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Small-volume volcaniclastic flow deposits related to phreatomagmatic explosive eruptive centres near Szentbékkálla, Bakony-Balaton Highland Volcanic Field, Hungary: Pyroclastic flow or hydroclastic flow?[1]

Freatomagmás kitörési centrumokhoz kapcsolódó vulkanoklaszt árüledékek Szentbékkálláról (Bakony–Balaton-felvidéki vulkáni terület): piroklaszt, vagy hidroklaszt ár?

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(13 ábra, 2 táblázat)

Key words: phreatomagmatism, hydrovolcanism, Bakony-Balaton Highland Volcanic Field, Pannonian Basin, pyroclastic flow, hydroclastic flow

Tárgyszavak: freatomagmatizmus, hidrovulkanizmus, Bakony–Balaton-felvidéki vulkáni terület, Pannóniai-medence, piroklaszt ár, hidroklaszt ár

Abstract

Volcanic sequences related to the late Miocene alkaline basaltic volcanic province of the Bakony–Balaton Highland Volcanic Field occur at Szentbékkálla near Lake Balaton, Hungary. Physical volcanology field mapping and geophysical investigations indicate the importance of phreatomagmatic explosive activity during the eruptive history of the region. In particular, geomagnetic and gravity models suggest that the main eruptive centres have a deep excavated root zone and maar structures at depth. Evidence of small-volume volcaniclastic flow deposits has arisen during recent mapping and field studies. The massive, unsorted, coarse-grained volcaniclastic flow deposits alternate with cross-bedded, matrix-rich, block-bearing lapilli tuff beds, pyroclastic surge deposits and mantle bedding, co-surge fall-out tuff layers. The main bodies of the volcaniclastic flow sequences consist of grey, massive, compact lapilli tuff beds. There is no any evidence of grading or inner sedimentary structures, nor welding in the individual beds or flow units. The flow units always contain a high proportion of semi-rounded to rounded gravel-like ultramafic xenoliths and broken olivine and pyroxene megacrystals (without any accumulation). The beds contain a high proportion of fragments of the whole known underlying sedimentary sequence. The main part of the volcaniclastic flow unit has a non-erosional contact with the underlying Pannonian (late Miocene) river gravel beds. The contact zone contains lithics picked

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up from the gravel beds. The proposed volcaniclastic flow deposits show several well-developed gas segregation pipes, which are filled with lithic lapilli. The juvenile fragments are usually micro-vesiculated and slightly palagonitized. Their composition, according to electrone microprobe analyses, range between tephrite, phono-tephrite and tephri-phonolite. Small altered, light-coloured glass shards with 62–69 w% SiO_2 (88–95 w%total) show a dacite/trachydacite and basaltic andesite composition. These glass shards were picked up from early explosive volcanic products. The present ridges represent former river-valleys occupied by the volcaniclastic flows. The transportation direction from north to south has been evaluated by interpreting horizontal transportation features (e.g. dune, antidune, scour fillings). According to the presence of gas segregation pipes, a distal facies of a volcaniclastic flow is indicated. The sedimentary structures of the deposits suggest a laminar, gravity-driven high-concentration, semi-fluidized flow movement. This is typical for pyroclastic flows, but the low juvenile fragment ratio (compare to pyroclastic flows) and their high hydroclast content indicate a hydroclastic source. We therefore introduce the term "hydroclastic flow" to stress the difference between real pyroclastic flows and flows generated due to collapsing margins of hydroclastic driven eruption clouds.

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Összefoglalás

Szentbékkálla kb. 20 km-re fekszik a Balaton északi partjától. A terület vulkáni képződményei a Bakony–Balaton-felvidék vulkáni terület felső-miocén alkáli bazalt vulkáni sorozatának része. A fizikai vulkanológiai térképezések és a geofizikai kutatások egyaránt felhívták a figyelmet a jelentős freatomagmás vulkanizmus lehetőségére a területen. A geofizikai tanulmányok (geomágneses és gravimetrikus mérések) mutattak rá arra, hogy az egyes kitörési központokhoz jelentős méretű kitörési csatornák és mélyre vágott maar kráterek tartozhatnak. A legújabb térképezések során sikerült azonosítani egy kis térfogatú vulkanoklaszt ár üledéket Szentbékkálla környékéről. Szerkezet nélküli, osztályozatlan, durvaszemcsés árüledékek váltakoznak keresztrétegzett, alapanyag dús, blokk gazdag lapilli tufa rétegekkel, melyek piroklaszt torlóár (alapi torlóár) és szórt piroklaszt üledékeknek tekinthetők. A vulkanoklaszt árüledék fő tömege szürke, szerkezet nélküli, kötött lapilli tufa rétegek sorozata. Semmi lényeges üledékföldtani jel nem mutatható ki a rétegekben. Az üledék nagy arányban tartalmaz enyhén kerekített–kerekített, kavicsszerű peridotit zárványokat véletlenszerű eloszlásban. A rétegek igen gazdagok törmelékekben, melyek az egész ismert felszín alatti formációkat képviselik. Az árüledék alapi zónája erózió nélküli átmenetet mutat a fekü pannoniai folyóvízi kavicsrétegekkel. A folyóvízi és vulkanoklasztikus rétegek határán a vulkanoklaszt üledék talpzónájában jelentős mennyiségű feltépett kavics található. A vulkanoklaszt ár üledékben néhány jól kifejlett gáz kilépési csatorna azonosítható, melyek általában lítikus törmelékekkel kitöltöttek. A juvenilis törmelékek általában mikrohólyagosak, enyhén palagonitosodottak. A kőzetüveg elemzések elektron mikroszondás adatai alapján tefrit–fono-tefrit–tefri-fonolit összetételek adódtak. Azonban kisméretű, világos színű, mállott üvegszilánkok elemzése 62–69 v% SiO_2 (88–95 v% total) mellett dácit/trachidácit bazaltos andezit összetételt mutatott. E törmelékek leginkább korábbi vulkáni kitörések termékeinek feltépett zárvanyai lehetnek. A terület jelenlegi dombhátai valószínűleg a korábbi vulkanoklaszt ár által kitöltött völgyek eróziós maradványai. A vízszintes szállításra utaló üledékföldtani jellegek elemzése az ár észak–déli irányú mozgását jelzi. A gáz kilépési csatornák megléte a vulkanoklaszt ár üledék kürtőtől távoli helyzetét mutatja. Az üledékföldtani jellegek azt mutatják, hogy az üledéket létrehozó közeg egy nagy sűrűségű, vízszintesen, gravitációs hatásra mozgó anyagár lehetett, mely tipikus a piroklaszt árakra. Azonban a leírt üledékek juvenilis szemcsearánya lényegesen kisebb mint az ismert piroklaszt ár üledékeké, s azok jobbára magma/víz kölcsönhatása során keletkezett hidroklasztok (hirtelen lehűlt, megdermedt vulkáni üveg), azaz a robbanásos kitörések hidroklasztikus folyamatokra, s nem a magma saját, jelentős gáztartalmából adódó széttöredezésre vezethetők vissza. Éppen ezért javasoljuk bevezetni a hidroklaszt ár (hidroklaszt ár üledék) kifejezéseket, e különbség kifejezésére, arra az esetre, ahol a nagy sűrűségű gravitációs tömegár hidroklasztikus kitörési felhő összeomlásából, s nem piroklasztikus kitörési felhő összeomlásából származik.

