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Lavas or ignimbrites? Permian felsic volcanic rocks of the Tisza Mega-unit (SE Hungary) revisited: A petrographic study


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MÁTÉ SZEMERÉDI^{1,2*} , ANDREA VARGA¹,
JÁNOS SZEPESI^{2,3}, ELEMÉR PÁL-MOLNÁR^{1,2} and
RÉKA LUKÁCS^{1,2}

¹ ‘Vulcano’ Petrology and Geochemistry Research Group, Department of Mineralogy, Geochemistry and Petrology, University of Szeged, Szeged, Hungary

² MTA-ELTE Volcanology Research Group, Budapest, Hungary

³ Isotope Climatology and Environmental Research Centre (ICER), Institute of Nuclear Research, Hungarian Academy of Sciences, Debrecen, Hungary

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ORIGINAL ARTICLE



ABSTRACT

Permian felsic volcanic rocks were encountered in petroleum exploration boreholes in SE Hungary (eastern Pannonian Basin, Tisza Mega-unit, Békés–Codru Unit) during the second half of the 20th century. They were considered to be predominantly lavas (the so-called “Battonya quartz-porphyr”) and were genetically connected to the underlying “Battonya granite.” New petrographic observations, however, showed that the presumed lavas are crystal-poor (8–20 vol%) rhyolitic ignimbrites near Battonya and resedimented pyroclastic or volcanogenic sedimentary rocks in the Tótkomlós and the Biharugra areas, respectively. The studied ignimbrites are usually massive, matrix-supported, fiamme-bearing lapilli tuffs with eutaxitic texture as a result of welding processes. Some samples lack vitroclastic matrix and show low crystal breakage, but consist of oriented, devitrified fiammes as well. Textural features suggest that the latter are high-grade rheomorphic ignimbrites.

Felsic volcanic rocks in SE Hungary belong to the Permian volcanic system of the Tisza Mega-unit; however, they show remarkable petrographic differences as compared to the other Permian felsic volcanic rocks of the mega-unit. In contrast to the crystal-poor rhyolitic ignimbrites of SE Hungary with rare biotite, the predominantly rhyodacitic–dacitic pyroclastic rocks of the Tisza Mega-unit are crystal-rich (40–45 vol%) and often contain biotite, pyroxene, and garnet. Additionally, some geochemical and geochronological differences between them were also observed by previous studies. Therefore, the Permian felsic volcanic rocks in SE Hungary might represent the most evolved, crystal-poor rhyolitic melt of a large-volume felsic (rhyodacitic–dacitic) volcanic system.

The Permian volcanic rocks of the studied area do not show any evident correlations with either the Permian felsic ignimbrites in the Feniş Nappe (Apuseni Mts, Romania), as was supposed so far, or the similar rocks in any nappe of the Codru Nappe System. Moreover, no relevant plutonic–volcanic connection was found between the studied samples and the underlying “Battonya granite.”

KEYWORDS

battonya, felsic volcanism, ignimbrite, lava, permian, volcanoclastite

*Corresponding author. ‘Vulcano’ Petrology and Geochemistry Research Group, Department of Mineralogy, Geochemistry and Petrology, University of Szeged, Egyetem u. 2, H-6722, Szeged, Hungary.
E-mail: szemeredi.mate@gmail.com

INTRODUCTION

Permo-Carboniferous large-volume silicic magmatism is a common feature of the European Variscides that was genetically controlled by a post-collisional to extensional tectonic setting (Cortesogno et al. 1998; Awdankiewicz 1999; Wilson et al. 2004; Paulick and Breitzkreuz 2005; Vozárová et al. 2009, 2015, 2016; Seghedi 2010; Wilcock et al. 2013; Letsch et al. 2014;

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Nicolae et al. 2014; Repstock et al. 2017; Ondrejka et al. 2018). Permian volcanic rocks associated with such magmatic activity are well-known in the Tisza Mega-unit (Tisza MU, Pannonian Basin; Fig. 1a) and exposed in several outcrops (Apuseni Mts, Romania, and Western Mecsek Mts, Hungary) and by boreholes (southern Transdanubia and the eastern Pannonian Basin, Hungary), representing all three Alpine facies zones of the Tisza MU (Mecsek, Villány–Bihor, and Békés–Codru Units; Fig. 1b; Szederkényi 1962; Barabás-Stuhl 1988; Hidasi et al. 2015; Szemerédi et al. 2016, 2017, 2020). Based on petrographic, whole-rock geochemical (including major and trace elements), and geochronological (zircon U–Pb ages) results all Permian felsic volcanic rocks within the Tisza MU are the products of the same volcanic epoch (266.8 ± 2.7 – 259.5 ± 2.6 Ma; Szemerédi et al. 2020).

Ancient volcanic rocks might have undergone various processes of syn- and post-volcanic alteration; thus, it could be a real challenge to determine their original volcanic facies. Primary textural features could have been overprinted or modified, making the genetic interpretation (e.g., pyroclastic rock or lava) of such rocks a difficult task for volcanologists (e.g., Allen 1988; Branney and Kokelaar 1992; Branney et al. 1992; Henry and Wolff 1992; Gifkins et al. 2005a, b). The incomplete destruction of primary textures and the different alteration styles can also have resulted in the development of false textures or pseudotextures. Thus, false pyroclastic textures (false shards, false eutaxitic texture) as well as false massive textures can have been formed, usually causing significant difficulties in the reliable interpretation of ancient volcanic rocks (Allen 1988; Gifkins et al. 2005a, b).

Permian felsic volcanic rocks of the Hungarian part of the Tisza MU were previously described and interpreted in the reports of uranium ore (southern Transdanubia) and

petroleum (SE Hungary) exploration work during the second half of the 20th century (e.g., Barabás-Stuhl 1988; Fülöp 1994; Kőrössy 2005a, b). According to the archive reports the rocks were considered to be dominantly lavas (“quartz-porphyr” using the appropriate paleovolcanic name; Szederkényi 1962; Szepesházy 1967; Barabás-Stuhl 1988; Kőrössy 2005a, b); however, modern petrographic observations (e.g., Hidasi et al. 2015; Szemerédi et al. 2016, 2017) reinterpreted most of them as ignimbrites in the area of southern Transdanubia. In a similar way such a (re)examination of the Permian felsic volcanic rocks in SE Hungary was also required.

Three main subsurface areas of the Permian felsic volcanic rocks can be distinguished within southern Transdanubia: (i) the Western Mecsek Mts, (ii) the Máriakémond–Báta Basement Range (Máriakémond–Báta BR), and (iii) the northern foreland of the Villány Mts (Fig. 1a; Barabás-Stuhl 1988; Szemerédi et al. 2016, 2017). The Western Mecsek Mts and the Máriakémond–Báta BR are represented by crystal-rich fiamme-bearing rhyodacitic–dacitic ignimbrites, while in the northern foreland of the Villány Mts such ignimbrites and subordinate felsic lavas occur (Szemerédi et al. 2016, 2017, 2020). In the Apuseni Mts (Fig. 1a; Codru and Biharia Nappe Systems) rhyodacitic–dacitic ignimbrites are present; however, they are accompanied by mafic-to-intermediate lavas (basalt and subordinate andesite) as the result of a mainly bimodal volcanic activity (Codru Nappe System; Nicolae et al. 2014; Szemerédi et al. 2018).

Detailed petrographic studies have not targeted the Permian felsic volcanic rocks of the eastern Pannonian Basin (Battonya–Pusztaföldvár Basement Ridge and Kelebia area, Hungary; Fig. 1a). These rocks were briefly described in the

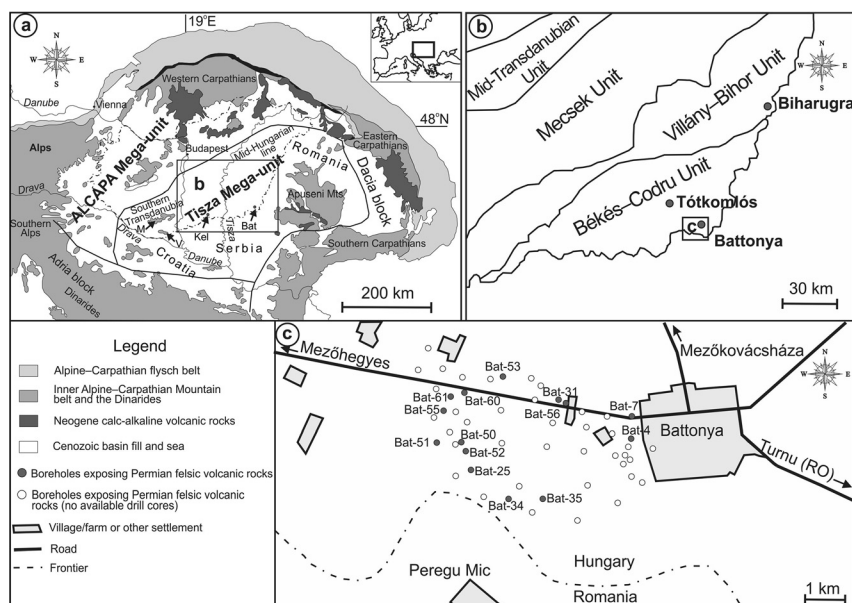


Figure 1. Tectonic sketch of the Pannonian Basin, pointing out the surface and subsurface distribution of the Permian felsic volcanic rocks (a), highlighting the subsurface occurrences in SE Hungary (b), especially in the Battonya area (c). Map base is modified after Szemerédi et al. (2020). Abbreviations: Bat: Battonya, Kel: Kelebia, M: Mecsek Mts, V: Villány Mts

previous reports of hydrocarbon exploration (Szepesházy 1967; Kőrössi 2005a, b). Geochemically, all of the Permian felsic volcanic rocks in the Tisza MU show similar general characteristics. Nevertheless, some weak chemical differences were observed in the samples of the Battonya–Pusztaföldvár Basement Ridge (Battonya–Pusztaföldvár BR) that are rhyolites according to the immobile element-based rock classification (Zr/TiO_2 vs. Nb/Y), while the others are rhyodacites–dacites (Szemerédi et al. 2020). Moreover, felsic pyroclastic rocks in SE Hungary proved to be slightly younger than other Permian volcanic rocks of the Tisza MU (Szemerédi et al. 2020).

