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# Blocky versus fluidal peperite textures developed in volcanic conduits, vents and crater lakes of phreatomagmatic volcanoes in Mio/Pliocene volcanic fields of Western Hungary

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**Abstract**

Volcanic fields in the Pannonian Basin, Western Hungary, comprise several Mio/Pliocene volcaniclastic successions that are penetrated by numerous mafic intrusions. Peperite formed where intrusive and extrusive basaltic magma mingled with tuff, lapilli-tuff, and non-volcanic siliciclastic sediments within vent zones. Peperite is more common in the Pannonian Basin than generally realised and may be also important in other settings where sediment sequences accumulate during active volcanism. Hajagos-hegy, an erosional remnant of a maar volcano, was subsequently occupied by a lava lake that interacted with unconsolidated sediments in the maar basin and formed both blocky and globular peperite. Similar peperite developed in Kissomlyó, a small tuff ring remnant, where dykes invaded lake sediments that formed within a tuff ring. Lava foot peperite from both Hajagos-hegy and Kissomlyó were formed when small lava flows travelled over wet sediments in craters of phreatomagmatic volcanoes. At Ság-hegy, a large phreatomagmatic volcanic complex, peperite formed along the margin of a coherent intrusion. All peperite in this study could be described as globular or blocky peperite. Globular and blocky types in the studied fields occur together regardless of the host sediment.


*Keywords:* phreatomagmatic; monogenetic; basanite; peperite; Pannonian Basin

## 1. Introduction

Peperite results from interaction between magma and wet sediment and exhibits a range of complex textures (Brooks et al., 1982; Hanson and Schweickert, 1982; Kokelaar, 1982; Lorenz, 1984; Kokelaar et al., 1985; Walker and Francis, 1986; Busby-Spera and White, 1987; White and Busby-Spera, 1987; Branney and Suthren, 1988; Kano, 1989; Riggs and Busby-Spera, 1990; Brooks, 1995). This paper deals with newly identified peperite occurrences within intra-continental monogenetic volcanic fields in Western Hungary (Embey-Isztin et al., 1985; Szabó et al., 1992; Embey-Isztin et al., 1993; Downes and Vaselli, 1995; Németh and Martin, 1999a,b). Peperite is common in a variety of geological settings and peperite-forming processes in a sub-volcanic region of a phreatomagmatic volcano are described from several sites (White, 1991; Vazquez and Riggs, 1998; White and

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McClintock, 2001; Martin and White, 2002) but have not been described yet in detail within vent settings. In addition, detailed outcrop-scale descriptions of complex contact relationships are given here the first time.

Peperite commonly has been described as being either blocky or globular, in some cases inferred to develop in response to properties of the host sediment (Busby-Spera and White, 1987). Other controls on peperite morphology have also been reported (e.g. Doyle and McPhie, 2000), but not previously from vent settings.

In this paper a detailed examination of peperite textures is given to analyse peperite forming processes within vent and crater zones of monogenetic volcanoes with the aim to review and document in detail the relationship between peperite texture and host sediment properties in conduits, vents and craters in Western Hungary. We also examine the roles of other controls on peperite morphology. In this paper volcanic conduit refers to the subsurface volcanic and non-volcanic debris filling pipe-like structure of phreatomagmatic volcanoes. We define vent as an aperture from the conduit to the crater of the volcano, meanwhile crater is used to signify the uppermost part of the feeding system of the volcano. To distinguish pyroclastic successions as conduit, vent or crater filling units is not easy in ancient eroded phreatomagmatic volcanoes. Here the pyroclastic texture, 3D stratigraphical relationships between volcanic and country rock units, and volcanic facies relationships among preserved volcanic units have been used to determine the context of the preserved volcanic rocks. In Western Hungary in majority of the preserved volcanic rocks represent diatremes (conduit filling pyroclastic rocks), vent, and crater filling units (Martin and Németh, 2004).

## 2. Geological setting

The Little Hungarian Plain and Bakony-Balaton Volcanic Fields are located in the western part of the Pannonian Basin, Hungary, about 170 km south-west of Budapest (Fig. 1). The Pannonian Basin is considered to be a back-arc basin (Horváth and Royden, 1981) with a subduction-related Neogene calk-alkaline volcanic chain at its northern to eastern margin (Póka, 1988; Szabó et al., 1992). During the Miocene, extensional tectonic events behind the subduction zone resulted in lithospheric thinning and asthenospheric welling (Stegena et al.,

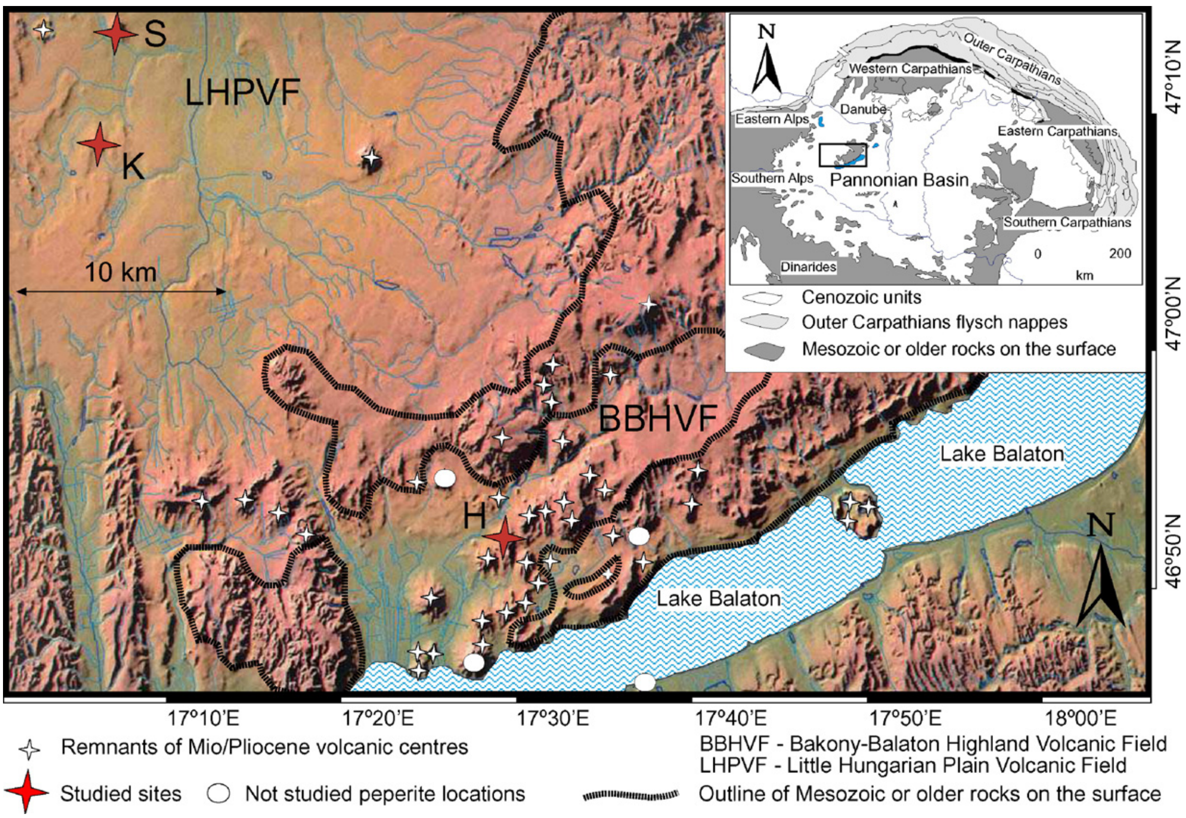


Fig. 1. Location map of the Little Hungarian Plain and Balaton Highland Volcanic Fields. S — Ság-hegy, K — Kissomlyó, H — Hajagos-hegy.