Introduction

The Bakony–Balaton Highland Volcanic Field (BBHVF) is located in the Central Pannonian Basin, Hungary. The BBHVF volcanic centres were active between approximately 7.54 Ma and 2.8 Ma (BALOGH et al. 1982, 1986; BALOGH 1995; BORSY et al. 1986) and produced mostly alkaline basaltic volcanic products (e.g. EMBEY-ISZTIN et al. 1993; SZABÓ et al. 1992; DOWNES & VASELLI 1995; DOWNES et al. 1995; HARANGI in press). The volcanism was related to post-extensional tectonic processes in the middle part of the Pannonian Basin (SZABÓ et al. 1992). The BBHVF eruptive centres are closely related to the eruptive centres of the Little Hungarian Plain Volcanic Field according to their composition, age and general eruption mechanism (HARANGI & HARANGI 1995; NÉMETH 1997). Volcanism at both fields was coeval: however, the eruptive mechanism and explosivity may have varied due to differing palaeo-environments and hydrogeology. (KÁZMÉR 1990; HARANGI & HARANGI 1995).

The BBHVF consists of more than 50 basaltic volcanoes (LÓCZY 1894, 1913; JUGOVICS 1915; 1969; JÁMBOR et al. 1981). This number is greatly underestimated because several complex eruptive centres comprise a large number of individual vents and probably individual volcanic edifices. The real number of eruptive vents range between 150–200 in this relatively small (~3500 km^2) area. The underlying basement of the volcanic field consists of thick Silurian schist, Permian red sandstone and Mesozoic carbonate beds. The basement forms a large-scale anticline which is locally covered by Tertiary sediments in local basins (KÁZMÉR & KOVÁCS 1985). The Silurian schist formation is a 400–600 m thick unit which contains alternating, very low-grade metamorphosed psammitic and pelitic beds (LELKES-FELVÁRI 1978). The Permian red sandstone is a thick (400–600 m), continental alluvial formation (MAJOROS 1980; 1983); here Mesozoic formations are represented by Triassic limestones and dolomites, which are directly related to the Triassic Eastern Alps (KÁZMÉR & KOVÁCS 1985). The younger sediments were deposited on an erosion surface in local sedimentary basins. In the Neogene section, before volcanism started, a large lake occupied the Pannonian Basin – namely, the Pannonian Lake (KÁZMÉR 1990). Lacustrine sandstones, mudstones and marl of the brackish Pannonian Lake are widespread in the Pannonian Basin (MÜLLER & SZÓNOKY 1989). These usually fine-grained clastic quartzofeldspathic sediments show a gradual transition from a deep environment into a shallower, more typical sedimentary environment. Prior to volcanism, the area was probably an alluvial plain (KÁZMÉR 1990). Volcanism was mostly subaerial but there is evidence of local subaqueous or emergent eruptions, (term used by KOKELAAR 1983; 1986). The eruption style was related to the distribution of palaeovalleys, formerly stream – occupied longitudinal systems with good water supply. These stream valleys developed by exploring preexsisting and probably reactivated, tectonic structures similar to the ones in the West Eifel volcanic field, as suggested by BÜCHEL (1993).

The BBHVF comprises a great variety of volcanic centres (e.g. maars, tuff rings, scoria cones) which are characteristic of intra-continental, mostly monogenetic alkaline basaltic volcanic fields – e.g. Hopi Buttes, Arizona (WHITE 1991), Western Snake River, Idaho (GODCHAUX et al. 1992), Eifel, Germany (BÜCHEL 1993), Massif Central, France (JUVIGNÉ et al. 1993).

Recently, a wide range of hydrovolcanic deposits have been identified on the BBHVF, but no volcaniclastic ("pyroclastic") flow deposits have been described yet (NÉMETH 1997; NÉMETH & MARTIN 1998). In this study we suggest that on the northern part of the Káli Basin a special type of pyroclastic flow (hydroclastic flow) formed during phreatomagmatic activity and produced volcaniclastic deposits with a high concentration of peridotite xenoliths and accidental lithics (*Fig. 1*).

Pyroclastic sediment gravity flows are usually hot, gas-particle, density currents (SPARKS 1976; FISHER & SCHMINCKE 1984, 1994; CAS & WRIGHT 1987). Their deposits are rich in crystals, glass shards and usually pumice. There are also lithic fragments in variable proportion depending upon 1) the composition of magma; 2) the country rock through which the materials rise; and 3) the ability of the currents to erode the surface over which they flow (FISHER & SCHMINCKE 1994). There are two end members of the pyroclastic sediment gravity flow deposits: 1) pyroclastic flow deposits that are relatively thick, poorly sorted, and which commonly but not invariably contain abundant fine-grained ash in the matrix, with only crude or no internal bedding; and 2) pyroclastic surge deposits that are relatively thin, better sorted than flow deposits, which are with or without abundant matrix fines, and well-bedded to cross-bedded. Surge deposits may occur beneath (ground surge), or on top (ash-cloud surge) of pyroclastic flows, or by themselves as a product of hydromagmatic activity (base surge) (FISHER & SCHMINCKE 1984, 1994; CAS & WRIGHT 1987). The term "ignimbrite" is used to describe a pyroclastic flow deposit which is rich in pumice and glass shards (FISHER & SCHMINCKE 1994). Pyroclastic sediment gravity flows can move rapidly over long distances. Their deposits are generally much thicker in valleys (valley fill deposits) than on ridges (overbank deposits) (FISHER & SCHMINCKE 1984, 1994). Differences in sedimentary structures, grain size and bedforms allow characterization of each type of deposit.

Volcaniclastic ("pyroclastic") flow deposits near Szentbékkálla

At the northern side of the Káli Basin there are 3 main hills (*Fig. 1*) and at the eastern side there is a large hydromagmatic maar volcanic complex (Fekete-hegy maar volcanic complex) with at least 3 eruptive centres (NÉMETH et al. 1997). These eruptive centres produced fine-grained lapilli tuffs, which crop out on the southern side of the hills. The top of the hill is covered by Strombolian scoria cone remnants and lava flows. On the western side, a large eroded Strombolian scoria cone and Hawaiian spatter cone complex with small

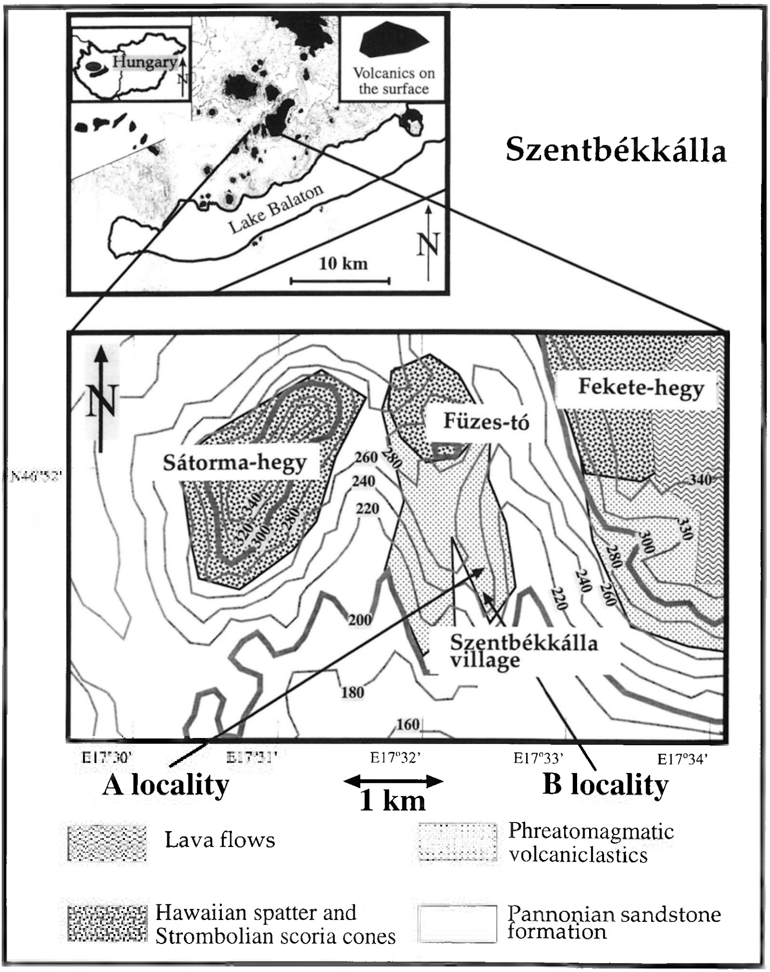

Fig. 1 Geological map of the Szentbékkálla area
1. ábra. A szentbékkállai terület földtani térképe

