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ORIGINAL ARTICLE

Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in Hungarian caves

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Abstract The examination of speleothems in the Hajnóczy and Baradla caves (northeastern Hungary) allows estimating an upper limit for horizontal peak ground acceleration generated by paleoearthquakes. The density, the Young's modulus and the tensile failure stress of the samples originating from a broken speleothem have been measured in a laboratory, whereas the natural frequency of intact speleothems was determined by in situ observations. The value of horizontal ground acceleration resulting in failure, the natural frequency and the inner friction coefficient of speleothems were assessed by theoretical calculations. The ages of the samples taken from a stalagmite 5.1 m in height (Baradla cave) have been determined by inductively coupled plasma mass spectrometry analysis and alpha spectrometry. The measured ages fall between 140,000 and 70,000 years; therefore, we assume the speleothem has not been changed since the end of this time interval. According to our modeling results, this speleothem has not been excited by a horizontal acceleration higher than 0.05 g during the last 70,000 years.

Keywords Speleothems · Paleoearthquakes · Earthquake hazard

1 Introduction

In territories with low or moderate seismic activity, the recurrence time of large earthquakes belonging to the same source zone can be as long as 10,000 years (Scholz 1990). Therefore, we cannot draw well-grounded inferences in the field of seismic hazard assessment using exclusively the data of earthquake catalogues, as they are based characteristically on 1,000- to 2,000-year observational period.

To obtain more reliable and realistic data regarding the frequency and magnitude of earth-

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quakes, we have to investigate paleoearthquakes that occurred before historic times.

Neotectonic and geomorphologic investigations can reveal the traces of paleoearthquakes only in some lucky circumstances, as erosion can easily destroy the superficial formations.

The research of the relationship between earthquakes and the growth, tilting and breaking of speleothems is promising, and investigations of this kind have been initiated in recent times.

Results of Forti and Postpischl (1984, 1988) show that examining the broken and tilted speleothems can be useful for revealing historic and paleoearthquakes. Delaby (2001) recognised the occurrence of a paleoearthquake while studying broken and tilted stalagmites in the Hotton cave (Belgium).

Cadorin et al. (2001) performed laboratory measurements and theoretical computations to determine the horizontal acceleration that was necessary to break the broken speleothems in the Hotton cave. According to their results, there was only one sample from the 34 ones that was broken at an acceleration of 2 m/s^2; other samples required a horizontal acceleration amplitude of at least 1 g. Hence, these speleothems could not be indicators of paleoearthquakes.

Lacave et al. (2000) determined by in situ measurements the natural frequencies of various type of speleothems, estimated curves describing the natural frequency as the function of the type and length of the speleothem, and computed the speleothems' viscous equivalent damping. Furthermore, Lacave et al. (2004) constructed vulnerability curves (probability of breaking vs. peak ground acceleration [PGA] functions) for classes of differently shaped stalactites.

Kagan et al. (2005) dated broken speleothems by U-Th and oxygen isotope method in two caves in Israel and found a mean recurrence interval of 10,000–14,000 years of large earthquakes affecting the territory.

Recently, Becker et al. (2006) gave a comprehensive critical review of speleoseismology. They describe processes other than earthquakes that can have the same or very similar effects on speleothems, and they conclude that, before a decision is made on the seismic origin of deformations and

