

Fluvial and aeolian landscape evolution in Hungary – results of the last 20 years research

Gy. Gábris*, E. Horváth, Á. Novothny & Zs. Ruszkiczay-Rüdiger

Eötvös University of Budapest, Institute of Geography and Earth Sciences, Department of Physical Geography, 1117 Budapest Pázmány sétány 1/C, Hungary.

* Corresponding author. Email: gabris@ludens.elte.hu.

Manuscript received: September 2011, accepted: August 2012

Abstract

Present study provides a review of the latest results on fluvial and aeolian landscape evolution in Hungary achieved by our team during the last 20 years.

- The Hungarian river terrace system and its chronology was described with special emphasise on the novel threshold concept. A revised terrace system was created by the compilation of novel terrace chronology and MIS data. Evolution of river terraces was not only governed by climatic factors but tectonic ones too. Incision rate of the Danube, and uplift rate of the Transdanubian Range (TR) was around 0.1-0.3 mm/a in the marginal zones of the TR (mostly based on the published U-series data) and was above 1 mm/a in its axial zone (based on ³He exposure age dating of strath terraces).
- According to a detailed geomorphological investigation of the different channel-planform morphologies in the Middle Tisza region and Sajó-Hernád alluvial fan, six phases of river pattern change and four incision periods were detected during the last 20,000 years.
- Wind polished rock surfaces dated by in situ produced cosmogenic ¹⁰Be suggest that deflation was active in Hungary as early as 1.5 Ma ago. According to these exposure age data, Pleistocene denudation rate of the study area (Balaton Highland) was 40-80 m/Ma.
- In sand covered areas the alternations of wind-blown layers and buried fossil soils provide information about climate and environment changes. In this study, periods of sand movement were mostly determined by optically stimulated luminescence (OSL) dating methods and five aeolian sand accumulation periods were recognised during the last 25 000 years.
- A new loess stratigraphical view was elaborated using the most recent dating methods (luminescence, AAR). The lower part of Mende Upper (MF₁₋₂) pedokomplex is suggested to represent the last interglacial period (MIS 5e). During the last interglacial/glacial period (MIS 5 - MIS 2) several soil-forming periods existed but the preservation of these paleosoils is variable depending on their paleogeomorphological position.

Keywords: river terrace formation, river channel-planform morphology, uplift rate, exposure age, sand-moving periods, loess stratigraphy, Quaternary, Hungary

Introduction

Palaeoenvironmental changes of the Quaternary Era are preserved in several continental deposits and landforms. Climate changes governed the surface erosion and accumulation processes in general. Geomorphologic effects of the climate changes are varied.

In our review we consider the fluvial processes in two different relations:

- the longer and stronger so called Milankovich climate cycles controlled changing mechanisms of the rivers, which resulted in terrace formation in the valleys of mountainous and hilly regions;
- the smaller and shorter climatic effects of the latest climate phases – sub-Milankovich cycles – can be recognised in the lowlands as well, where different river pattern systems have developed. In these areas of subsidence landforms and sediments of older climate periods are covered by younger strata.

The investigation of Pleistocene aeolian sediments like wind-blown sand and loess layers and their stratification provides insight in palaeoenvironmental conditions. The loess of the Carpathian Basin developed under cold steppe conditions, while the buried soil horizons reflect a different, warmer and more humid environment. The climatic fluctuations affected the sandy material too. Strong winds moved the sand from the barren surfaces during the dry periods, while the sand surfaces were gradually covered by vegetation during the wetter and milder periods: forest or steppe-like soils formed and the dunes were fixed.

Chronological and palaeoenvironmental analyses and results from ocean-floor and ice core studies brought revolutionary methodical and theoretical changes in Quaternary science. This renewal highlighted important information about Pleistocene climate changes compared to the Milankovich climate curve. Currently, climate-controlled phenomena are linked to the smaller scale fluctuations within the Oxygen Isotope Stages (MIS). Attempts to correlate events, sediments and other formations that are far from each other are not well established. In the geomorphologic point of view it would be important to correlate models of surface evolution – e.g. formation of fluvial terraces, deposition of freshwater limestone, phases of deflation,

loess-paleosoil sequences, etc. – with the number, frequency, length and intensity of recently confirmed episodes of climate.

This study aims at providing a review of evidences of climatically controlled fluvial and aeolian evolution during the Quaternary in Hungary and their relationship with the global climate events.

Geological, geomorphological setting

The Carpathian Basin comprises several sub-basins in constant subsidence separated by uplifting basement units. Between the Little and the Great Hungarian Plain, where sediment accumulation has been more or less continuous since the late early Miocene, the Transdanubian Range (TR) forms a 300-900 m high range composed of Palaeo-Mesozoic rocks with Neogene cover (sedimentary and volcanic lithology) (Fig. 1).

Almost the entire Carpathian Basin belongs to the catchment area of the Danube River, which is the only river cutting through the TR and connecting the two lowland areas of the basin system. Several terrace remnants occur in this antecedent valley section of the Danube, which terrace remnants perform an upwarped pattern towards the axial zone of the TR relative to the modern river profile (Pécsi, 1959; Gábris, 1994; Ruzsíkiczay-Rüdiger et al.,

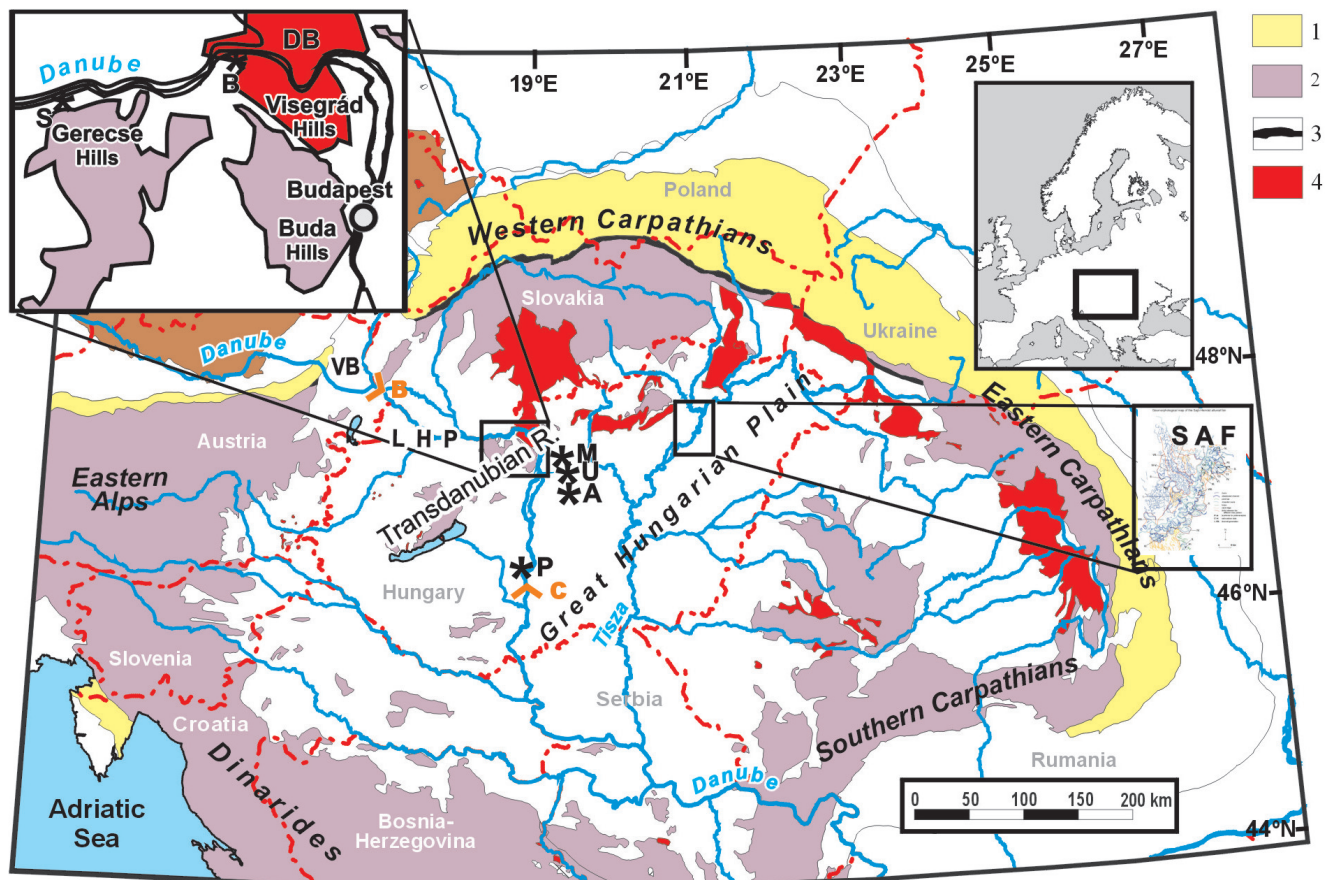


Fig. 1. Location of the study area. 1 – flysch nappes; 2 – pre-Tertiary units; 3 – Pieniny klippen belt; 4 – Neogene volcanic rocks; VB – Vienna Basin; LHP – Little Hungarian Plain; DB – Danube Bend or Visegrád Gorge, SAF – Sajó Alluvial Fan; Loess outcrops: S – Süttő; B – Basaharc; M – Mende; U – Úri; A – Albertirsa; P – Paks; B-C – Location of the longitudinal profile along the Danube of Fig. 4.

2005a; Gábris & Nádor, 2007 and references therein). Incision and valley formation of the Danube tributaries followed the main river and developed terraced valleys as well. In the lowlands, due to their ongoing subsidence, only the Late Pleistocene and Holocene deposits and landforms can be observed on the surface.

Fluvial terrace formation

The Hungarian Danube valley can be divided into five sections. In the transitional areas from the subsiding lowlands towards the uplifting TR gravel terraces have developed in slightly uplifted position, which are often covered by loess-paleosoil layers and/or wind blown sand. Then, at the marginal zones of the TR the river is cutting through carbonate rocks (Gerecse and Buda Hills). Here strath terraces are frequently covered by fluvial material, travertine, loess and/or aeolian sand. The Danube Bend area, where the river incised into middle Miocene andesite, represents the axial zone of the TR (Figs 1. and 4.). Here alluvial cover of the strath terraces is usually missing from the higher horizons, which have been preserved in a very fragmented pattern due to their elevated position.

The climate controlled terrace formation theory was worked out in Hungary by Kéz (1934) and Bulla (1941). Their work was improved and completed by Pécsi (1959), whose study has been the basis of research during the next 50 years; but certainly, numerous modifications and refinements have been done to the scheme (e.g. Gábris, 1997). Previously it appeared reasonable to explain terrace formation as a process connected to glacial-interglacial climate changes recognised in the neighbouring Alps (a summary in Pécsi, 1959). Accordingly, former authors described four (Kéz, 1934), than six (Bulla, 1941) and later eight (Pécsi, 1959) climate controlled Pleistocene terraces in the Carpathian Basin. Terraces were marked from the lowest to the highest by Roman numerals. Terrace no. II represented the Würm, III the Riss, IV Mindel and V was connected to the Günz glacial. Based on further geomorphologic evidence, the youngest floodfree terrace (last glaciation) was sub-divided into two terrace levels – II/a and II/b (Marosi, 1955; Pécsi, 1959).

Now – in the possession of numerous new data on climate changes, terrace development and improved age control – it seems, that we have to revise the former hypotheses defining terrace forming mechanisms and dating of the terraces on the basis of the view of the novel threshold concept and MIS curve. For a longer period of time fluvial processes are aiming at a steady state or state of equilibrium, which is followed by drastic changes: rapid incision or deposition. Any slight modification of a single factor is not sufficient to induce changes in an equilibrium system, because changes occur only by exceeding critical or limiting circumstances, when changes are radical. These are called threshold values (Schumm, 1979; Green & McGregor, 1987). When – in this model – components of environmental change reach such thresholds, the fluvial system adapts to the new circumstances rapidly, hence morphology of the

valley transforms significantly (e.g. Vandenberghe, 1987; 2008; Vandenberghe et al., 1994; Kozarski, 1991; Kasse et al 2005). Consequently, it can be stated that:

1. Incision can occur at the beginning of each climate phase but the process is longer and stronger during the transition from the cold-dry phase into the warm-humid phase than vice versa.
2. Incision is relatively fast and limited to a shorter period of time compared to the longer – lasting from a few thousand years to several ten thousand years – phase of steady state, when sediment accumulation or river meandering is the main process.