The aim of this study is to provide a detailed petrographic description of the Permian felsic volcanic rocks of SE Hungary, using all available drill cores and thin sections from the boreholes near the villages of Battonya, Biharugra, and Tótkomlós (Fig. 1b and c). Furthermore, we attempt to interpret the former and new descriptions in the light of modern volcanological views of the ancient, altered volcanic sequences (e.g., Gifkins et al. 2005a, b).

Geologic background

In SE Hungary, ca. 50 boreholes (near the villages of Battonya, Biharugra, Kelebia, Mezőkovácsháza, Nagyszénás, Pitvaros, Pusztaföldvár, Tótkomlós, and Végegyháza) of hydrocarbon exploration work penetrated felsic volcanic rocks, predominantly within the Battonya–Pusztaföldvár BR (Figs 1c and 2; Szepesházy 1967; T. Kovács and Kurucz 1984;

Császár 2005; Kőrössi 2005a, b). The highest density of drilling is represented by the ca. 60 km² Battonya area (Fig. 1c) and most of the materials of the presented study derive from there (Szepesházy 1967; Császár 2005; Kőrössi 2005a). The Permian felsic volcanic rocks are collectively named the Gyűrűfű Rhyolite Formation in the Hungarian lithostratigraphic literature and they form the regionally most widespread Permian formation (Fülöp 1994; Császár 2005; Szemerédi et al. 2020). Stratigraphically, the basement of the volcanic rocks consists of Permian continental red beds (Korpád Sandstone Formation) but they are also often underlain by Variscan metamorphic rocks (two-mica schist and gneiss) or S-type granites (“Battonya granite,” Fig. 2; T. Kovács and Kurucz 1984; Fülöp 1994; Császár 2005; Kőrössi 2005a, b). The overlying formation is the Triassic Jakabhegy Sandstone; however, in most cases the volcanic rocks are covered by much younger Cenozoic sediments (e.g., Miocene sandstone). The Permian felsic volcanic rocks were penetrated in their greatest thickness in the Tótkomlós-I borehole (~400 m, Fig. 2; Császár 2005; Kőrössi 2005a). According to the archive reports the felsic volcanic rocks in SE Hungary were described as “quartz-porphyr” and predominantly interpreted as lavas or subvolcanic rocks with subordinate amounts of pyroclastics (Szepesházy 1967; Fülöp 1994; Császár 2005; Kőrössi 2005a, b). A volcanic–plutonic connection was also supposed between the Permian volcanic rocks (thought to be dykes or lavas) and the underlying “Battonya granite” (thought to be Variscan) despite

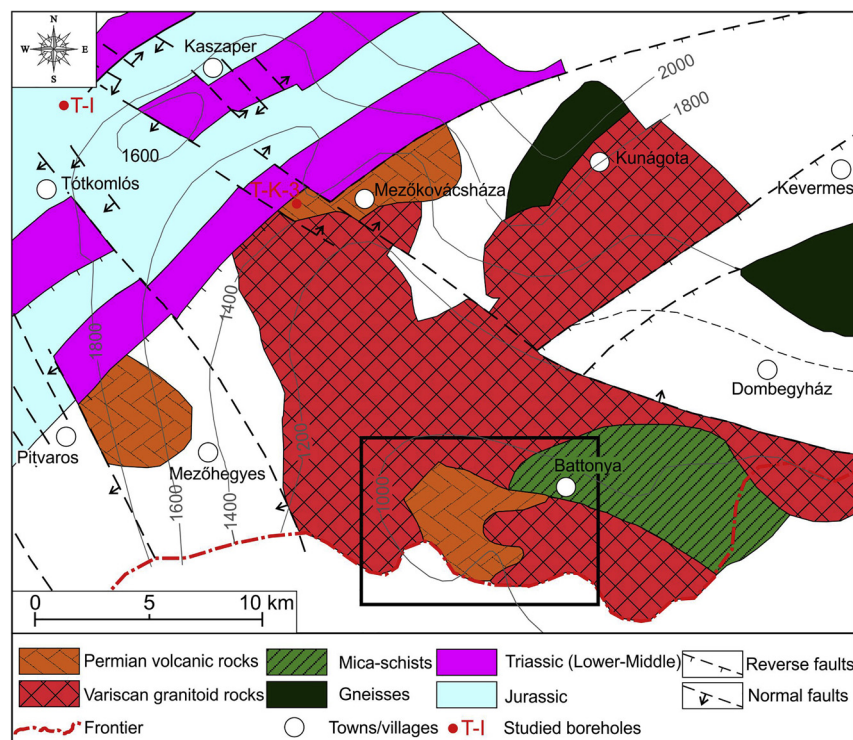


Figure 2. Basement formations in the eastern Pannonian Basin (SE Hungary, Tisza Mega-unit, Békés-Codru Unit), pointing out the Battonya area (black rectangle) and two of the studied boreholes. Abbreviations: T-I: Tótkomlós-I, T-K-3: Tótkomlós-K-3 (modified after Kurucz 1977; T. Kovács and Kurucz 1984)

Table 1. The most important data of the studied samples and boreholes in SE Hungary and the summary of the results of the archive reports and this study. Samples with available whole-rock (major and trace elements) geochemical data are put in italics and bold while samples with zircon U-Pb ages are highlighted by asterisk (data in Szemerédi et al. 2020). Lithofacies (Lf) description are listed in Table 2

Sample code	Borehole (core)	Depth	Total depth	Previous name	This study	
					Lithology	Lf
ÁGK-1790	Battonya-4 (4)	1020.4–1025.5 m	1044.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1790-2	Battonya-4 (4)	1020.4–1025.5 m	1044.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
Bat-7 (Via-79)	Battonya-7	1058.0–1058.2 m	1060.0 m	quartz-porphry	pyroclastic	accfrichT
ÁGK-1798	Battonya-25 (2)	1026.0–1031.0 m	1042.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1799	Battonya-25 (3)	1031.0–1034.0 m	1042.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1802	Battonya-31 (3)	1029.5–1031.0 m	1044.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1243	Battonya-34	1029.0–1030.5 m	1042.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1271	Battonya-35 (6)	1058.0–1062.0 m	1066.0 m	felsite	pyroclastic	emLT
ÁGK-1818	Battonya-50 (1)	1020.0–1023.0 m	1053.0 m	felsite	pyroclastic	emLT
ÁGK-1274	Battonya-50 (2)	1053.0 m	1053.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1819	Battonya-51 (2)	1023.0–1024.5 m	1050.0 m	felsite	pyroclastic	emLT
ÁGK-1821	Battonya-51 (4)	1027.2–1028.0 m	1050.0 m	felsite	pyroclastic	emLT
ÁGK-1823	Battonya-52 (1)	1022.0–1024.0 m	1050.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1824	Battonya-52 (2)	1032.0–1033.5 m	1050.0 m	felsitic quartz-porphry	pyroclastic	rheoLT
ÁGK-1825	Battonya-53 (2)	1028.6–1033.0 m	1050.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1828-1	Battonya-55 (2)	1025.0–1028.0 m	1050.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1828-2	Battonya-55 (2)	1025.0–1028.0 m	1050.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1830	Battonya-56 (3)	1033.5–1034.5 m	1045.0 m	quartz-porphry	pyroclastic	emLT
ÁGK-1831	Battonya-60 (2)	1025.0–1027.0 m	1045.0 m	felsite	pyroclastic	emLT
ÁGK-1833	Battonya-61 (3)	1028.0–1031.0 m	1053.0 m	quartz-porphry	pyroclastic	rheoLT
ÁGK-1339	Biharugra-I (20)	3157.0–3158.0 m	3200.0 m	quartz-porphry	pyroclastic	lmLT
ÁGK-1340	Biharugra-I (21)	3198.0–3198.5 m	3200.0 m	ignimbrite	pyroclastic	lmLT
ÁGK-1340-2	Biharugra-I (21)	3198.0–3198.5 m	3200.0 m	ignimbrite	pyroclastic	lmLT
BATR/1*	Tótkomlós-K-3	1669.0–1674.0 m	1686.0 m	quartz-porphry	pyroclastic	lmLT
BATR/2*	Tótkomlós-K-3	1669.0–1674.0 m	1686.0 m	quartz-porphry	pyroclastic	lmLT
ÁGK-1267	Tótkomlós-K-3 (17)	1669.0–1674.0 m	1686.0 m	quartz-porphry	pyroclastic	lmLT
T-I 13 MF	Tótkomlós-I (13)	3248.0–3249.0 m	3998.0 m	quartz-porphry	pyroclastic or lava	vlava-likeT
T-I 14 MF	Tótkomlós-I (14)	3267.0–3268.0 m	3998.0 m	quartz-porphry	pyroclastic or lava	vlava-likeT
T-I 15 MF	Tótkomlós-I (15)	3402.0–3404.0 m	3998.0 m	quartz-porphry	pyroclastic or lava	vlava-likeT

Table 2. Terminology used for the characterization of the lithofacies of the Permian felsic volcanic rocks in SE Hungary (modified after Branney and Kokelaar 2002; Sommer et al. 2013)

Facies code	Lithofacies description
emLT	Eutaxitic, massive, matrix-supported, porphyric, fiamme-bearing lapilli tuffs
rheoLT	Felsitic, matrix-supported, porphyric, fiamme-bearing rheomorphic lapilli tuffs
accfrichT	Matrix-supported, fine-grained, felsitic ash tuff with coated particles
lmLT	Lithic-rich, massive, strongly sericitized, poorly-sorted volcanoclastics
vlava-likeT	Spherulitic vitrophyric lava-like ash tuffs

the absence of any geochemical or geochronological evidence (Szepesházy 1967). Based on the strongly similar stratigraphic column of the Tótkomlós-I borehole (i.e., between 2,693 and 3,998 m beneath the surface: Mesozoic sedimentary rocks, Permian volcanic rocks and continental red beds, possible Precambrian granites; Kőrössi 2005a), the Battonya–Pusztaföldvár BR was correlated with the Finiş

Nappe of the Codru Nappe System (Codru NS), Apuseni Mts, Romania (Szepesházy 1979; Császár 2005; Kőrössi 2005a). Recently, however, Nicolae et al. (2014) documented crystal-rich, garnet-bearing pyroclastic rocks in the Finiş Nappe, that suggests differences when compared to the Permian volcanic rocks of the aforementioned areas.