lava flows occupied the area (Sátorma-hegy). Between these two morphological highs there is an elongated 5–6 km long ridge from the Füzes-tó to the Káli Basin (*Fig. 1*). From the highest point on the northern side a gently dipping ridge is traceable down to the Káli Basin lowland. The ridge is 1–3 km wide, and at Szentbékkálla village it forks into two individual ridges. On the northern side of the ridge, around the Füzes-tó area, there are many fragments from dense and vesiculated spindle bombs enclosing peridotite xenoliths in openwork or fine-grained sideromelane lapilli and ash matrices, forming volcaniclastic deposits (NÉMETH & SZABÓ 1998). There are volcaniclastic deposits between Füzes-tó and Káli Basin which also contain a high quantity of peridotite xenolith fragments (up to 40 cm in diameter), and crustal lithics such as limestones, dolomites, schist fragments and sandstone fragments from the Silurian, Permian, Mesozoic and Pannonian strata. A lack of suitable outcrops between Füzes-tó and Szentbékkálla village prevents exact stratigraphical correlation of the observed deposits. The structure of the deposits in large outcrops is only visible near Szentbékkálla. We separate two types of lithofacies in this region on the basis of their juvenile/lithic fragment ratio, composition, sedimentary structures and distribution (*Fig. 1* and *Fig. 2*).

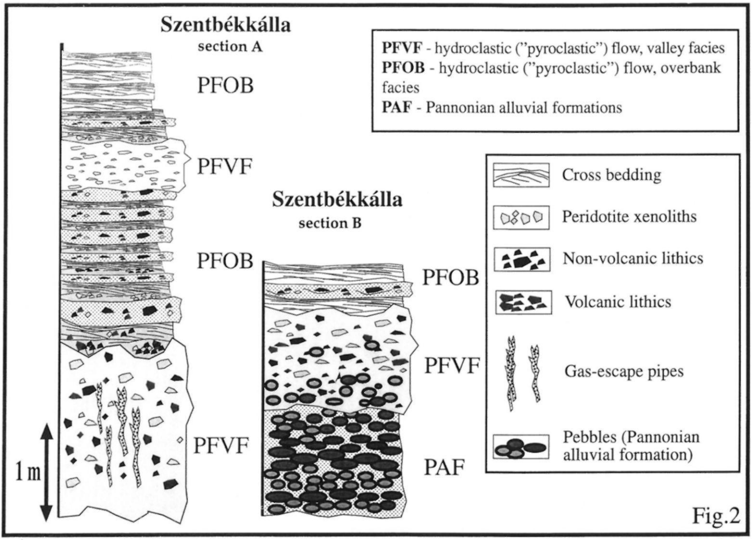

Fig. 2. Simplified stratigraphy columns of the Szenbékkálla section "A" and "B"
2. ábra. A szentbékkállai "A" és "B" feltárás egyszerűsített rétegoszlopa

Volcaniclastic ("pyroclastic") flow valley filling facies (PFVF)

The lower part of the Szentbékkálla open-air theatre outcrop shows a minimum 2.5 m thick succession (*Fig.* 2). This succession is a grey, polimict volcaniclastic breccia, block-bearing lapilli tuff. The lower part of the sequence is massive, but in a higher stratigraphic position, faint clast alignments give a crudely bedded impression (*Fig.* 3). The massive volcaniclastic beds are compact and show crude joints locally. The matrix of the lithofacies comprises

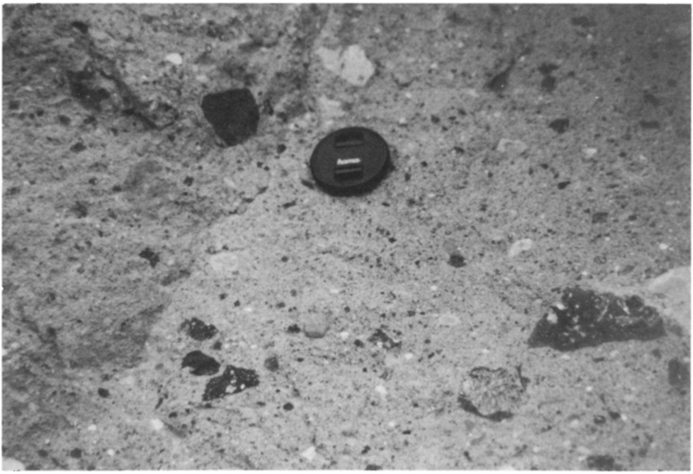

Fig. 3 Photo of the massive PFVF lithofacies from the Szentbékkálla section "A"
3. ábra A PFVF litofácies áttekintő képe a szentbékkállai "A" feltárásból

fine-grained volcaniclastic sand or silt. Large clasts are dominantly accidental lithics (min. 85 v% of total) with a wide range of lithology from the pre-volcanic stratigraphy (*Fig.* 3 and *Table* 1). The main proportion of the lithics are Mesozoic carbonates (e.g. limestones, dolomites, and marls), which comprise up to 70 v% of the total large "accidental lithics" (term used after FISHER & SCHMINCKE 1984, p. 90 and p. 239); they are up to 25 cm in diameter, with an average size of 2–5 cm. There is also a small amount of Paleozoic schist, quartzite (15 v% of total large accidental lithics, up to 5 cm in diameter, average 0.5 cm), and occasionally larger Pannonian Sandstone fragments (5 v% of total large accidental lithics, up to 35 cm in diameter, average 2 cm). The accidental lithics are broken angular fragments. The carbonates and smaller Pannonian sandstone fragments are more rounded. The clasts are not coated with any particles. The Pannonian sandstone fragments and the Mesozoic carbonate clasts are usually thermally affected. They show a mm thick baked rim. Clasts are not oriented

Summary of the features of the PFVF and PFOB lithofacies

A PFVF és PFOB litofáciesek tulajdonságainak összefoglalása

Table I – I. tábla

PS – Pannonian sandstone formation, PZS – Palaeozoic schists, M – Mesozoic formations, ACL – accidental lithics