On the other hand, effects of the climate can be modified – weakened, strengthened or even overwritten – locally by vertical tectonic movements. The role of tectonic uplift and subsidence must be taken into account when considering the terrace evolution of one particular river or at one definite location.

Global Pleistocene chronostratigraphy and Hungary's fluvial terraces

Studying the Oxygen Isotope curve (Broecker & van Donk, 1970) revealed approximately one hundred-thousand-year cycles in the course of climatic fluctuations. These cycles are divided by events of ‘terminations’, that is, periods of rapid deglaciation due to climatic warming (Fig. 2).

Connection of the global Pleistocene MIS stratigraphy with terrace chronology is based on the theory that gravel aggradation took place during the long, relapsing cooling periods, when the river was able to keep its steady state conditions. Then terraces were created during the rapidly warming phases of terminations, when rivers reach their critical or limiting factors, by the down-cutting fluvial erosion within a few thousands or ten thousands years. From the two surface forming momentums – sedimentation and valley incision – we consider the age of the incision as the terrace's age.

Terminations are marked by Roman numerals (e.g. T I, T II, etc.) and can be characterised differently. Among them there are stages with stronger and weaker, faster and slower, longer or shorter warming periods. For that reason, their geomorphologic effect – in this case the river incision – may differ in degree.

The terrace system in Hungary starts with the lowest terrace-like horizon, the terrace no. I. This level and the lower and higher floodplains are not real terraces as they may be affected by river flooding. These horizons have been created during the Holocene, and most probably in the case of older terraces similar levels have also been formed. However, our current research methods (dating techniques) do not yet allow their distinction.

Methods of palaeontology used for classic dating of terraces are not applicable for proving this system because of scattered findings and insufficient resolution of the age data. During the last decades, fast improvement of ‘absolute’ chronological

methods allowed more precise age determination of terrace covering formations – wind-blown sand, loess-paleosol bodies, travertines, and tephra layers – giving better time constraints on terrace formation than before. In the following section an attempt of the correlation of recently dated terrace horizons to the oxygen isotope chronology (Gibbard & Van Kolfschoten, 2005) is presented.

Relationship between terminations and fluvial terraces in the Carpathian Basin

Formerly the valley incision of the II/a terrace level was considered to be of Holocene age because its surface cover is young aeolian sand only and Pleistocene loess cover is missing. Since then, significant progress has been made in dating of sand movements. Initially, using ¹⁴C data (Borsy et al., 1982, 1985; Lóki et al., 1994), then by using luminescence dating techniques we successfully obtained evidence and revealed late-glacial phases of deflation (Ujházy, 2002).

According to the latest results from a gravel-pit on the II/a Danube terrace (Szentendre Island, Kisoroszi), two fossil soil strata, located above the fluvial gravel and sand were found. Their radiocarbon ¹⁴C age measured on charcoals is 12,036±105 ¹⁴C BP (14,129-14,007 cal BP) and 12,232±125 ¹⁴C BP (14,938-14,879 cal BP) respectively (Ujházy et al., 2003; Fig. 11). Between the two soils a thin layer of wind-blown sand proves that this surface was affected by deflation and therefore, it must have been already flood-free during deposition of this sand. The thermoluminescence age of this sand layer is 14,050±230 years, which data well agrees with the results of radiocarbon dating. In other places this fluvial terrace level is covered by freshwater limestone layers dated respectively between 12-30 ka years. Evaluation of the data in the light of the MIS curve is as follows.

Termination I started with the warming period subsequent to the Late Glacial Maximum (LGM), which is called Ságvár-Lascaux Interstadial (Sümegei et al., 1998) in Hungary. This exceptionally short warming period occurred between 19-17 ka cal BP and it had a considerable geomorphologic effect at several locations (Gábris et al., 2002; Gábris & Nagy, 2005). This phase, together with the succeeding, even stronger early Bølling warming period, played significant role in switching the Danube from its steady state to perform incision and create terrace no. II/a.

Therefore, the youngest flood-free terrace level dates to the end of the Pleistocene, that is, it has become a real terrace at the beginning of Termination I. The deposition of the fluvial material of terrace II/a, in contrast, might have taken place during the long (tens of thousand years) lasting, previous 2-4 Oxygen Isotope Stages (Fig. 2).

Where the Danube valley is cutting through carbonate hills, the higher terraces are frequently covered by travertine. These formations proved to be very useful to determine the age of terraces. For terrace-chronological purposes only travertine bodies deposited on ancient floodplain levels should be used. Collected chronological data of travertine covering the successive terrace levels (summarised see in Kretzoi & Dobosi 1990) are presented in Fig. 2. The radiometric data from the most recent and repeated measurement of the above mentioned travertine layers (Kele et al., 2006; Kele, 2009) indicate roughly the same results. The lack of travertine deposition coincides with the periods of incision or in other words with the Terminations. By the combination of chronological data of terrace covering freshwater limestones and the MIS terminations it can be concluded, that:

- the formation or incision of the terrace referred to as II/b in Hungarian terminology can be regarded as completed during Interstadial 18 rapid and great climate change. Its gravel aggradation must have happened during Late Riss or MIS 6. (Fig. 2);

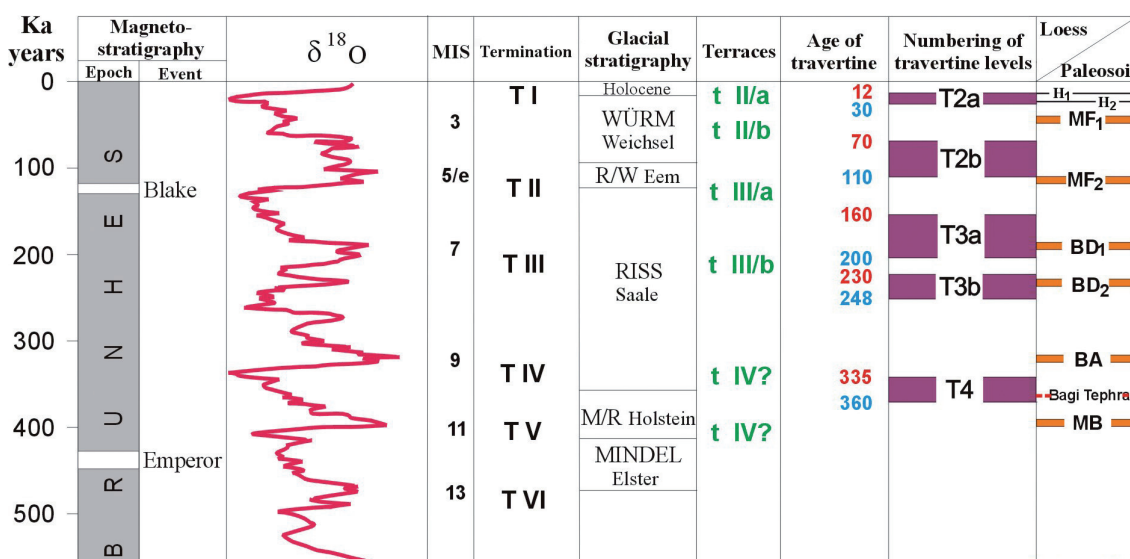


Fig. 2. Correlation between the oxygen isotope stratigraphy (Gibbard & Van Kolfschoten 2005) and the river terraces, travertine layers (beginning and ending of the formation), paleosols (Gábris 2007).

- the Termination II is connected to the morphological appearance of the terrace III/a;
- Termination III was the transition into the warm MIS 7 and it took place 190-180 ka BP. The formation of terrace III/b can be placed to the time period of termination III;
- based on the Buda Castle Hill's investigations, it is possible, that the terrace IV had already become flood-free probably during Termination IV and travertine layers deposited onto this surface. Finally it is difficult to decide, whether the creation of terrace IV occurred associated to Termination IV or Termination V (Fig. 2).

Formation of Hungarian rivers' higher and older terrace V might have taken place before Terminations VII and VIII. Currently, though, we do not have sufficient amount of data for determining more accurate ages. On the other hand, evaluation of the above dataset suggests that in some cases the former terrace classification does not prove correct, therefore it needs further refinement.

Figure 3 displays the revised terrace system of the marginal zones of the TR created by the compilation of novel terrace chronology and MIS data.

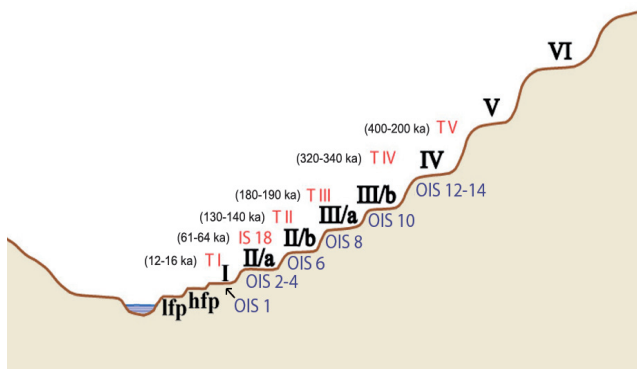


Fig. 3. Generalised profile of the terrace system of the Danube valley in Hungary (Gábris 2011).

Tectonic deformation of Danube terraces

Development of the terrace system bordering the Danube River in the Carpathian Basin was controlled by Quaternary climate oscillations and vertical motions of the Transdanubian Range (TR). As the Danube is the only river cutting through the TR (Fig. 1) elevation of the coeval terraces is a good indicator of the amount of vertical displacement at diverse sections along the river. Incision and terrace development of the Danube tributaries is supposed to have followed the main river. This is why chronological data belonging to a primary tributary of the Danube, mainly concerning the travertines and terraces of the Gerecse Hills, (Által-ér, Vértesszőlös, see Kele, 2009 and references therein) are considered as relevant indicators of tectonic deformation along the Danube as well.

On the other hand, reconstruction of coeval terrace horizons is problematic due to several reasons. 1) Strath and aggradational terraces may have formed simultaneously at different river sections as a response of the combination of climatic and tectonic factors. 2) Owing to subsequent erosion of the uplifted areas, the higher terraces are presently segmented; only small remnants have remained from the higher and older horizons.

On the basis of geomorphological and geological observations (e.g. Pécsi, 1959; Rónai, 1985; Kaiser, 1997) and geodetic levelling (Joó, 2003) locations of the uplifting and subsiding areas are well defined (Fig. 4), but the amount and timing of the uplift is more difficult to constrain. Absolute chronological data obtained at different valley sections from several terrace horizons may help to understand terrace evolution and decipher the incision history of the Danube River.

The existing terrace chronology – the so called 'traditional terrace system' in the Danube valley was based mostly on geomorphological, sedimentological and paleontological data. However these data allowed only a relative chronology, which was valid at certain river sections and did not provide numerical ages of the terrace horizons. This system was later

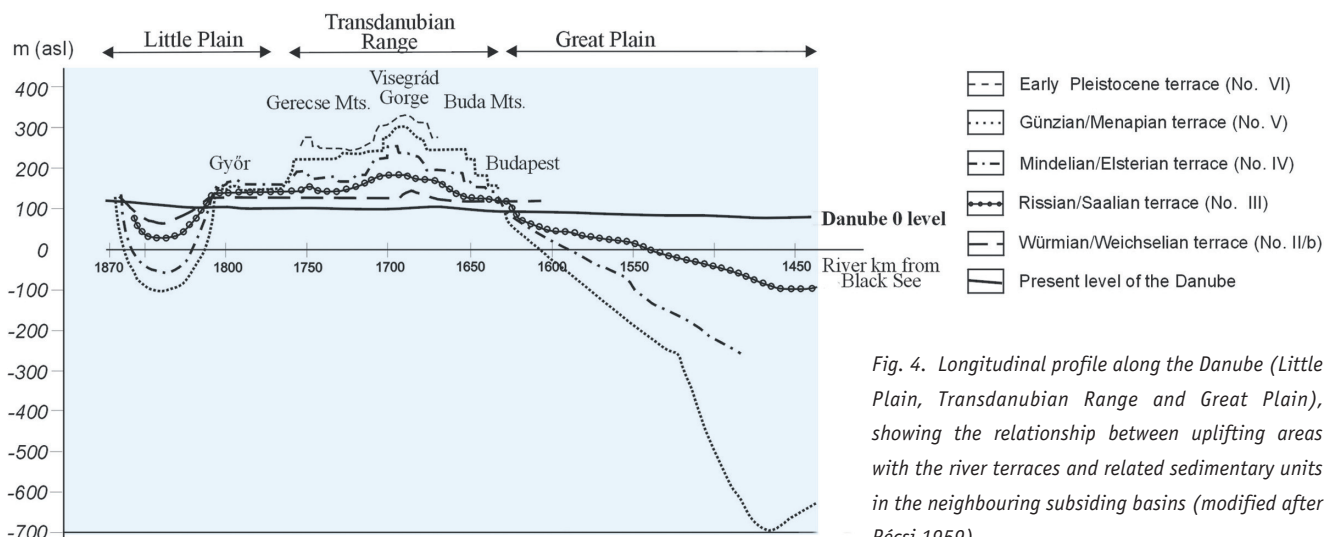


Fig. 4. Longitudinal profile along the Danube (Little Plain, Transdanubian Range and Great Plain), showing the relationship between uplifting areas with the river terraces and related sedimentary units in the neighbouring subsiding basins (modified after Pécsi 1959).

reconsidered and completed by some numerical ages (Kretzoi & Pécsi, 1982) but it has been accepted without major changes until the beginning of the 21st century (Gábris & Nádor, 2007).

