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Reconstruction of Pliocene fluvial channels feeding Lake Pannon (Gödöllő Hills, Hungary)

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Abstract: During Pliocene to Pleistocene times, following the infill of Lake Pannon an alluvial plain was formed in the Pannonian Basin. The main bulk of terrestrial sediments are floodplain silts and clays; sandy to gravelly channel fill deposits comprise a smaller volume, but are excavated in several outcrops, as in Gödöllő Hills. In the studied outcrops five facies units were described: medium-grained trough cross-bedded sand, medium-grained sand with compound cross-bedding, small channel fills with bedding parallel to basal concavity, fine-grained cross-laminated sand and massive silt to mud. Significant fining upward is rare, but decreasing thickness of cross-sets is often present in sands, defining cycles with heights of about 5 m. In the same outcrops, lateral accretion surfaces were also observed; together with cyclicity, they indicate point bar deposits of meandering rivers. Data from boreholes and a railroad cut has shown that channel fill sands are isolated within the floodplain sediments, but amalgamation of 3–4 channel fill sandbodies is common. The bankfull depth of the rivers depositing the studied sediments were estimated as 5–8 m. Direction of bend migration is indicated by lateral accretion surfaces, whilst a compound cross-bedded sandbody proved to be a confluence bar. Compared to the size of recent rivers, it can be concluded that one of the trunk rivers infilling the basin crossed the study area in the Pliocene. Paleocurrent data show that the river flowed to the southeast, towards the eastern subbasin of Lake Pannon.

Key words: Pliocene, Gödöllő Hills, sedimentology, field observations, channel development, alluvial plain, bars.

Introduction

It has been known for decades (Mucsi & Révész 1975) that the Late Miocene to Pliocene Lake Pannon was filled up by huge amounts of siliciclastic sediments distributed via a fluviodeltaic system, and fluvial deposits in the upper part of the basin infill were recognized much earlier (Lőrenthey 1905). However, the sedimentary features of the rivers — namely their sinuosity, single- or multi-channel character, direction and size of channels — remained unknown. Only the occasionally preserved terrestrial fauna of the fluvial deposits, mostly mammals (Mottl 1939; Gaál 1946, 1953; Jaskó & Kordos 1990), got highlighted. There might be several reasons for ignorance: poor and ever-changing outcrop conditions, the lack of fossils as tools of stratigraphic correlation and last, but not least the lack of hydrocarbon reservoirs in the youngest — fluvial — part of the system. The aim of this paper is twofold. We would like to demonstrate how detailed reconstruction — including development of individual channels or processes building different types of bars — of a fluvial paleoenvironment can be made even in an area where sediments are visible only in a few small outcrops. Secondly, we would like to show how these small details can contribute to understanding the features of the fluvial system.

Geological setting

Pliocene sediments of Gödöllő Hills were deposited in the latest phase of the infilling of the Late Miocene to Pliocene (11.5–4 Ma) Lake Pannon. The lake reached its greatest extension about 9 million years ago, when it covered the whole Pannonian Basin (Fig. 1) and had more than 1000 m of depth in its deepest parts (Magyar et al. 1992), but huge deltaic systems carrying sediments from the Alps and the Carpathians started to fill it rapidly mainly from the northwest and the northeast. As the infill progressed, a widespread alluvial plain was formed in the area, first in the northern part of the basin, than it expanded southwards. Thickness of alluvial succession reaches 1000 m in some parts of the central areas of the basin (Juhász 1994). Pliocene alluvial sediments — composed of mostly floodplain silts and clays with intercalating sandy channel fill deposits — are known as Nagyalföld Variegated Clay Formation in the studied part of the basin (Gajdos & Papp 1997). This formation correlates with the lithologically similar Hanság Formation in the Little Hungarian Plain, and Kolárovo Formation in the Slovak part of the Danube Basin, of which the latter consists of a remarkable amount of gravel beside sands and clays. On the northern edge of the Pannonian Basin, Quaternary uplift has inverted the basin fill (Horváth 1995). As a consequence in the study area — at the junction area of the uplifting hills and the subsiding plains — much of the succession has been eroded, so that the thickness of the remaining part of these alluvial sediments is not more than 100–200 m, and they crop out at many places. Borehole data demonstrate that the bulk of them consist of variegated clay and silt formed on floodplains, while sandy or gravelly channel fill deposits comprise a smaller volume. In the Gödöllő Hills three major outcrops (Fig. 2) — a sand pit and the railroad cut in