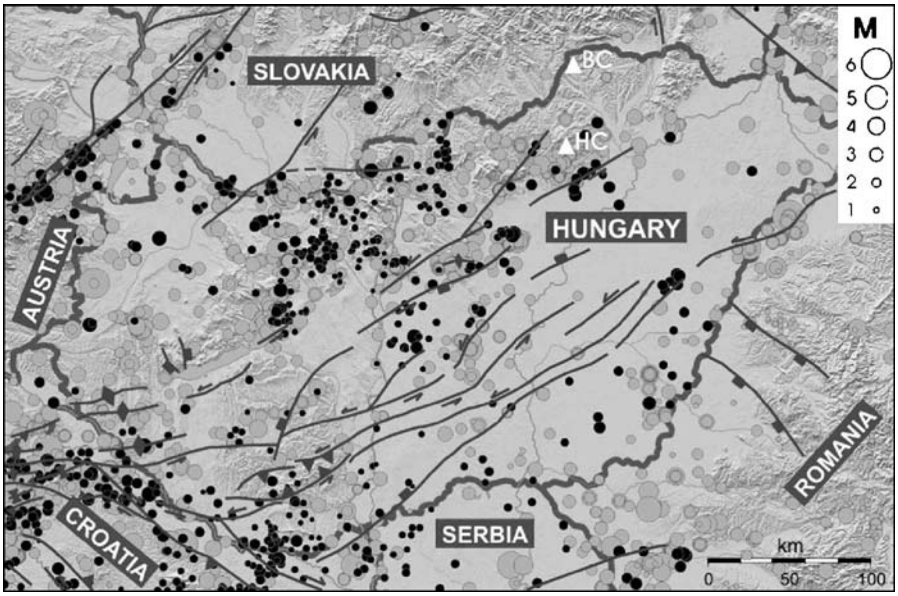


Fig. 1 Location of the Baradla and Hajnóczy caves (*BC* and *HC*, respectively) and the historical and instrumental seismicity of the Pannonian region. The epicenter distribution of historical (456–1994) earthquakes are displayed by *gray circles*, whereas *black circles* represent recent (1995–2004) well-located events (after Tóth et al. 2007). The *size of the circles* is proportional to the magnitude. The *black lines* illustrate the neotectonic active structures after Horváth et al. (2006). The *rectangles, triangles* and *arrows on the lines* indicate normal, reverse and strike-slip faults, respectively, whereas the *diamonds* show the anticlines

damages found in caves, alternative explanations must be taken into consideration as well.

The connection between earthquakes and the breaking and tilting of speleothems has not yet been investigated in Hungary, but research about the age and formation of dripstones proved to be successful (Lauritzen and Leél-Őssy 1999).

The territory of Hungary is rather rich in dripstone caves, they can be found in several regions of the country (e.g. Transdanubian Central Range, Mecsek and Villány Mountains, Bükk Mountains, the Aggtelek Karst). Based on the review of the Hungarian speleological literature (e.g. Kordos 1984), discussions with experts and our visits to caves, it seems that, in Hungary, only in the Hajnóczy and Baradla caves (Fig. 1) can be found speleothems that are well suited to the paleoseismic investigations; that is, they have the necessary large height/diameter ratio (Cadorin et al. 2001). Our preliminary investigations suggested that the stalagmites of these caves can break even at low horizontal acceleration. These speleothems therefore could be used as indicators whether or not large paleoearthquakes occurred within the given region.

During our research, the density, the Young's modulus and the tensile failure stress of speleothem samples have been measured in laboratory for subsequent theoretical modeling, whereas the natural frequency of intact speleothems was determined by in situ observations. The value of horizontal ground acceleration resulting in failure, the natural frequency and the inner friction coefficient of speleothems were assessed by theoretical calculations. The ages of the samples originating from a specific stalagmite have been determined by inductively coupled plasma mass spectrometry (ICP-MS) analysis and alpha spectrometry.

2 Seismicity of Hungary

The seismic activity inside the Pannonian basin (Fig. 1) can be considered moderate compared to that of the peripheral areas (Tóth et al. 2002). Construction of a reliable seismotectonic model for this territory proved to be a challenging task, due to the relatively small number of earthquakes and the diffuse distribution of epicenters.

Nevertheless, nowadays, it is clear that the earthquake activity and present-day deformation are mainly driven by the counterclockwise rotation and northwards indentation of the Adriatic microplate (e.g. Bada et al. 1999). The rheological weakness of the Pannonian lithosphere (Gerner et al. 1999; Lenkey et al. 2002) poses a constraint on the maximum magnitude of earthquakes, and as a consequence, the largest part of the events occurs at shallow depths (Tóth et al. 2002).

According to the Hungarian Earthquake Catalogue (Zsíros 2000), which contains earthquakes as from the year 456 A.D., the maximum observed magnitude was 6.3 in the Hungarian part of the Pannonian basin.

In spite of the diffuse characteristics of the earthquake activity, some zones with above average seismic activity can be identified in Hungary. They are mainly located in the western and central part of the country, whereas the level of seismicity in the northeastern part of Hungary is rather low.

The map of the expected PGA with a 90% probability of non-exceedance in 50 years (475-year return period) for the Pannonian region compiled by Tóth et al. (2006) shows that the expected PGA is 0.068 g in the vicinity of the Baradla cave and 0.086 g near the Hajnóczy cave.

3 The caves

The Baradla cave (Fig. 2) is the longest cave of Hungary (with a length of around 26 km, from which approximately 5 km belongs to Slovakia) and is one of the UNESCO's World Heritage Sites. The cave is located in Northern Hungary, in the Gömör–Torna karst region. It has been known since prehistoric times and was used as a shelter and a dwelling in the Paleolithic and Neolithic periods. The cave's passages have been formed in the Middle and Upper Triassic limestone (partly in dolomitic limestone). The horizontal and vertical dimensions of the passages can reach a value of a few 10 m. The Baradla cave is decorated with a large amount of stalagmites, stalactites and dripstone pillars of a maximum height of 18 m.

