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Quantification of Quaternary vertical movements in the central Pannonian Basin: A review of chronologic data along the Danube River, Hungary

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Abstract

This study aims at a new quantification of neotectonic deformation of the central part of the Pannonian Basin. We use terrace levels and associated travertine as well as speleothem data along the Danube River to quantify its incision rate and thus, estimate the amount and rate of uplift at the axis of the Hungarian Mountain Range (HMR).

Several terrace levels and other geomorphic features along the Danube river are indicative for Quaternary uplift of the axial part of the emerging Hungarian Mountain Range. While the correlative terraces are at considerable height at the axis of the HMR, the terraces are gradually dipping below the basin fill of the adjacent lowlands. The correlation of the terrace segments is difficult because of their poor preservation, small size and variable height. The geomorphologic horizons indicate gradual incision of the river throughout the Quaternary during simultaneous deformation. However, no reliable chronological data have been available so far to quantify landscape-forming processes such as uplift, incision or erosion rates.

A reconsideration of existing published data for three consecutive segments of the Danube valley yields incision rates between 0.14 and 0.41 mm/year for the last 360 ky, with the highest value for the area of the Danube Bend. Accordingly, the middle to late Quaternary uplift rate of the axial zone of the HMR exceeded significantly that of the marginal areas. These rates represent an approximation as some quantitative data are still controversial. Our results suggest that formation of the Danube terraces is result of river incision triggered by the uplift of the HMR and modified by periodic climate changes.

Keywords: River incision; Uplift rate; Quaternary; Terrace chronology; Pannonian Basin

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1. Introduction

The Pannonian Basin comprises several sub-basins separated by uplifting basement units (Fig. 1). In the

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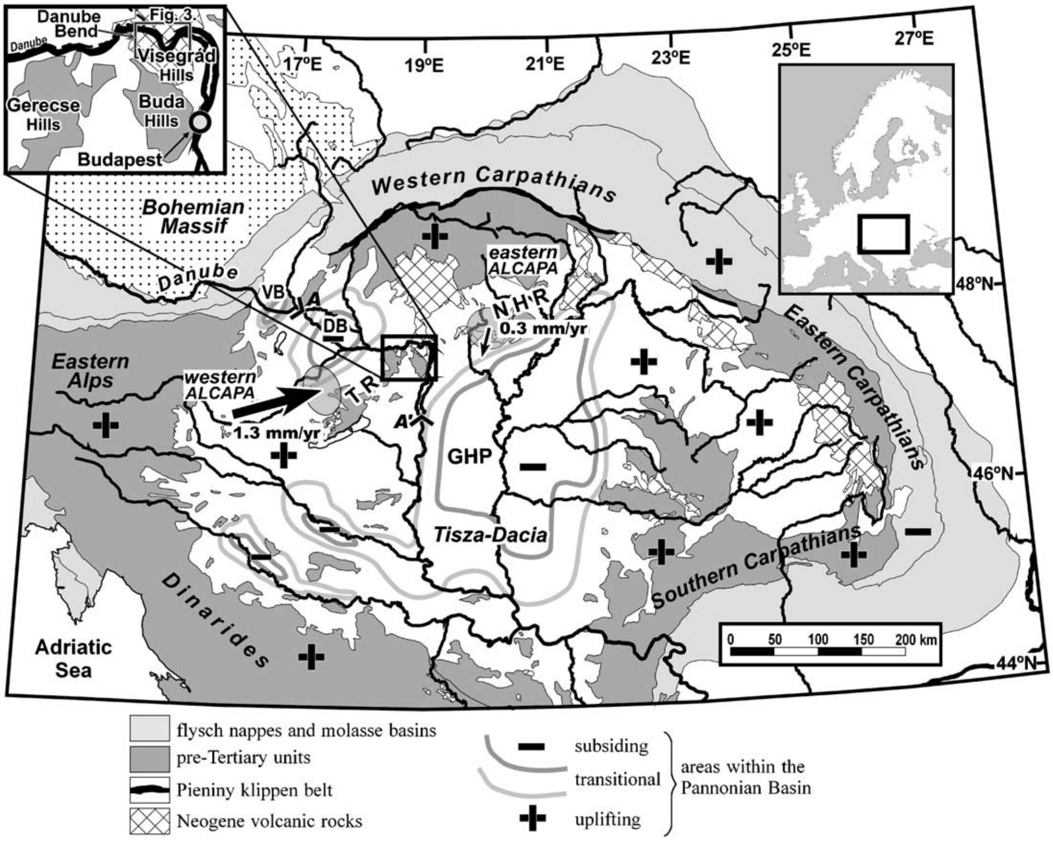

Fig. 1. Recent vertical and horizontal motions in the Pannonian Basin system. Uplifting and subsiding areas were mapped (after Horváth and Cloetingh, 1996). The areal extent of uplifting and subsiding areas is well defined, but there are only estimates about the timing and rate of the vertical motion. The research area is indicated with the black rectangle and subset image. The direction and speed of horizontal displacement of the western and eastern ALCAPA units is indicated with black arrows and ellipsoid of confidence at 95%/error of 1 sigma. The reference frame is the Bohemian Massif (Grenerczy et al., 2000). Active deformation between the two parts of the ALCAPA unit is accommodated within a wide zone in the central part of the Pannonian Basin, and takes place mainly in form of accelerated vertical movements. A–A′ indicates the position of section of Fig. 2 along the Danube. VB: Viena Basin, DB: Danube Basin, GHP: Great Hungarian Plain, TR: Transdanubian Range, NHR: North Hungarian Range. The NHR and the TR are parts of the Hungarian Mountain Range.

Danube Basin (DB) and Great Hungarian Plain (GHP) the sediment accumulation has been more or less continuous since the late early Miocene. The uplifting Hungarian Mountain Range (HMR) separates these sub-basins from each other. The HMR is a NE–SW trending hilly area of uplifted pre-Miocene rocks with an altitude of 300–1000 m asl. The modern Danube is the only river which cuts through the HMR dividing it into two parts: the Transdanubian Range (TR) and the North Hungarian Range (NHR). At this location the Danube has formed a narrow, deeply incised gorge with steep slopes and several strath terraces. This segment of the Danube valley is called the Danube Bend, or Visegrád Gorge after the name of the ancient fortress, the Visegrád Castle, which guards the exit of the gorge. The age and development of this peculiar landform has been a prominent question for the Hungarian geomorphology of the last century (e.g. Cholnoky, 1925; Kéz, 1933; Bulla, 1941; Láng, 1955; Noszky, 1935; Pécsi, 1959; Gábris, 1994; Karátson et al., 2001). Upstream and downstream of the Danube Bend, karst areas of the Gerecse and Buda Hills occur (Fig. 1). Several gravel terraces and travertine horizons have developed on their slopes facing the Danube (e.g. Pécsi, 1959; Schréter, 1953).

Incision in the mountains (HMR) and aggradation in the lowlands (DB, GHP) occurred simultaneously in a relatively small area along the Danube with similar climatic conditions. In addition, terraces along the Danube are upwarped relative to the modern river profile (Fig. 2). These observations led Noszky (1935) and Pécsi (1959) to suggest relative upwarping of terraces caused by faster uplift of the Danube Bend area with respect to the neighbouring DB and GHP.

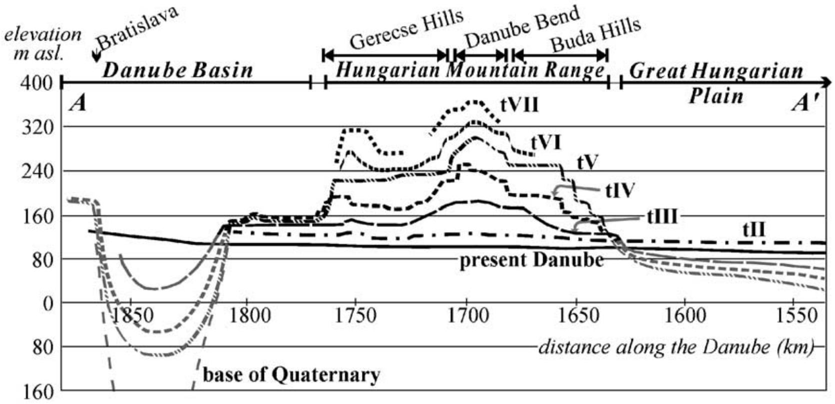

Fig. 2. The elevation of the terrace levels along the Danube River between the DB and the GHP (according to Pécsi, 1959). The position of the section is marked on Fig. 1. The upwarping deformation pattern of the terraces indicates differential uplift of the area. Terrace levels reach their maximum height at the axis of the HMR, i.e. in the Danube Bend area. The terrace horizons gradually dip towards the subsiding lowlands, where they smooth into the basin fill sequence. Here correlatable sediment horizons can be followed; these reflect the amount of subsidence (see details in the text).