LA	Protolith	Areal distribution	Sedimentary structures and textures	Juvenile fragments and their composition	Depositional processes
PFVF	Grey, polimict, massive volcanoclastic breccia, lapilli tuff. Min. 85v% of total large clasts (1 cm<) ACL. ~70v% of large ACL areM carbonates up to 25 cm in diameter, average ~ 5 cm. Large ones angular small ones rounded. ~15v% of large ACL are PZS or quartzite up to 5 cm in, diameter, average 0.5 cm, angular shape ~ 5v% of large ACL are PS up to 35 cm in diameter. Large ones angular, small ones rounded. ~15v% of total large ACL are volcanic (cogenetic and/or lithic). Matrix is dominantly palagonite, altered glass.	Szentbékkálla "A" and "B" locality and probably between Szentbékkálla and Füzes-tó (there are no sufficient outcrops)	Massive, non graded, unsorted character. Faint bedding in the upper part by scoriaceous fragment strings. No impact sags, no well developed scour fill structures. Slightly columnar jointed characteristics in the lower level of the sequence ("A" locality) Thermal effect on several clasts. Strong alteration on the acidic volcanic glasses (88-92 v% of total during microprobe analysis). Gas segregation pipes, entrapped, fluidised accretionary lapilli rich beds. Large amount of peridotite xenoliths	Two generation of volcanic glasses: **a.,** light color, slightly red alteration, oriented microliths, rounded, symmetric vesicles, acidic composition (88-92v% of total): dacite – tracyte **b.,** darker color, brown sideromelane lapilli, elongated, ovoid vesicles, microliths, trachytic texture. Basanite – phono-tephrite/ trachy basalt, basaltic trachy-andesite composition (92-100 v% of total)	Phreatomagmatic explosive eruption generated high density laminar plug flow transportation where large clasts are transported in a stratified flow body. Pyroclastic flow, but according to the dominant hydroclastic juvenile material and the large amount of excavated lithics: hydroclastic flow valley filling facies
PFOB	Gray, bedded, cross bedded lithofacies, upward well bedded. Min. 95v% of large clasts (1cm<) ACL. ~85v% of large ACL are M carbonates up to 50 cm in diameter, average, ~5 cm. ~5v% of large ACL are PS up to 5 cm in diameter. Matrix is dominantly palagonite, altered glass.	In both ridges around Szentbékkálla village, detailed areal correlation is not possible due to lack of outcrops.	Cross bedded, dune, antidune bedded unsorted, non graded lapilli tuff beds alternating with fine grained mantle bedding 1-5 cm thick rim type accretionary lapilli rich beds. In lower level at "A" locality no impact sags, but scour filling behind large clasts. Upward few impact sags. Flow direction: from north to south.	Two generation of volcanic glasses but the type a glass is rarer than in PFVF. The composition of the glasses similar to the PFVF lithofacies glass composition.	Phreatomagmatic explosive eruption generated horizontal moving high concentration, wet and low temperature, high density turbulent flow, diluted pyroclastic (hydroclastic) flow body, overbank facies

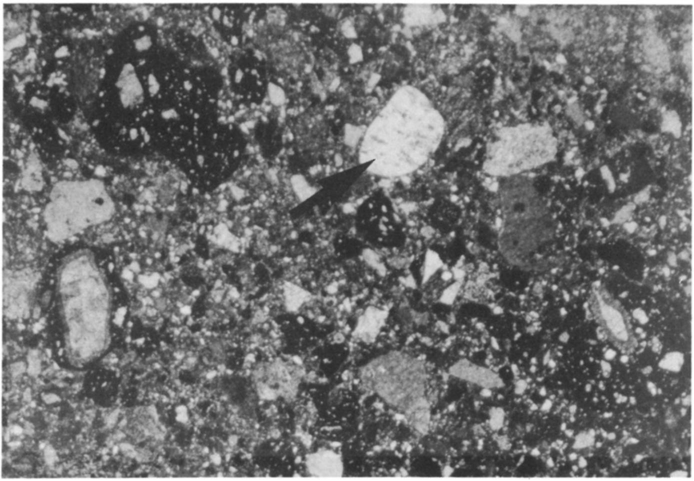

Fig. 4. **Photomicrograph of Pannonian** pebble clasts picked up from the basal zone of the hydroclastic ("pyroclastic") flow units at the Szentbékkálla section "B" (short side of the picture is 2 mm)

4. ábra. Feltépett pannoniai kavics fragmentum a hidroklasztit (piroklasztit) ár üledék alsó zónájából a szentbékkállai "B" feltárásból (a kép rövidebb oldala 2 mm)

nor stretched. An Echinoidea fossil from the pre-volcanic Triassic beds was found withouth evidence of any thermal effect on its rim. Crystalline igneous rock fragments differ from known basaltic lava rocks occuring at the surface in this region and they are probably disrupted fragments from the sub-volcanic region. Many clasts were picked up from the underlying pebble beds at the Szentbékkálla "B" locality, on the bottom of the flow body (*Figs 2, 4, 6*). This pebble concentration decreases as upwardly in the section but is still represented around 3–4 m above the base at the Szentbékkálla section "B". In general, there is no sorting or gradational texture in the entire massive unit. The large clasts caused no impact structure or scour fillings.

The major body of the proposed volcaniclastic flow contains relatively fresh, small, vesiculated sideromelan glass shards up to 1 mm in diameter (*Fig. 5*). The shards are usually slightly elongated, but there are also block-type glass shards without any vesicles. The vesicles are usually rounded, elongated and filled by secondary microcrystalline calcite. The larger sideromelane clasts have a palagonitized rim which penetrates into the inner zone of the glass shard. A representative glass composition of major element data is shown in *Table 2;* however, the acurarcy is limited by the small size of the shards and the secondary process that has affected them. Two different types of volcanic glass

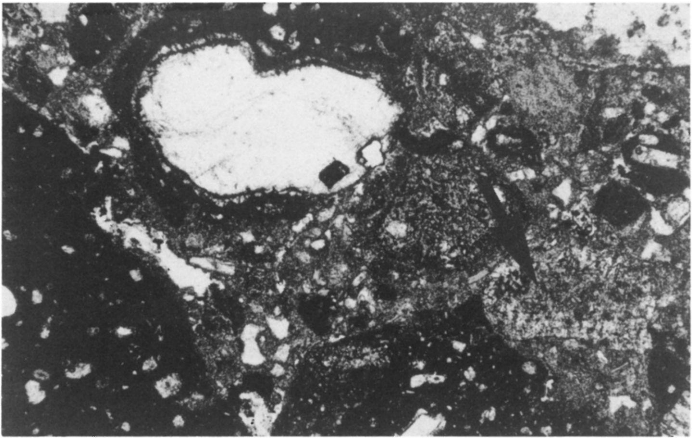

Fig. 5. Sideromelane shards from the PFVF lithofacies at Szentbékkálla section "A" (short side of the picture is 1 mm)

5. ábra. Szideromelán szemcse a szentbékkállai "A" feltárás PFVF litofácieséből (a kép rövidebb oldala 1 mm)

were identified: a) A dark coloured, (brown, yellow), irregularly shaped glass with oriented microliths (trachytic texture) and elongated, oriented vesicles. This type of glass has 49–54 w% SiO_2. Measurements were 92–96 w% of the total and most shards showed slight to moderate palagonization. b) A glass lighter in colour (e.g. white, cream) with a few to no microliths, with rounded to slightly elongated vesicles. This type is, locally, slightly red and has higher SiO_2 (62–69 w%) content, but measurements were 90 w% of total, occasionally 95–96 w%. The low alkaline ratio implies a significant loss of alkali due to alteration and thus the simple 100 w% normalization of data is different from the real composition of the glass (FISHER & SCHMINCKE 1984, p. 314). In this case the dacitic glass could have been originally phonolitic or trachydacite glass shards. Near Szentbékkálla, the sideromelane shards from hydrovolcanic lapilli tuffs showed 3 different composition groups, suggesting a complex volcanological situation in this relatively small area. Group A): ranges between predominantly tephrite, phono-tephrite and tephri-phonolite (*Table* 2). These data, in general, are similar to the glass compositions of other eruptive centres from the BBHVF (NÉMETH & MARTIN 1999). Group B): ranges from trachy-basalt to basaltic trachy andesite; this could be interpreted as an altered version of group A, from estimations of significant alkaline loss during alteration of sideromelane to clay minerals and palagonite (*Table* 2). Group C): ranges from basaltic andesite to dacite which, even calculating significant alkaline loss during alteration, shows a different composition compared to groups A and B respectively (*Table 2*). The volcanic glasses in groups A and B represent juveniles from Szentbékkálla and group C probably represents older glass picked up from pre-volcanic clasts. In this case we have to estimate a large volcanic pile