In the Baradla cave, the broken speleothems are abundant. Most of them can be found near the entrance and all along the tourist paths. These

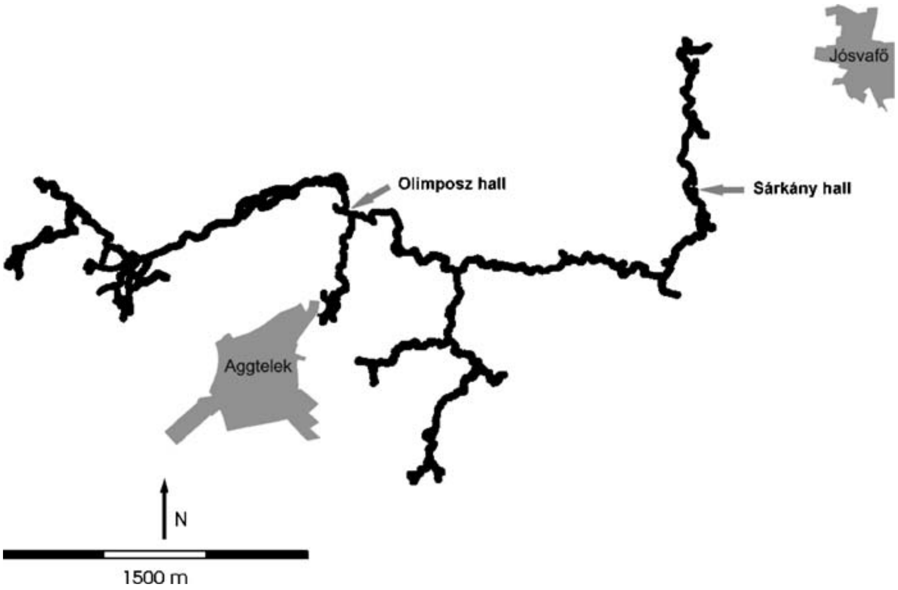


Fig. 2 Map of the Baradla cave

damages are probably attributable to human influence. According to Jakucs (1952), in the nineteenth century, the cave tour guides broke the speleothems with their sticks for the tourists. The deep impact marks and fractures oblique to the growth axis of speleothems also indicate an anthropic origin (see e.g. Crispim 1999). The growth of speleothems has continued from the time of breaking, but only a very thin coating formed suggesting that the damages occurred recently. In the Baradla cave, stalagmites several meters in height and up to almost 1 m in width can be found, which are tilted or broken. These ones are situated on clay or debris slopes or near the watercourse. The collapse, breaking and tilting of these speleothems might have been caused by sliding or soil creeping, or they might have been washed away by running water. Conclusively, our investigation seem to suggest that the damaged speleothems are not of seismic origin.

The Hajnóczy cave (Fig. 3) can also be found in Northern Hungary, in the southern part of the Bükk Mountains. The cave, which was discovered in 1971, has been formed in the Middle and Upper Triassic flinty, gray limestone. It has a complicated layout and possesses multiple levels. Its structure extends vertically for 135 m, and the total length of the known passages is around 3,000 m. In the

