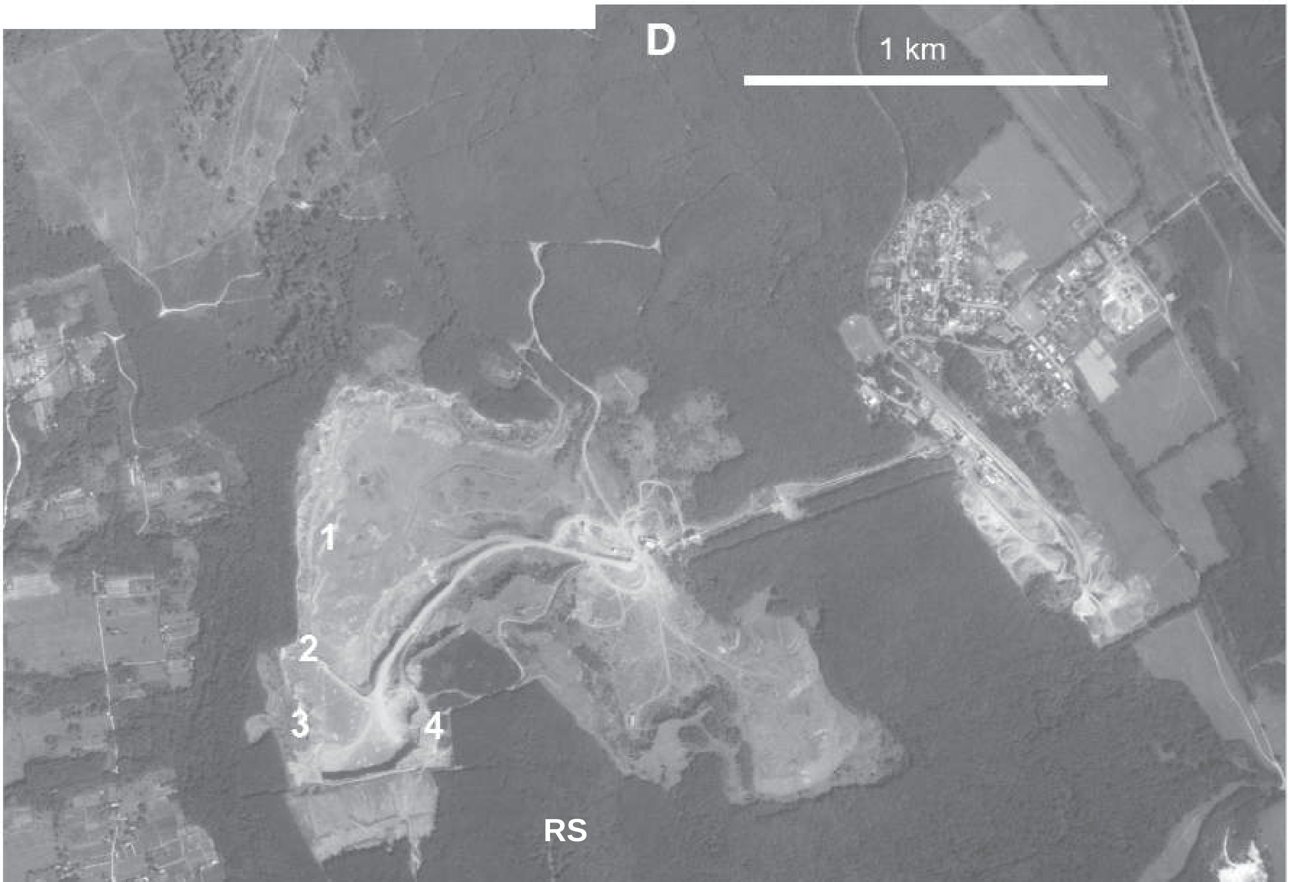


Location of the Uzsa basanite capped mesa in the western Pannonian region



The Uzsa region shown on a DTM looking to north-west

A detail of the 1 to 25,000 topography map of the Uzsa region shows the 3D relationships of the topography in relationship with the location of the large basalt quarry in Uzsa



