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Formal definition and description of lithostratigraphic units related to the Miocene silicic pyroclastic rocks outcropping in Northern Hungary: A revision

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Abstract: Repeated explosive eruptions of large volume silicic magmas during the early- to mid-Miocene resulted in pyroclastic deposits covering at least 50,000 km^2 in the Pannonian Basin. They form extended marker horizons and therefore these pyroclastic formations have a great stratigraphic importance. Lithostratigraphic characterization and classification of these rocks go back for more than a century and have been used widely in geological mapping among other things. In this paper, we outline the former stratigraphical schemes developed for silicic pyroclastic products in Northern Hungary; however, using the new geochronological, volcanological, petrological, and geochemical results, we propose a revision of the lithostratigraphic units, including the unit names as well. Four main units are distinguished, named, and described following the International Stratigraphic Guide. Stratotypes of the revised units were also redefined based on accessibility and representativeness. The four newly-defined lithostratigraphic units are the following: (1) The Tihamér Rhyolite Lapilli Tuff Formation (formerly Gyulakeszi Fm.), 18.2–17.1 Ma (Ottnangian–Karpatian); (2) The Bogács Dacite Lapilli Tuff Formation (formerly classified into the Tar Fm.), 16.8–16.2 Ma (Karpatian); (3) The Tar Dacite Lapilli Tuff Formation, 15.1–14.8 Ma (Badenian) and (4) The Harsány Rhyolite Lapilli Tuff Formation, 14.7–14.4 Ma (Badenian) – four formerly existing formations merged in the latter. Three of these units have corresponding distal volcanic products recognized around Hungary and beyond the Pannonian Basin as well. A correlation of the scattered volcanic products can be made based on lithological characteristics, as well as the chemical composition of glass shards, juvenile clasts, and zircon.

Keywords: lithostratigraphy, silicic volcanism, Carpathian–Pannonian Region, Miocene, pyroclastic rock horizons, lapilli tuff.

Introduction

Lithostratigraphic characterization and classification of geological formations are pivotal in describing a rock succession in order to get a better understanding of the spatial and temporal relationship among each other, and outline the geological evolution of a region. For the last decade, particular efforts have been made to apply lithostratigraphy to volcanic rocks and volcano geology when considering their specific characteristics (e.g., Groppelli & Martí 2013; Martí et al. 2018; Lucchi 2019; Németh & Palmer 2019). Volcanic units, which are related to large-volume explosive eruption events, play a fundamental role, since they can be regionally followed as marker beds and can be precisely dated by various geochronological methods. On the other hand, the lithostratigraphy of even single compound volcanoes is more complex and heterogeneous compared to sedimentary successions, although build-up of such volcanic series is relatively short-lived (several 100 thousands of years; e.g., Davidson & de Silva 2000) and of limited extension (from hundreds of meters to just a few kilometers, except for the fallout deposits). In Hungary, construction of a robust lithostratigraphic system goes back for decades (e.g., Fülöp et al. 1975; Császár 1997; Gyalog 2005) and forms a strong base for geological mapping, where lithostratigraphic units have been defined and correlated for each geological period. In these schemes, volcanic formations play an important role, particularly for the Neogene, when the formation of the Pannonian Basin was accompanied by various volcanic activities relating to compositionally-diverse magmas as a result of various geodynamical processes (e.g., Lexa & Konečný 1974; Konečný et al. 1983, 2002; Szabó et al. 1992; Harangi 2001; Seghedi et al. 2004; Pécskay et al. 2006; Harangi & Lenkey 2007; Lexa et al. 2010; Seghedi & Downes 2011; Harangi & Lukács 2019). Our knowledge on their formation age, lithology, and geochemistry has increased considerably during the last two decades. Therefore, a revision of the former lithostratigraphic units (Császár 1997; Gyalog & Budai 2004; Gyalog 2005) became necessary.

The Hungarian Stratigraphic Committee (Magyar Rétegtani Bizottság in Hungarian, abbr: MRB) led a major campaign during 2020–2021 in order to update and, if possible, simplify the lithostratigraphic units in Hungary. The igneous and metamorphic formations were discussed by the Working Group of Igneous and Metamorphic Rocks (in Hungarian: Magmás és Metamorf Munkabizottság; abbr: MMMB; (https://foldtan.hu/mrb_munkabizottsagok). First, the concept of the lithostratigraphic classification and nomenclature of the igneous and metamorphic rocks was outlined. Experts of the International Stratigraphic Commission were also asked to specify certain questions. All the former lithostratigraphic units were evaluated in detail and, whenever necessary, they were revised and the descriptions were integrated with new data. The suggested descriptions prepared by experts were discussed and finally approved with the consensus of the active members of the MMMB. The most significant modifications were made for the Paleogene to Neogene volcanic rocks, which are closely associated with the formation and evolution of the Pannonian Basin. Although a detailed description of each lithostratigraphic unit has been prepared, only a short summary is planned to be involved in the publication of the complete formation list of Hungary.

In this paper, we describe in detail the lithostratigraphic units of the large-volume explosive silicic pyroclastic sequences accumulated during the early to mid-Miocene, since they hold stratigraphic importance on a regional scale and have been distally recognized beyond the Pannonian Basin (Lukács et al. 2018; Rocholl et al. 2018). In Hungary, they were traditionally divided into three units called the lower, middle, and upper rhyolite tuff (Schréter 1912, 1923; Noszky 1927, 1931; Pantó 1965; Hámor 1985; Jámbor 2008) and these have been extensively used in geological literature. The initial formal lithostratigraphic subdivision was also based on this three-fold system (Hámor 1985). Here, we provide a summary of the former nomenclature of these pyroclastic bodies and present an updated formal definition and description of the lithostratigraphic units related to this time interval of Northern Hungary. The revised unit names are presented both in Hungarian and in English, and their map indices are shown in Table 1 along with the formerly used names and indices.

Geological background

The syn-rift evolution of the Pannonian Basin was accompanied with the formation of andesitic to dacitic volcanic areas and explosive eruptions of large volume Si-rich magmas during the early to mid-Miocene (from ~20 to ~11 Ma, Lexa et al. 2010). These volcanic products have subduction-related geochemical characteristics, although they are connected to lithospheric extension rather than to an ongoing subduction process (Lexa & Konečný 1974, 1998; Nemčok & Lexa 1990; Harangi 2001; Harangi & Lenkey 2007; Harangi et al. 2007; Kovács & Szabó 2008; Lukács et al. 2018). Due to this extension, the relatively thick lithosphere of the continental block encircled by the Alps, Carpathians and Dinarides thinned considerably during the early to mid-Miocene presumably due to the retreating subduction along the Eastern Carpathians (Royden et al. 1982; Csontos et al. 1992; Horváth 1993; Tari et al. 1999; Konečný et al. 2002; Horváth et al. 2006, 2015; Balázs et al. 2016, 2017). During this period, mantle-derived mafic magmas intruded beneath and into the thick continental crust and warmed it up, which consequently led to a physical state when large volume (>1000 km^3) silicic magma reservoirs could form in the upper crust (Lukács et al. 2018). A considerable part of these magma emplacements occurred along the border zone of the ALCAPA (Alps–Carpathians–Pannonian Basin) and Tisza–Dacia microplates. Successive explosive eruptions of large volume (>10–100 km^3) magmas presumably associated with caldera formation processes occurred in several phases from the late Early to early Middle Miocene. Based on the compilation of K/Ar age data (Pécskay et al. 2006), the chronostratigraphic position was traditionally placed between the Eggenburgian and Sarmatian, while Lukács et al. (2018, 2021a) determined the timescale of this volcanism between 18.2 and 14.4 Ma on the basis of zircon U–Pb dating in Northern Hungary (except for the Tokaj Mts. – Nyírség area) (Fig. 1 and the map found in the electronic supplementary material = ESM). These pyroclastic products include the formerly-defined lower, middle, and most of the upper rhyolite tuff formations (Paul & Göbl 1866a; Noszky 1912; Schréter 1912), which were thought to have Eggenburgian–Ottnangian, Karpatian, and late Sarmatian formation ages (Hámor et al. 1980), respectively. In addition, a younger (13.5–11.0 Ma) silicic explosive volcanism also occurred in the Tokaj Mts., which is not discussed here (e.g., Gyarmati et al. 1976; Gyarmati 1977; Pécskay et al. 1986, 1987; Pécskay & Molnár 2002; Gyarmati & Szepesi 2007; Zelenka et al. 2012; Szepesi et al. 2019; Lukács et al. 2021b). Eruptions of silicic magmas resulted in tephras covering extensive areas often with 10–100s meter thickness both in submarine and subaerial environments of the Central Paratethys and therefore, they have crucial stratigraphic importance. Interpolating field and borehole data from the Hungarian territory (Lukács et al. 2018) concluded that more than 4000 km^3 silicic explosive volcanic products were deposited in the Pannonian Basin during the early to mid-Miocene. The usually loose and thus easily-erodable tephras were often reworked and redeposited

Table 1: Former and revised lithostratigraphic unit names and stratotypes as accepted by the MRB. For further information about stratotypes, refer to ESM (Electronic Supplementary Material).

Previous formal (1; Gyalog L. Ed 2005) and informal (2) lithostratigraphic unit name (with Hungarian name) and map code	**Revised lithostratigraphic unit name (with Hungarian name) with map code and abbreviation**	**Synonyms (with Hungarian names)**	**Stratotype(s)**
(1) Gyulakeszi Rhyolite Tuff Formation (Gyulakeszi Riolittufa Formáció); (2) lower rhyolite tuff (alsó riolittufa) $^{g}M_1$	**Tihamér Rhyolite Lapilli Tuff Formation** (Tihaméri Riolit Lapillitufa Formáció) $^{ti}M1$; TRLTF	Tihamér Formation, Tihamér Rhyolite Tuff Formation (Tihaméri Formáció, Tihaméri Riolittufa Formáció)	(a) Tihamér quarry, Eger; (b) Ipolytarnóc
(1) Tar Dacite Tuff Formation Bogács Ignimbrite Member (Tari Dácittufa Formáció, Bogácsi Ignimbrit Tagozat); (2) middle rhyolite tuff (középső riolittufa) $^{t}_{b}M1$	**Bogács Dacite Lapilli Tuff Formation** (Bogácsi Dácit Lapillitufa Formáció) $^{bo}M_1$; BDLTF	Bogács Formation (Bogácsi Formáció)	(a) Vén Hill and Ábrahámka quarry; North of Bogács (b) North of Tibolddaróc
(1) Tar Dacite Tuff Formation (Tari Dácittufa Formáció) $^{t}M_1$ **Borsodbalaton Rhyodacite Tuff Formation** (Borsodbalatoni Riodácittufa Formáció) $^{bb}M_2$ **Felnémet Rhyolite Tuff Formation (**Felnémeti Riolittufa Formáció) $^{f}M_2$ (2) middle rhyolite tuff (középső riolittufa)	**Tar Dacite Lapilli Tuff Formation** (Tari Dácit Lapillitufa Formáció) $^{t}M_2$; TDLTF	Tar Formation (Tari Formáció), Tar Dacite Tuff Formation (Tari Dácittufa Formáció)	(a) Fehérkő quarry, Tar (b) Nagyeresztvény Quarry, north of Demjén
(1) Harsány Rhyolite Tuff Formation (Harsányi Riolittufa Formáció) $^{ha}M_{2\text{-}3}$ **Galgavölgy Rhyolite Tuff Formation (**Galgavölgyi Riolittufa Formáció) $^{gv}M_2$ **Felnémet Rhyolite Tuff Formation (**Felnémeti Riolittufa Formáció) $^{f}M_2$ **Lénárddaróc Rhyolite Tuff Formation** **(**Lénárddaróci Riolittufa Formáció) $^{ld}M_2$ (2) upper rhyolite tuff (felső riolittufa), Kőkötőhegy Member (Kőkötőhegyi Tagozat)	**Harsány Rhyolite Lapilli Tuff Formation** (Harsányi Riolit Lapillitufa Formáció) $^{ha}M_2$; HRLTF	Harsány Formation; Harsány Rhyolite Tuff Formation (Harsányi Formáció; Harsányi Riolittufa Formáció)	(a) Western part of Tibolddaróc (b) Kakarcsó Hill, Lénárddaróc

in the subaerial to marine environment; therefore, volcaniclastic material involves both primary and secondary formations. Additionally, most of these volcanic products are buried by younger sediments due to significant subsidence and sedimentary infill of the basin areas. All of these make the recognition and correlation of the pyroclastic deposits difficult. The volcanic centres and calderas also subsided and got buried; therefore, their exact locations have not been constrained yet. Nevertheless, inferences for the caldera locations have been proposed based on pyroclastic rock thickness and juvenile clast size variations (e.g., Szakács et al. 1998; Lukács et al. 2010; Hencz et al. 2021), as well as seismic and geophysical studies (Zelenka et al. 2004a, 2012). The silicic pyroclastic rocks related to this silicic volcanism crop out in the greatest thickness in two main areas: in the Bükkalja volcanic field (BVF; Fig. 1), which is located in the southern foothills of the Bükk Mts. known as Bükkalja (e.g., Szakács et al. 1998; Harangi et al. 2005; Pentelényi 2005; Lukács et al. 2007, 2018), and in the Tokaj Mts. (Gyarmati 1977; Pécskay et al. 1986; Gyarmati & Szepesi 2007; Szepesi et al. 2019; Lukács et al. 2021b). In addition, they have a regional extent and are found in smaller outcrops and several boreholes in Northern Hungary, as well as in the Great Hungarian Plain and in Transdanubia (Székyné Fux et al. 1987; Zelenka et al. 2004a; Lukács et al. 2010, 2015, 2021a; Petrik et al. 2019).