The margins of the Transdanubian Range: the Gerecse and Buda Hills

A review and compilation of existing published data (Ruszkiczay-Rüdiger et al., 2005a and references therein) for the last 360 ka yielded incision rates between 0.14–0.23 mm/y for the margins of the TR (Gerecse and Buda Hills; Fig. 1) and 0.41 mm/y for the Danube Bend. Accordingly, the Middle to Late Quaternary uplift rate of the axial zone of the TR exceeded significantly that of the marginal areas, well in agreement with previous studies. During Early Quaternary times the calculated uplift/incision rates were one order of magnitude slower (0.02–0.06 mm/y), with no significant differences at different valley sections. These rates represent an approximation, as some quantitative data are still controversial.

One of these problematic sites is Basaharc (Fig. 1), where the terrace was described as II/b (Pécsi, 1959). But based on the newly determined (OSL) ages of marked fossil soils discovered in it (Basaharc Double (BD) and Basaharc Base (BA)), and mainly on the basis of the occurrence of Bagi Tephra (~350 ka years (Horváth, E., 2001)) the terrace should be significantly older; we, therefore, can identify it as terrace IV.

New uranium-series dating ($^{230}\text{Th}/^{234}\text{U}$) results of travertines in the Buda and Gerecse Hills (Kele, 2009) suggest that there is no direct link between the age of a travertine-covered geomorphic horizon and its elevation above the current valley floor. E.g. in the Buda Hills a travertine body (Gellért Hill, Kele et al., 2009) formerly considered to be Early Pleistocene (Terrace IV–V of the Danube) because of its elevation now was dated as 250–180 ka old (ages relevant for the III horizon). On the other hand, another data set (Rózsadomb, Kele et al., 2011) supports the former age elevation based on the travertine horizons (with U series ages around 350 ka; IV).

New travertine studies suggest that freshwater limestone could develop under glacial and interglacial climate as well, provided that there was enough precipitation to keep the karstwater-springs in operation. On the other hand, travertine ages suggest that different vertical tectonic movements occurred in the Buda and Gerecse Hills even within a small area. Besides, this area is affected by gravitational movements/sliding of the travertine bodies which are underlain by Oligocene clay formations (Pécsi, 1959). These three factors led to a mosaic-like age-elevation pattern of the dated travertine bodies. However, several age data are burdened with error bars as large as 25–30%, sometimes even higher. Accordingly, further age determinations would be necessary to provide more accurate age constraints.

Uplift rates determined by Kele (2009) averaged around 0.3 mm/y – thus were somewhat higher than rates calculated

by Ruszkiczay-Rüdiger et al. (2005a) – but showed a significant scatter between 0.1 and 0.5 mm/y at different blocks of the studied area.

The special part of the Transdanubian Range: the Danube Bend

At the Danube Bend (Fig. 1) the River cuts through Miocene volcanic rocks forming a narrow gorge (Visegrád Gorge) with steep slopes and fragmented remnants of strath terraces. As sedimentary cover is missing from these terraces, until recently, reconstructions relied only on geomorphologic observations and correlation of erosion surfaces over large distances. Exposure age dating using in situ produced cosmogenic ^3He allowed determining the minimum exposure ages of uncovered strath terraces in the Danube Bend area (Ruszkiczay-Rüdiger et al., 2005b), which proved to be significantly younger than it was suggested by previous authors. Accordingly, incision of the Danube in the Visegrád Gorge started only during middle Pleistocene times, compared to the early Pleistocene onset suggested before. The incision rate of the Danube estimated by the ^3He exposure age data was ~1.6 mm/a, which agrees favourably with geodetic levelling data indicating fast (>1 mm/a) present day uplift rate for the Danube Bend region (Joó, 2003). However this rate is about four times higher than values calculated on the basis of previous chronological data sets.

The cosmogenic ^3He exposure ages suggest that horizons of the Danube Bend, which formerly were suggested to belong to the IV terrace level on the basis of their elevation would have been abandoned by the Danube only during the last glacial phase. However, these ages are minimum ages; and a likely effect of erosion of the strath surfaces could not be considered.

Another factor, which could not be taken into account during the calculation of the exposure ages is the possible existence of an alluvial cover on the currently uncovered terraces, which was subsequently removed. Currently, the lower terraces in the Danube Bend (up to III) are covered by gravelly-sand sediments of the Danube. Such alluvial material could have a shadowing effect on the strath surface of the terrace. In this case the ^3He exposure ages show the time of the disappearance of this sediment, which is evidently younger than the real terrace age. However, fast disappearance of all cover sediments (if existed) from these geomorphic horizons after ca 270 ka would still point to the existence of a phase of intensive uplift during the second part of the Middle Pleistocene (around MIS 9–10).

Consequently, due to differential tectonic deformation in the Transdanubian Range it is not correct to consider coeval terraces located at the same altitude along the river. Valley sections have their own history of terrace formation, with a different number and age of terraces. It is impossible to follow these levels along the entire valley, especially concerning terraces older than the last glacial phase. Tectonic deformation

could lead to poor development of some terraces at some valley sections and make others more characteristic, or make some horizons doubled at one part of the valley, which appear as a single terrace level at others.

River pattern changes on the plains

Methods of chronology and reconstruction of fluvial evolution

The presented geomorphologic map of the study area – Middle Tisza valley and the Sajó–Hernád alluvial fan – shows the geographical distribution of the varied meandering and braided river patterns as well as the erosional steps, formed during episodes of incision (Fig. 5). This map was drawn using detailed topographic maps (1:10,000), aerial photographs and field observations (Gábris & Nagy, 2005). Distinct regions are characterised by different channel-planform morphologies resulting from different fluvial mechanisms (deposition and lateral erosion). These are separated by erosional scarps, which mark incision events. Late Pleistocene and Holocene climatic and tectonic controls are reflected partly by meandering and anastomosing channel pattern changes, partly by erosional

scarps that mark phases of erosion and accumulation. This work has led to the surface mapping of a ‘horizontal stratigraphy’ and it is part of a larger research project in the Tisza region.

The chronology of the abandoned river meanders is based on pollen analyses (Nagy & Félegyházi, 2001; Magyar, 2002), which are supported by malacological analyses (Krolopp & Sümegei, 1995). A number of radiocarbon data contribute to the age determination of the meanders (Davis & Passmore, 1998). On the aeolian sand dunes some luminescence data supported the chronology (Ujházy et al., 2003, Gábris, 2003). Field research, radiocarbon dating and pollen analysis were carried out in cooperation with the Vrije Universiteit, Amsterdam (Vandenberghe et al., 2003; Kasse et al., 2010) and with the University of Debrecen (Gábris et al., 2001).

Based on the meandering and braided river pattern styles separated mainly by erosional scarps six distinct phases of river pattern change and four incisions have been detected (Gábris & Nagy, 2005). Fig. 6. shows the relative chronology of these river style variations. The different phases characterised by braided and meandering pattern are indicated by Roman numerals and the incision episodes are indicated by letters, both on the diagram of Fig. 6, the map of Fig. 5. and in the text.

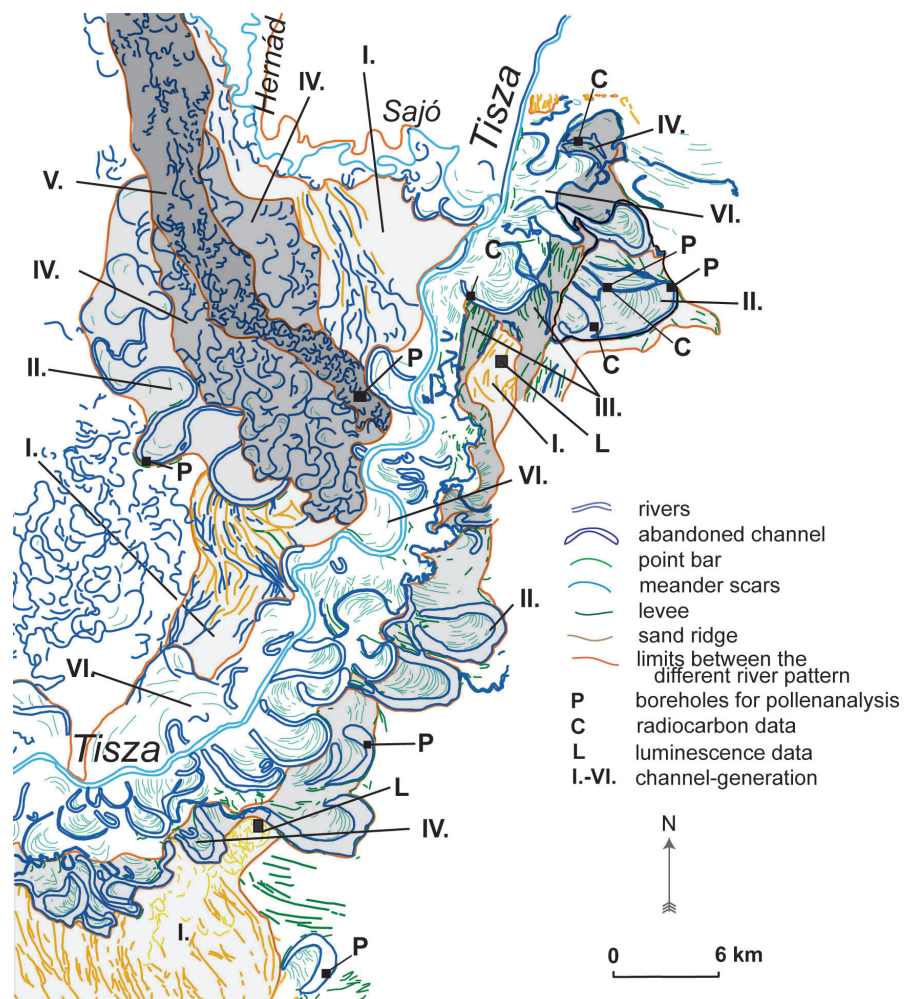


Fig. 5. Geomorphologic map of the Middle-Tisza and Sajó-Hernád alluvial fan region (Gábris & Nagy, 2005).

Phases of fluvial style changes

The oldest surface is characterised by loess-covered linear sand ridges, interpreted as levees of a braided river system (phase I). The wind modified the sandy areas, and deflation landforms occur locally (Gábris et al., 2002). Based on a radiocarbon data and on a pollen diagram (Vandenberghe et al., 2003; Kasse et al., 2010) their age appears to relate to the coolest period of the Upper Pleniglacial between 19-23 ka cal BP (18-21 ka ¹⁴C BP), hence to the Last Glacial Maximum.

The termination of this phase is clearly marked by a distinct incision phase (A). An erosional step developed between the preceding surface and the lower plain characterised by a meandering river pattern. This incision-period was probably caused by climate change.