The location of significant volcanological features are shown in detail on the airphoto of the Uzsa region. Note the hill stands 50 metres above the lava plateau that is formed by red scoriaceous lapilli tuff (RS). Location codes in the quarry: (1) zones of pillowed lava foot breccias, (2) rosette-like columnar jointed basanite in the axis of the quarry inferred to be a master lava tube, (3) location of massive to weakly bedded lapilli tuff and tuff breccia in the central part of the quarry inferred to be a result of phreatomagmatic explosive eruption products that have been remobilized in the crater/vent zone of the volcano of Uzsa, (4) bedded scoriaceous lapilli tuff and tuff breccia interpreted as a part of a scoria cone

A

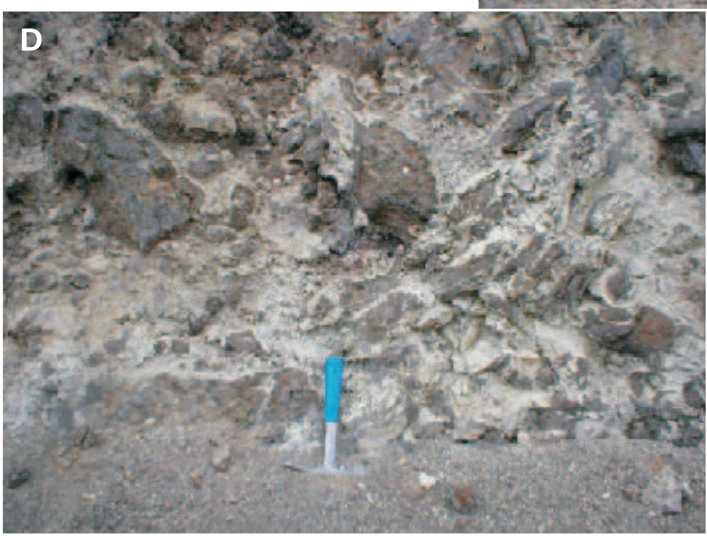
Columnar jointed coherent basanite in the western quarry wall of Uzsa

Basanite columns at Uzsa are about 20–25 cm wide. A perpendicular view to the columns shows that columns are predominantly pentagonal

B

C

Vesicular basal zone of a coherent basanite at Uzsa



D

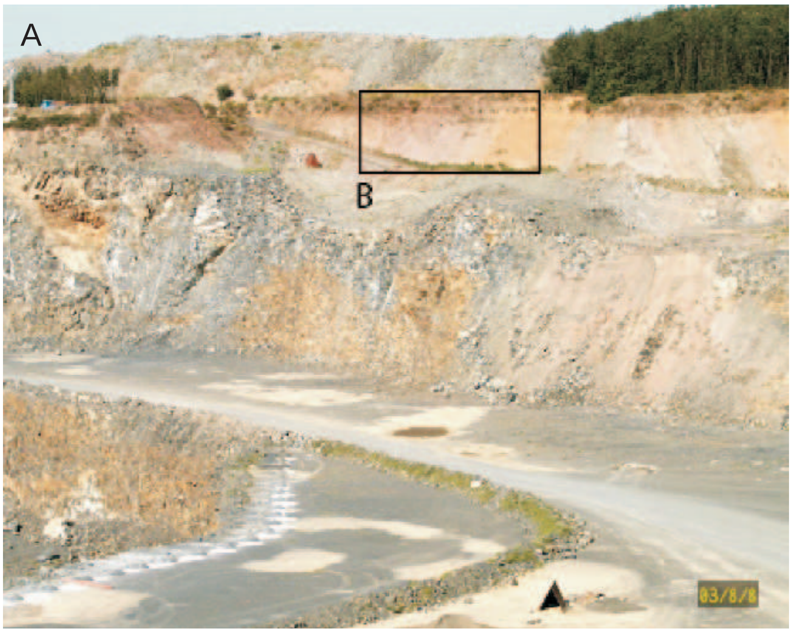
Well packed pillow-like structure of the lava foot of a lava flow at Uzsa

Onion-like jointing pattern near the margin of the coherent magmatic body at Uzsa

A coherent basanite tube forming a half circle (white line), rosette-like joint pattern in the western side of the quarry at Uzsa. Note that the rosette-like jointing pattern gradually defect to more platy jointing pattern near the margin of the flow