Lithostratigraphic unit names and nomenclature of volcaniclastic rocks

Stratigraphy and geologic mapping of volcanic areas involving application of lithostratigraphic unit classification (International Stratigraphic Guide – ISG, 1994; presented at https://stratigraphy.org/) have been discussed for decades due to the complexity of volcanic successions within a restricted area and within a limited timeframe (Groppelli & Viereck-Goette 2010; Groppelli & Martí 2013; Martí et al. 2018). In principle, volcanic stratigraphy is defined as the stratigraphic and chronological order of eruptions or products of eruption series involving inter-eruptive periods, when epiclastic or reworked volcanics are deposited or unconformities formed by volcano-tectonic events (Groppelli & Martí 2013). With the advent of sequence stratigraphy, identification of unconformity-bounded stratigraphic units became an important issue in conventional stratigraphy (Catuneanu et al. 2009, 2011) and this played a major role also in volcanostratigraphic schemes (Lucchi 2013). In the mapping of volcanic areas, volcanologists developed slightly distinct hierarchical schemes compared to conventional stratigraphy, since they sometimes used a combination of lithological and facies characteristics in the definition of lithostratigraphic units (Martí et al. 2018). Furthermore, in young volcanic areas (particularly in Italy), the unconformity bounded stratigraphic unit (synthemic units, ISG, 1994) concepts were introduced (Branca et al. 2004, 2011; Bellotti et al. 2006; Lucchi et al. 2010; Palladino et al. 2010; Norini et al. 2014; Lucchi 2019), where the formal lithostratigraphic units (groups, formations, members, etc.) were integrated and often grouped by the unconformity bounded stratigraphic units (supersythems, synthems, and lithosomes). Although this scheme appears to work well in relatively young, Quaternary

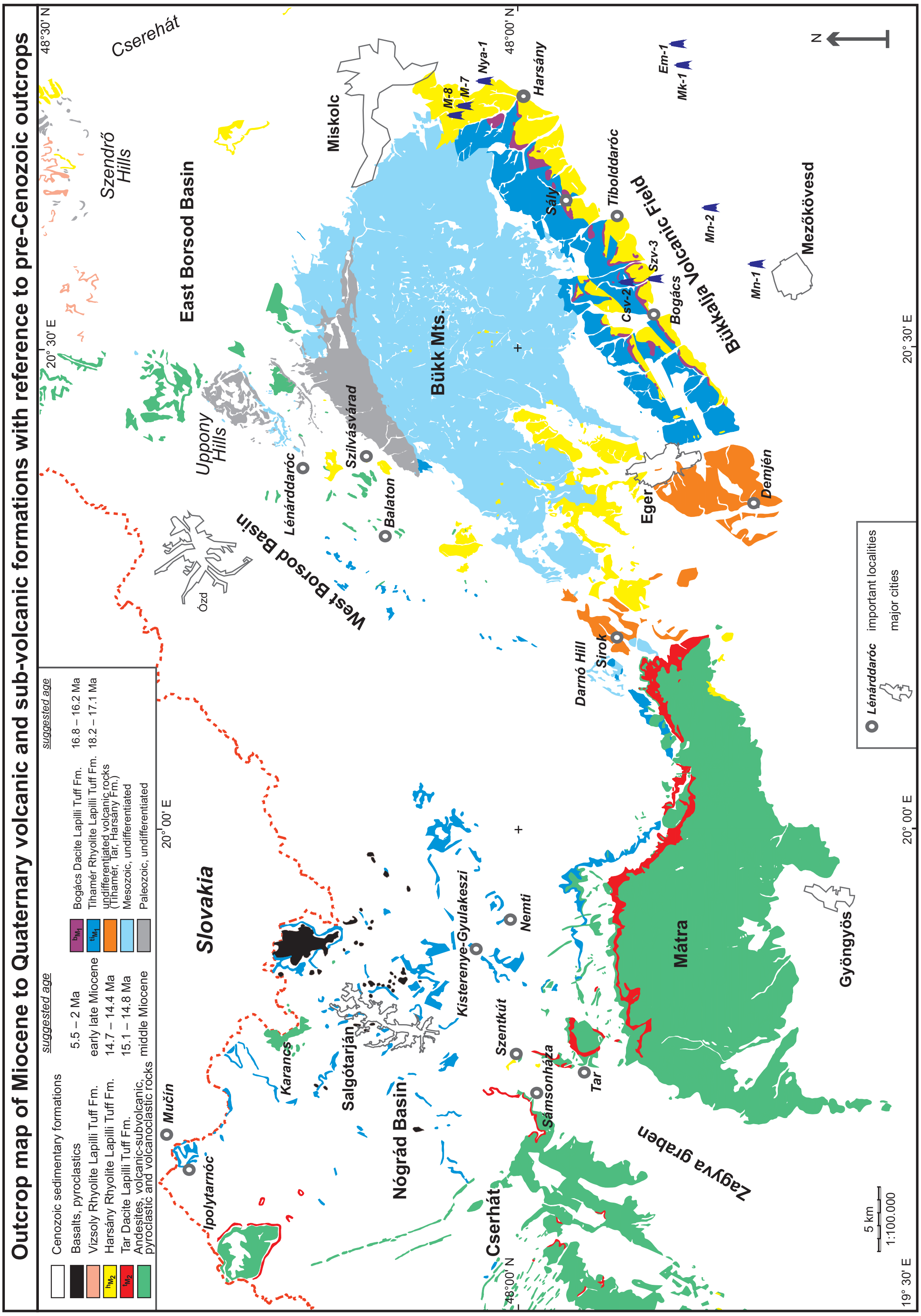

Fig. 1. Geological outcrop map of Northern Hungary showing the areal extent of the defined lithostratigraphic units of the Miocene silicic volcanic rocks in addition to other Miocene to Quaternary volcanic and sub-volcanic and pre-Cenozoic formations. The map is based on the work of Gyalog and Síkhegyi (2005; https://map.mbfsz.gov.hu/fdt100/; for detailed references refer to ESM). Note that the areas with orange colour code (undifferentiated volcanic rocks) include several formations not properly distinguished yet by field mapping. This was previously classified as Felnémet Rhyolite Tuff Formation, which has been revised in this work and no longer valid.

volcanic areas, inconsistencies arise when this system is attempted to apply in variously eroded, paleovolcanic areas, as well as in a larger region with sedimentary basins, where mostly the traditional stratigraphic schemes were used. Detailed discussions of these stratigraphic concepts and their applications in the mapping of volcanic areas are found in Martí et al. (2018) and in Németh & Palmer (2019).

According to the ISG (1994), the name of a lithostratigraphic unit contains an appropriate and unique geographic name followed by either the lithological name or the unit-term (Group, Formation, Member, Bed and Flow) indicating its rank. While the ISG prefers the latter one, the Hungarian stratigraphic guide (Fülöp et al. 1975) suggests the usage of both the lithological and unit-terms after the geographic name. In the Hungarian stratigraphy, the lithostratigraphic names have traditionally three parts only with a few exceptions and this is also suggested by the MRB in the present revisions. Although the authors of this paper do not entirely agree with the practice of the MRB and would rather suggest the usage of geographic and unit-term name formulae, we comply with the decision of the committee. Based on the ISG (1994), the geographic part of the unit name should refer to permanent, natural, or artificial features, i.e., to a stratotype or type-locality of the defined lithostratigraphic unit, and the name should not be misleading (i.e., no other locality with the same name is found in the country). Furthermore, the lithological name should be a simple, generally-accepted term that reflects the dominant rock type within the unit.

In the case of volcaniclastic rocks, the terminology for the lithology is not unequivocal. They can be primary explosive volcanic products (i.e., pyroclastic formations) or variously reworked materials. Pyroclastic formations are usually bedded or massive rock bodies or unconsolidated deposits (tephras), which are characterized primarily by their clast-size distribution, similarly to clastic sedimentary formations and also by the petrochemical character of the juvenile components (i.e., fragments derived from the erupted magma). The lithological nomenclature of pyroclastic rocks was proposed by Fisher (1961), and since this pioneering paper, it has been widely accepted (e.g., Fisher & Schmincke 1984; Cas & Wright 1988; White & Houghton 2006). The MMMB suggested following this classification scheme and the usage of the dominant lithological terms (tuff, lapilli tuff, lapillistone, tuff breccia, agglomerate, pyroclastic breccia) in the lithostratigraphic names. This is consistent with the nomenclature of clastic sedimentary rocks (e.g., mudstone, siltstone, sandstone, breccia, conglomerate), which is also based on clast-size distribution. Distinction between primary (i.e., pyroclastic) and secondary volcaniclastic deposits is often not obvious, particularly in paleovolcanic areas; therefore, we suggest treating such deposits/rocks as primary until unambiguous evidence arises for just the opposite. Note that secondary volcaniclastics (e.g., volcanogenic sandstone, Di Capua et al. 2021) are different from post-volcanic reworked sedimentary deposits called "epiclastics" (following Fisher 1961; White & Houghton 2006), which are derived from the weathering of lithified volcaniclastic deposits (or from any other rock types). In volcano-sedimentary environments, mixing of sedimentary and volcanic clasts also occur often, and this results in a deposit known as tuffite in the case of more than 25 vol% sedimentary component.

In the following, we describe the lithostratigraphic units of the early- to mid-Miocene explosive volcanism of large volume magmas in the Hungarian part of the Pannonian Basin. These units were accepted by the MMMB and the MRB as official revision of the formal units. We also summarize the formal descriptions of the units (prelude), followed by the detailed revised descriptions.

The revised lithostratigraphic units

One of the aims of the revision was to simplify the formal lithostratigraphy of the Si-rich pyroclastic rocks which had contained seven formations related to Northern Hungary (except for the Tokaj Mts., Table 1, Fig. 1 and ESM). The new suggestion comprises four primary lithostratigraphic units (i.e., Formation) that can be distinguished based on lithology. The new units mostly correspond to more than one volcanic eruption; therefore, they may be further divided into informal eruption units (e.g., eruptive periods, epochs, episodes, phases, Fisher & Schmincke 1984; Lucchi 2013) and allow for the identification of more lithologically-important and distinct lithofacies as formal subunits (Members, Beds, Flows). Some of the eruption units may serve as stratigraphic horizons in correlation studies based on their distinct radiometric age, geochemical, or paleomagnetic properties. The brief summary of the lithostratigraphic units and their spatial occurrences in Northern Hungary are given in Table 1. and Fig. 1, respectively.