1974; Royden and Horváth, 1988). Intraplate volcanism began with trachyandesitic to trachytic explosive and effusive eruptions, which were followed by alkaline basaltic eruptions in the western part of the Pannonian Basin. From Late Miocene to Pleistocene, alkaline basaltic volcanism characterised this region (Embey-Isztin et al., 1985, 1993; Szabó et al., 1992; Downes and Vaselli, 1995; Németh and Martin, 1999a,b). Both the Balaton Volcanic Field and the Little Hungarian Plain consist of eroded remnants of scoria cones, tuff rings, and maars (Jugovics, 1969; Jámbor et al., 1981; Németh and Martin, 1999a).

The underlying rocks of the volcanic fields consist of Silurian schists, Permian red sandstone and Mesozoic carbonate beds. In the Neogene, just shortly before volcanism began, a large lake called Pannonian Lake occupied the Pannonian Basin (Kázmér, 1990). The lacustrine sandstones, mudstones, and marls of the brackish Pannonian Lake are widespread (Kázmér, 1990). The immediate pre-volcanic sedimentary rocks at the studied areas belong to different facies of the Late Miocene Pannonian Sandstone Formation (Bence et al., 1999), the sequences of which consist dominantly of conglomerate, sandstone and mudstone deposited in a fluvio-lacustrine environment. Recent studies based on facies analyses of Late Miocene fluvio-lacustrine sediments, high resolution seismic sections, and paleontological evidence suggested that lacustrine sedimentation related to the Pannonian Lake ceased ~9 to 8 Ma ago in both volcanic areas (Magyar et al., 1999). This implies that volcanism occurred in both areas in subaerial settings, possible along fluvial valleys likely have been filled with swamps, small streams or lakes, providing substantial surface water to fuel phreatomagmatic volcanism as well as water saturated loose sediments available to be involved in peperite formation (Németh and Martin, 1999a,b; Martin and Németh, 2002, 2004).

We do not intend to give detailed description and interpretations on the host sediments and their depositional processes here, but provide basic descriptions of the host sediments and volcanic edifices, which are important to peperite forming processes. This is followed by description and discussion of the peperites identified in Western Hungary.

## 3. Description of Hajagos-hegy maar/tuff ring sequence (Bakony-Balaton Highland Volcanic Field)

The bulk of the volcanic rocks and underlying sedimentary formations are not well exposed at Hajagos-hegy (Fig. 1). Only scattered outcrops of volcaniclastic rocks are located on the northern side of Hajagos-hegy. These rocks are few tens of metres thick and underlie capping basanite lava flows. This volcaniclastic sequence dips 15° towards the centre of the Hajagos-hegy. The volcaniclastic beds consist mostly of coarse-grained (lapilli size) and fine-grained (ash size) bed couplets. Coarse-grained lapilli tuff beds display normal grading. The basic, slightly micro-vesicular, predominantly tachylite lapilli are semi-rounded and display rims of altered glassy material. A few small, angular and blocky grains of sideromelane show slightly oriented pyroxene, olivine and rare feldspar microcrystals further referred as microlites. The lapilli are interpreted as clasts derived from a pre-existing cemented deposit, with the clastic rims around larger volcanic glass shards, country rock fragments and crystals representing adhering remnants of the matrix of a former lapilli tuff. The lapilli tuff beds are inferred to consist of reworked pyroclastic rocks deposited in a volcanic depression such as a maar or crater lake of tuff ring. Fine-grained beds largely consist of lapilli and ash of sideromelane and/or palagonite. Fine-grained beds show low-angle cross bedding and cross-lamination; they commonly fine upwards. On the basis of overlying pillow basalts, the normally graded, well-bedded character of fine-grained beds, and low angle cross-stratification, the fine-grained beds are interpreted as $T_{b,c}$ turbidites.

The inference that the preserved volcanic successions represent an eroded maar/tuff ring is supported by the following: (1) there is a well-localized, semi-circular negative Bouguer-anomaly and positive magnetic anomaly (Kovácsvölgyi S, unpublished data), (2) the

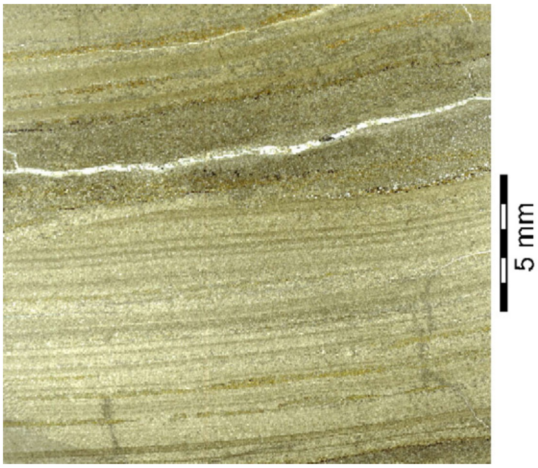


Fig. 2. Photomicrograph of laminated post-tuff ring lacustrine siltstone that have been invaded by lava (plan parallel light) from Kissomlyó.

volcaniclastic sequences have semicircular gently inward dips forming a dish-like structure, (3) the structure is filled with basanite lava flows comprising up to three distinct units with individual thicknesses of up to 10 m each. The above facts and the 3D facies relationships between volcanic and non-volcanic units suggest that the preserved volcanic units are part of an eroded maar/tuff ring and represent the vent to a crater zone.

The volcanic depression is partly filled with reworked volcaniclasts that are inferred to have been deposited in a crater lake. The vent zone of the Hajagos-hegy volcano was occupied by volcaniclastic slurry and large (metre-scale) chunks of irregular-shape siliciclastic sediments derived from rocks immediately underlying the volcanic sequences. Dykes subsequently invaded the vent-filling mixture of sediments to form both globular and blocky peperite.

## 4. Kissomlyó tuff ring sequence (LHPVF)

Kissomlyó is a flat, semi-circular (~1000 m in diameter, 100–150 m deep, up to 50 m estimated thickness) mound of volcaniclastic rocks and lava flows that forms a butte above the surrounding area. Kissomlyó rests on Late Miocene fluvio-lacustrine sand and siltstone with a sharp, gently inward-dipping, angular unconformity (Martin and Németh, 2005). The volcaniclastic mound is covered by a horizontally bedded, muscovite-rich, finely parallel and cross-laminated siltstone (Fig. 2) up to 8 m thick having a sharp, angular contact with the underlying volcaniclastic beds (Martin and Németh, 2005). The siltstone was invaded by basanite lava up to 10 m thick that destroyed the original laminated structure of the host sediment and formed globular peperite.