While thickness of Quaternary strata below the lowlands reflects an increase of accommodation space and considerable sediment accumulation, incision of the Danube into the HMR suggests uplift and erosion. This spatial distribution of river behaviour is indicative of differential vertical movements along the Danube, with areas of relative uplift and subsidence in the HMR and the adjacent lowlands, respectively. Consequently, Pécsi (1959) described the incised HMR-section of the Danube valley as antecedent, where tectonic forcing has been overriding climatic effects. Pécsi (1959) defined the role of climate as periodic modifier of the river flux and sediment supply, which could have played an important role in the timing the terrace formation. Accordingly, morphotectonic consequences can be derived from the incision history of the Danube considering the influence of climate oscillations.

Currently the locations of the uplifting and subsiding areas are well defined, but there are only speculations about the timing and amount of uplift and subsidence. A quantitative re-evaluation of existing chronologic data and new dating projects are essential for better understanding of Quaternary vertical movements of the HMR. Several relative and recently some absolute chronological studies were carried out in the area to date river terraces and other landforms. A compilation of available chronological data sets is presented in this paper and novel Quaternary incision rates have been derived from them for three different segments of the Danube valley. New exposure age dating results of the Danube Bend terraces are presented and discussed by Ruszkiczay-Rüdiger et al. (in press).

2. Geologic, tectonic framework

During the early Miocene the convergence of the Adriatic microplate and the European plate caused an anomalously thickened crust in the Eastern Alps. This led to the extrusion of the North Pannonian or ALCAPA (ALpine–CArpathian–PAnnonian) unit to the east (Csontos et al., 1992). During the escape (early to mid-Miocene), extensional deformation – i.e. syn-rift phase – of the lithosphere took place behind the Carpathian loop (Horváth, 1993; Fodor et al., 1999).

In the late Miocene thermal subsidence – post-rift phase – occurred and the brackish to freshwater Pannonian Lake covered the area of the Pannonian Basin system. In the deepest sub-basins of the GHP up to 6000 m of lake sediments have been deposited during this phase (Rónai, 1985; Horváth et al., 1988). Marginal ranges of the Pannonian Basin and the HMR, were also covered by several hundred meters of late Miocene sediments, as suggested by fission track analysis of buried and exhumed rocks (Dunkl and Frisch, 2002). From the end of the late Miocene, as a consequence of the continuing push of the Adriatic plate, structural inversion started. The gradual build up of a compressional stress field has resulted in large-scale folding of the Pannonian lithosphere, which is the main reason for the presence of uplifting and subsiding areas in the Pannonian Basin (Horváth and Cloetingh, 1996; Bada et al., 1999; Fig. 1).

The disappearance of the Pannonian Lake is the time when exhumation of the pre-late Miocene strata, and development of the modern drainage pattern of the Pannonian Basin started, with the paleo-Danube as the axis of the drainage network. Consequently the onset of the incision of the Danube into the HMR is one of the most important milestones of the Plio–Quaternary morphotectonic development of the Pannonian Basin system.

In the Pannonian Basin several indications exist about Quaternary structural deformation. The earthquakes detected along active faults in historical times suggest that active deformation is still taking place (Tóth et al., 2002). According to high precision GPS measurements, the western part of the ALCAPA unit is moving towards the relatively stable eastern part with a rate of 1.3 mm/year while its eastern part shows much smaller differential motion with respect to the reference European plate (Grenerczy et al., 2000). This movement is accommodated within a wide zone in the central part of the Pannonian Basin. Our study area, the middle reach of the Danube in Hungary is situated in this accommodation zone where present-day internal shortening can be related to accelerated vertical movements (Fig. 1).

The Plio–Quaternary differential vertical movements are well documented, and numerous evidences suggest that these motions still continue: (1) several hundred meters of Quaternary sediments have been deposited in the deepest sub-basins of the DB and GHP (Rónai, 1985), and ongoing alluvial sedimentation in the basin interior allows for relative subsidence in recent times. (2) Geodetic levelling data indicate >1 mm/year present day uplift rate for the HMR region and 2–4 mm/year subsidence for the DB and GHP (Mike, 1969; Joó, 1993). Although precision of geodetic data for the determination of tectonic deformation rates is limited (Demoulin, 2004), regional trends of the vertical motions are clearly expressed by these data. (3) In the TR several geomorphic horizons refer to significant Plio–Quaternary uplift: (a) elevated position of several denudation surfaces (Kretzoi and Pécsi, 1982; Kaiser, 1997); (b) upwarping of Quaternary fluvial terraces of the Danube and some tributaries (e.g. Pécsi, 1959; Kretzoi and Pécsi, 1982; Gábris et al., 1993; Gábris, 1994); (c) gradually lower position of Pliocene and Quaternary travertine occurrences associated with base level fall (Schréter, 1953; Schweitzer and Scheuer, 1995); (d) several gallery levels of hydrothermal cave systems in the Buda and Gerecse Hills. (e) In the Hungarian Mountain Range the Plio–Quaternary sedimentary cover is missing or is restricted to a few meters of clay, loess, sand and slope debris indicating significant erosion since late Miocene times. The dissected landscape of this area allows for significant river incision, which maybe the result of tectonically induced uplift in relatively recent times.

3. Overview of earlier terrace studies

3.1. Description of the studied area

The Gerecse and Buda Hills consist mainly of Mesozoic carbonate rocks with a thin Paleogene–Miocene carbonate and clastic cover. These hills represent the marginal zone of the uplifting HMR (Fig. 1). Upstream of the Danube Bend, in the Gerecse Hills Pécsi (1959) distinguished seven terrace levels. Thick alluvial sand and gravel of the terraces generally overlies late Miocene sediments. These terraces are typically covered by freshwater limestone. Downstream of the Danube Bend, in the Buda Hills the position of the terrace and travertine horizons resembles the northern slopes of the Gerecse Hills. However, only four river terraces were described here as fluvial sediments are missing from higher topographic levels (Pécsi, 1959).

The majority of published chronological data about the Danube terraces originate from the Gerecse and Buda Hills. In these areas the presence of fluvial sediments and freshwater limestone enabled to establish a terrace chronology based on paleonthologic, sedimentologic, and geomorphologic dating techniques (e.g. Kéz, 1933; Láng, 1955; Noszky, 1935; Pécsi, 1959).

The Danube Bend area, where the river incised into middle Miocene andesites, represents the axial zone of the HMR. Conservation of terrace horizons at this narrow segment of the valley is poor (Figs. 3 and 4) because the lateral migration of the river has destroyed most of its previous strath surfaces. Valley sides are steep, the terrace remnants are mainly present as isolated sub-horizontal or gently dipping slope segments forming small plateaus. Steep slopes of deeply incised tributaries also indicate fast incision in relatively recent times. Terraces in the Danube Bend are assumed to have higher elevation than correspondent terrace levels upstream and downstream (e.g. Kéz, 1933; Láng, 1955; Noszky, 1935; Pécsi, 1959; Gábris, 1994). The terraces gradually lower towards the marginal areas of the HMR and progressively smooth into the aggradational sequence of the DB and GHP (Fig. 2). However, correlation of the terraces traced along the river is questionable because terrace chronology in the Danube Bend relies almost exclusively on the geomorphic position of the terrace remnants. The lack of datable material hindered the age determination of the terraces so far. Recently Ruszkic-

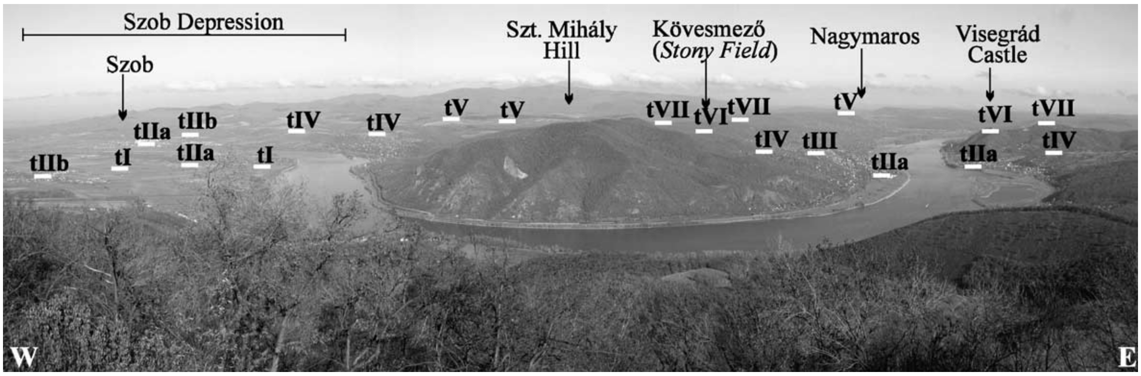

Fig. 3. W–E oriented view of the Danube Bend from 639 m asl in the Visegrád Hills, south of the village of Dömös. Terrace horizons are indicated with white lines. Steep slopes indicate young incision, only remnants of the terrace horizons have been preserved. Most of the terraces are unpaired (for map view see Fig. 4, for cross sections refer to Fig. 5).

zay-Rüdiger et al. (in press) has started new chronologic research the Danube Bend area.

