Badenian (middle Miocene) continental paleoenvironment in the Novohrad–Nógrád Basin (Central Paratethys): a volcano-sedimentary record from the Páris-patak Valley in Hungary

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Badeni (középső miocén) folyóvízi őskörnyezet a Palócföldön: vulkáni-üledékes rétegsorok a Páris-patak völgyéből

Összefoglalás

A késő badeniben képződött andezit piroklaszt összletbe két szintben is konglomerátumból, homokkőből és agyagkövekből álló vulkanoklasztos rétegsor települ a Páris-patak völgyében és a környező völgyekben Nógrádszakáltól északra, a magyar–szlovák határ közelében. A vizsgált képződmények a Közép-Szlovákiai neogén vulkáni mező peremén rakódtak le. A vulkanoklasztos üledékek szállítási mechanizmusa és képződési környezete pontos meghatározása érdekében terepi szedimentológiai elemzéseket végeztünk, ennek során megfigyeltük a vulkanoklasztos rétegek fácieseit, többek közt oldalirányú és függőleges szemcseméret-változásokat, üledékszerkezeteket, szöveti és összetételbeli változásokat, valamint a fáciesegyüttesek geometriáját és összefogazódásait. A kovásan cementált vulkanoklasztos rétegek szemcséi uralkodóan andezitek, kb. 5% klasztot tűzkő, kvarcit, gránit, csillámpala, gneisz, tufa (lapillikő) és szenesedett fadarabok alkotnak. A szemcseméret a nagyobb hömpölyöktől a durva kavicson, a nagy- és középszemű homokon át az agyagos kőzetlisztig terjed. A durvaszemcsés fáciesegyüttesbe vastag, durván rétegzett, táblás geometriájú vagy néhány méter széles lencse alakú, főleg szemcsevázú konglomerátumok tartoznak, melyek talpa erozív, s melyben a szemcsék középső (b) tengelye szerinti zsindelyesség gyakori. Ugyancsak előfordulnak az előzőekkel váltakozó kavicsból felépülő táblás keresztrétegzettségű kötegek is. A finomszemcsés fáciesegyüttest keresztrétegzett, kavicsos homokkő és tufitos, agyagos aleurolitlencsék alkotják. Emellett ritkábban, de a homokban előfordulnak sík- és keresztlemezesség, vízkiszökési szerkezetek is. Mindkét együttesben találunk feltépett agyagklasztokat, melyek legnagyobb átmérője az 1 métert is eléri, jelezve, hogy a rétegsorban legalább ilyen vastag pelitrétegek, felhagyott mederkitöltések is lehettek az üledékképződéssel egy időben. A fáciesegyüttesek több helyen is rétegtani szintben éles eróziós talpú, 0,5–4 m vastag, felfelé csökkenő szemcseméretű rétegsorokat alkotnak. Ezek sekély, folyásirányban és kissé oldalirányban épülő hosszanti zátonyokkal feltöltött mederkitöltések, kiterjedt, lapos kavicstakarók és zátonyok üledékei, melyek mozgása áradások legnagyobb sebességű szakaszaihoz köthető. A szemcsék zsindelyessége, a keresztrétegzések dőlésiránya és a kövült fatörzsek irányítottsága jelzi az egykori szállítási irányokat. Az üledék görgetett fenékhordalékként szállítódott ~D, a felső szintben ~Ny felé. Időnként törmelékfolyások is megjelentek. A medrekben mozgó, kisebb keresztrétegzett homoktestek a kis/közepes vízhozamú időszakokban jöttek létre. A szemcseméret változékonysága a vízhozamok gyakori ingadozására utal, a növényi és egyéb gerinces maradványokat is figyelembe véve egy alapvetően nedves éghajlatú időszakban. A területen 4–5 méter mély, közepes méretű, kis kanyargósságú medrek rekonstruálhatóak, melyek a Lysec paleovulkán DK-i peremterületén egy kavicsos, fonatos folyó üledékes rendszerét alkották. A benne felhalmozódó vulkanoklasztos üledék a kitörések közötti nyugalmi időszakokban, leginkább csapadékos éghajlaton a korábban lerakódott piroklasztok átülepítéséből származhat.

Kulcsszavak: késő badeni, őskörnyezet, fonatos folyó, fácieselemzés, zsindelyesség, szállítási irány, Novohrad–Nógrád Geopark, Lysec

Abstract

Two levels of volcaniclastics, comprising conglomerates, sandstones and mudstones, are interbedded with upper middle Miocene (upper Badenian) andesite pyroclastics near the Hungarian–Slovakian border in the distal region of the Central Slovakian Neogene Volcanic Field. Based on the field sedimentological investigations, the facies of the volcaniclastics (e.g., lateral and vertical grain size changes, sedimentary structures, textures, clast composition), their geometry and field relationships are documented herein with the aim of reconstructing the depositional environment. The silica-cemented volcaniclastics are mostly andesite clasts with only ~ 5% being granitoid, quarzitic, and tuff clasts as well

as charred fossil wood fragments. The coarse-grained facies association includes crudely stratified, tabular or lenticular, clast-supported pebble-cobble conglomerates with erosive basal surfaces, b-axis imbrication, alternating with sets of cross bedding. The fine-grained facies association comprises cross-bedded pebbly to medium-grained sandstone and lenses of tuffaceous clayey siltstone with rare horizontal lamination and water-escape structures. Rip-up mudstone clasts, with diametre up to 1 m, are present in both facies associations, revealing the co-existence of abandoned silty palaeo-channel plugs. Facies associations are arranged in several 0.5–4-m-thick, fining-upwards successions that likely formed in shallow channels as downstream to laterally accreting longitudinal bars, extensive gravel sheets and bars that migrated in peak flow during floods. Palaeocurrent indicators (i.e., clast imbrication, direction of planar cross-bedding, orientation of petrified wood logs) show bedload transport by traction currents, initially towards ~S, and later towards ~W. Intermittently debris flows also occurred. Cross-bedded sandstones formed as in-channel transverse bars during medium/low discharge. Variation of grain size shows frequent discharge fluctuations during permanently wet conditions in the late Badenian. The 4–5-m-deep, low-sinuosity channels were part of a high-energy, gravel-bed braided-river system on the south-eastern foothills of the Lysec palaeovolcano. Here, pyroclastics were reworked and redeposited as volcaniclastics during inter-eruption, high-discharge episodes.

Introduction

The upper Badenian (middle Serravallian) volcani-clastic rock succession outcropping north of the village of Nógrádszakál (Hungary) is an epitome of the adage that goes: "geology does not follow political boundaries". This is because, at least in part, the geological makeup in the area, which lies immediately east of the Hungarian–Slovakian border, conforms to that in the Central Slovakian Neogene Volcanic Field (e.g., CHERNYSHEV et al. 2013; *Figure 1A, B*). The upper middle Miocene near Nógrádszakál comprise primarily of pyroclastic andesitic units that are interbedded with subordinate volcaniclastics that range from conglom-erates, sandstones and mudstones. The volcaniclastics are exposed in the picturesque Páris-patak Valley, also dubbed as the "Palóc Grand Canyon", which has been well-known among tourists for decades. The interest in the geological history of the area has grown significantly since the establishment of the Novohrad–Nógrád Geopark in the 2010 (https://www.nogradgeopark.eu/en/novohrad-nograd-geopark). Although the unique lithological characters and mappable nature of the volcaniclastics N of Nógrádszakál has been recognized by HÁMOR (1997), the palaeoenviron-mental setting of these volcaniclastics is debated in the Hungarian geological literature, with some authors sug-gesting a coastal marine (e.g. HÁMOR 1985, TUBA 1985), while others proposing a fully continental, alluvial setting of deposition (e.g., NOSZKY 1923; BOGSCH 1942; BARTKÓ 1952; KORDOS-SZAKÁLY 1984a, b). This study focuses on the field sedimentological investigations pertaining to the genesis of the upper Badenian volcaniclastic rocks exposed

in the Páris-patak and neighbouring valleys, north of Nógrádszakál (*Figure 1*).

Geological background

Separated by the gorge of the Ipoly/Ipel' River, the hilly, forested area N of Nógrádszakál (*Figure 1*) is the geo-morphological and geological continuation of the southern Slovakian mountains (e.g., GAÁL 1905, BOGSCH 1942, NOSZKY et al. 1952, BARTKÓ 1952, BALOGH et al. 1966). The nearest peak is that of the Lysec palaeo-volcano (*Figure 1A*), the K-Ar radioisotopic dating of which gave a late Badenian age of 13.05±0.51 Ma (PÉCSKAY 2012). This age is corroborated by the biostratigraphy of the underlying marine successions in southern Slovakia (e.g., VASS et al. 2005, KOVÁČ et al. 2017, HUDÁČKOVÁ et al. 2020). Forming part of the Central Slovakian Neogene Volcanic Field (e.g., CHERNYSHEV et al. 2013; *Figure 1A*), the intense eruptions of andesitic volcanic material in the Lysec area produced pyroclastics and interbedded volcaniclastics that were deposited initially in nearshore marine and then in essentially continental settings as the Badenian shoreline was displaced southward (e.g., KONEČNÝ et al. 1995, VASS 2002, KONEČNÝ & LEXA 2002, PÉCSKAY 2012, MANDIC et al. 2019, HUDÁČKOVÁ et al. 2020, LEXA et al. 2010). This upper Badenian volcaniclastic succession is termed the Lysec Formation in Slovakia (e.g., KONEČNÝ et al. 1983, VASS 2002, KONEČNÝ & LEXA 2002, HUDÁČKOVÁ et al. 2020), however across the Hungarian border, N of Nógrádszakál, the same rocks have been mapped as part of the Nagyhársas Andesite (e.g., PRAKFALVI 2012,

→**Figure 1.** Location, stratigraphy and sedimentology of the study area
A) Position of the study area within Central Europe and within the middle Miocene regional palaeogeography (modified after ZELENKA et al. 2004, KOVÁČ et al. 2017). B) Simplified geological map of the study area (KUN-JÁGER 1997). Legend same as in C) Base map from Kartográfiai Vállalat 2001, original scale 1:10 000. For the Slovakian geological map, see https://apl.geology.sk/gm50js. C) Geological cross-sections showing the spatial relationship of the two volcaniclastic levels to the other main stratigraphic units in the study area. For location, see B. D) Simplified geological log of the Nógrádszakál–2 deep structural borehole (BH Nsz–2). Adapted from HÁMOR (1985). E) Generalized sedimentary facies log of the two volcaniclastic levels in the study area. Note that the lower level is finer compared to the upper level. For facies codes, see Table I

