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U-series dating and isotope geochemical study of the Gellért Hill (Budapest) travertine

Sándor Kele*
Institute for Geochemical Research
Hungarian Academy of Sciences, Budapest

Gyula Scheuer
Budapest

Attila Demény
Institute for Geochemical Research
Hungarian Academy of Sciences, Budapest

Chuan-Cou Shen, Hong-Wei Chiang
Department of Geosciences
National Taiwan University, Taipei

Travertine is quite a common formation in the area of Budapest (Hungary) indicating strong hydrothermal activity during the Pliocene and Quaternary. It covers former terraces of the Danube River and older geomorphologic horizons; thus, it is an important archive to date fluvial terraces and tectonic movements. Despite numerous investigations performed on these deposits, only few radiometric data are available so far and the absence of the exact timing information hindered paleoclimatic interpretation. The area of Gellért Hill consists mainly of Upper Triassic dolomite, but Quaternary travertine can also be found. In this study a detailed petrographic and stable isotope geochemical study of four travertine sites (1. Ifjúsági Park; 2. Számadó u. (Street); 3. Kelenhegyi u. (Street); 4. Somlói u. (Street)) of the Gellért Hill area is presented, along with analyses on the recent carbonate deposits of Gellért Hill and Sárosfürdő. The travertine of Ifjúsági Park and Számadó u. are spring cone deposits, while the travertine of the Kelenhegyi u. represents a shallow-water depositional environment. Based on the paleontological studies of Jánossy (in Scheuer and Schweitzer, 1988) the Gellért Hill travertine was thought to have been formed during the Lower Pleistocene; however, no radiometric age dating had been performed on these deposits prior our study. Our U/Th analyses yielded ages of 250±44 ky for the Ifjúsági Park travertine (220 m asl) and 180±49 ky for the Számadó u. travertine (195 m asl). These new U/Th ages are in contradiction with the previously assumed Lower Pleistocene age, implying gradual relative decrease in the paleokarst water-level and proving that the elevation of the individual travertine deposits not necessarily show their relative age. The uplift rates of Gellért Hill calculated from the U/Th age data and elevation of travertine occurrences range between 0.47 and 0.52 mm/yr, which is significantly higher than the uplift rates calculated for the Rózsadomb area (0.20 0.25 mm/yr; Kele et al., submitted). The difference in the incision rates between the individual sub-areas suggests that selective uplift was characteristic

Addresses: S. Kele, A. Demény: H-1112 Budapest, Budaörsi u. 45, Hungary
Gy. Scheuer: H-1126 Budapest, Szendrő u. 6, Hungary
S. Chuan-Cou, C. Hong-Wei: No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan 106

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*Corresponding author: E-mail: keles@geochem.hu

for the Buda Hills during the Middle Pleistocene; thus, up-scaling reconstruction of paleokarst water-level for the whole area from a given locality is not possible.

Oxygen isotope analyses of recent carbonate deposits of Gellért Hill, Sárosfürdő and Rudas Spa revealed that these calcites precipitated under non-equilibrium conditions, and the measured calcite-water oxygen isotope fractionation show the same positive shift relative to "equilibrium values" as was observed in the case of the recently-forming Egerszalók travertine (Kele et al. 2008). Assuming that the water of the paleo-springs of Gellért Hill derived from precipitation infiltrated during interstadial periods of the Pleistocene and considering non-equilibrium deposition (i.e. using the empirical calcite-water oxygen isotope fractionation of Kele et al. 2008), their calculated paleotemperature could range between 22 (±4) °C and 49 (±6) °C. Based on the $\delta^{18}O_{travertine}$ differences the Ifjúsági Park and the Számadó u. spring cone type travertine was deposited from the highest temperature water, while from the lowest temperature water the travertine of Kelenhegyi u. was formed.

Key words: travertine, Gellért Hill, uranium-series dating, Middle Pleistocene, stable isotopes, uplift

Introduction

Travertine and freshwater tufa deposits formed in lakes and rivers are one of the most important continental climate-related deposits. They have been widely studied since the end of the 19th century (Weed 1889), but their potential to provide a high-resolution terrestrial paleoclimate record was discovered only in recent decades (e.g. Hennig et al. 1983; Ford and Pedley 1996; Pentecost 1995).

Travertine is a frequent deposit in Hungary and is widespread in the area of Budapest (Buda Hills) as well, indicating strong hydrothermal activity during the Pliocene and Quaternary. Since it covers the former terraces of the Danube River and older geomorphologic horizons, it is an important archive for dating fluvial terraces and tectonic movements. The study of Hungarian travertine goes back to the beginning of the 20th century. After the first field observations of Kormos and Schréter (1916), Horusitzky (1939) and Schréter (1953), sedimentological and morphological investigations on travertine became popular research subjects in the 1970s (e.g. Scheuer and Schweitzer 1988). The travertine deposits of the Gerecse and Buda Hills were correlated with the terrace levels of the Danube River and its tributaries by Pécsi (1959) and Kretzoi and Pécsi (1982) based mainly on geomorphological, sedimentological and biostratigraphic considerations. Although further detailed studies have been conducted (e.g. Bakacsi 1993; Kele et al. 2003; Korpás et al. 2004), geochemical and stable isotope geochemical analyses of travertine were rather scarce in Hungary until the early 2000s (Rózsavölgyi 1964; Mihályi-Lányi 1964; Opauszky et al. 1964; Szöőr et al. 1992). In the last years Földvári et al. (2003), Kele et al. (2003), Korpás et al. (2004), Kele et al. (2006), Veres (2007), Kele et al. (2008), Sierralta et al. (2010), Kele (2009) and Kele et al. (submitted) published stable isotope results from Hungarian travertine sites. Despite numerous research project performed on these deposits, radiometric age data from Hungarian travertine deposits have rarely been reported (e.g. Pécsi 1973; Schwarcz 1980; Schwarcz and Skoflek 1982; Kretzoi and Pécsi 1982; Hennig et al. 1983; Schwarcz and Latham 1984), although they are essential for exact paleohydrological, paleoclimatological and tectonic conclusions. Leél-Őssy et al. (2009) determined 195 ky (+11 ky, –10 ky) ages on cave raft calcites collected from the Citadella Crystal Cave located at 167 m (asl) in Gellért Hill, but no radiometric age dating analyses have been performed so far on the travertine of the study area.

On Gellért Hill four travertine sites (1. Ifjúsági Park; 2. Számadó u.; 3. Kelenhegyi u. 4. Somlói u.) were described by Schréter (1953) and Scheuer and Schweitzer (1988) (Fig. 1). The primary goal of this study is to provide the first radiometric age data from these deposits in order to calculate the uplift rate of Gellért Hill. Additionally, sedimentological and stable isotope analyses were performed in order to reconstruct depositional environments of the Gellért Hill travertine deposits and to estimate the temperature of their parent thermal springs.