The well-bedded volcaniclastic deposits consist of alternating tuff, lapilli tuff and lapillistone beds (Fig. 3). Single layers are normal to reverse graded (Fig. 3) and locally show cross stratification. The beds are up to 3 cm thick, generally plane parallel but also showing extensive scour structures. Angular to semi-rounded basaltic lithic ash gains and lapilli, blocky to slightly elongate non- to moderately vesicular and non- to moderately microlite-rich sideromelane glass shards, clinopyroxene, broken, commonly olivine xenocrysts and a large amount of quartzofeldspathic accidental lithic clasts of silt to sand size are the main constituents. The average of all grain size ranges from 0.5 to 1 cm but larger clasts up to 6 cm also occur occasionally. The angular shape of the juvenile clasts and the presence of non- to moderately vesicular sideromelane glass shards strongly suggests fragmentation of magma by interaction with external water. The sharp edges, blocky shapes and the unaltered texture of volcanic glass shards of volcaniclastic rocks from Kissomlyó, and the sedimentary features such as impact sags, low-angle cross bedding, and antidune structures all are indicative of a primary origin for the dominant proportion of the beds as base surge and alternating fall deposits (e.g. Fisher and Schmincke, 1984; White, 1991). Other beds within the volcaniclastic mound of Kissomlyó show clearly textural characteristics of remobilization such as abundance of abraded commonly rounded volcanic glass shards and broken crystals of pyroxene or olivine and bedding characteristics typical of water-deposited tephra. Such remobilisation is well-known in subglacial (Skilling, 1994) or shallow subaqueous settings (Mueller et al., 2000; Belousov and Belousova, 2001). Tephra may have been remobilised immediately after deposition in an aqueous environment (crater lake; Németh and Martin, 2002, 2004). Lava flows subsequently entered the crater lake and mixed with the unconsolidated wet sediments were present in the crater.

Fig. 3. Alternating coarse–fine lapilli tuff and tuff sequence (arrow) from the tuff ring unit of Kissomlyó.

## 5. Ság-hegy phreatomagmatic volcanic complex (Little Hungarian Plain Volcanic Field)

Ság-hegy is a complex volcano consisting of several volcaniclastic sequences rich in both volcanic glass shards and accidental lithic fragments from country rocks. The pyroclastic succession consists of well bedded and dune bedded, unsorted pyroclastic rock units. The micro and macrotexutral characteristics of the pyroclastic succession indicate a phreatomagmatic origin for these beds. Feeder dykes intruded and cross cut the phreatomagmatic deposits, often forming peperite along their margins. The lowest series of beds comprises unsorted and non-graded to normal-graded, alternating tuff and lapilli tuff beds (Fig. 4). Soft-sediment deformation, cross bedding, undulating bedding, beds of accretionary lapilli and deep,

Fig. 4. Phreatomagmatic lapilli tuff and tuff sequence which was intruded by lava lake-fed sills and dykes from the Ság-hegy. Note the undulating bedding planes (line) and the coarse clast accumulation zones (dashed lines).

well-defined impact sags are common. Juvenile clasts of fine ash to fine lapilli size are predominantly angular, non- to highly vesicular sideromelane glass shards. Vesicular sideromelane shards tend to be stretched and slightly fluidal. A variable number of tachylite shards are present but they are less common than sideromelane shards. Broken quartz and mica crystals are common in addition to the typical magmatic phenocrysts such as clinopyroxenes and olivine. Lithic clasts of <5 cm in diameter are predominantly derived from the Late Miocene fluvio-lacustrine units underlying the volcanic sequence and they often form plastically deformed clots.

The characteristics of Ság-hegy deposits suggest that the initial units are pyroclastic deposits of phreatomagmatic eruptions formed as a consequence of interaction of rising basaltic magma and water-saturated unconsolidated sediments. The pyroclastic units are inferred to have been subaerially deposited by alternating base surges and fall, to form a tephra ring around the erupting vent(s). The interbedded, scoriaceous layers in the phreatomagmatic sequences were previously interpreted at Ság-hegy as the product of non-uniform interaction of water with different magma batches, so that some reached the surface without phreatomagmatic interactions (e.g. Harangi and Harangi, 1995).

## 6. Peperite

Peperite has been divided in this study into two end-member textural types, which correspond to blocky and globular as defined by Busby-Spera and White (1987). Peperite with fluidally shaped clasts of centimetre to -metre size is called globular peperite. Peperite with blocky, mainly angular clasts of intrusive igneous rock within host sediment is called blocky peperite (Busby-Spera and White, 1987). Table 1 gives an overview of host sediments, magma composition and peperite textural types identified. In the Pannonian Basin and in many other cases the intrusive igneous rock develops both blocky and fluidal forms intermixed together in various proportions, as also noted by Busby-Spera and White (1987), Martin (2000) and Hanson and Hargrove (1999). On the basis of a well studied site in California, globular peperite tends to develop where magma

Table 1
Simplified summary of peperite types identified from the western Pannonian Basin

| Locality | Host sediment | Host sediment properties | Igneous rocks | Peperites |
|---|---|---|---|---|
| Hajagos-hegy | Sand and silt possible from the Pannonian Sandstone Formation | Fine-grained, well bedded, well sorted | Basanitic dykes and lava flows | Blocky, minor globular |
| Hajagos-hegy | Sand from inter-lava flow siliciclastic units | Fine-grained, well bedded, well sorted | Basanitic lava flows | Globular |
| Kissomlyó | Marly silt- and mud, post-tuff ring lacustrine beds | Very fine-grained, beds structure-less between pillow lobes, but micro-laminated in basal position, very well sorted | Basanitic dykes and lava flows | Globular, minor blocky |
| Hajagos-hegy | Maar-forming sequence (tephrite volcanic glass composition) | Alternating coarse- and fine-grained lapilli tuff, tuff beds, moderately sorted | Basanitic dykes | Globular, minor blocky |
| Sághegy | Tuff ring-forming sequence (tephrite volcanic glass composition) | Alternating coarse- and fine-grained lapilli tuff and tuff beds, poorly to moderately sorted | Alkali basalt lava flows and dykes | Blocky, minor globular |

intrudes fine-grained host sediments such as silt or mud (Busby-Spera and White, 1987). In the same place in contrast blocky peperite forms more commonly in coarser-grained hosts such as coarse sand or conglomerate (Busby-Spera and White, 1987). In this study, however, evidence is presented to demonstrate that there is no direct control by host sediment grain size on types of peperite developed along dyke or lava flow/lake margins associated with the craters of these phreatomagmatic volcanoes.

## 7. Description of blocky peperite

Blocky peperite has been identified in this study at two localities (Hajagos-hegy and Ság-hegy) associated with host sediments that differ in grain size, mineralogical composition and sedimentary structures. At each of the localities blocky peperite occurs in association with feeder dykes or sills within a phreatomagmatic volcano where magma interacted with either (1) the subsurface phreatomagmatic pyroclastic deposits of the volcano or (2) large collapsed beds of sand and/or silt that slid into the vent zone of the same volcano. At each locality blocky peperite is associated with (1) fine-grained siliciclastic sediments or (2) pyroclastic deposits rich in fine-grained matrix, often derived from disrupted siliciclastic beds. Blocky peperite at each locality is breccia-like, and is related both to columnar jointed basanite, and to the margins of fluidally shaped magmatic bodies.