3.2. The "traditional" terrace chronology

According to Pécsi (1959) and Kretzoi and Pécsi (1982) 6–8 terrace horizons are present in the Danube valley. Several authors (e.g. Pécsi, 1959; Kretzoi and Pécsi, 1982; Gábris, 1994, Schweitzer and Scheuer, 1995) attempted to include the terrace remnants of different genetic types from all segments of the Danube valley into a uniform terrace system. This approach has predestined the path of the terrace studies in Hungary for decades, although Pécsi (1959) emphasized that the numbering of the terraces referred to their relative age, and it did not mean strictly the same time for their formation.

The "traditional" terrace chronology was constructed by Pécsi (1959) and modified by Kretzoi and Pécsi (1982). They correlated the terrace forma-

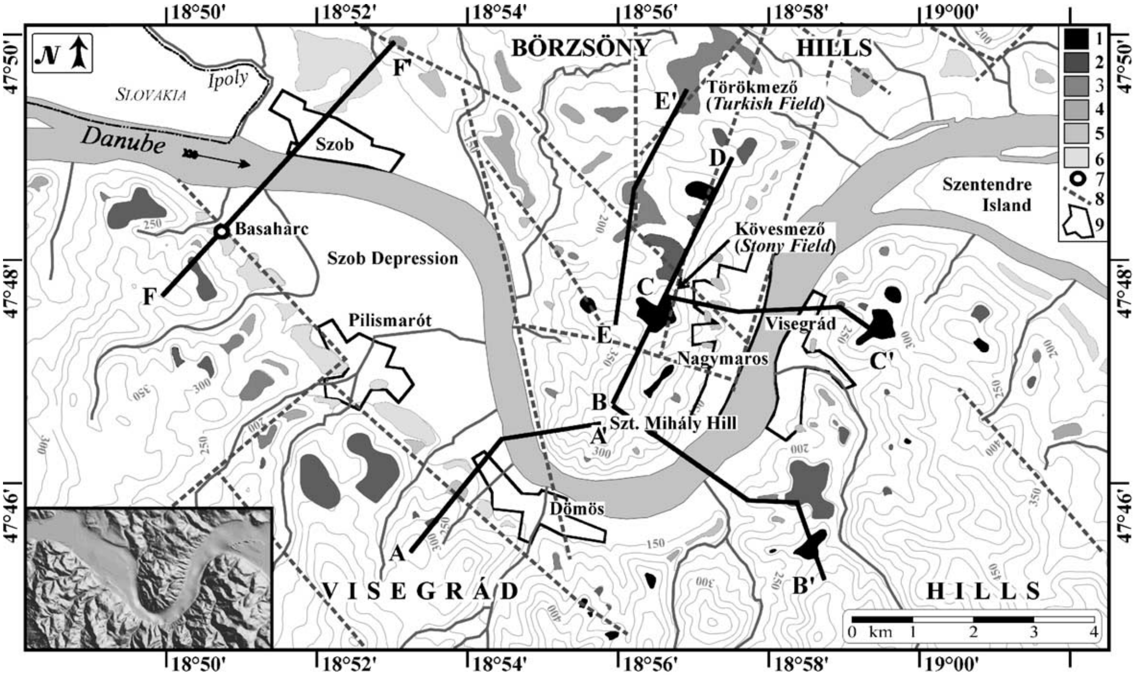

Fig. 4. Contour map of the Danube Bend area with remnants of river terraces. Terraces after Pécsi (1959) and fault pattern after Korpás and Teplánszky (1999). Note that in many cases terraces were identified only on geomorphic considerations. The inset shaded relief map visualises steep topography of the area. 1: tVII, 2: tVI, 3: tV, 4: tIV, 5: tIII, 6: tIIb terraces, 7: luminescence dated loess profile, 8: fault, 9: settlement. Black lines and codes (A–A′) indicate position of cross sections of Figs. 5 and 6.

tion with the classical periods of the Quaternary Alpine glaciations (Günz, Mindel, Riss, Würm). Because of the lack of sufficient datable material, at that time this was the only way of defining some time constraints for the age and development of the Danube valley despite the uncertainties of this method. Qualitative ages were not coupled to absolute ages (Table 1), which hindered quantitative incision and uplift rate determination.

In the "traditional" terrace system of Pécsi (1959) the following criteria were used to correlate and date the terraces: (1) relative height of the terrace, (2) sedimentologic properties (grain size distribution; roundness of the pebbles; heavy minerals of the sand fraction), periglacial phenomena within the sediments, travertine, loess or eolian sand cover of the terrace (3) paleontology (age of the fossils found within the alluvial and cover sediments; e.g. Mottl, 1942; Jánossy, 1979 and references therein). Later the accessibility of (4) paleomagnetic data (e.g. Latham and Schwarcz, 1990) and (5) some Th/U ages of the travertine bodies on top of terraces enabled a reconsideration of the "traditional" system (Kretzoi and Pécsi, 1982 with references therein, and in Table 3).

3.3. "*Traditional*" *age and number of the terraces*

According to the "traditional" chronology (Pécsi, 1959) the numbering of the terraces begins with lowest, youngest and best-preserved horizon. The levels are indicated from tI to tVIII (Figs. 3–6 and Table 1). The youngest terrace is the terrace tI, the early Holocene terrace of the Danube (5–6 m above the Danube). The second terrace is divided into two horizons: the tIIa is the first flood-free horizon 8–14 m above the Danube. Its age is late Würm according to its late glacial fauna and to the lack of loess cover. The tIIb lies 20–26 m above the Danube and the aggradation of the alluvial material of this horizon has been placed in the last interglacial or end of the penultimate (Riss) glacial. Paleonthologic and archaeologic finds, periglacial mixing of the alluvial material and an up to 20 m thick loess–paleosoil cover place the formation of this level before the last glacial. A travertine body situated on terrace tIIb in the Western Gerecse yielded Th–U-disequilibrium ages around ~100 ka (Table 3. and references therein). The vertical deformation of the two lowest levels is small. They appear as more or less continuous horizons along the Danube valley. In the Danube Bend area the presence of alluvial material of considerable thickness is restricted to the tI and tII levels.

Table 1
Age and relative elevation of the terrace horizons

Terrace	Suggested age (Pécsi, 1959; Kretzoi and Pécsi, 1982)	Minimum age (ka)	Elevation above the modern Danube (± 15%, m)		
			Gerecse Hills	Danube Bend	Buda Hills
tVIII	Pliocene	2400≪	–	380	–
tVII	Pliocene	2400	190	280	–
tVI	Pre-Günz	1800	155	230	–
tV	Günz	800	100	205	–
tIV	Mindel	360	70	150	55
tIII	Early Riss	170	40	80	30
tIIb	Late Riss–early Würm	100	20	26	21
tIIa	Late Würm	12	9	14	10
tI	Early Holocene	8	5	6	6
Floodplain	Recent	0	3	3	3

Qualitative ages have been derived from the "traditional" terrace system (Pécsi, 1959; Kretzoi and Pécsi, 1982). Absolute ages are minimum ages estimated by the compiled chronologic data sets. Elevation is the average height of certain horizon above the modern Danube (see details and references in the text).