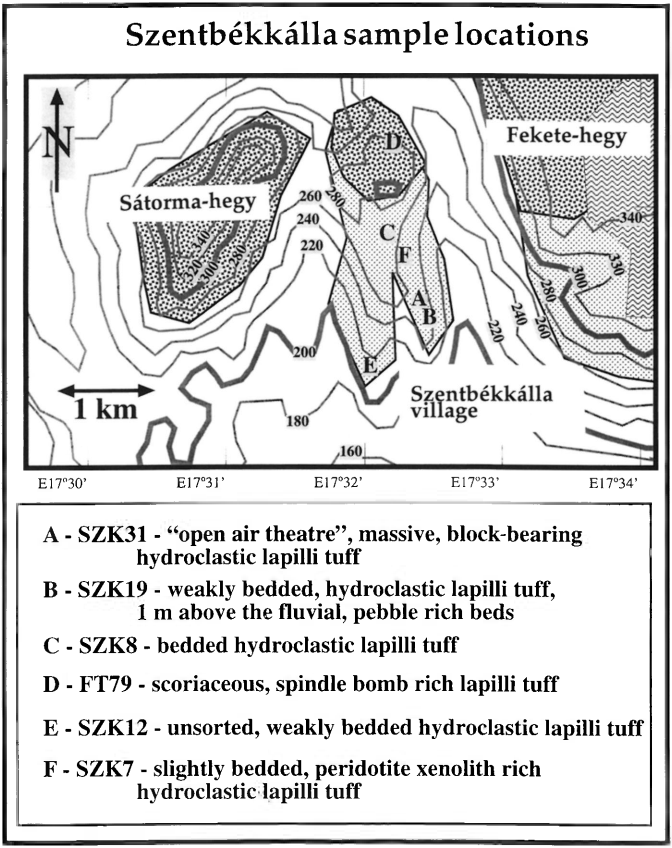

Fig. 6. Map showing the localities of collected volcaniclastic samples for microprobe analysis

6. ábra. A vulkanoklasztitok juvenilis üvegtartalmának elemzésére gyűjtött minták térképe

Major element compositions of samples from the Szentbékkálla region using microprobe analysis (15 kV acceleration on JEOL 8600 Superprobe)

Főelem analízisek összefoglaló táblázata a Szentbékkálla környéki vulkanoklasztitok juvenilis üvegtartalmának elemzésére

Table II – II. tábla

Locality	SZK31 LCG	SZK31 LCG	SZK31 LCG	SZK31 BG	SZK31 BG	SZK19 LCG	SZK19 BG	SZK8 LCG	FT79 LCG	SZK12 LCG	SZK7 LCG
SiO2	66.382	55.331	60.80	42.20	42.44	54.14	44.18	48.811	54.612	52.43	49.501
Al2O3	15.679	20.206	12.41	17.82	17.94	17.82	18.23	19.188	19.776	18.86	18.027
TiO2	1.275	2.255	0.55	2.33	2.36	2.31	2.23	2.354	2.469	2.14	2.578
FeO	6.041	9.08	8.46	7.07	7.18	7.50	7.52	8.16	9.669	7.58	8.945
MnO	0.065	0.128	0.00	0.19	0.09	0.13	0.26	0.156	0.152	0.17	0.176
MgO	1.894	3.057	3.22	4.07	4.06	3.73	3.46	3.595	2.956	2.76	3.603
CaO	1.445	7.26	2.09	9.41	9.77	9.69	9.64	8.767	7.093	6.81	8.707
Na2O	0.457	0.613	0.11	4.69	4.37	4.95	4.67	2.43	1.181	6.01	2.343
Na-total	*5.338*	-	*11.73*	*13.84 ?*	*13.24 ?*	-	*11.37*	*6.34*	-	-	*5.382*
K2O	1.875	1.541	0.74	3.08	2.90	3.14	3.11	2.625	2.355	3.65	3.079
Total	95.119	99.4765	88.38	90.85	91.13	103.41	93.30	96.0914	100.272	100.39	96.9642
SiO2	69.79	55.331	68.82	46.45	46.57	52.35	47.35	50.80	54.612	52.43	51.05
Al2O3	16.48	20.206	14.05	19.61	19.69	17.23	19.54	19.97	19.776	18.86	18.59
TiO2	1.34	2.255	0.62	2.56	2.59	2.23	2.39	2.45	2.469	2.14	2.66
FeO	6.35	9.08	9.58	7.78	7.88	7.25	8.06	8.49	9.669	7.58	9.23
MnO	0.07	0.128	0.00	0.21	0.10	0.13	0.28	0.16	0.152	0.17	0.18
MgO	1.99	3.057	3.64	4.48	4.46	3.6	3.71	3.74	2.956	2.76	3.72
CaO	1.52	7.26	2.37	10.36	10.72	9.37	10.33	9.12	7.093	6.81	8.98
Na2O	0.48	0.613	0.12	5.16	4.80	4.79	5.01	2.53	1.181	6.01	2.42
K2O	1.97	1.541	0.84	3.39	3.18	3.04	3.33	2.73	2.355	3.65	3.18
Total	100	99.4765	100	100	100	100	100	100	100.272	100.39	100
Name	Dacite - *Trachy dacite ?*	Basaltic andesite	Dacite – *Phonolite*	Tephrite *Foidite ?*	Tephrite *Foidite ?*	Basaltic trachy - andesite	Phono-tephrite *Foidite ?*	Trachy-basalt *Phono-tephrite*	Basaltic andesite	Phono-tephrite	Trachy-basalt *Phono-tephrite*

LCG – light colour glass , BG – brown color glass. Measurement was taken on JEOL 8600 Superprobe, using polished thin section, 15 kV acceleration voltage, 10 – 20 _m beam diameter, OXIDE9 standard. Na-total - assuming that all the total loss is Na loss, thus 100-total added to Na_2O

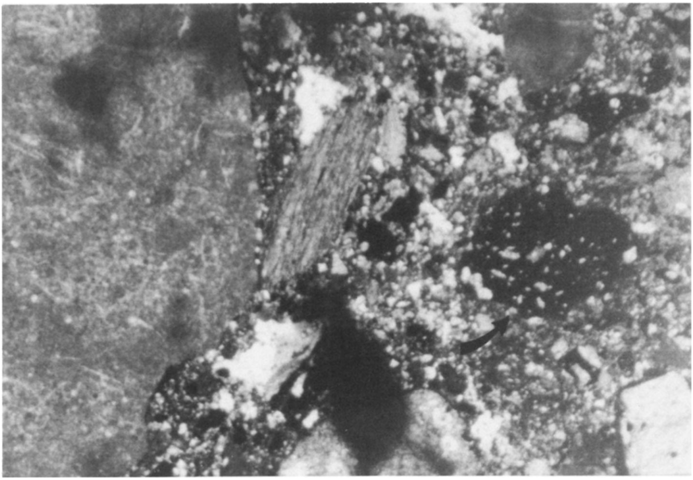

Fig. 7. Tachylite clast from the PFVF lithofacies at Szentbékkálla section "A" (short side of the picture is 2 mm)

7. ábra. Tachylite szemcse a szentbékkállai "A" feltárás PFVF litofáciesébõl (a kép rövidebb oldala 2 mm)

in the shallow sub-surface region with basaltic andesite - andesite - dacite, or simply phonolitic composition; this is unusual in the BBHVF. The phonolitic composition is a better fit to the tephrite–phono-tephrite–tephrite magma evolution lineage: this is probably an important magma evolution lineage of the BBHVF according to glass composition analyses by NÉMETH & MARTIN (1999).

The volcaniclastic sequence contains a small amount of tachylite glass up to 3 mm in diameter, probably as reworked clasts from the product of earlier magmatic (e.g. Strombolian eruptions or from simultaneously active Strombolian vents) explosive events (*Fig. 7*). The tachylite glass shards are usually rounded and they are widely distributed in the same stratigraphic unit. Neither the sideromelane nor tachylite glasses show welding or stretching.