MATERIALS AND METHODS

During the second half of the 20th century, hundreds of boreholes were drilled by the legal forerunner of the Hungarian Oil & Gas Company Plc (MOL Rt.) in the eastern Pannonian Basin (Hungary) in order to explore hydrocarbon reservoirs (Szepesházy 1967; Császár 2005; Kőrössi 2005a, b). The drilling usually ended in Permian felsic volcanic rocks, representing the Paleozoic basement of the Tisza MU (Fig. 2). Drill cores from 17 boreholes (2–3 pieces/borehole) and 29 thin sections from three subsurface occurrences of the Permian felsic volcanic rocks, namely the Battonya, the Biharugra, and the Tótkomlós areas, have been available for the present study at the Department of



Mineralogy, Geochemistry and Petrology, University of Szeged (Table 1; Fig. 1b). The most important data of the sampling sites and the investigated thin sections are summarized in Tables 1 and 2. The studied boreholes in the Battonya area are also highlighted in Fig. 1c.

Petrographic studies, including mineralogical and textural observations, were conducted on hand specimen and thin sections. In this study, modal compositions (vol%)

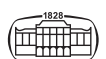
were generally estimated based on micropetrography. Nevertheless, modal (volume) proportions of rock-forming minerals, fragments, as well as groundmass were also measured, quantitatively at least, on one selected representative sample of each distinct lithofacies, using a grid of 500 cells for each measurement (Table 3). The terminology used in the petrographic descriptions and interpretations were derived from the following principal references:

Table 3. Modal (volume) proportions (in %) of rock-forming minerals, fiammes, as well as the groundmass, measured quantitatively at least, on one selected representative sample of each distinct lithofacies. The meaning of the abbreviations applied for the lithofacies (facies code) are described in Table 2. Abbreviations: bt: biotite, cp: coated particle, f: fiamme, g: groundmass, kfs: K-feldspar, L_v: volcanic lithic clast, L_{nv}: non-volcanic lithic clast, pl: plagioclase, qz: quartz. *In the case of *lithic-rich, massive, strongly sericitized, poorly-sorted volcanics* strongly sericitized groundmass and altered juvenile fragments (fiammes and glass shards) were indistinguishable and given together as groundmass

Sample	Lithofacies	qz	kfs	pl	bt	f	g	L _v	L _{nv}	cp
ÁGK-1821	emLT	3.5	3	1.8	0	11.5	80.2	0	0	0
ÁGK-1830	emLT	7.5	4.9	5	0.1	9.6	72.9	0	0	0
ÁGK-1828-2	rheoLT	12	4.6	3.1	0	9.9	70.4	0	0	0
Bat-7 (Via-79)	accfrichT	2.1	7.9	0	0	0	89.0	0	0	1.0
ÁGK-1340	lmLT	8.3	4	1.8	0.1	*	69.3	14.5	0	0
BATR/1	lmLT	9.3	1.3	0.7	0	*	76.4	8.2	4.1	0
T-I 14 MF	vlava-likeT	5.5	4.1	0.4	0	0	90.2	0	0	0

Table 4. Table of the most significant terms used in the petrographic descriptions and interpretations, explaining their meaning. Some references are given for each expression

Term	Meaning	References
Axiolite	Product of high-temperature devitrification of silicic glass. Spherulitic aggregate arranged at right angles to central axis rather than from a point	Gifkins et al. (2005b)
Coated particles	Fragile aggregates comprised of a crystal, crystal fragment, pumice or lithic clast partially covered in fine ash particles	Brown et al. (2012)
Eutaxitic texture	Pre-tectonic foliation defined by the parallel alignment of fiammes	Gifkins et al. (2005a,b)
Felsitic texture	Igneous texture comprised of a very fine-grained groundmass of mosaic quartz and alkali feldspar crystals	MacKenzie et al. (1982)
Fiamme	Flame-like, glassy or devitrified lenses, which define a pre-tectonic foliation	Gifkins et al. (2005a,b)
Lava-like	Extremely high-grade (intensely welded) ignimbrite lithofacies that is texturally indistinguishable from lava	Branney et al. (1992); Branney and Kokelaar (1992)
Rheomorphic	Any non-particulate flow structure that formed prior to lithification	Branney et al. (1992); Branney and Kokelaar (1992)
Spherulite	Product of high-temperature devitrification of silicic glass. Radiating aggregates or bundles of acicular and fibrous crystals	Lofgren (1971); Gifkins et al. (2005b); Breitzkreuz (2013)
Vitroclastic texture	Pyroclastic texture that is composed of glass fragments cemented by glass	Branney et al. (1992); Branney and Kokelaar (1992)
Vitrophyric texture	Inequigranular volcanic texture in which larger crystals (porphyres) are embedded in glassy groundmass	Gifkins et al. (2005b)



Branney and Kokelaar (1992), Branney et al. (1992), Henry and Wolff (1992), McPhie et al. (1993), Branney and Kokelaar (2002), Gifkins et al. (2005a, b), Paulick and Breitzkreuz (2005), Brown et al. (2012), and Breitzkreuz (2013). The most important terms used in the petrographic descriptions and interpretations as well as the abbreviations of each lithofacies name are summarized in Tables 2 and 4, respectively.

RESULTS

Based on the petrographic observations, five distinct lithofacies can be distinguished among the volcanic rock samples (Table 2) which are separately described and interpreted below.

Eutaxitic, massive, matrix-supported, porphyric, fiamme-bearing lapilli tuffs (emLT)

The presence of the *emLT* lithofacies was demonstrated in five boreholes in the study area, namely wells Battonya-35, Battonya-50, Battonya-51, Battonya-56, and Battonya-60 (see details in Table 1) in the Battonya–Pusztaföldvár BR, Békés–Codru Unit (Fig. 1c).

Description. Felsic rocks are purplish or greenish gray in color, and can be classified as massive, non-porous matrix-supported lapilli tuffs that consist of macroscopically dark, flattened, devitrified fiammes (10–12 vol%), usually mm in size, together with various poorly-sorted and fragmented phenocrysts (8–18 vol%) in a fine groundmass of predominantly quartz and feldspar (73–80 vol%).

Well-visible oriented texture (Fig. 3) is defined by deformed, devitrified glass shards (from ~100 µm up to the

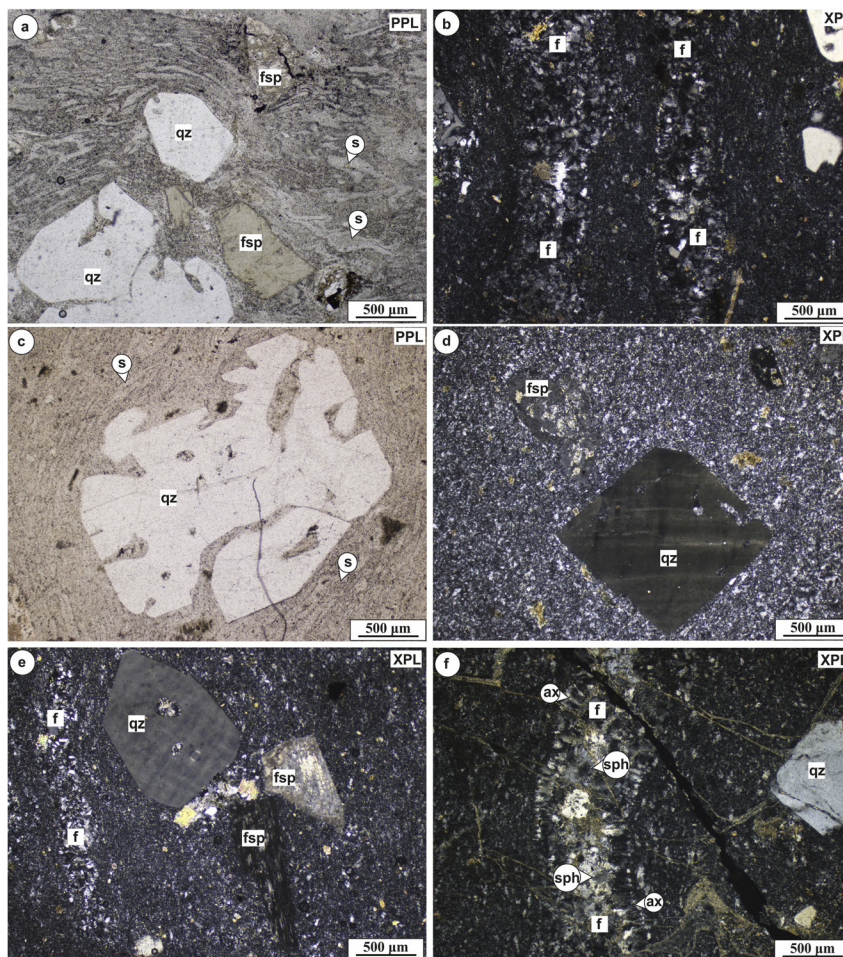


Figure 3. Photomicrographs of the *eutaxitic, massive, matrix-supported, porphyric, fiamme-bearing lapilli tuffs (emLT)*, Battonya area. (a) Sample ÁGK-1830, eutaxitic texture defined by deformed, elongated glass shards with subhedral quartz and feldspar phenocrysts. (b) Sample ÁGK-1830, oriented, devitrified fiammes replaced by mosaic of quartz and feldspar microcrysts. (c) Sample ÁGK-1821, subhedral, resorbed, porphyritic quartz surrounded by deformed glass shards. (d) Sample ÁGK-1821, subhedral quartz crystal with deformation lamellae. (e) Sample ÁGK-1830, subhedral, resorbed quartz, K-feldspar (above), and plagioclase (below) phenocrysts and devitrified fiamme replaced by mosaic of quartz and feldspar. (f) Sample ÁGK-1831, devitrified fiamme with axiolites at the rims and spherulites inside it, in a brecciated sample. Abbreviations: ax: axiolite, f: altered fiamme, fsp: feldspar, qz: quartz, s: altered glass shard, sph: spherulite, PPL: plane polarized light, XPL: crossed polars

size of the fiammes; Fig. 3a and c) and devitrified fiammes (from several mm in size up to 1.5–2.5 cm; Fig. 3b, e, and f). In the fiamme rims, axiolites are common, whereas rare spherulites occur inside it (Fig. 3f). Fiammes and altered glass shards in the fine groundmass are replaced by mosaic quartz and feldspar (Fig. 3b and e). Inside the larger fiammes quartz and feldspar crystals (from 200 to 300 μm up to 1 mm) and secondary minerals (e.g., carbonate, sericite, and opaque minerals) are also present.