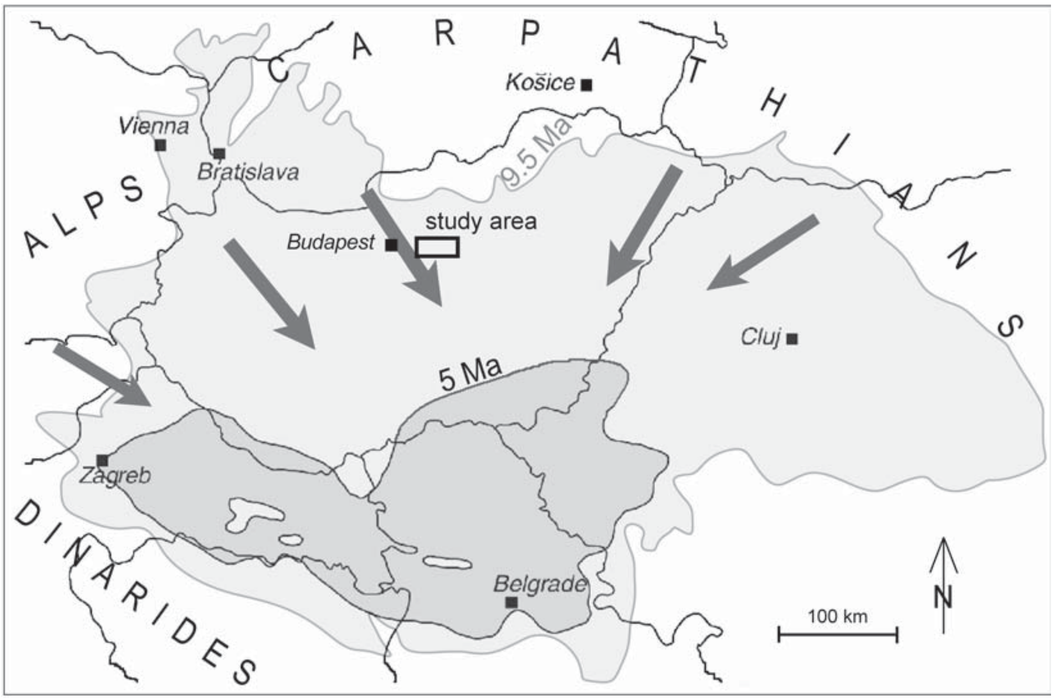


Fig. 1. Contour of Lake Pannon at about 9.5 and 5 million years ago (after Magyar et al. 1992 and Magyar, pers. comm., 2006). The main directions of infilling river systems are indicated by the arrows.

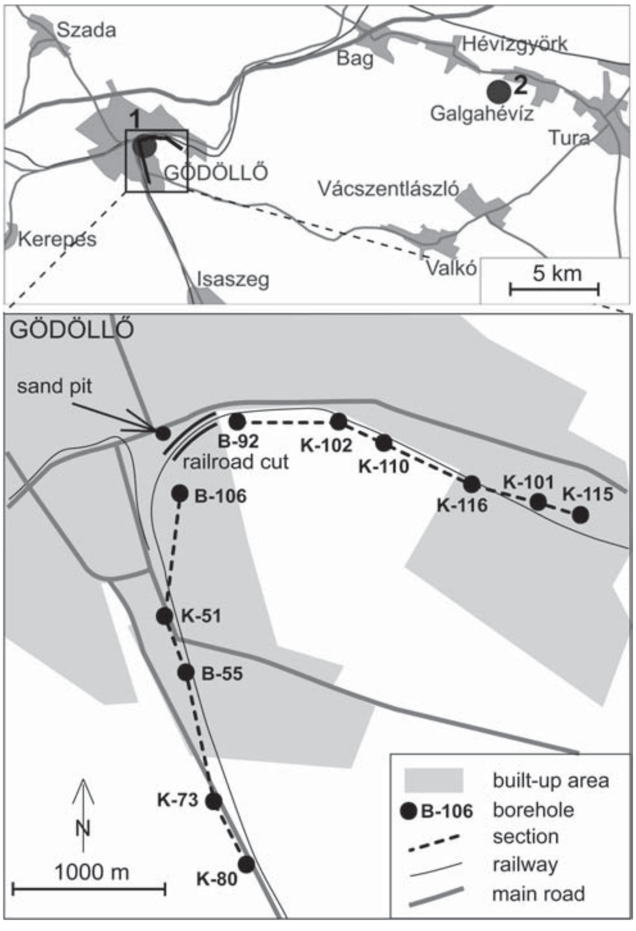


Fig. 2. Location map of the studied outcrops and boreholes.

Gödöllő and an another abandoned sand pit at Galgahévíz — were studied, where mainly the coarse-grained lithologies are exposed.

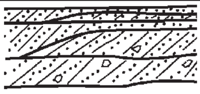
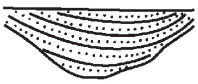
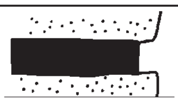
The age of the succession cropping out in the Gödöllő area was determined first by Mottl (1939) using mammalian fossils found during the construction of the railroad cut. Her results showed that the sand was deposited in the Middle Pliocene (~4 Ma); later Gaál (1953), Jaskó & Kordos (1990) also got Early–Middle Pliocene ages from the same fossils. Unfortunately, fossils were not found in any other place, therefore sediments of individual outcrops cannot be correlated exactly within the interval given by their stratigraphic position. Alluvial origin of the sand was already mentioned by Szentes (1943). Palynological analysis of the Nagyalföld Formation (Nagy 2005) and the abundance of variegated clay in its deposits in many parts of the Pannonian Basin (Pécsi 1985) indicate a climate warmer and drier than the present one (with annual average temperature about 13 °C), with no major changes during the Pliocene.

Description of the studied outcrops and facies units

Facies classification

In the last few decades many systems were proposed for classifying sedimentary structures of fluvial deposits, of which the classification of Miall (1988) is one of the most commonly used systems. Three lithofacies of Miall's classification (unit St, Sp, Sr) appear unambiguously in the studied outcrops (Table 1); the lithology of a fourth one

Table 1: Classification of lithofacies identified in the study area (cf. Miall 1988).

Lithofacies	Code	Description of lithofacies	Interpretation
	St	Medium- to fine-grained trough cross-bedded sand	Dunes (channel deposits)
	Sp	Medium- to fine-grained planar cross-stratified sand	Ripples
	Sr	Fine-grained cross-laminated sand	Linguoid or transverse bars
	Sc	Medium-grained sand with bedding parallel to basal concavity	Channel fills
	Fm	Massive silt and mud	Overbank (floodplain) deposits

(Fm) was described by Ferenczi (1936) in the documentation of the railroad cut and can also be recognized in the successions of the studied boreholes. Although the original classification of Miall (1988) does not contain it, sand with bedding parallel to basal concavity (unit Sc) was described as an individual lithofacies by García-Gil (1993). Miall has used the term "scour fill" for this facies characterized by 'erosional scours' and 'crude' cross-bedding.

In the studied outcrops, where macrostructures at the scale of channel size are also visible, identifying the facies units already yields information about the processes which have created the bedforms. Some of these lithofacies and some distinctive spatial associations of them can be interpreted as different architectural elements — such as floodplain deposits or different types of bars — within the river system.

Gödöllő sand pit

This outcrop consists of a shorter (15 m) west-east oriented and a longer (50 m) north-south oriented wall (Fig. 3).