Tihamér Rhyolite Lapilli Tuff Formation/Tihaméri Riolit Lapillitufa Formáció

Prelude:

This lithostratigraphic unit is the redefinition and revision of the former Gyulakeszi Rhyolite Tuff Formation or the so-called lower rhyolite tuff, which is widespread in the Pannonian Basin and the surrounding area. The lower rhyolite tuff was identified and treated as an early Miocene stratigraphic key-horizon just beneath the major coal formation in Northern Hungary, dating back to more than 100 years (Paul & Göbl 1866a,b; Schafarzik 1892; Noszky 1927, 1931). Nevertheless, the exact stratigraphic position of this horizon was debated even at that time (Ferenczi 1942; Horusitzky 1942). This caused different published age interpretations, i.e., the Burdigalian (Schréter 1940) and the Burdigalian–Helvetian (Csepreghyné Meznerics 1956). Finally, the Paratethys Working Committee of the Commission of Mediterranean Neogene Stratigraphy (C.M.N.S.) set up a stratotype (Kisterenye–Gyulakeszi; Hámor 1971, Fig. 1) and positioned the pyroclastic horizon at the base of the Ottnangian stage. The K–Ar dating results suggested an older, Eggenburgian age (19.6±1.4 Ma; Hámor et al. 1978; Fig. 2); however, this was not considered precise enough to overwrite the stratigraphic classification based on the presumed age of the overlying sedimentary sequence.

The first detailed description of the Gyulakeszi Rhyolite Tuff Formation as an official lithostratigraphic unit appeared in the monograph of "Geology of the Nógrád-Cserhát Area" (Hámor 1985), which, despite the radiometric age data, defined it chronologically in the Ottnangian. In the Bükkalja area, Márton & Pécskay (1998) published K–Ar ages for the pyroclastic rocks and found that the oldest lower tuff complex has a similar age and therefore can be correlated with the Gyulakeszi Rhyolite Tuff Formation (Fig. 2). Póka et al. (2004) published K–Ar ages for the pyroclastic rocks occurring in the Cserhát area that showed a significant range between 21.4±2.3 Ma and 17.1±1.6 Ma (Fig. 2). Another constraint for the relative chronology of the silicic pyroclastic rocks was given by paleomagnetic rotation data. Márton & Márton (1996), Márton & Pécskay (1998), and Márton et al. (2007a) proposed that the oldest pyroclastic unit, i.e., the lower rhyolite tuff is characterized by a major, ca. 75–98° counterclockwise (CCW) rotation with respect to the present magnetic north, whereas the younger pyroclastic units have less or no rotation (Fig. 2). The combination of paleomagnetic and paleostress data (Márton & Fodor 1995) or the fault-slip data alone (Fodor et al. 1999; Petrik 2016) were also considered a powerful correlation tool, while the minimal horizontal stress axes show an almost uniform clockwise rotation through the Miocene (Fig. 2).

Vass et al. (2006) and Márton et al. (2007b) recognized that the pyroclastic rocks near Ipolytarnóc, which were thought to belong to the lower rhyolite tuff, have different paleomagnetic properties compared to the other rocks which belong to the Gyulakeszi Rhyolite Tuff Formation, i.e., they show less rotation relative to the present north. And so, Vass et al. (2006) suggested that the pyroclastic rocks at Ipolytarnóc form a distinct, younger unit and called it the Fehér hegy Formation. Nearly at the same time, Pálfy et al. (2007) published surprisingly (at least based on the former knowledge) young plagioclase Ar–Ar ages (17.02±0.14 Ma and 16.99±0.16 Ma) for the Ipolytarnóc and Nemti localities and a roughly similar, although a little bit older ID-TIMS zircon U–Pb age (17.42±0.04 Ma) for an Ipolytarnóc rock sample (Fig. 2). These results placed the eruptions in the late Ottnangian to early Karpatian ages following the traditional Paratethys chronostratigraphy. Lukács et al. (2018) conducted a thorough zircon U–Pb dating campaign in the Bükkalja volcanic field, where they defined two eruption units as the oldest volcanic products: the Eger ignimbrite (17.5 Ma) and the Mangó ignimbrite (17.1 Ma) that had been chronologically identical to the Ipolytarnóc ages published by Pálfy et al. (2007; Fig. 2). The two ignimbrite units were consistent also with the suggestion provided by Szakács et al. (1998), who distinguished two subunits of the lower tuff complex in Bükkalja. Later, Lukács et al. (2021a) studied further pyroclastic rock occurrences in Northern Hungary, including samples from four different sites at Ipolytarnóc, as well as from Nemti (Fig. 1). All of these zircon U–Pb age data resulted in Ottnangian–Karpatian ages, which fit well with the Eger and Mangó ignimbrite ages. This correlation was corroborated by zircon trace element data. As a result, the Ipolytarnóc pyroclastic rocks have chronological and geochemical similarities with the Eger ignimbrite, whereas the Nemti (Arany Hill) pyroclastic rocks have Mangó ignimbrite affinity (Lukács et al. 2021a). Also noteworthy is that no older pyroclastic rocks have been found so far in this area. New Ar–Ar radiometric data for pyroclastic rocks at the continuation of the Ipolytarnóc succession in Southern Slovakia (Lipovany area) gave 17.49±0.54 Ma and 17.28±0.06 Ma ages (Šarinová et al. 2021; Fig. 2). Therefore, the newly obtained, more accurate, and precise radiometric age data all point to a younger age of the Gyulakeszi Rhyolite Tuff Formation and, as a consequence, also for the overlying Salgótarján Formation.

Concerning the name of the lithostratigraphic unit, it was misleading, since there is a village called Gyulakeszi in the Tapolca Basin of the Balaton Upland area, western Hungary. Originally, the Gyulakeszi name was given after a homestead near Kisterenye (Fig. 1), where the rhyolitic pyroclastic rock is well-exposed (Hámor 1985). The MMMB and the MRB decided to revise the geographic name of this lithostratigaphic unit including its description based on the above-mentioned newly-published results. Since these oldest pyroclastic rocks, which had formed between 17.5 and 17.1 Ma, can be distinguished with difficulties in the field and are close in age, the committee suggested a common, single lithostratigraphic unit for them. They mostly belong to the Karpatian stage, although the Ipolytarnóc site belongs to the late Ottnangian, if accepting the still debated concept of Sant et al. (2017) for the exact numerical age boundary between the Ottnangian and Karpatian (17.25 Ma).

Origin of the name, stratotypes:

The lithostratigraphic unit is named after the Tihamér quarries found in southeast Eger (Tihamér part of Eger; Fig. 1, ESM), where the lower, abandoned quarry exposes the 17.5 Ma Eger ignimbrite and the upper, presently still active quarry shows the 17.1 Ma Mangó ignimbrite. Between these pyroclastic flow units, several thin pyroclastic deposits/layers and an unconformity boundary can be observed. In the surroundings, several further abandoned and private quarries can be visited (partly by permission), where these rocks are exposed in >50 m thickness. Further auxiliary stratotype was defined east of Ipolytarnóc (Borókás-árok; Fig. 1, ESM). Geological sections of the stratotypes are given in ESM.

Definition, description:

The Tihamér Formation predominantly comprises massive, poorly sorted pumice- or fiamme-bearing lapilli tuff, sometimes with block-sized juvenile clasts and subordinate tuff (rarely lapillistone) beds (Fig. 3). The unwelded rocks are

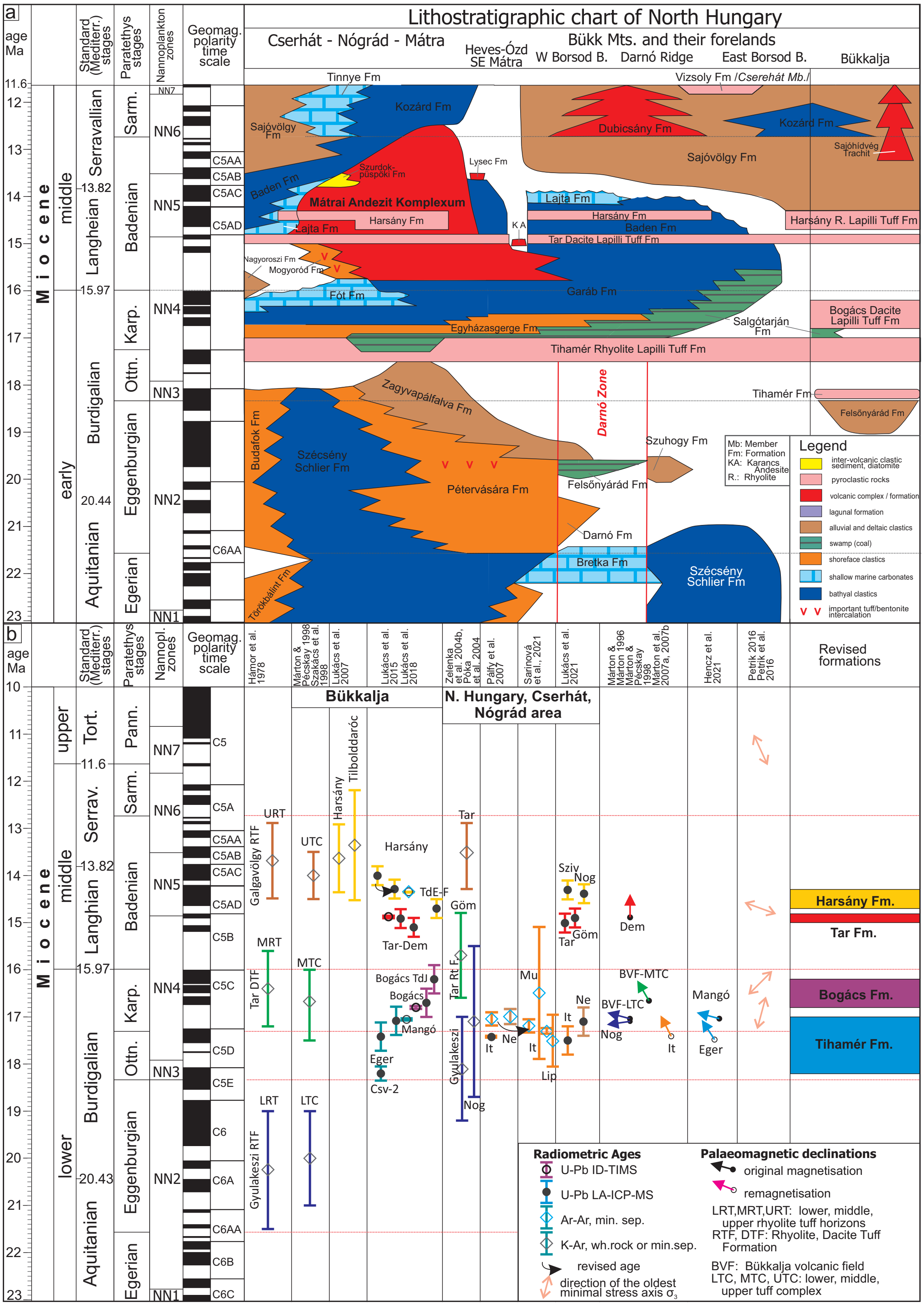

Fig. 2. a — Modified stratigraphic chart of the lower and middle Miocene lithostratigraphic units in Northern Hungary (following Rman et al. 2021) with the Mediterranean and regional stages (Krijgsman & Piller 2012), the calcareous nannoplankton zones and the geomagnetic polarity time scale (following Gee & Kent 2007). Lower Miocene sedimentary units are compiled following O. Sztanó (pers. comm.). **b** — Published radiometric age, paleomagnetic and structural data related to the revised lithostratigraphic units (It: Ipolytarnóc, Ne: Nemti, Mu: Mučín, Lip: Lipovany, Göm: Gömör Hill, Nog: Nógrád region, Sziv: Szilvásvárad, TdE-F: E and F units of Tiboldaróc section in Lukács et al. 2015, Dem: Demjén, Nagyeresztvény Tar: Tar, Fehérkő quarry; Note: Colour code of paleomagnetic directions refer to the same locality as their age data, except for the grey ones, which represent unit averages).

usually light grey or whitish grey, while the welded variations are blackish or dark grey in colour often with a silver shine. The welded facies is distinguished as the Kisgyőr Ignimbrite Member (Pentelényi 2005, Fig. 3). The chemical composition of the bulk rocks (juvenile fragments and lithic clast free bulk rocks) is rhyolitic (SiO_2 >70 %, Fig. 4). The mineral assemblage contains quartz, plagioclase, biotite, rarely sanidine, and amphibole (<<1 %). Zircon, apatite, allanite, and Fe–Ti oxides occur as accessories. The lapilli tuff contains mostly pyroxene andesitic lithic clasts and dacitic, rhyolitic, or sedimentary rocks in less amounts. Fauna remnants in the primary deposits were not found; however, in some occurrences, roots, charcoal or silicified plant remains occur (Ipolytarnóc, Hably 1985; Kordos 1985).