The largest meanders (phase II) occurred in two geographically separated regions, on the Sajó alluvial fan and the eastern border of the Tisza valley. These two meander generations seem to be similar in age, but different in size and origin. In the Tisza valley the meanders are larger and indicate the main river of the GHP. On the alluvial fan the meanders of this generation are smaller in correlation of the lower discharge of the Sajó-Hernád (Tisza's tributaries). We obtain three pollen diagrams

from this meander generation. The diagram from the largest meander suggests an age older than Late Glacial (Fig. 6). Two other boreholes were drilled in a large and narrow palaeochannel of the Tisza valley. The channel lag in the lower part of the sediment core contains very few pollen indicating an extremely cold period. In one of these meanders we have a conventional radiocarbon date: 20,470±310 ¹⁴C BP (Davis & Passmore, 1998) from the base of the channel fill. On the basis of the radiocarbon dating and the pollen content of the abandoned meander fill we suggest that the meander was formed during the increased water discharge just after the Last Glacial Maximum when periglacial circumstances dominated in the water catchment area of the great river (Gábris, 1995). Sedimentation in the oxbow lake has continued until recent times.

The next phase (III) is characterised by the second braided period. The remains of this morphology occur only in two small areas in the Tisza valley in the NE part of the study area.

On the alluvial fan a large region represents the fourth period (phase IV) characterised by abandoned medium sized meanders, but these surfaces lie below the preceding level of the meandering rivers and this position indicates a downcutting period (phase B) in the fluvial development. A core site was located on the alluvial fan of Sajó River but only some *Pinus* sp.

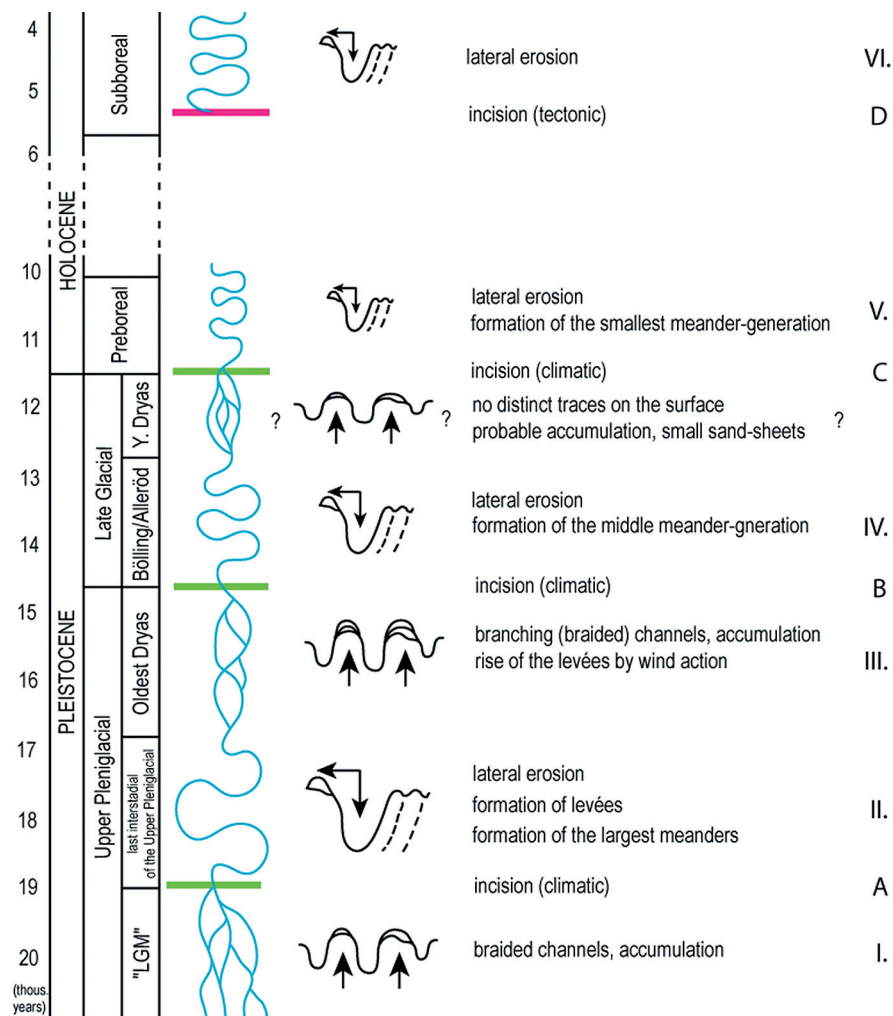


Fig. 6. Diagram of the reconstructed fluvial style changes on the Middle-Tisza and Sajó-Hernád alluvial fan region (Gábris & Nagy 2005).

pollen were found in the basal part of the borehole sample which was not enough to indicate the age and the environment of the period of its formation. However, the pollen record suggest an age of the early period of Younger Dryas (Magyari, 2002). Therefore, meander formation may relate to the Allerød.

During the transition between the cool, dry Younger Dryas and the warmer, more humid Preboreal the rivers cut down again (Vanderberghe, 2008; Vandenberghe et al., 1994; Kasse et al., 2005) into the surface of the alluvial fan (phase C). As a result, rivers widened their meanders in this level and formed the next channel generation (phase V). This smallest meander generation of the Sajó River extends over the axis of the alluvial fan. The boundary between this surface and the level of the preceding meander generation is marked by a distinct step. Based on the pollen diagram the infilling of the smallest size abandoned meanders started at the beginning of Subboreal.

In the late Holocene the Tisza River cut again into the surface (phase D), and this is indicated by well-developed erosional steps on both sides along the above mentioned meander generation. This lowest surface of the Tisza valley is characterised by overdeveloped young meanders (phase VI). One of the abandoned meanders has a radiocarbon age: 4070 ± 100 ^{14}C BP (Davis & Passmore, 1998). The abandoned riverbed of this meander generation of the Tisza River were artificially cut-off during the river regulation works in the last 150 years, which clearly reflects modern anthropogenic impact.

Deflation periods

In the Pannonian Basin widespread occurrence of aeolian landforms and sediments has been recognised. The role of deflation in the Pliocene-Quaternary evolution of transdanubian relief was recently investigated by Csillag et al. (2010) and Sebe et al (2011). Wind polished rocks or ventifacts have been described from several locations, mostly in the western part of the Carpathian Basin (Jámbor, 2002; Sebe et al, 2011). Based on the results of previously mentioned studies, most probably older deflation phases existed as well. A first approach to determine the real timing of these periods was done using in situ produced cosmogenic ^{10}Be exposure ages of wind-polished rock surfaces (Ruszkiczay-Rüdiger et al., 2011).

Cosmogenic ^{10}Be exposure dating of wind-polished rock surfaces

Exposure age of wind-polished surfaces was determined using in situ produced cosmogenic ^{10}Be in the CEREGE-CNRS laboratory in France (Ruszkiczay-Rüdiger et al., 2011). Ventifacts were sampled in the Balaton Highland (Fig. 1), where denudation is considered to have happened mostly by deflation (Sebe et al., 2011 and references therein). These sampled surfaces were erosion resistant, silica-cemented remnants of the Upper Miocene Lake Pannon sediments, which are otherwise easily affected by erosion. They are composed mainly of quartz, and are therefore ideal for cosmogenic ^{10}Be studies.

Recently it has been demonstrated that using depth profiles – thus considering all particles (neutrons and muons) involved in the production of cosmogenic nuclides (for methodology refer to Siame et al., 2004; Braucher et al., 2009; Hein et al., 2009) – it is possible to determine both denudation rate and exposure age of a surface. This is a great advantage with respect to single surface samples, as this technique allows establishing erosion rate-corrected exposure ages of the ancient rock surfaces.

Depth profiles on wind-faceted hard rock provided ^{10}Be exposure age – denudation rate pairs as shown in Table 1 (Ruszkiczay-Rüdiger et al., 2011). Accordingly, the 200 m level in the basins was exposed 1.56±88 Ma ago, the 170 m horizon 865±65 ka ago and aeolian denudation reached the 140 m level 287±23 ka ago. At 175 m elevation (Kővágóórs) ^{10}Be measurements occurred along a depth profile in loose sand with the aim of constraining directly the denudation rate of this material, and control our calculations using the age and elevation of the hard rock depth profiles. Fast denudation of the loose sand did not allow the determination of the exposure time at this location; the reported age reflects only a steady state of cosmogenic nuclide accumulation and decay.

A first conclusion on exposure ages derived from the depth profiles demonstrates that deflation was active and strong already ca 1-1.5 Ma ago. No wind erosion of similar age has been reported from Europe so far.

Local denudation rate of 3.44-3.84 m/Ma resulted to be low (Table 1), which explains why the silica-cemented rocks have been prepared from their surrounding composed of loose sandy material.

Regional denudation rate was calculated using the ^{10}Be exposure ages and the elevations of the wind-polished hard

Table 1. Cosmogenic ^{10}Be exposure age – denudation rate pairs for the sampled depth profiles (for more details and measurement technique refer to Ruszkiczay-Rüdiger et al., 2011).

Location	Latitude (DD)	Longitude (DD)	Elevation (m)	Lithology	^{10}Be exposure time (a)	^{10}Be denudation rate (m/Ma)
Kelemen-kő	46.8906	17.5560	198	sandstone	1,560,534±88,442	3.44±0.19
Kővágóórs	46.8642	17.6217	175	sand	257,293±46,871	56.07±11.95
Kómagas	46.8648	17.4978	171	sandstone	864,813±65,191	3.84±0.29
Salföld	46.8323	17.5630	141	sandstone	286,799±23,121	0±0

rock surfaces, which were interpreted as remnants of fossil geomorphic horizons. Accordingly, regional denudation in the Tapolca and Kál Basins varied between 40 and 80 m/Ma, which are in harmony with the ^{10}Be denudation rate of 56.1 ± 12 m/Ma calculated directly from the loose sand depth profile at Kővágóörs (Ruszkiczay-Rüdiger et al. 2011).

Periods of aeolian sand movement

Widespread regions of the Carpathian Basin are covered by Late Pleistocene and Holocene aeolian sand sediments (Fig. 7). The parent material of the wind-blown sand derives mostly from the ancient alluvial fans of the Danube and Tisza river systems (i.e. Nyírség and Danube-Tisza Interfluve). The alluvial silt- and sand-sized material was deflated and accumulated in adjacent areas mostly after short-distance transportation.

Sand was moved by the wind during the drier and colder stadial/glacial periods, while the dunes were fixed during the warmer and wetter interstadials/interglacials due to expansion of the vegetation cover and soil formation. The alterations of sand and buried soil layers are important archives of the Late Pleistocene/Holocene climate and environment changes.

The first chronology of the sand-moving periods from the Nyírség and the Tisza-Bodrog Interfluve (NE of Great Plain) was proposed by Borsy et al. (1982, 1985) using radiocarbon dating. Organic materials from buried soils, which are intercalated within the sand dunes were investigated by the radiocarbon method to estimate the age of aeolian sand activity. This means,

radiocarbon data are related to the soil formations and not to the aeolian phases, therefore they can be considered as tool for indirect dating method of periods of wind blown sand accumulation.

Direct dating of sand movement periods became also possible from the mid 80's, using different luminescence dating methods (like thermoluminescence (TL), Infrared Stimulated Luminescence (IRSL) or Optically Stimulated Luminescence (OSL) using blue light), which give the burial time of the deposits. The first luminescence dating study of dune sands near the River Danube was carried out by Ujházy (in Gábris et al., 2000) and the chronology, based on the radiocarbon and luminescence methods was elaborated by Gábris (2003). Recently, sand dunes from the middle and southern part of the Danube-Tisza Interfluve, along the Tisza river and from the southern part of the Nyírség were investigated using OSL dating of quartz grains in combination with radiocarbon dating (Nyári & Kiss, 2005; Kiss et al., 2006, Gábris et al., 2011; Novothny et al., 2010) (Fig. 7).