Massive to weakly bedded lapilli tuff and tuff breccia in handspecimen in the western part of the Uzsa quarry

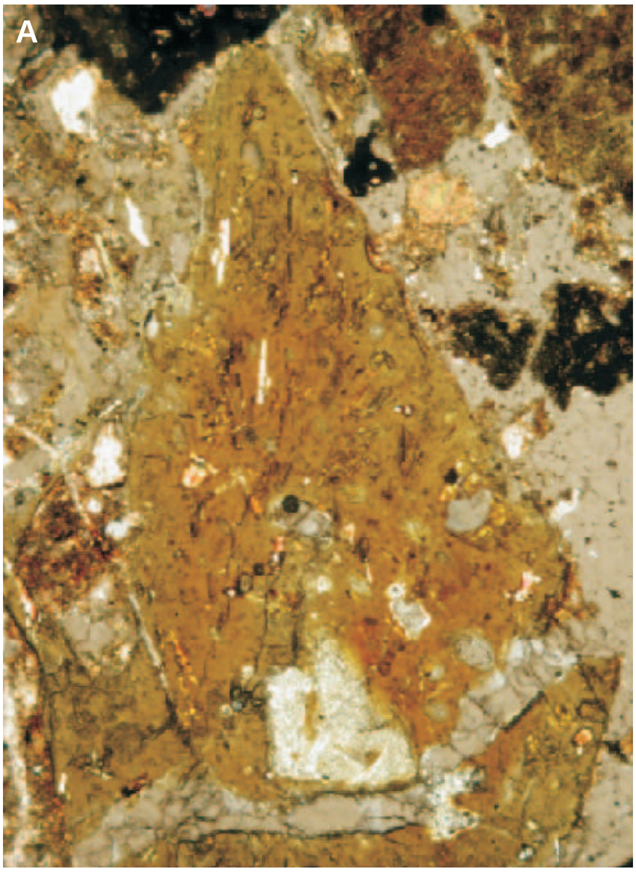
Red scoriaceous, weakly bedded lapilli tuff and tuff breccia in the southern margin of the Uzsa quarry



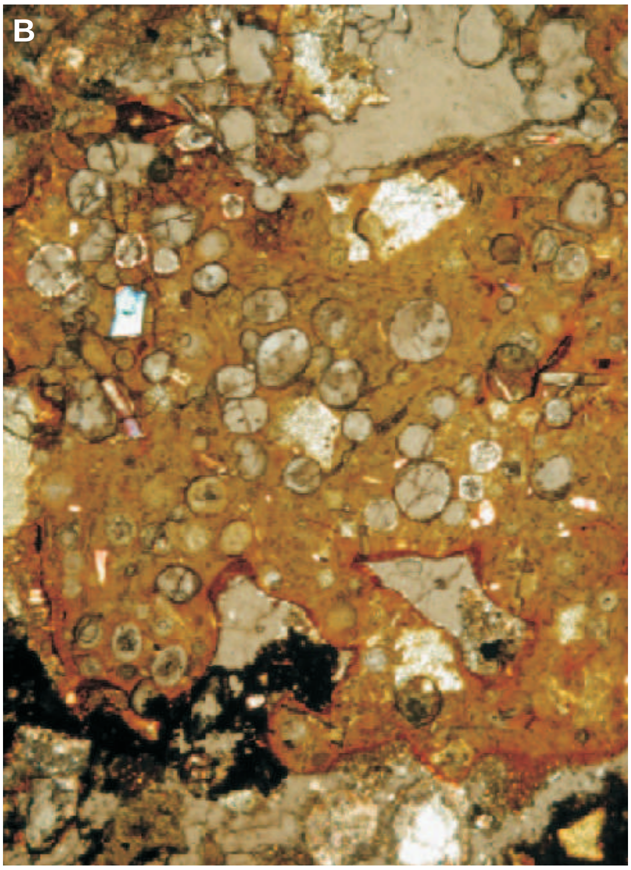
Textural features of the scoriaceous lapilli tuff succession show characteristics for remobilisation of tephra on a volcanic flank

The massive structure of the pyroclastic breccia of Uzsa is more prominent in a close up view