The lapilli tuff formation mostly represents the pyroclastic flow deposits (ignimbrites) formed by Plinian-type eruptions. Subordinate pyroclastic fall and surge deposits contain occasionally accretionary lapilli. They originated from temporarily, closely-packed eruptions with shorter or longer repose times, and the main units derived most likely from different sources, as well as distinct magma reservoirs. Stratigraphically above the ignimbrite facies of the Eger and Mangó eruption units, tuff, accretionary lapilli-bearing tuff, and lapilli tuff are often found, mostly as primary layers and sometimes as reworked volcaniclastic material. In the Bükkalja, an older pyroclastic deposit with an age of 18.2 Ma was found in a drilling core of a borehole (Csv-2; Fig. 1), and this shows different geochemical properties as well (Lukács et al. 2018). It must be noted that this is a single volcanic occurrence having such an age in Northern Hungary.

The possible locations of the eruption centres have been suggested by several works. Szakács et al. (1998) inferred an eruption centre for the lower tuff complex south of Eger based on thickness data (borehole and outcrop) and pumice size distribution, which corresponded to magnetic anomalies. Lukács et al. (2010) suggested the presence of a possible source for one of the lower units of the BVF near Miskolc, east of the Bükkalja, based on a 250 m thick, apparently continuous primary pyroclastic flow deposit in the boreholes south of Miskolc (M-7 and M-8, Fig. 1) that showed a welded horizon inside. Recently, Hencz et al. (2021) inferred an eruption centre for the Mangó ignimbrite also to the east of Bükkalja, 5–15 kilometres from the village of Sály.

Bulk rock and zircon chemical composition data of the rocks from the Mangó ignimbrite differ slightly from the Eger ignimbrite unit and therefore, they can be used as correlation tools to make links between the type units and the sporadically exposed occurrences (Lukács et al. 2018, 2021a).

Thickness:

In the Bükkalja region, including the borehole data south of it, the bulk thickness is between 150–450 meters, and a gradual thickening southward from the Bükk Mts. towards the Great Hungarian Plain can be observed (Pentelényi 2005; Petrik 2016). A much less thickness can be observed in the sporadic occurrences of Northern Hungary.

Stratigraphic position:

In the Bükkalja, the Tihamér Fm. is underlain by the Miocene Felsőnyárád (or Zagyvapálfalva) Formation, or by Mesozoic to Paleogene successions (Fig. 2). Here, it is covered mostly by the younger pyroclastic units of the BVF (Bogács, Tar, and Harsány Formations); however, the exact contacts can be rarely seen. In the Borsod and Novohrad–Nógrád Basins, it is covered mostly by the Salgótarján Browncoal Formation. In the northern foreland of the Mátra Mts., as well as in the Cserhát area, it is deposited on the Pétervására and Zagyvapálfalva Formations (in Ipolytarnóc, directly on top of fluvial beds with footprints and plants (Hably 1985; Kordos 1985) and is overlain by the Salgótarján Browncoal or Garáb Schlier Formation; these two latter bracket the unit to the late Ottnangian–Karpatian time span (Holcová 2001; Püspöki et al. 2009). In the southern Transdanubia (Mecsek Mts. and surroundings, ESM), it occurs within the Szászvár Formation (e.g., Hámor 1970; Árva-Sós & Máthé 1992).

Age: Early Miocene; Ottnangian–Karpatian; 18.2–17.1 Ma.

The pyroclastic rocks of this unit were generated by several large explosive eruptions, as well as eruption phases that were sometimes with some quiescence periods between them, although all of this occurred in the early Miocene. The published K–Ar ages ranged between 21 and 18.5 Ma (Hámor et al. 1978; Márton & Pécskay 1998, Fig. 1) with a generally large uncertainty of ~0.6–1.4 Ma. The most accurate and precise age data were provided by zircon U–Pb and plagioclase Ar–Ar methods (Pálfy et al. 2007; Lukács et al. 2015, 2018, 2021a; Šarinová et al. 2021, Fig. 2). The oldest eruption unit known so far in this area is the pyroclastic bed in the Csv-2 borehole that gives 18.2±0.3 Ma zircon age (LA-ICP-MS; Lukács et al. 2018). The Eger ignimbrite unit in the Bükkalja area has a zircon U–Pb LA-ICP-MS age of 17.5±0.3 Ma, while the Mangó ignimbrite unit 17.055±0.024 Ma and 17.1 ±0.3 Ma zircon U–Pb ID-TIMS and LA-ICP-MS age, respectively (Lukács et al. 2018). The ignimbrite of Ipolytarnóc and Nemti (Fig. 1) gave 17.19±0.14 Ma and 17.16±0.16 Ma plagioclase Ar–Ar ages, respectively (corrected from Pálfy et al. 2007 by Šarinová et al. 2021). The interpreted zircon U–Pb ages of the pyroclastic rocks are 17.42±0.04 Ma (ID-TIMS age; Pálfy et al. 2007) and 17.5–17.2 Ma (LA-ICP-MS ages; Lukács et al. 2021a) at Ipolytarnóc, while at the Nemti – Arany Hill (Arany-hegy) it is 17.1±0.3 Ma (LA-ICP-MS age; Lukács et al. 2021a). In Northern Hungary, no older than 17.5 Ma ages have been obtained so far for the scattered pyroclastic deposits (except for the rocks of the Csv-2 borehole). The pyroclastic deposits in the Mecsek Mts. south of Máza (ESM) have similar zircon U–Pb ages and thus, can be part of the TRLTF (Lukács R., in prep). All of these ages point to late Ottnangian to Karpatian stages, except for the Csv-2 unit, which can be placed near the Eggenburgian–Ottnangian stage boundary.

Paleomagnetic data can constrain the age of the formation of this unit, partly through magnetostratigraphy and partly through declination values, because the Miocene volcanic

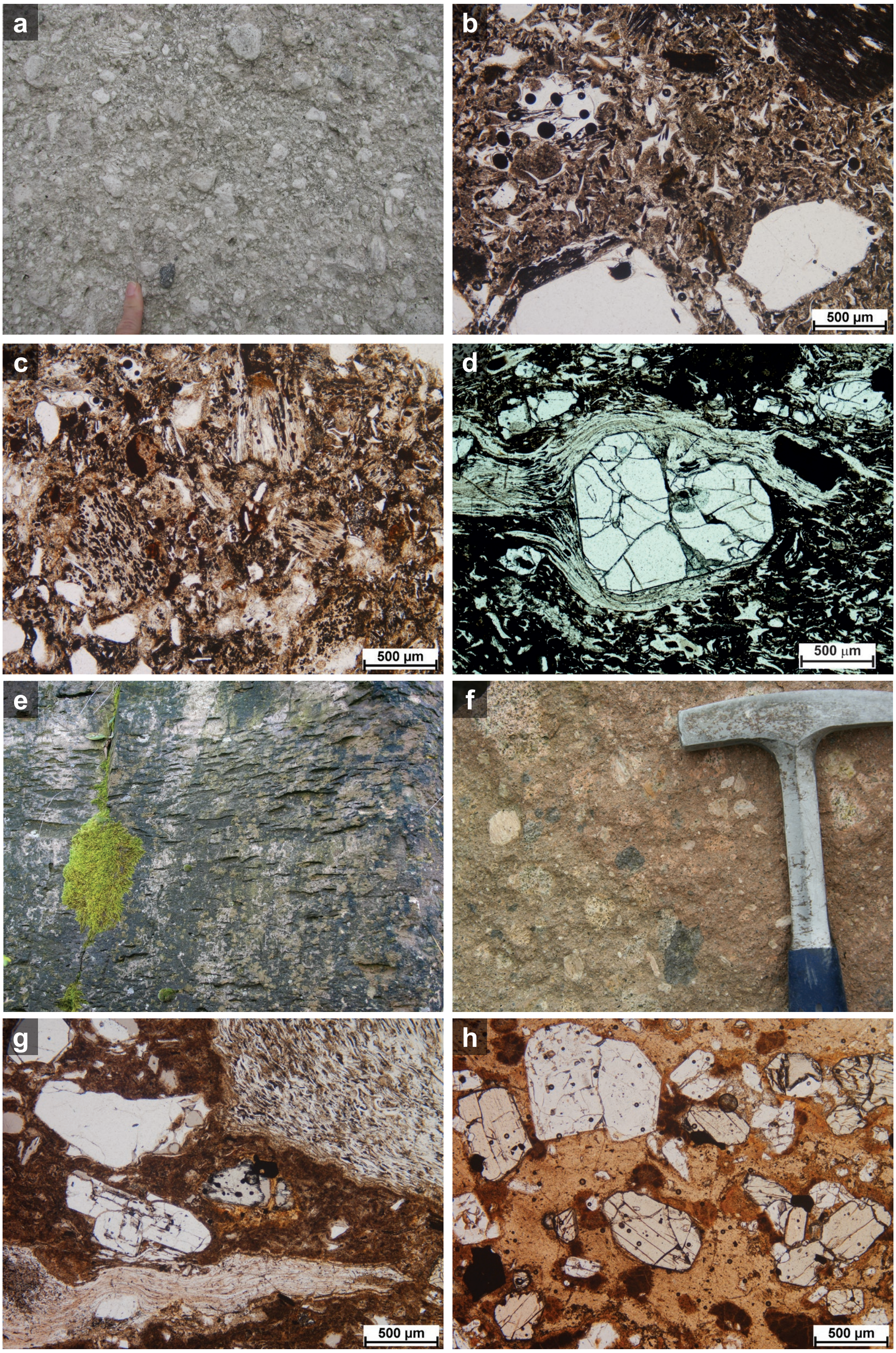

Fig. 3. Tihamér Rhyolite Lapilli Tuff Formation: **a** — unwelded pumiceous lapilli tuff, Mangó cliffs, Mangó unit; **b** — microscopic photo of the unwelded ignimbrite showing pumices and glass shards, as well as quartz, plagioclase, and biotite crystals, Eger, Tihamér quarry, Mangó unit; **c** — typical microscopic photo of the ignimbrite at Ipolytarnóc, Eger unit; **d** — microscopic photo of fiamme bearing welded ignimbrite, north of Demjén (Kisgyőr Ignimbrite Member). Bogács Dacite Lapilli Tuff Formation: **e** — fiamme-bearing welded ignimbrite, Vén Hill, Bogács; **f** — mixed juvenile clast-bearing (black scoriae and white pumices) pyroclastic rock, Ábrahámka, Bogács; **g** — microscopic photo of the fiamme-bearing welded ignimbrite showing various types of fiamme, plagioclase and orthopyroxene crystals, Vén Hill, Bogács; **h** — microscopic photo of a big fiamme in the strongly-welded ignimbrite at Tibolddaróc, orthopyroxene and plagioclase crystals are embedded in glassy matrix. Localities are indicated in Fig. 1.