The shape and alluvium of higher horizons are usually less preserved. In the Danube Bend the tIII and tIV are present as poorly developed, uncovered strath surfaces (Figs. 3–6). However, in the Gerecse and Buda Hills these surfaces are frequently covered by alluvial gravel, freshwater limestone and loess bodies. The fauna described from these horizons represent the Riss and Mindel glacials; Th/U ages derived from travertines on these horizons are older than 175 and 360 ka, respectively (Tables 2 and 3. and references therein).

Larger vestiges of the tV and tVI levels are preserved on the northern slopes of the Szt. Mihály Hill (Figs. 4 and 6). These horizons are frequently developed above erosional remnants of post-volcanic (still mid-Miocene) limestone bodies. Sometimes rounded alluvial quartzite pebbles are scattered on tV, tVI and tVII suggesting a Danubian origin (Láng, 1955; Pécsi, 1959). In the Gerecse Hills travertine bodies also overlie these terraces. In the Buda Hills surfaces with alluvial material above the tIV terrace are missing. The tV and tVI levels were placed to the Günz and pre-Günz glacials mostly on the basis of geomorphologic considerations.

According to their sedimentologic investigations, Kretzoi and Pécsi (1982) considered the tVI terrace as the first horizon of Danubian origin. They assumed that its formation took place around the beginning of the Pleistocene. The uppermost tVII–tVIII horizons were first included into the Danubian terrace system (Pécsi, 1959). However, later stratigraphic investigation of

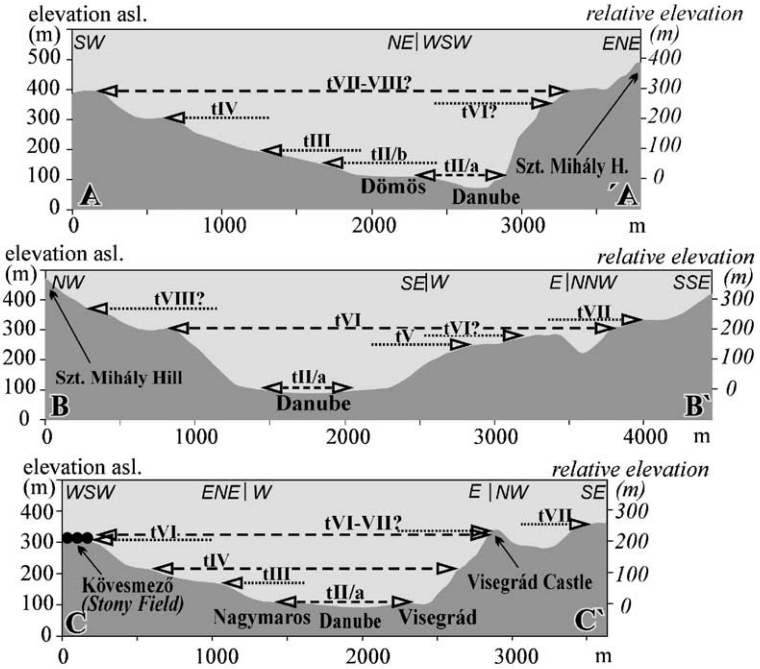

Fig. 5. Paired (dashed arrows) and unpaired (dotted arrows) terraces of three typical cross-sections of the Danube Bend. Position of the cross sections is shown on Fig. 4. tI–VIII: geomorphic horizons, *relative elevation* means the elevation above the modern Danube (101 m asl). Most of the terrace horizons are unpaired: there are no correlative geomorphic levels on the opposite side of the river. A–A′ and C–C′ profiles are characteristic for the N–S trending sections of the valley within the Danube Bend: they are asymmetrical; on one side the complete absence of the lower terrace levels can be observed, while on the opposite side a nice sequence of terraces has developed. B–B′ section is representative for the middle reach of the Danube Bend: it is more symmetrical, valley sides are steep, terraces between tIIa and tV are missing.

gravel and travertine bodies of these horizons in the Gerecse Hills did not support their Danubian origin and were re-classified as remnants of Pliocene pediments (Kretzoi and Pécsi, 1982). The "traditional" age of the first Danubian horizon (tVI) places the onset of the formation of the Danube Bend into the early Pleistocene. This assumption provides the only age estimation for the onset of the incision of the paleo-Danube into the emerging HMR.

3.4. Uncertainties of the "*traditional*" chronology and new age data

Several difficulties are hampering relative and absolute dating of the terraces:

(1) In the Danube Bend strath terraces are predominant, in the upstream and downstream sections either type of terraces is present along the valley. Strath terraces are result of periodic incision of a river into the bedrock. Incision is suggested to be the combined result of continuous tectonic uplift and climate-induced fluctuations of the water and sediment flux. Fill terraces develop by aggradation of alluvial material as a consequence of increased sediment load or decreased water flux (Burbank and Anderson, 2001). It is essential to differentiate between fill and strath terraces, as the mechanisms/driving forces of their formation are partly different.

(2) The terrace surfaces are not continuous along the valley (Figs. 4 and 5), and conservation of terraces on both sides of the valley is relatively rare. Formation of unpaired terraces is more characteristic for the Danube valley. Unpaired terraces represent geomorphic horizons at a certain elevation traceable only at one side of the valley. The cross-sections on Fig. 5 show that unpaired terraces can be found in all segments of the river at varying elevation. Some terrace horizons are completely missing from certain sections of the river valley (e.g. the horizons between tIIa and tV on B–B′ profile). Fluvial erosion of the subsequently incising river frequently destroys terraces of one (or both) valley-side(s). Differential vertical motions can change the elevation of originally paired terraces. Both scenarios (subsequent erosion and differential vertical motion) can account

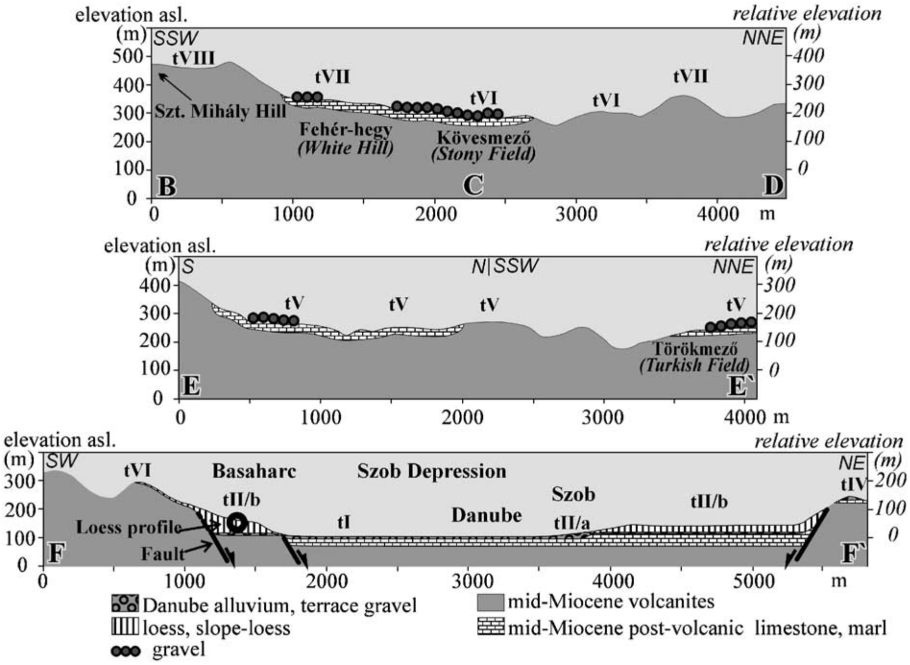

Fig. 6. Cross sections of the area north of the Danube Bend (B–C–D, E–E′) and across the Szob Depression (F–F′). Position of the cross sections is shown on Fig. 4. tI–VIII: geomorphic horizons described by Pécsi (1959), *relative elevation* means the elevation above the modern Danube. The tV–VI terraces are preserved as well developed horizons on the northern side of the Szt. Mihály Hill. These horizons are frequently developed on post-volcanic, mid-Miocene limestone. Some of these horizons are covered by a scattered gravel mantle (B–C–D and E–E′ sections). A prominent horizon around 260–280 m asl can be recognised in the area north of Szt. Mihály Hill (E–E′, tV of Pécsi, 1959). The western rim of the Szt. Mihály Hill block, represents a slightly higher (300–320 m asl) level (B–C–D). According to Pécsi (1959) these surfaces belong to the tVI–tVII levels. F–F′ profile across the Szob Depression shows the postvolcanic limestone body in a downfaulted position (modified after Pécsi, 1959). Along the bounding faults of this depression Quaternary displacement or landslides are possible. Therefore the Basaharc loess profile may be in secondary position, in which case its age not allows for calculation of the incision rate of the Danube (see details in text).

for incomplete terrace successions of the Danube valley. The resultant varying relative height of the horizons at different reaches of the valley makes geomorphic correlations dubious.