Massive fine grained lapilli tuff unit of Uzsa

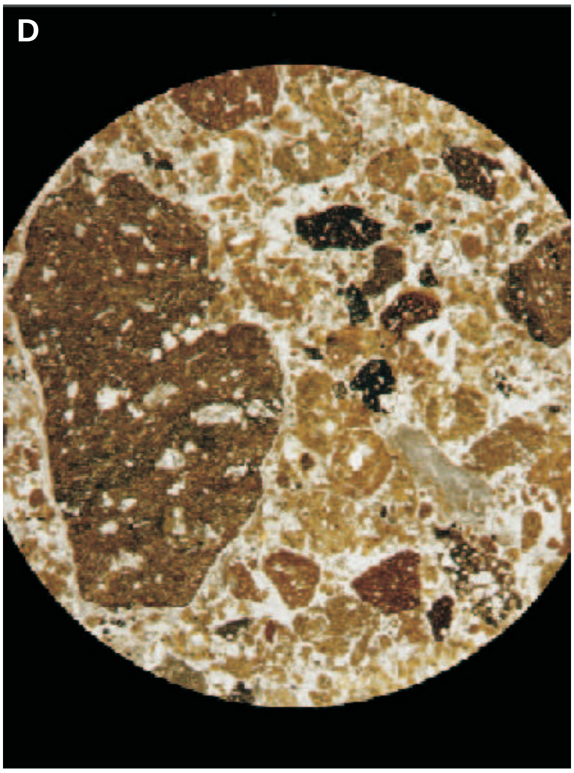


Photomicrograph of blocky, moderately vesicular tephritic glass shard from the Uzsa pyroclastic succession. The short side of the photo is 2 mm. [plan parallel polarized light]



Photomicrograph of a glass shard of the lapilli tuff unit of Uzsa. They are commonly palagonite rimmed (dark zone). The short side of the photo is 2 mm. [plan parallel polarized light]

Blocky shaped, dense volcanic lithic fragment in a fine-grained matrix of a tuff breccia of Uzsa



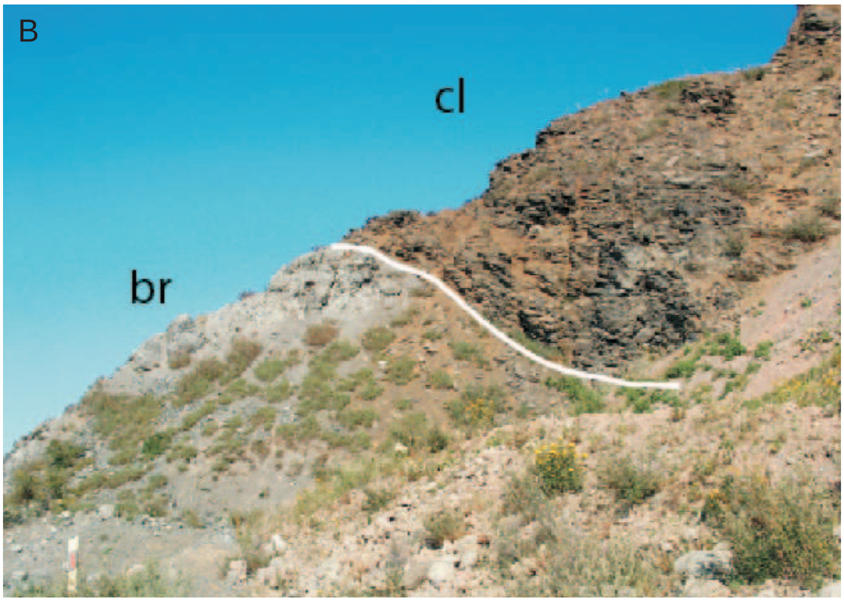
The matrix of the tuff breccia of Uzsa is rich in volcanic glass shards indicating its phreatomagmatic origin as it is shown in the photomicrograph. [plan parallel polarized light, the view is about 2 cm across]

Irregular contact (thick white line) between weakly bedded (straight white line represents bedding), ill-sorted lapilli tuff and basanitic intrusion in the upper level of the Uzsa quarry

In a close up view of the lapilli tuff at Uzsa the bedding is more prominent and cauliflower bombs (white circle) can be recognized indicating magma–water interaction during fragmentation