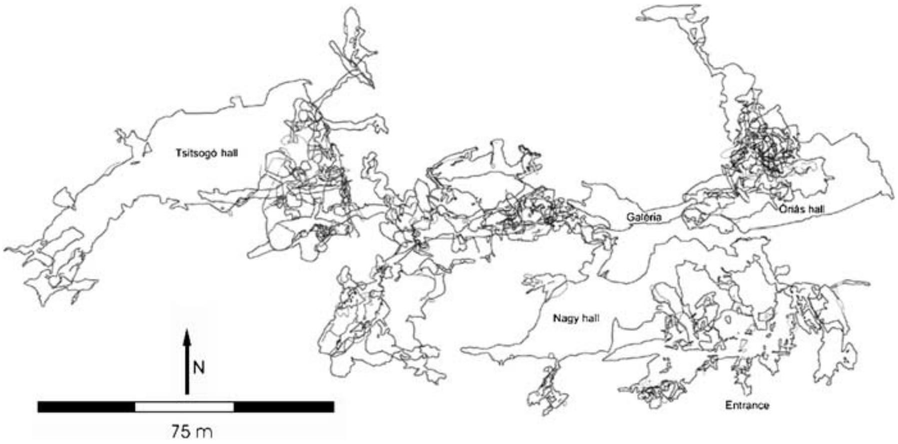


Fig. 3 Map of the Hajnóczy cave

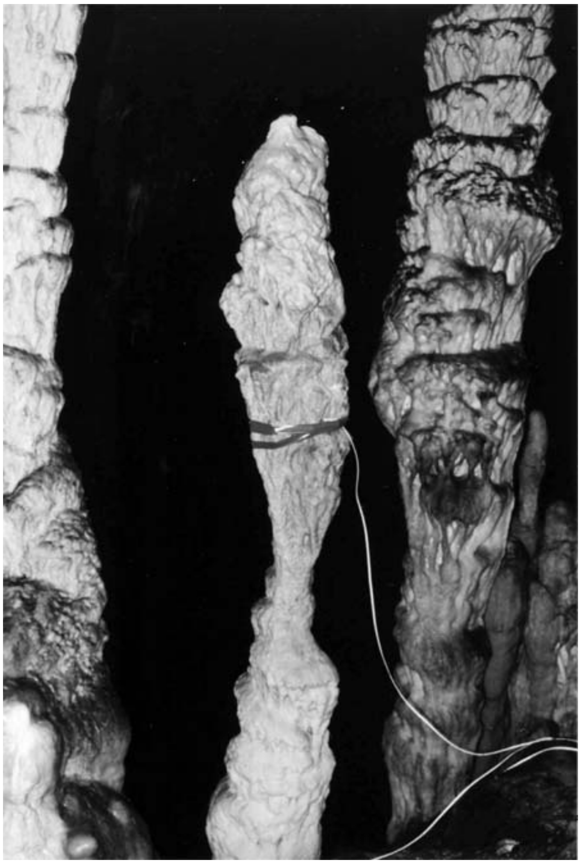


Fig. 4 A stalagmite (Speleothem N° 3) in the Sárkány hall of the Baradla cave

passages, the traces of hydrothermal activity can be found, which indicates that hot aqueous solutions probably played an important role during their formation. The Hajnóczy cave is exceptionally rich in speleothems. In its large halls, the slim and tall stalagmites and columns are typical (they often have a diameter of a few centimetres and a height of several metres).

The Hajnóczy cave is practically free of broken speleothems. This observation can be explained by the lack of human influence, as it has only been discovered recently.

It is known that, with the deepening of the caves, the attenuation of the seismic waves rises (Becker et al. 2006). Therefore, it is important to mention that the caves where the investigated speleothems stand are situated at shallow depth. The Olimposz hall in the Baradla cave is located at 35–40 m below surface, the Sárkány hall in Baradla cave is situated at 45–50 m depth, and the surface above both halls makes up a platform ridge. The Hajnóczy cave can be found in 60 m depth beneath the surface, topographically under a hillside.

4 Non-intrusive examination of speleothems

Considering that the in situ measurements had to be done non-intrusively, we confined ourselves only to determine the dimensions and natural frequency of speleothems.

To measure the natural frequency, small amplitude forced vibration was obtained by a gentle hit using one's hand or a rubber hammer. The horizontal acceleration of the speleothem was registered by an SM6 geophone (its natural frequency is 4.5 Hz) and a SIG SMACH SM-2 digitiser. The geophones were mounted by means of adhesive tape onto the speleothems (Figs. 4 and 5). The sampling rate of the analog–digital converter was

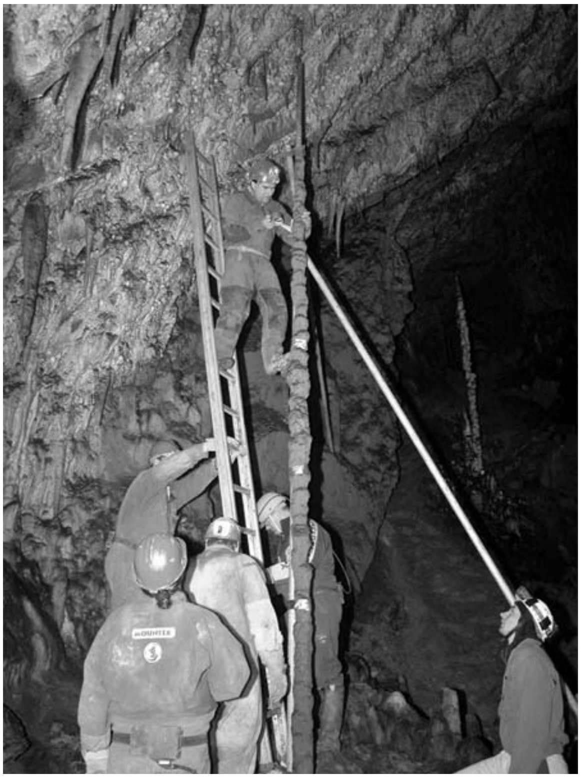


Fig. 5 Sampling a stalagmite of 5.1 m high (Speleothem N° 6) in the Olimposz hall of the Baradla cave

set to 256 Hz, whereas the cut-off frequency of the anti-aliasing filter was 50 Hz.

The power spectral density of the vibration has been determined by fast Fourier transform. The measured traces and their spectra for certain speleothems are displayed in Figs. 6, 7 and 8.

Table 1 shows, among other parameters, the horizontal and vertical dimensions of the seven studied speleothems and the in situ measured natural frequencies (f_0).

The diameter of the dripstones ranges between 4 and 30 cm, but the characteristic diameter (which parameter describes the typical horizontal dimension) of the more or less cylindrically shaped speleothems falls in the range of 5 and 11.5 cm. Their height varied from 2.1 to 5.1 m.