The major mineral assemblage consists of predominantly subhedral, rarely euhedral quartz (42–43 vol%) and K-feldspar (28–36 vol%), together with plagioclase (22–27 vol%) and very rare biotite as a mafic component (<1 vol%). Quartz crystals (up to 3 mm) are usually resorbed (Fig. 3a, c, and e), but rarely euhedral (Fig. 3d) phenocrysts with straight extinction; smaller crystalloclasts (broken, shard-like crystals) also appear. It is important to note that some large quartz crystals show a characteristic deformation feature (i.e., deformation lamellae; Fig. 3d). K-feldspar crystals (up to 5 mm) are usually resorbed, fragmented, and moderately altered (sericitized, carbonatized; Fig. 3a and e), showing Carlsbad twinning. Some K-feldspar with overgrowth (K-feldspar as well) on their resorbed margin are also present. Polysynthetic twinned euhedral or subhedral plagioclase (Fig. 3e) crystals (up to 2 mm) as well as opaque pseudomorphs of euhedral biotite crystals (up to $\sim 600 \mu\text{m}$) are less common. As an accessory component, small (<100 μm) subhedral or euhedral zircon crystals occur in the fine groundmass. Some samples from the Battonya-60 borehole are strongly brecciated that destroyed the primary texture (Fig. 3f).

Interpretation. The major mineral assemblage (predominantly quartz and K-feldspar, less plagioclase and rare biotite) of the rocks suggests a rhyolitic composition. The unsorted massive appearance points to a pyroclastic flow (ignimbrite) origin. Oriented, eutaxitic texture indicates high-temperature plastic deformation of the vitroclasts (both pumice and glass shards; e.g., Gifkins et al. 2005a, b). Strong devitrification affected the juvenile fragments, creating high temperature crystallization domains (HTCDs; Breitzkreuz 2013). This effect is demonstrated by spherulites inside the fiammes and axiolites at their rims (Fig. 3f). Additionally, incipient to strong welding is indicated by the flattened fiammes and sintering glass shards that determines the observed orientation of the rocks (e.g., Gifkins et al. 2005a, b; Fig. 3a and b), corresponding to the eutaxitic texture mentioned above. Purplish gray color of the macroscopic samples indicates the oxidation of the Fe-phases at high temperature during welding, while the greenish tones point to different degrees of subsequent mineralization (e.g., the formation of celadonite and/or chlorite during secondary alteration processes).

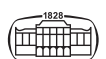
Felsitic, matrix-supported, porphyric, fiamme-bearing rheomorphic lapilli tuffs (rheoLT)

The presence of the *rheoLT* lithofacies was demonstrated in eight boreholes in the study area, namely wells Battonya-4,

Battonya-25, Battonya-31, Battonya-34, Battonya-52, Battonya-53, Battonya-55, and Battonya-61 (see details in Table 1) in the Battonya–Pusztaföldvár BR, Békés–Codru Unit (Fig. 1c).

Description. The samples of this group are purplish or greenish-gray in color, and can be classified as massive non-porous matrix-supported felsic volcanic rocks, having a similar mineralogical composition (20 vol% phenocryst content: 61% quartz, 23% K-feldspar, and 16% plagioclase) as the *emLT* lithofacies (Fig. 3). Crystalloclasts are less common compared to the former lithofacies. The groundmass (70 vol%) predominantly contains fine-grained homogeneous mosaics of quartz, feldspar, and sericite (Fig. 4a–c). However, in some parts (e.g., around coarser phenocrysts or separately in the matrix), mm-sized oriented patches (10 vol%, up to 2–2.5 mm) of coarser (150–200 μm) groundmass crystals with the same composition, showing no definite, sharp edge and rarely spherulites inside them, do occur (Fig. 4d–f). The mentioned patches (Fig. 4d–f) of predominantly quartz and feldspar bear well-visible orientation that could barely be observed macroscopically but always in thin sections in crossed polars (Fig. 4). On the other hand, such an orientation could be observed neither in the fine-grained part of the groundmass (Fig. 4a–c) nor in plane-polarized light in the whole material. According to the observed features, these rocks have a predominantly felsitic, porphyric texture (Fig. 4a–c); however, the oriented patches of coarser groundmass crystals, resembling altered fiammes, show eutaxitic characteristics (Fig. 4e and f). These two distinct textural features can be commonly observed in one thin section next to each other as is displayed by a representative sample in Fig. 4.

Interpretation. The major mineral assemblage with predominant quartz and K-feldspar phenocrysts suggests the same rhyolitic composition. However, the genetic interpretation (pyroclastic rocks or lavas) of the samples is rather difficult. Parts showing felsitic, porphyric texture with homogeneous groundmass and resorbed, large phenocrysts resemble silicic lavas, apparently suggesting a coherent lava facies origin (McPhie et al. 1993; Fig. 4a–c). However, the mm-sized oriented patches of coarser (150–200 μm) quartz, feldspar, and sericite crystals in the groundmass with no definite, sharp edge (Fig. 4d–f) could be interpreted as the remnants of devitrified fiammes. Based on the observed features, including the lack of vitroclastic texture and lithic clasts, low crystal breakage, but the presence of lineations (devitrified fiammes), the most feasible is that these samples are high-grade rheomorphic ignimbrites (Branney and Kokelaar 1992; Branney et al. 1992; Henry and Wolff 1992). As the result of rheomorphism and/or devitrification, vitroclastic features (i.e., well-visible altered glass shards in the groundmass) are lacking; however, the orientation of the flattened devitrified fiammes (Fig. 4) indicates a rheomorphic flow that postdates or might have occurred during the ignimbrite emplacement and deposition (Branney et al. 1992; Henry and Wolff 1992). Each step of the spectrum can be seen in Fig. 5 from eutaxitic welded ignimbrites (*emLT*



lithofacies), having a vitroclastic texture with evident altered fiammes and glass shards (a–b) to high-grade rheomorphic ignimbrites (c–f) with barely recognizable remnants of fiammes. Thus, the samples of the *rheoLT* lithofacies could represent the same ignimbrite sheet as the *emLT* lithofacies; however, they were formed along slightly different (i.e., higher) temperature and compositional circumstances, e.g., lower volatile content, minimizing the amount of vesiculation, resulting in low explosivity of the eruptions (low crystal breakage) in the Battonya area (Henry and Wolff 1992).

Matrix-supported, fine-grained, felsitic ash tuff with coated particles (*accfricht*T)

The presence of the *accfricht*T lithofacies was demonstrated only in one borehole in the study area, namely the Battonya-

7 borehole (see details in Table 1), Battonya–Pusztaföldvár BR, Békés–Codru Unit (Fig. 1c).

Description. The crystal-poor (quartz: 2 vol%, K-feldspar 8 vol%) sample shows a fine-grained felsitic groundmass (89 vol%) of quartz, feldspar, and sericite with good sorting; however, it differs from all the other samples of the Battonya area in containing mm-sized coated particles (armored pellets, formed around porphyric quartz crystals, 1 vol%; Fig. 6a–c). The size of the particles ranges between 0.8 mm and 1.7 mm (but never reaches the lapilli size: 2 mm), while the quartz crystals in the center range between 0.5 and 0.8 mm.

Interpretation. Armored lapilli and pellets are typical in pyroclastic fallout, flow, and surge deposits formed by ash accumulation around coarser crystals (in this case porphyric quartz) under wet conditions (Brown et al. 2012). In this way the sample could be associated with the ignimbrite lithofacies (*emLT* and *rheoLT*), most possibly formed in a pyroclastic ash cloud (air-fall ash deposit). Good sorting of

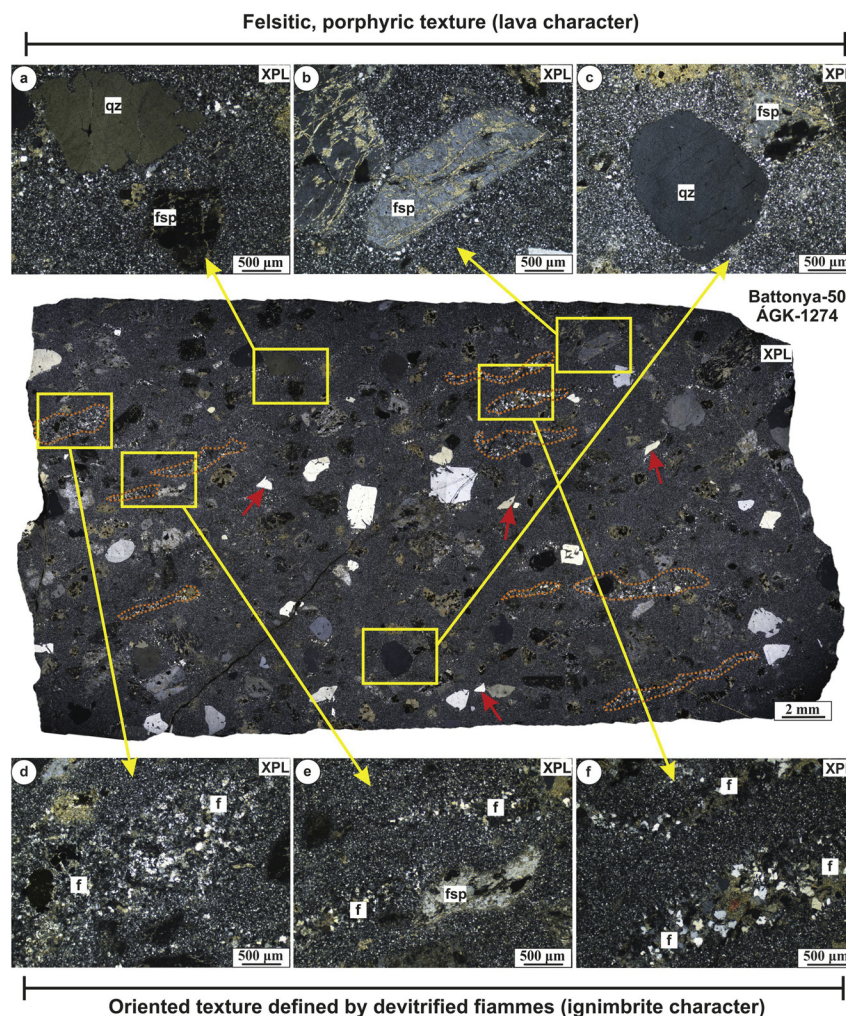


Figure 4. Photomicrographs of the *felsitic, matrix-supported, porphyric, fiamme-bearing rheomorphic lapilli tuffs (rheoLT)*, Battonya area, sample ÁGK-1274 (Battonya-50 borehole), highlighting apparent coherent texture (a–c) and oriented (eutaxitic) parts (d–f) of the sample. (a–c) Homogeneous groundmass with mosaics of quartz and feldspar microcrysts (crystalloclasts and devitrified glass shards) and subhedral, resorbed phenocrysts. (d–f) Remnants of oriented fiammes indicating rheomorphic flow that postdate or might have occurred during the ignimbrite emplacement and deposition. Note: significant differences in the size of the phenocrysts and the presence of some angular, broken crystals (crystalloclasts pointed by red arrows). Abbreviations: f: altered fiamme, fsp: feldspar, qz: quartz, XPL: crossed polars