The most significant sand movement period in the Carpathian Basin started in the beginning of the Late Pleniglacial, by the time the alluvial fans of the rivers were not flooded anymore. The scarce vegetation cover was not able to protect this alluvial silt- and sand-sized material from the effect of the strong, mostly North-Westerly winds. Deflation reached its maximum intensity during the LGM. This sand moving period – as the most significant Pleistocene sand movement period in the Carpathian Basin – was detected by Sümegei (1993) and Krolopp et al. (1995) using radiocarbon age determination. Wind-blown



Fig. 7. Sand covered areas in Hungary and location of the most important dated sand dunes. Localities of the radiocarbon data (fig. 2. in Gábris et al. 2003): 1 – Kisorozvány; 2 – Aranyosapáti; 3 – Székely; 4 – Nyírmihálydi; 5 – Vajdácaska; 6 – Bodroghalom; 7 – Kenézlő; 8 – SSE of Debrecen; 9 – Dunavarsány; 10 – Kisoroszi; 11 – Jászfelsőszentgyörgy; 12 – Háy-tanya; 13 – Szeged-Óthalom.

sand accumulation during LGM was revealed at three sites along the River Tisza (Polgár, Egyek, Abádszalók) using IRSL and OSL dating (Fig. 8).

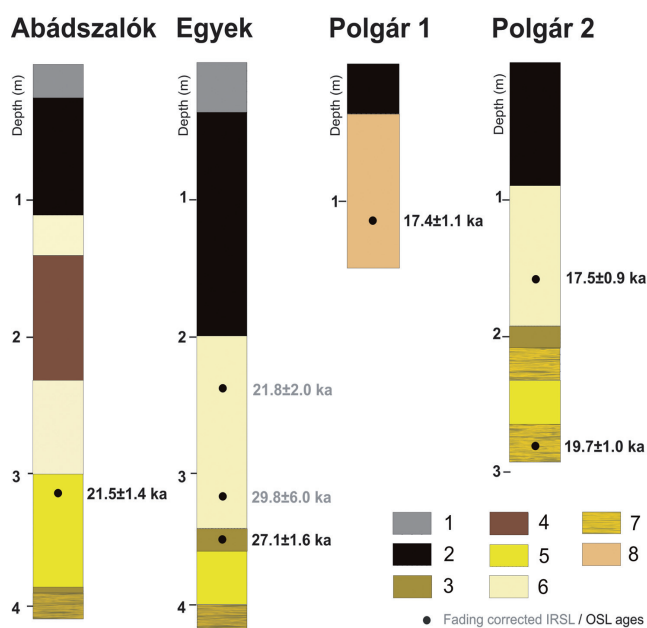


Fig. 8. Sand profiles and OSL/IRSL dating of quartz/feldspar grains along the Tisza River. Legend: 1 – banking up; 2 – soil; 3 – fossil soil; 4 – loess; 5 – sand; 6 – coarse sand; 7 – fine sand; 8 – sand and silt (Novothy et al., in prep.).

The milder and wetter climate of the following interstadial period (named Săgvăr-Lascaux in Hungary) favoured the expansion of the vegetation cover, which could protect the surface against wind erosion. This process was supported by the intensive dust accumulation and the significant loess cover helped to fix the dunes. This process is detected along the River Tisza at the aforementioned three sites (Polgár, Egyek, Abádszalók), where aeolian sand layers are overlaid by loess cover with a thickness of 0.5-1.5 m (Fig. 8). This loess cover also preserved the Late Pleniglacial surface for long time and hindered any latter sand movements (Novothy et al., in prep).

Bare and non-protected sand covered surfaces could again be mobilised by the strong winds of the following stadial period (Oldest Dryas), between 17-14 ka. This sand movement period is poorly demonstrated in Hungary (in contrast with the Netherlands: Kasse et al., 2007), however, in a sand dune at Tura (in the Galga valley, Gödöllő Hills) one of the sand-blowing periods correlates with the Oldest Dryas (Fig. 9), as evidenced by both, IRSL and OSL dating results (fading corrected IRSL age of 15.5 ± 1 ka and OSL age of 15.6 ± 1 ka) (Novothy et al., 2010).

During the warmer and wetter climate of the Bølling period of the Late Glacial the surface was covered by steppe-forest or steppe vegetation, which hampered the re-mobilisation of the accumulated sand. Well-developed soil horizons formed on the sandy surface, preserving remnants of the ancient vegetation, which provided organic materials for radiocarbon dating. The first dating investigations were carried out by Borsy et al. (1982, 1985).

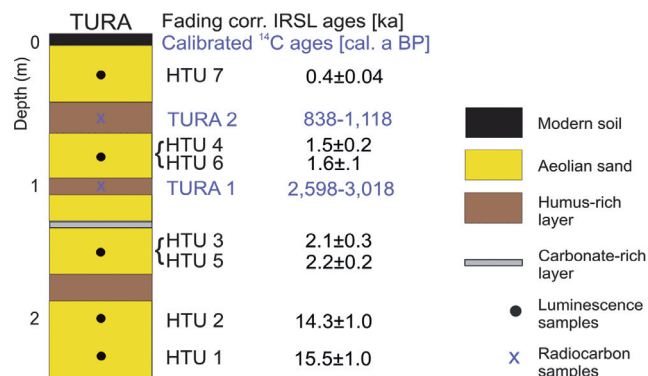


Fig. 9. Sand profile dated by luminescence and radiocarbon methods from Tura (Novothy et al., 2010).

The warmer period was interrupted by the short colder cycle of the Older Dryas stadial which is confirmed by IRSL and OSL dating at Tura, which was followed by rapid warming during the Allerød. At the end of the Late Glacial strong winds and regression of the vegetation led again to sand re-mobilisation due to dynamic cooling during Younger Dryas, which resulted in accumulation of sand layers with a thickness of maximum 10 m. Sand-moving periods during Younger Dryas are evidenced by IRSL dating results from sand dunes along the Danube (Fig. 10) at Dunavarsány (Ujházy et al., 2003) and Pócsmegyer (Gábris et al., 2011) yielding ages of 12 ± 1.9 ka and 11.9 ± 1.9 ka, respectively. IRSL dating results are in agreement with radiocarbon data, which indicates, that IRSL ages are slightly effected by underestimation due to anomalous fading of IRSL signal of feldspar (Ujházy et al., 2003).

Due to the favourable climate of the Preboreal phase of the Holocene the closing vegetation cover protected the sand surface from further deflation. Sand-movement renewed again during the Boreal phase, when increasing aridity led to retreated vegetation and therefore sand mobilisation has again started. This deflation is confirmed by IRSL dating results from three sites along the Danube (Fig. 10-11) yielding IRSL ages of 8.1 ± 0.5 ka, 8.4 ± 1.3 ka and 8.4 ± 1.6 ka, respectively (Ujházy et al., 2003). However, the affected area was significantly smaller than it was during previous deflation periods. On the aeolian sand deposited 8200 ± 300 years ago (Gábris et al., 2011) a brown forest soil developed in the Danube valley, which preserved the surface through 3-7 thousand years in this region. Later it was covered in some places by aeolian sand again in different periods (Gábris et al., 2011). The higher humidity during the first part of the Atlantic phase decreased dramatically the extent of the deflation affected areas but the drier second part of the Atlantic favoured also for sand mobilisation, as it is evidenced at Dunavarsány (IRSL age of 6 ± 0.5 ka) (Ujházy et al., 2003). This deflation indicates the latest climatically controlled arid phase in the Holocene.

Climate governed sand mobilisation ceased from the Subboreal phase of the Holocene, however sand movements still occurred in various places and increased intensity during the

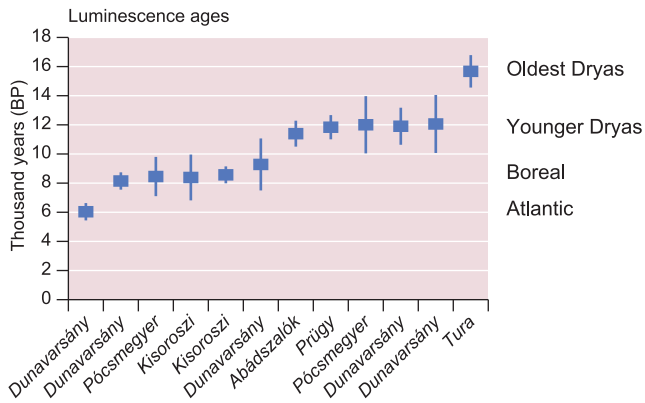


Fig. 10. Diagram of the luminescence dated aeolian sand layers from six characteristic sand dunes.

late-Subboreal and Subatlantic phase. But there was mostly triggered by human activities (Gábris 2003). The luminescence dating of the uppermost sand layers of the dune at Pócsmegyer (Gábris et al., 2011) yielded evidence for sand movement during the Subboreal and early Subatlantic phases (IRSL ages of 3.7 ± 0.9 ka and 2.9 ± 0.02 ka) due to the activity of the Middle and Late Bronze Age population. Recent studies mainly focused on historical periods of aeolian sand activity. Sand dunes from the middle and southern part of the Danube-Tisza Interfluvium (Nyári & Kiss, 2005; Kiss et al., 2006), near the Tisza River (Gábris & Túri, 2008) and from the southern part of the Nyírség (Kiss & Sipos, 2006) were investigated using archaeological findings, OSL and radiocarbon dating. One of the youngest sand blowing periods was traced from the sand profile at Tiszakürt. OSL ages represent sand blowing periods from historical times from the 11-12th (Hungarians turned from semi-nomad husbandry to agriculture), and from the 18th centuries when the agriculture was restored after destruction under Turkish Rule (Gábris & Túri, 2008).

Loess and paleosol sequences

Loess is an important sediment archive, it covers about 30% of the Hungary, and the maximum thickness of the loess sequences reaches 40-50 m. It covers different geomorphologic surfaces e.g. terraces, foothills, hilly landscapes and it is intercalated by fossil soils, which are indicators of the warmer and more humid periods.

The first descriptions of loess in Hungary are from the 19th century but the first age estimations appeared in the beginning of the 20th century in connection with the Milankovich theory (Bulla 1938). The development of different absolute age determination techniques (^{14}C , thermoluminescence and later optically stimulated luminescence, AAR) resulted in significant changes in the chronological framework of loess formation. The loess paleosol sequences of Hungary with the absolute chronological data are presented in Table 2.

In the early work of Pécsi (1975) the upper part of the Mende Base (MB2) paleosol was suggested to represent the last interglacial. The fact that MB2 is the first Brown Forest Soil from the top in both reference loess sections at Paks and Mende confirmed the assumption of Pécsi (1975, 1987), which was based on the convention of the INQUA Stratigraphic Commission (1961). This hypothesis survived for decades despite of the conflicting arguments and the results of different age determinations. The study of Wintle and Packman (1988) stated a markedly different view, placing the position of the Last Interglacial much higher in the loess sequence, in the MF2 paleosol, as proposed by Kukla in 1977. Based on the controversial absolute age determinations (Zöller & Wagner, 1990; Zöller et al., 1994 and Lu 1990 in Pécsi & Richter, 1996), Pécsi (1995) revised his chronology and accepted that the lower part of the Basaharc Double paleosol (BD2) represents the last interglacial.

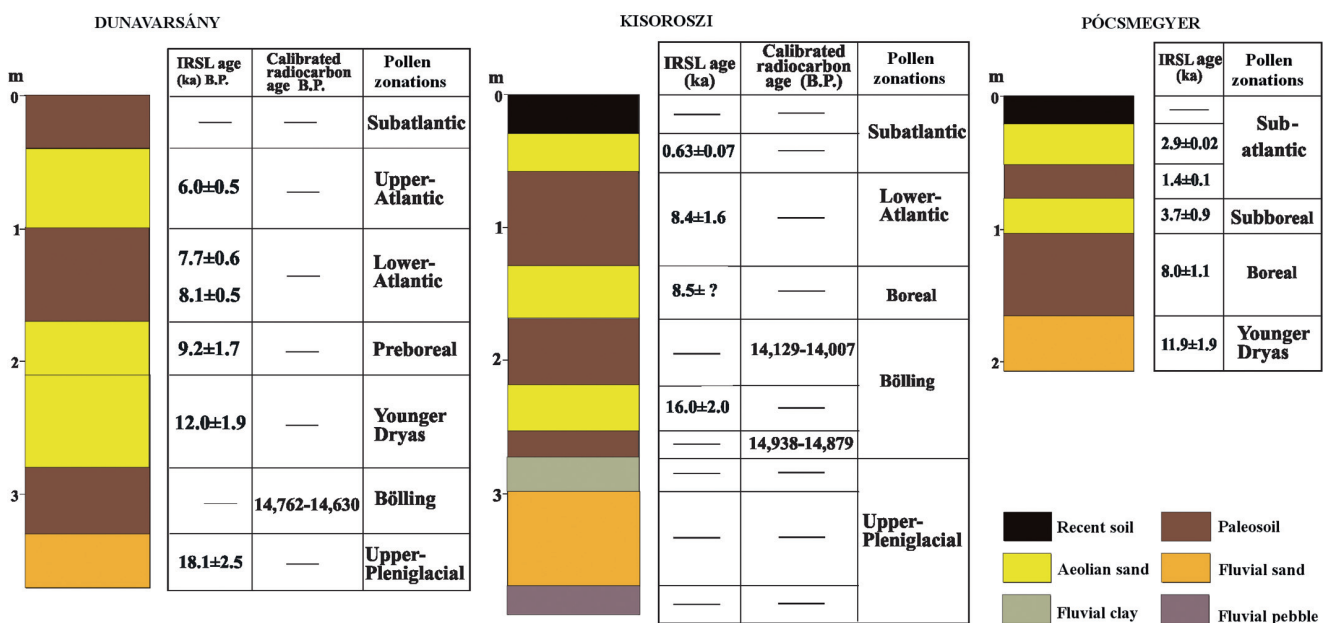


Fig. 11. Luminescence and radiocarbon dated sand profiles along the Danube (Ujházy et al., 2003; Gábris et al., 2011).