White, semi-rounded, carbonate-rich silt (white circles) as accidental lithic fragment in the basal tuff breccia of Uzsa

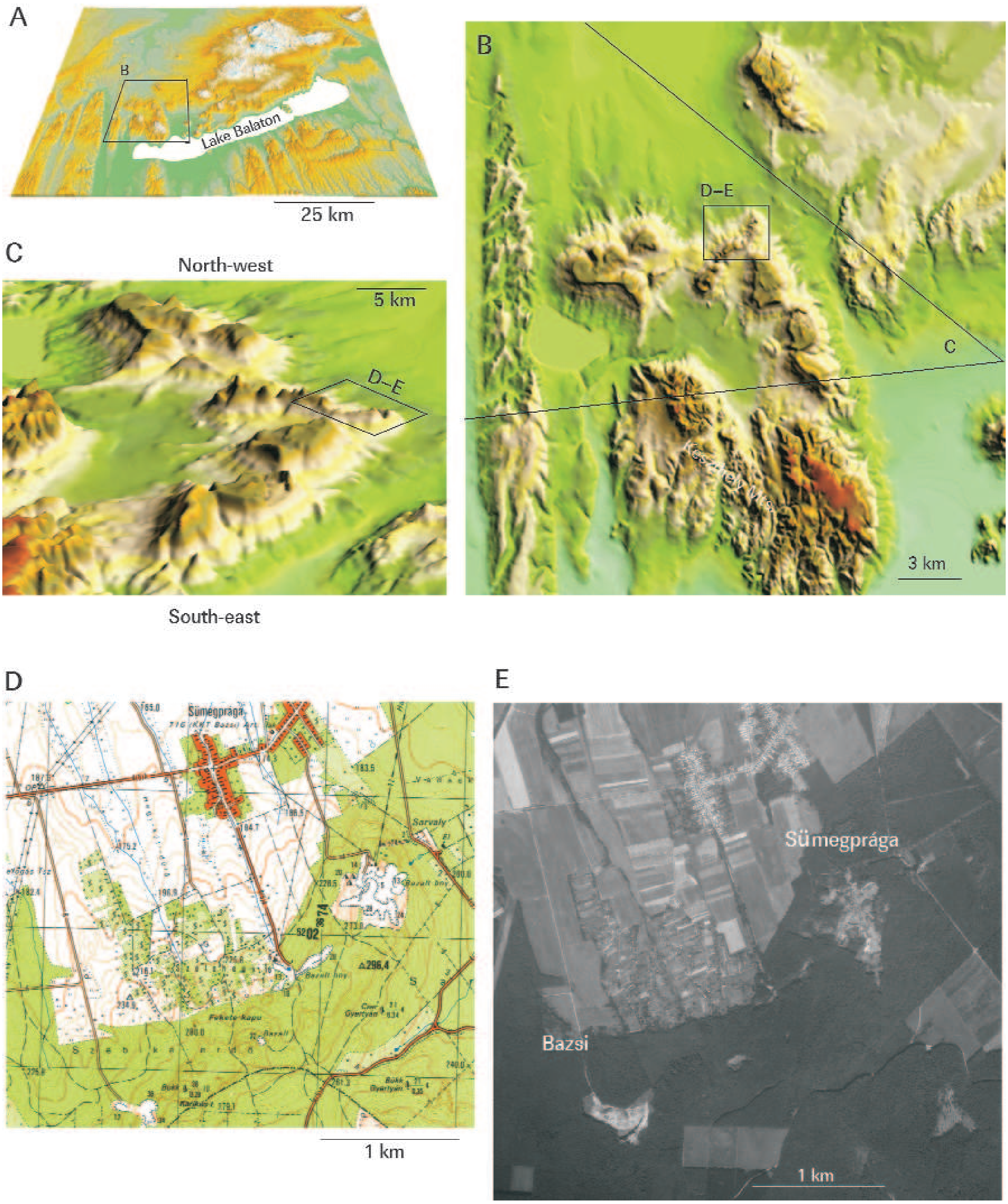
Fluidally shaped moderately vesicular lava spatter in a scoriaceous lapilli matrix from the south-eastern margin of the Uzsa quarry