→**1. ábra.** *A vizsgált terület elhelyezkedése, rétegtani és szedimentológiai felépítése*
A) A kutatási terület földrajzi és középső miocén ősföldrajzi helyzete (ZELENKA et al. 2004, KOVÁČ et al. 2017 alapján). B) Egyszerűsített földtani térkép (KUN-JÁGER 1997) melynek alapja a Kartográfiai Vállalat 2001, 1:10 000 térképe, jelkulcsa C)-vel egyező. A felhasznált szlovák földtani térkép elérhető https://apl.geology.sk/gm50js. C) Földtani szelvények mutatják a két vulkanoklasztos szint és a többi képződmény rétegtani viszonyait. A szelvények nyomvonala a B) ábrán. D) A Nógrádszakál–2 (Nsz–2) szerkezetkutató fúrás által feltárt egyszerűsített rétegsor, HÁMOR (1985) alapján. E) A vulkanoklasztos összlet általános üledékes rétegoszlopa, melyen megfigyelhető, hogy az alsó összlet szemcsemérete valamivel kisebb a felsőénél. Részletes magyarázat a szövegben és a kódokat összegző I. táblázatban
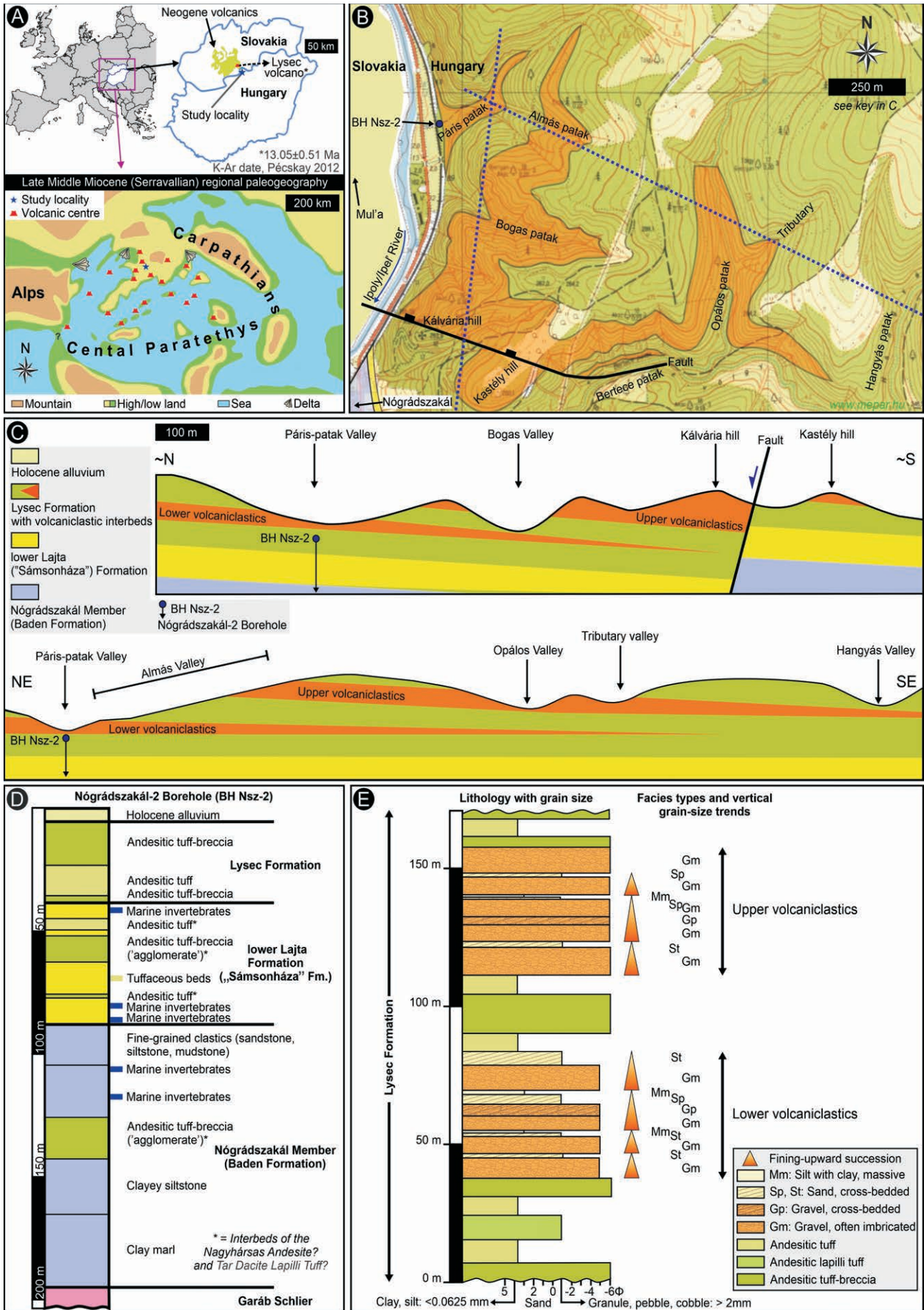
Venczel & Hír 2015), as well as part of the upper Lajta Formation (e.g., Hámor 1985, Prakfalvi 2012). The former is part of the Mátra–Cserhát Volcanic Complex in northern Hungary, which in addition to the main igneous rock units, it also contains marine volcanogenics (e.g., Karátson et al. 2001, Di Capua et al. 2021). Based on K–Ar radioisotopic dating, it appears to be 14.5–16.3 Ma old (Zelenka 2010, Kercsmár et al. 2015), and thus slightly older than the Lysec volcanics. In addition to the direct lithostratigraphic correspondence with the Lysec Formation (see Kun-Jáger 1997 for details), the late Badenian age of the andesitic volcaniclastic succession N of Nógrádszakál is also supported by the biostratigraphy of the unconformably underlying lower to middle Badenian and older rocks (e.g., lower Lajta Limestone Formation, Nógrádszakál Marl Member of the Baden Formation and Garáb Schlier Formation; *Figure 1D*) that were extensively investigated in the vicinity of the study area in boreholes and surface exposures (e.g., Hámor 1985, Hír 2013, Venczel & Hír 2015, Hír et al. 2016). The fossil assemblages in these older rocks are not only age diagnostic but also show the predominantly shallow marine origin of these underlying rocks. In contrast to this, the fossils from the volcaniclastic rock record near the Paris-patak Valley, both from the pyroclastics and volcaniclastics, indicate a predominantly continental origin. Except for rare, reworked, isolated sponge spicules, unidentified shark and batoid teeth that exclusively occur in the oldest volcaniclastic layers, all other fossils in Paris-patak Valley and environs (*Figure 1B*) are remains of unequivocally terrestrial or freshwater organisms (e.g., Gaál 1905, Tuba 1985, Hír 1993). These fossils include diverse late Badenian plants (e.g., *Ginkgo, Tetraclinis, Equisetum, Parrotia, Populus, Ulmus, Salix, Alnus, Ostrya, Pterocarya*, palms and other evergreen species) suggesting gallery-forest as well as riparian conditions in proximity of water (Kordos-Szakály 1984a, b) as well as animals ranging from microvertebrates (frogs, snakes; Hír 1993) to various megaherbivores. The latter fauna comprises the mandibles with molars of a rhinocerotid (*Aceratherium*? or *Hoploaceratherium*? *tetradactylum*? Gaál 1905, Varga 1994, Gasparik M. pers. comm. 2020), a molar of a mammutid proboscidean (*Zygolophodon turicensis*; Schlesinger 1922; Gasparik 2001, 2004) and a molar of an odd-toed ungulate (*Chalicotherium grande*; Hír 1993). While the vertebrate fossils were collected from the volcaniclastics (e.g., Hír 1993), the above-listed plant fossils originate from the pyroclastics (e.g., Kordos-Szakály 1984a). Because of the foregoing and based our primary mapping both in Hungary and Slovakia (see Kun-Jáger 1997), the studied succession is regarded as part of the Lysec Formation herein.

Material and methods

The upper Badenian volcaniclastic succession out-cropping N of Nógrádszakál, in Páris-patak Valley (GPS 48° 11' 40.73"N, 19° 31' 49.04"E) and environs, and in particular its volcaniclastics (chiefly andesitic conglomerates,

sandstones, mudstones) were geologically mapped at metre-scale (*Figure 1B, C*). The extent of the overall study region is ~1.5 km² (*Figure 1B*) in heavily forested area, where the vegetation cover is high all year around, and thus fair-quality exposures are found mainly in incised stream valleys and rarely in hillside sections. The primary data was collected in 1997, and in our recent revisit of the site noted that some of the outcrops have been destroyed or significantly changed due to natural weathering and/or depositional processes. The studied stratigraphic interval is a maximum 200-m-thick volcano-sedimentary succession, which extends from the basal pyroclastics (e.g., andesitic tuff-breccias ('agglomerates'), andesitic tuffs, andesitic lapilli tuffs *sensu* Le Maitre et al. 2002) into the volcaniclastics that occur in two mappable stratigraphic levels (*Figure 1B, C, D*).

This study uses the mature, standard method of qualitative lithofacies classification and analysis based on works by Miall (1978a, 1985, 1988, 1996, 2016). In this standard field sedimentological *modus operandi*, the key sedimentary facies properties of the volcaniclastics, including but not limited to lateral and vertical grain size changes, sedimentary structures, textures, clast composition, as well as the geometry and field relationships of the facies, were documented in field sketches, photographs and representative centimetre-scale sedimentary facies logs. For the qualitative assessment of the sedimentary facies architecture, the fair-quality (but rarely 3-dimensional) exposures of the volcaniclastics were turned into outcrop lithofacies maps, which illustrate on field-drawn outcrop sketches, the spatial distribution of the lithofacies and outline the key sedimentological surfaces in each outcrop. The presence of carbonates was tested regularly with 10% dilute hydrochloric acid. To reconstruct the sediment supply direction (see methods in e.g., High & Picard 1974, Miall 1974, Dasgupta 2002) in the studied stratigraphic interval, a total of 417 palaeocurrent indicators were measured that included clast imbrication (400 data points), planar cross-bedding (10 data points) and petrified wood log orientation (7 data points). Clast imbrication was measured in batches of 25 clasts within one given layer and always on the intermediate (b) axis of clasts as this was the only imbrication direction in them. In case of the fossil wood logs, the strike of their long (a) axis was recorded.