The calcareous cement of the sand forming horizons mostly follows the bigger-scale bedforms, making them

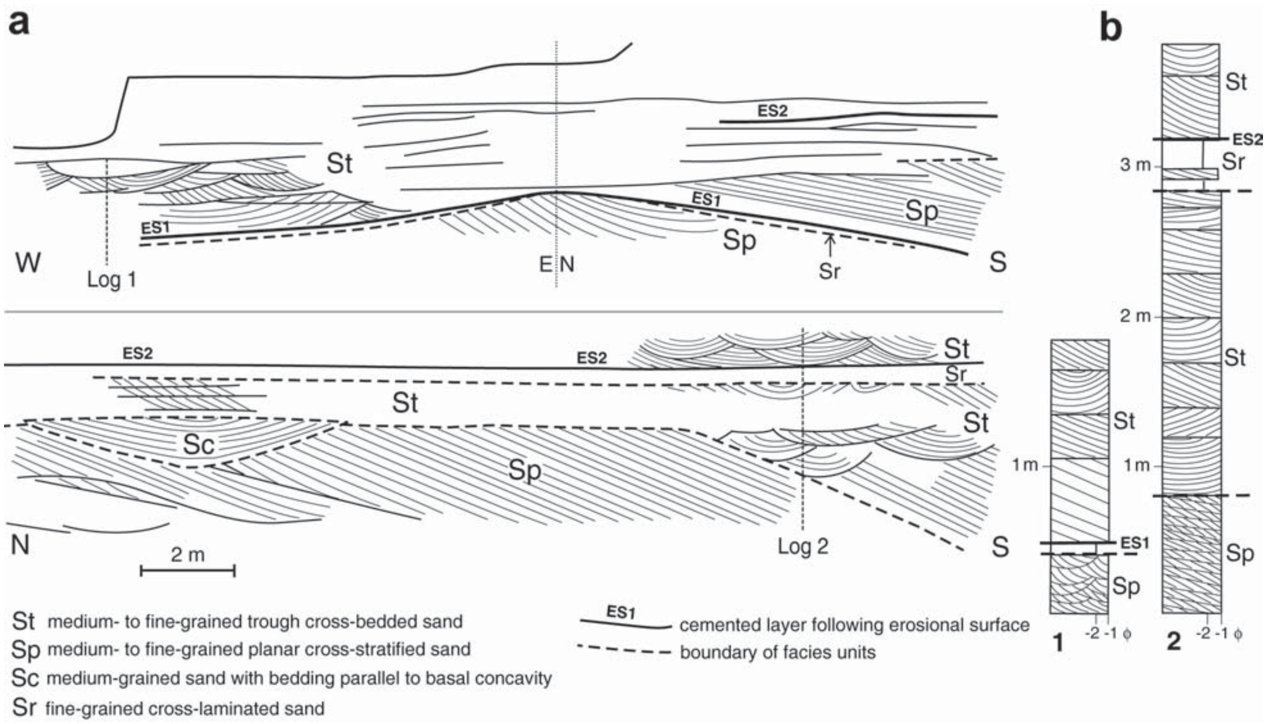


Fig. 3. Sketch, logs and facies units of the Gödöllő sand pit.

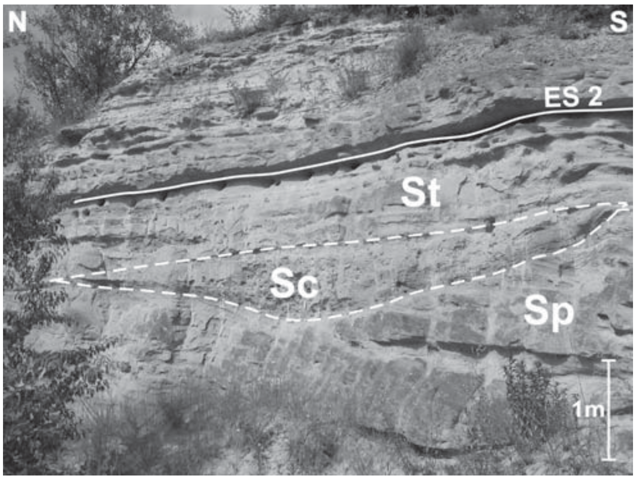


Fig. 4. Unit Sc and the surrounding bedforms in the Gödöllő sand pit.

more easily recognizable, elsewhere cementation has made the observations difficult in some parts of the outcrop.

One of the most remarkable cemented horizons appears at a height of 2 m at the joining of the two walls. From this point, it apparently dips both to the west and to the south, its real dip is about 15° to the southwest. Another, seemingly horizontal cemented layer is visible at a height of 4 m on the north-south oriented wall. Both cemented beds follow erosional surfaces, as they cut into units made up of fine-grained cross-laminated sand described later. These surfaces will be referred later on as ES1 and ES2 respectively. The upper one (ES2) divides the outcrop into two main parts. Four facies units were identified on the basis of grain size and sedimentary structures (Figs. 4, 6).

Unit St: *medium- to fine-grained trough cross-bedded sand*

This facies unit mainly consists of moderately sorted, medium-grained sand. As in all the sandy facies units of the studied outcrops, most of the grains are quartz, mixed with only a few percent of feldspars, biotite and muscovite. Between the two main cemented layers, unit St is visible on the biggest surface, and it is the only recognizable unit in the upper part of the outcrop. The height of individual cross-sets is between 10 and 65 cm, their width is up to 5 m; they are mainly wedge-shaped in sections parallel to paleocurrent direction. Paleocurrent directions indicated by the dips of cross-strata in the axes of the bedforms are mostly towards the east-southeast (Fig. 5c).

The size of bedforms or thickness of cross-sets decreases upwards up to the cemented erosional surface ES2 (Fig. 3). Parallelly in the uppermost cross-sets, grain size also starts to decrease and fine-grained beds of unit Sr can also be found. Collaterally the deviation of paleocurrent directions increases: cross-strata of some sets dip to the northeast or to the south. Above the erosional surface, both the thickness of the trough cross-bedded sets and the grainsize is increasing again. In addition paleocurrent directions are somewhat different, they are towards the south-southeast.