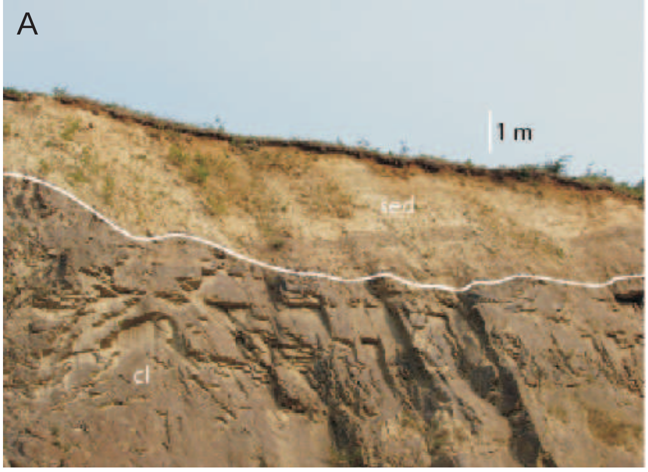


Coherent basanite (cl) and pyroclastic breccia (br) irregular contact in the top-most volcanic units of Uzsa indicating some close relationship between lava flow and clastic rocks in this part of the quarry

Coarse grained pyroclastic breccia at Uzsa

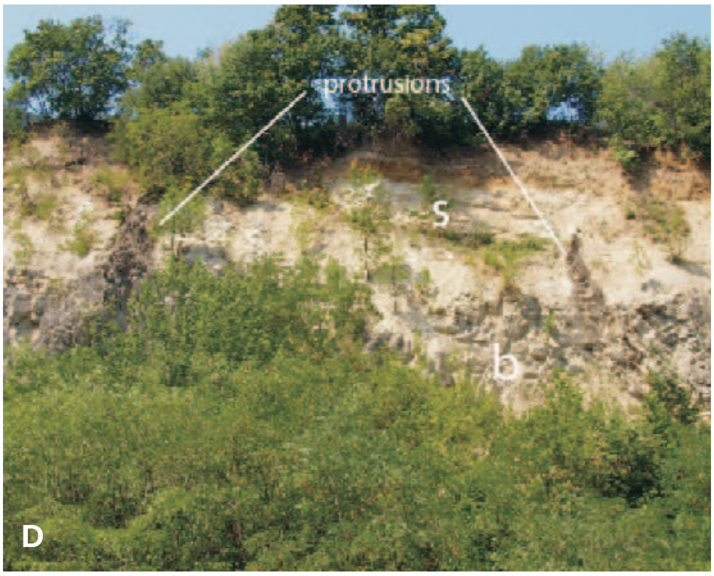
A well developed ridge north of the Keszthely Mts runs from north-east to south-west where predominantly basanitic coherent lava bodies crop out (A, B, C). The northernmost location is a former quarry, Sümegprága (D and E), where basanite shows radial jointed pattern and have intrusive contact with the host siliciclastic sediments (silt, sand).