(3) The size and roundness of the pebbles is not necessarily the same all along the river within a coeval horizon, thus the ability of these sediment properties for terrace correlation is questionable.

Table 2
Age and relative elevation of travertine horizons with conformable terrace levels

Gerecse Hills			Conformable terrace horizon	Buda Hills		
Travertine horizon	Age (ka)	Elevation above the modern Danube (± 15%, m)		Travertine horizon	Age (ka)	Elevation above the modern Danube (± 15%, m)
T_{12}	–	–	Late Miocene	$T_{11–12}$	9000	380
$T_{10–11}$	8000	220	shorelines	T_{10}	7000	320
$T_{8–9}$	4000	170	tVII–tVIII	$T_{8–9}$	–	260
T_7	2400	140	tVI–tVII	T_7	–	160
T_6	1800	140	tV–tVI	T_6	–	140
T_5	780	120	tV	T_5	780	110
T_4	360	80	tIV	T_4	360	70
T_3	200	60	tIII	T_3	175	50
T_2	100	20	tIIb	T_2	70	20
T_1	10	7	tIIa	T_1	10	7

Qualitative ages have been derived from the “traditional” terrace system (Pécsi, 1959; Kretzoi and Pécsi, 1982). Absolute ages are minimum ages estimated by the compiled chronologic data sets. Elevation is the average height of certain horizon above the modern Danube (see details and references in the text and Table 3.).

Table 3
Published absolute chronologic data used for the quantification of the terrace ages

Travertine horizon	Age (ka)	Method	References
T_5 Gerecse, Buda	>780	Reverse polarity	Latham and Schwarcz, 1990
T_4 Gerecse,	<780	Th/U	Hennig et al., 1983
Buda	>350	Normal polarity	Latham and Schwarcz, 1990
T_3 Buda	~175	Th/U	Kretzoi and Pécsi, 1982
	248 ± 67		Pécsi, 1973
T_3 Gerecse	202 ± 20	Th/U	Hennig et al., 1983
	190 ± 45		
T_2 Buda	60–70 ± 20	Th/U	Pécsi, 1973
			Kretzoi and Pécsi, 1982
	101 ± 10		Pécsi, 1973
T_2 Gerecse	98 ± 10	Th/U	Schwarcz and Skoflek, 1982
	135 ± 11		Hennig et al., 1983
T_1 Buda	~9.5	^{14}C	Kretzoi and Pécsi, 1982
T_1 Gerecse	12 ± 10	^{14}C	Kretzoi and Pécsi, 1982

Th/U and paleomagnetic data are from the travertine horizons; ^{14}C data are from charcoal from the alluvial material.

(4) The sediment cover is missing or very thin on a large number of the horizons, which hindered the age determination of each terrace remnant. Thence ages are extrapolated to these surfaces based on their geomorphologic position.
(5) Relative chronologic data were not quantified; only wide absolute age-ranges could be attached to the terraces and;
(6) The absolute age data are very few, and the time-range of these methods is restricted to the last 350 ky.

During the last decades numerous quantitative studies have been performed which allow to give time constraints for the formation of the geomorphic horizons of the Danube valley. These include (1) luminescence dating of loess profiles overlying the lower terrace levels (Frechen et al., 1997); (2) Th/U dating of travertine horizons covering the geomorphic levels on the flanks of the Gerecse and Buda Hills (Pécsi, 1973; Kretzoi and Pécsi, 1982; Hennig et al., 1983; Schwarcz and Skoflek, 1982); (3) paleomagnetic measurements on travertines (Latham and Schwarcz, 1990), and (4) Th/U dating of karstwater-connected speleothems (Leél-Össy, 1997; Leél-Össy and Surányi, 2003; Takács-Bolner and Kraus, 1989).

In this study, for the older horizons where no absolute ages were available, we interpreted relative data in accordance with the Quaternary chronology most widely accepted in the Hungarian literature, with the Plio-cene–Pleistocene boundary at 2.4 Ma. For the younger series we compiled absolute and relative ages. For the older horizons paleonthologic data were used mostly from the general works of Mottl (1942), Pécsi (1959) and Jánossy (1979) and references therein. On this basis we defined minimum ages of the terraces (Tables 1 and 2), which enabled calculation of maximum incision rates. Elevation of the terrace horizons was derived from Pécsi (1959), and height of the travertine bodies was defined by Schréter (1953) and Schweitzer and Scheuer (1995). The elevation of the Danube is 103 m asl in the Gerecse Hills, 101 m in the Danube Bend and 96 m in the Buda Hills.

4. Quantification of existing terrace data

Incision of a river induces base level fall in the surrounding hills. Accordingly the incision rate of a river can be calculated by the age and elevation of the terraces and other landforms connected to the base level. In karst regions travertine and cave formation is connected to the karstwater level, which mirrors the position of the local base level. Consequently these geomorphic horizons are tools for the quantification of river incision. However, local ages and rates must not be projected upstream and downstream the river because of varying rate of vertical movements and different mechanisms of terrace formation (i.e. fill and strath).

4.1. Incision rates calculated using terraces and travertine horizons in the Gerecse and Buda Hills

On the northern slopes of the Gerecse and eastern slopes of the Buda Hills terraces and travertine bodies are arranged in an interconnected system: travertines are overlying geomorphologic horizons, like terraces and pediment surfaces. Accordingly the chronological data sets of the terraces and travertines can hardly be separated (Table 2). Fig. 7 shows elevation range and age of the major travertine occurrences and cave systems of the Buda Hills. The suggested ages frequently are morphologically based extrapolations.

According to Schweitzer and Scheuer (1995), up to 12 travertine horizons have developed in the Danube valley. They marked travertine horizons with “T” and Arabic numbers to differentiate between terrace codes (“t” and roman numbers). Two series of travertine can be distinguished: the lower-younger series (T_1–T_6) were deposited on terrace surfaces (tIIa–tVI). The higher-older series (T_7–T_{12}) are overlying older geomorphic horizons. The youngest and lowest travertine

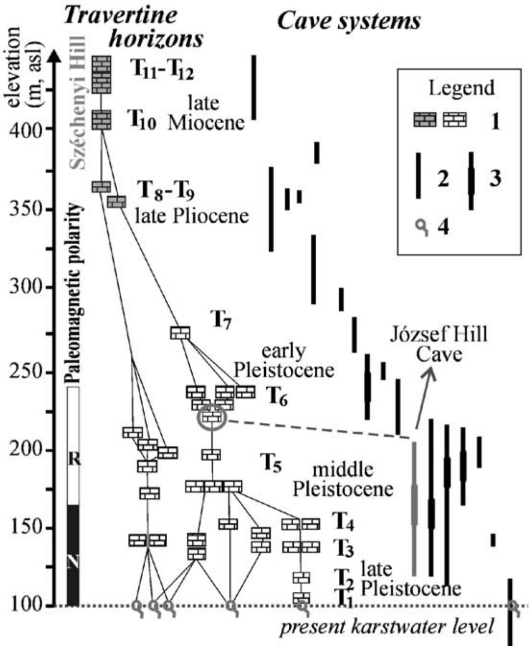

Fig. 7. Position above the karstwater level of travertine horizons and hydrothermal cave systems above the karstwater level in the Buda Hills (modified after Takács-Bolner and Kraus, 1989). The chronology for the older horizons has been derived mostly from paleonthologic, geomorphologic and sedimentologic data (see details and references in the text). Th/U ages and paleomagnetic data with references are indicated in Table 3. Th/U dating results of the József Hill Cave are demonstrated on Fig. 9. 1: travertine horizons (Tertiary and Quaternary); 2: elevation range of larger cave systems; 3: elevation range of the largest cave systems with main passage levels indicated with wider bars; 4: present karstwater spring.

is the T_1, (107 m asl), the oldest and highest is the T_{12} (493 m asl).

Absolute chronologic data (Table 3) exist only for the younger series. The T_6 and T_5 levels have reverse magnetic polarity, i.e. they are older then 0.78 Ma. The T_4 level showed normal polarity, thus it proved to be younger than 0.78 Ma (Latham and Schwarcz, 1990). The Th/U method is only applicable for the age determination of the youngest horizons, because its limitation to ages younger than 350 ka (Schwarcz, 1989). When the Th/U data resulted older in age than 350 ka, we take 360 ka as minimum age of the horizon (T_4).