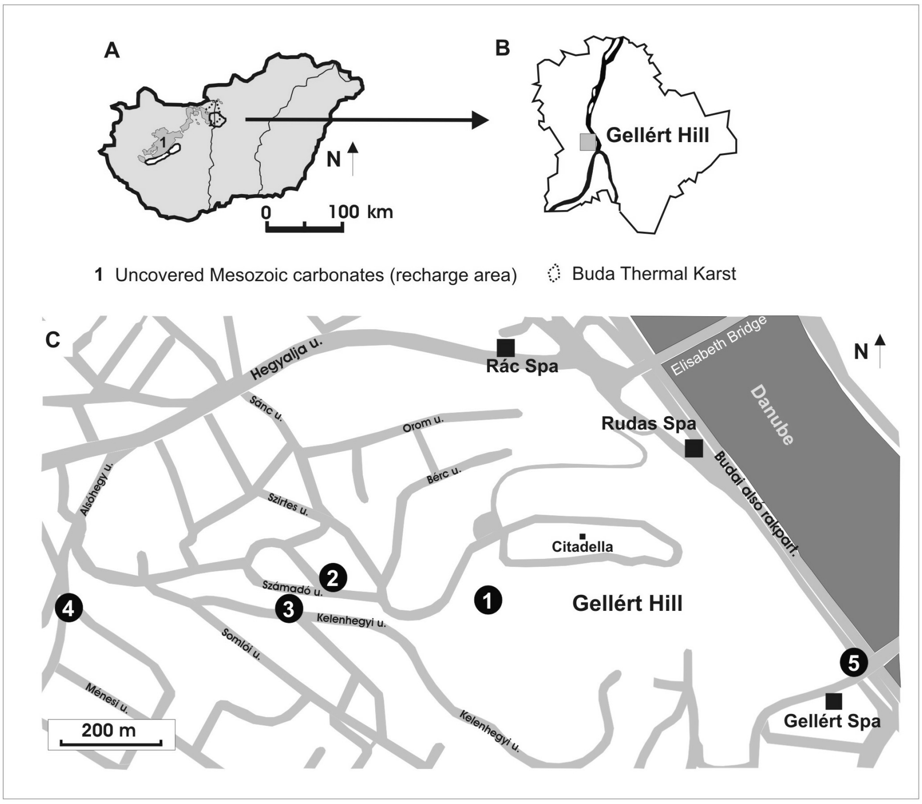


Fig. 1
A) Map of Hungary, indicating the location of the Buda Thermal Karst and its recharge area in the Transdanubian Central Range (modified after Erőss et al. 2006). B) Schematic map of Budapest showing the location of the studied Gellért Hill are. C) Travertine occurrences on Gellért Hill (the map is a modified version from Google and Tele Atlas). The locations of the travertine occurrences are shown after Kele (2009). Travertine occurrences: Ifjúsági Park (1), Számadó u. (2), Kelenhegyi u. (3), Somlói u. (4), Sárosfürdő (5)

Geologic, structural and hydrogeologic background

The geologic buildup of Gellért Hill was presented in detail by Korpás et al. (2002) (Figs 2 and 3). The main part of Gellért Hill consists of Upper Triassic dolomite containing organic-rich marl and clay-marl intercalations. A thin cherty limestone is intercalated with or covers the dolomite. The Upper Eocene begins with conglomerate (9–25 m in thickness), breccia and sandstone deposits. The content of the marl matrix increases upward, up to the Buda Marl. Sandstone and nummulitic limestone (Szépvölgyi Limestone) intercalations prevail in the upper part of the section. The bryozoic Buda Marl is covered by shallow bathyal clay (Oligocene Tard Clay and Kiscell Clay) and then by the Upper Oligocene Törökbálint Sandstone, which is known only from drilling cores in the area. The Quaternary is represented by travertine, loess, slope deposits and fluvial gravel and sand.

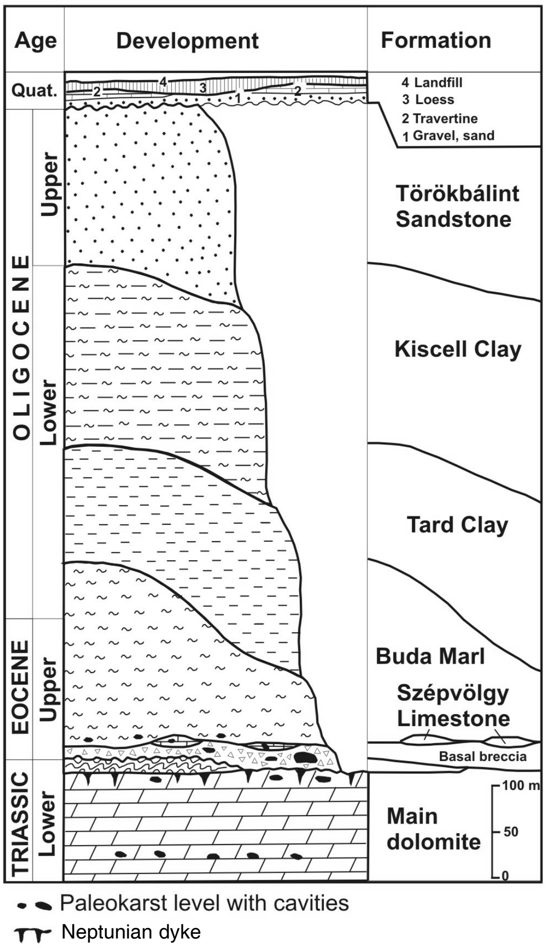


Fig. 2
Lithostratigraphic column of the Gellért Hill area (modified after Korpás et al. 2002)

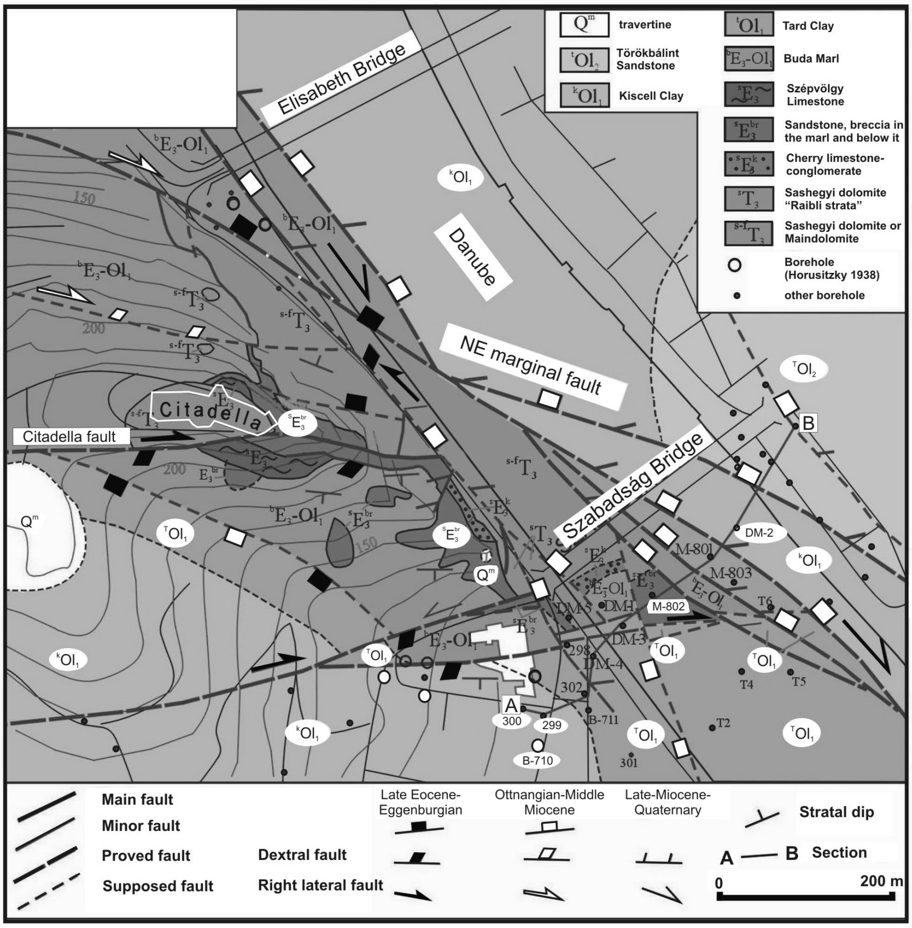


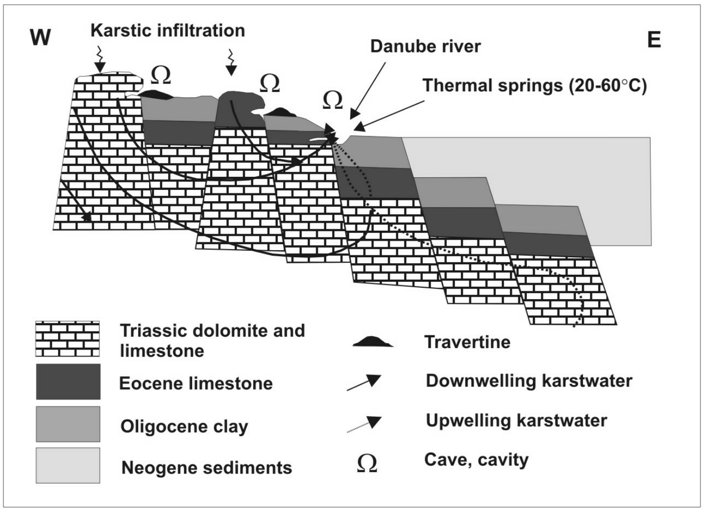
Fig. 3
Geologic map of the Gellért Hill area (modified after Fodor, 2001 in Korpás et al. 2002)