There are a few well-developed gas segregation pipes in the Szentbékkálla section "A" (which is like an open-air theatre) (*Fig. 8*). They are a maximum 1 m long, 2–10 cm wide, irregularly shaped, and filled with coarse-grained lithics up to 2 cm in diameter. The lithics have a very wide range of origin, but are mostly crustal xenoliths. Volcanic clasts are rare. Above the gas segregation pipes, a few large clasts are concentrated in an openwork texture. Fine material in these zones is elutriated and seems to have moved is an upward direction forming slightly fluidized structures in the sequence. The fluidized

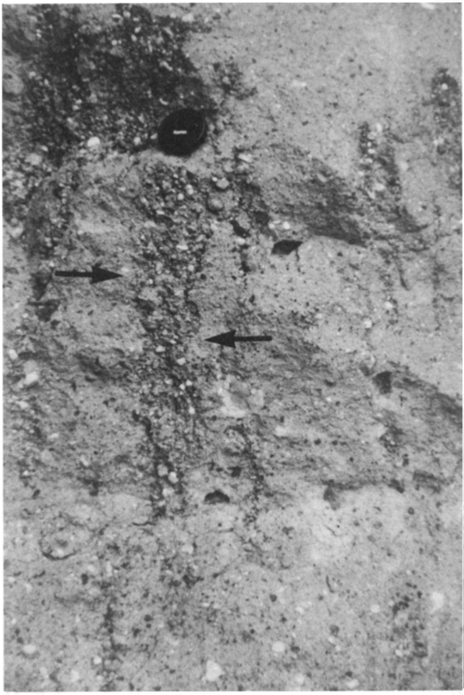

Fig. 8. Gas-segregation pipes from the PFVF lithofacies at **Szentbékkálla** section "A"

8. ábra. Gázkilépési csatornák a szentbékkállai "A" feltárás PFVF litofácieséből

zones have irregular diffuse borders with a large number of accretionary lapilli up to 1 cm in diameter (*Fig. 9*). The accretionary lapilli are ovoid and slightly flattened in shape. Individual accretionary lapilli show a well-developed rim up to 1–2 mm thick. The gas escape pipes are in the lower exposed part of the Szentbékkálla section "A" (open-air theatre) volcaniclastic unit.

The volcaniclastic sequence contains extremely high amounts of peridotite xenoliths (up to 10 cm in diameter). The lherzolit fragments do not show any orientation or significant accumulation in any part of the sequence. There are some samples which have a thin, glassy rim.

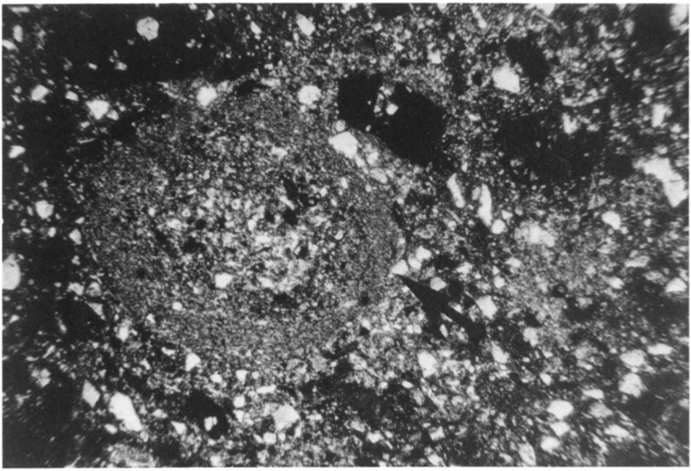

Fig. 9. Accretionary lapilli rich, plastically deformed (fluidized) fragments from the massive PFVF lithofacies at Szentbékkálla section "A" (short side of the picture is 1 mm)

9. ábra. Akkréciós lapilli gazdag, plasztikusan deformált (fluidizált) fragmentum a PFVF masszív litofáciesből, a szentbékállai "A" feltárásból

Volcaniclastic ("pyroclastic") flow overbank facies (PFOB)

The upper part of the Szentbékkálla open air theatre (section "A" locality) is formed by a crudely bedded, cross bedded lithofacies (*Fig. 10, Table 1*). Compositionally, similar to the lower PFVF lithofacies but the smaller grain size of large clasts and the well-defined bedding distinguishes this unit from the basal one. The relative ratio among the accidental lithics has changed, compared to the lower unit. The Mesozoic limestone and dolomite clasts (up to 50 cm in diameter) are more abundant and larger than in the PFVF. Schist fragments and Permian red sandstone fragments are less common and their grain size is smaller (up to 5 cm in diameter). The carbonate clasts are angular, broken and there is less evidence of any thermal effect on their surface. Large Pannonian sandstone fragments are not so frequent as in the PFVF facies, but quartzo-feldspathic grains Pannonian sandstone origin are more common in the matrix. Behind the large, mainly angular clasts, scoriaceous particle concentration zones are common. Scoriaceous clast strings – forming 1–5 cm thick, 50–100 cm long upward concave bases with slightly upward convex top lenses – are also common. The scoriaceous fragments are not larger than 1 cm in diameter.

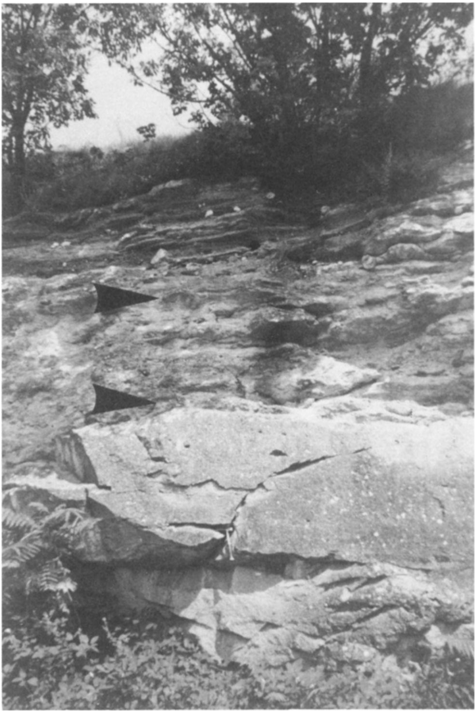

Fig. 10. Cross-bedded PFOB lithofacies at Szentbékkálla section "A" (top of the outcrop)

10. ábra. Keresztrétegzett PFOB litofácies a Szentbékkálla "A" feltárásnál

In the PHOB lithofacies there are very fine-grained grey or brown cross-bedded units which are a few cm thick in the upper part of the sequence. In general, the fine-grained, cross-bedded and cross-laminated units are more dominant in the upper part of the sequence. The cross beddings are low angle, indicating a north to south transportation direction. Usually the individual cross-bedded strata are covered by mantle bedding fall out beds (a few cm thick) with a large amount of accretionary lapilli (up to 1–2 mm in diameter) (*Fig. 10*). The accretionary lapilli are usually concentrated on the top of the individual beds.

There are no bomb sags in the major body of volcaniclastics (Szentbékkálla section "A" PFVF lithofacies). The large clasts show no disturbance in underlying deposits. Faint bomb sags are locally visible in the upper PFOB lithofacies but they are not typical.

Discussion

We interpret the Szentbékkálla deposits as a small volume volcaniclastic ("pyroclastic") flow (FISHER & SCHMINCKE 1984, 1994) succession related to base surge and fallout deposits. This interpretation is supported by the following field evidence.