Results

General characteristics

The 100–150-m-thick volcaniclastic succession N of Nógrádszakál contains volcaniclastics in two distinct stratigraphic levels (*Figure 1B, C, E*). The Paris-patak Valley only exposes the lower volcaniclastic level, whereas its tributaries, the Almás and Bogas Valleys, expose both volcaniclastic levels (*Figure 1B, C*). Fair-quality exposures of the upper volcaniclastic level are also found in the Opal Valley and its tributary (*Figure 1B, C*). The grain size in both volcaniclastic levels range from very coarse pebbles and cobbles to clayey silts (*Figures 1D, 2*), with the maximum clast size being 0.8–1 m (the largest clasts are always made up of andesites). Relative
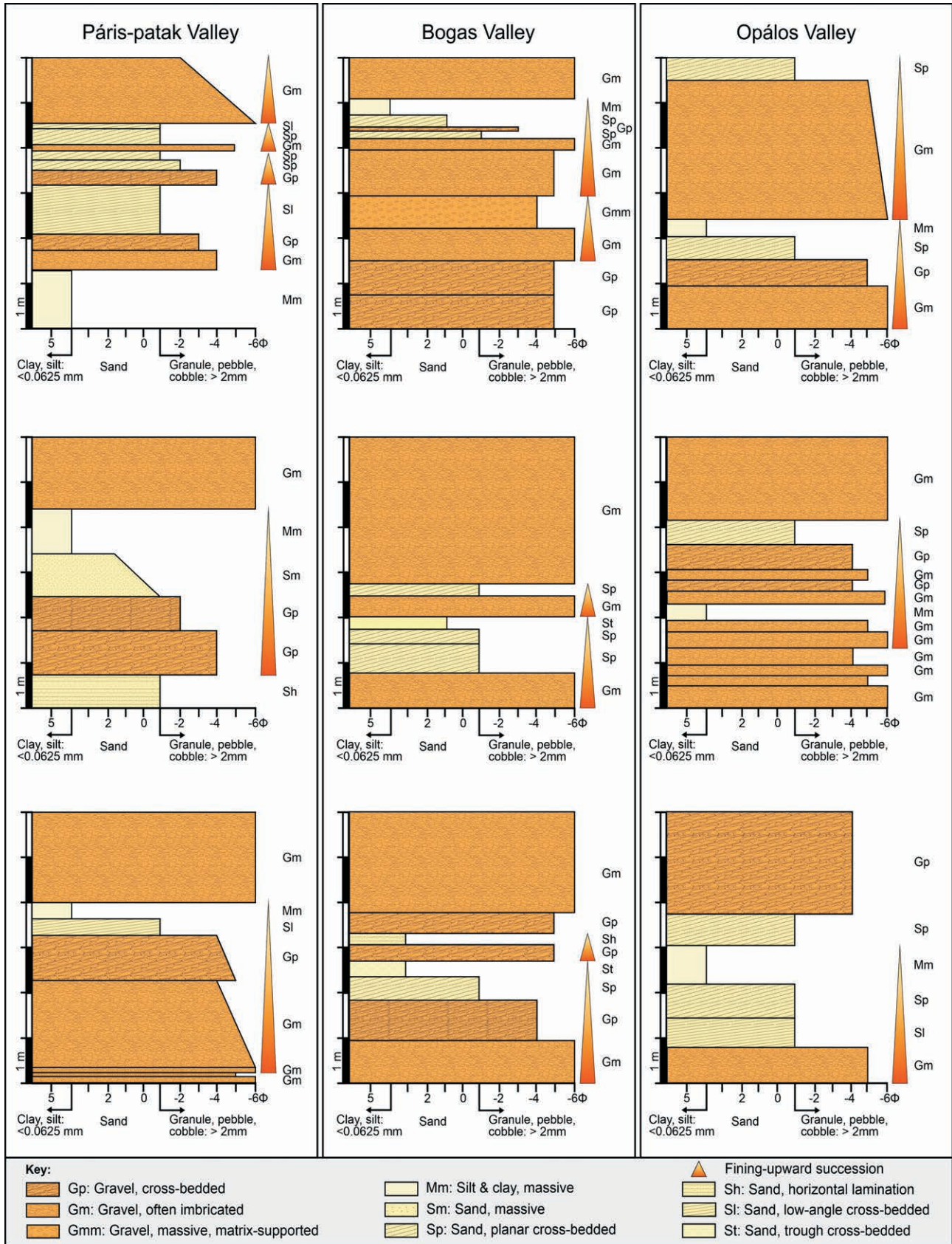
Figure 2. Representative centimetre-scale sedimentary facies logs from the lower (Páris-patak Valley) and upper (Bogas and Opálos Valleys) volcaniclastic level
For location of the valleys, see Figure 1. For facies codes, see Table I

2. ábra. Jellegzetes centiméter-léptékű felvételen alapuló üledékes rétegoszlopok az alsó (Páris-patak völgye) és a felső (Bogas- és Opálos-völgy) vulkanoklasztos szintből
A völgyek helyszínrajza az 1. ábrán. Részletes magyarázat a szövegben és a kódokat összegző I. táblázatban

to the upper level, the abundance of the sandstones is higher and the average clast size in the conglomerates is about two times smaller (average diametre: 4–5 cm) in the lower volcaniclastic level (*Figure 1D*). All layers show limited lateral continuity of a few metres only and no individual layer can be traced across adjacent outcrops irrespective of their proximity to each other. Therefore, the centimetre-scale sedimentary facies logs (*Figure 2*), which were measured in the same volcaniclastic level within a given valley (e.g., Páris-patak Valley or Bogas Valley) cannot be correlated to each other. The sedimentary logs also show that the volcaniclastic levels comprise several, fining-upwards successions that range in thickness from ~0.5 to ~4 m (average thickness ~2 m; *Figure 2*). These successions commence with an erosive, often irregular basal surface that underlies the coarse-grade member in each of the successions. The grain size of the fine-grade member is variable from very coarse, pebbly sand to clayey silt, without an apparent relationship to the thickness of the fining-upwards succession.

Clast composition

The clasts are up to 95% andesites with variable texture, the most common being aphanitic. Other clast types, which are 6–7 cm in size on average, include quartz, chert, quartzite (3–4%) as well as rare granite, mica schist, gneiss and tuff (1–2%). In each valley, granite cobbles and up to 50-cm-diametre boulders are rare but present. Up to 90% of andesite clasts are well or very well rounded, non-spherical and less commonly moderately spherical. The non-volcanic clasts are rounded, and moderately spherical. The quarzitic clasts are smooth (without chatter marks) but poorly rounded and non-spherical. Tuff clasts are always poorly rounded. All conglomerate clasts across the study area are either moderately or poorly sorted; well-sorted clast populations are absent, hence, the conglomerates are submature both texturally and compositionally. Among the quarzitic clasts, rounded petrified fossil wood fragments, which are 4–10 cm in length and black in colour, are also common. Moreover, in both volcaniclastic levels, fossil wood fragments with a blackened outer crust (either charred or coalified) are common; they are typically 20–40 cm long and 5–30 cm in diametre.

In the sandstones and the matrix of the conglomerates, the sand-size fraction is medium- to coarse-grained and predominantly andesitic in composition. The quartz sand content is maximum 15–20%. The mud-size particle content, which was shown to be mostly montmorillonite by Tuba (1985), can be very high, especially in the fine-grained rock types (e.g., clayey siltstones). All rocks types are assumed to be silica cemented, because field-based 10% dilute hydrochloric acid testing did not detect carbonates.

Palaeocurrents

Orientation data from measured palaeocurrent indicators (i.e., dip direction of imbricated clasts' intermediate axis, foresets in planar cross-bedding and strike direction of

the long axis in petrified wood log) is shown in conventional rose diagrams in *Figure 3*. It is worth noting that the petrified wood log data in the Páris-patak Valley is from a cross-bedded conglomerate layer in which the foresets dip direction is perpendicular to the strike of the logs' long axis. This is important, because it suggests that the wood logs were likely transported perpendicular to the flow direction, possibly as bedload, rolling around their long axis. This would be in contrast to the transport mode, for example, in debris flows, where wood logs often (but not exclusively – see Muir et al. 2015 and references therein) get transported with their long axis aligned parallel to the flow direction. As illustrated in the rose diagrams and associated data table in *Figure 3*, the consistency of all palaeocurrent data groups is high and the data is unidirectional. These are parameters in line with low sinuosity fluvial channels typical in braided rivers or braided alluvial fans (e.g., Rust 1972, 1978; Rust & Koster 1984; Steel & Thomson 1983). The palaeocurrent direction in the planar cross-bedding and wood logs (both taken in the Páris-patak Valley) are from the lower volcaniclastic level and suggest a flow direction from ~N to ~S (*Figure 3A, 3B*). All 400 clast imbrication data are from the upper volcaniclastic level and suggest a flow direction approximately from ~E to ~W (*Figure 3D*).

## Facies classification and description

Based on the standard method of qualitative lithofacies classification (*Table I*), the volcaniclastic sedimentary rocks in the study area can be grouped into the following two main facies associations:

(1) Coarse-grained facies association of conglomerates, which accounts for more than 90% of the rock types in the study area (e.g., *Figures 2, 4, 5*);

(2) Fine-grained facies association of sandstones and subordinate clayey siltstones (e.g., *Figures 2, 6, 7, 8*), which shows a higher abundance only locally, mostly in the lower volcaniclastic level, especially in the Páris-patak Valley, where it accounts for 20% of the rock types (*Figures 1D, 2*).

The **coarse-grained facies association** is dominated by conglomerates (*Table I*) that typically occur in tabular, sheet-like beds that can be traced laterally for up to 10 m, across most of the outcrops, which are typically narrow (<10 m wide; *Figures 4A, 5C, 8A, 8C*). It is possible that these beds are more continuous laterally, given that within a given exposure, the beds maintain a fairly uniform thickness. The tabular conglomerates are thus mostly bound by erosion surfaces that are fairly even at the base (*Figures 4A, 7C, 8A, 8C*) and slightly downward dipping at the top, however gently undulating basal erosion surfaces also occur (e.g., *Figure 4F, 4G, 6A*). Lenticular conglomerates are less common (*Figures 4, 5C, 5D, 6A*), and typically occur as 0.5–2 m thick and 3–8 m wides units. Within the lenses, the grain-size often decreases laterally and vertically (*Figure 5*).

The most common facies type in the study area is the massive to faintly bedded, clast-supported conglomerate (facies Gm) that ranges in thickness from 0.5 to 3 m
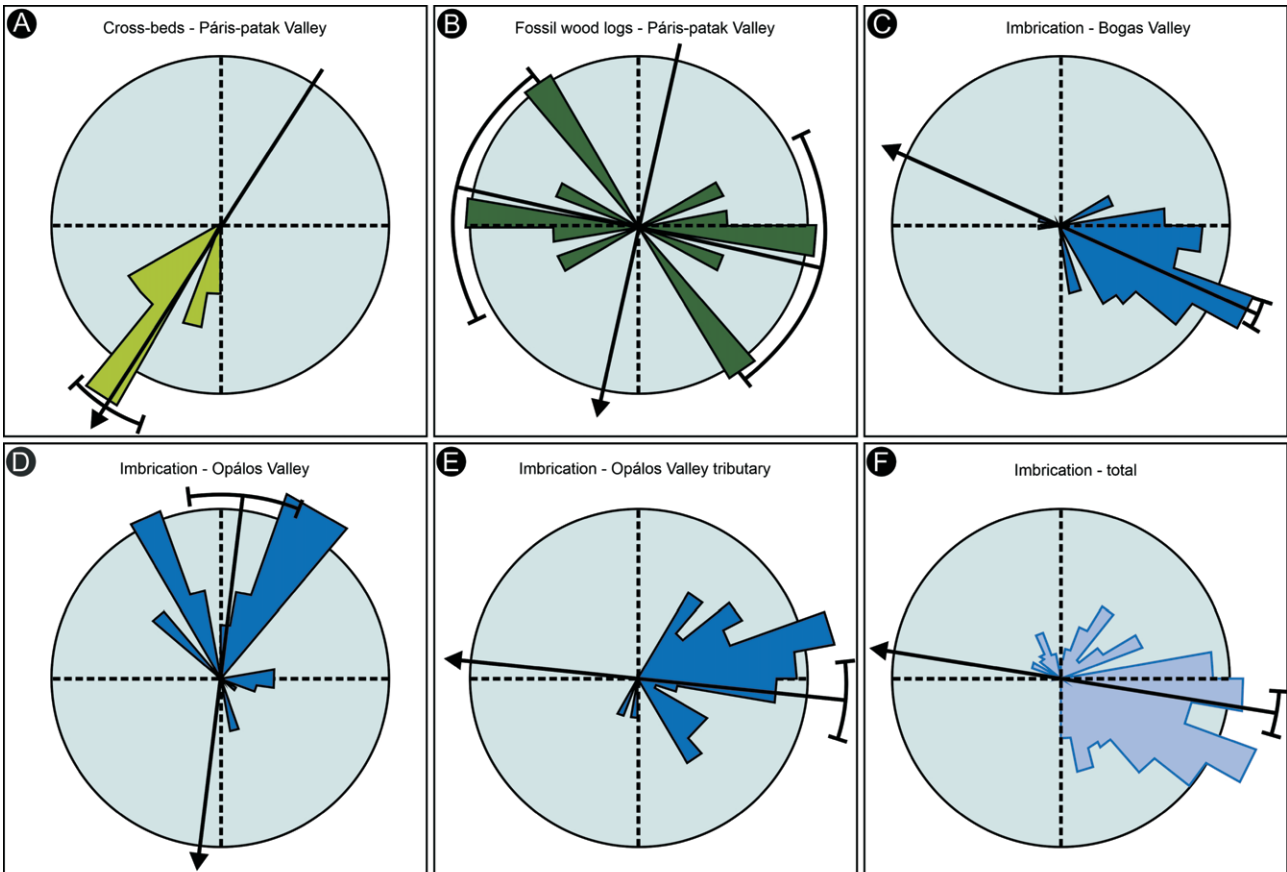
Data collection field sites	**A** – Cross-beds in Páris-patak Valley	**B** – Fossil wood logs (strike) in Páris-patak Valley	**C** – Imbrication in Bogas Valley	**D** – Imbrication in Opálos Valley	**E** – Opálos Valley tributary	**F** – All imbrication data
Population	10	7	225	100	75	400
Maximum percentage	30	28.6	17.3	11	13.3	10.5
Mean percentage	20	20	7.1	3.7	5.3	3.2
Standard deviation in %	7.07	7.38	4.82	2.93	3.31	2.95
Vector mean (degree)	312.88	283.59	113.93 (+180)	6.9 (+180)	95.81 (+180)	98.98(+180)
Confidence interval (degree)	10.16	42.68	3.77	15.47	10.89	5.87
Magnitude of resultant vector	0.96	0.62	0.88	0.48	0.7	0.6