Blocky peperite with quartz sandstone and lapilli tuff host sediment (Fig. 5) occurs at Hajagos-hegy and is inferred to be the result of interaction of a lava lake with sediment that occupied the maar basin. This type of peperite consists of a fine-grained, brown to light brown, sandy matrix with angular basanite fragments (Fig. 5). The siliciclastic host sediment most closely resembles sandstone from the Pannonian Sandstone Formation in terms of its grain size, colour, composition and texture. Depending on the level of exposure, the host sediment comprises quartz sandstone or at higher levels, lapilli tuff. The lapilli tuff is coarse grained, but is however, always rich in fine-grained tuff matrix (Fig. 6). The fine-grained basanite fragments show a very thin chilled margin (max. 0.1 cm); average clast size reaches a few cm in diameter, but locally large clasts up to 25 cm in diameter are also present. The small basanite fragments (cm-scale) form a jigsaw-fit structure that seems to float in the fine-grained matrix (Fig. 6). Some of the basanite blocks are large (metre-scale) and located up to several metres from the intrusions. These large igneous fragments also show jigsaw fit structures, which are more common near the coherent lava that formed an irregular margin of a lava lake with the host sediment. Commonly the original bedding in the host sediment has been destroyed by fluidization, the effect of which is clearly visible at microscope-scale (Fig. 7). The juvenile clast/host sediment ratio decreases sharply within few metres from the contact with the intrusion.

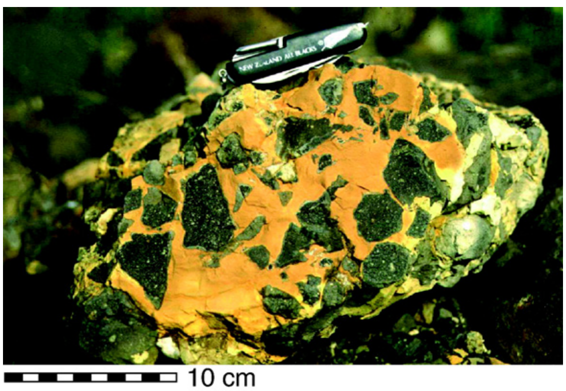


Fig. 5. Blocky peperite in hand-specimen from the Hajagos-hegy. The angular basanite clasts are in siltstone host.

### 7.1. Interpretation of blocky peperite

Columnar jointing in the remnant of the lava lake, which infilled the crater, is radiating. Due to the unconsolidated stage of the host sediments the lava propagated into the phreatomagmatic deposits and the quartz sediments generating peperite. Blocky peperite was formed at Hajagos-hegy along the contacts between basanite intrusions and quartz sand from the pre-volcanic sedimentary succession as well as by interaction with the pyroclastic succession of the tuff ring from the Hajagos maar. The magma was disrupted by quench fragmentation in contact with wet sediment, which led to coarse mixing (Kokelaar, 1982; Wohletz, 1986; Hanson, 1991). Jigsaw-fit-textures record in situ fragmentation. Development of blocky peperite during magma mingling with fine-grained siliciclastic sediments, such as documented from Hajagos-hegy, clearly indicates that factors other than coarse host grain size can lead to its development (Brooks, 1995; Doyle, 2000).

## 8. Description of fluidal peperite

Fluidal peperite occurs at all studied localities in both fine-grained siliciclastic sediments and coarse-grained phreatomagmatic lapilli tuffs. However, the lapilli tuffs that comprised host sediment for intruding basanitic magmas are poorly sorted and always contained a high amount of fine ash matrix, often rich in clay minerals or

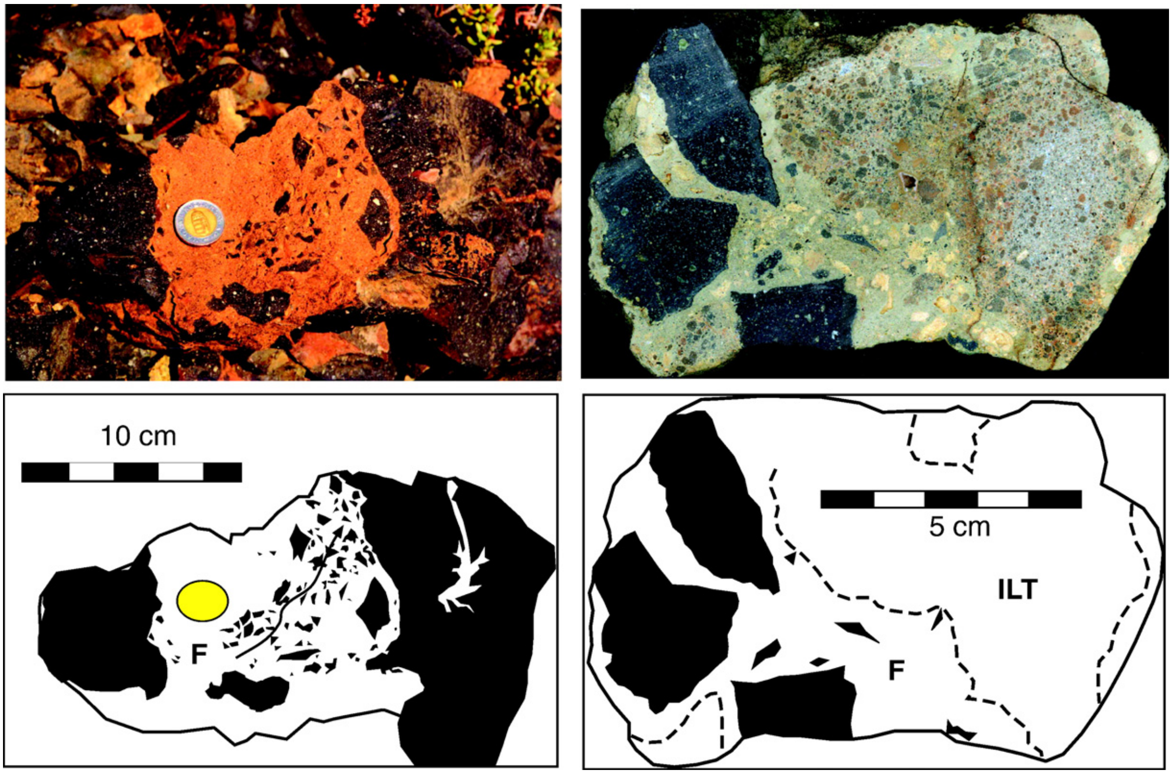


Fig. 6. Blocky peperites in hand-specimen from the Hajagos-hegy. The host is in both sample coarse-grained lapilli tuff. Note the "stream" of clasts (arrow) in the left picture and the fine-enriched regions due to fluidization (F) on the right-hand side pictures. ILT — texturally intact lapilli tuff.

muscovite and fine quartz grains derived from pre-volcanic sedimentary units during maar-forming magma-wet sediment interaction.

Fluidal peperite is a common peperite type in Hajagos-hegy where the host is either (1) lapilli tuff/tuff (Fig. 8) or

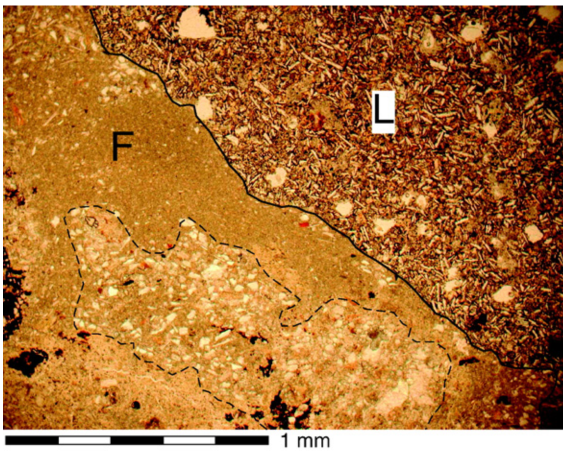


Fig. 7. Photomicrograph of a fluidization texture (F), defined by fine-enriched zone along the angular basanite clasts (L). The host sediment is fine-grained silt.