Concerning the older travertines only paleonthologic data and geomorphic considerations are available. Their ages presented in Table 2 are the result of an attempt of their quantification, and are minimum ages. Travertines $T_{6–7}$ are suggested to cover terraces from tV to tVII developed during the early Pleistocene and late Pliocene; these ages are supported by microfauna described in the Gerecse Hills (Scheuer and Schweitzer, 1988). Their minimum ages are tentatively placed at 1.8 and 2.4 Ma. The age of the $T_{8–9}$ horizons is even more uncertain: Schweitzer (1997) determined their age as 4.0 Ma because they cover Pliocene pediments. The highest travertine bodies ($T_{10–12}$) cover late Miocene shoreline-sediments. Their age between 7.0 and 9.0 Ma is suggested by their characteristic late Miocene fauna.

The minimum ages of the travertine occurrences could be plotted against their elevation (Fig. 8A). The slope of the regression line fitted to the data points gives the rate of the base level fall, which equals the incision rate of the Danube River.

The older travertine series, between 360 and 9000 ka, provide an incision rate of 0.04 mm/year for the Buda Hills, and 0.02 mm/year for the Gerecse Hills. The younger data set, between 360 ka and present yield considerably faster rates: 0.18 and 0.16 mm/year, re-

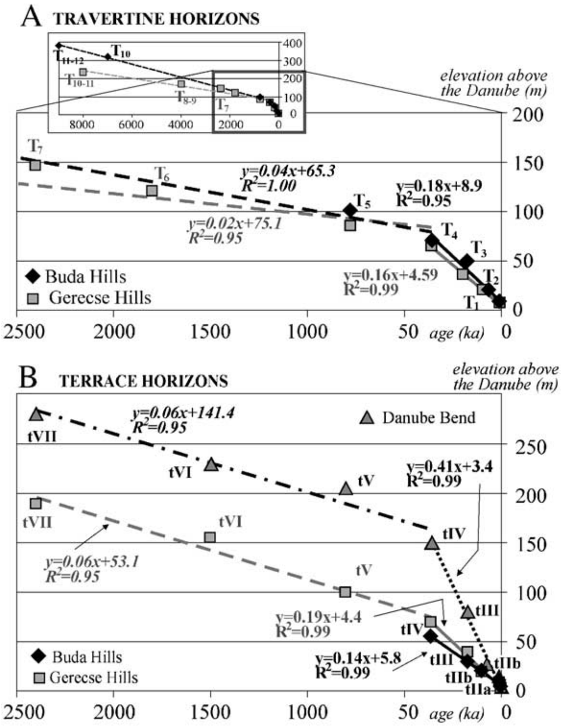

Fig. 8. A: Age and elevation of travertine horizons of the Buda (black rhombus) and Gerecse Hills (grey rectangles). The grey trendline has been fitted to the Gerecse Hills and a black one to the Buda Hills data. B: Age and elevation of terrace horizons of the Buda (black rhombus), Gerecse Hills (grey rectangle) and the Danube Bend (grey triangle). Slope of the trendlines is the base level drop/incision rate. Equations of the older series appear with inclined fonts. Note the significant break in the slope of the trendlines at 360 ka coinciding with the applicability limit of the Th/U method. Above this age the chronology is dubious: age data are uncertain and there is no information about the date of onset of the uplift. Therefore trendlines above this age appear as dashed lines indicating their unreliable nature (see details in text). See data in Tables 1–3 references the text and in Table 3, incision rates in Table 4.

spectively (Table 4). The terraces cover a shorter period of time than travertines. They yield 0.06 mm/year for the Gerecse Hills for the period between 2400 and 360 ka. The older terraces are missing from the Buda Hills, thus there is no data for this period. The incision rate for the younger series (360–0 ka) resulted in 0.19 for the Gerecse and 0.14 mm/year for the Buda Hills (Fig. 8B, Table 4). Travertine and terrace ages yielded similar results in both Buda and Gerecse Hills. This may be the consequence of the above-described interconnected chronologic database, and their comparable position on the NW and SE margins of the TR.

The break in the slope of all trendlines is at 360 ka. It has to be emphasized that this sudden increase of the incision rate 360 ka coincides with the upper limit of applicability of the Th/U method, which is currently the source of most of the absolute chronologic data. Accordingly, this abrupt acceleration of the incision is assumed to be an artefact arising from the age-limitations of this technique. There is no information about the onset of the incision, which could have occurred any time between the late Miocene and the early Pleistocene. This poorly constrained time interval of several million years (0.36–9 Ma) makes the linear incision rates older than 360 ka very uncertain. The trendlines are only of informative character showing the scenario of constant incision between 9000, 2400 and 360 ka. Numerous other possibilities are imaginable when later onset of the incision yields faster rates for shorter time intervals. Until more reliable data for older horizons become available any further debate remains highly speculative, therefore in this paper we omit this discussion.

Table 4
Calculated incision rates of the Danube River on the basis of different types of geomorphic horizons and for different time scales

	Geomorphic horizon		Incision rate (mm/year)
Gerecse Hills	Travertine horizons	8000–360 ka	0.02*
	Terrace horizons	2400–360 ka	0.06
	Travertine horizons	360–0 ka	0.16*
	Terrace horizons	360–0 ka	0.19
Buda Hills	Travertine horizons	9000–360 ka	0.04*
	Terrace horizons	2400–360 ka	–
	Travertine horizons	360–0 ka	0.18*
	Terrace horizons	360–0 ka	0.14
	Speleothems	360–0 ka	0.23*
Danube Bend	Terrace horizons	2400–360 ka	0.06
	Terrace horizons	360–0 ka	0.41

Data indicated by a *refers to the local base level drop, which is adjusted to the incision of the Danube. Incision rate of the Danube can be taken as valid approximation of the uplift rate of the HMR.

4.2. Incision rate calculated using terraces of the Danube Bend

Because of the lack of sediment cover of the higher terraces in the Danube Bend, there are no independent chronologic data about these levels (tIII–tVIII). Moreover, as it was described above, most of the terrace remnants in the area are small, unpaired remnants of the ancient horizons (Figs. 3 and 4). In the "traditional" terrace system the terrace-chronologies from the Gerecse and Buda Hills were projected to the Danube Bend area (e.g. Pécsi, 1959). Being aware of the uncertainty of this correlation, in the following we quantify the "traditional" terrace ages for the Danube Bend similarly to the Gerecse and Buda Hills. Our aim here is to have a complete overview about the chronologic information implied in the "traditional" system.

On the grounds of this "chronology" the calculated incision rate for the Danube Bend area is 0.06 mm/year for the first period (2400–360 ka), and 0.41 mm/year for the last 360 ka (Fig. 8C, Table 4). The incision rate of the older period resembles the rates derived from the terraces and travertines of the Gerecse and Buda Hills upstream and downstream of the Danube Bend. The younger series (tIV–tI) yielded considerably higher values for the Danube Bend than for the same epoch upstream and downstream. The break in the trendline is again at 360 ka, which has its roots in the methodological limitations described in the previous section. Therefore the incision rate derived for the older period has no actual meaning as valid incision rate. Faster incision rate in the Danube Bend than in the Gerecse and Buda Hills during the younger period is simply a consequence of the geomorphologic observation of larger vertical deformation of the Danube Bend terraces (e.g. Noszky, 1935; Pécsi, 1959).

5. Th/U dating of speleothems

Some of the hydrothermal cave systems of the Buda Hills are highly ornamented by wide range of mineral associations. The precipitation of some calcite and aragonite minerals is closely related to the position of the karstwater level, thus the age of the mineral fixes the karstwater table to a certain elevation. Determining the Th/U age of the mineral formations is indicative for changes of the position of the karstwater level.

The József Hill Cave is situated in the eastern part of the Buda Hills within a distance of 1 km from the Danube River. The main passage level of the cave is between 120 and 180 m asl (20–80 m above the Danube). Hence its elevation range coincides with the younger terraces and travertine horizons up to the fourth level (tIV, and T4). A freshwater limestone body is situated on the surface above the cave at the height of 220 m asl (around the height of the T_6 travertine horizons, Figs. 7 and 9).