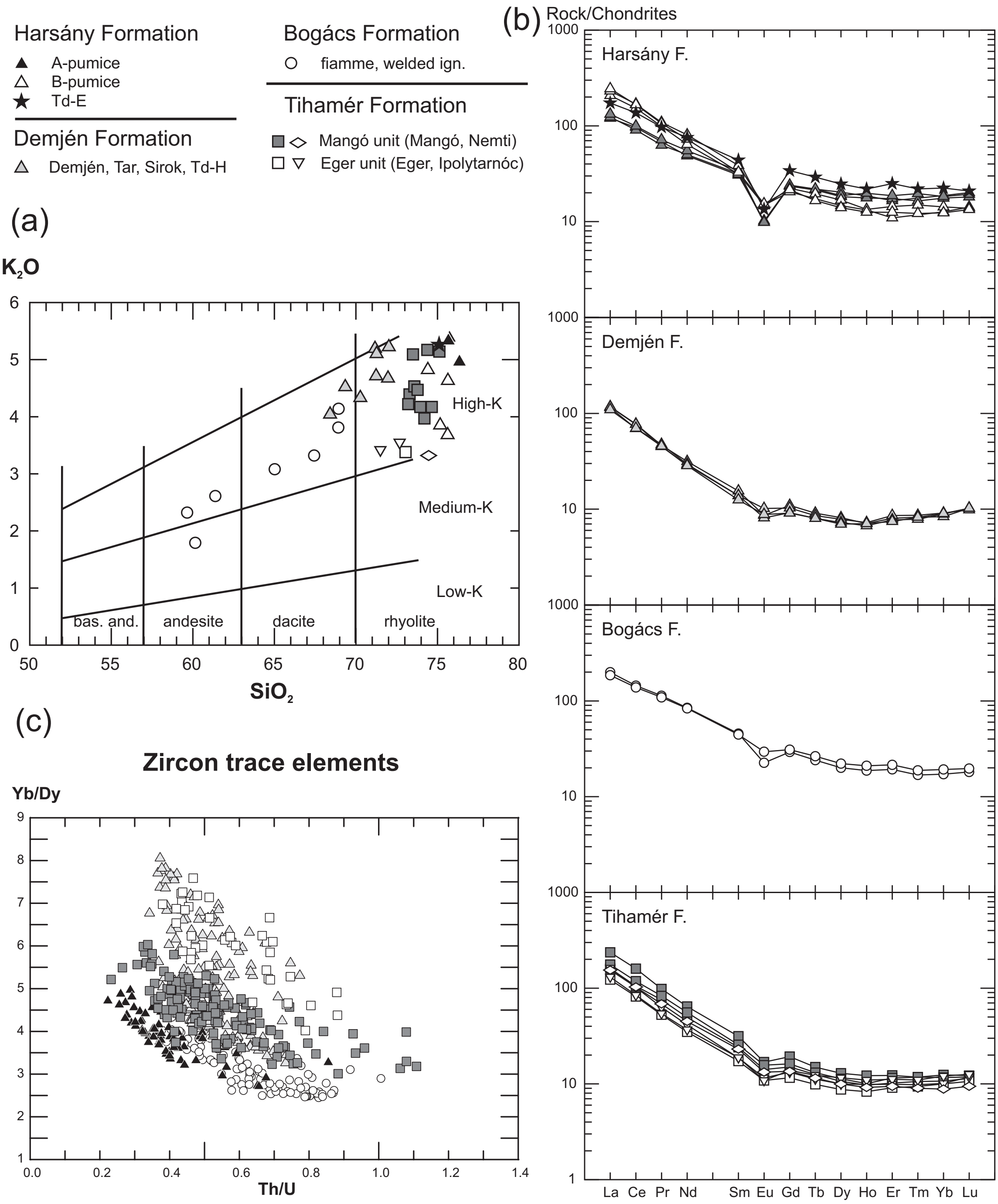

Fig. 4. Geochemical features of the four main silicic pyroclastic formation in Northern Hungary. **a** — Bulk rock major element composition of juvenile clasts; **b** — bulk rock chondrite normalized (Sun & McDonough 1989) rare earth element diagrams; **c** — trace element ratios of zircon crystals. For data reference see Harangi et al. (2005), Lukács et al. (2007, 2015, 2018, 2021a), Czuppon et al. (2012).

rocks and sediments appear to show distinct and systematic rotation patterns. In the BVF, the Mangó ignimbrite shows site-averaged mean declinations between −88 and −119° (average −106°, α_{95}=7°), meaning ~75° counterclockwise (CCW) rotation with respect to the present north (Márton & Márton 1996; Márton & Pécskay 1998) and new data also confirm similar declinations (Hencz et al. 2021, declination: 275–302°; Fig. 2). These declination values are also typical for the lower rhyolite tuff unit occurrences in the Novohrad–Nógrád Basin (Dc=−82, α_{95}=11°, 98° CCW; Nemti, Kisterenye; Márton & Márton 1996) and it matches the values measured in south Slovakia just near the border (Márton et al. 1996; Vass et al. 2006, Bukovinka Fm.). However, there are outliers from this general picture, for instance, some/all sites of the Eger ignimbrite unit have a systematic overprint in magnetisation with a declination value between 320–334° (normal polarity, Márton

& Márton 1996; Hencz et al. 2021). The latter declinations were measured also for the pyroclastic rocks of Ipolytarnóc (Márton et al. 2007b), which have identical zircon U–Pb ages with the 17.5 Ma Eger ignimbrite. This highlights that remagnetization cannot be excluded for certain sites of the TRLTF, particularly for the older, Eger ignimbrite and related pyroclastic rocks both in the Bükkalja and Novohrad–Nógrád regions (Hencz et al. 2021). On the other hand, the measured reverse polarities would fit into the classification of the C5Dr (Vass et al. 2006) or C5Cr chronozones (Fig. 2). The formation also shows a distinct fracture pattern, while fractures formed by NNE–SSW extension only appear in this and not in younger formations (Fig. 2) (Márton & Fodor 1995; Petrik et al. 2016).

Occurrence:

Bükkalja, northern foreland of the Mátra Mts., Novohrad–Nógrád Basin, Cserhát (Fig. 1), southern Transdanubia (Mecsek Mts.), Sárszentmiklós (Mezőföld Area, ESM)

Bogács Dacite Lapilli Tuff Formation / Bogácsi Dácit Lapillitufa Formáció

Prelude:

The dacitic pyroclastic rocks in the Bükkalja volcanic field is a well-recognized formation, usually occurring at the top of the southward dipping hills and forming west–east trending belts. Initially, it was interpreted as an effusive volcanic product (Balogh 1964), although Pantó (1963) identified these rocks as ignimbrite. New volcanological studies pointed out that it is a welded ignimbrite (Capaccioni et al. 1995; Szakács et al. 1998; Czuppon et al. 2012) that is distinct from the other pyroclastic units based on the mineralogical assemblage (it contains pyroxene and minor amphibole). Póka et al. (1998) suggested that magma mixing played an important role in the petrogenesis, which is corroborated by the detailed geochemical work of Czuppon et al. (2012).

Márton & Márton (1996), Márton & Pécskay (1998), and Márton et al. (2007a) pointed out that this unit can be distinguished clearly based on the paleomagnetic declination data showing a ca. 30° CCW rotation with regard to the present magnetic north. The K/Ar age data ranged between 16 and 17.5 Ma, but with large uncertainties (Márton & Pécskay 1998; Fig. 2). The most recent zircon U–Pb dating yielded a 16.8 Ma age (Lukács et al. 2018; Fig. 2). In terms of lithostratigraphy, this unit was formerly thought to belong to the Tar Dacite Tuff Formation (Gyalog 1996) and was separated within it as the Bogács Member (Gyalog 2005; Radócz & Gyarmati 2005) or Bogács Ignimbrite Member (Pentelényi 2005).

The unique petrological character of the mostly welded dacitic pyroclastic rocks in the Bükkalja region gave an excellent stratigraphic marker horizon. The welded ignimbrite facies of the formation gives a robust layer that can be followed even subsurface in boreholes (e.g. Radócz & Gyarmati 2005; Lukács et al. 2015, Fig. 1) and on seismic sections (Petrik 2016); therefore, its validity as a key-stratigraphic unit is confirmed. The striking petrological and age differences with respect to the rocks of the Tar Dacite Lapilli Tuff Formation (~16.8 Ma, Karpatian versus ~14.9 Ma, Badenian, of the latter one; Lukács et al. 2018, 2021a) suggest the separation of the Bogács unit as an independent lithostratigraphic unit. The progenitor Bogács Ignimbrite Member was restricted to the welded facies only (Pentelényi 2005), whereas Czuppon et al. (2012) pointed out that there is a lower unwelded ignimbrite facies and an upper mixed juvenile-clast bearing pyroclastic flow subunit in addition to the more widespread welded ignimbrite. Furthermore, Lukács et al. (2007, 2015, 2018) recognized an overlying accretionary lapilli-bearing tuff layer (called Td-L layer) that has the same age and belongs to the same multi-phase eruption event. And so, the new lithostratigraphic unit should include all of these subunits.

Origin of the name, stratotype:

The best outcrops of the formation can be found at Bogács and Tibolddaróc (Fig. 1). The name refers to the locality (Bogács), where the most complete outcrops of this unit are found. The lower, unwelded, and the fiamme-bearing subunits are nicely exposed north of Bogács, at the Vén Hill (Vénhegy), Hintó Valley, while the upper subunit with the strongly mixed juvenile clasts can be studied in the Ábrahámka quarry northwest from Bogács (Fig. 1, ESM). Similarly well-exposed outcrops are located north of Tibolddaróc, where the welded facies with big fiamme is overlain by the mixed subunit and here, also the uppermost bed with >1 cm sized accretionary lapilli can be seen. The Szent Márton church in Bogács is made of the rocks of this lithostratigrapic unit.

Definition, description:

The Bogács Formation occurs in the BVF, as well as in the surrounding boreholes. It comprises dominantly-welded and non-welded lapilli tuff in addition to tuff and tuff breccia, which are the deposits of pyroclastic flows (ignimbrite) and fall produced by mostly magmatic (and at the end by phreatomagmatic) eruptions (Fig. 3). The volcanic rock succession, from the bottom upwards, shows a continuous transition from a felsic (rhyolitic) to a more mafic (dacitic–andesitic) compositional character reflected in the bulk rock chemistry (SiO_2 70–65 %, even down to 50 %; Fig. 4) and in the mineral assemblage (from quartz, plagioclase, biotite to plagioclase, pyroxene, amphibole, biotite, ilmenite upwards) as described by Radócz & Gyarmati (2005) and Czuppon et al. (2012). Zircon, apatite, and Fe–Ti oxides are accessory phases in all facies. Zircon trace element composition differs significantly from the other units and therefore, it is an effective correlation proxy (Lukács et al. 2021a; Fig. 4). The juvenile rock fragments are pumices, various fiamme and scoria, whereas lithic clasts are subordinate (<1 %; mostly andesitic, less dacitic) compared to other pyroclastic units in Northern Hungary.

Detailed volcanology, petrology, and geochemistry of the BDLTF is given by Czuppon et al. (2012), who divided it into different subunits. The lower part is characterised by light grey to rose-grey unwelded pumice-bearing lapilli tuff, which crops out only in a few localities. It continuously turns into a reddish fiamme-bearing welded facies (Fig. 3e). The sizes of fiamme reach up to 20 cm. This fiamme-bearing welded facies is the most widespread and can be found along a SW–NE trending belt across the Bükkalja volcanic field. This subunit again shows a continuous transition to the upper pyroclastic flow facies (mostly lapilli tuff, but subordinately tuff breccia), which has a characteristic mixed juvenile clast population (various pumices and scoria, as well as composite scoria-pumice clasts; Fig. 3f), rich in crystals supported by a predominantly red vitroclastic matrix. The large petrological and compositional variation of this subunit was explained by mixing and mingling of a felsic magma with a more mafic one (Póka et al. 1998; Czuppon et al. 2012). Czuppon et al. (2012) suggested that before and during the eruption, mixing and mingling of compositionally-distinct crystal mush bodies and melt lenses occurred. The uppermost layers are white-yellowish to white-light brown accretionary lapilli-bearing tuff and tuff layers intercalated with reworked ash-sized volcaniclastics (volcanogenic sandstone; Lukács et al. 2007, 2018). Szakács et al. (1998) identified a sporadically-occurring fluvial deposit as being the youngest known bedrock of the Bogács Fm. and suggested subaerial deposition.

The Bogács Fm. could have been formed by a closely-packed series of pyroclastic flows and falls with only short intervening quiescence periods deriving from an unknown volcanic centre. Szakács et al. (1998) inferred the source of the eruption to be northeast of the present Mezőkövesd area based on gravity anomaly and paleomagnetic anisotropy interpretations (Fig. 1).

Thickness:

In the Bükkalja and based on borehole data, the average thickness of the typical reddish welded and unwelded rocks is 30 meters, maximum 50–70 m.