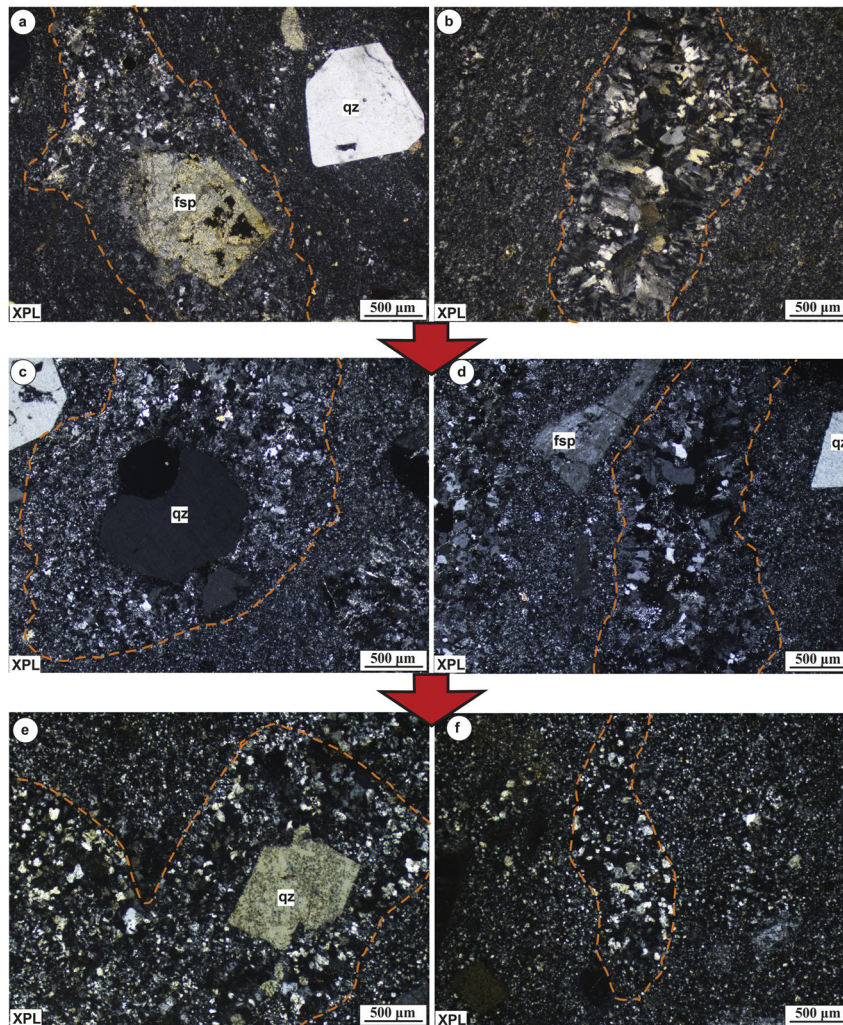


Figure 5. Photomicrographs showing the states of the ignimbrite grade continuum from eutaxitic welded ignimbrites to high-grade rheomorphic ignimbrites (*emLT* and *rheoLT*). (a–b) Eutaxitic ignimbrites (*emLT*, sample ÁGK-1830 and 1821, respectively), containing fiammes with well-visible, definite edge and fine-grained groundmass crystals (devitrified glass shards and crystalloclasts). (c–d) Moderately rheomorphic ignimbrites (*rheoLT*, sample ÁGK-1790), containing fiammes with visible edge and coarser groundmass crystals. (e–f) Strongly rheomorphic, extremely high-grade ignimbrites, containing fiammes with barely visible edge and coarser groundmass crystals (*rheoLT*, sample ÁGK-1243). Abbreviations: fsp: feldspar, qz: quartz. XPL: crossed polars. Altered, devitrified fiammes are highlighted by orange dashed lines

the sample (contrary to the poorly-sorted ignimbrites; *emLT* and *rheoLT*) also strengthens the aforementioned genetics. Armored pellets are absolutely unique not only regarding the samples of the Battonya area but also all Permian ignimbrites of the Tisza MU.

Lithic-rich, massive, strongly sericitized, poorly-sorted volcaniclastics (*lmLT*)

The presence of the *lmLT* lithofacies was demonstrated in two boreholes in SE Hungary, namely the Biharugra-I and the Tótkomlós-K-3 boreholes (see details in Table 1), Villány-Bihar Unit and Békés–Codru Unit, respectively (Figs 1b and 2).

Description. The samples are purplish or greenish-gray in color, massive non-porous pyroclastic or volcanogenic sedimentary rocks that consist of completely sericitized juvenile fragments (from ~100 µm sized glass shards up to

1–2 mm long fiammes; Fig. 7a and f), various fragmented crystals (11–14 vol%, up to mm size) and subrounded lithics (12–15 vol%, up to 2–3 cm, but generally around 1–5 mm; Figs 7e and 8) with a wide range of origin in a fine matrix (69–76 vol%) of sericite, quartz, and feldspar. The mentioned components show very poor sorting in all samples and their proportion is extremely variable.

Very thin bands of sericite up to ~2.5 mm (showing no preferred orientation) occur in all of the samples (Fig. 7a and f). Randomly oriented µm-sized patches of sericite can be found in the fine groundmass as well. The aforementioned components are most possibly altered, devitrified juvenile fragments (the former: altered, sericitized fiammes, the latter: sericitized glass shards).

Generally two different types of phenocrysts and lithics could be distinguished in the mixed material: (1) primary magmatic crystals and felsic volcanic lithics (8–15 vol%),

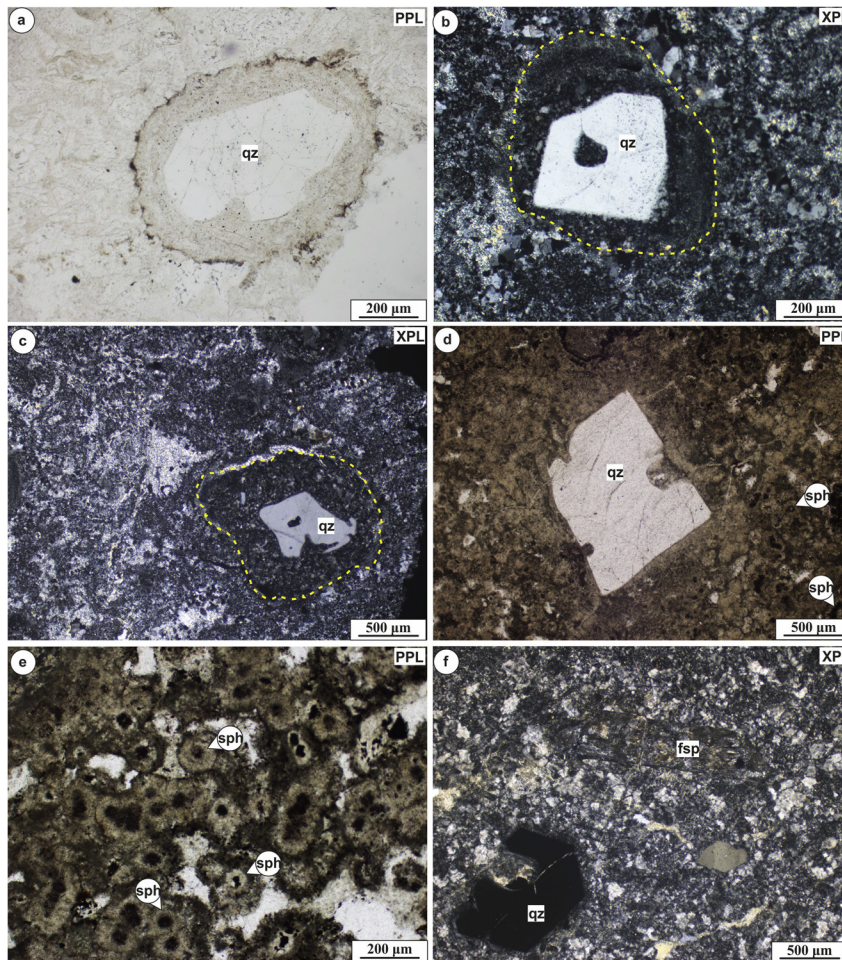


Figure 6. Photomicrographs of the *matrix-supported, fine-grained, felsitic ash tuff with coated-particles (accfricht: a–c)* and the *spherulitic, vitrophyric lava-like ash tuffs (vlava-likeT: e–f)*, Battonya and Tótkomlós areas, respectively. (a–c) Sample Bat-7 (Via-79), coated particles (armored pellets) formed around subhedral, resorbed quartz crystals. (d) Sample T-I 14 MF, subhedral, porphyric quartz and spherulites in the matrix. (e) Sample T-I 14 MF, completely spherulitic groundmass. (f) Sample T-I 13 MF, subhedral quartz and sericitized feldspar crystals in the matrix affected by pervasive crystallization. Abbreviations: fsp: feldspar, qz: quartz, sph: spherulite, PPL: plane polarized light, XPL: crossed polars

suggesting volcanogenic origin and (2) not magmatic or presumably older (plutonic) crystals (e.g., polycrystalline, metamorphic quartz or microcline, respectively) and non-volcanic (e.g., sedimentary or metamorphic) lithics (0–4 vol%).