Figure 3. Rose diagrams based on palaeocurrent indicators from the study area
A–B are cross-bed and wood log data from the lower volcaniclastic level, whereas C–F are clast imbrication in facies Gm from the upper volcaniclastic level. Note the different main palaeocurrent direction in the lower vs. upper levels. For statistical details of each dataset, see summary table. For location of the valleys, see Figure 1

3. ábra. *Az üledékszerkezetekben mért szállítási irányok (nyilak) rózsadiagramokon*
A) keresztrétegzés és B) fatörzsek orientációja alapján az alsó vulkanoklasztos szintből, és C–F) Gm fáciesű rétegek klasztjainak zsindelyességéből a felső vulkanoklasztos szintben. Az alsó és a felső szint szállítási irányai közt jelentős eltérés mutatkozik. A statisztikai adatok a táblázatban, a mérések helye az 1. ábrán látható

(*Figures 2, 4–8*). The most common and striking feature of facies Gm is clast imbrication (*Figure 4A, 4B*) that is particularly prominent around larger, very coarse pebbles and cobbles. Imbrication is exclusively along the clasts' intermediate axis. Within a given facies Gm layer, upwards and lateral grain size decrease is present, but not too common (*Figures 2, 5B, 5C, 5D*). Nesting mostly within facies Gm and rarely occurring as individual beds, local-ised patches of matrix-supported conglomerates also oc-cur (facies Gmm; e.g., *Figures 2, 5B*). Although facies

Gmm is rare in the Páris-patak Valley, it is common in the other outcrop areas.

Cross-bedded conglomerates (especially facies Gp, less so Gt) are the second most common rock types in the study area (*Figures 2, 4D, 4E, 4G, 4H, 5, 6C*). They occur in thinner (average 0.5 m) beds compared to those of facies Gm. Lateral and upward reduction in clast size within individual gravel foresets is common (*Figures 4D, 4H, 7A*). It is noteworthy that the upward reduction in clast size in >1-m-thick beds (*Figure 2*) likely resulted from the amal-

Table I. Fluvial lithofacies descriptions and interpretations (modified after Miall 1978a, 1985, 1996) from the studied stratigraphic interval N of Nógrádszakál. Also see Figures 2–8 for the sedimentary facies logs and the facies relationships in the field. Note that the facies codes are indicated on the close-up images and sketches of the outcrops

I. táblázat. A folyóvíz összletekre használatos litofáciesek leírása és értelmezése (*Miall 1978a, 1985, 1996 alapján*) a vizsgált, Nógrádszakáltól északra kibukkanó rétegsorban. V. ö. az üledékes rétegoszlopokkal a fáciesek kapcsolatát bemutató panorámaszelvényekkel, közelképekkel (2–8. ábrák), ahol a fáciesek kódja segíti azok azonosítását

Facies code *Fáciesek kódja*	Facies shown in figure *Fáciesek ábraanyaga*	Description *Leírás*	Interpretation *Értelmezés*
Gm	4A–D, 4F–H, 5B–D, 6A, 6C–D, 7A, 7C, 8A–C	Gravel, clast-supported, massive or slightly bedded. Imbrication very common. Upward and lateral clast size decrease occurs. Forms the coarse member in upwards-fining successions. Contains clayey siltstone rip-up, fossilized wood, andesite, and other rare non-andesitic clasts types. The most common facies. *Szemcsevázú, szerkezetmentes vagy durván rétegzett kavics. Egymást követő rétegek, lencsék többnyire csökkenő szemnagyságúak, a zsindelyesség nagyon gyakori. Feltépett agyagos-aleurolitklasztok, szénült fadarabok, andezit és más ritka exotikus anyagú szemcsék alkotják. Ez a leggyakoribb fácies.*	Forms as longitudinal bedforms in channels, possibly during high magnitude discharge events. Horizontal bedding indicates sustained flow. Roundness of non-andesitic clasts may indicate long travel distances or high energy grinding action in traction currents. *Hosszanti rétegformaként épül medrekben valószínűleg nagy víz- és üledékhozamú események (árvizek) alkalmával*
Gmm	4D, 5B	Gravel, matrix-supported, massive. Rare facies. *Mátrixvázú, szerkezetmentes kavics. Ritkán jelenik meg*	Forms from plastic debris flow during bank collapse, due to renewed channel flow strength. Lack of structures can mean rapid reduction in flow speed and/or sudden sediment overloading and/or "sieve" deposits *Törmelékfolyásból rakódik le, melyet megnövekedett áramlásintenzitás kiváltotta partomlás vagy extrém csapadékesemény okoz. A szerkezetek hiányát hirtelen sebességcsökkenés, gyors lerakódás vagy a kisebb szemcsék utólagos beszűrődése a nagyok közti pórustérbe okozhatja.*
Gp	4C–D, 1E, 4G–H, 5A–D, 6C–D, 7A–C, 8B–C	Gravel, clast-supported, mostly planar, rarely trough cross-bedded. *Szemcsevázú, általában táblásan, ritkán vályúsan keresztrétegzett kavics*	Forms as down-current migrating gravel bars in open channels. *Kavicszátonyok folyásirányú vándorlásával épül nyílt medrekben.*
Sm	4H, 6C, 7A, 7C	Sand, mostly coarse-grained, occasionally medium-grained, with pebbles, massive. Often contains wood fragments. Rare facies. *Szerkezetmentes, kavicsos, főleg nagy-, kisebb részben középszemcsés homok. Gyakoriak a fadarabok benne. Ritka fáciestípus.*	Forms due to mass movements (hyperconcentrated or debris flows) in floods or bank collapse. Alternatively, primary structures destroyed by recent weathering or bioturbation or dewatering as pore water escapes and deforms soft sediment (occurs during fast rates of sedimentation). *Áradásokhoz kapcsolódó tömegmozgás (hipersűrű ár) vagy partomlás üledéke. Az sem kizárt, hogy az elsődleges szerkezetet, az ülepedést követő bioturbáció vagy a pórusfolyadék hirtelen távozása (likvidizációja) tüntette el. Utóbbi gyors üledékfelhalmozódást jelez. Végső soron a jelenkori felszínközeli mállási folyamatok is felülírhatják.*
Sh	4D, 5B, 5D, 6C	Sand, mostly medium-grained, horizontal lamination. Very rare facies. *Síklemezes, középszemcsés homok. Nagyon ritka fáciestípus.*	Forms as plane bedforms in upper flow conditions in shallow water depths. *Szuperkritikus (sebes) áramlási tartománybam, azaz gyorsan áramló, nagyon sekély vízben képződő rétegforma.*
Sl	4C, 6D, 7A, 8A	Sand, mostly coarse-grained, occasionally medium-grained; low-angle cross-bedding (foreset dip angle <10°). Rare facies. *Kis szögű keresztrétegzés (dőlése <10°) főleg nagy-, kisebb részben középszemcsés homokban. Ritka fáciestípus.*	Forms as barforms, scour fills, humpback or washed-out dunes, antidunes. *Lapos zátonyforma, mélyedéskitöltés vagy sebesbe váltó áramlással formált, eltérített düne szerkezete.*
St	4F, 4H, 5D, 6C–D, 7A	Sand, mostly coarse-grained, occasionally medium-grained; trough cross-bedding. Rare facies. *Vályús keresztrétegzés főleg nagy-, kisebb részben középszemcsés homokban. Ritka fáciestípus.*	Forms as down-current migrating sinuous-crested dunes in higher flow velocities than Sp. *Folyásirányban vándorló, hajladozó gerincű dűnék szerkezete, mely csendes áramlási tartománybam, de az egyenes gerincű dűnékhez képest nagyobb sebességű áramlás esetén jön létre.*

Table I continuation
I. táblázat folytatása

Facies code *Fáciesek kódja*	Facies shown in figure *Fáciesek ábraanyaga*	Description *Leírás*	Interpretation *Értelmezés*
Sp	1C, 1E–H, 5A–B, 5D, 6A–D, 7A–C, 8A, 8C	Sand, mostly coarse-grained, occasionally medium-grained; planar cross-bedding. May contain wood fragments and charred wood debris. The most common sandstone facies. *Táblás keresztrétegzés főleg nagy-, kisebb részben középszemcsés homokban. Tartalmazhat fadarabokat és szénült fatörmeléket. A legyakoribb homokfácies.*	Forms as down-current migrating straight-crested dunes (transverse bedforms) in more moderate flow regimes than St. *Folyásirányban vándorló, egyenes gerincű dűnék, keresztzátonyok szerkezete, mely csendes áramlási tartományban, de a hajladozó gerincű dűnékhez képest kisebb áramlási sebesség esetén jön létre.*
Sr	–	Sand, fine-grained; ripple cross-lamination. Extremely rare facies. *Keresztlemezes-aprószemcsés homok. Nagyon ritka fácies.*	Forms from the migration of ripples in a low flow regime. *Csendes áramlási tartományban mozgó áramlásfodrok szerkezete.*
Mm	5B, 7A, 8A–C	Silt-size fines, massive or rarely faintly laminated. Plant fossils are common. Lacks visible bioturbation structures. Desiccation cracks in one outcrop. Rare facies. *Szerkezetmentes vagy ritkán lemezes aleurolit, növénymaradványokkal, lenyomatokkal. Látható bioturbáció nélkül. Egy feltárásában száradási repedésekkel. Ritka fácies.*	Forms from suspension settling in waning floods in abandoned channels or overbank areas. Absence of laminations likely indicates quick deposition (e.g., mudflows) rather than pervasive bioturbation. Subaerial exposure of wet sediment caused drying and cracking. *Állóvízben lebegtetett hordalékból ülepedik árvizek után felhagyott medrekben vagy gáton túli ártéren. A lemezesség hiánya valószínűleg gyors ülepedést (pl. iszapfolyások) jelez, esetleg átható bioturbációt. A nedves pélitek szárazulati kitettsége kiszáradáshoz, felcserepesedéshez vezethet.*

Facies codes: G = Gravel, S = Sand, M = mud, t = trough cross-bedding, p = planar cross-bedding, h = horizontal lamination, m = massive/matrix-supported (context dependent), l = low-angle, r = ripple.