Unit Sp: *medium- to fine-grained planar cross-stratified sand*

Unit Sp forms a 30 m wide, at least 2 m high sandbody on the northern part of the north-south oriented wall, surrounded by trough cross-bedded sand. Its upper boundary is a horizontal erosional surface (Fig. 3); downwards the unit continues below the lower, inclined cemented layer of the outcrop, but its lower boundary is not exposed.

The cross-strata of the planar cross-bedded sand are 2–5 cm thick with dips about 15–20° to the south (Fig. 5a). However, they have compound structure: every single cross-stratum is built up by 0.5–1 cm thick laminae dipping to the southeast (Fig. 5b). Although lithological features and dip directions do not vary significantly within the sandbody, this unit contains several, low angle internal erosional surfaces also dipping to the south.

Unit Sc: *medium-grained sand with bedding parallel to basal concavity*

The lower boundary of this unit (Fig. 4) is a sharp, concave erosional surface cutting into unit Sp and — in its uppermost part — into unit St. Moderately sorted medium-grained sand fills the big trough-like form. The upper boundary is also an erosional, but almost horizontal surface. The unit is made up of about 1 cm thick beds parallel to the basal concave surface. Their dip is steep towards the east-southeast measured in the axis of the form. As the pa-

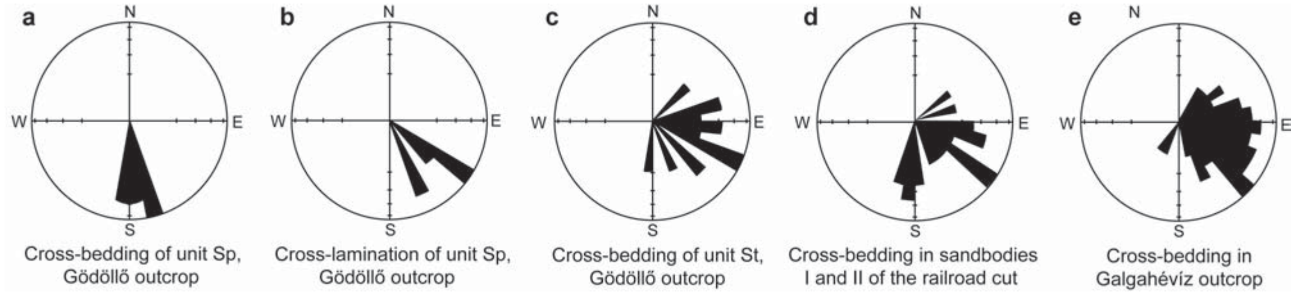


Fig. 5. Rose diagrams (equal area) show that paleocurrent directions are generally towards the east-southeast with quite low deviation. In unit Sp it is shown by smaller-scale bedforms, while bigger-scale cross-strata indicates the direction of bedform accretion itself.

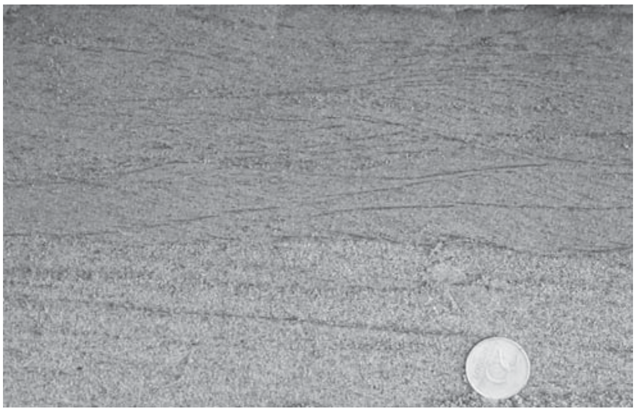


Fig. 6. Climbing cross-laminated sand (unit Sr) in the Gödöllő sand pit (scale is 2 cm).

leocurrent direction differs from that of unit St, the bedform is much bigger than "troughs" of unit St, and as it deeply cuts into the underlying beds, it was formed by different processes.

Unit Sr: *fine-grained cross-laminated sand*

This unit appears at two horizons: only a 2–5 cm thin layer underlies the erosional surface ES2, but below ES1 a 50 cm thick bed made up mostly of climbing cross-lamination (Fig. 6) is present.

Gödöllő, railroad cut

The railroad cut located in 100 m distance from the Szabadság Road (Fig. 2) outcrop exposed Pliocene sediments on a much bigger surface in the 30's, when it was documented by Ferenczi (1936; Fig.7). Nowadays observations can be made only in some places because of soil and vegetation cover. In these places trough cross-bedded sand equivalent to unit St is exposed. However, the section made by Ferenczi shows that the bulk of the sediments is silt and clay, which can be described as an individual facies unit (unit Fm sensu Miall 1988). These are either brown or blueish grey, without macrofauna, containing some coalified vegetable detritus and some calcareous nodules with 1–2 cm of diameter. Within the fine sediments there are some 1–5 m high, 30–130 m wide, lens-shaped interbeddings of sand (numbered III to V). Sand in greater thickness appears only near the southwestern and the eastern end of the railroad cut (sandbodies I and II). In the southwestern part, west of a sharp surface dipping at 60° to the east — interpreted as a normal fault — sand is exposed in the whole height of the outcrop with only a thin interbedding of mud. The studied sand pit is also located west of this fault (Fig. 7), within the same thick sandbody (I). The smallest sandbodies (III and V) cannot be followed on opposite cut walls, unlike the largest one (IV). Present paleocurrent data from sandbodies IV and VI are towards the SSE and ESE; the larger sandbodies I and II show southeastern paleoflow (Fig. 5d), but in sandbody II there are some larger-scale surfaces indicated by cementation dipping at low angles to the SW.