(2) quartz sand/siltstone. Lapilli tuff and tuff-hosted peperite is present over areas up to several metres across and is characterized by complex relationships between intrusive basalt and tuff or lapilli tuff. The volcaniclastic host most closely resembles the maar-forming volcaniclastic and/or vent-filling pyroclastic deposits in its composition and texture. In the vicinity of the intrusion, sedimentary structures were destroyed, but further away from the contact they are well preserved. The basanitic lava that invaded the host locally shows fluidal margins as a result of fluid–fluid mingling of magma and fluidized or liquefied sediment (Fig. 8). Fluidization of the fine matrix of the volcaniclastic host is recorded by oriented crystals, glass shards and quartz grains preserved alongside larger (cm-scale) juvenile clasts which are mainly globular (Fig. 8) in appearance. The pillow-shaped blobs are typically about 20 cm long (Fig. 8) but in places are associated with larger, ellipsoidal or tongue-like bodies up to 1 m.

Another type of globular peperite has been identified both at Hajagos-hegy (Fig. 9) and Kissomlyó (Fig. 10) tuff rings. At both sites it has developed at the base or margin of the lava lake as pillow bodies there are fairly regular in size and shape. Commonly the fluidal magmatic fragments are detached from the main pillow-lava body

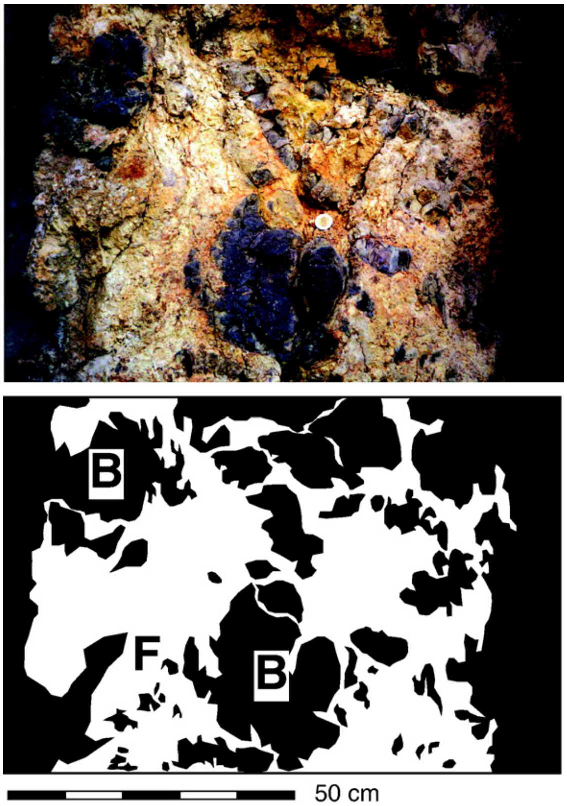


Fig. 8. Globular peperite from Hajagos-hegy formed in coarse-grained lapilli tuff host. B — basanite, F — fluidization.

and mingled with the host quartz sand. Piles of basanite pillows are up to 1 m thick and densely packed, i.e. there is little volume of inter-pillow matrix. At Kissomlyó globular peperite occurs beneath a lava lake that filled the crater (Fig. 10a). Pillow-shaped lobes up to 2 m in length penetrated into the wet, finely laminated, cross-laminated lacustrine sediment deposited in the crater-lake to form globular peperite. Lava mingled with the unconsolidated sediment, incorporating sediment grains and destroying its original texture by fluidization and other mechanical effects (Fig. 10b). Fluidally shaped juvenile clasts in a wide size-range are dispersed along the base of the lava flow as are also some blocky ones (Fig. 10a). There are disconnected pillows, which are detached from the main lava flow and float in the host sediment (Fig. 10a).

### 8.1. Interpretation of fluidal peperite

Magma commonly forms tabular-shaped intrusions when filling fractures in lithified rocks, which may be oriented according to the prevailing stress field. In poorly consolidated sediments the effect of the regional stress field weakens and crack propagation is inhibited causing the intrusions to become irregular (e.g. Kano, 1989). Detached pods of magma and the development of globular peperite (Busby-Spera and White, 1987) are facilitated by fluidization of the host sediment (Kokelaar, 1982). Fluidization involving pore water and unconsolidated sediment is driven by expansion of intensely heated pore fluid, which may entrain material away from the contact and form globular peperite (Busby-Spera and White, 1987). This results in destruction of original bedding of the sediment. The sediment farther away from the contact is usually undisturbed, as observed at Hajagos-hegy.

The pillowed basal zone of lava with textures inferred to represent intimate mixing and mingling with siliciclastic sediments at both Hajagos-hegy and Kissomlyó is interpreted as a peperite, which formed in shallow water (few metres depth) at the margin of the lavas.

We infer that globular peperite at Hajagos-hegy formed subaqueously, when lava flows were emplaced onto sediments in a shallow water body.

Peperite at Kissomlyó is interpreted to have been developed during emplacement of lava flows into a crater lake filled with laminated lacustrine beds. The presence of

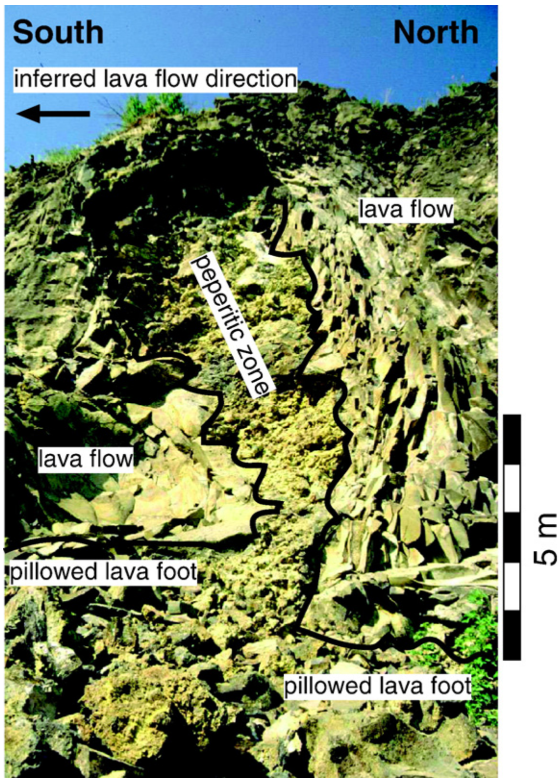


Fig. 9. Globular peperite formed at the base of a lava flow at Hajagos-hegy. The host sediment is fine inter-lava silt.