1. A massive, unsorted primary volcaniclastic body, representing a laminar flow structure, with no possibility of delicate any mixing of different particles during transport (Szentbékkálla section "A", PFVF lithofacies);

2. A high frequency of peridotite xenoliths with different grain sizes are usually related to a large magmatic body emplacement in the subvolcanic region (mostly Szentbékkálla section "A", PFVF lithofacies, but evident all around the region);

3. A high frequency of deep excavated fragments from the entire underlying sedimentary strata indicate a deep explosion focus (all over the region) (Mesozoic limestones, dolomites - ~10 - 100 m depth under the syn-volcanic surface; Permian red sandstone fragments - ~ 100 - 500 m depth under the syn-volcanic surface; schist fragments - ~500 to maybe as much as 2500 m (under the syn-volcanic surface);

4. No bedding sags around the large clasts and poor sorting suggest a high-density laminar flow transportation in which the large clasts were transported in a stratified flow body (PFVF and PFOB lithofacies);

5. Scour-filling structures in random distribution (mostly in Szentbékkálla section "A" locality, PFOB lithofacies)

6. Gas escape pipes on the bottom part of the massive unit representing strong evidence for a high degree of fluidization (Szentbékkálla section "A";

7. Field relation with pre-volcanic stream valley with a valley-filling character; overbank deposits (Szentbékkálla section "B", continuous transition between fluvial pebble beds to volcaniclastic beds);

8. Stratigraphic relationship of base surge and fall-out beds in the larger area around Szentbékkálla village (*Fig. 1*).

It should be noted that many of the features of the PFVF and PFOB lithofacies are characteristic of both an ignimbrite (pyroclastic flow - term used after FISHER & SCHMINCKE 1984 suggestion, p. 222; please note that the term "ignimbrite" used after SPARKS et al. 1973 is restricted to pumiceous pyroclastic flows – i.e. pumice-flow deposits – and their deposits, regardless of the degree of welding or volume) and lahar origin. This is indicated by valley pounding, non-erosional basal contact poor sorting etc. (FISHER & SCHMINCKE 1984). However, some features (e.g. high content of volcanic glass, bread crust scoria fragments, absence of internal structures such as bedding, cross-bedding, occurrence of steam-escape pipes etc.) better conform with an "ignimbrite" origin (FISHER & SCHMINCKE 1984).

The large number of small sideromelane fragments among the juvenile shards (even if they are altered) suggests that phreatomagmatic magma/water interaction was important throughout the eruptions.

The occurrence of gas-escape pipes in the studied PFVF lithofacies strongly suggest that the Szentbékálla section "A" represents a middle or distal facies position. This is around 4–7 km away from the former vent according to the FREUNDT & SCHMINCKE (1986) calculation and the analysis of the Laacher See small-volume phonolitic pyroclastic flow units.

The larger clasts are usually not more then 40 cm in diameter in the Szentbékkálla section's "A" PFVF and PFOB lithofacies. These data, according to the small-volume pyroclastic flows from Laacher See (FREUNDT & SCHMINCKE 1986), also indicate a distance of 4–5 km from the former vent. Therefore the former vent is located somewhere to the north of the Szentbékkálla village, about 4–7 km away. The high abundance of large spindle bombs with large peridotite xenoliths, spatter deposits and the unsorted, unbedded characteristics of the volcaniclastics in that region (Füzes-tó) could represent a vent zone (NÉMETH & SZABÓ 1998). However, at this stage there is not sufficient data to establish if this vent was the source of the volcaniclastic flow deposits or just a local Strombolian scoria cone that operated there. Further geochemical analysis of the volcanic glass shards as well (as finding more outcrops) are required in order to determine if the Füzes-tó region is a source of the small-volume volcaniclastic flow sequence.

Eruption mechanism

According to our observations, the following eruptive history is available for modelling the volcanic history of the Szentbékkálla area (*Fig. 11*).

A: Stream valley(s) on the former Pannonian lacustrine sediment is/are filled by gravelly, fluvial beds (probably north to south transportation).

B: Initial phreatomagmatic explosions occurred near to the surface region due to the water content of stream valley sediments (e.g. sideromelane clasts and a large amount of accidental lithics from the subsurface strata). The explosion locus (due to the drying process of a porous media aquifer) migrated downwards at high speed following the model of LORENZ (1986). The explosion locus probably quickly reached the fracture - controlled aquifer (given the presence of the large number of Mesozoic carbonate fragments), where the karst water could have fuelled the phreatomagmatic processes (NÉMETH & MARTIN 1998). The magma supply was probably continuous (even increasing) producing more efficient phreatomagmatic interaction between magma and (at this stage) the probably karst water system (Tihany type maar volcano, according to NÉMETH & MARTIN 1998, NÉMETH et al., in prep. model). The explosion produced a high particle concentration eruption column, producing the effect of a continuous (even increasing), input of disrupted material, which became heavy and overweighted. Thus its margin collapsed and produced small-scale volcaniclastic flow units (i.e. a special type of "pyroclastic flow"),

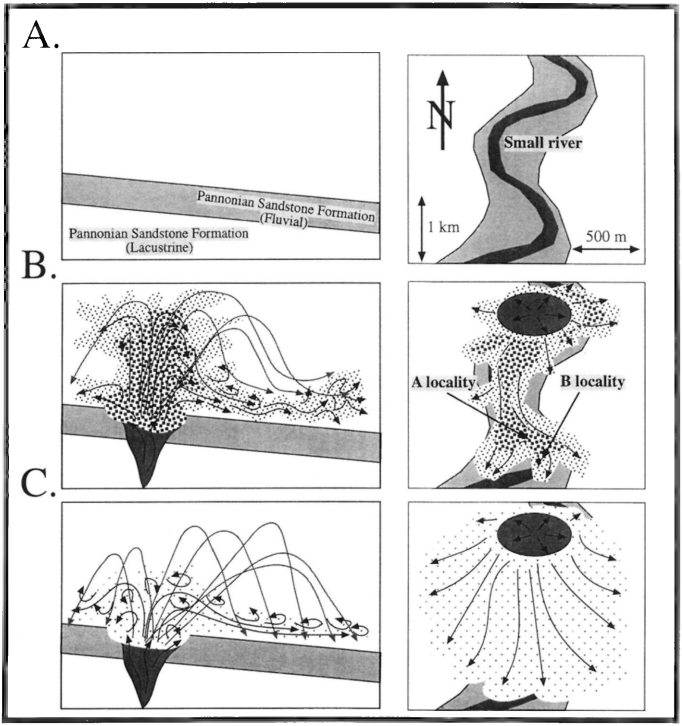

Fig. 11. Eruptive history of the hydroclastic ("pyroclastic") flow forming activity in the Szentbékkálla region. A – fluvial depositional environment on the lacustrine sedimentary erosion surface, B – maar-forming hydroclastic eruptive activity with pyroclastic ("hydroclastic") flow generating phase, C – decreasing magma or/and water supply to fuel hydromagmatic explosions, normal base surge and phreatomagmatic fall out forming period

11. ábra. Vulkánkitörési model a szentbékkállai vulkanoklasztit ("piroklasztit") ár keletkezésére. A – folyóvízi üledékképződési környezet a Pannon tavi üledékek eróziós felszínén, B – hidroklasztikus explóziók maar krátert vágnak a felszínbe, piroklasztit (hidroklasztit) ár képződési szakasz, C – csökkenő víz és/vagy magma utánpótlás az explóziók normál alapi torlóár és freatomagmás hullott piroklasztit képző folyamatokba fordulásával jár which travelled downwards following the palaeo-topography (north to south transportation dirrection according to the PHOB lithofacies features). During flow, water from the streams was trapped into the flow body and clastic material was picked up (e.g. pebbles in the lower level of volcaniclastics).

C: With decreasing magmatic supply (or a sudden cut off of the water supply) the efficiency of the phreatomagmatic process decreased. At this stage normal base surge and fall-out processes occurred (i.e. as shown by the normal base surge and fall-out beds at the top of PHOB lithofacies at Szentbékkálla section "A").