Fácieskódok: G = kavics, S = homok, M = agyag, aleurit, t = vályús keresztrétegzés, p = táblás keresztrétegzés, h = síklemezesség, m = szerkezetmentes vagy mártixvázú (helyzettől függően), l = kis szögű, r = áramlás fodor.

gamation of several bedforms that lacked clear bedding planes. Moreover, intercalation of gravel foresets with coarser and finer clasts (with the latter often being sandy) is also present (*Figure 4D, 4E, 4H*). Locally, the forests are tangential to the basal erosional bounding surface of the beds (*Figure 4H*). Foreset inclination is 20–30 degrees (i.e., in *Figures 4D, 4H, 5B* inclinations in Gp is vertically exaggerated).

The **fine-grained facies association** is dominated by coarse-grained and less commonly medium-grained, often pebbly sandstones (e.g., *Figures 4E, 4H, 5D, 6B*) and clayey siltstones (facies Mm; *Table I, Figures 2, 4–8*). It usually forms <1 m thick (maximum ~2.3 m), either tabular or more commonly lenticular beds especially in the upper member of fining-upwards successions (*Figures 2, 5–8*). It may also occur as isolated, shallow lenses within facies Gm (*Figure 4F*) and at the contact of facies Gm and Gp (*Figure 4H*). Planar cross-bedding (facies Sp) is by far the most common facies type in the sandstones, however trough cross-bedding (facies St), low-angle cross-bedding (Sl), horizonal lamination (facies Sh) and massive sandstones (facies Sm) also occur (*Figures 2, 4–8*). Facies Sm is dominant in association with water-escape structures (*Figure 7*) as well as with

petrified fossil wood fragments and rip-up siltstone clasts (*Figure 5B*). Ripple cross-laminated sandstones (facies Sr) are exceptionally rare.

In facies Sp, the foreset inclination is 15–20 degrees, and intercalation of coarse- to very coarse-grained, often granular and medium-grained foresets is also present. Within one outcrop area, the foreset dip direction is unimodal, and although foresets in adjacent beds can be directed in strongly diverging directions (e.g., *Figure 4F*), but never in opposite directions. In the Opál Valley, coarse-grain size, charred wood debris (*Figure 8A*) occurs along foreset laminae in a planar cross-bedded, coarse-grained sandstone (facies Sp).

Clayey siltstones (facies Mm) are rare, can be sandy, and form up to 1.5–2 m thick, laterally more persistent, tabular (*Figure 8A*) or thinner lenticular beds that show strongly eroded upper contacts (*Figure 8B, C*). The latter geometry is far more common than the former. Most siltstones are massive; horizontal lamination is extremely rare, and when present it occurs in the sandier varieties. Desiccation cracks were only recorded in the railway cutting on Kálvária Hill (*Figure 1B, C*). Ranging in size from few cm to 1.5 m, irregular and angular rip-up clasts of clayey siltstones are
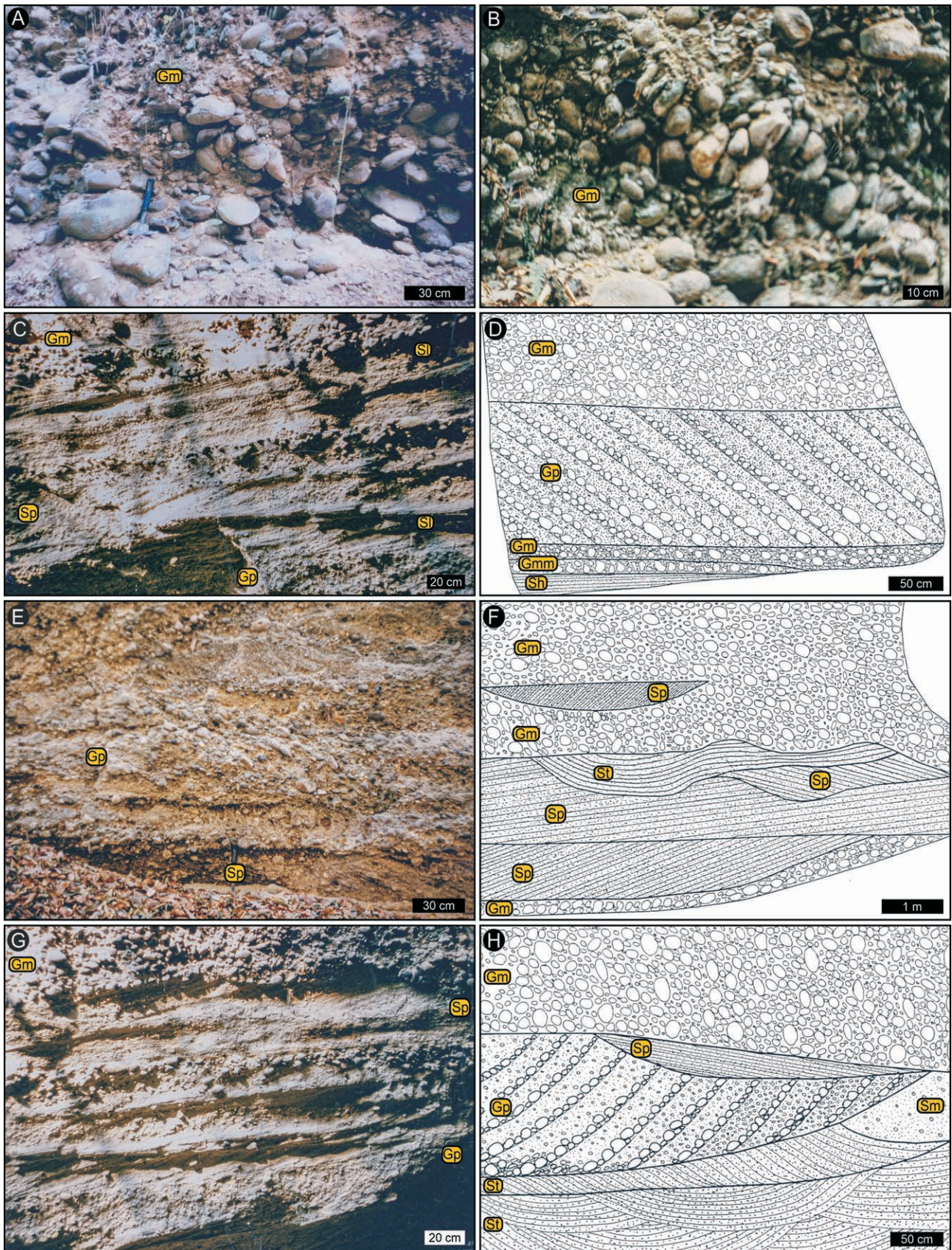
Figure 4. Close-ups of the different facies associations. Coarse- grained facies shown mainly in A–E, whereas fine-grained facies illustrated mostly in grained in F–H
See text for details. For facies codes, see Table I

4. ábra. Változatos homok és konglomerátum fáciesek jellemző váltakozása a durva- (A–E) és finomszemcsés (F–H) fáciesegyüttesekben

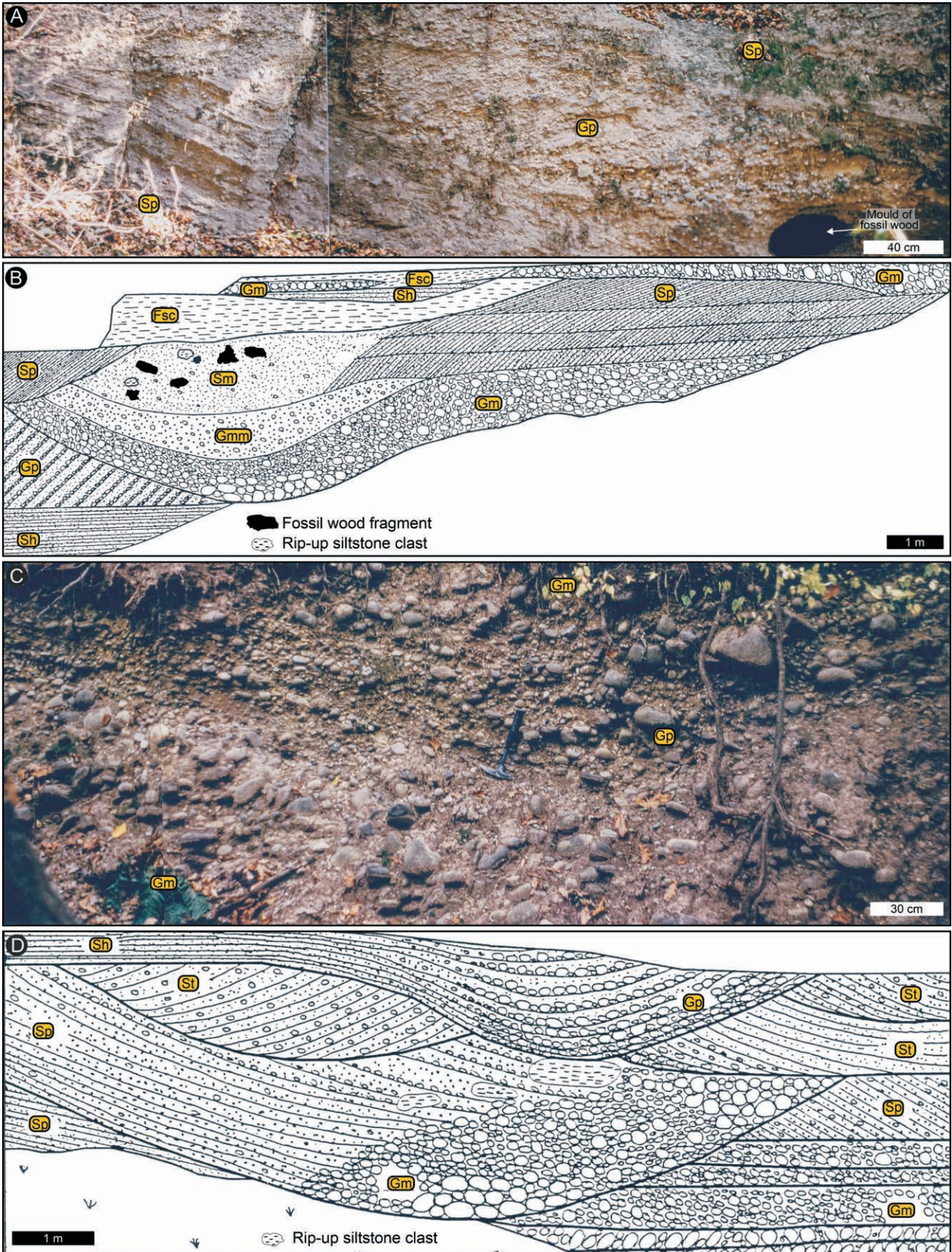*Részletes magyarázat a szövegben és a kódokat összegző I. táblázatban*