Stratigraphic position:

In the Bükkalja volcanic field, the underlying unit is mostly the Tihamér Formation, however, direct contact between the two units is only sporadically exposed (Fig. 2). Nevertheless, it is difficult to identify it because of the fairly similar character of the lowermost felsic unwelded pyroclastic flow deposit of the Bogács Formation to the rhyolitic ignimbrite of the Tihamér Formation. The BDLTF is overlain by the Tar Dacite Lapilli Tuff Formation or the Harsány Rhyolite Lapilli Tuff Formation (Fig. 2). The most continuous stratigraphic section from the Bogács to the Harsány Fm. can be found at Tibolddaróc (Lukács et al. 2007, 2015; Biró et al. 2020, Fig. 1, ESM).

Age: Early Miocene; Karpatian; 16.8–16.2 Ma.

The K–Ar ages are in the range from 16 to 17.5 Ma on biotite separates and bulk rock samples (Márton & Pécskay 1998; Fig. 2). More recent zircon U–Pb age data (Lukács et al. 2018) on the fiamme and various juvenile clasts of the upper mixed unit gave an age of 16.846±0.059 Ma by ID-TIMS and 16.8±0.3 Ma by LA-ICP-MS methods (Fig. 2). The accretionary lapilli-bearing tuff layer and the overlying reworked volcaniclastics in the uppermost part of the formation gave 16.7±0.3 and 16.2±0.3 Ma age by LA-ICP-MS method, respectively. The reverse paleomagnetic polarity (Márton et al. 2007a) of the rocks indicates its formation between the C5Cn.3n and C5Dn subchrons (C5Cr: 16.726–17.277 Ma; interpretation of Lukács et al. 2018; Fig. 2). The paleomagnetic rotation data suggest ~30° counterclockwise rotation with respect to the present magnetic north (Márton & Márton 1996; Márton & Pécskay 1998). It is interesting to note, however, that some of the remagnetised units of the Tihamér Formation also show the same amount of rotation (Fig. 2) (Hencz et al. 2021). The oldest faulting having affected this formation was marked by an (E)NE–(W)SW extension (Márton & Fodor 1995; Petrik et al. 2016).

Occurrence:

Based on our present knowledge, the Bogács Fm. occurs only in the Bükkalja volcanic field and in boreholes south of the area (Fig. 1).

Tar Dacite Lapilli Tuff Formation/Tari Dácit Lapillitufa Formáció

Prelude:

The previous name of this lithostratigraphic unit was the middle rhyolite tuff (e.g., Schréter 1912; Noszky 1931), and it is thought to be the most voluminous Miocene silicic pyroclastic deposit in the Pannonian Basin. It was identified very early that a younger horizon exists stratigraphically above the lower rhyolite tuff horizon; however, the age and the exact stratigraphic position of this pyroclastic unit were unclear, since some occurrences were mistakenly correlated with both older and younger pyroclastic rocks (e.g., Schafarzik 1892; Vogl 1907; Schréter 1937). It was placed either to the Tortonian (Noszky 1940; Jámbor et al. 1966) or the Burdigalian and Helvetian (Vitális 1940), or to the boundary between the Helvetian and Tortonian (e.g., Bartkó 1952) stages. Hámor (1972, 1985) classified it into the Karpatian regional stage as indicated by the available K–Ar radiometric dates (16.4±0.8 Ma on average, Hámor et al. 1978; Fig. 2). A detailed description of the Tar Dacite Tuff Formation as an official lithostratigraphic unit of the middle rhyolite tuff was published in the monograph about the geology of the Nógrád–Cserhát area (Hámor 1985). The lithostratigraphic unit was named after a type locality at the village of Tar (Fehérkő quarry, Fig. 1), northwest of the Mátra Mts. Three tuff complexes in the Bükkalja region were identified, and based on their dacitic composition, the K–Ar ages (17.5–16.5 Ma), and paleomagnetic rotation data (ca. 30° counter-clockwise rotation, Márton & Pécskay 1998, fig. 12), Szakács et al. (1998) correlated their middle tuff complex with the Tar Dacite Tuff Formation. This was named the Bogács Ignimbrite Member by Pentelényi (2005), who also classified it into the Tar Dacite Tuff

Formation. Note as well that this belongs to the Bogács Formation, which we have previously defined in this paper as a separate lithostragigraphic unit. During the geological mapping in the Bükk area, Pelikán et al. (2005) identified a new pyroclastic unit that they called the Felnémet Rhyolite Tuff Formation, and since it was thought to have a Badenian age, they separated it from the Bogács Ignimbrite Member and the Tar Dacite Tuff Formation. In the northern foreland of the Bükk Mts, at the western part of the Borsod Basin, Radócz (2004) identified Badenian rhyodacitic to dacitic pyroclastic deposits. He defined it as a new lithostratigraphic unit and named it the Borsodbalaton Rhyodacite Tuff Formation. The reason for the separation was the recognition of the Badenian age (based on paleontological data) that contrasted the postulated Karpatian age (e.g., Gyalog 2005) of the official Tar Dacite Tuff Formation.

The Karpatian age of the type locality (Fehérkő quarry at Tar, Fig. 1, ESM) of the Tar Dacite Tuff Formation was debated by Zelenka et al. (2004b), who proposed a formation age of 13.9±0.6 to 13.5±0.7 Ma based on K–Ar dating (Fig. 2). Since this age was significantly younger than the one thought to characterize the Tar Dacite Tuff Formation, they suggested setting out a new stratotype for this unit at the nearby Gömör Hill (Gömör-hegy) where they published a K–Ar age of 15.9±0.6 Ma for the outcropping pyroclastic deposit (Fig. 2). Harangi et al. (2005) found a close correlation between the ignimbrites at Tar and Demjén as well in the southwestern Bükkalja, based on trace element composition of the glass shards. This was supported by a similar paleomagnetic rotation property (no rotation; Márton et al. 2007a) and the fact that Szakács et al. (1998) considered that the ignimbrites at Demjén (Nagyeresztvény area, Fig. 1, ESM) belong to the upper tuff complex in Bükkalja.

The controversial age and lithostratigraphic position of the dacitic ignimbrites at Tar and Demjén were discussed in detail by Lukács et al. (2015, 2018, 2021a), who published zircon U–Pb ages (Fig. 2) and pointed out that they were formed at 14.9 Ma, well within the Badenian. This new, accurate age result, as well as additional geochemical data, led to the need for revision of the former ideas and urged to constrain the stratigraphic position better, as well as the areal extent of the Tar Dacite Tuff Formation.

The similar amphibole-bearing mineral assemblage, as well as the typical rhyodacitic–dacitic geochemical and unique trace element composition (Harangi et al. 2005; Lukács et al. 2015, 2018), including the common zircon U–Pb ages (15.1–14.9 Ma) suggested the collection of the former Tar Dacite Tuff, the Borsodbalaton Rhyodacite, and the primary rhyodacitic–dacitic pyroclastic rocks of the Felnémet Rhyolite Tuff Formations into the revised Tar Dacite Lapilli Tuff Formation. Furthermore, the Bogács ignimbrite in the Bükkalja, which had been formerly considered as a member of the Tar Dacite Tuff Formation, proved to be older (16.9 Ma) and compositionally distinct and was thus separated from them as a new lithostratigrahic unit (Bogács Dacite Lapilli Tuff Formation).

Origin of the name, stratotype:

The predecessor formation was named after the town of Tar in Nógrád (northwestern margin of the Mátra Mts.; Fig. 1) by Paul & Göbl (1866a) and by Noszky (1912) as the representative of the middle rhyolite tuff horizon. The Fehérkő quarry offers one of the best outcrops for this pyroclastic rock, although a thick pyroclastic section of this unit is exposed also at Demjén (Fig. 1). In the Fehérkő quarry, a nearly 30 m thick massive pumice-bearing lapilli tuff with segregation pipes and several block-sized pumices with mostly andesitic lithic clasts are exposed, formed by successive pyroclastic flows (Fig. 5b, c). Although Zelenka et al. (2004b) argued against this stratotype, the new zircon geochronological results contradicted their results and strengthened the validity of the Fehérkő quarry at Tar being the type locality of the Tar Dacite Tuff Formation (Lukács et al. 2018, 2021a).

Definition, description:

The Tar Formation predominantly comprises pumice-bearing lapilli tuff and tuff (Fig. 5), which can be related to a large volume, ignimbrite-forming Plinian explosive eruption or a closely-packed eruption series. Locally, phreatomagmatic (phreatoplinian) layers with accretionary lapilli were also identified (Harangi et al. 2005; Lukács et al. 2007, 2018; Biró et al. 2020). The volcanic product of this eruption could have had the largest volume (several 100's km^3) within the early- to mid-Miocene silicic volcanic suite, and the volcanic ash had spread and was deposited far from the Pannonian Basin too (Lukács et al. 2018).

In the Nagyeresztvény quarry at Demjén (Bükkalja, Fig. 1), slightly welded, massive ignimbrite occurs (called the Demjén ignimbrite unit by Lukács et al. 2015; Fig. 5a), while westward silicified facies are also observable. Several pyroclastic flow units divided by thinner (~10 cm) fall layers can also be recognised in some of the outcrops (e.g., in Sirok, Demjén and Tar; Gál et al. 2020, Fig. 1). In the western part of Tibolddaróc, a continuous pyroclastic section first described by Lukács et al. (2007) contains a maximum 15 m thick unit known as unit H (Lukács et al. 2015, 2018) and is composed of accretionary lapilli-bearing ash flow and fall deposits, which had been correlated with the Demjén ignimbrite unit. This unit was also identified in Bogács (Harangi et al. 2005), and the two sections were later correlated with detailed, physical volcanological observations and informally called the Jató member by Biró et al. (2020). According to the volcanological interpretation by Biró et al. (2020), the volcanic succession represents a single eruption phase that was initially subdivided by dry magmatic and successive wet phreatomagmatic eruptions.

Deposition of the pyroclastic material belonging to the Tar Fm. occurred mostly subaerially (e.g., Bükkalja, Northern Mátra), however, a significant part of the pyroclastic formations was deposited and/or reprocessed under water (e.g., Hámor 1985; Budai et al. 1999; Selmeczi & Kókay 2004). The volcanic centre(s) of this large eruption event, presumably caldera, is not known yet, however, the considerable thickness