Table 2. Age determinations of the Hungarian loesses. TL – Thermoluminescence; OSL – Optical Luminescence; R/W – Riss-Würm interglacial; I1 – I6 young and L1 – old loess horizons; h1-2 – humic horizons; MF – Mende Upper Paleosoil; BD – Basaharc Double paleosoil; MB – Mende Base paleosoil.

Loess	Borsy et al. 1979	Butrym-Maruszczak 1984	Wintle-Packman 1988	Zöller 1987	Zöller 1988	Zöller-Wagner 1990	Lu 1991, 1992	Pécsi 1995	Frechen et al. 1997. Novothny et al. 2002, 2009
Paleo soils and humus horizons	TL (Paks)	TL (Paks)	TL (Basaharc, Mende, Paks)	TL (Basaharc)	TL (Paks)	TL + molluscs (Mende)	TL (Paks, Mende, Basaharc)	¹⁴ C, TL estimation (Paks, Mende, Basaharc)	TL+OSL (Paks, Mende, Basaharc, Albertirsa, Úri, Süttő)
I1		19.6±2.4 21.7±2.6	15.8±1.3 17.6±1.4						
h1								W3 (16-17)	
I1			23.2±1.9				27±2.5		
h2								W2/W3 (27-32)	
I2		25.7±3.1	24.0±2.0						(25-35)
MF1		28.7±3.7	20.9±1.7			44.3±2.7		W2/W3 (45-60)	
I3			43.4±3.8						(50-60)
MF2		33.5±4.5	R/W (74.7±6.5)			69.3±5.4	73.7±5.1	W1/W2 (85-105)	OIS 5 (65-130)
I4		35.0±4.2	R (79.2±6.1)	94±9	114±11				OIS 6 (>130)
BD1		37.8±4.2				R/W 116±17	R/W	R2/W1 (120-140)	
		39.0±4.7			144±14	141±14	114±12		
BD2		41.4±5.0		R/W	R/W	147±12		R2/W1 (150-170)	
I5		45.0±5.5 53.0±6.5 77.0±10.0		135±12 163±18	159±17 172±18	207±16	153±15		
BA		81.0±10.6 87.0±11.3						R1/R2 (195-230)	
I6	105±17	98.0±13.0			190±17				
MB1	R/W	121.0±16.0				270±26		MR3/MR4 (280-310)	
MB2	R/W	124.0±17.0						MR2/MR3 (320-360)	
L1	110								

Based on thermoluminescence (TL) and infrared stimulated luminescence (IRSL) results (Frechen et al., 1997), supported by other methods, such as amino acid stratigraphy (Oches and McCoy, 1995), malacological and pedological evidences the position of the last interglacial has been moved to a higher position in the loess stratigraphy of Hungary however it was still not unequivocal which paleosoil represents it.

It is clear that a loess chronostratigraphy can not be established based on the order and number of the intercalating paleosoils as different local conditions lead to different type of soil formation during the same climate zone. It also means that the use of the terminology of Pécsi (1975) is not suitable anymore, but it must be sustained until a new concept is worked out and becomes widely accepted (Table 3). Therefore, any kind of absolute age determination has a great importance to create a reliable chronological frame for this work.

Our most recent studies on Hungarian loess sequences – as it is detailed later – have been expanded in space and time, as more loess outcrops were involved into our investigations (Albertirsa, Úri, Süttő) and the formerly investigated profiles (Basaharc, Paks) were partly resampled and different luminescence techniques (fading corrected IRSL, post IR-IRSL, IR-RF) have been applied to get more precise age determination (Novothny et al., 2009; Novothny et al., 2010).

Chronological studies indicate large discontinuities in the Upper Pleistocene loess in the key sections at Basaharc, Mende and Paks (Wintle & Packman, 1988; Zöller et al., 1994; Frechen et al., 1997) suggesting that most of the last interglacial to early glacial record is missing from the Hungarian loess sequences (Table 3). The same situation occurred at the loess section at Albertirsa (Novothny et al., 2002), where a surprisingly young luminescence age was determined from the lower (MF2-type) paleosoil. Luminescence ages showed a huge time gap as well, but besides revealed the lack of the last interglacial paleosoil in this section (Novothny et al., 2002). This fact has raised the question whether the similarly big time gaps (50-60 ka between the ages above and below the MF2 paleosoil) in the earlier investigated profiles at Paks, Mende and Basaharc (Frechen et al., 1997) suggest also the lack of the last interglacial paleosoil. Since the other European loess-paleosoil sequences do not show this hiatus and the last interglacial soil formation is detectable, local conditions, such as stronger erosion due to neotectonic movements might be responsible for it.

This problematic, missing part of the generalised loess section is preserved in the loess outcrop at Süttő where a small paleo-valley is filled up with a reddish brown fossil soil, which is laterally tapering and fading out. This paleosoil is overlain by

Table 3. Most recent luminescence ages of the Hungarian loesses. l1-4 – loess horizons; h1-2 – humic horizons; MF1-3 – Mende Upper Paleosoils.

		Basaharc	Mende	Albertirsa	Űri	Süttő
OIS2	l1			20.6±4.9		22.1±1.6
	h1			16.8±4.8		18.0±2.2
	l1			19.2±2.2	20.5±1.7	27.1±2.4
				21.7±4.8	20.2±1.7	25.9±3.2
	h2			22.9±2.9	22.9±1.8	
OIS3	l2	28.2±4.4	27.2±2.8 34.1±3.2 32.5±3.2			31.2±2.2 34.7±4.7
	MF1			29.1±5.2 37.1±4.2	25.6±2.1	
OIS4	l3		55.0±5.4	53.0±8.7	39.4±3.2 56.1±4.5	55.2±5.9 58.3±6.4 58.2±4.7 53.2±2.1 75.3±4.7
	MF2			65.9±10.7		71.5±5.7
	MF3?					84.1±5.7
OIS5						93.7±21.1 106±13 137±23
OIS6	l4	156.1±46.3 121.0±13.6 128.6±28.1	148.7±13.7	120.0±19.0		125±20 116±15 137±25 138±8

a dark brown, chernozem-like paleosol and then two thinner brownish steppe-like soils, bracketed by loess layers. Fading corrected luminescence ages supported by other methods such as AAR, MS (Novothny et al., 2009, 2010) clearly show the presence of the last interglacial soil formation, which is not yet confirmed anywhere else in Hungary (Table 3). In the middle part of the section a stronger and a weaker soil formation took place in MIS3, representing the warmest and most humid period of MIS3, consistent with MF1 in the Pécsi's classification (Pécsi, 1975) and the h2 humic layer, respectively. The loess profile at Süttő is important because of the very detailed multi-proxy investigations, which allow an excellent paleoenvironmental reconstruction of the penultimate and last glacial periods.

The loess outcrop at Űri developed in the Upper Pleistocene and contains two paleosoils (MF1 and most probably MF2) and a humic horizon (h1). Despite of its small thickness, this section is important due to the strong (2-5 cm thick) charcoal layer in the MF1 paleosol, which is typical for the European loesses of the same age as well, and represented also in Hungary in the outcrop of Mende.

Conclusions

The Hungarian river terrace system and its chronology were renewed considering the novel threshold concept. Two different periods are determined in terrace evolution: a state of equilibrium during the long glacial phases and short transitional phases at the end of glacial cycles – the terminations. A revised terrace chronology of the Danube was created on the basis of the age data of the travertine bodies covering terrace surfaces and compared to MIS data.

Dating results of terrace surfaces, fluvial sediments and/or travertine and loess cover of the terraces enabled to give better time constraints on terrace evolution and thus a better understanding of Quaternary vertical motions. River incision/tectonic uplift rate could be higher than 1 mm/a in the axial zone of the TR – a rate significantly higher than it was suggested before –, and was around 0.1-0.3 mm/a in its marginal areas during the last 350 ky. Tectonic deformation in the TR could locally modify the development of climatically controlled terraces. Tectonic deformation could lead to poor development of some terraces at some valley sections and make others more characteristic, or make some horizons doubled at one part of the valley, which appear as a single terrace level at others. Valley sections have their own history of terrace formation, with a different number and age of terraces.

During the cold, dry phases of the Pleistocene the strong winds formed the surface. Aeolian processes were favoured by the scarce vegetation and the considerable amount of fine grained material, which could be mobilised. The age of wind erosion and sediment accumulation are possible to determine using exposure age dating and luminescence methods, respectively. This way it is possible to estimate the significance of the wind in the Quaternary landscape evolution of Hungary.

Exposure ages derived from wind polished rock surfaces dated by in situ produced cosmogenic ¹⁰Be suggest that deflation was active and strong in Hungary as early as 1.5 Ma ago. No wind erosion of similar age has been reported from Europe so far. Moreover, our result suggests that during the Quaternary wind erosion could lead to significant surface denudation in the continental climate zone in Central Europe. According to these exposure age data, Pleistocene aeolian denudation rate in the study area (Balaton Highland) was 40-80 m/Ma.

The other aspect of the aeolian processes is the sediment accumulation. Considerable amount of dust deposited and formed loess in the Carpathian Basin during the Pleistocene. Accumulation processes of the glacial/stadial periods were interrupted by the soil forming periods of the interglacial/interstadial times. Thus the loess-palaeosol sequences are one of the most significant and detailed terrestrial archives of the Quaternary, which provide detailed and direct record of palaeoenvironmental changes.

Our dating techniques (luminescence and radiocarbon dating, AAR method) are able to date Middle- to Late-Pleistocene

sediments. Therefore our interest is mostly focused on the younger/youngest part of the accumulated loess-palaeosol sequences, their older part is unfortunately beyond our potential. By the compilation of several profiles the reconstruction of an ideal stratigraphical record was possible for the Carpathian Basin from the penultimate glacial (MIS 6) to the last glacial (MIS 2). According to our knowledge, the basically cold, dry and windy climate (glacials/stadials) of the Pleistocene was interrupted by milder and wetter periods (interglacials/interstadials) at least 6 times (MIS 5e, c, a, MIS 3 and MIS 2).

The climate during the MIS 5 and 3 probably was similar to the climate today (similar mean temperatures but sometimes less, sometimes more moisture) therefore, brown forest steppe-like soils or chernozem soils could develop on the loess. During MIS 2 the small climate variations – like slight warming or humidity changes – can be tracked in the loess profiles as humus rich horizons (h1 and h2). According to our detailed and multiproxy investigations, it can be concluded that different local conditions may lead to different type of soil formation within the same climate spell.