Figure 5. Four different examples of lenticular beds in the coarse- and fine-grained facies associations. Fossil wood and rip-up clasts are common in the cross-bedded and massive facies. For facies codes, see Table I

5. ábra. Kisebb-nagyobb lencse alakú testek, több méter mély mederformák a durva- és finomszemcsés fáciesegyüttesekben. Kövült fatörzsek és feltépett agyagkavicsok is gyakoriak a keresztrétegzett és a szerkezetmentes fáciesben is. A fácieskódok magyarázata az I. táblázatban
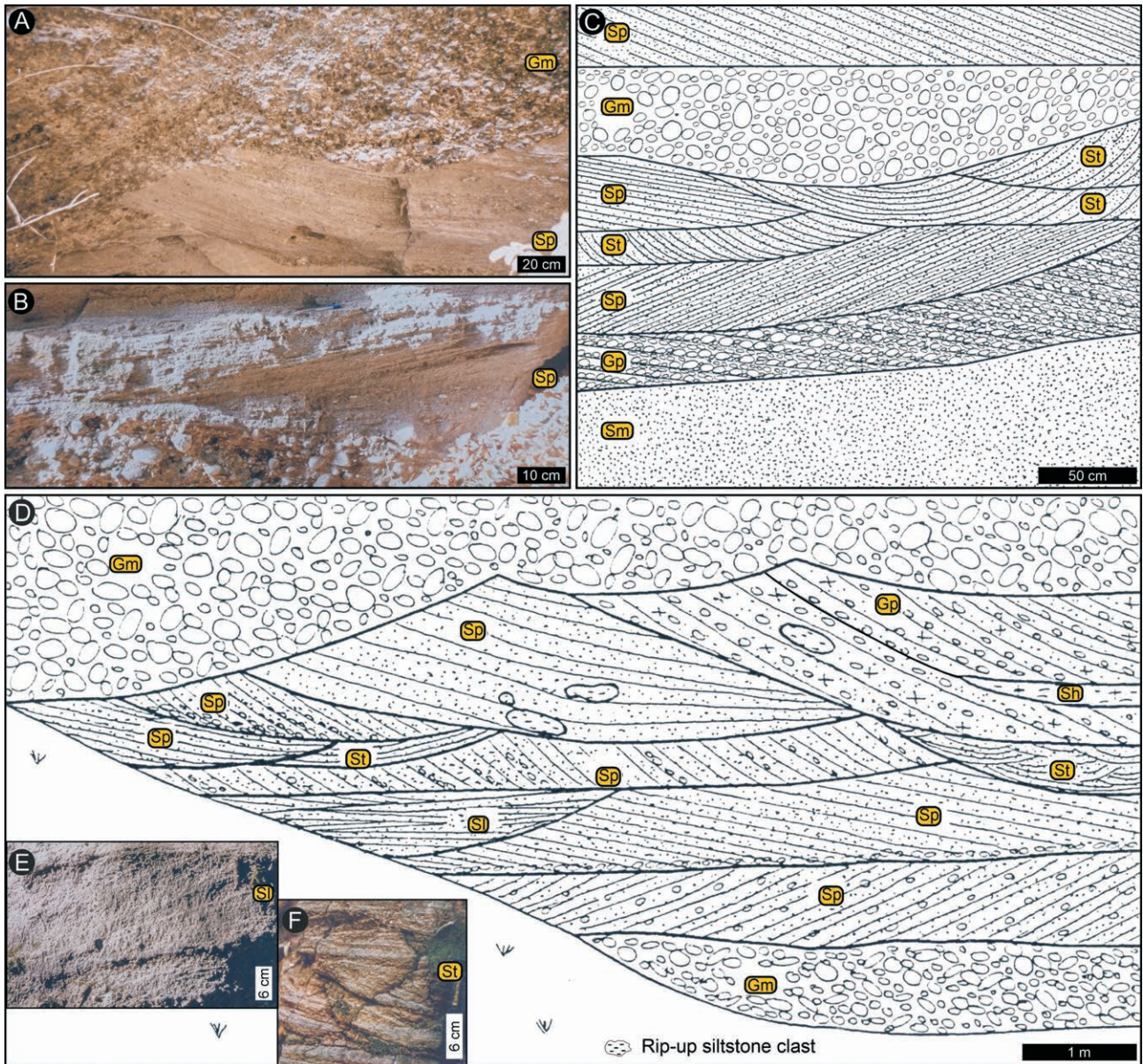
Figure 6. Close-ups of various types of cross-bedded sandy facies from the fine-grained facies association
See text for details. For facies codes, see Table I

6. ábra. Különböző keresztrétegzésű homokfáciesek a finomszemcsés fáciesegyüttesben
*Részletes magyarázat a szövegben és a kódokat összegző I. táblázatban*

common in the cross-bedded conglomerates and sandstones (*Figures 5B, 5D, 6D, 8B, 8C*). Among the volcaniclastic facies types, leaf impressions (*Figures 8D, 7E*) and fossil wood fragments with a blackened outer crust (either charred or coalified) are most common in facies Mm.

Facies interpretation

The following general characteristics of the volcaniclastics N of Nógrádszakál collectively point to an alluvial depositional setting: limited lateral continuity of the beds that prevents their correlation; the lenticular, channel-form bed geometries; the presence of the fining-upwards successions; the textural and compositional submaturity of the clasts; the

smooth, chatter-marks free quarzitic clasts; the high abundance of clast imbrication, sharp erosion surfaces and cross-bedded layers; the unidirectional, high consistency palaeo-current data, and last but not least, the dominance of fossil continental biota (both vertebrates and plant fossils).

More specifically, the conglomerates (facies Gm, Gmm, Gp) in the coarse-grained facies association signal high energy, powerful currents during deposition. In particular, the common, clast-supported facies types (Gm, Gp) are likely products of extensive gravel sheets or bars that migrated in the direction of traction currents. The coarse-grained sediments were carried as bedload during peak flow conditions (RUST 1978, COLLINSON 1996). Typically, such extensive gravel sheets and bars lack internal structures,
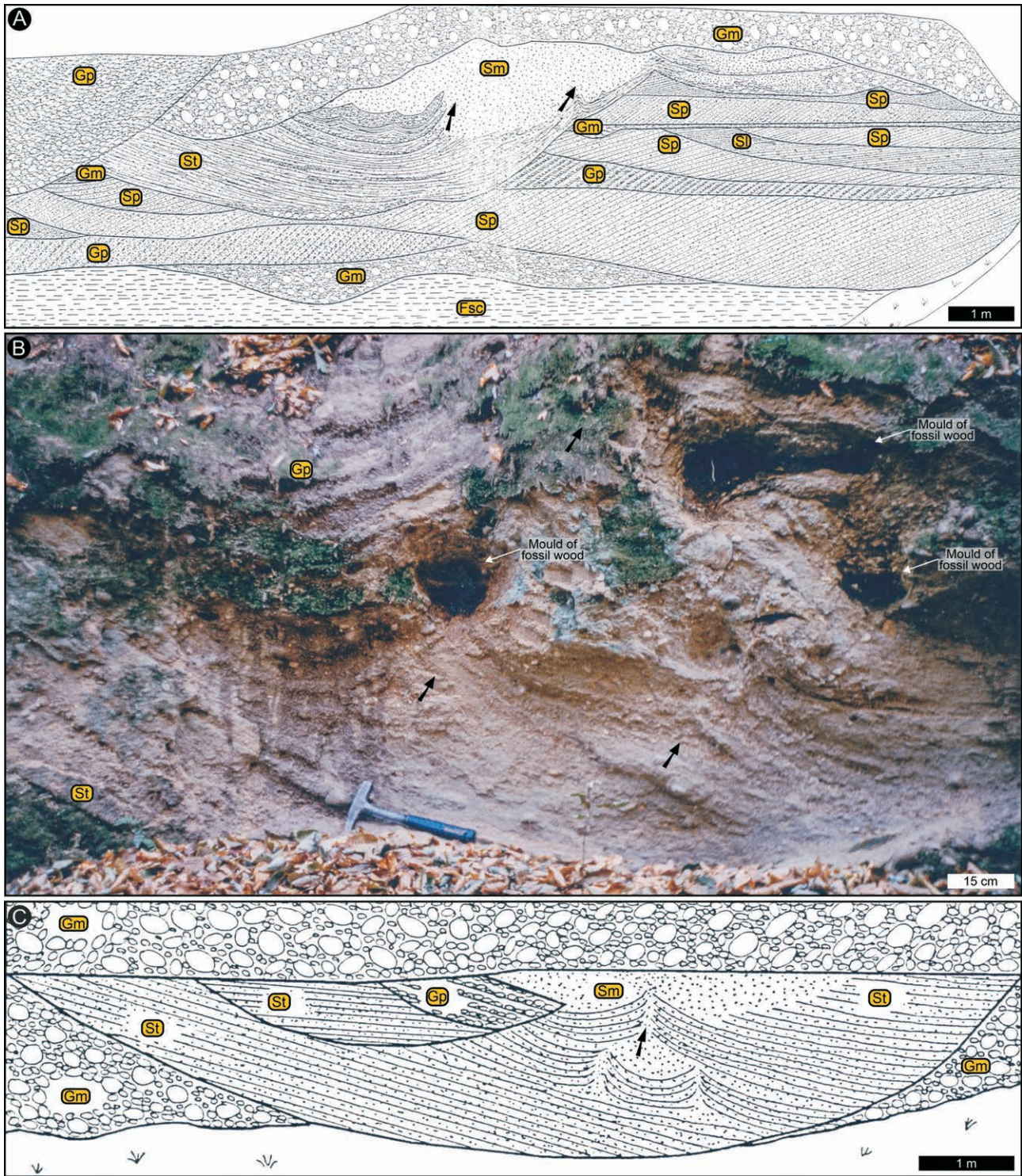
Figure 7. Water-escape structures (marked with black arrows) in cross-stratified (St) and massive (Sm) sandstones of the fine-grained facies association

Note the moulds of fossils wood. For facies codes, see Table I

7. ábra. Vízkiszökési kürtők (fekete nyilak) vályús keresztrétegzettségű (St) és szerkezetmentes (Sm) homok fáciesben a finomszemcsés fáciesegyüttesben. Kövült fatörzsekágak lenyomata is figyelemre méltó