Trough cross-stratification (unit St) is not the only structure appearing in these sandbodies. In sandbody VI a 10 m wide and 1 m high trough-like form appears, which has been assigned to facies unit Sc. The dip of its cross-stratification towards the SSE (measured in the axis of the form) corresponds to the dips of the surrounding smaller — mainly 30–60 cm high — cross-sets. Nearby, above the trough cross-stratified sets there is a 15–20 cm thick fine-grained sand layer with climbing ripples (unit Sr). At the top of this layer a cemented horizon developed overlain by mudstones.

Sand pit at Galgahévíz

Galgahévíz is situated 15 km to the east of Gödöllő (Fig. 2). According to the geological map of Szentes (1943) the same Pliocene sand is cropping out around the village. The 5–10 m high outcrop consists of two, 150 m

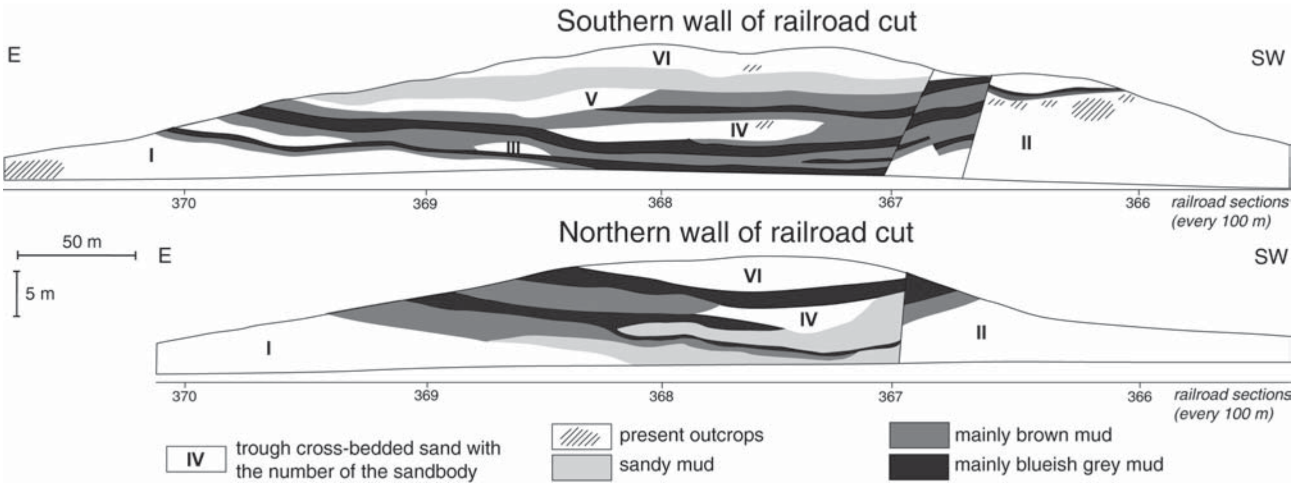


Fig. 7. Sections of railroad cut, Gödöllő (after Ferenczi 1936).

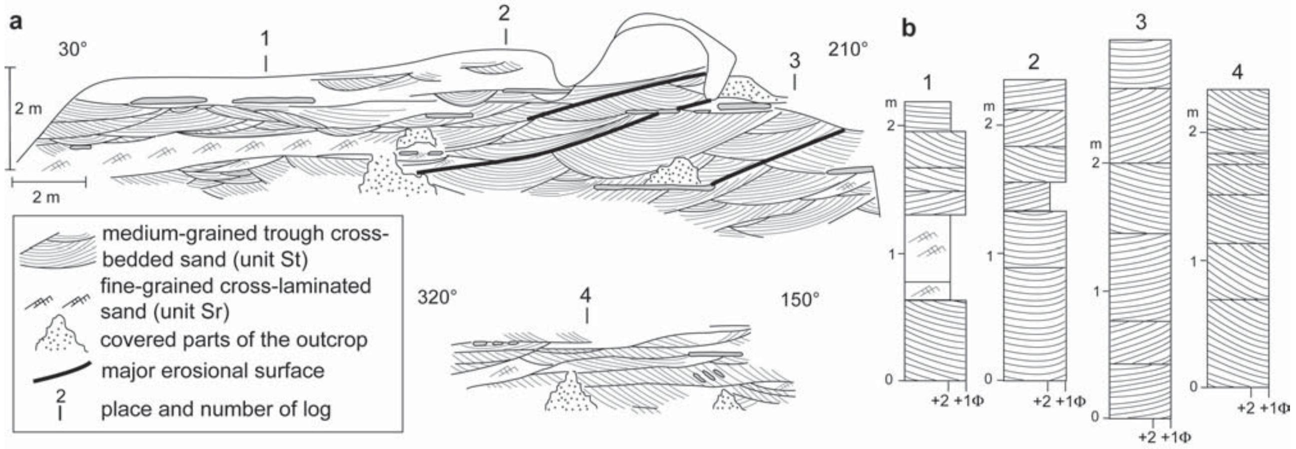


Fig. 8. Sketches and logs of Galgahévíz outcrop.

and 80 m long roughly perpendicular walls (Fig. 8) Unfortunately large portions are covered by vegetation. Only two facies units — known from the Gödöllő sand pit — can be distinguished.

St: *medium- and fine-grained trough cross-bedded sand*

This unit composes the bulk of the outcropping deposits. Height of cross-sets varies between 10 and 120 cm, but adjacent bedforms can be of different scale. Grainsize is significantly larger in the higher cross-sets. In spite of this diversity, cross-sets with thickness of 80–120 cm occur only on the lowest part of the section, while 4–5 m above the smallest ones become more frequent (Fig. 8). This is followed by a covered interval which suggests that softer (silty to clayey) lithology is present. At the uppermost part of the section cross-stratified sand appears again. On the NW-facing wall many "troughs" are asymmetrically truncated by other ones on their northeastern side, although paleocurrent directions (towards the E–SE) are nearly perpendicular to this wall. These erosional surfaces gently dip to the NE. Cross-sets on the SW-facing wall are wedge-shaped with foresets dipping also to the E–SE (Fig. 5e).