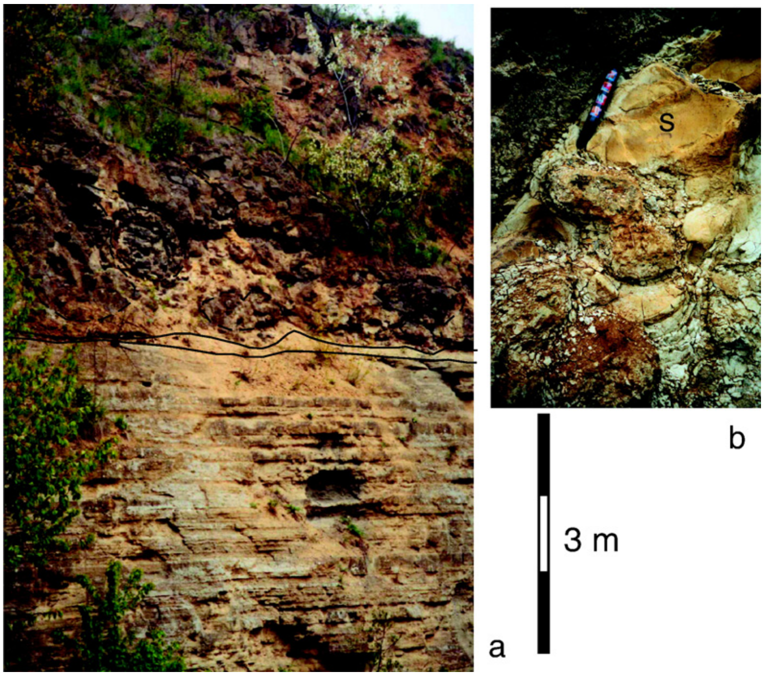


Fig. 10. Globular peperite formed where lava flow invaded crater lake filling post-tuff ring lacustrine micro-laminated silt (outlines) at Kissomlyó (a). Note the metre-size pillow lobes (a) in sand matrix (dashed line). Invaded lacustrine sediments (s) became structure-less and strongly lithified (b).

laminated lacustrine sediments overlying the pyroclastic tuff ring units indicates that significant time passed between the phreatomagmatic events that formed the initial tuff ring and subsequent lava emplacement. The emplaced basanite lava flows truncated, mixed, and mingled with the fine-grained silicic crater lake deposits, destroying their original texture and bedding, and forming globular peperite (Fig. 10b).

## 9. Description of mixed fluidal and blocky peperite

At Ság-hegy phreatomagmatic volcanic complex (Little Hungarian Plain Volcanic Field) blocky and globular peperite also occurs along the margins of intrusions such as oblique dykes and sub-horizontal sills (Fig. 11). An oblique dyke intrudes into a sill that formed peperite in an alternating phreatomagmatic fine-coarse lapilli tuff unit (Fig. 11). The contact zone of the oblique dyke is planar, whereas the margins of the sill are irregular with lava clasts (up to 50 cm) dispersed into the pyoclastic host (Fig. 11). In this and other localities of the Ság-hegy volcanic complex the sills have jagged and brecciated margins (Fig. 12a), and intrusion occurred along unconformities in the tuff ring sequence (Martin and Németh, 2004). Basanite clasts in the globular peperite are up to 1 m long. Most of the smaller lava clasts are, however, blocky and polyhedral, with sharp corners, though others have partly rounded margins. Jigsaw-fit textures are locally preserved. The inner part of the sill and larger lava bodies are aphanitic and non-vesicular, whereas the margins of these bodies and smaller clasts show high vesicularities (Fig. 12a). The strongly vesicular zones show increasing vesicle sizes from the inner part to the margins. Sizes of vesicles vary from large (up to 1 cm) to small (up to 0.2 cm). The vesicles are commonly ragged and elongate.

The original bedding of the host phreatomagmatic tephra along the sill margin was destroyed by fluidization, resulting in a homogenized, fines-enriched zone in the host up to few tens of centimetres in thickness (Fig. 12a). These homogenized zones appear to form a halo around the coherent lava bodies (Fig. 12b). Larger lava fragments often form vertical alignments.

### 9.1. Interpretation of mixed fluidal and blocky peperite

Mixed globular and blocky peperite in the same host sediment indicates a change in fragmentation and mixing mechanism of host and intruding body during magma–wet sediment interaction. Intrusion along unconformities in the tuff ring sequence may have enhanced sill formation due to decreased stress, which allowed an easier emplacement. The initial magma

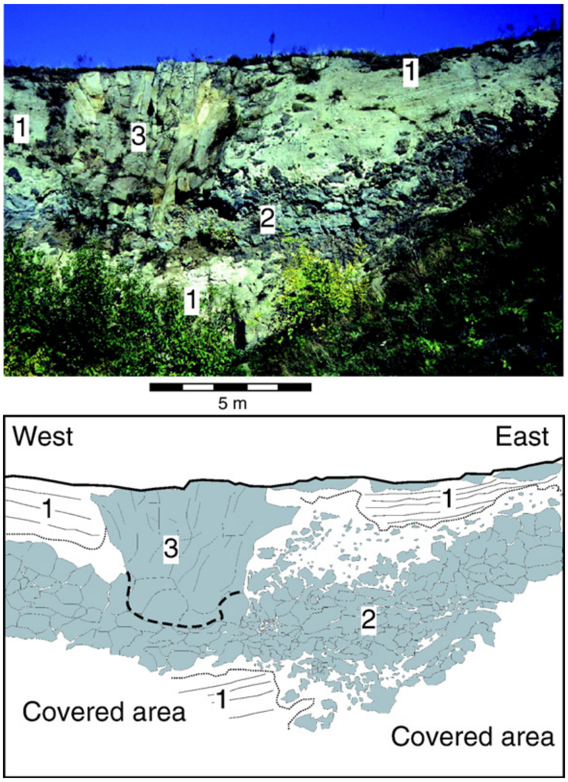


Fig. 11. Basanite sill (2) with wide peperitic margin intruded into a alternating coarse–fine phreatomagmatic lapilli tuff/tuff sequence (1) at Ság-hegy. A late basanite dyke intruded the sequence (3) without significant mixing or mingling with the sill (dashed line). Note the destroyed bedding in the pyroclastic units.

fragmentation and mixing with sediment is interpreted to have been the result of tearing apart of magma and shaping of the magma–sediment interface into globular, pillow-shaped bodies (Doyle, 2000). Blocky peperite was formed due to phreatomagmatic reactions and/or quench fragmentation in the course of breakdown of insulating vapour films at the sediment–magma interface (White, 1996).

## 10. Discussion

Several types of peperite occur in the Pannonian Basin (Fig. 13). These include (1) blocky and globular peperite related to lava lakes in the centre of Hajagos-hegy maar/tuff ring and Ság-hegy phreatomagmatic volcanic complex and (2) globular peperite associated with lava flows that infilled tuff rings at Hajagos-hegy and Kissomlyó. Peperite clearly (1) demonstrates contemporaneity of volcanism and sedimentation of the host sediment (e.g. Hanson and Schweickert, 1982; Einsele, 1986; Kano, 1989; Maas, 1992; Summer and Ayalon, 1995), (2) postdates tuff ring formation and accumulation of maar lake deposits and (3) highlights the importance of peperite in paleoenvironmental modeling of the Bakony-Balaton Highland and Little Hungarian Plain Volcanic Fields.