Gellért Hill is bordered by tectonic lines and the area is strongly influenced by structural movements (Wein 1977; Korpás et al. 2002). Three Tertiary stress fields affected the area, but a Triassic event is also possible according to Korpás et al. (2002). The Tertiary stress fields characterize four deformational events. The oldest, NNE–SSW tension created the E–W trending "Citadella Fault". Due to its dextral normal synsedimentary motion, the southeastern part of the hill subsided ca. 100 m (Korpás et al. 2002). The fault deformed the only partly consolidated sediments and induced creep, sliding, and replacement deposition of the Upper Eocene-lowermost Oligocene clastics. Faulting includes steeply dipping sedimentary dikes with sandy marl and limestone fillings. Most of dikes and the marl itself were silicified due to thermal fluids circulating along the main fault (Korpás et al. 2002). After the Early Oligocene the western segment of the "Citadella Fault" was reactivated and connected to another dextral normal fault south of Gellért Hill. The Ottnangian-Middle Miocene phase created large normal slip on the northeastern boundary fault of Gellért Hill. The fault is situated below the rock cliff at the Elisabeth Bridge and crosses the Danube, branching into several fault strands. This fault represents the eastern boundary fault of the entire Buda Hills and might have accumulated up to 1000 m of separation. The fault was reactivated during the late Miocene–Quaternary, due to ESE–WNW tension.

To correctly evaluate the results of the analyses performed on the travertine (which is the best evidence of paleo-spring activity), it is necessary to obtain an overview the hydrogeology of the investigated area. Many authors have already studied the thermal springs of Budapest and its hydrogeology (e.g. Schréter 1919; Schafarzik 1921; Víg and Horusitzky 1940; Papp 1962; Scheuer 1964; Vendel and Kisházy 1964; Alföldi et al. 1968; Kovács and Müller 1980; Erőss et al. 2008), while stable isotope studies on the thermal waters have been performed by Deák (1978), Babidorics et al. (1998) and Fórizs et al. (2007). The history of development of the paleo-thermal springs of Budapest were outlined by Scheuer and Schweitzer (1980a, b). In the latest years radon and radium measurements were performed by Palotai et al. (2005) and Fekete (2006).

Gellért Hill belongs to the Buda Thermal Karst containing thermal springs with elevated temperatures (35–43°C), which are connected to the NW–SE normal fault zone of the area (Korpás et al. 2002). The main aquifers of the Buda Thermal Karst are both Mesozoic carbonates and Eocene limestone. The Buda Thermal Karst is in subsurface connection with the groundwater system of the Transdanubian Central Range 200 km away from the Buda Hills in a W–SW direction. The several thousand meter-thick Mesozoic carbonate sequence of the Transdanubian Central Range serves as an aquifer and karstic recharge area for the Buda Thermal Karst. The cold water infiltrated in the Transdanubian Central Range is heated up by thermal convection during its long regional-scale flow and discharge to the surface as thermal water on the right (western) side of the Danube, and in the riverbed along the step-faulted boundary of the uplifted hills and the subsided basin to the east (Kovács and Müller 1980; Fig. 4). At the eastern margin of the Buda Hills many medium and high temperature thermal springs discharge close to the current level of the Danube River (e.g. Békásmegyer, Attila Spring, Óbuda, Árpád Spring, Pünkösdfürdő, Lukács-Császár Spa, etc.). Some of these springs discharge water directly from the lowest karstic blocks (e.g. springs of the Gellért and Rudas Spas), while others reach the surface breaking through permeable deposits (Római Spa and Attila Spring at Békásmegyer) (Scheuer and Schweitzer 1989). Recent carbonate precipitations can be easily found at these springs and thermal wells (e.g. Béke well, Dagály; Zsigmondi-5 well, Margitsziget).

Fig. 4
Schematic cross-section and model of the Buda Thermal Karst system (modified after Kovács and Müller 1980)



The springs discharging at Gellért Hill are characterized by uniform chemical composition and temperature (Erőss et al. 2008) and their discharge is indirectly influenced by the Danube River, which represents the base level of erosion. Based on ^{14}C measurements of Deák (1978) the age of these waters is 5000 to 16000 years. Babidorics et al. (1998) presented $\delta^{18}O_{water}$ values around –11.6‰ (V-SMOW) from the Gellért Tunnel, suggesting that the water infiltrated in the Ice Age (i.e. more than 10 ky ago). All of the springs of Gellért Hill (e.g. Mátyás Spring, Juventus Spring, Gül Baba Spring, Ősforrás Spring, etc.) discharge from Triassic dolomite and they supply the Rác, Rudas, and Gellért Spas (Alföldi et al. 1968). Traces of paleo-thermal spring activity are well visible as travertine deposits, spring caves and cavities on and around Gellért Hill. Active thermal springs fed the Rác, Rudas and Gellért Spas, while some of them discharge at the bottom of the Danube River. Carbonate precipitations are observable on the surface of the hot (40°C) water of the Gellért Tunnel and at the Gül-baba Spring (Fig. 5E, F). The most spectacular recently forming carbonate of the Gellért Hill area is the "travertine beard" in the Rudas Spa (Fig. 6), which was studied in detail by Veres (2007). Holocene travertine can also be found below the building of the Rudas Spa, which can be considered as the deposit of the Hungária, Udvari, or the Kossuth Springs (Papp 1942) and around the Rác Spa (Hajnal et al. 2005). The temperatures of the Gellért Hill springs are generally higher than 40°C and their temperature and discharge rate is in close relationship with the water level of the Danube River.

Materials and methods

Altogether four travertine occurrences (two of them [Ifjúsági Park, Számadó u.] are autochthonous and two allochthonous [Somlói u., Kelenhegyi u.]) were sampled in the area of Gellért Hill (Fig. 1). During field trips, beside sampling and