Magmatic crystals are porphyric subhedral quartz (59–82 vol%; Fig. 6b) with straight extinction and many broken, angular fragments (100–200 μm; Fig. 7a, d, and f); subhedral, strongly sericitized, often Carlsbad-twinned K-feldspar (13–28 vol%), and polysynthetic plagioclase (6–13 vol%, Fig. 7c) with broken feldspar fragments (100–200 μm) and euhedral, idiochromatic biotite (<1 vol%, up to 600 μm; Fig. 6b and d) rarely replaced by opaque minerals. As an accessory component, subhedral broken, fractured zircons (up to 150 μm) also occur in the groundmass. Volcanic lithics (8–15 vol%) form four main groups: (i) felsic lithics with felsitic or spherulitic texture (~60%; Figs 7e and 8a), (ii) quartz-feldspar-biotite porphyric lithics with fine matrix (~15%; Fig. 8b), (iii) felsic lithics with recognizable oriented juvenile components (glass shards, smaller fiammes)

(pyroclastite; ~10%; Fig. 8c), (iv) and dark-colored, fine-grained, hematitized (mafic-intermediate?) lithics (~15%; Fig. 8d).

Coarser polycrystalline quartz grains with undulose extinction are also present as well as mm-sized crystals of muscovite (Fig. 7e), microcline (Fig. 7f), and biotite.

Non-volcanic lithics (0–4 vol%) are the following: fine-grained reddish or brownish sedimentary lithics (claystone or siltstone; ~30%; Fig. 8e); metamorphic lithics built up by undulose quartz and muscovite (mica schist or gneiss; 15%) and polycrystalline metamorphic quartz (~55%; Fig. 8f).

Interpretation. Strongly sericitized juvenile fragments (altered glass shards and fiammes) have an unequivocally pyroclastic origin. The lack of preferred orientation of the pyroclastic material suggests non-welded texture. Crystals could be primary magmatic such as resorbed, magmatic quartz, K-feldspar, plagioclase, and biotite or derive from older igneous and metamorphic rocks (polycrystalline quartz with undulose extinction, microcline, muscovite). Lithics also represent a wide range of origin; volcanic clasts

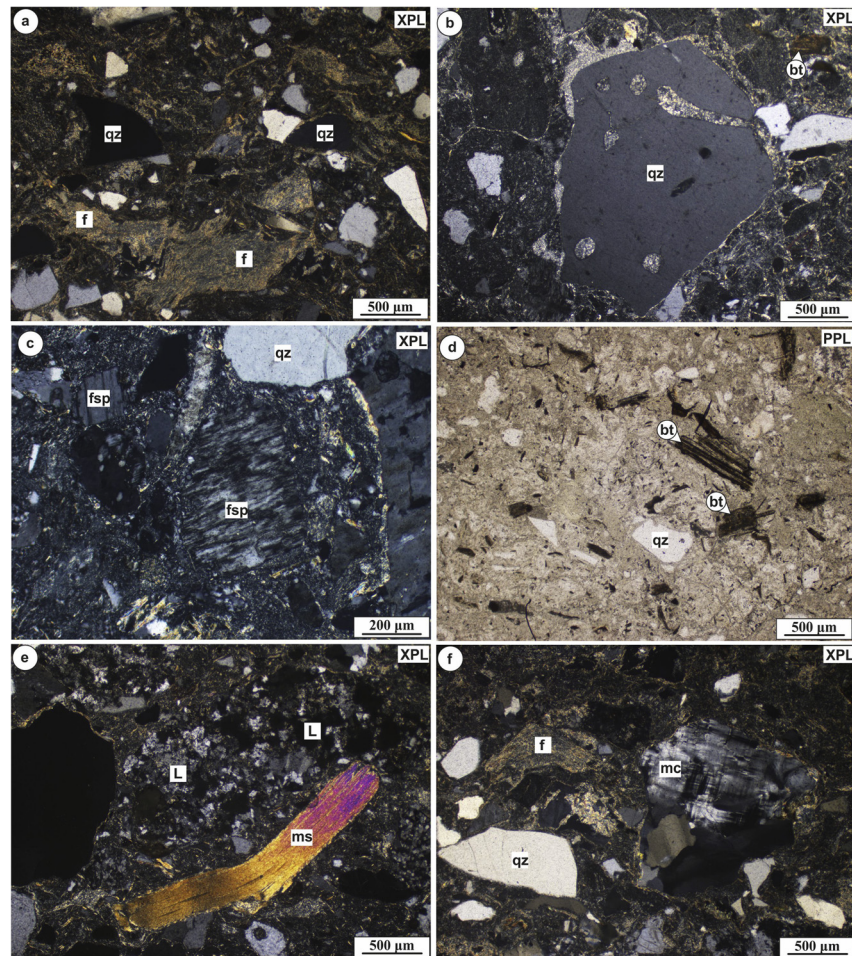


Figure 7. Photomicrographs of the lithic-rich, massive, strongly sericitized, poorly-sorted volcanoclastics (*lmLT*), Biharugra and Tótkomlós areas. (a) Sample BATR/1, poorly-sorted volcanoclastite, containing sericitized fiammes and angular fragments of quartz. (b) Sample ÁGK-1340-2, subhedral, resorbed magmatic quartz and euhedral biotite crystals. (c) Sample ÁGK-1339, subhedral polysynthetic plagioclase (left) and K-feldspar (right) crystals. (d) Sample ÁGK-1340-2, fragmented quartz and euhedral biotite crystals. (e) Sample ÁGK-1267, muscovite and felsic volcanic lithic clast, having felsitic texture. (f) Sample BATR/1, porphyritic microcline, broken quartz crystals and sericitized juvenile fragments. Abbreviations: bt: biotite; f: altered fiamme, fsp: feldspar, L: lithic clast, mc: microcline, ms: muscovite, qz: quartz, PPL: plane polarized light, XPL: crossed polars

(Figs 7e and 8a–d) are more abundant than lithics from the underlying sedimentary (claystone, siltstone) or metamorphic (mica schist or gneiss) rocks (Fig. 8e and f). The chaotic texture with various subrounded lithics, juvenile and crystal fragments suggests that sedimentation and volcanic activity could occur simultaneously. The rocks could be interpreted as resedimented volcanic rocks (Tótkomlós-K-3) or the more mixed material of the Biharugra-I borehole as a volcanogenic sedimentary rock (tuffaceous sandstone according to the grain size; McPhie et al. 1993).

Spherulitic, vitrophyric lava-like ash tuffs (*vlava-likeT*)

The presence of the *vlava-likeT* lithofacies was demonstrated in the Tótkomlós-I borehole (Figs 1b and 2), Békés–Codru Unit. Drill cores from 3 separate depths were observed (drill cores 13–15, see details in Table 1). In this area, corresponding to a separated tectonic block of the basement, the Permian sequence is covered by Mesozoic sedimentary

basement formations (Fig. 2). The cores exposed felsic volcanic rocks in a minimum thickness of 156 m; however, they are petrographically rather homogeneous; only the lowest part of the sequence (drill core 15) differs in being strongly deformed in brittle style (brecciated).

Description. Samples of the Tótkomlós-I borehole show vitrophyric texture with 10 vol% quartz and altered feldspar phenocrysts in a devitrified, completely spherulitic groundmass (90 vol%; Fig. 6d and e). The diameter of the spherulites range between 50 and 100 μm . On the other hand, no additional textural features (i.e., remnants of juvenile fragments) could be observed. The major mineral assemblage is rather similar to the ignimbrites of the Battonya area with porphyritic (up to 1–2 mm) euhedral or subhedral quartz (55 vol%; Fig. 6d and f) and sericitized or carbonatized feldspar crystals (45 vol%; Fig. 6f), showing low-crystal breakage.

Interpretation. According to the mineralogical composition, the samples of the Tótkomlós-I borehole are rhyolites;