Globular peperite is thought to represent styles of coarse mixing during fuel–coolant-interactions (FCIs) between the magma and the sediment-laden impure coolants in phreatomagmatic settings (White, 1996; Hooten and Ort, 2002). FCIs involve the sudden contact between a cold, vapourisable liquid (coolant) and a hot liquid (fuel). This interaction is translated to work by the expansion of the liquid coolant to the vapour phase, producing a stable and isolating vapour-film, which serves as insulation between the melt and the

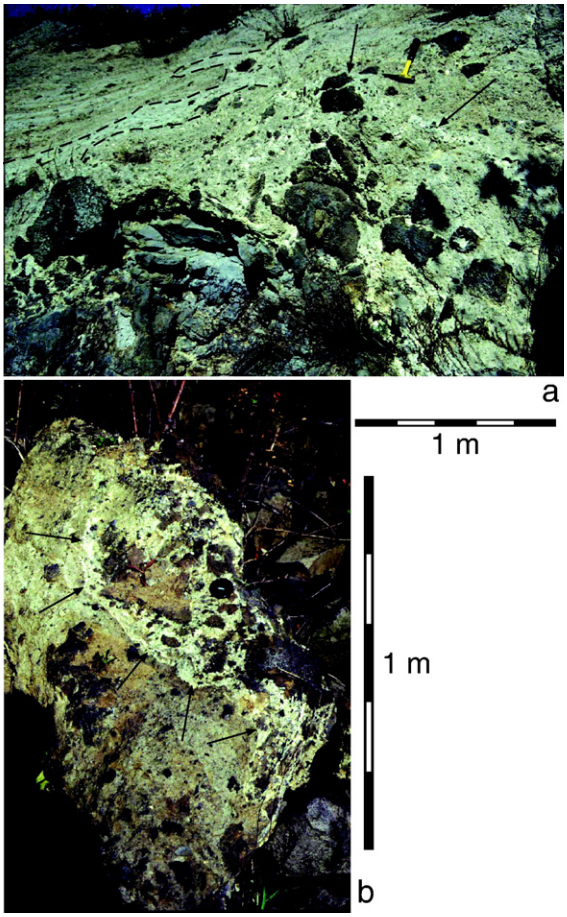


Fig. 12. Fines-enriched halo (dashed line and arrows in both picture) around peperitic intrusion margins from Ság-hegy. In (a) a dispersed zone of basanite clasts is visible surrounded with an irregular whitish sediment halo (arrows) inferred to reflect strong fluidization. In (b) a well-developed halo is visible along a basanite sill-intruded lapilli tuff beds at Ság-hegy. Note the distinct colour difference of the halo (arrows) and the host.

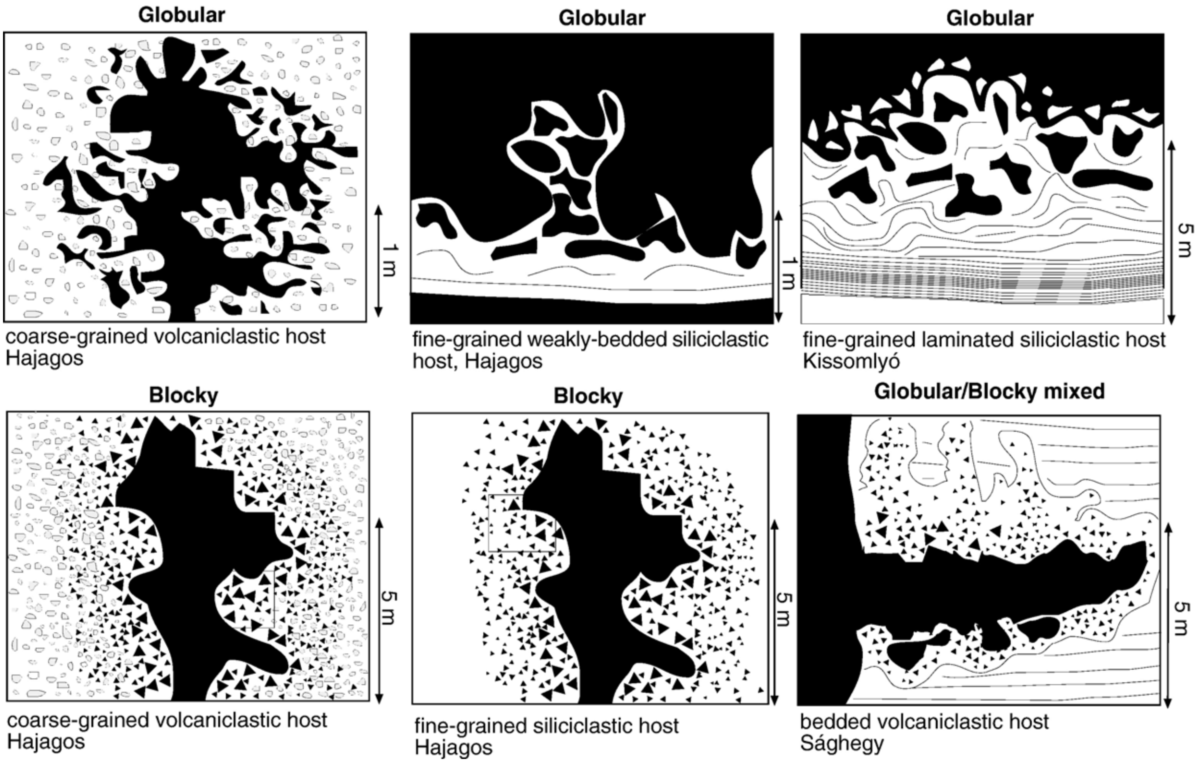


Fig. 13. Simplified schematic representation of peperites identified in the studied areas of the Pannonian Basin.

surrounding water (White, 1996). This allows the magma, at least initially, to develop complex, globular forms without undergoing brittle quench fragmentation (White, 1996). Busby-Spera and White (1987) suggested that the absence of fluidal peperite in coarse-grained sediment in their study area was due partly to the relatively high permeability of the host, which allowed rapid escape of heated pore fluids and thereby inhibited formation of stable, insulating vapour films around intruding magma bodies. They recognised two different kinds of end-members and suggested that the formation of globular peperite is mainly related to fine-grained host sediments, whereas blocky peperite occurs in general within coarse-grained sediments. Direct grain-size effects were interpreted to be the main control on formation of blocky vs. fluidal peperite from a single intrusion, reflecting the fact that coarser-grained sedimentary particles cannot be entrained in the streaming vapour films surrounding intrusive bodies (Kokelaar, 1982; Busby-Spera and White, 1987). Busby-Spera and White (1987) argued that the basic textural differences of peperites would inevitably play a role in development. In the examples from the Pannonian Basin, however the presence of both globular and blocky peperite in host-sediment with the same grain-size (e.g. globular peperite in coarse-grained volcaniclastic host at Hajagos-hegy and blocky peperite in the same type of host at Ság-hegy) implies different fragmentation mechanisms during magma/wet-sediment interaction at the two sites. Such changes independent from host grain sizes have also been documented or suggested from other areas (Brooks et al., 1982; Goto and McPhie, 1996; Doyle, 2000) but not in association with small volume intracontinental alkaline basaltic phreatomagmatic volcanoes. Magma fragmentation, and mixing with sediment described from the Pannonian Basin are related to complex intra-vent processes similar to those described by Hooten and Ort (2002) associated with phreatomagmatic volcanoes, which may involve (1) tearing apart of the magma and shaping of the magma/sediment interface into globular geometries by fluidization or liquifaction (Zimanowski and Buttner, 2002) of the host-sediment, (2) mechanical force of intrusion of the magma, (3) framework clast-matrix ratio of the host-sediment and (4) water content of the host-sediment.