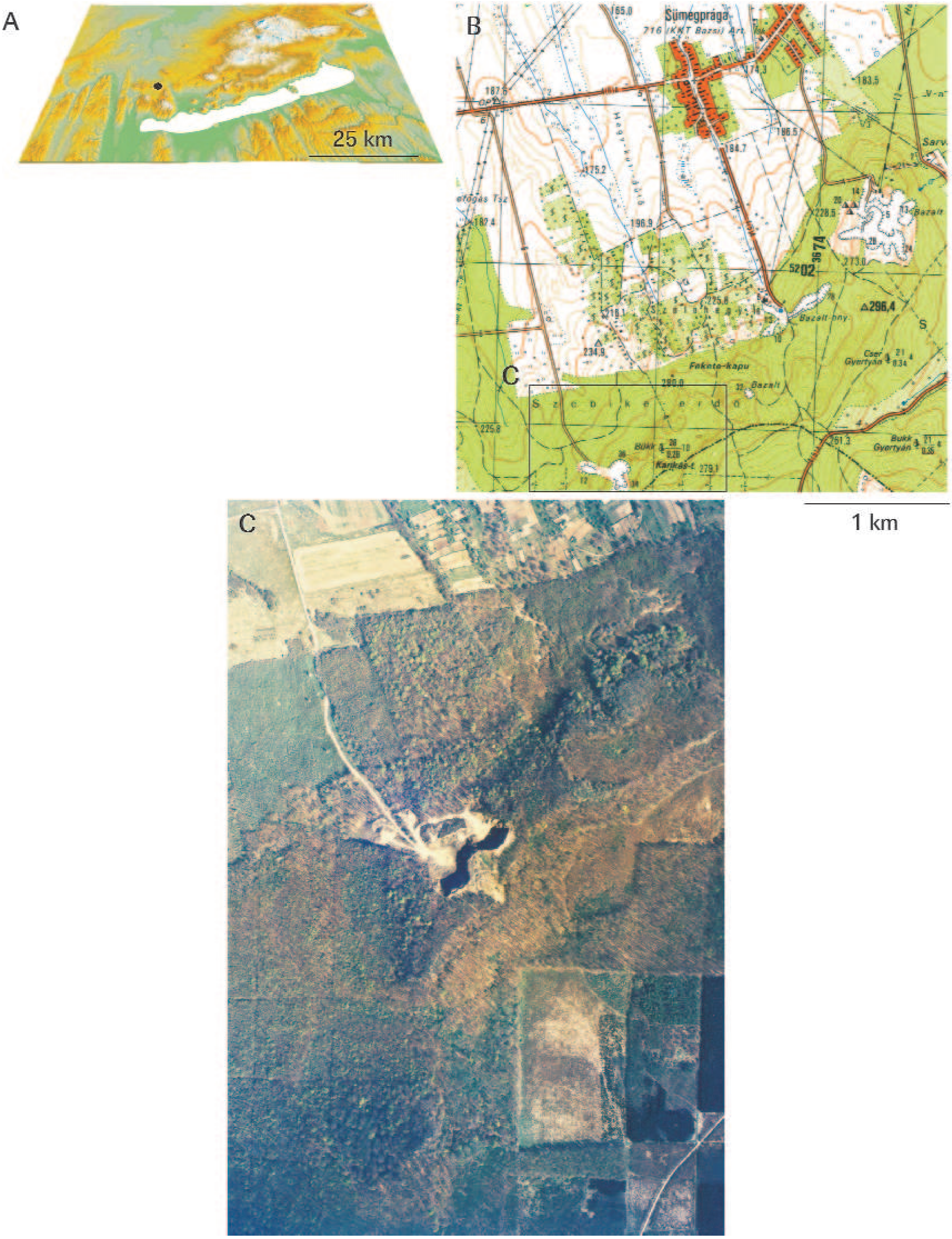
Two types of intrusive coherent magmatic bodies from Sümegprága. A) a tabular unit (cl) with irregular contact (white line) to the host sediment (sed) and B) a rosette-like columnar jointed magmatic unit (cl) with irregular contact to the host sediment (white line)

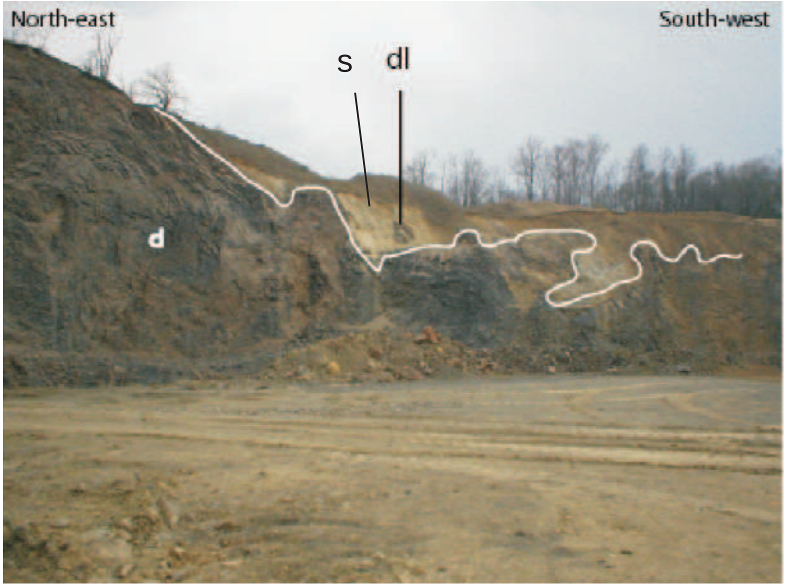
Baked silt/sand (s) at the contact of basanitic body (cl) and host sediment (photo courtesy of Manuella Kramer)