Sr: *fine-grained cross-laminated sand*

Normal to climbing cross-laminated sand occur as interbeddings between the bedforms of unit St. Most of these have an overall thickness about 5–20 cm, rarely up to 50 cm and an average length of 1–2 m.

Boreholes in Gödöllő

In Gödöllő area, many boreholes (Fig. 2) drilled for water exploration have penetrated the Pliocene fluvial deposits underlying a few meters of Quaternary sediments. Borehole data (Fig. 9) show that the upper 100 m of the succession is made up by sand and finer-grained sediments in nearly equal quantities. One or more thick (10–30 m) layers of sand — sometimes interrupted by thin (1–2 m) pelitic horizons — can be found in almost every borehole. Between the thick layers of sand, successions consist of mainly silt and mud with some 1-3 meters thick sandy interbeddings. The latter cannot be correlated to each other even between neighbouring boreholes; however, thick sandbodies can be followed within a distance of 500–1000 m.

Interpretation of depositional environment and architectural elements

Depositional environment

As it was described above, successions of boreholes in Gödöllő area include thick (10–30 m) and thinner (1–3 m) layers of sand interbedding between silts and muds; the railroad cut also consists of mainly silt and mud with interbedded sandbodies. The former are typically floodplain deposits; such a high ratio (a bit higher than 50 %) of them suggests that the sediments were deposited by meandering rivers (cf. Bridge & Diemer 1983; Collinson 1986).

The thicker sandbodies can be interpreted as point bar deposits; their thickness can significantly exceed the value established for individual point bars, as amalgamation of sandbodies above each other is an abundant phenomenon in such successions built up by channel and floodplain deposits. Although channel belts are relocated by avulsion, later they usually get back to their previous position, above former channel deposits which can be eroded more easily (cf. Puigdefabregas & Van Vliet 1978; Bridge & Leeder 1979; Bridge 2003). 2–3 m thick layers of sand found in the successions can be deposits of smaller channels, which existed only temporarily after an avulsion, but flow did not become permanent in them, therefore their channel floors were not eroded as deeply as it was in the parent channels. Sandy layers not thicker than 1 m are interpreted as deposits of crevasse splays. The presence of crevasse sands also supports the meandering character of the ancient rivers.

Prevalence of trough cross-stratification (unit St) and variations in set thickness may indicate that sediments of

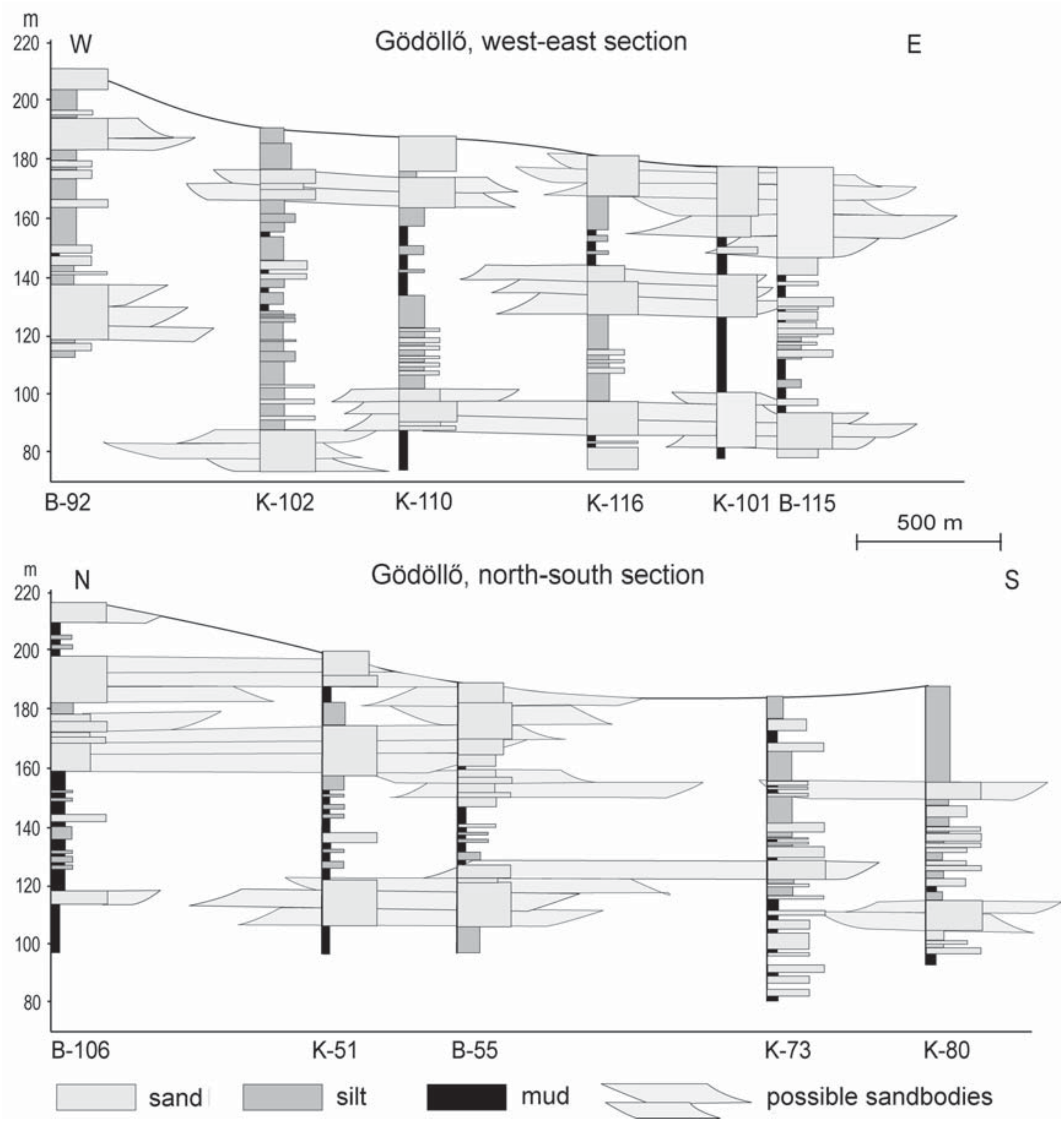


Fig. 9. Lithological columns of boreholes in Gödöllő with possible sandbodies.

the Galgahévíz outcrop were also deposited by a meandering river. This is supported by the succession of a borehole located about 800 m from the outcrop, with alternating layers of sand and silt.