Th/U series dating of the speleothems of the József Hill Cave allowed the reconstruction of changes in the karstwater table during the last 350 ky (Table 5, Fig. 9). Above 180 m asl, speleothems yielded ages older then 350 ka. On the basis of the general pace of mineral formation in the Buda Hills Leél-Össy (1997) estimated the date of the onset of cave-dissolution in the József Hill Cave around 500 ka. Before this age the karstwater level had to be above cave, thus a data point of ~500 ka was placed to 200 m asl (Fig. 9) as the estimated onset of the cave evolution (Leél-Össy, 1997; Leél-Össy and Surányi, 2003). This tentative datum has been omitted in the calculation of the incision rate.

The Th/U data are shown in Table 5. Sampling sites and changing position of the karstwater table appears on Fig. 9A and are represented in an age–elevation plot on Fig. 9B. The oldest age at 180 m asl is slightly older than 350 ky (sample X1), therefore its age appears as 360 ka in the data set. The youngest age of 66 ka was measured on sample X6 situated at 117 m asl. These speleothems form a few meters under the karstwater table, with the exception of the subaerial sample X4. Data suggest a generally decreasing trend of karstwater level with a brief rebound around 200 ka. Climatic changes, in other words changes in humidity conditions, can cause fluctuations in the karstwater table as reported from other cave systems of the Buda Hills (Kraus, 1993). The slope of the trendline through the Th/U data points yields 0.23 mm/year as the rate of the base level drop for the last 360 ky. This rate slightly exceeds the rates derived from the younger series of

Table 5
Type, elevation and Th–U-disequilibrium age of speleothems in the József Hill Cave

Sample code	Dated speleothem	Position of karstwater table	Sample elevation (m asl)	Estimated karstwater level (m asl)	TH/U age (ka)
X1	Calcite crust	Above	180	185	350<
X2	Cave raft	Above	153	160	245
(X3)*	Dried surface underlying sample X3			150	(220)
X3	Calcite crust	Above	160	165	206
X4	Aragonite	Below	155	150	158
X5	Flowstone	Above	125	130	93
X6	Cave raft	Above	117	122	66
–	Present karstwater level		100	100	0

The estimated karstwater level has been derived from the relative syngenetic position of the speleothem with respect to the karstwater table (Leél-Össy, 1997).

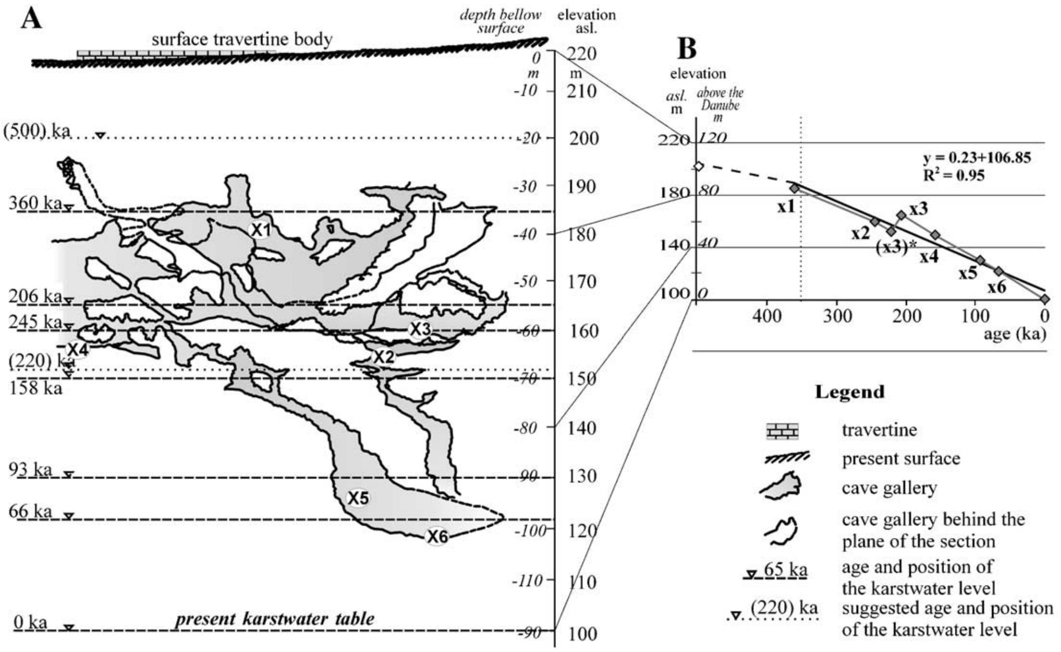

Fig. 9. Th/U dating of speleothems (after Leél-Össy, 1997). A: Cross section of the József Hill Cave with sample sites, suggested position and age of the karstwater level during the last 500 ky. B: Age–elevation plot of the karstwater level changes controlled by the incision of the Danube River. See data in Table 5. (X3)*: The calcite crust of sample X3 developed on a surface of polygonally broken clay. Accordingly this gallery level had been abandoned by the water for a couple of thousand years before the deposition of the calcite crust.

travertine and terrace horizons (between 0.14 and 0.19 mm/year), however, given the uncertainties involved, the results agree favourably.

6. Luminescence data

Based on geomorphic and paleonthologic considerations (Pécsi, 1959) the terrace at Basaharc belongs to the tIIb horizon (i.e. 80–100 ka, for location see F–F′ section on Figs. 4 and 6). Gravel of the terrace tIIb at Basaharc lies 24 m above the present level of the Danube River. Alluvial sandy-silty-clayey sediments of 13 m thickness, and a 25 m thick loess–paleosoil sequence cover the terrace gravel (Fig. 10).

The loess sequence is intercalated with three well-developed soil horizons. The luminescence age (both TL and IRSL) of the loess above the uppermost soil is 30 ka BP. The loess below this soil horizon proved to be older than the applicability range of the method, i.e. a minimum age of 130 ka can be accepted for these horizons (Frechen et al., 1997). The presence of a large time gap around the first paleosoil horizon is in good agreement with results of luminescence dating of other Hungarian loess sequences (e.g. Frechen et al., 1997; Novothny et al., 2002). In the loess below the lowermost soil horizon a volcanic tephra layer (Bag Tephra) has been described (Horváth, 2001). Geochemically this tephra proved to be similar to the volcanic rocks belonging to the Italian Monte Vulture, which erupted around 350 ka. Accordingly, the estimated age of this volcanic ash layer is around 350 ka (Pouclet et al., 1999). However, within the lowermost (BA) soil horizon a skull of an *Ursus spaeleus* was found (Mottl, 1942) which is considered as typical for the first part of the last glaciation (i.e. around 80 ka; Jánossy, 1979).

The contradiction in the data above appears to be irresolvable: low position (above the tIIb terrace level) and paleonthologic data support a “young” age, however luminescence and tephrochronological records indicate a significantly older age (>350 ka, i.e. tIV) of this terrace. The location of the profile offers an alternative explanation for the observed inconsistency.

The Basaharc loess profile lies at the margin of the Szob Depression (Figs. 4 and 6). This small basin is situated within the Miocene volcanic complexes, and is bounded by normal to oblique slip faults (Fodor et al., 1999; Korpás and Teplánszky, 1999). Middle Miocene, postvolcanic carbonates are preserved within the basin in downfaulted position below the level of the Danube (F–F′ section of Fig 6). The same strata are located around 230 m on the northern rim if the Szob Depression and around 300 m asl north of the Szt. Mihály Hill (under tV–tVI levels, B–C–D, E–E′ sections on Fig. 6). The age of this depression is uncertain, however the bounding faults (active or inactive) could have played a major role in shaping the Danube course in the Danube Bend area. Along these faults Quaternary vertical movements and landsliding are probable. Accordingly, it is possible that the entire sediment sequence of the terrace at Basaharc lies in a downfaulted or downslided position. This theory is supported by the observed inwards – towards the hillslope – dip of the paleosoil layers within the loess sequence. In this case the age of this terrace level is not indicative for the incision rate of the Danube. Neverthe-