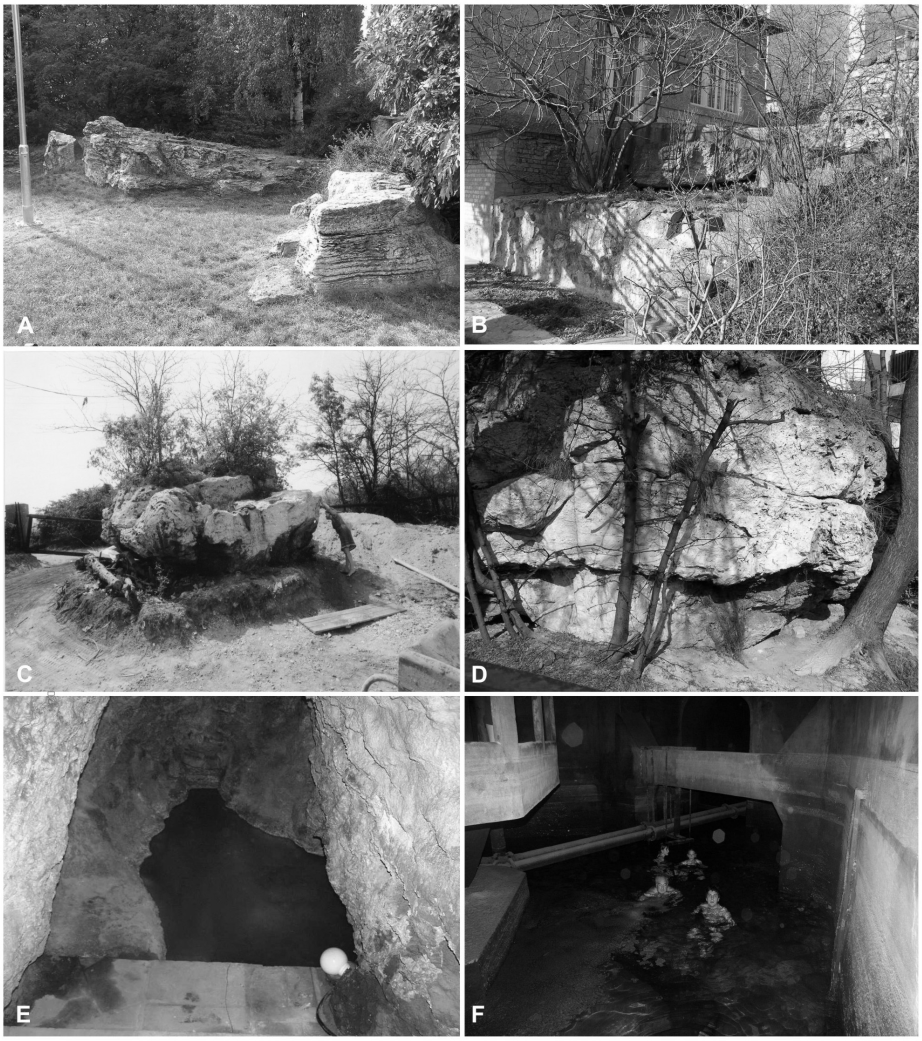


Fig. 5
Pictures of the most important travertine occurrences of the Gellért Hill area: A) Remnant of a spring cone in Ifjúsági Park; B) Travertine located along Kelenhegyi u. 76; C) and D) Travertine block in the garden of Számadó u. 7; E) Recent carbonate precipitations in the Gül Baba spring cavity located at the foot of Gellért Hill, close to the Danube River; F) Ősforrás. The surface of the water is covered by a thin calcite layer. In the water Szabolcs Leél-Őssy on the left and Sándor Kele on the right; The C photo was taken by Gyula Scheuer in the 70s, while the F photo was taken by Mehmet Oruç Baykara

sedimentological observations, the geographic position and elevation of the occurrences were also determined using a GPS device. Detailed petrographic analyses were conducted on the main lithofacies types of each occurrence using polished thin sections and optical microscope to infer the depositional environment. For the microfacies description the terminology of Folk (1959) and Dunham (1962) were used.

Stable carbon and oxygen isotope measurements were performed on 15 travertine samples using Finnigan delta S and delta Plus XP mass spectrometers at the Institute for Geochemical Research, Hungarian Academy of Sciences, Budapest, Hungary. Carbon and oxygen isotope analyses of bulk carbonate samples were carried out using both the conventional phosphoric acid method (H_3PO_4 digestion method at 25°C) of McCrea (1950) and the continuous flow technique (Spötl and Vennemann 2003). Standardization was conducted using laboratory calcite standards calibrated against the NBS 18 and NBS 19 standards. All samples were measured at least in duplicate and the mean values are given in the standard delta notation in permill (‰) relative to V-PDB ($\delta^{13}C$) and V-SMOW ($\delta^{18}O$) following the equation $\delta = (R_{sample}/R_{standard} - 1) \times 1000$, where R_{sample} and $R_{standard}$ are the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in sample and standard, respectively. Reproducibilities are better than ±0.1‰ for $\delta^{13}C$ and $\delta^{18}O$ values of carbonates.

U/Th dating was completed in the High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University (Taipei, Taiwan). Three samples from two travertine sites collected from the area of Gellért Hill were analyzed using a Thermo Electron Neptune Multi-Collector - Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) (Shen et al. 2002, 2006, 2008). The technique is based on the precipitation of uranium at the moment of deposition of carbonates in the absence of thorium. After carbonate deposition, due to the radioactive decay of ^{234}U the ^{230}Th concentration starts increasing in the carbonate; hence the $^{230}Th/^{234}U$ ratio of the travertine depends on its age (Edwards et al. 1987; Richards and Dorale 2003). Before high-precision U/Th analyses, the samples were prepared (crushed, weighed and cleaned using ultrasonic cleaning methods) in ultra-clean laboratory conditions ("class-10 000" geochemical cleanroom) using a "class-100 laminar-flow clean working bench". U-Th chemistry was performed in the Geochemistry Technology Laboratory of the Department of Geosciences, National Taiwan University (NTU). Travertine sub-samples (0.1–0.3 g) were prepared with chemical methods described by Edwards et al. (1988) and Shen et al. (2003) for U-Th chemistry.

Samples were spiked with a ^{229}Th–^{233}U–^{236}U triple-spike isotope dilution method to correct mass bias and determine uranium concentration (Shen et al. 2002). A protocol, using one newly-developed MasCom secondary electron multiplier (SEM) with repelling potential quadrupole (RPQ), was employed. Only 1–4 ng of U is required to reach the 2-sigma reproducibility of 1–2‰. The absence of significant difference between measurements of standards and carbonate samples on ICP-sector-field-MS (Shen et al. 2002), and on MC-ICP-MS, certify the developed MC-ICP-MS methodology. Uranium and thorium were separated by Fe co-precipitation and anion-exchange chromatography. The uranium and thorium aliquots were dissolved in 1% HNO_3 + 0.005 N HF for instrumental measurements (Shen et al. 2002). The obtained ages are absolute ages given as years before present.

For U/Th measurements clean, dense and white-colored massive travertine samples were chosen to avoid contamination with clay-minerals which would provide additional ^{232}Th pollution. However, since the travertine samples are surficial carbonate deposits, they contained high amount of detrital Th, which lowered the accuracy of the measurements. Thus, age corrections were applied, because even a small amount of U-derived Th may have an effect on the U/Th age of the samples. The average accuracy was ±47 ky (Table 1).

Table 1

Stable carbon- and oxygen isotopic composition, approximate radiometric age, elevation above sea level and GPS coordinates of travertine occurrences of Gellért Hill

Name	**$\delta^{18}O_{average}$**	**$\delta^{18}O_{average}$**	**$\delta^{13}C_{average}$**	**Age**	**h (asl)**	**GPS coordinate**
	[‰, V-PDB]	[‰, V-SMOW]	[‰, V-PDB]	ky	m	
Gellért Hill, Ifjúsági park	–12.9	17.6	1.9	250 000 ±43	220	N 47º29 155' EO 19º02 606'
Gellért Hill, Számadó u.	–10.7	19.9	0.5	180 000 ±49	195	N 47º29 182' EO 19º02 302'
				160 000 ±50		
Gellért Hill, Kelenhegyi u.	–9.9	20.7	–2.9		175	N 47º29 148' EO 19º02 220'
Gellért Hill, Somlói u.	–11.3	19.3	–0.5		150	N 47º29 177' EO 19º01 892'
Gellért Hill, Ősforrás	–14.9	15.6	1.2	recens	104*	N 47º29 04.99' EO 19º03 09.99'
Rudas Spa*	–15.1	15.3	1.4	recens	122*	N 47º29 20.30' EO 19º02 52.19'

*based on Veres 2007

Results

Sedimentology and microfacies description

The Pleistocene travertine deposits of the Buda Hills were formed in diverse depositional environments (e.g. lake, valley-side, spring cone deposits) (Scheuer and Schweitzer 1988; Kele 2009); thus, their morphology is quite variable. In this study four travertine sites were investigated from Gellért Hill: (i) a remnant of a spring cone (or fissure ridge) on the top of Gellért Hill, Ifjúsági Park (220–215 m asl (Fig. 5A); (ii) 4–5 m high spring cone at Számadó u. 7 (195 m asl, Fig. 5C and D) and the detrital travertine of (iii) Kelenhegyi u. 75. (170 m asl, Fig. 5B) and (iv) Somlói u. (150 m asl). In general, the travertine of Gellért Hill is a grayish-white, dense, hard and sometimes laminated carbonate rock.