Architectural elements

Unit St and Sr: point bar

Within the trough cross-stratified sand (unit St) at the Gödöllő sand pit, below ES2 the size of bedforms definitely decreases upwards, while the dispersion of paleocurrent data increases and grain size also becomes smaller with the appearance of cross-lamination (unit Sr). These changes indicate gradual decrease of the energy of paleoflow. Trough cross-stratification of unit St was formed by sinuous-crested dunes with heights of about a few decimeters (cf. Collinson 1986), while Sr was formed as current ripples or climbing ripples. The latter may point to decreased velocity of flow by cut-off (cf. Walker 1984). In a fluvial environment, the most common reason for that is the infilling of a migrating channel as the main current is shifted away by the accretion of a bar. Such cycles may occur in braided rivers (Bridge 2003), but they are characteristic of point bars of meandering rivers (Allen 1970). As the main current is placed further by meander development, floodplain deposits close the cycle (e.g. unit Fm in the railroad cut) or the next channel is incised and amalgamation of channel-belt deposits occur (Puigdefabregas & Van Vliet 1978; Bridge & Leeder 1979).

Above ES2 of the Gödöllő outcrop, a new cycle starts with larger — 50–60 cm high — trough cross-sets. On the northeast-southwest oriented wall of the Galgahévíz sand pit, unit St and Sr also build up at least two sedimentary cycles. Whilst the cross-sets with thicknesses of about 1 m occur only on the lowest part of the outcrop, smaller ones become more frequent at heights of 4–5 m, but the upper boundary of the cycle is not exposed. However, it might be located at about 6 m of height, because on the upper part of the wall, thicker cross-sets (with height reaching 50 cm) occur again, which can belong to another cycle. Thickness of cross-sets and grain size decreases upwards also within this cycle: fine-grained cross-laminated sets start to appear in its upper part.

Unit Sp: confluence bar

The large cross-stratified sandbody of the Gödöllő sand pit is surrounded by the trough cross-bedded sand, in which set thickness does not exceed 65 cm. In contrast, unit Sp can be evaluated as one continuous cross-set with at least 3 m of height, in which individual cross-strata are up to 10 m long. These structures can be caused by transverse bars, which are much bigger and have lower height/length ratio than dunes (cf. Cant & Walker 1978). Compound structures are also typical in large-scale bars, as smaller bedforms can migrate on their surface parallelly to the flow direction (Jackson 1976; Khan 1987).

Foresets of unit Sp dipping towards the east-southeast indicate that this was the flow direction in the ancient channel. Large-scale cross-strata of unit Sp dip, however, towards the south (Fig. 5a), which shows the direction of accretion of the sandbody. The difference between these values would be enough to evaluate unit St as a laterally accreted bar, but dip directions of cross-laminae within its compound cross-strata (137° on average) indicate that above this bar water flowed to the southeast, which is closer to the direction of accretion. Thus the difference between the directions of paleoflow and bar accretion is only 33°, which means an intermediate stage between lateral and downstream accretion. This can be developed on bars of braided rivers during floods, when they are covered by water; the other possible explanation is a bar building up of sediments carried by a confluencing channel (cf. Bridge 2003; Fig. 10a). In this case the confluence bar accretes obliquely to the main channel, while stream direction above it can be anywhere between the direction of the main and the confluencing flow.

In meandering systems, confluence bars mostly form where chute channels cutting point bars join the main channel: these bars are referred to as "chute bars" (Collinson 1986). As channels cannot be followed further because of the lack of outcrops, we cannot decide whether the planar cross-stratified sandbody in Gödöllő outcrop was a chute bar or a bar formed at the confluence of two distinct channels.

After the influent flow ceased, sediments of unit St continued to deposit on the top of the confluence bar. Later on, probably during a successive flood, erosion has formed a secondary bar-top channel (Fig. 10b) cutting into the sediments of unit Sp and St. Unit Sc was most probably created by rapid infill of that channel. Paleoflow direction of the bar-top channel fits the directions of the main flow.

Thus, in summary, two fining-upward sedimentary cycles of a meandering river appear in the Gödöllő sand pit.

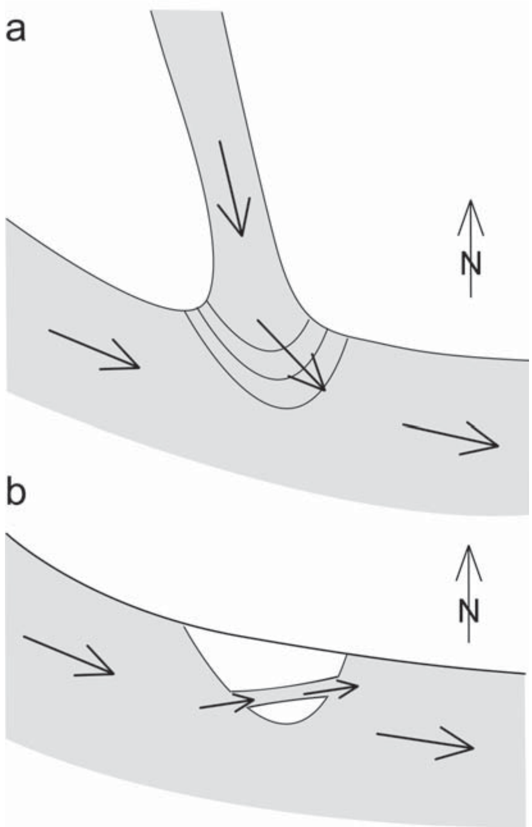


Fig. 10. a — Bar accretion and current directions at the confluence. **b** — Secondary channel cutting into sediments of the former confluence bar (without scale).