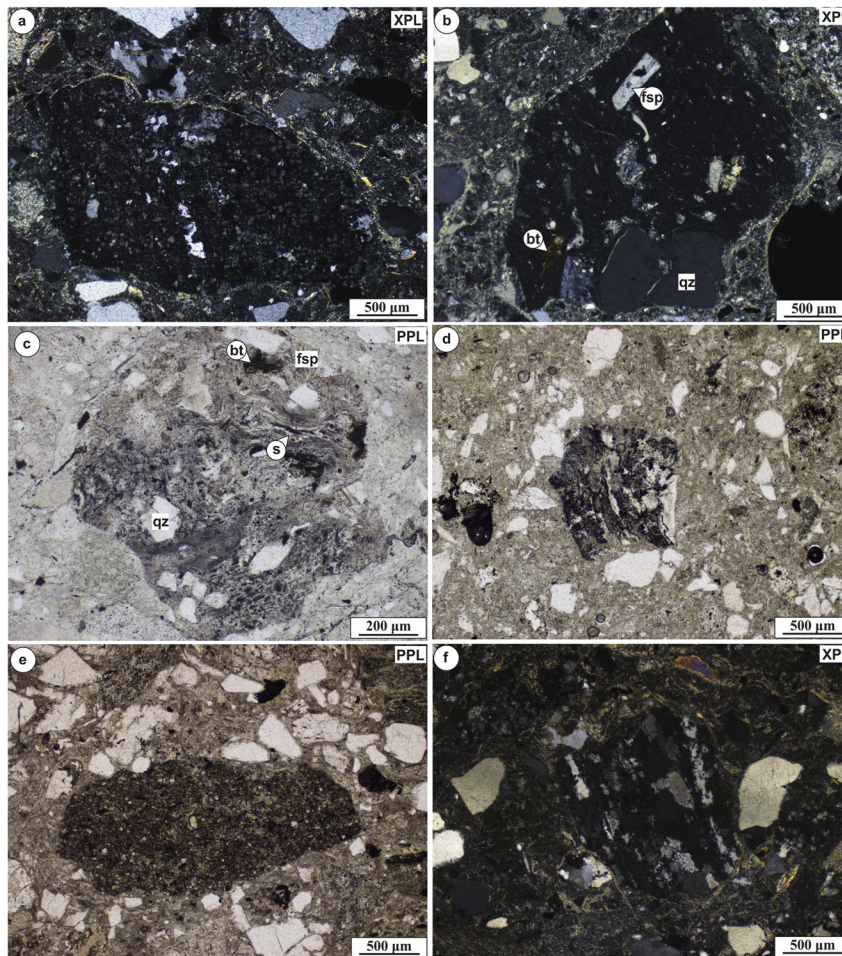


Figure 8. Volcanic (a–d) and non-volcanic (e–f) lithics from the *lithic-rich, massive, strongly sericitized, poorly-sorted volcanoclastics (ImLT)*. (a) Sample ÁGK-1267, felsic lithic clast, having felsitic, spherulitic texture. (b) Sample ÁGK-1340, quartz-feldspar-biotite porphyric lithic clast, having fine groundmass. (c) Sample ÁGK-1339, felsic lithic clast, containing recognizable oriented juvenile components (glass shards); pyroclastite clast. (d) Sample ÁGK-1267, dark-colored, fine-grained, hematitized (mafic-intermediate?) lithic clast. (e) Sample BATR/1, fine-grained sedimentary lithic clast (claystone or siltstone). (f) Sample ÁGK-1267, polycrystalline metamorphic quartz. Abbreviations: bt: biotite, fsp: feldspar, qz: quartz, s: altered glass shard, PPL: plane polarized light, XPL: crossed polars

however, their genetic interpretation is very complicated. Spherulitic texture suggests high-temperature crystallization which could be the feature of the inner part of both lavas and welded ignimbrite sheets (Breitkreuz 2013). Although the thickness (~150 m, measured from borehole data, Table 1) and some textural features (e.g., spherulites in microcrystalline matrix) are consistent with the central part of silicic lavas (Orth and McPhie 2003), the altered vitroclastic groundmass, broken phenocrystals, and compositional similarity to all the other studied lithologies (i.e., pyroclastic rocks) might indicate a pyroclastic origin. The spherulite and groundmass crystallization could occur in the interior of the unit under moderate cooling conditions (ΔT : 50–200 °C, Swanson et al. 1989). Lower breccia zones could generally point to brittle fragmentation near the flow base; however, in this case, taking into consideration the tectonic evolution of the Tótkomlós area (see details of the local faulting in Fig. 2), it is more probable that tectonic deformation and brecciation occurred. In some samples, the entire rock, even the spherulitic matrix, is crosscut by fractures.

DISCUSSION

Petrographic (re)interpretations according to the new observations and archive reports

New petrographic observations resulted in a quite different approach to Permian volcanism in SE Hungary. The detailed description and classification of textural features allow us to distinguish between different transport and emplacement mechanisms associated with effusive and explosive eruption styles. Based on the variations in lithology, the studied samples were identified mainly as pyroclastic rocks (predominantly ignimbrites) and volcanic sediments. The textural investigations established the discrimination of two major lithofacies groups: (i) the Battonya area is represented by crystal-poor (8–20 vol%) welded (with eutaxitic texture: *emLT*) and rheomorphic ignimbrites with rhyolitic composition that often resemble lavas (*rheoLT*), while, the other group (ii) consists of

strongly sericitized, lithic-rich, reworked pyroclastic (probably non-welded ignimbrites) and volcanogenic sedimentary rocks that occur in the Tótkomlós and Biharugra areas, respectively (*lmLT*).

Interpretation of rheomorphic ignimbrites was difficult as they do not have vitroclastic groundmass and show low crystal breakage. However, oriented and devitrified fiammes in these rocks without sharp, definite edge serve as potential evidence of their rheomorphic origin. Such parts of the samples were previously interpreted as the alternation of volatile-rich and volatile-poor bands within the presumed lava flow by Szepesházy (1967). It is important to note that, in the ca. 60 km² area (Fig. 1c), all felsic volcanic rocks are derived from similar well depths of the boreholes (Table 1; Fig. 2). Their average minimum thickness is around 20 m (with no information about the whole thickness of any volcanic sequences near Battonya), and the calculated minimum volume of the volcanic products is 1.2 km³. The lack of characteristic lava-associated facies variations (e.g., no brecciated lava carapace facies) in an area that could be commensurable with a rhyolitic lava flow (or dome) rather points to an ignimbrite sheet that consists of altered crystal-poor, fiamme-bearing lapilli tuffs with rhyolitic composition formed under distinct steps of the ignimbrite grade continuum (Branney et al. 1992; Henry and Wolff 1992). Most possibly, however, only a piece of an ignimbrite sheet was drilled in the Battonya area, as both conventional and rheomorphic ignimbrite sheets are generally much more extensive (their length is up to ~60 km and max. thickness is ~100 m; Henry and Wolff 1992). The Battonya-7 borehole encountered a pyroclastic rock with armored pellets (around quartz crystals; *accfrichT*), suggesting its formation in a pyroclastic ash cloud under wet conditions. Beside the fact that such coated particles are so far unique regarding the Permian volcanism of the Tisza MU, they reinforce the explosive origin of the surrounding rocks (i.e., *rheoLT* facies < 1 km away). Moreover, Permian volcanic rocks of the Tisza MU are dominantly felsic ignimbrites, while lavas are rather subordinate (Nicolae et al. 2014; Szemerédi et al. 2016, 2017, 2018, 2020).

Reworking of such pyroclastic rocks could result in the volcanogenic sedimentary sequences of the Biharugra and the Tótkomlós areas that are rich in volcanic lithics and sericitized juvenile fragments. These rocks could have been formed in a basin where volcanic and non-volcanic sedimentation occurred at the same time. Such volcanogenic sedimentary rocks are also known from the Western Mecsek Mts within the Cserdi Conglomerate Formation that covers the Permian felsic volcanic rocks in that region (Varga 2009). The various volcanic lithics in *lmLT* might suggest multiple-phase Permian volcanic activity that was also documented from the Apuseni Mts (Codru NS; Nicolae et al. 2014). In the Tótkomlós-I borehole, the felsic volcanic rocks (drill cores from three distinct depths) have vitrophyric texture, completely spherulitic groundmass and minor broken crystals. Based on these features (with the lack of altered fiammes) it is not possible to interpret the samples unequivocally (ignimbrites or lavas); however, it is the most

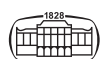
probable that they represent the ultimate step of the ignimbrite grade continuum as lava-like ash tuffs (*vlava-likeT*; Branney et al. 1992; Henry and Wolff 1992). However, being part of a tectonic block separate from the Battonya area (Fig. 2), it is also possible that these samples represent a completely distinct (i.e., younger or older) volcanic episode.

According to the previous petroleum exploration reports (Szepesházy 1967; Kőrössi 2005a) a direct plutonic–volcanic relationship was supposed between the “Battonya quartz-porphry” (thought to be Lower Permian) and the underlying Variscan “Battonya granite.” This view was based on the interpretation that the former represents either sub-volcanic or surficial lavas that continue as granite towards crustal depths. Our new volcanological interpretation precludes such a direct connection between the ignimbrite and the underlying granite and suggests tectonic or erosional unconformity between them.

Syn and post emplacement textural development

As ancient volcanic rocks might be affected by various processes of alteration, their primary (syn) and secondary (post emplacement) textural features could be rather difficult to distinguish (e.g., Allen 1988; Branney and Kokelaar 1992; Branney et al. 1992; Henry and Wolff 1992; Gifkins et al. 2005a, b). Based on the petrographic observations of the studied rocks, various lithofacies were distinguished (Table 2); however, some general textural features do deserve additional discussion. All of these features are summarized in Table 5, and the relative timescale of the related processes is displayed in Fig. 9, which is based on several experimental and volcanological case studies (Lofgren 1971; Swanson et al. 1989; Stevenson et al. 1994; Orth and McPhie 2003; Breikreuz 2015). Primary (magmatic) phenocrysts are similar in all lithofacies, suggesting compositionally similar rhyolitic sources (crystallization above 850–800 °C and low ΔT ; Swanson et al. 1989). Microcrystalline groundmass of quartz, feldspar, and sericite is also a common feature of the studied samples. Felsitic textures suggest pervasive groundmass crystallization simultaneously and after microlith formation (at high ΔT ; Swanson et al. 1989), while spherulite formation as another type of post emplacement high-temperature (800–500 °C) groundmass crystallization occurred at restricted point sources at moderate (50–150 °C) ΔT (*vlava-likeT*; Swanson et al. 1989; Breikreuz 2013).

Eutaxitic textures with flattened, deformed, devitrified fiammes and glass shards were formed by welding processes (e.g., Gifkins et al. 2005a, b). Irregular, randomly-oriented devitrified juvenile fragments occurring in the samples of the Biharugra and the Tótkomlós areas suggest the lack of welding processes (non-welded pyroclastic or volcanogenic sedimentary rocks; McPhie et al. 1993; Gifkins et al. 2005a, b). However, the devitrification of juvenile fragments occurred at lower temperatures (<500 °C) than the microlith formation (850–650 °C) or the crystallization of spherulites (Fig. 9; Lofgren 1971; Swanson et al. 1989; Stevenson et al. 1994; Orth and McPhie 2003; Breikreuz 2015). The



quenching experiments on Miocene calc-alkaline silicic glasses predicted the solidification temperature around 690–710 °C (Szepesi et al. 2019), while the minimum welding temperature can be reduced by the variations in H₂O content (~600 °C; Quane and Russel 2005).

Volcanic and non-volcanic lithics were ripped by explosive eruptions and represent older components than the host material. Coated particles were formed by ash accumulation around coarser crystals under wet conditions in the ash cloud of eruption or pyroclastic density flow (Brown et al. 2012).