Fig. 6 →
Picture of the still depositing "travertine beard" in the Rudas Spa (the photo was taken in 2005; Veres 2007)

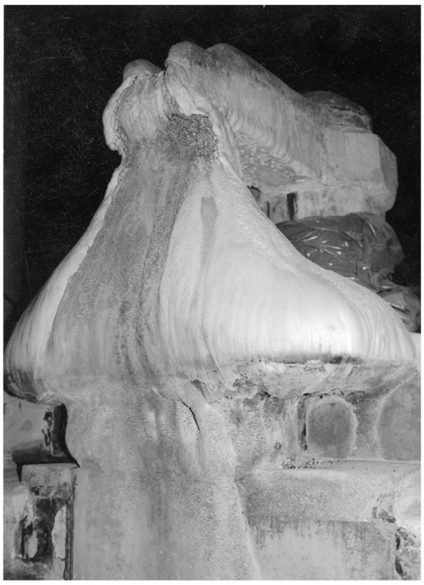
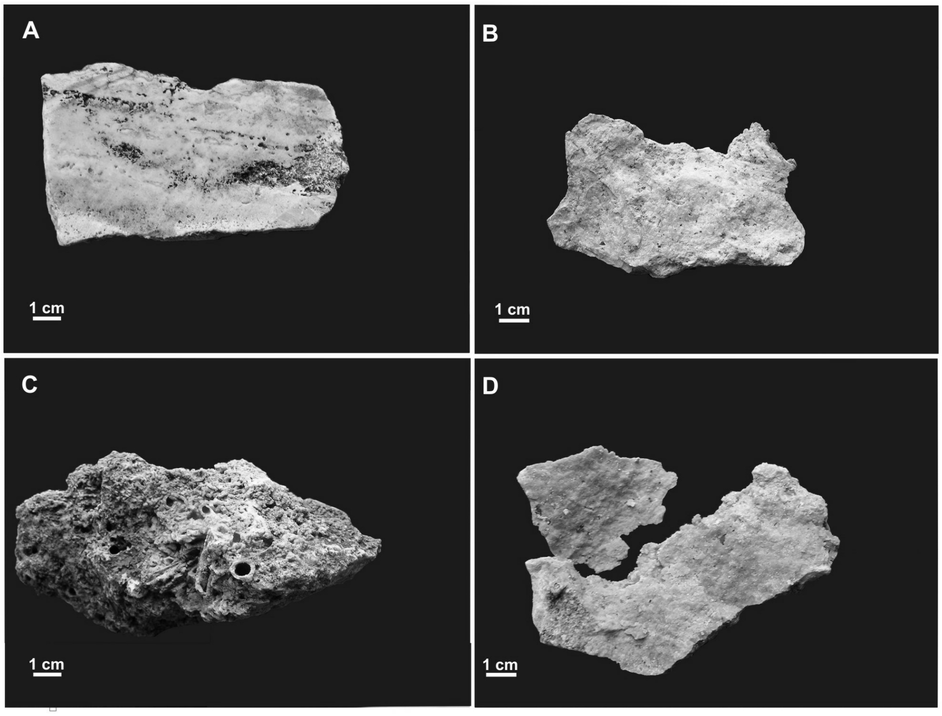


Fig. 7↓
Macroscopic photos of the characteristic travertine samples collected from the Gellért Hill area: A) Layered travertine from the fossil spring cone (fissure ridge?) located in Ifjúsági Park. B) Homogeneous travertine sample from the fossil spring cone of Számadó u. 7. C) Photograph of a phytohermal travertine sample collected close to Kelenhegyi u. D) Massive, pore-free travertine (calcarenite) located close to Somlói u.



The Pleistocene travertine of the Ifjúsági Park is well-layered, grayish-white in color, has pelmicritic texture and it is free of flora and fauna (Fig. 7A, Fig. 8A). The samples collected from the 4–5 m high and 5 m wide fossil spring cone of Számadó u. 7 are hard, finely layered (sometimes homogeneous), they have pelmicritic texture and contain oncoids (Fig. 8B) and plant remnants as well. The autochthonous travertine of the Kelenhegyi u. 76 (Fig. 5B) is located in a private area; thus, it was not accessible. The travertine debris along the street contains remnants of plants forming phytohermal structure (e.g. Fig. 7C) and it has micritic-microsparitic texture (Fig. 8C). There is only one massive, allochthonous travertine block close to the Somlói u. which has pelmicrosparitic texture and it contains remnants of shells of ostracods, but peloids dominate in the texture (Fig. 7D, Fig. 8D).

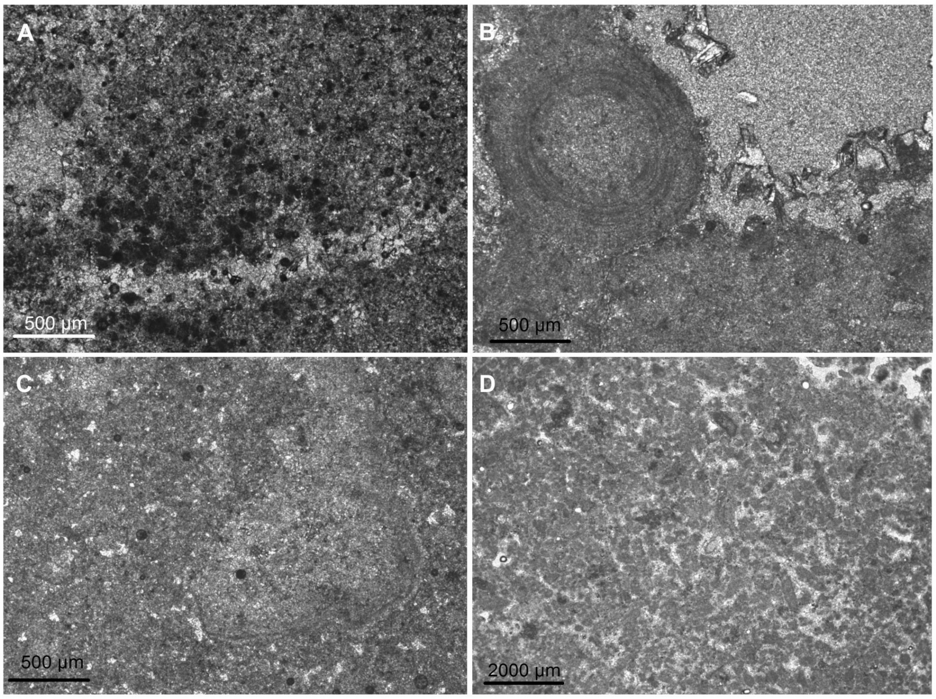


Fig. 8
Microphotographs of typical microfacies and micromorphological features of the travertine collected from the Gellért Hill area: A) Flora and fauna-free pelmicritic texture from the Ifjúsági Park travertine; B) Oncoid in the pelmicritic texture of the Számadó u. travertine; C) Micritic-microsparitic texture from the allochthonous Kelenhegyi u. travertine and pelmicrosparitic texture from the allochthonous travertine block of Somlói u. (D). In the latter example remnants of shells can also occur

Results of U/Th dating measurements

Table 1 contains the approximate age data, together with the precision of the measurements. The data prove that the travertine of Gellért Hill was formed during the Middle Pleistocene, about 160–250 ky ago. The travertine of Ifjúsági Park (220 m asl) yielded an age of 250±44 ky, while the travertine block of Számadó u. 7 (195 m asl) showed younger ages (160±50 ky, 180±49 ky).

Stable C and O isotope compositions

Stable carbon and oxygen isotope measurements were performed on all samples collected from the four investigated travertine occurrences and the results are shown in Table 2. The measured isotope compositions vary within wide ranges: the $\delta^{13}C$ values range between –5.9‰ and +2.0‰ (V-PDB), while the $\delta^{18}O$ values vary between +16.2‰ and +22.0‰ (V-SMOW). The analyses of the recent carbonate precipitation at the ősforrás spring yielded $\delta^{13}C$ and $\delta^{18}O$ values (1.5‰ and 15.3‰, respectively) similar to those of the "travertine beard" of the Rudas spring ($\delta^{13}C$: 1.4‰, $\delta^{18}O$: 15.3‰) determined by Veres (2007) Table 1).