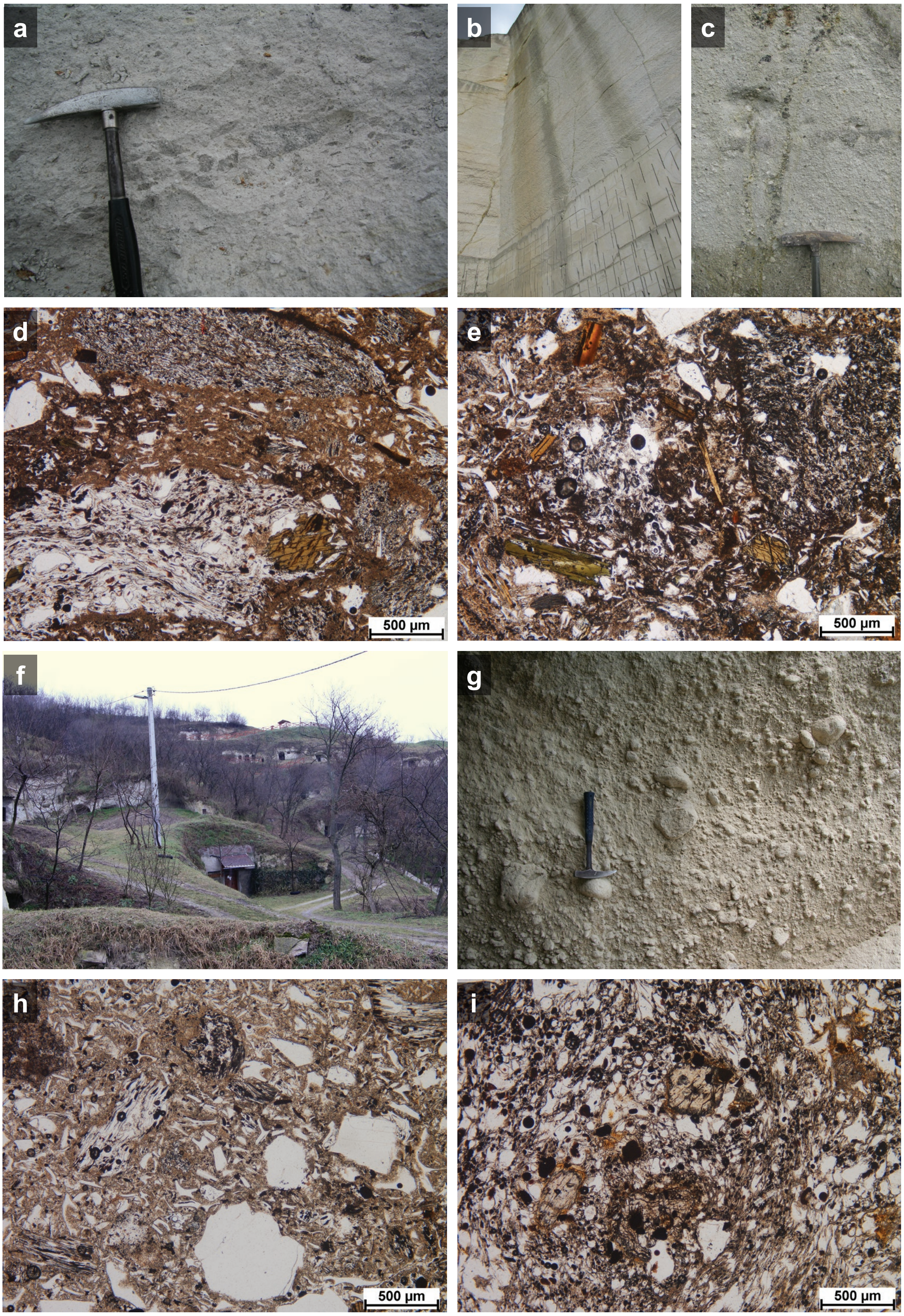

Fig. 5. Tar Dacite Lapilli Tuff Formation: **a** — slightly-welded lapilli tuff with flattened pumices, Demjén ignimbrite, Nagyeresztvény quarry, Demjén; **b** — unwelded pumiceous lapilli tuff, Fehérkő quarry, Tar; **c** — segregation pipes in the Tar ignimbrite, Fehérkő quarry, Tar; **d** — microscopic photo of the Demjén ignimbrite with flattened pumices and glass shards, plagioclase, bitotite, and amphibole crystals, Nagyeresztvény quarry, Demjén; **e** — microscopic photo of the Tar ignimbrite with pumice clasts, glass shards, plagioclase, amphibole and biotite, Fehérkő quarry, Tar. Harsány Rhyolite Lapilli Tuff Formation: **f** — wine cellars carved in the Harsány ignimbrite, Tibolddaróc; **g** — unwelded block-bearing lapilli tuff, Harsány ignimbrite Tibolddaróc; upper right; **h** — microscopic photo of the Harsány ignimbrite with pumices and glass shards, quartz, plagioclase and biotite crystals, Tibolddaróc; **i** — microscopic photo of a B-type pumice with orthopyroxene and plagioclase crystals, Tibolddaróc. Localities are indicated in Fig. 1.

data at Tar, Sirok, and Demjén might infer it around the Mátra area (Lukács et al. 2015, 2018, Fig. 1).

The less-altered rocks of the Tar Fm. are either white or light grey, while their chemical composition is dacitic to rhyodacitic (SiO_2=68–70 %; Fig. 4). The mineral assemblage typically contains plagioclase, biotite, diagnostically amphibole (<5 %) and rarely quartz (<1 %). Zircon, apatite, and Fe–Ti oxide minerals occur as accessories. The lapilli tuffs contain mostly pyroxene andesitic and less frequently dacitic lithic clasts with similar mineralogy to the host. The chemical composition of the bulk rocks (pumices) and the volcanic glass shards as well is characteristically different from the other Badenian pyroclastic rocks of Northern Hungary, since it shows typical heavy rare earth element depletion and less negative Eu-anomaly (Harangi et al. 2005; Lukács et al. 2018, 2021a; Fig. 4). Zircon trace element composition is also distinct and serves as an effective correlation tool for recognising the scattered deposits of the Tar Fm. (Lukács et al. 2021a).

Thickness:

The formation thickness is variable, from less than a meter to tens of meters on the surface (Demjén, Sirok, and around Tar 30–50 m), while in boreholes it was interpreted to reach even >100 meter in thickness (around Demjén it was assumed to reach >150 m; in the Tar boreholes ~100 m). The thickest deposition is assumed to be found around Demjén.

Stratigraphic position:

In the Bükkalja region, the underlying formation is mostly the Bogács Dacite Lapilli Tuff Formation or the Tihamér Formation (Fig. 2). Between the Bükk and Mátra, as well as in the Nógrád Basin and the Cserhát area, it mostly covers Karpatian–Badenian marine sedimentary layers (Garáb Schlier or Baden Formation) or the Hasznos Volcaniclastite of the Mátra Complex (Gál et al. 2020). In the Mátra Mts., it occurs between volcanic formations with andesitic composition (Hasznos Volcaniclastite and Nagyhársas Andesite Formation). The formation is overlain either by the Nagyhársas Andesite (Mátra, Cserhát), or the Harsány Rhyolite Lapilli Tuff (Bükkalja) or a thick volcanoclastic series similar to the Nagyhársas Andesite, but without lava formations and variable, as well as having a dominant andesitic compositon, sometimes with thicker or thinner dacitic pyroclastic intercalations (between the Bükk and Mátra Mts.; Fig. 2). Correlated distal tuff occurrences, often showing fluvial or marine redeposition are mostly observed within marine sedimentary formations; e.g., within the Budafa Formation in the Mecsek Mts. (Hámor 1970); in the Fót Formation in the Berhida, Bh-3 borehole (Kókay et al. 1991); in the vicinity of Sámsonháza (Hámor 1985) and near the village of Balaton (in boreholes; Radócz, unpublished manuscript).

Age: Middle Miocene; Badenian; 15.1–14.8 Ma.

The most accurate age data of the Tar Fm. was obtained by zircon U–Pb ID-TIMS dating (14.880±0.014 Ma; the Nagyeresztvény quarry representing the Demjén ignimbrite unit) completed by zircon U–Pb LA-ICP-MS (from 15.1±0.2 to 14.9±0.2 Ma) geochronology including the Tar stratotype locality (Lukács et al. 2015, 2018, 2021a; Figs. 1, 2). The Badenian age is supported by intercalated sediments with Badenian fauna. Paleomagnetic rotation determined from several places corresponds mostly to the recent one with reverse polarity, while in some cases they show transitional values to directions typical for the Bogács Dacite Lapilli Tuff (Márton & Márton 1996; Márton & Pécskay 1998; Márton et al. 2007a). The new ages of the Demjén ignimbrite unit together with its reverse paleomagnetic polarity (Márton et al. 2007a) indicate that the deposition time falls within the short C5Bn.1r subchron (15.034–14.888 Ma; interpreted by Lukács et al. 2018; Fig. 2). The oldest faulting observed in this formation seems to have been marked by ESE–WNW extension, which is different from the fractures and stress field in the Bogács Fm. (Fig. 2) (Márton & Fodor 1995; Petrik et al. 2016).

Occurrence:

Proximal (lapilli tuff) occurrences are in the western part of the Bükkalja volcanic field (around Demjén, Fig. 1) along the northern and north-eastern margin of the Mátra Complex and in the Nógrád–Cserhát area (Fig. 1.). Distal rhyodacitic–dacitic tuff occurrences were identified and correlated in the Borsod Basin, the Transdanubian Mountains, and the Mecsek Mts. in the Badenian succession (ESM). In addition, a large number of boreholes has penetrated the Tar Fm. in the Great Hungarian Plain.

Harsány Rhyolite Lapilli Tuff Formation/Harsányi Riolit Lapillitufa Formáció

Prelude:

Whithin the Miocene silicic pyroclastic deposits, the upper rhyolite tuff horizon was defined as having formed during the Sarmatian (Jámbor 2008). In the Cserhát area, Hámor (1985) classified it as the Galgavölgy Rhyolite Tuff Formation. In the Bükkalja area within the three-folded subdivision system, Szakács et al. (1998) defined their upper tuff complex as the representative of the upper rhyolite tuff horizon. Póka et al. (1998) and Harangi et al. (2005) pointed out, however, that it can be further subdivided into two compositionally-distinct units found principally at Demjén and Harsány, respectively. Lukács et al. (2007, 2009) studied the latter one in detail and informally defined the Harsány ignimbrite and reconstructed its petrogenesis. Based on the K–Ar radiometric ages (Márton & Pécskay 1998; Lukács et al. 2007, 2010), biostratigraphic data, and the results of the latest geological mapping in the Bükk Mts. (1996–2002), additional new lithostratigraphic units were suggested (Gyalog & Budai 2004) – they are the Harsány Rhyolite Tuff Formation (Badenian–Pannonian, in the BVF by Pentelényi 2005), Lénárddaróc Rhyolite Tuff Formation (Late Badenian–Sarmatian) and the Felnémet Rhyolite Tuff Formation (Badenian–Sarmatian). Formerly, all of these were considered part of the upper rhyolite tuff horizon or Galgavölgy Rhyolite Tuff Formation (Hámor 1998, Jámbor 2008), although their suggested formation age ranged from the Badenian to early Pannonian (Fig. 2).

Within the Harsány Rhyolite Tuff Formation of the BVF, three members were defined: Badenian Kőkötőhegy Member having mostly primary pyroclastic rocks; Sarmatian Bábaszék Member containing mostly reworked pyroclastic materials and tuffites and the early Pannonian Szorosvölgy Member having only reworked volcaniclastic deposits, tuffites and diatomite (Pentelényi 2005). The Lénárddaróc Formation (Radócz 2004) represents rhyolitic pyroclastic rocks occurring in the West Borsod Basin and possibly have Late Badenian to Sarmatian age (without radiometric ages). Its best outcrop is in Lénárddaróc, the Kakarcsó Hill described by Fodor et al. (2005). The Felnémet Rhyolite Tuff Formation was defined by Pelikán et al. (2005) and a short description was given in Gyalog & Budai (2004). This formation comprised all rhyolitic and dacitic primary pyroclastics (welded lapilli tuff, tuff) that were intercalated with tuffites (tuffaceous sandstone, conglomerate, mudstone) of Badenian and Sarmatian age occurring in the western foothills of the Bükk Mts. and between the Mátra and Bükk Mts. (Fig. 1).

The principal aim of the lithostratigraphic unit revision was to integrate our latest knowledge on these rocks and simplify the stratigraphic divisions. In the revision, we grouped all the previously mentioned, mostly Badenian rhyolitic primary pyroclastics and their directly-related, reworked volcaniclastics into the Harsány Rhyolite Lapilli Tuff Formation, since they were usually inseparable in the field and share common lithological features. Tuffites and volcanic sedimentary rocks younger than the Badenian were classified into the Sajóvölgy Formation.

Origin of the name, stratotypes:

The geographical name of this formation was first introduced by Pentelényi (2005), based on his geological mapping works. He described several outcrops around the village of Harsány in the eastern part of the Bükkalja volcanic field (Fig. 1). A large abandoned quarry showing the typical rhyolitic pumice-rich lapilli tuff (ignimbrite; Lukács et al. 2007, 2009) of the formation occurred in the northern part of the village of Harsány, but later the quarry was entirely recultivated. However, a similar, well-exposed occurrence was later described in the western part of Tibolddaróc (Lukács et al. 2007, 2015), which is still accessible and therefore suggests here as serving as the stratotype of the Harsány Fm. (Figs. 1, 5f, g, ESM). The accretionary lapilli-bearing pyroclastic flow deposits of the Harsány Fm. are best exposed at the Kakarcsó Hill, west of Lénárddaróc (Fodor et al. 2005); therefore, this locality can be used as an additional stratotype showing this specific facies of the lithostratigraphic unit (Fig. 1, ESM).