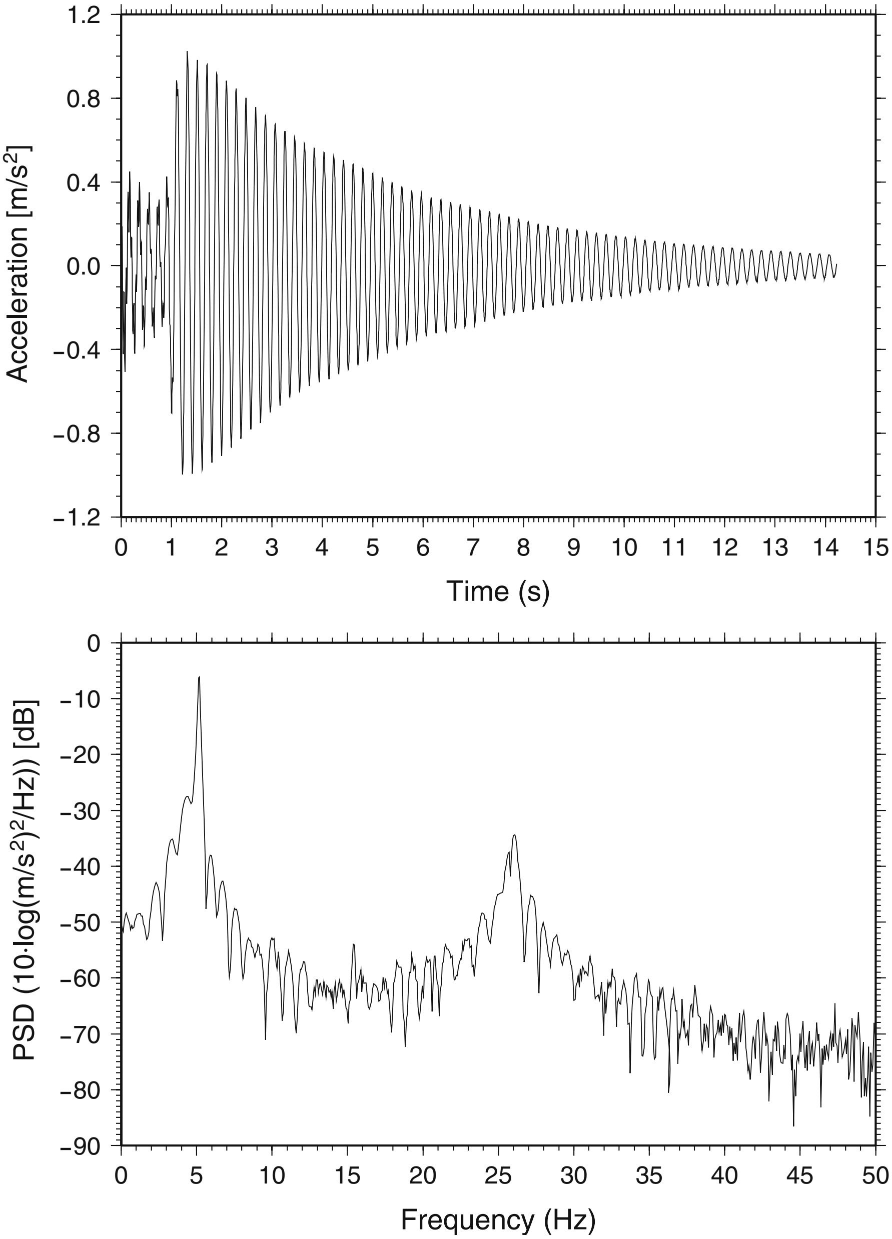