Table 2
Stable carbon and oxygen isotopic composition of travertine deposits of Gellért Hill

Name	**Sample number**	**$\delta^{18}O$** [‰, V-PDB]	**$\delta^{18}O$** [‰, V-SMOW]	**$\delta^{13}C$** [‰, V-PDB]
Gellért Hill, Ifjúsági park	1	–14.3	16.2	1.9
	2	–12.4	18.1	2.0
	3	–10.0	20.6	0.2
	4	–12.1	18.5	1.9
	5	–12.9	17.6	1.9
Gellért Hill, Számadó u.	1	–10.9	19.7	0.2
	2	–9.2	21.4	1.7
	3	–11.0	19.6	–0.2
	4	–11.7	18.9	0.3
Gellért Hill, Kelenhegyi u.	1	–11.0	19.5	0.2
	2	–9.9	20.7	–3.1
	3	–8.7	22.0	–5.9
Gellért Hill, Somlói u.	1	–11.3	19.3	–0.5
Gellért Hill, Õsforrás	1	–15.1	15.3	1.5
	1b	–14.7	15.8	1.0

Discussion

Paleoenvironmental reconstruction of the Gellért Hill travertine

Paleoenvironmental reconstruction of the travertine located in the Gellért Hill area have already been performed by many authors in the last decades, under better sampling conditions. Most of the travertine was quarried in the 19th century. Papp (1942), Schréter (1953), Scheuer and Schweitzer (1974, 1980, 1988), studied the Gellért Hill travertine in detail and Szőőr et al. (1992) performed some sporadic stable isotope analyses, but no detailed microfacies study, geochemical analyses or radiometric dating on these deposits have been performed yet. Scheuer and Schweitzer (1974) described five travertine occurrences on Gellért Hill facing Német Valley. In this chapter, previously published formation models and our new results are compared, which sometimes support, but in some cases modify the earlier results.

Remnants of travertine spring cones are common in the Buda Hills (e.g. Törökvész lejtő, Szemlő Hill; Kele 2009; Kele et al., submitted) and this observation is true for the Gellért Hill area as well. The travertine deposits of Gellért Hill are small and belong mainly to spring cone type deposits, due to the fact that during their deposition the absence of any morphological depression hindered the formation of lake depositional environments. This could be due to the assumption that the Gellért Hill area was never flooded by the Danube; thus, the river was not able to form depressions for lakes fed by thermal springs.

The travertine of Ifjúsági Park (220–215 m asl, Fig. 5A) was described as a Pliocene warm-water lake deposit by Papp (1942), and Scheuer and Schweitzer (1988) also suggested a lacustrine depositional environment. Previous papers by Scheuer and Schweitzer (1988), Szőőr et al. (1992) and Scheuer et al. (1993) suggested a Lower Pleistocene age for the travertine based on the bear fossil Ursus deningeri described by Dénes Jánossy at the Felszabadulási monument. However, based on our new U/Th age data the travertine of Ifjúsági Park is much younger (250±44 ky), suggesting Middle Pleistocene spring activity in the Gellért Hill area, where the sedimentological characteristics of the occurrence indicate a spring cone or fissure ridge depositional environment.

The 4–5 m high and 5 m wide travertine block located in the garden of Számadó u. 7 sz. (195 m asl; Fig. 5C, D) was previously described as Lower Pleistocene tetarata-type travertine; however, based on its cone-like morphology it is presumably a preserved center of a travertine spring cone. Remnants of plants can also occur in this compact, well-layered but sometimes homogeneous deposit, but its lacustrine origin can be excluded based on its small size and morphology. The presence of oncoids in thin sections (Fig. 8B) could indicate both the presence of bacterial activity and agitated water. Radiometric U/Th analyses of this travertine again yielded Middle Pleistocene ages (180±49 ky and 160±50 ky), which are younger than those of the travertine of Ifjúsági Park

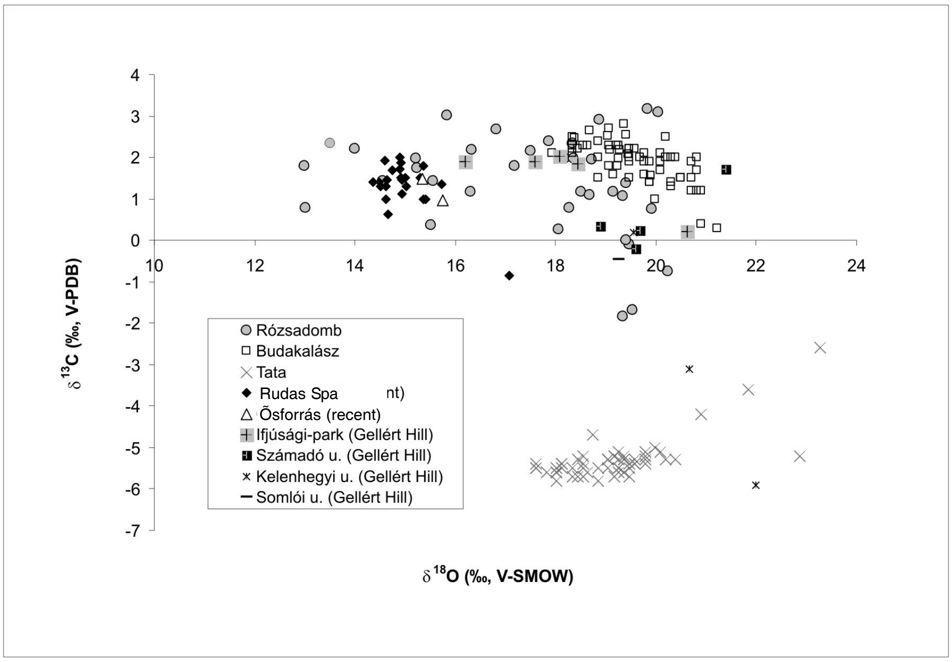


Fig. 9
Comparison of the stable isotopic values of travertine of Gellért Hill, the Upper Pleistocene travertine of Tata, Porhanyó Quarry (Western Gerecse; Kele et al. 2006), the Pleistocene Budakalász travertine (Buda Hills; Kele et al. 2003), the Pleistocene travertine of the Rózsadomb (Kele et al., submitted) and the Holocene carbonate precipitation of Rudas Spa (Budapest; Veres 2007)

situated at higher altitude, that would be of an older age according to Scheuer and Schweitzer (1988).

The travertine deposits of Kelenhegyi u. (170 m asl) and Somlói u. in their current preservation are not suitable for paleoenvironmental reconstruction, due to their weak exposure. However, the plant remnants in the travertine of the Kelenhegyi u. infer shallow water, while the massive, pore-free travertine of Somlói u. (150 m asl, Fig. 7D) points to an open lake environment. The latter occurrence was mentioned by Schréter (1953) and described by Scheuer and Schweitzer (1988) as a tetarata-type limestone.

Discussion of stable isotope data

Origin of CO_2

The interpretation of the $\delta^{13}C_{travertine}$ requires special care, since the CO_2 may derive from various sources, like decarbonation of limestone, mantle degassing, hydrolysis and oxidation of reduced carbon, etc. (Pentecost 2005); isotope fractionation processes during and after travertine deposition can also mask the source composition. Thus, in order to get more reliable paleoclimatological and paleoenvironmental data from travertine, a better understanding of the processes governing their precipitation and geochemical composition – including stable isotopes – is needed.

Comparing the previously published stable isotope data from the Gerecse and Buda Hills (Kele et al. 2003, 2006; Veres 2007; Kele 2009; Sierralta et al. 2010; Kele et al., submitted) and the new stable isotope data from the Gellért Hill travertine, significant differences can be observed in both the $\delta^{13}C$ and $\delta^{18}O$ values between the localities (Fig. 9). The $\delta^{13}C$ values of travertine of the Buda Hills (Budakalász, Rózsadomb, etc.) range mostly between +1‰ and +3‰, while the $\delta^{13}C$ values of that collected from the Gerecse Hills are generally lower in average ($-7‰ < \delta^{13}C < 0‰$) (Kele et al. 2006; Kele, 2009). Among the Pleistocene travertine deposits of Gellért Hill, only that of Ifjúsági-park shows $\delta^{13}C$ values around +2‰, while the other three occurrences show significantly lower $\delta^{13}C$ values (Table 2). Especially the travertine detritus of the Kelenhegyi u. show negative $\delta^{13}C$ values, probably due to the presence of plant debris (represented by remnants in the phytohermal structure) and possible contribution of the isotopically light organic CO_2 derived from plant matter decay (Fig. 7C, Fig. 9).