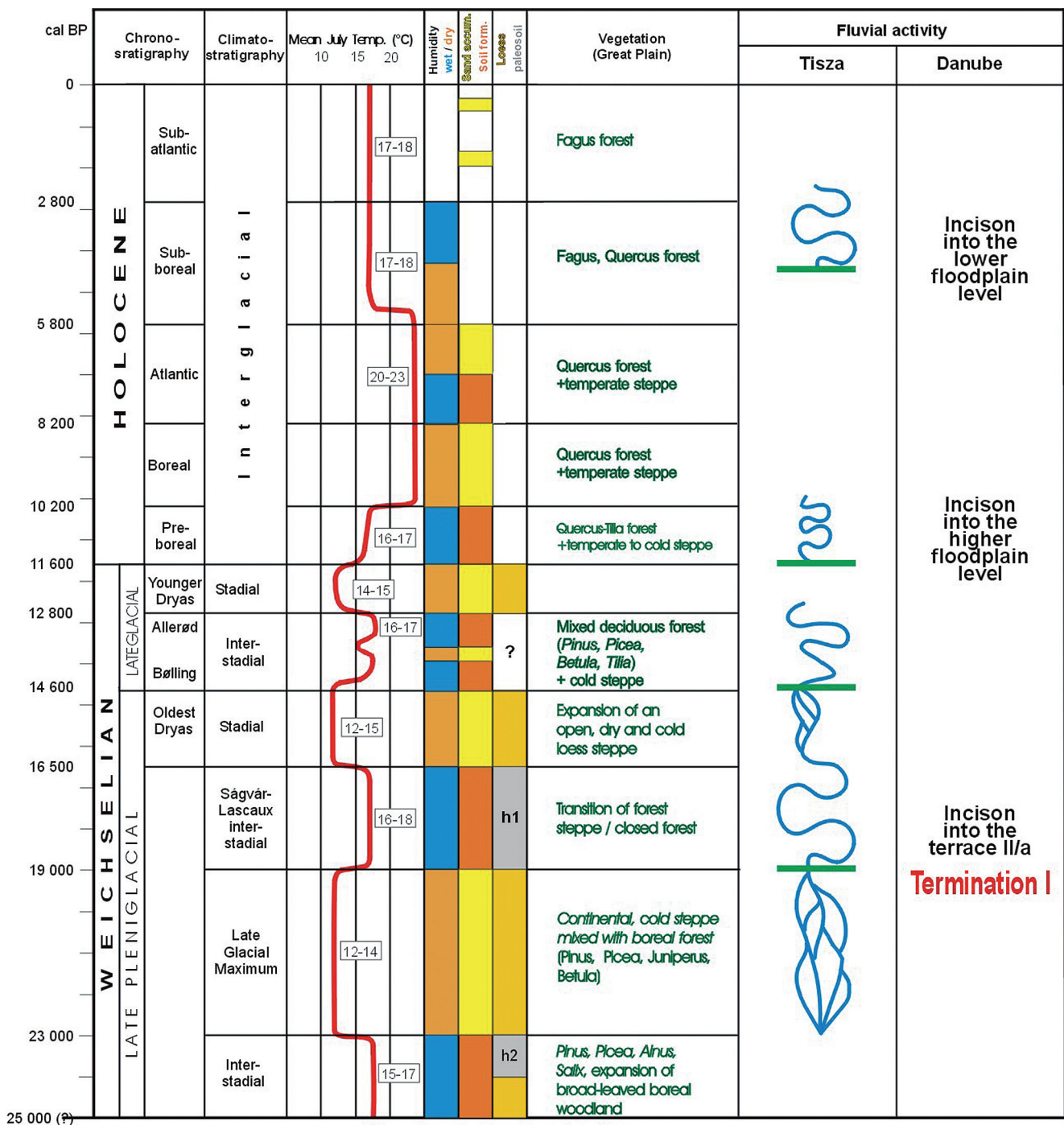


Fig. 12. Palaeoenvironmental changes in Hungary during the last 25 ky. The figure is based on Gábris & Nádor (2007), modified and completed by the authors.

Approaching to the Holocene the preservation of the Quaternary records and landforms is improving; therefore we can extract more detailed information about climate and paleoenvironmental changes (Fig. 12). Loess formation ceased by the Holocene but wind-blown sand accumulation and sand re-mobilisation continued. The alternations of sand layers and intercalated fossil soils preserved the effects of the past climatic changes. During the Late Pleniglacial-Holocene these changes can be tracked based on the investigations of sand dunes. According to luminescence and radiocarbon dating results five aeolian sand accumulation periods were recognised in the investigated profiles during the last 25,000 years (Fig. 12). Climate governed sand movement periods occurred during the LGM, the Dryas stadials, the Boreal and the Late Atlantic phases, while sand mobilisation triggered mostly by human activities is dominant since the Subboreal phase.

The same time span is covered by the fluvial evolution investigations on the Middle Tisza region and Sajó-Hernád alluvial fan. Geographical distributions of the different channel pattern types (meandering or braided) and erosional steps – which mark deepening phases – were determined on the study areas. Examination of the derived ‘horizontal stratigraphy’ enabled the recognition of six distinct phases of river pattern change and four incision periods. These phases of river pattern change were governed by climatic changes and therefore, they correlate well with the magnitude of the aeolian activity. Periods of braided channel formation occurred in colder, dryer climate (LGM, Oldest Dryas), which indicated sand movement periods as well. Development of meandering river pattern occurred during milder and more humid climate spells with increased water discharge. Therefore, these meandering phases correlate well with periods of sand dune stabilisation and soil formation (Ságvár-Lascaux interstadial, Allerød, Preboreal and Subboreal phases).

The correlation between the climate change, channel pattern types alteration, loess and sand accumulation, soil formation during the last 25,000 years in Hungary are summarised and presented in Fig. 12.

Acknowledgement

We are grateful to Jef Vandenberghe who promoted the progress of our research team by PhD courses and several times by field work experiences.

We would like to thank the support and contributions of several institutions. We are indebted to the Hungarian Scientific Research Fund (grant number OTKA 68219, 100315, T029798, F043715, NK60455, K062478 and F042799). Novothny thanks the DAAD (German Academic Exchange Service) and the Leibniz Institute for Applied Geophysics in Hannover for the Leibniz-DAAD Fellowship. Ruzsiczay-Rüdiger thanks for exposure age determination the EUROBASIN Marie Curie Fellowship of the EU, and the Netherlands Centre for Integrated

Solid Earth Science (ISES), the Bolyai János Scholarship of the HAS, the EGT/Norwegian Financing Mechanism and MZFK (Zoltán Magyary Public Foundation of Higher Education), Hungary. The AMS measurements performed at the ASTER AMS national facility (CEREGE, Aix en Provence) were supported by the INSU/CNRS, the French Ministry of Research and Higher Education, IRD and CEA.

References

- Borsy, Z., Csongor, É., Sárkány, S. & Szabó, I.**, 1982. Phases of brown-sand movements in the North-East part of the Great Hungarian Plain. *Acta Geographica Debrecina* 20: 5-33.
- Borsy, Z., Csongor, E., Lóki, J. & Szabó, I.**, 1985. Recent results in the radiocarbon dating of wind-blown sand movements in the Tisza–Bodrog Interfluve. *Acta Geographica Debrecina* 22: 5-16.
- Braucher, R., Del Castillo, P., Siame, L., Hidy, A.J. & Bourlès, D.L.**, 2009. Determination of both exposure time and denudation rate from an in situ produced ^{10}Be depth profile: A mathematical proof of uniqueness. Model sensitivity and applications to natural cases. *Quaternary Geochronology* 4: 56-64.
- Broecker, W. S. & Van Donk, J.**, 1970. Insolation changes, ice volumes and the O18 record in deep-sea cores. *Rev. Geophys. Space Phys.* 8: 169-198.
- Bulla B.**, 1938. Der Pleistozäne Löß im Karpathenbecken. III. *Földtani Közlöny* 68: 33-58.
- Bulla B.**, 1941. A Magyar medence pliocén és pleisztocén terrasza. *Földtani Közlöny* 69: pp. 199-230.
- Csillag, G., Fodor, L., Sebe, K., Müller, P., Ruzsiczay-Rüdiger, Zs., Thamóné-Bozsó-E. & Bada, G.**, 2010. A szélerózió szerepe a Dunántúl negyedidőszaki felszínfejlődésében. *Földtani Közlöny* 140: 463-481.
- Davis, B.A.S. & Passmore, D.G.**, 1998: Upper Tisza Project: Radiocarbon analyses of Holocene alluvial and lacustrine sediments. Interim report on current analyses to the Excavation and Fieldwork Committee, Univ. of Newcastle 7.
- Frechen, M., Horváth, E. & Gábris, Gy.**, 1997. Geochronology of Middle and Upper Pleistocene loess sections in Hungary. *Quaternary Research* 48: 291-312.
- Gábris Gy.**, 1994. Pleistocene evolution of the Danube in the Carpathian Basin. *Terra Nova* 6: 495-501.
- Gábris Gy.**, 1997. Gondolatok a folyóteraszokról. *Földrajzi Közlemények* 121: 3-16.
- Gábris, Gy.**, 2003. A földtörténet utolsó 30 ezer évének szakaszai és a futóhomok mozgásának főbb periódusai Magyarországon. *Földrajzi Közlemények*, 127: 1-14.
- Gábris, Gy.**, 2008. Relation between the time scale of the river terrace formation and the Oxygen Isotope Stratigraphy in Hungary. *In: Kertész, Á. & Kovács, Z.* (eds): Dimensions and trends in Hungarian Geography. *Studies in Geography in Hungary* 33. Akadémiai Kiadó (Budapest): 19-31.
- Gábris, Gy. & Nagy, B.**, 2005. Climate and tectonic controlled river style changes on the Sajó-Hernád alluvial fan (Hungary). *In: Harvey, A.M., Mather, A.E. & Stoks, M.* (eds): Alluvial fans: Geomorphology, Sedimentology, Dynamics. *Geol. Soc. London, Spec. Publ.* 251: 61-67.
- Gábris, Gy. & Nádor, A.**, 2007. Long-term fluvial archives in Hungary: response of the Danube and Tisza rivers to tectonic movements and climatic changes during the Quaternary: a review and new synthesis. *Quaternary Science Reviews* 26: 2758-2782.