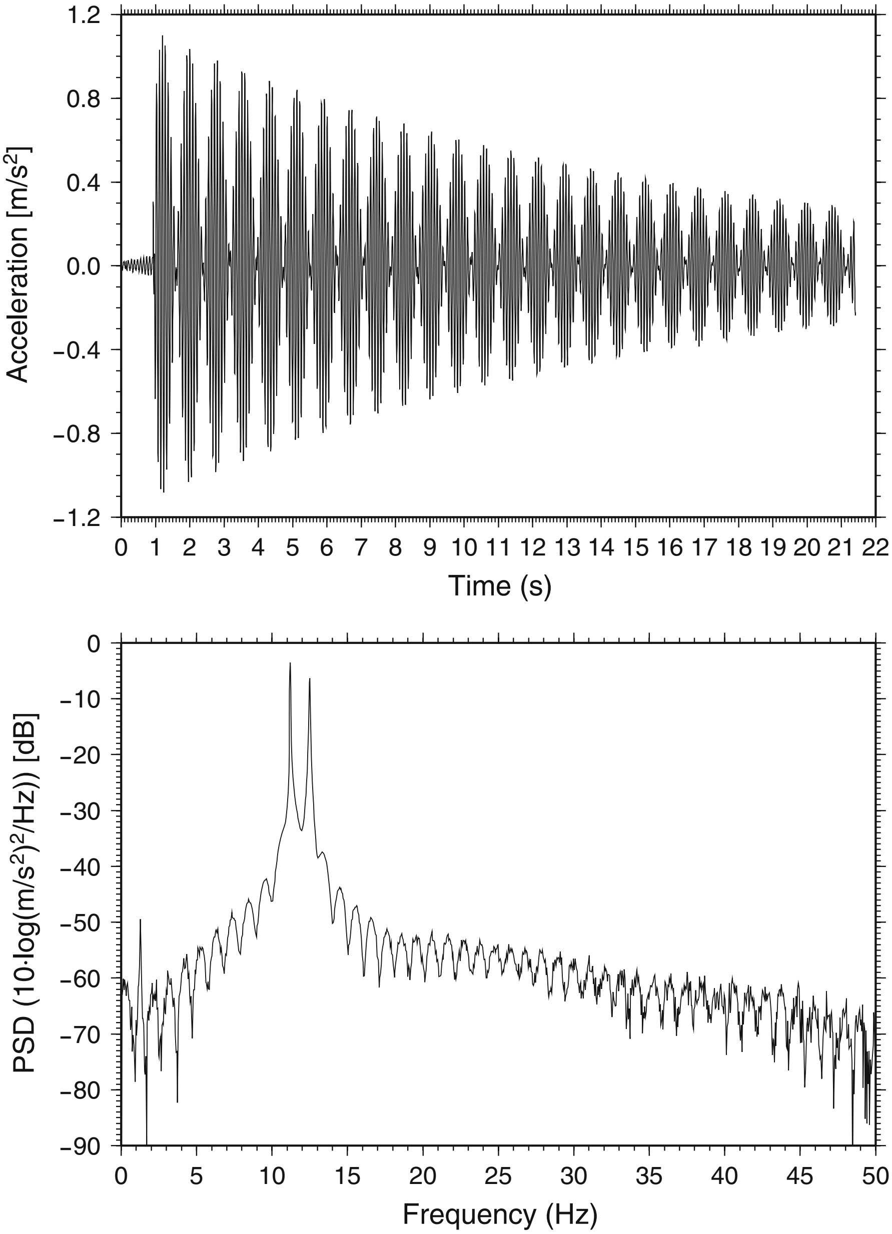