Small, vertical protrusion of basanite (b) that intruded from a master sill into the host sediment (s) at Sümegprága (photo courtesy of Claudia Henke)

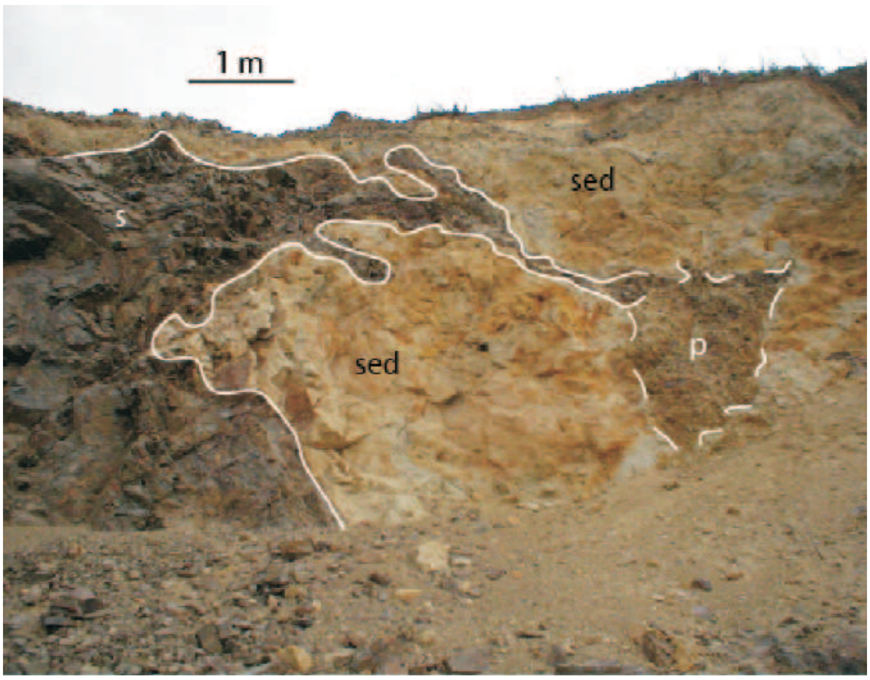
Location of the Bazsi quarry (A, B) with an outline of the currently active quarry on an airphoto (C)



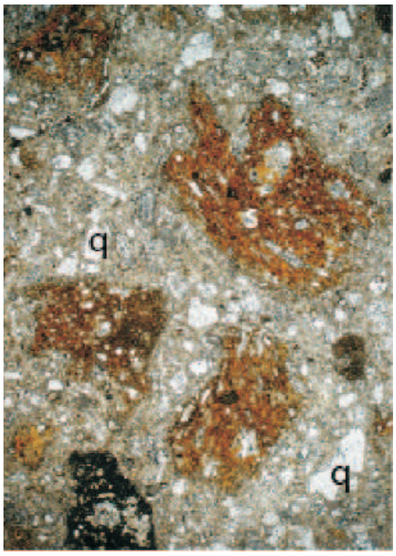


Overview of the master sill (d) of Bazsi. Note the very irregular shape of the sill (white outline) and the detached coherent lobe (dl) "floating" in the host (s)

Peperitic margin of a sill (s) at Bazsi



Small sill (white line) that protruded from a master sill (s) into a host sediment (sed) at the upper level of Bazsi. The sill then inflated and terminated into a volcaniclastic unit (white dashed line) that is seemingly disperse into the host sand/silt matrix, and forming peperite (p)



Photomicrograph [plan parallel polarized light, the short side of the photo is about 4 mm) of a lapilli tuff derived from the Tátika. Note the angular quartz fragments (q) derived from the immediate pre-volcanic Neogene rock units. The pyroclastic rocks contain abundant sideromelane glass (s, which are blocky and moderately vesicular and thus indicative for phreatomagmatic fragmentation