Definition, description:

The formation contains greyish white, high-silica rhyolitic (SiO_2>70 %), pumice-bearing lapilli tuff (ignimbrite), subordinate tuff, and associated secondary volcaniclastics (reworked pyroclastic deposits; Fig. 5). The pumices and the matrix contain quartz, Na-rich plagioclase, biotite, subordinate sanidine as phenocrysts, and accessoric zircon, apatite, allanite and Fe–Ti oxide minerals. Lukács et al. (2009) identified two types of pumices (A-type and B-type) in the outcrops of Tibolddaróc and Harsány that mingled during the volcanic eruption (Fig. 5h, i). They show distinct bulk rock, glass, and biotite major and trace element chemical compositions (Fig. 4), where the A-type pumices represent the dominant magma type. In the B-type pumices, orthopyroxene is occasionally found. Zircon trace element composition is also diagnostic for the Harsány Formation. The Harsány ignimbrite was formed by large Plinian-type explosive volcanic eruptions, which could have produced several pulses of pyroclastic flows, as well as ash-fall events. In the Bükkalja near Tibolddaróc and Harsány (Fig. 1), the pumice size reaches 30–40 cm, implying a proximal setting. In certain pyroclastic ash-flow deposits (e.g., Lénárddaróc, Szentkút; Fig. 1), segregation pipes and accretionary lapilli are common (Fodor et al. 2005; Lukács et al. 2021a), suggesting wet ash condition, possibly related to phreatomagmatic eruption. In Tibolddaróc, below the typical Harsány ignimbrite, tuff and lapilli tuff layers (together in ~1.5 m thickness) occur having a similar mineral assemblage and chemical composition to the Harsány ignimbrite, and they form the lowest part of the HRLTF (Lukács et al. 2007, 2015).

The pyroclastic deposits contain various lithic clasts, mostly rhyolitic (often perlite/obsidian) and fewer dacitic and andesitic fragments. Volcanic center(s) are not known; however, it is inferred from clast size distributions and thickness data to be east of Miskolc (Fig. 1), which is east or northeast from the Bükk Mts. (Lukács et al. 2010). Deposition of the pyroclasts possibly occurred mainly subaerially, although shallow marine deposition (e.g., Szentkút; Fig. 1) and reworking/preprocessing were also identified.

Thickness:

Thickness of the formation is variable, from tens of metres (at the surface) to possibly several 100 meters according to borehole data and seismic reflection data interpretations (e.g., Nyékládháza-1, Nya-1, Mezőkeresztes, Mk-1; Mezőnyárád, Mn-1; Emőd, Em-1; Fig. 1, Lukács et al. 2010; Petrik 2016).

Stratigraphic position:

In the Bükkalja as well as southward in the Vatta–Maklár graben (ESM), the underlying formations are either the Bogács Dacite Lapilli Tuff Formation or the Tar Dacite Lapilli Tuff Formation, and rarely the Tihamér Formation or their intercalating sedimentary formations (Fig. 2). In the Cserhát area (e.g., Szentkút; Fig. 1), pyroclastic rocks of the Harsány Formation are intercalated within the Badenian Lajta Limestone and can be found as tuffs, lapilli tuffs, and reworked tuffs also within the andesite-dominated volcanoclastic series above the Tar Formation (Fig. 2). The formation is covered by Sarmatian and/or early late Miocene (Pannonian) sedimentary formations (e.g., Sajóvölgy Fm., Kozárd Fm., Endrőd Marl Fm.; Fig. 2). The upper part of the Harsány Fm. often contains reworked pyroclastic materials or have interlayered sedimentary beds (accretionary lapilli-bearing tuff, tuff, tuffaceous sandstone, siltstone, diatomitic tuffite), whose paleontologic record suggests Badenian age (former Kőkötőhegy Member of Harsány Rhyolite Tuff F; Pentelényi 2005). It is overlain by reworked rhyolitic ash-bearing volcanic sandstone, which is tuffaceous sandstone having Sarmatian and Pannonian fossil assemblage. Although Pentelényi (2005) considered these latter units to be different members of the Harsány Fm. (former Bábaszéki and Szorosvölgy Members of the Harsány Rhyolite Tuff Fm.; Pentelényi 2005), they can be regarded as part of the Sajóvölgy Formation, dominated by variable clastic sedimentary rocks.

Age: Middle Miocene; Badenian; 14.7–14.4 Ma.

The accurate formation age of the Harsány ignimbrite was determined by zircon U–Pb ID-TIMS and sanidine Ar–Ar geochronology (14.361±0.016 Ma and 14.358±0.015 Ma ages, respectively; Lukács et al. 2018). Additional occurrences within and outside the Bükkalja (e.g., Szilvásvárad at West Borsod Basin and Szentkút, Vadász-gödör in Nógrád, Fig. 1) were dated also by zircon LA-ICP-MS technique and this provided a similar result (14.3±0.2 Ma and 14.2±0.2 Ma; Lukács et al. 2015, 2018, 2021a, Fig. 2). The similar ages and the similar chemical composition and petrology suggest a common eruption event with several eruption phases. This is named the Harsány ignimbrite eruption unit (Lukács et al. 2018, 2021a). This large ignimbrite-forming eruption was preceded by smaller explosive eruption events as represented by the tuff and lapilli tuff beds beneath the Harsány ignimbrite at Tibolddaróc (Tiboldaróc E-F unit, 14.7±0.2 Ma, Lukács et al. 2018, ESM) and the upper layers of the borehole Mezőnyárád, Mn-2 (samples from 1263–1268 m and 1184–1189 m depths) and the drilling cores of the Szekrény-völgy boreholes (e.g. Szv-3) at Tard (samples from 200.3–204 m and 243.7–250 m depths, Lukács et al. 2015; Fig. 1). Note that the former K–Ar ages for the Harsány ignimbrite showed younger data (13.65±0.72 Ma and 13.35±1.01 Ma; Lukács et al. 2007), possibly because of Ar-loss (Fig. 2).

Most of the paleomagnetic data indicate declinations close to the present north (Márton & Márton 1996; Márton et al. 2007a). However, a few sites may show 15–30° CCW rotations, although the unequivocal correlation of paleomagnetically-sampled sites and radiometrically-dated locations has not been carried out yet.

Most of the fault slip data indicate extensional to transtensional deformation that are estimated to be younger than the early Badenian (ESE–WNW to SSE–NNW extensional stress axis fields, Fodor et al. 1999; Fodor et al. 2005; Petrik 2016; Petrik et al. 2016). The Szilvásvárad site appears to represent an outlier where the earliest deformation could belong to the main rifting phase (ENE–WNW extension, early to middle (?) Badenian, Beke et al. 2019) (Fig. 1).

Occurrence:

Rhyolitic pyroclastic rocks overlying the Bogács and Tar Formations in the BVF and its surroundings (from Sirok to Miskolc) can all be placed in this formation. In the western Borsod Basin, some occurrences also belong to this formation (e.g., Lénárddaróc, Szilvásvárad, Fig. 1; Fodor et al. 2005; Pelikán et al. 2005; Beke et al. 2019). Scattered pyroclastic deposits in the Mátra and eastern Cserhát (Fig. 1) can also be classified into this unit.

Stratigraphical importance and correlation potential

The large volume explosive silicic eruptions in the Pannonian Basin produced thick proximal deposits, as well as distal layers reaching several hundreds of kilometres away from the centres. Rocholl et al. (2018) and Lukács et al. (2018) summarized the chronostratigraphic correlation opportunities between several far-distal volcanic ash deposits in central and southern Europe with proximal volcanic occurrences in the Pannonian Basin. Lukács et al. (2021a) provided additional results and a correlation between distal and proximal deposits in Northern Hungary. More recently, several new publications (e.g., Rybár et al. 2019; Brlek et al. 2020; Sant et al. 2020; Danišík et al. 2021) reported Miocene distal silicic pyroclastic occurrences in the surroundings of Hungary and even farther than were proposed to link with the early- to mid-Miocene silicic volcanic formations of the Pannonian Basin. The high-precision Ar–Ar and zircon U–Pb data complemented with geochemical data proved to be powerful tools for finding the appropriate correlations between the proximal and distal occurrences (e.g., Lukács et al. 2015, 2018, 2021a; Rybár et al. 2019; Brlek et al. 2020; Šarinová et al. 2021). Glass trace element (Harangi et al. 2005) and zircon trace element compositions discriminate the main eruption units (Lukács et al. 2021a; Fig. 4) of the BVF well, although pumice and bulk rock data can also be effectively used for it (Lukács et al. 2018, Fig. 4).

The revised lithostratigraphic system for the early- to mid-Miocene silicic pyroclastic formations in Hungary presented in this paper could help link volcanic occurrences found in the nearby countries. Since they occur mostly as intercalations in sedimentary successions, for the most part, no unique formation names have been given to them. The oldest Miocene pyroclastic beds in Southern Slovakia are found in the terrestrial sedimentary succession called the Bukovinka Formation (Vass 1983). This is equivalent of the Zagyvapálfalva Formation in Hungary, which underlays the oldest silicic pyroclastic horizons. Thus, the tuff beds of the Bukovinka Formation can be correlated with the Tihamér Formation. Vass et al. (2006) and Márton et al. (2007b) noted that different paleomagnetic rotations were obtained for the pyroclastic rocks at Ipolytarnóc and for the surrounding areas (Fig. 1). Therefore, they distinguished the volcanic products at Ipolytarnóc as the Fehér hegy Formation and regarded it to be younger that those in the nearby areas (classified into the former Gyulakeszi Fm.). More recently, Hencz et al. (2021) described pyroclastic fall deposits in the Bükkalja volcanic field that has similar paleomagnetic properties to the Ipolytarnóc volcanic rocks. In the BVF, these rocks belong to the Eger ignimbrite unit within the Tihamér Formation. Since Lukács et al. (2021a) pointed out that the pyroclastic rocks at Ipolytarnóc have the same age and geochemistry as the Eger ignimbrite, they are thus the oldest in the area, and the paleomagnetic difference can be also solved by remagnetization as suggested by Hencz et al. (2021) for the BVF rocks (Fig. 2). Nevertheless, both units were incorporated into the newly-defined Tihamér Formation, which thus includes the so-called Fehér hegy Formation as well. Thin tuff beds in the Laksáry Formation (Danube Basin, Slovakia) and in the Celovce Formation (East Slovakian Basin), as well as occurrences in the Daranovac Fm (N. Croatian Basin, Brlek et al. 2020) may also be correlated with the pyroclastic rocks of the Tihamér Formation (ESM). The Badenian Tar Formation includes the pyroclastic deposits of one of the largest explosive eruption events in the Carpathian–Pannonian Region. The distal deposits of the 14.9 Ma dacitic–rhyodacitic volcanic products can presumably be correlated with distal occurrences around Hungary as interlayered tuff beds, such as in the dominantly clastic sedimentary Haloze Formation in Slovenia and the Bajtava Formation, as well as in the bathyal sedimentary succession of the Modrý Kameň Formation or in the shallow water of the Jakubov Fm. in Slovakia (Vienna Basin, Sant et al. 2020). However, Rybár et al. (2019) and Brlek et al. (2020) also recognised slightly older tuffs in Slovakia, in the Devínska Nová Ves Fm. and in Croatia in the Vejalmica Fm. with an Ar–Ar age of 15.23±0.04 Ma and 15.34±0.32 Ma, 15.43±0.32 Ma, respectively. This indicates that the picture is more complicated; therefore, further studies are ongoing. In turn, much less is known about the occurrence of the 14.4 Ma Harsány Formation in the surrounding countries. Nevertheless, silicic pyroclastic rocks with a similar age and chemical composition (Lukács et al. 2015) are found in the Transylvania Basin, where it is called Dej Tuff (Pošepný 1867; Szakács et al. 2012). Although Szakács et al. (2012) argued that the age of the Dej tuff is 14.8–15.1 Ma, de Leeuw et al. (2013) proposed a 14.38±0.06 Ma age based on ^{40}Ar/^{39}Ar dating, whose age fits well with that of the Harsány ignimbrite. In the Styrian Basin, Austria, the tuff of the Florian Fm. has a 14.31±0.27 Ma (Ar–Ar; Sant et al. 2020) age, which is also comparable with the Harsány Fm. Further studies are required to better constrain the correlation of the scattered pyroclastic deposits in which the proposed new lithostratigraphic scheme can provide a solid framework. In such studies, zircon could be a particularly good correlation tool even in case of thorough alteration of the volcanic products (Lukács et al. 2021a).

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