Local and regional correlation

Based on the Mesozoic evolution (Alpine nappe stacking) of the Tisza MU, the Békés–Codru Unit was correlated with the Codru NS, Apuseni Mts (Szederkényi et al. 2013 and references therein; Fig. 10). Thus, the area of this study (based on the lithological sequence of the Tótkomlós-I borehole) was correlated with the Finiş Nappe, Codru NS (Szepesházy 1979; Kőrössi 2005a; Fig. 10). Regarding the petrography, however, significant differences were found between the samples of the Codru NS (Finiş, Dieva, and

Moma Nappes, based on Nicolae et al. 2014) and the felsic volcanic rocks of SE Hungary (Békés–Codru Unit). Pyroclastic rocks in the Apuseni Mts are crystal-rich (~40 vol%) and contain abundant biotite, altered pyroxene, and accessory garnet crystals (Nicolae et al. 2014; Szemerédi et al. 2018). On the other hand, the samples of this study show much lower crystal content (8–20 vol%); biotite is very rare and no pyroxene or garnet crystals were identified. Neither is any evidence of bimodal Permian volcanic rocks known from the boreholes of SE Hungary, while in the Codru NS cogenetic basalts and subordinate andesites also occur (Nicolae et al. 2014).

Such petrographic differences were also found between the Permian felsic volcanic rocks of southern Transdanubia and the samples of this study. In the Western Mecsek Mts and Máriakéménd–Báta BR, crystal-rich (40–45 vol%) ignimbrites occur that contain hematitized biotite and strongly altered pyroxene as mafic components (Szemerédi et al. 2016, 2020). At the northern foreland of the Villány Mts similar (biotite and pyroxene-bearing) ignimbrites with accessory garnet are present and they are accompanied by subordinate felsic lavas (Szemerédi et al. 2017).

Table 5. Summary of the most significant textural features observed by each lithofacies of the Permian felsic volcanic rocks in SE Hungary. Abbreviations are listed in Tables 2 and 3. Additional abbreviations: fsp: feldspar, qz: quartz, ser: sericite. The frequency of the distinct textural features is given by the following: (+): rare, (++): moderate, (+++): frequent, (–): not present

Feature	emLT	rheoLT	accfrichT	lmLT	vlava-likeT
Microcrystalline matrix	qz, fsp	qz, fsp, ser	qz, fsp, ser	ser, qz, fsp	qz, fsp
Spherulites	+	+	–	–	+++
Eutaxitic	+++	+	–	–	–
Glass shards	flattened (qz, fsp)	–	–	thin bands (ser)	–
Fiammes	flattened (qz, fsp)	flattened (qz, fsp)	–	irregular (ser)	–
Broken phenocrysts	++	+	–	+++	+
Lithics	–	–	–	++	–
Non-volcanic lithics	–	–	–	++	–
Coated particles	–	–	++	–	–

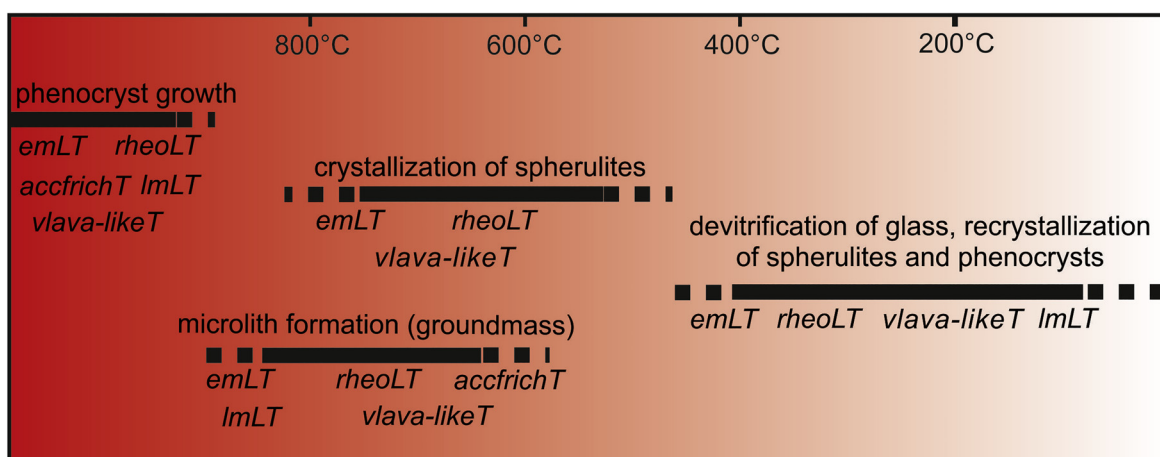


Figure 9. The relative timescale of the most significant processes in textural development of the Permian felsic volcanic rocks. Each process is marked by its representative lithofacies (modified after Lofgren 1971; Swanson et al. 1989; Stevenson et al. 1994; Orth and McPhie 2003; Breitzkreuz 2015)



Tisza Mega-unit					
Southern Transdanubia, eastern Pannonian Basin (Hungary)			Apuseni Mts (Romania)		
Békés–Codru Unit	Battonya–Pusztaföldvár Basement Ridge	crystal-poor ignimbrites (rhyolitic)	Codru Nappe System	Arieșeni Unit	crystal-rich ignimbrites (rhyodacitic-dacitic, low-grade metamorphic)
	Kelebia area	crystal-rich ignimbrites (rhyodacitic-dacitic, low-grade metamorphic)		Gârda Unit	
Villány–Bihar Unit	Máriakémond–Báta Basement Range	crystal-rich ignimbrites (rhyodacitic-dacitic)	Bihar Autochthon Unit	Moma Unit	bimodal volcanism (crystal-rich rhyodacitic-dacitic) ignimbrites and mafic-intermediate lavas)
	Northern foreland of the Villány Mts	garnet bearing crystal-rich ignimbrites and lavas (rhyodacitic-dacitic)		Dieva Unit	Finis Unit
Mecsek Unit	Western Mecsek Mts	crystal-rich ignimbrites (rhyodacitic-dacitic)		Bihar Unit	Permian volcanic or volcano-sedimentary deposits are sporadic

Figure 10. Correlation between the Alpine facies zones of the Tisza Mega-unit (Hungary) and the tectonic units of the Apuseni Mts, highlighting the results of Szepesházy (1979). Data are based on Szederkényi et al. (2013), Nicolae et al. (2014); and Szemerédi et al. (2020)

The mentioned petrographic differences are consistent with the slighter geochemical and geochronological distinctions revealed by our previous studies (Szemerédi et al. 2020). According to the immobile element-based rock classification (Zr/TiO_2 vs. Nb/Y ; Winchester and Floyd 1977), felsic volcanic rocks in SE Hungary are predominantly rhyolites (samples of this study), while felsic volcanic rocks from southern Transdanubia and the Apuseni Mts (Nicolae et al. 2014) are rhyodacites–dacites. The immobile element (high field strength elements, rare earth elements) patterns are rather uniform for all Permian volcanic rocks of the Tisza MU; however, the highest values are shown by the samples of SE Hungary in both light and heavy rare earth elements (Szemerédi et al. 2020). Regarding the geochronological results (zircon U–Pb ages), the samples of this study are slightly younger (259.5 ± 2.6 Ma from BATR/1 and BATR/2 samples, Tótkomlós–K-3 borehole) than all the other Permian felsic volcanic rocks of the Tisza MU, which range between 263.4 ± 2.7 and 266.8 ± 2.7 Ma (Szemerédi et al. 2020).

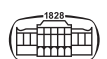
Emplacement of the Permian felsic volcanic rocks in SE Hungary within the Permian volcanic system of the Tisza Mega-unit

The new results suggest that the Permian felsic volcanic rocks in SE Hungary (Battonya, Biharugra, and Tótkomlós areas) might represent the youngest and most evolved, crystal-poor rhyolitic magmas of a large-volume silicic (crystal-rich rhyodacitic–dacitic) volcanism with slighter geochemical, geochronological, and remarkable petrographic differences compared to other Permian felsic volcanic rocks in the Tisza MU. Based on the Alpine evolution of the Tisza MU, the Békés–Codru Unit was correlated with

the Codru NS (Apuseni Mts; Fig. 10); however, Permian felsic volcanic rocks in SE Hungary do not show any correlation with similar rock types (felsic ignimbrites) in any nappes of the Codru NS (based on Nicolae et al. 2014); neither the garnet-bearing crystal-rich samples of the Finis Nappe (as was supposed by Szepesházy 1979), nor the ignimbrites of the Dieva and Moma Nappes that are part of the bimodal volcanic suite (Nicolae et al. 2014). Such crystal-poor ignimbrites are unknown as yet from the Tisza Mega-unit and might represent a petrographically and geochemically distinct, younger (~ 259 Ma; Szemerédi et al. 2020) episode of the Permian volcanism in the Pannonian Basin.

CONCLUSIONS

1. Permian felsic volcanic rocks in SE Hungary were previously described and interpreted in the archive reports of petroleum exploration predominantly as lavas (“Battonya quartz-porphry”). We showed that they are predominantly welded or rheomorphic (Battonya area), rarely lava-like ignimbrites (Tótkomlós-I borehole), and reworked pyroclastic/volcanogenic sedimentary rocks (Tótkomlós and Biharugra areas).
2. Volcaniclastites from the Biharugra and the Tótkomlós areas consist of various felsic volcanic and non-volcanic lithics and might suggest a multiple-phase Permian volcanic activity that was also documented from the nearby Apuseni Mts, Romania (Codru Nappe System; Nicolae et al. 2014).
3. Felsic volcanic rocks in SE Hungary belong to the Permian volcanic system of the Tisza Mega-unit; however, some significant petrographic differences (crystal-poorness, rare biotite, no pyroxene or garnet crystals)



were observed compared to other Permian felsic volcanic rocks in the Tisza Mega-unit (Nicolae et al. 2014; Szemerédi et al. 2020). Thus, Permian volcanic rocks in SE Hungary might represent the most evolved, crystal-poor rhyolitic magmas of a large-volume silicic (crystal-rich, rhyodacitic–dacitic) volcanic system.

4. In contrast to the previous hypothesis (Szepesházy 1979; Császár 2005), Permian felsic volcanic rocks of the Battonya area do not show any correlations with either the similar samples of the Finiş Nappe, Codru Nappe System, or the Permian felsic volcanic rocks in any nappes of the Codru Nappe System, and there is no relevant plutonic–volcanic connection between the (presumably older) “Battonya granite” and the “Battonya quartz-porphry.”

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