Fig. 6 The oscillation of the stalagmite of 3.35 m high (Speleothem N° 1) in the Sárkány hall of the Baradla cave and its power spectral density

Fig. 7 The oscillation of the Speleothem N° 3 in the Sárkány hall of the Baradla cave and its power spectral density



Consequently, the height/diameter ratios were exceptionally large ($24.7 \leq H/D \leq 72$). It is interesting to note that the maximum H/D ratio found by Cadorin et al. (2001) for the speleothems of the Hotton cave was only 20.

The measured natural frequencies are in the range of 1.4 and 27.9 Hz, but only in two cases from the seven was f_0 above 25 Hz, in the other cases it fell below 13 Hz.

5 Oscillation of stalagmites – theoretical considerations

In our modeling, the stalagmites were considered as vertical cylinders of height H and diameter D with a circular cross-section. We supposed that the bottom of the cylinders is firmly fixed to the ground and the top can move freely. The material of the stalagmites was considered homogeneous.

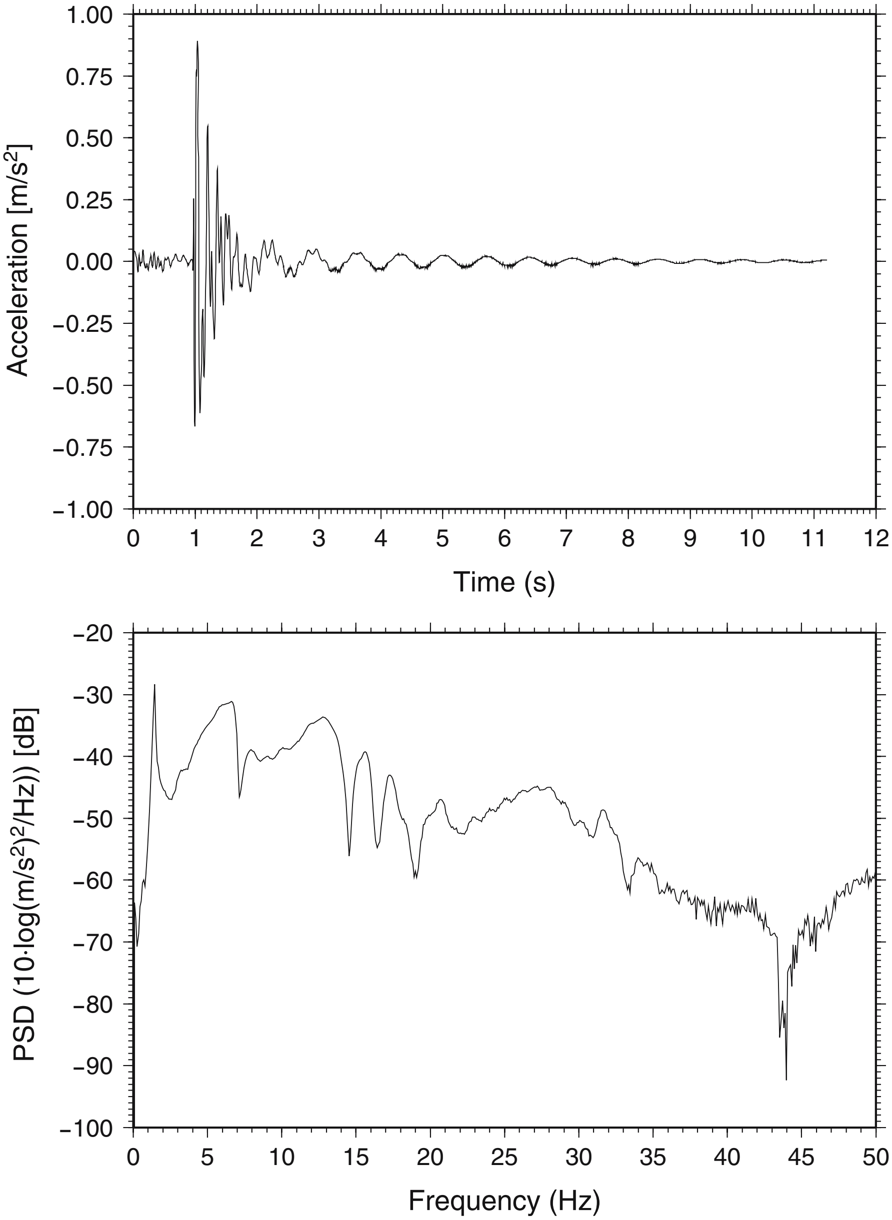


Fig. 8 The oscillation of the stalagmite of 5.1 m high (Speleothem N° 6) in the Olimposz hall of the Baradla cave and its power spectral density. The dripstone is cracked at 4.76 m high, which can justify the presence of the relatively strong secondary peaks at higher frequencies

Following the study of Ferencz and Péterfalvi (2002), the coordinate axes x and z correspond to the vertical and horizontal directions, respectively, and moreover, the z axis is directed towards the hypothetic earthquake epicenter.

The driving acceleration (f), originating from the elastic waves of the earthquake, depends on the time (t), but not on the x coordinate. However, to obtain the equation of motion, it is useful to write f as $f(x,t) = f(t)\sum_{i=0}^{\infty} s_i(x)c_i$, where $\sum_{i=0}^{\infty} s_i(x)c_i = 1$, as the $s_i(x)$ eigenmodes of the speleothem form a complete orthonormal system of eigenfunctions.

The restoring force per unit length arising in bended rods is proportional to the fourth derivative of the displacement:

$$F_e(x,t) = -EI\frac{\partial^4 z(x,t)}{\partial x^4}, \qquad (1)$$

Table 1 Geometrical parameters of the investigated speleothems, the horizontal acceleration needed to break them and their theoretical and measured natural frequencies

N°	Description	H [m]	D [m]	H/D	a_g [m/s^2]	f_0 [Hz] theoretical	f_0 [Hz] measured
1	Stalagmite Baradla cave Sárkány hall	3.35 (3.35–3.45)	0.075 (0.045–0.12)	44.7	1.13	2.8	5.1
2	Pillar Baradla cave, Sárkány hall	3.9 (3.79–3.9)	0.07 (0.045–0.08)	55.7			25.8
3	Stalagmite Baradla cave, Sárkány hall (Fig. 4)	2.85	0.12–0.29 complicated form				11.3, 12.5
4	Stalagmite Baradla cave, Sárkány hall	2.84	0.115 (0.08–0.15)	24.7	2.41	5.9	9.8
5	Stalagmite Baradla cave, Sárkány hall	2.1	0.085–0.28 upwards thickening				27.9
6	Stalagmite Baradla cave, Olimposz hall (Fig. 5)	5.1 (cracked at 4.76)	0.085 (0.075–0.1)	60.0	0.55	1.3	1.4
7	Stalagmite Hajnóczy cave, Óriás hall	3.6	0.05	72.0	0.65	1.6	4.0

where E is the Young's modulus and I is the bending moment.