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except for clast imbrication and rare, faint horizontal bedding. Moreover, they often show upward and down-current clast size decrease (SMITH 1974, REID & FROSTICK 1994, COLLINSON 1996). The high abundance of the

erosional surfaces that bound these facies types (e.g., *Figures 4–8*) indicate that the energy level, and possibly the water level too, fluctuated during deposition, conditions that are common during waning flow (MIALL 1996).
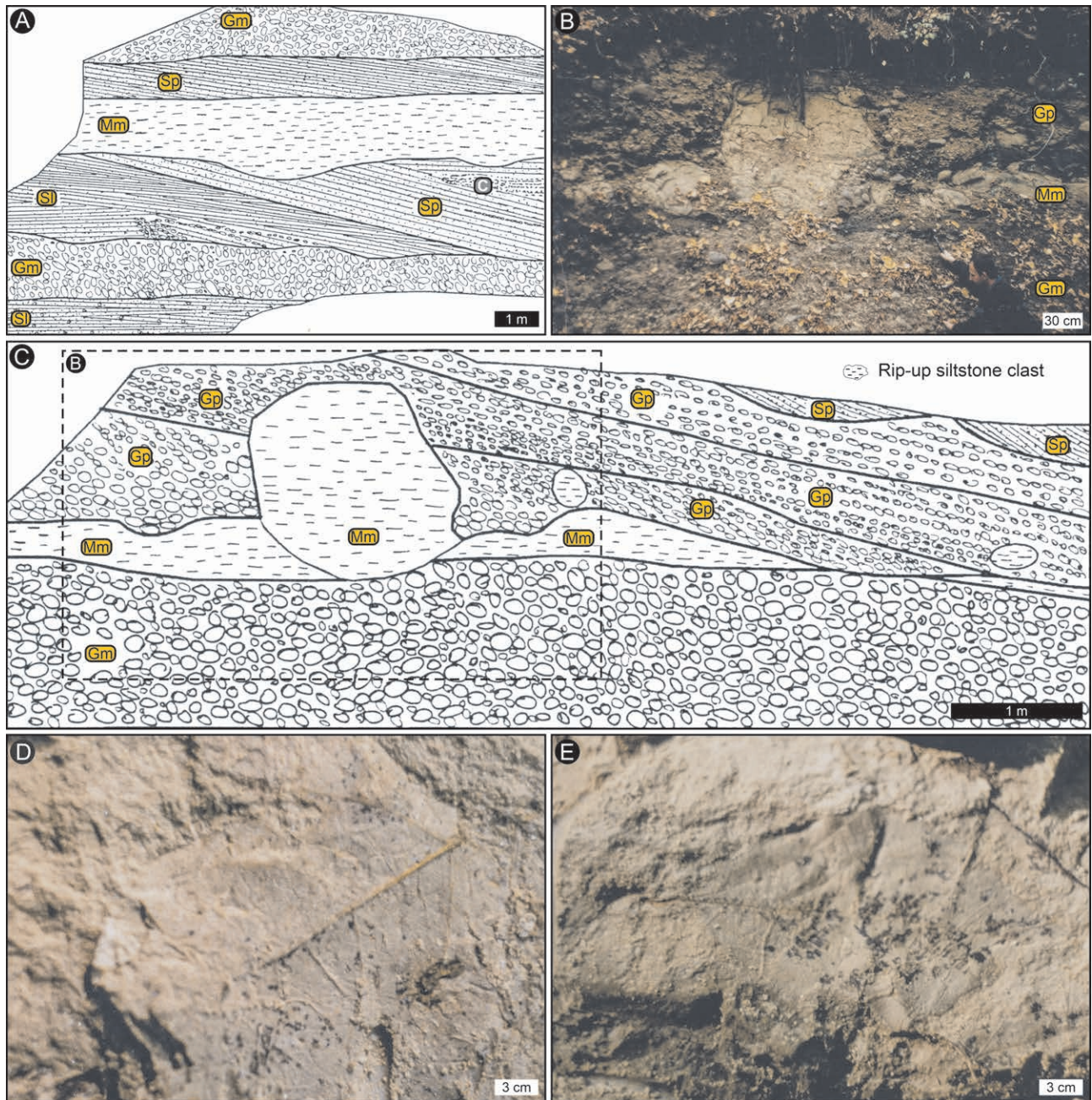
Figure 8. Clayey siltstone facies (Mm) of the fine-grained sedimentary facies associations with charred wood debris (marked with 'C' in A) and leaf impressions (in D and E). Rip-up mud-clasts up to a meter size are shown on B and C

See text for details. For facies codes, see Table I

8. ábra. *Agyagosaleurolit-fácies (Mm) a finomszemcsés fáciesegyüttesben szénült fatörmelékkel („C" jelzi az A) ábrán) és növénylenyomatokkal (D és E). B) és C) méter átmérőjű és kisebb feltépett agyagklasztok*

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Matrix-supported conglomerates (facies Gmm) nested within and interbedded with clast-supported conglomerates (facies Gm) have also been explained with lowering and fluctuating discharge (Steel & Thompson 1983, Reid & Frostick 1994). Facies Gmm may be the product of rapid deposition from mass movements (*Table I*) but could also result from natural sediment sieving processes. This occurs after peak discharge, when the deposition of the coarsest clast fraction is followed by that of the finer (sand, silt) size particles, which can infiltrate among the larger clasts, *in situ* displacing their originally close-fitting clast fabric and decreasing the sorting (e.g., Collinson 1996). Moreover, intercalation of sandy and pebbly foresets in cross-bedded conglomerates (facies Gp; *Figure 4E*) are also evidence for fluctuating discharge (Reid & Frostick 1994). The lenticular conglomerates (*Figures 5, 6*) are interpreted as small- to medium-size channels (see below).

Relative to the coarse-grained facies association, the

sandstones in the fine-grained facies association are interpreted as sediments that originate from moderate energy currents. The cross-bedded sandstone facies (Sp, St, Sl) are considered here as deposits of down-current migrating, in-channel sand dunes that formed under variable, but overall moderate flow strength, typical during lower discharge periods (*Table I*). Because the outcrops are not high-quality, three-dimensional exposures, it is possible that the diverging forests in facies Sp are in fact partially exposed trough cross-beds (facies St), and thus their scarcity is somewhat apparent. Alternatively, the diverging Sp forests may have resulted during waning flow, when flow within the main channel might have bifurcated into shallow and slightly diverging sub-ordinate channels. The preserved maximum thickness of planar cross-beds (~2.3 m) is a reasonable proxy for the minimum height of in-channel bedforms, which in turn can help estimate the palaeo-channel depth. For this, the ratio between the height of sand bars and total bankfull depth in the modern Brahmaputra River is used (Miall 2006). This ratio is ~0.5, which would imply medium-sized, fairly shallow fluvial channels (Miall 2006). This estimated value of ~ 4–5-m-deep channels in the late Badenian is similar to the channel-depth estimates proposed for gravel-bed braided rivers by Lunt et al. (2004). It is worth noting that because in small outcrops the true thicknesses of facies Gm (*Figure 2*) is difficult to ascertain (see *Figure 4F*, where without the sandstones lens, the thickness of facies Gm could be overestimated), and thus using the thickness of the conglomerate beds as channel-depth proxies might be misleading.

Massive conglomerates and sandstones (facies Gmm and Sm; *Table I*), the well-developed water escape abundance (*Figure 7*), the abundance of plant fossils and the extremely rare occurrence of desiccation cracks can be taken collectively to indicate rapid sedimentation in a permanently wet, moist, and overall high energy setting that was rarely if ever subjected to major, persistent dry episodes. The clayey siltstones represent the lowest energy deposition in the study area, which likely occurred during waning flows (*Table I*). Traditionally in fluvial systems (e.g., Miall 1985, 1996), such fine-grained facies are associated with overbank sedimentation or within channel settling of suspended sediment during low discharge periods. The predominantly lenticular, often eroded geometry (*Figures 8B, 8C*) of the facies and its subordinate overall abundance (*Figure 2*) show that facies Mm is likely associated with settling from suspension within channels. The latter configuration is also supported by the occurrence of the facies as rip-up clasts within coarser grained facies (Gp, Sp) associated with higher energy depositional conditions (*Figures 5B, 6D, 8B, 8C*).

Discussion

Based on field sedimentological evidence, the volcaniclastics N of Nógrádszakál originated in a high energy alluvial system where extensive gravel sheets and subordinate finer grained (sandy, silty) layers were deposited within medium-sized, approximately 4–5 m deep, low sinuosity fluvial channels. This high energy alluvial setting was permanently wet, moist, and was subjected to frequent discharge fluctuation but rarely to any persistent desiccation. The fluctuating discharge during the depositional events is also supported by the clast size analysis conducted by Tuba (1985).

Pebble to cobble clast-size populations with the overall characteristics shown in the volcaniclastics N of Nógrádszakál require bedload-carrying, competent transport medium that are common in (but not limited to) steep gradient rivers and on alluvial fans in proximal intermountain regions (Rust 1978, Miall 1992, Cyples et al. 2020). Typically, such high energy channels have low sinuosity and form a braided network of unstable, laterally shifting channels (e.g., Rust 1978, Miall 1992). The mobility of the channels is chiefly driven by the high amount of bedload-transported sediment, which being non-cohesive and sparsely vegetated, becomes repeatedly mobilized and thus impedes the establishment of stabile channel margins (e.g., Rust 1978, Reid & Frostick 1994, Miall 1992, Collinson 1996).

Braided channel networks on alluvial fans and in fluvial systems (including alluvial plains) within the proximal parts of basins deposit sediments with high facies similarity and differentiating their products in sedimentary record remains elusive even if exposed in high quality (i.e., large and 3-dimentional) outcrops (e.g., Rust 1978; Heward 1978; Miall 1978a, b, 1992, 1996, 2006, 2016; Rust & Koster 1984; Bridge 1993; Lunt et al. 2004; Harvey et al. 2005; Sambrook Smith et al. 2006, Hartley et al. 2010, Cyples et al. 2020). In case of alluvial fans, especially in large systems, some of the often cited criteria for their identification are: (1) the abrupt facies changes in proximal-to-distal regions, (2) radial palaeocurrent distribution (i.e., low consistency ratio), and (3) higher abundance of mass movement (debris flow) deposits, especially in the proximal regions (e.g., Rust 1978, Miall 1978b, Rust & Koster 1984, Ventra & Clarke 2018). The volcaniclastics N of Nógrádszakál do not appear to meet the above criteria for alluvial fans, however excluding the possibility that they formed on an alluvial fan is not warranted, because the current data is limited to a small study area that is lacking high-quality exposures. Even though the uncertainty in determining the exact depositional environment remains high with the available data, it is postulated that the low sinuosity channels were likely part of a proximal braided fluvial system rather than an alluvial fan. This assertion is supported by the varied clast composition in the volcaniclastics, which, albeit in low abundance, contain quartz, chert, quartzite, granite, mica schist and gneiss clasts as well (in addition to the omnipresent andesites). It is possible that the rare non-andesitic clasts may have been sourced by igneous processes as xenoliths from pre-Badenian units. However, this mixed clast composition together with the palaeocurrent indicators are better explained with a heterogenic source area to the ~N and ~E of Nógrádszakál, for which there is ample evidence in the geological make-up of those areas (e.g., borehole Bu–4 in Prakfalvi 1996, also see MINGEO 1987,

Plašienka 2018). Moreover, a proximal fluvial system at Nógrádszakál is also more likely than an alluvial fan when considering not only the overall thickness of the volcaniclastics but also the dominant palaeocurrent direction in the context of the late Badenian regional palaeogeography (*Figure 1A,* e.g., Kováč et al. 2017).