The stable C isotope compositions of travertine can indicate thermal, magmatic and metamorphic processes; however, the isotope data should be accompanied by detailed geologic knowledge of the area, involving sedimentological and tectonic features. The $\delta^{13}C$ value of travertine is controlled by the relative amounts and carbon isotope compositions of dissolved inorganic carbon components derived from limestone dissolution during water migration and from CO_2 dissolution from different sources (air, oxidation of organic matter, thermometamorphic reactions, etc.).

The analyses of the recent carbonate precipitation at the Gellért Hill Ősforrás spring resulted in $\delta^{13}C$ and $\delta^{18}O$ values similar to those of measured from the "travertine beard" of the Rudas spring by Veres (2007) (Table 1). Besides, the $\delta^{13}C$ values of recent carbonates are similar to the average values measured so far on the Pleistocene travertine of the Buda Hills. Thus, the origin of the dissolved carbonate (the recharge area and the underground flowpath) and the origin of CO_2 have not changed significantly since the Pleistocene. Many former studies have already dealt with the origin of CO_2 (e.g. Turi 1986; Minissale 2004) and with the geochemical classification of travertine (Pentecost and Viles 1994; Kele et al. 2003; Pentecost 2005; Kele et al. 2008). In the Buda Hills the measured $\delta^{13}C_{travertine}$ values are similar to the C isotope data (ranging between 0 and +3‰) measured on the primary (marine) carbonates of the Transdanubian Range (Hungary) (Fig. 11 in Haas and Demény 2002).

Paleotemperature calculations

The $\delta^{18}O$ values of travertine are controlled by many parameters, among which the most important are temperature and $\delta^{18}O$ value of the travertine-depositing thermal water. These parameters are in close relation with climate; however, the effect of diagenesis on the $\delta^{18}O_{travertine}$ values cannot be neglected during the interpretation of the stable isotopic data. For warm and wet climatic periods, relatively high $\delta^{18}O$ values are characteristic, while during colder periods the situation is reversed, which shows the importance of the isotopic composition of water. The $\delta^{18}O_{travertine}$ value is also controlled by the temperature of the parent water. In the case of stable isotopic equilibrium and assuming constant $\delta^{18}O_{water}$ it can be stated that the higher the temperature of the travertine-depositing thermal water, the lower the $\delta^{18}O_{travertine}$ value, and vice versa. In the case of calcite-water oxygen isotopic equilibrium the temperature of formation (i.e. the paleotemperature) can be calculated using the equation of O'Neil et al. (1969), which was modified by Friedman and O'Neil (1977):

$$10^3 \ln\alpha = (2.78 \times 10^6) / T^2 - 2.89 \qquad (1)$$

where: $\alpha = (\delta^{18}O_{carbonate} + 10^3) / (\delta^{18}O_{water} + 10^3)$

Thus, in the case of isotopic equilibrium the $\delta^{18}O_{travertine}$ value is determined by the temperature of the travertine-depositing thermal water and its $\delta^{18}O$ value. Consequently, 1°C change in temperature equals 0.24‰ shift in the $\delta^{18}O_{travertine}$ (Craig 1964; Andrews 2006). It is important to note that the travertine was not necessarily deposited under equilibrium conditions (Kele et al. 2008; Kele et al., submitted) and its deposition cannot be precisely described with the above (1) equation.

Stable oxygen isotope analyses of recently forming carbonate and spring water were conducted at two localities of the Gellért Hill area (the Ősforrás spring and the Rudas Spa), while the $\delta^{18}O_{water}$ values and temperature data were also available from the literature. Thus, it was possible to examine the relationship between the Δcalcite-water values of the recent calcite precipitations and the theoretical values calculated using the equation of Friedman and O'Neil (1977). For the calculations the $\delta^{18}O_{water}$, data of Babidorics et al. (1998) and Fórizs (unpublished, measured in 2008) were used, while the $\delta^{18}O_{travertine}$ values of the Rudas Spa were taken from Veres (2007). It must be mentioned that the $\delta^{18}O_{water}$ values of the Rudas Spa show no significant change between 1998 and now, so they can be used for calculations. Figure 10 shows that the measured Δcalcite-water values show the same positive shift as was observed in the case of the recently forming Egerszalók travertine (Kele et al. 2008).

According to Babidorics et al. (1998) the waters infiltrated during the Ice Age (more than 10 ky ago) are characterized with $\delta^{18}O$ values between –14‰ and –11‰, while the Holocene waters generally have $\delta^{18}O$ values between –9.3‰ and 10‰. The mean $\delta^{18}O$ values of the Gellért Hill travertine occurrences range between 17.6 and 20.7 (‰, V-SMOW) (Table 1), while when considering all samples the $\delta^{18}O$ values vary between 16.2 and 22 (‰, V-SMOW) (Table 2).

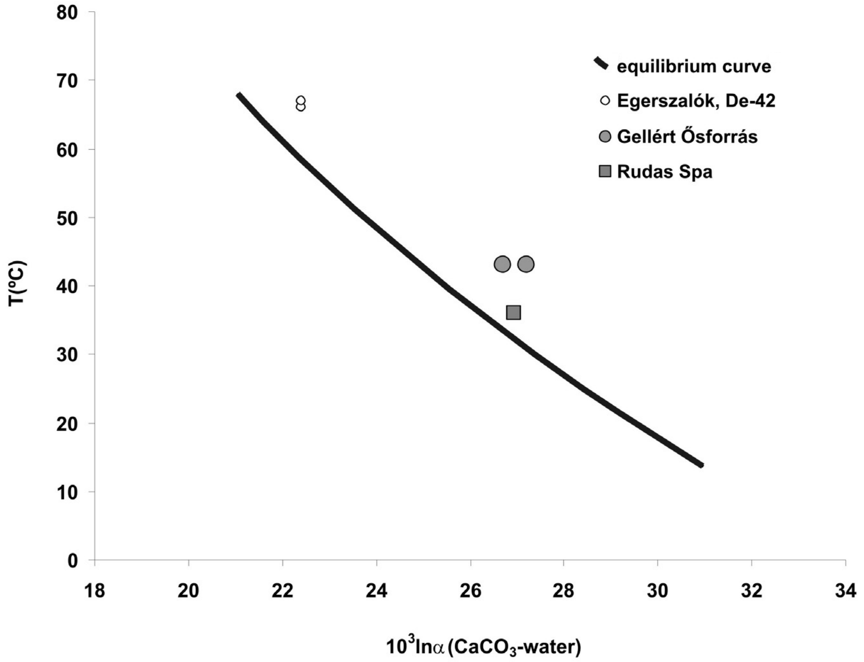


Fig. 10
Fractionation of oxygen isotopes between calcite and water vs. the measured temperature. Beside the recent carbonate precipitations of Gellért Hill, Ősforrás and Rudas Spa, the values of the recent Egerszalók travertine (Kele et al. 2008) are also shown. Equilibrium values were calculated based on the equation of Friedman and O'Neil (1977) in the 10–70°C temperature range

Pleistocene climate changes could have influenced both the temperature and the oxygen isotope composition of the thermal springs; thus, both their temperature and O isotope composition could have been different from those of today. Since our U/Th measurements on the Gellért Hill travertine deposits yielded Upper Pleistocene ages between 160 and 250 ky, Holocene water infiltration can be excluded. However, during the Pleistocene warm periods could have occurred with $\delta^{18}O$ values slightly lower than those of the Holocene waters. Assuming that the water of the paleo-springs of Gellért Hill derived from precipitation infiltrated during interstadial periods of the Pleistocene, then their $\delta^{18}O$ value could be around –12‰ (±1‰); thus, the calculated paleo-temperatures (using the equation of Friedman and O'Neil 1977) could range between 14 (±4) °C and 41 (±6) °C. Since Kele et al. (2008) demonstrated that the use of the "equilibrium" equation of Friedman and O'Neil (1977) underestimates the real deposition temperature by about 8°C (and the same phenomenon was observed at Gellért Hill as discussed above), then we can conclude that the temperature of the travertine-depositing paleo-springs of Gellért Hill could have been between 22 (±4) °C and 49 (±6) °C.