- Gábris Gy. & Túri Z.**, 2008. Homokmozgás a történelmi időkben a Tiszazug területén. *Földrajzi Közlemények* 132: 241-250.
- Gábris Gy., Krolopp, E. & Ujházy, K.**, 2011. Későglaciális-holocén környezetváltozás Duna-menti homokbuckák komplex vizsgálata alapján. *Földtani Közlöny* 141: 445-468.
- Gábris Gy., Horváth, E., Novothny, Á. & Ujházy, K.**, 2000. Environmental changes during the Last-, Late- and Postglacial in Hungary. *In: Kertész, Á. & Schweitzer, F. (eds): Physico-geographical Research in Hungary. Studies in Geography in Hungary* 32. Akadémiai Kiadó (Budapest): 47-61.
- Gábris Gy., Félegyházy E., Nagy B. & Ruzsiczay Zs.**, 2001. Climate and tectonic controlled river style changes in the Middle Tisza Plain. *Global Correlation of the Late Cenozoic Fluvial Deposits*. 21-24 April, Prague, Programme & Abstracts, 8 pp.
- Gábris Gy., Horváth, E., Novothny, Á. & Ujházy, K.**, 2002. History of environmental changes from the Last Glacial period in Hungary. *Praehistoria* 3: 9-22.
- Gibbard, P. & Van Kolfschoten, T.**, 2005. The Pleistocene and Holocene Epochs. *In: Gradstein, F.H., Ogg, J.G. & Smith, A.G.: A Geologic Time Scale 2004*. Cambridge Univ. Press: 441-452.
- Green, C.P. & McGregor, D.F.M.**, 1987. River terraces: A stratigraphical record of environmental change. *In: Gardiner, V. (ed.): Proceedings of the First International Geomorphology Conf. 1986. Part I*. J. Wiley & Sons Ltd: 977-987.
- Hein, A.S., Hulton, N.R.J., Dunai, T.J., Schnabel, C., Kaplan, M.R., Naylor, M. & Xu, S.**, 2009. Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. *Earth and Planetary Science Letters* 286: 184-197.
- Horváth E.**, 2001. Marker horizons in the loesses of the Carpathian Basin. *Quaternary International* 76/77: 157-163.
- Jámbor, Á.**, 2002. A magyarországi pleisztocén éleskavics előfordulásának és földtani jelentőségük. *Földtani Közlöny* 132: 101-116.
- Joó, I.**, 2003. Results and problems of research on present vertical movements of the Carpathian region (in Hungarian). *Geodézia és Kartográfia* 55: 12-15.
- Kaiser, M.**, 1997. A geomorphic evolution of the Transdanubian Mountains, Hungary. *Zeit. für Geomorphologie N.F. Suppl.-Bd.* 110: 1-14.
- Kasse, C., Hoek, W.Z., Bohncke, S.J.P., Konert, M., Weijers, J.W.H., Cassee, M.L. & Van der Zee, R.M.**, 2005. Late Glacial fluvial response of the Niers-Rhine (western Germany) to climate and vegetation change. *Journal of Quaternary Science* 20: 377-394.
- Kasse, C. Vandenberghe, D., De Corte F. & Van den haute, P.**, 2007. Late Weichselian fluvio-aeolian sands and coversands of the type locality Grubbenvorst (southern Netherlands): sedimentary environments, climate record and age. *Journal of Quaternary Science* 22: 695-708.
- Kasse, C., Bohncke, S.J.P., Vandenberghe, J. & Gábris, Gy.**, 2010. Fluvial style changes during the last glacial-interglacial transition in the middle Tisza valley (Hungary). *Proceedings of the Geologists Association* 121: 180-194.
- Kele, S.**, 2009. Investigation of travertines from the Carpathian Basin: paleo-climatological and sedimentological analysis (in Hungarian with English summary). PhD Thesis, Eötvös University Budapest, 176. p.
- Kele, S., Korpás, L., Demény, A., Kovács-Pálffy, P., Bajnóczi, B. & Medzihradzky, Zs.**, 2006. Paleoenvironmental evaluation of the Tata Travertine Complex (Hungary), based on stable isotopic and petrographic studies. *Acta Geologica Hungarica* 49: 1-31.
- Kele, S., Scheuer, Gy., Demény, A., Shen, Ch-C. & Chiang, H-W.**, 2009. U-series dating and isotope geochemical study of the Gellért Hill (Budapest) travertine. *Central European Geology* 52: 199-224.
- Kele, S., Scheuer, Gy., Demény, A., Shen, Ch-C. & Chiang, H-W.**, 2011. Uranium-series dating and geochemical study of the travertines located on the Rózsadomb Hill (Budapest) (in Hungarian with English abstract). *Földtani Közlöny* 141: 445-468.
- Kéz, A.**, 1934. A Duna győr-budapesti szakaszának kialakulásáról. *Földrajzi Közlemények* 62: 175-193.
- Kiss, T. & Sipos & Gy.**, 2006. Emberi tevékenység hatására meginduló homokmozgások a Dél-Nyírségben egy zárt buckaközi mélyedés szedimentológiai elemzése alapján. *Földrajzi tanulmányok Lóki József 60. születésnapja alkalmából*. Kossuth Egyetemi Kiadó (Debrecen): 115-124.
- Kiss, T., Nyári, D. & Sipos Gy.**, 2006. Homokmozgások vizsgálata a történelmi időkben Csengele területén. *In: Kiss, A., Mezősi, G., Sümegey, Z. (szerk.): Táj, környezet és társadalom. SZTE Éghajlattani és Tájföldrajzi, Természeti Földrajzi és Geoinformatikai Tanszék (Szeged): 372-382*
- Kozarski, S.**, 1991. Wartha – a case study of a lowland river. *In: Starkel, L., Gregory, K. & Thornes, J. (eds): Temperate Palaeohydrology*. J. Wiley and Sons Ltd (London): 189-215.
- Kretzoi, M. & Dobosi, V.** (eds), 1990. *Vértesszőlős. Site, man and culture*. Akadémiai Kiadó (Budapest).
- Kretzoi, M. & Pécsi, M.**, 1982. Pliocene and Quaternary chronostratigraphy and continental surface development of the Pannonian Basin. *In: Pécsi, M. (ed.): Quaternary Studies in Hungary, INQUA, Hungarian Academy of Sciences, Geogr. Res. Inst., Budapest: 11-42*.
- Krolopp, E., Schweitzer, F., Scheuer, Gy., Dénes, Gy., Kordos, L., Skoflek, I. & Jánosy, D.**, 1976. Quaternary Formation of the Castle Hill in Buda. *Földtani Közlöny* 106: 193-228.
- Krolopp, E., Sümegi, P., Kuti, L., Hertelendi, E. & Kordos, L.**, 1995. Szeged-Öthalom környéki löszképződmények keletkezésének paleoökológiai rekonstrukciója. *Földtani Közlöny*, 125: 309-361.
- Krolopp, E. & Sümegi, P.**, 1995. Palaeoecological reconstruction of the Late Pleistocene, based on Loess Malacofauna in Hungary. *GeoJournal* 36: 213-222.
- Kukla, G.J.**, 1977. Pleistocene land-sea correlations I. Europe. *Earth-Science Reviews* 13: 307-374.
- Lóki, J., Hertelendi, E. & Borsy, Z.**, 1994. New dating of blown sand movement in the Nyírség. *Acta Geographica Debrecina* 32: 67-76.
- Magyari E.**, 2002. Climatic versus human modification of the Late Quaternary vegetation in Eastern Hungary. Ph.D. Thesis, University of Debrecen, Hungary
- Marosi S.**, 1955. A Csepel-sziget geomorfológiai problémái. *Földrajzi Értesítő* 4: 279-300.
- Nagy, B. & Félegyházi, E.**, 2001. A Sajó-Hernád hordalékkúp későpleisztocén mederhálózatának vizsgálata. *Acta Geographica Debrecina*, 35: 221-22.
- Novothny, Á., Horváth, E. & Frechen, M.**, 2002. The loess profile at Albertirsa, Hungary – improvements in loess stratigraphy by luminescence dating. *Quaternary International* 95-96: 155-163.
- Novothny, Á., Frechen, M., Horváth, E., Bradák, B., Oches, E.A., McCoy, W. & Stevens, T.**, 2009. Luminescence and amino acid racemization chronology and magnetic susceptibility record of the loess-paleosol sequence at Süttő, Hungary. *Quaternary International*, 198: 62-76.

- Novothy, Á., Frechen, M. & Horváth, E.**, 2010. Luminescence dating of sand movement periods from the Gödöllő Hills, Hungary. *Geomorphology* 122: 254-263.
- Novothy, Á., Frechen, M., Horváth, E., Krbetschek, M. & Tsukamoto, S.**, 2012. Infrared stimulated luminescence and infrared-radiofluorescence dating of quaternary sediments in Hungary. *Quaternary Geochronology*, in press.
- Nyári, D. & Kiss, T.**, 2005. Homokmozgások vizsgálata a Duna-Tisza közén. *Földrajzi Közlemények* 129:133-146.
- Oches, E.A. & McCoy, W.D.**, 1995. Aminostratigraphic evaluation of conflicting age estimates for the 'Young Loess' of Hungary. *Quaternary Research* 44: 160-170.
- Pécsi, M.**, 1959. *Entwicklung und Morphologie des Donautales in Ungarn.* Akadémiai kiadó, Budapest, 345 p.
- Pécsi, M.**, 1975. Stratigraphical subdivision of the Hungarian loess sections. *Földrajzi Közlemények* 23: 217-230
- Pécsi, M.**, 1987. Type locality of young loess in Hungary at Mende. In: Pécsi, M. & Velichko, A.A. (eds): *Paleogeography and loess.* Akadémiai Kiadó Budapest, 35-55.
- Pécsi, M.**, 1990. Geomorphological position and absolute age of the Vértesszőlős lower paleolithic site. In: Kretzoi, M. & Dobosi, V. (eds): *Vértesszőlős – site, man and culture.* Akadémiai Kiadó (Budapest): 27-41.
- Pécsi, M., & Richter, G.**, 1996. Loess: Origin – Classification – Landscape. *Annals of Geomorphology.* Gebrüder Brontraeger, Berlin-Stuttgart, 1996: 391.
- Pécsi M., Schweitzer F., Balogh J., Balogh Jné. M., Havas J. & Heller, F.**, 1995. A new loess-paleosol lithostratigraphical sequence at Paks (Hungary). *Loess in Form 3, Geographical Research Institute Hungarian Academy of Science:* 63-78.
- Rónai, A.**, 1985. *Quaternary Geology of the Great Hungarian Plain (in Hungarian).* Geologica Hungarica, ser. Geol. 21: 332-333.
- Ruszkiczay-Rüdiger, Zs., Fodor, L., Bada, G., Leél-Össy, Sz., Horváth, E. & Dunai, T.J.**, 2005a. Quantification of Quaternary vertical movements in the central Pannonian Basin: A review of chronologic data along the Danube River, Hungary. *Tectonophysics* 410: 157-172.
- Ruszkiczay-Rüdiger, Zs., Dunai, T.J., Bada, G., Fodor, L. & Horváth, E.**, 2005b. Middle to late Pleistocene uplift rate of the Hungarian Mountain Range at the Danube Bend (Pannonian Basin) using in situ produced ³He. *Tectonophysics* 410: 173-187.
- Ruszkiczay-Rüdiger, Zs., Braucher, R., Csillag, G., Fodor, L., Dunai, T.J., Bada, G., Bourlès, D. & Müller, P.**, 2011. Dating Pleistocene aeolian landforms in Hungary, Central Europe, using in situ produced cosmogenic ¹⁰Be. *Quaternary Geochronology* 6: 515-529.
- Schumm, S.A.**, 1979. Geomorphic thresholds – concept and its applications. *Transactions of the Institute of British Geographers* 4: 485-515.
- Sebe, K., Csillag, G., Ruszkiczay-Rüdiger, Zs., Fodor, L., Thamó-Bozsó, E., Müller, P. & Braucher, R.**, 2011. Wind erosion under cold climate: A fossil periglacial mega-yardang system in Central Europe (Western Pannonian Basin, Hungary). *Geomorphology* 134/3-4: 470-482.
- Siame, L., Bellier, O., Braucher, R., Sébrier, M., Cushing, M., Bourlès, D.L., Hamelin, B., Baroux, E., De Voogd, B., Raisbeck, G. & Yiou, F.**, 2004. Local erosion rates versus active tectonics: cosmic ray exposure modelling in Provence (South-East France). *Earth and Planetary Science Letters* 220: 345-364.
- Sümeği, P.**, 1993. Sedimentary geological and stratigraphical analysis made on the material of the Upper Palaeolithic settlement at Jászfelsőszentgyörgy-Szunyogos. *Tisicum*, 8: 63-76.
- Sümeği, P., Krolopp, E. & Hertelendi E.**, 1998. Palaeoecological reconstruction of the Ságvár-Lascaux Interstadial. *Acta Geographica Debrecina* 34: 165-180.
- Thomsen, K.J., Murray, A.S., Jain, M. & Bøtter-Jensen, L.**, 2008. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. *Radiation Measurements* 43: 1474-1486.
- Ujházy, K.; Gábris, Gy. & Frechen, M.**, 2003. Ages of periods of sand movement in Hungary determined through luminescence measurements. *Quaternary International* 111: 91-100.
- Vandenbergh, J.**, 1987. Changing fluvial processes in small lowland valleys at the end of the Weichselian Pleniglacial and during the Late Glacial. *First Internat. Geomorph. Congr. Manchester, Proceedings*, J. Wiley & Sons: 731-744.
- Vandenbergh, J., Kasse, C., Bohncke, S. & Kozarski, S.**, 1994. Climate-related river activity at the Weichselian-Holocene transition: a comparative study of the Wartha and Maas rivers. *Terra Nova* 6: 476-485.
- Vandenbergh, J., Kasse, K., Gabris Gy., Bohncke, S. & Van Huissteden, K.**, 2003. Fluvial style changes during the last 35.000 years in the Tisza valley. XVI INQUA Congress, 23-30 July, Reno, Nevada, USA. Abstracts, 68 pp.
- Vandenbergh, J.**, 2008. The fluvial cycle at cold-warm-cold transitions in lowland regions: a refinement of theory. *Geomorphology* 98: 275-284.
- Wintle, A.G. & Packman, S C.**, 1988. Thermoluminescence ages for three sections in Hungary. *Quaternary Science Reviews* 7: 315-320.
- Zöller, L. & Wagner, G.A.**, 1990. Thermoluminescence dating of loess – recent developments. *Quaternary International* 7/8: 119-128.
- Zöller, L., Oches, E.A. & McCoy, W.D.**, 1994. Towards a revised chronostratigraphy of loess in Austria with respect to key sections in the Czech Republic and in Hungary. *Quaternary Geochronology (Quaternary Science Reviews)* 13: 465-472.