The study area appears to have been the downslope extension of the Lysec foothills to the SE as shown by geological characters of the upper Badenian volcaniclastics (i.e., pyroclastics and volcaniclastics) that are exposed NW of Nógrádszakál in southern Slovakia (e.g., Balogh et al. 1966; Konečný et al. 1983, 1995; Kun-Jáger 1997). This is supported by our observation of the southern Slovakian volcaniclastics, which are characterized by an overall clast population that is on average larger, less rounded, more monomictic (with only 1% of clasts being non-andesites). These differences are minor and can be explained by the proximal, more source-ward position (i.e., closer to the Lysec volcano) of the southern Slovakian sites relative to those N of Nógrádszakál (c.f., Davies et al. 1978, Fisher & Schmincke 1994, Orton 1996). Moreover, the pyroclastics (andesitic tuff-breccias, andesitic tuffs, andesitic lapilli tuffs, etc.) that are interbedded with the volcaniclastics (*Figure 1B, 1C*) are also similar in the two regions and were likely and mainly sourced from the andesites of the Lysec palaeo-volcano in the late Badenian. The two levels of volcaniclastics occurring within the pyroclastics (*Figure 1B, 1C*) are explained by the discontinuous eruption history of the Lysec palaeo-volcano, with the volcaniclastics having been mainly deposited in the quiet, inter-eruption episodes, whereas the pyroclastics representing the syn-eruptive times when pyroclastic flows (block-and-ash flows) and also lahars occurred (e.g., Konečný et al. 1995; Kun-Jáger 1997; Lexa et al. 2010). As common in active volcanic regions (e.g., Davies et al. 1978, Fisher & Schmincke 1994, Orton 1996), the syn-eruptive deposits on the foothills of the Lysec palaeo-volcano were reworked by powerful alluvial processes, which at least in the sector N of Nógrádszakál, occurred in braided channels that drained initially from ~N to ~S and then from ~E to ~W (*Figure 3*). The water level fluctuations in these braided channels (*Figure 9*) were likely driven by discharge fluctuations linked to seasonal variation in precipitation. Moreover, as typical in braided rivers (e.g., Rust 1978; Heward 1978; Miall 1978a, b, 1992, 1996, 2006, 2016; Rust & Koster 1984; Bridge 1993; Lunt et al. 2004), scouring of channels and transportation of sediments occurred during high flow stages, whereas deposition, via the expansion/generation of gravel sheets and sand bars, took place during low flow stages.
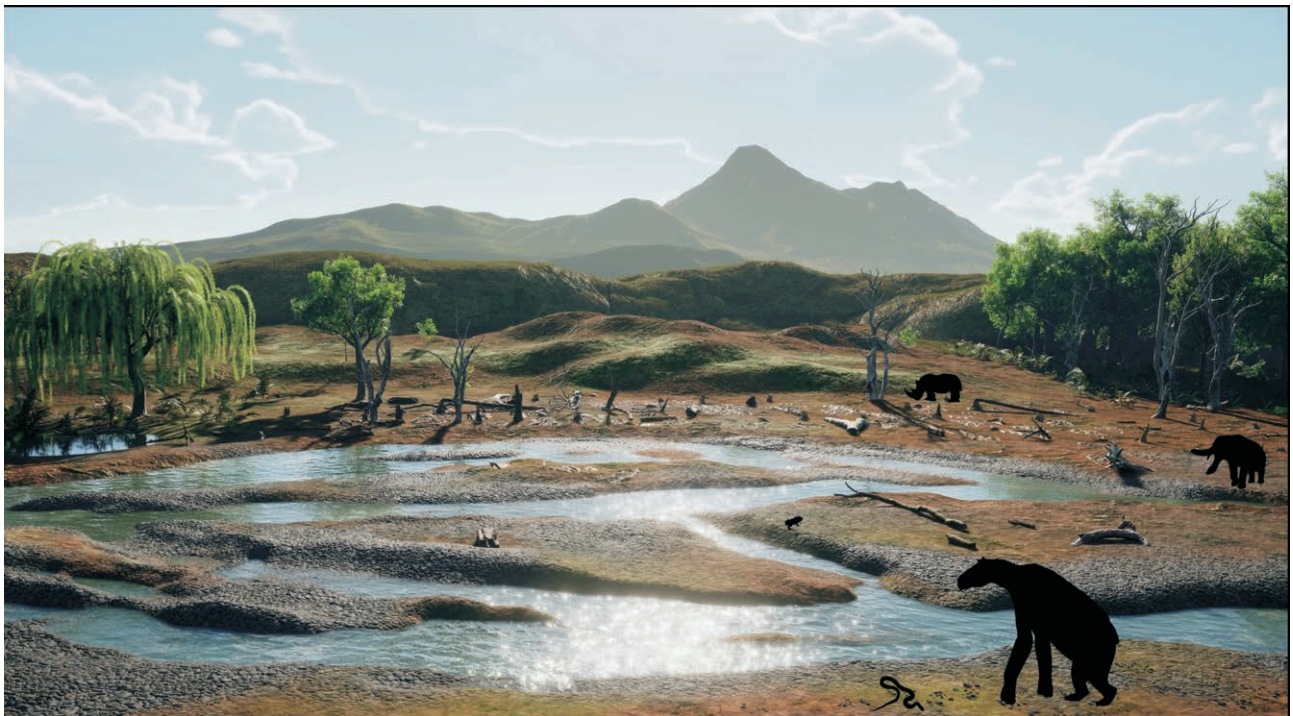
Figure 9. Late Badenian environment N of Nógrádszakál

Foreground: gravel-bed, braided river during moderate flow stage with the outlines of the key terrestrial biota (e.g., megaherbivores, frogs, snakes) including some plant types (e.g., *Ulmus, Salix, Alnus*). Background: the highest mountain is the temporarily dormant Lysec palaeo-volcano. Fauna silhouettes from PhyloPic.com by Steven Traver, Nobu Tamura, Beth Reinke (adapted under creativecommons.org/licenses/by/3.0/) as well as Gasparik 2004 with the permission of the author. The animation of the palaeo-environment (without animals) is available here: https://youtu.be/hUbxiIQJNFk

9. ábra. Késő badeni őskörnyezeti rekonstrukció a mai Nógrádszakáltól északra

Az előtérben közepes vízállással a kavicsos medrű, fonatos folyó a környező élővilág fő képviselőivel, nagy testű növényevőkkel, gerincesekkel (békák, kígyók) és a jellegzetes növényzettel (pl. szil-, fűz-, éger-félék). A háttérben a klasztok forrásául szolgáló, éppen szunnyadó Lysec paleovulkán magasodik. A faunakörvonalak forrása: PhyloPic.com (Steven Traver, Nobu Tamura, Beth Reinke munkái, creativecommons.org/licenses/by/3.0/) és Gasparik 2004 (a szerző engedélyével). Az őskörnyezeti rekonstrukció animációja (állatok nélkül) itt tekinthető meg: https://youtu.be/hUbxiIQJNFk

The abundance and the large size of allochthonous fossil wood in the volcaniclastics N of Nógrádszakál (for their distribution and maximum size, also see PRAKFALVI 2012) are taken as evidence for destructive natural events (e.g., volcanic eruptions, high magnitude floods) that were capable of uprooting and transporting mature trees. Additionally, those fossil wood fragments that have charred/coalified outer crusts as well as the charred plant debris (*Figure 8A*) could indicate wildfires, which have been linked to massive sedimentation events in the geological record not only in volcanically active areas but also in regions of high plant productivity (e.g., BELCHER et al. 2013, MUIR et al. 2015, BORDY et al. 2018). As it is evident from the abundance and richness of plant fossils (KORDOS-SZAKÁLY 1984a, b) and well as the megaherbivore remains (GAÁL 1905, SCHLESINGER 1922, GASPARIK 2001, HÍR 1993) collected in the study area, the Nógrádszakál landscape in the late Badenian was lushly vegetated (*Figure 9*) and thus supplied abundant accumulations of dry biomass, which could fuel potential wildfires.

As illustrated by the regional palaeogeography (e.g., KARÁTSON et al. 2001, KOVÁČ et al. 2017, DI CAPUA et al. 2021) as well as the marine affinity of the oldest fossils (e.g., ray and shark teeth, sponge spicules – HÍR 1993) recovered from the basalmost volcaniclastics N of Nógrádszakál, the late Badenian palaeoshoreline was in the southern proximity. However, with time, due to the intensification of the Lysec volcanic activities and regional geodynamics (e.g., KONEČNÝ et al. 1995, KOVÁČ et al. 2017), the shoreline migrated further south, and this increased the relative proportion of continental depositional settings in this region. In addition, similar middle Miocene volcano-sedimentary settings have been reconstructed at the southern foothills of the Štiavnica Stratovolcano and Vtáčnik Volcanic Field (e.g., Zlaté Moravce Formation; ŠARINOVÁ et al. 2018). Moreover, a coastal upper Badenian setting was documented at the foothills of the Visegrád–Börzsöny–Burda Volcanic Field as well (NOVÁKOVÁ et al. 2020). In the view of the regional paleogeography (*Figure 1A*), and the paleo-currents documented here (*Figure 3*), it is possible that the late Badenian braided fluvial system near Nógrádszakál continued towards west-southwest, until it reached the shoreline of the North Central Paratethys Sea.

With the available data, it is difficult to ascertain temporal changes from the lower to the upper volcaniclastic levels N of Nógrádszakál, however the larger clast size (*Figure 2*) and eastward directed palaeoflow (*Figure 3*) are noted in the upper level. This could be explained with the changes in drainage both in its intensity and direction. The cause of the drainage direction change remains elusive. It may be linked to voluminous volcanic detritus supply (e.g., MANVILLE et al. 2007, 2009; MAJOR 2020), a climate that became wetter, tectonics that increased the regional palaeo-slope gradients or a combination of these effects. The sedimentological evidence in the study area is not suitable to meaningfully demonstrate any climate change. Without attempting to promote a single occurrence of desiccation cracks as climate proxy, it is noted that these sedimentary structures only occur in the upper level. The onset of a wetter climate during the deposition of the studied stratigraphic interval is to some extent supported by the palaeobotanical findings of KORDOS-SZAKÁLY (1984b, p. 55), who showed that relative to the lowermost level, the middle pyroclastic level (sampled in the Páris-patak Valley) revealed a more varied and allochthonous plant fossil assemblage that also contains taxa requiring wetter conditions, in proximity of water (in addition to evergreen taxa and those needing riparian conditions as well as "drier soil and a slope with southern exposure"). The potential increase in slope relief also might be connected to uplift in the northern part of the Pannonian Basin. This could have been related to large-scale processes like mantle upwelling below the volcanic edifice (e.g., HARANGI & LENKEY 2007, HARANGI & LUKÁCS 2019) or to smaller-scale tilting and uplift of footwall blocks between extensional half grabens (e.g., FODOR et al. 1999, BALÁZS et al. 2018, BEKE et al. 2019, ŠUJAN et al. 2021).

Conclusion

The upper Badenian volcaniclastics, comprising pyroclastics and volcaniclastics exposed N and NW of Nógrádszakál in Hungary and southern Slovakia, respectively, are the deposits that formed during syn- and inter-eruptive depositional phases of the late Badenian Lysec volcano. The sedimentological characteristics of the volcaniclastics N of Nógrádszakál show that the andesite conglomerate-dominated, fining-upwards successions were deposited as gravel sheets and sand bars in a high energy braided fluvial system with medium-sized, ~4–5 m deep, low sinuosity channels. Initially, the drainage was southwards but with time it became westwards directed. The alluvial setting was permanently wet, moist, and was subjected to discharge fluctuations, likely during large, seasonal downpour events. The lushly vegetated landscape was not only home to megaherbivores, frogs and snakes, but also to a diverse and rich plant population that supplied fuel to potential wildfires and abundant woody debris that was entombed in the alluvial sediments.

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