Blocky peperite results from quench fragmentation of the magma and/or mild phreatomagmatic reactions due to the break-down of the insulating vapour films at the magma/wet-sediment interface. Examples presented here support conclusions of Brooks et al. (1982) and Doyle (2000) that is not only the grain-size of the host that controls the formation of different kinds of peperite. A change in viscosity and/or magma flux rate may involve a change in temperature, a change in microlite crystallinity and change in gas content (Polacci and Cashman, 1999). Low-viscosity fluid magma may favour the formation of globular peperite, whereas high viscosity immobile magma instead will form blocky peperite upon cooling across the brittle/ductile transition.

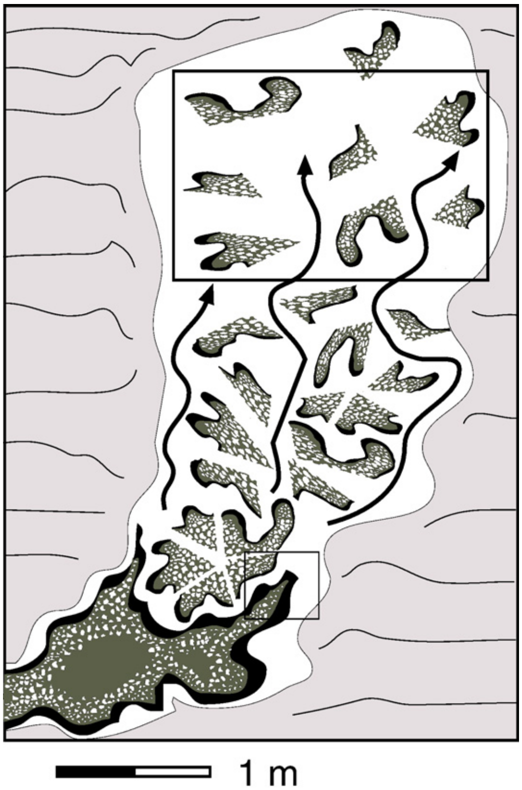


Fig. 14. A model representing the development of fluidized halo around intruding sills/dykes. The sill margin tends to be globular according to the thermodynamic properties of the intrusion and the intruded sediments, physical characteristics of the host and the speed of the intrusion. The host sediments in each studied locality were rich in fine matrix that was easy to remobilize due to heat and mechanical disturbance caused by the intrusion. This process led to a development of a fluidized, fine enriched halo around the intrusion. In a sudden change of the intrusion physical parameters, local suppressed phreatomagmatic disruption may have occurred time to time, dispersing the disrupted lava clasts in a broad zone around the explosion site. In the explosion site angular clast (blocky peperite) would be more expected to be, in contrast in the axis of the intrusion large globular zones may have been remained intact. In this model the scale of observation is crucial to define blocky or globular characters of the developed peperite.

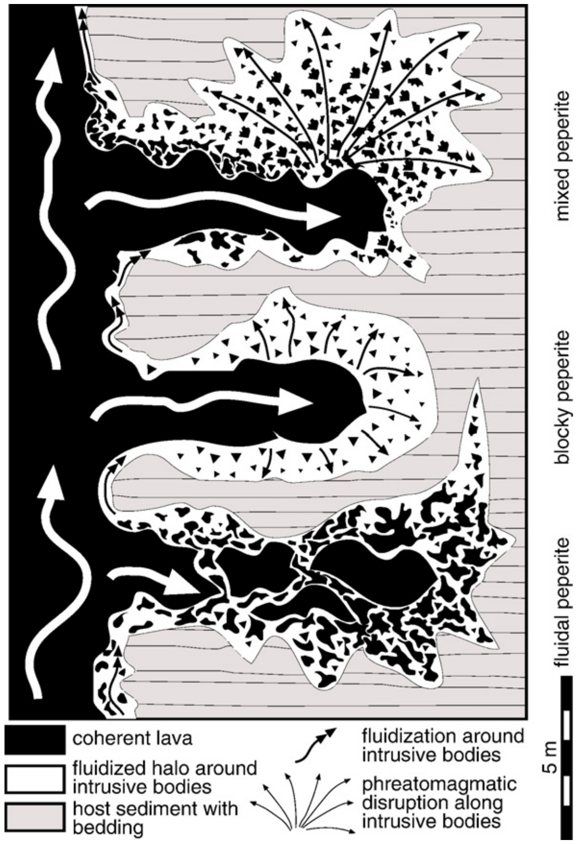


Fig. 15. Summary of the typical scenarios inferred to have operated during dyke or sill intrusion in the BBHVF. The coexistence of different type of peperite in the same type of host (e.g. lapilli tuff or epiclastic sediments) suggests that peperite formation is a function of local irregularities in the host, and the intruding melt and highlights the importance of the scale of observation.

The abundance of jigsaw-fit textures at Hajagos-hegy, for example, implies that quench fragmentation was an important clast-generating process, probably occurring together with dynamic stressing of chilled margins (Kokelaar, 1986; Hanson, 1991). Peperite textures may also be a function of the emplacement rate of the magma.

Mechanisms for generating structure-less textures in blocky peperite include minor steam explosions and/or progressive disruption of previously formed peperite masses during forceful emplacement of new magma pulses (Hanson and Hargrove, 1999), due to disruption of vapour films. The host sediment's thermal properties are also demonstrated to be controlling factors of developing different peperite textures (Martin, 2000; Martin and White, 2002). With thermodynamic models information can be provided regarding the conditions of the sediment and intruding dykes, which then allows reconstruction of the thermodynamic evolution of the contact zones between dykes and sediment (Martin and White, 2002).

It is difficult, however, to quantify the physical properties driving transitions in fragmentation mechanism because of the complex and rapidly changing states of the components. In addition, our study illustrates considerable great complexity of intrusive/effusive processes in phreatomagmatic intra-vent/intra-crater settings.

Based on field observations we conclude that all coherent lava bodies involved in the peperite-forming process had a cm- to m-scale strongly fluidized and/or liquefied zone forming a halo around them (Figs. 12 and 14). This halo is generally easy to distinguish from the undisturbed sediment by its lighter colour and lack of sedimentary structures. An enrichment of fines beyond fluidized zones is suggestive of fluidization processes enhanced by the heat of the magmatic bodies. Commonly the halo is narrow in places where globular peperite has developed, whereas the halo is up to a metre wide in areas with blocky peperite. There is a clear transition from irregular margins of sills or dykes (globular peperite) to disrupted, angular shaped, originally globular fluidal clasts or blocks (blocky peperite) (Figs. 14 and 15). The classification of the different peperite end-members is strongly related to the scale of observation (Figs. 14 and 15).

## 11. Conclusions

Peperite style (globular vs. blocky) in the studied sites is not only controlled by host sediment properties, and in particular grain-size, because (1) blocky and globular peperite each occur in host-sediment with the same average grain-size and sorting in the Pannonian Basin; (2) both globular and blocky peperite occur together in the same host sediment. Peperite textures identified in the western Pannonian Basin are: (1) globular peperite in coarse-grained pyroclastic deposits; (2) closely packed globular peperite in fine-grained epiclastic siltstones; (3) loosely packed globular peperite in fine-grained epiclastic siltstones; (4) blocky peperite in coarse-grained pyroclastic units; (5) blocky peperite in fine-grained epiclastic siltstone; (6) blocky and globular peperite in coarse-grained pyroclastic deposits (Fig. 13).

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