The river flowed towards the east-southeast at this place. Within the lower cycle, a larger-scale bar was formed, probably at the confluence of a chute channel and the main one.

Accretion of point bars

Point bars on the inner side of meanders accrete laterally, nearly perpendicular to flow direction. This is often — but not always — shown by lateral accretion surfaces dipping at low angles (from 1–2° — which is hardly visible in an outcrop — to 15–20°) towards the direction of accretion (Collinson 1986; García-Gil 1993; Willis 1993a,b). Lateral accretion surfaces are outlined in sandbody II of the railroad cut.

Paleoflow directions indicated by dip of cross-strata in this sandbody were generally from the northwest towards the southeast. Cemented horizons in the same sandbody, dipping towards the southwest — perpendicularly to the paleoflow — probably follow the surfaces of lateral accretion. Based on this, at the given stratigraphic level the ancient river which ran to the SE, had a meander loop migrating to the SW.

Compared to the Gödöllő outcrop, decrease of cross-set size is less uniform in Galgahévíz: there are significant differences between the sizes of adjacent bedforms. Larger variability of the discharge of the ancient channel is a probable reason for this: although the channel became shallower gradually at a given point as the point bar accreted, alternating periods of floods and low water could result significant variability in water depth and size of the developing bedforms. This variability could cause quite long breaks in lateral accretion of the point bar; probably erosion during these periods produced erosional surfaces a few meters long gently dipping towards the north-northeast within unit St (Fig. 8). The dip directions of these internal erosional surfaces indicate the direction of point bar accretion towards the north-northeast, compared to the perpendicular paleocurrent directions (Fig. 5). The direction of lateral accretion is supported by the fact that most cross-sets are eroded on their northeastern side.

Size of the ancient channels

The depth of an ancient channel can be estimated on the basis of the thickness of exposed cross-sets. Allen (1968) proposed the following equation for this estimation:

$$h = 0.086 \cdot H^{1.19}, \text{ thus: } H = \sqrt[1.19]{\frac{h}{0.086}}$$

where h is the height of dunes, H is the formative flow depth over the sedimentary structure, in meters. Others (Jackson 1976; Allen 1980; Flemming 2000; Bridge 2003) noticed that water depth/dune height ratios falls in the range of 3–20, therefore Allen's equation should be considered as a rough estimation only. Counting with the height of the thickest cross-sets — which are surely lower than the dunes that formed them — the result show that flow depth has reached at least 5 meters at the Gödöllő outcrops. As larger-scale bars cannot rise above the surface of the water, their height — in our case the thickness of unit Sp — gives the minimal possible value for water depth. In the outcrop, this unit is 3 m thick, but its real thickness probably exceeds this, because the lower part of the ancient bar is partially covered. In Galgahévíz, point bar deposits are at least 6 m thick in the lower sedimentary cycle. On the basis of the height of the largest cross-sets — using the equation of Allen (1968) — channel depth may have attained about 8–9 meters.

Conclusions

In the studied Pliocene sequence, based on the ratio of channel and floodplain deposits and successions of sedimentary structures, meandering rivers were reconstructed, suggesting that the studied part of the Pannonian Basin was probably dominated by meandering rivers in the Pliocene. That indicates a paleotopography with quite low relief and probably lower flux of sediment compared to the northern Danube Basin, where chiefly braided river deposits of the same age were identified in the Kolárovo Formation (Kováč et al. 2006). This difference probably indicates that the uplifting of the Gödöllő Hills had not started by the time of deposition of the studied sediments. Lack of gravels and relative abundance of floodplain fines in the Pliocene of Gödöllő Hills is probably due to its longer distance from the source of the sediments. Paleocurrent directions show that the studied rivers were flowing from the northwest towards the southeast, in harmony with existing paleotopographical models (e.g. Magyar et al. 1992) of Lake Pannon. Based on this direction, the probable source area is thought to be in the Western Carpathians, which were already elevated and eroding in the Pliocene.

The depth of the ancient rivers could be estimated from the size of cross-sets, and the height of point bar deposits. River depth at bankfull discharge may have been around 5 m in Gödöllő area, while it has reached about 8–9 m at Galgahévíz. This larger river might have had a less uniform water discharge. Compared to recent rivers of the Pannonian Basin, the latter means the scale of Tisza, the second greatest river of the basin, while 5 m of bankfull depth is typical of its major tributaries (like the Körös and Maros). Under the quite arid paleoclimate the Pliocene rivers should have had at least as large drainage areas as the recent rivers with the same size. This supports the view that their source area was not located closer than the Western Carpathians, although parts of the Transdanubian and North Hungarian Range could be already uplifting in the Pliocene (Csillag et al. 2004).

However, it should be considered that the studied outcrops and boreholes do not map the whole succession, therefore they do not exclude the possibility of a larger temporal and spatial variance of river styles (e.g. meandering or braided) and paleoflow directions. Analysis of seismic profiles show that some northwest–southeast trending faults of the Gödöllő Hills area could have been active in the Pliocene (Fodor et al. 2005), which could have locally changed the topography and river style, but the quantity of data accessible from the sedimentary succession does not allow a more detailed reconstruction.

Within the point bar deposits of the Gödöllő outcrop, a large compound cross-stratified sandbody was found, which is thought to be a confluence bar, as its paleocurrent directions significantly differs from that of the surrounding trough cross-bedded sand. Cemented beds and low angle erosional features were interpreted as lateral accretion surfaces, dipping perpendicularly to flow directions. Thus migration of individual meander loops was reconstructed to SW at Gödöllő and to NE at Galgahévíz. On the basis of the reconstructed channel sizes and directions, we can conclude that one of the trunk rivers infilling the basin flowed across the present Gödöllő area in the Pliocene.

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