Based on the available stable isotope data and microfacies descriptions, relative differences in paleo-temperatures can be calculated between the occurrences. Since there are differences between the $\delta^{18}O$ values of the Gellért Hill travertine occurrences, it cannot be excluded that the temperature of their parent thermal springs was different. However, diagenesis can affect the $\delta^{18}O_{travertine}$ values, causing differences in the oxygen isotopic compositions due to the presence of secondary carbonates. Among the deposits of Gellért Hill the Ifjúsági Park and the Számadó u. spring cone type travertine could have been deposited from the highest temperature water, since they have the lowest $\delta^{18}O_{travertine}$ values, while from the lowest temperature water the travertine of the Kelenhegyi u. was deposited. In the latter the remnants of plants also indicate moderate temperature conditions and a possible lacustrine depositional environment.

Uplift rates: spatial and temporal variations

The majority of the age data of Hungarian travertine presented in preceding papers are based mainly on paleomagnetic measurements (Latham and Schwarcz 1990; Lantos 2004), paleontological remnants (i.e. Jánossy 1979) and geomorphological considerations; only sporadic radiometric (U/Th) dating analyses have been performed (e.g. Kretzoi and Pécsi 1982). Our U/Th data are the first from the Gellért Hill travertine and they are important in the reconstruction of the past structural development of the Buda Hills. The Pleistocene uplift history of the Buda Hills has attracted special attention in recent years. For the calculations of uplift rates Leél-Őssy (1997), Leél-Őssy and Surányi (2003) and Szanyi et al. (2009) used U/Th data from cave deposits, while Ruszkiczay-Rüdiger et al. (2005) summarized the previously published (paleontological, paleomagnetic, U/Th and ^{14}C) age data and used them for the calculations. According to Burbank and Anderson (2001) the incision/uplift rate can be calculated based on the following equation:

(1) i (rate) = [elevation (mm) – elevation of Danube asl (mm)] / age (yr)

When calculating uplift rates it must be assumed that travertine deposition took place on or close to the elevation of the Danube River, which is the general erosion level of the area. U/Th ages measured from terrace-cover travertine show only the minimum age of the covered surface. Besides, the individual travertine occurrences are characterized only with a single U/Th measurement, although the deposition of the entire travertine mass of a given occurrence often took some hundred thousand years (e.g. Sierralta et al. 2010). If the youngest sample of the occurrence is used for the calculation of the uplift rate, then the maximal uplift rate will be calculated, while using the oldest sample of the occurrence the calculated uplift rate can decrease significantly. For terrace dating lacustrine travertine is the most appropriate type of deposit, since slope and tetarata-type travertine usually form from springs located above the erosion level; thus, they cannot be used for precise dating. The calculated uplift rates are affected by the error of the U/Th measurements (in this study this is ± 50 ky) caused by the Th contamination of travertine; thus, we determined the minimal and maximal uplift rates in the case of both studied occurrences. The calculated uplift rate in mm/yr is only an average value which obscures the nature of the tectonic processes and can be regarded as reliable if the uplift of the area and the incision of the river was continuous. It is more likely (and the presence of terraces supports this hypothesis) that the uplift rate was higher than the calculated values and the uplift process was periodic.

Using radiometric age data of the carbonate precipitations of the József Hill cave, Leél-Őssy (1997) determined 0.15–0.3 mm/yr, while Ruszkiczay-Rüdiger et al. (2005) calculated a 0.23 mm/yr average uplift rate for the Buda Hills. Based on literature data from the cover deposits of the terraces, Ruszkiczay-Rüdiger et al. (2005) concluded that the incision (uplift) history of the Danube River in the Gerecse and Buda Hills can be divided into two periods characterized with different uplift rates: between 9 my and 360 ky, 0.02 and 0.04 mm/yr, while in the last 360 ky of the Pleistocene, 0.16 and 0.18 mm/yr. However, the conclusions of Ruszkiczay-Rüdiger et al. (2005) were only rough estimates due to the scarcity of precise age data. Since at the time of earlier age determination studies (e.g. Latham and Schwarcz 1990) the upper age limit of the U/Th dating technique was only 360 ky, the uplift rate calculations from deposits older than 360 ky become quite uncertain, as was emphasized by Ruszkiczay-Rüdiger et al. (2005). The other problem is that the starting date of the incision (uplift) and its change with time is not known. Szanyi et al. (2009) dated calcite sheets from the Pál-völgyi cave and for the time period of 500–280 ky they calculated a 0.06–0.3 mm/yr uplift rate, whereas using the data published by Leél-Őssy (1997) and the samples located below 155 m asl in the Pál-völgyi cave for the 280–70 ky interval, they determined 0.16 mm/yr (i.e. accelerating) uplift.

Kele (2009) published a series of new U/Th data from the travertine of the Buda Hills, which play an important role in the reconstruction of the Pleistocene development of the Danube Valley. The steep morphology of Gellért Hill can itself be regarded as evidence of high uplift rate. Uplift rates calculated from travertine deposited at different elevations at Ifjúsági Park (220 m asl, 250±44 ky) and Számadó u. (195 m asl, 180±49 ky) resulted in rates of 0.47 mm/yr (0.40–0.57 mm/yr) and 0.52 mm/yr (0.41–0.71 mm/yr), respectively, which are higher than the results of earlier calculations. Besides, calculations using the U/Th data measured on the travertine of the Rózsadomb (i.e. Barsi u., Bimbó u., Szőlészeti Kutatóintézet, Apostol u.) resulted in incision/uplift rates between 0.20–0.25 mm/yr (Kele et al., submitted). The data indicate that the area of Gellért Hill was uplifted about two times faster than the Rózsadomb, which implies selective uplift for the area of the Buda Hills during the Pleistocene, as was suggested (but not proved) by Wein (1977).

If the uplift rate is calculated from the age and elevation data of the two localities studied here, then a value of 0.35 mm/yr is obtained, meaning that the rate was significantly higher than 0.5 mm/yr in the last 160 ky, as is also shown by the data for the Számadó u. locality. These calculations are based on the general assumption that travertine is formed at the bank of River Danube, i.e. at the erosion base. If the studied travertine had formed at higher elevations, then the calculated uplift rate would be lower. Formation of the younger travertine occurrence at about 10 m higher than the erosion base would yield an uplift rate about 0.25 mm/yr. Our data suggest that either the uplift rate changed in space and time, or the spring discharge locations migrated.

Conclusions

In this paper we present detailed sedimentological and geochemical investigations performed on the Gellért Hill travertine. Based on textural observations and oxygen isotope compositions the travertine of Ifjúsági Park and Számadó u. are spring cone deposits and formed from higher temperature thermal water than the travertine of Kelenhegyi u., which could have been deposited in a shallow water environment. Measured calcite-water oxygen isotope fractionations in the case of recent carbonate precipitations of the Gellért Hill, Sárosfürdő and Rudas Spas show that the calcite was precipitated under non-equilibrium conditions. Assuming that the water of the paleo-springs of Gellért Hill derived from precipitation infiltrated during interstadial periods of the Pleistocene, and considering non-equilibrium deposition (i.e. using the empirical calcite-water oxygen isotope fractionation of Kele et al. 2008), the calculated paleotemperature could range between 22 (±4) °C and 49 (±6) °C. Our new U/Th data proved that the area of Gellért Hill was characterized by thermal spring activity during the Middle Pleistocene (~160–260 ky ago), contrary to previously published theories. From the elevation level and radiometric age of the Ifjúsági Park (250±44 ky, 220 m asl) and Számadó u. travertine deposits (180±49 ky, 195 m asl) a relative decrease of the paleokarst water-level can be reconstructed. The uplift rates calculated from the U/Th age data and elevation of travertine occurrences ranges between 0.47–0.52 mm/yr in the area of Gellért Hill and differ significantly from the rates calculated for the Rózsadomb area (0.20–0.25 mm/yr; Kele et al., submitted), suggesting selective uplift of the different blocks of the Buda Hills during the Middle Pleistocene.

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