Conclusion

In summary, facies variations in the deposits resulted in 1) the interaction between the volcaniclastic ("pyroclastic") flow and palaeomorphology, 2) the relative abundance of the lithic and juvenile components supplied by the source, and 3) the variation of the flow regime (*Fig. 12*). Due to the poor outcrop availability we were not able to trace the exact geometrical structure of the volcaniclastic ("pyroclastic") flow deposits and the pre-volcanic topography. Nevertheless we can propose some guidelines for reconstruction of the volcanic activity and depositional environment. The differences between the two lithofacies (PFVF and PFOB) were caused by the interaction between a density-stratified flow and topography. Lithofacies PFVF and PFOB at the Szentbékkálla open-air theatre outcrop ("A" locality) is a representative site for modelling a volcaniclastic ("pyroclastic") flow deposit emplacement. The lower part is characterized by a thick, coarse-grained and massive valley facies, which vertically grades into a thin layered and fine-grained overbank facies. The vertical transition between the two facies represents changes in the mainstream of the individual flow according to the in situ geometrical changes of the valley, where the flow moved in a downward direction. Vertical variations of structures resulted from flow unsteadiness during emplacement and, hence, depended on the variation of the suspended load fallout from the low-concentration upper part of the flow to the high-concentration boundary layer. This vertical facies change could also represent sudden changes in the energy of the volcaniclastic ("pyroclastic") flow-forming explosions. Similar cases were reported by FREUNDT & SCHMINCKE (1986) and SCHUMACHER & SCHMINCKE (1990) from the Laacher See volcano, Germany and PERROTTA & SCARPATI (1994) from Campi Flegrei, Italy, and GIANETTI (1998) from the Roccamonfina volcano, Italy.

New measurements of major elements on fresh glass shards of volcaniclastics showed a large geochemical variation within a small area (*Fig. 6; Table 2*). The new data of "dacitic" glass from the volcaniclastic ("pyroclastic") flow shows that there was an unusual volcanic pile in the subvolcanic region. The tephrite/ basanite–phono-tephrite–tephri-phonolite composition suggests alkaline magma evolution, causing phreatomagmatic explosive activity with volcaniclastic ("pyroclastic") flow-forming events. Using the definition for

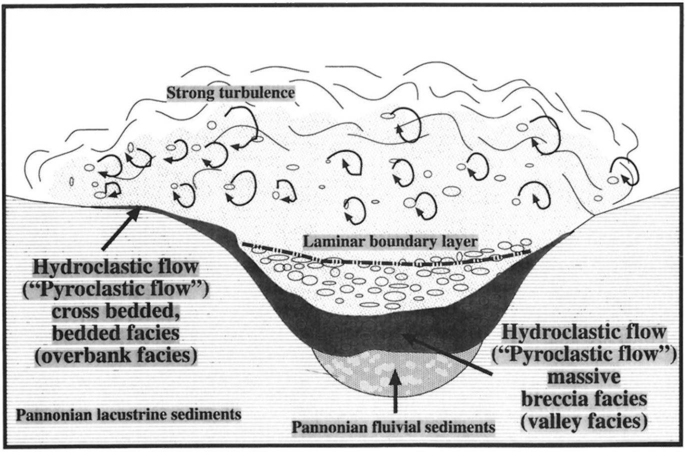

Fig. 12. Facies relation between PFVF and PFOB

12. ábra. A PFVF és PFOB litofáciesek kapcsolata

ignimbrites (regardless of their composition, temperature and welding), as a pyroclastic flow, density gravity flow (FISCHER & SCHMINCKE 1984) is also a possible reason for the Szentbékkálla small-volume volcaniclastic ("pyroclastic") flows. Because of the many transitional varieties of pyroclastic flows, it is recommended that the term ignimbrite be used for all deposits formed by the emplacement of pyroclastic flows. SPARKS (1976) suggested that the term "pyroclastic flow" be used for high-concentration semifluidized bodies moving essentially with a laminar motion. Sedimentary characteristics of this type of transportation, and the conditions of the volcaniclastic processes, are demonstrated at Szentbékkálla. In many instances pyroclastic flows contain not more than 5 v% of lithic fragments (FISHER & SCHMINCKE 1984). These are mostly juvenile lithics, but most of the pyroclastic flows contain a significant amount of pumice. The deposits around Szentbékkálla, as demonstrated, are high in accidental lithics and the juvenile fragments make up less than ~15 v% of the total volume. The juvenile fragments (volcanic glass) are chilled basic fragments (e.g. basanite, phono-tephrite, tephri-phonolite), having their origins in phreatomagmatic magma/water interaction. The compositional characteristics of the deposits are significantly different compared to ignimbrite-type deposits, even though the physical processes (i.e. transportation, deposition) seem to be the same. To stress these differences, we propose a new term hydroclastic flow to describe these deposits. In both cases – pyroclastic or hydroclastic – the flow body – forming process is related to the overweight

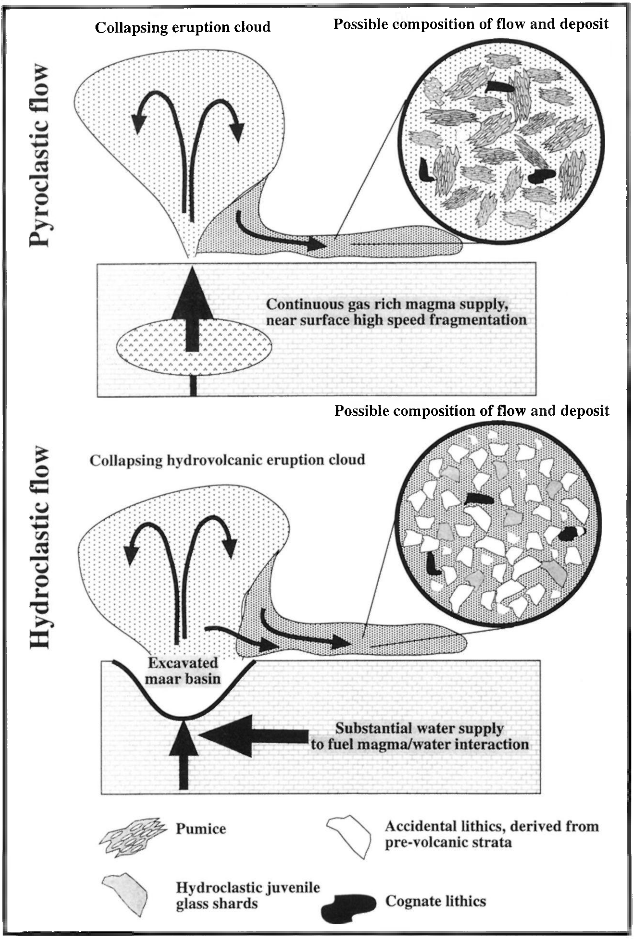

Fig. 13. Origin of pyroclastic and hydroclastic flows and their textural characteristics

13. ábra. Piroklaszt és hidroklaszt ár keletkezési modelek és a keletkező üledékek szerkezete of the eruption cloud. This led to its collapse, thus producing horizontal laminar gravity currents. The difference between the two systems is justified only in the clast composition (*Fig. 13*). In the case of a pyroclastic flow-forming process (simplified model) the explosion is triggered by the high magmatic gas content of the magma. The eruption cloud will be overfilled by volcanic juvenile fragments (mostly pumice), and picked and torn up juvenile lithic fragments; this mass will then travel as a laminar gravity flow (*Fig. 13*). In the case of hydroclastic flow, the eruption initially is triggered by the magma/water interaction, where the water was subsurface water. If the water and magma supply is continuous the phreatomagmatic explosions continuously excavate the subsurface strata, producing an overweighted eruption cloud which will collapse and feed a laminar, gravity flow. This produces deposits which will have the same sedimentary characteristics as normal pyroclastic flow deposits. The difference between the two sediments will be in their juvenile and lithic clast ratio, and the juvenile glass shard texture (i.e. magmatic–hydromagmatic glass). It is most likely that the above-mentioned hydroclastic flow-forming process is strongly related to the eruption mechanism of Tihany-type maar volcanoes, as described by NÉMETH et al. (in preparation).

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