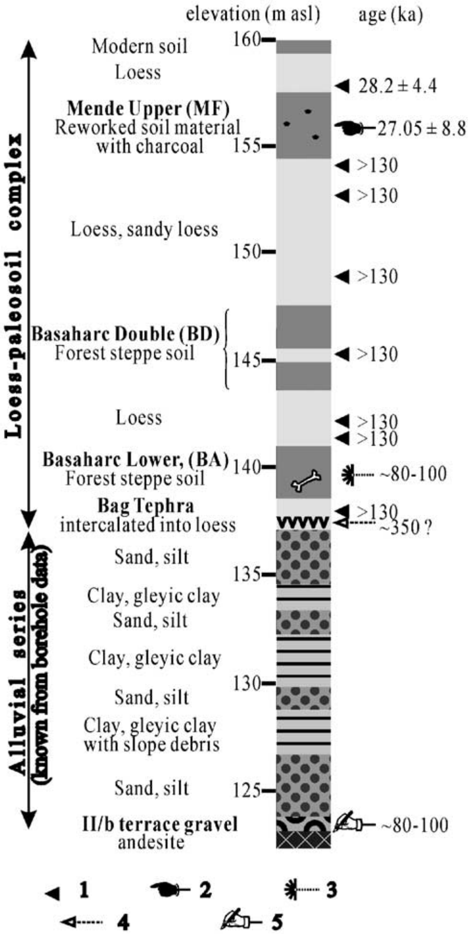

Fig. 10. Loess profile at Basaharc with chronologic data (compiled after Pécsi, 1959; Frechen et al., 1997). The location of the profile is indicated on Figs. 4 and 6 (F–F′). The alluvial series are situated 24 m above the Danube. According to the traditional terrace system (Pécsi, 1959) this level belongs to the tIIb horizon. Paleonthologic and geomorphic data support a young age. Luminescence and tephrochronology suggest a significantly older age. 1: luminescence data (Frechen et al., 1997), 2: radiocarbon age (Kretzoi and Pécsi, 1982), 3: paleonthologic data (Mottl, 1942), 4: age based on geochemical similarity of clinopyroxenes in Bag Tephra (Pouclet et al., 1999), 5: age derived from the geomorphic position of the terrace gravel (Pécsi, 1959).

less, the possible downfaulted position of this terrace level does not offer a resolution for the conflicting paleonthologic and absolute age data.

7. Discussion and conclusions

A thorough revision of chronological data from terraces of the Danube River in the central Pannonian Basin revealed several problems in correlation and absolute dating of the terraces. New dating studies have been started along different sections of the Danube. These methods are limited to the last ~50, ~130, ~350 ky (radiocarbon, luminescence, Th/U, respectively). For older terraces only relative ages are available.

7.1. Rates of incision and uplift

Our calculations revealed significant difference between the incision rates of the older period (9000, 2400–360 ka), and the last 360 ky of the Pleistocene. The coincidence of the lower limit of absolute age dating and the time of the “break” in incision rates points to an artefact caused by the lack of appropriate dating methods for the older horizons.

For the time interval between (9000) 2400 and 360 ka the incision rates are calculated to be between 0.02 and 0.06 mm/year. However, information about the onset of the incision is missing. These incision rates can only be taken as tentative values for a scenario of constant uplift since the formation of the uppermost horizons. A more detailed reconstruction of the older period is not feasible with the data available.

Nevertheless, data may still point to an accelerating trend of the vertical motion towards present, which seems to be in accordance with the gradual build-up of compressional stresses related to the neotectonic inversion of the Pannonian Basin, and locally to the shortening between the western and eastern parts of the Pannonian Basin (Grenerczy et al., 2000). The time of the onset of the incision and the real incision rate of the older period are key questions for further morphotectonic research.

The data series between 350 ka and present are more reliable as they are supported by absolute ages. Our calculations demonstrate that the incision rate of the axial zone in the HMR, the Danube Bend area has been considerably higher (0.41 mm/year), than the rates of the marginal areas, the Gerecse and Buda Hills (0.23–0.14 mm/year; Figs. 8 and 11). This is in agreement with the concept of differential vertical motion of the axis and the margins of the uplifting HMR. Although the reliability of the incision rates calculated for the Danube Bend is limited, which is the result of the limitations of the “traditional” terrace chronologic data set. In the marginal areas, the fastest uplift rate (0.23 mm/year) is registered by the karstwater level fall measured through Th/U dated speleothems. This rate has been obtained from a sample set independent from terrace and travertine series, and thus yields consistent information on the incision/uplift history of the Buda Hills.

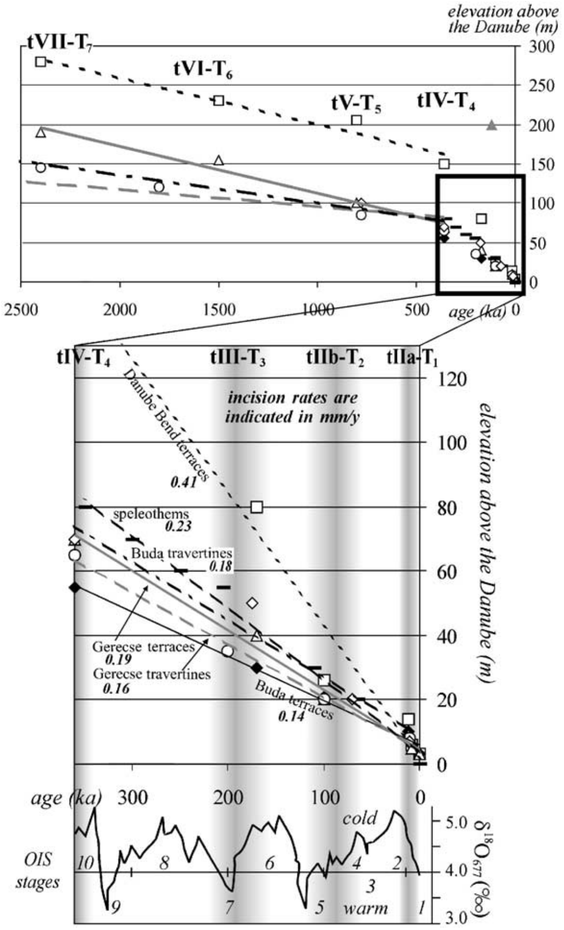

Fig. 11. Aggregate age–elevation plot of terrace chronologic data sets for the last 2500 ky, with special emphasize on the last 360 ky. Incision rates are indicated with bold and inclined numbers next to the trendlines. Absolute chronologic data are available for the time between 360 ka and present, which permits more detailed and trustworthy reconstruction. Periods of terrace-formation are enhanced with gray shadows, and correlated with the δ^{18}O proxy of the site ODP 677 (Shackleton et al., 1990). Accordingly some periods of climatic transition coincide with periods terrace formation, regardless of the trend of the climate change.

Our study provides a morphology-based semi-quantitative approximation of differential vertical motion across the HMR. According to our results the incision of the Danube has been 2–3 times faster in the Danube Bend then in the Buda and Gerecse Hills during the last 350 ky. The antecedent valley formation and the differential uplift are supported by several data sets, and geodetic levelling also indicates fast uplift in the axial zone of the HMR (Mike, 1969; Joó, 1993). Further research is required to define more accurate time constraints about the incision of the Danube, particularly in the Visegrád Gorge.

7.2. Periods of terrace formation

The classical climatic geomorphologic approach (Soergel, 1939; Büdel, 1948) determined the way of timing the terrace formation during the establishment of the "traditional" terrace chronology. Accordingly terrace aggradation was considered as characteristic of the glacials and carving into the levels was supposed to be an interglacial process. More recent observations seem to challenge this simplistic model. The transitional periods between glacials and interglacials have the most important role in carving the terrace levels. River incision occurs in periods of climatic instability i.e. transition from glacial to interglacial, and aggradation is a process characteristic of stable climate during both glacials and interglacials (e.g. Gábris, 1997; Tucker and Slingerland, 1997; Veldkamp and van Dijke, 2000; Nádor et al., 2003; Vandenberghe, 2003). Climatic change can induce terrace formation in stable and constantly uplifting areas however, local tectonic movements modify the regional effect of the climate.

Grey shading on Fig. 11. shows the periods of terrace formation during the last 350 ky derived from the compiled terrace chronologic data set. According to the marine oxygen isotope record of ODP 677 borehole (Shackleton et al., 1990) these periods coincide neither with glacial nor with interglacial climate. Instead, they represent transitional periods characterised by unstable climatic conditions. However, not all transitional phases appear morphologically as terrace horizons, and terrace formation seems to be independent of the direction of climatic change (i.e. from cold to warm or from warm to cold). Therefore we can conclude that terrace formation along the Danube was result of the emergence of the Hungarian Mountain Range during an epoch of significant climate changes. The joint effect of these driving forces led to cyclic changes of water flux and sediment supply. As a consequence, periodic terrace carving, valley widening and terrace aggradation occurred. Resolution of the existing chronologic data does not permit the recognition of phases of faster or slower vertical motion; some periods of climate change are apparently reconcilable with the terrace ages (Fig. 11).

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