The energy of the oscillating stalagmite dissipates due to the inner friction. The corresponding force per unit length is equal to

$$F_f = -\kappa q^2 \frac{\partial^4 \dot{z}(x,t)}{\partial x^4}, \tag{2}$$

where κ is the inner friction coefficient and q is the cross-section of the speleothem. The dot above the variable denotes its time derivative. Our equation of motion:

$$\rho q f(x,t) + F_e(x,t) + F_f(x,t) = \rho q \ddot{z}(x,t), \tag{3}$$

If only the fundamental mode of the vibration ($s_0(x)$) is considered, we get

$$c_0 s_0(x) f(t) - \alpha \frac{\partial^4 z(x,t)}{\partial x^4} - \beta \frac{\partial^4 \dot{z}(x,t)}{\partial x^4} = \ddot{z}(x,t) \tag{4}$$

with $\alpha = EI/\rho q$ and $\beta = \kappa q/\rho$, ρ is the density of the speleothem. The solution of the equation of motion is

$$z(x,t) = \frac{c_0}{a}\big[\sinh(\lambda_0 x) - \sin(\lambda_0 x) + B(\cosh(\lambda_0 x) - \cos(\lambda_0 x))\big] \int_0^\infty f(t-\tau) e^{-b\tau} \sin(a\tau) \mathrm{d}\tau \tag{5}$$

where $c_0 \approx -0.57481$, $a = \sqrt{\alpha\lambda_0^4 - \beta^2\lambda_0^8/4}$, $b = \beta\lambda_0^4/2$, $B = -(\sin(\lambda_0 H) + \sinh(\lambda_0 H))/(\cos(\lambda_0 H) + \cosh(\lambda_0 H))$ and $\lambda_0 \approx 1.8751/H$.

If the effect of the inner friction can be neglected ($\beta^2\lambda_0^4 \ll \alpha$), it is possible to show that the natural frequency of a stalagmite:

$$f_0 \approx \frac{1}{\pi}\sqrt{\frac{3.1 E D^2}{16 \rho H^4}} \tag{6}$$

The static, horizontal ground acceleration resulting in failure (Cadorin et al. 2001):

$$a_g = \frac{D\sigma_u}{4\rho H^2} \tag{7}$$

where σ_u is the tensile failure stress of the speleothem. It can be seen that both the natural frequency and horizontal ground acceleration resulting in failure depend on the geometrical properties of the stalagmite in the same way, i.e. they are proportional to D/H^2.

6 Mechanical properties of speleothems

Laboratory measurements were performed on samples originating from a speleothem that was found lying broken on the ground in the Olimposz hall of Baradla cave.

According to our results, the average density is 2,394 kg/m^3, the standard deviation of the measured 16 values is 155 kg/m^3.

The Young's modulus has been calculated using the data of a uniaxial compressive strength test. The mean value is 20,813 MPa, the standard deviation 5,921 MPa (the number of the samples was four). The mean tensile failure stress of the 13 samples was 1.62 MPa (with standard deviation of 0.48 MPa), which has been measured by the Brazilian test.

Using the free vibration decay of a stalagmite, we can determine the inner friction parameter. The horizontal acceleration along a freely oscillating stalagmite is $\ddot{z}(x,t) = d(x)\, e^{-bt} \sin(at)$ where d is simply the product of constants and x-dependent parameters.

The "smoothly" decaying oscillation of Speleothem N° 1 (Fig. 6) allows the estimation of its κ coefficient. The parameters (d,b,a) have been computed by least squares fitting. From the resulting $b = 0.236$ 1/s value, the inner friction is $\kappa = 2.61 \cdot 10^6$ kg/(ms). This value justifies the neglect of the effect of inner friction in computing the natural frequency (e.g. in the case of Speleothem N° 1 $\alpha/(\beta^2\lambda_0^4) \approx 1{,}300$).

The measured natural frequency of the investigated speleothems changed in the range of 1.4–27.9 Hz.

It is interesting to note that our results are very close to the ones gained by Lacave et al. (2000). In Fig. 1 of their paper, they show the estimated natural frequency values for speleothems of different type, based on in situ measurements in French caves. The measured frequencies for our speleothems N° 1, N° 6, and N° 7 fall between their two curves describing the natural frequency of stalagmites with diameters of 5 and 10 cm (the frequency value belonging to stalagmite N° 4 with a characteristic diameter of 11.5 cm is close to this stripe from above). As the diameter of the abovementioned speleothems lies in this 5- to 10-cm range, we can conclude that the frequency values determined in the two studies are in very good agreement in spite of the different measuring techniques.

If the natural frequency is below 20 Hz (which is the approximate upper limit of the frequency range of nearby earthquakes), then resonance can occur (this is the situation in five cases from the seven). Our analysis did not take into consideration the phenomenon of resonance, which means that, in reality, the dripstones would break at a lower value of horizontal acceleration than the computed one.

The observed and theoretical natural frequencies (Table 1) differ at most by a factor of 2.5 (the theoretical values were in every case smaller than the measured ones). The difference probably comes from the used approximations, as the shape of the speleothems more or less differ from the shape of a cylinder, their material is not homogeneous, and the material parameters are based on measurements performed on a specific speleothem.

It can be observed that the maximum horizontal acceleration measured on the Speleothem N° 6 (Fig. 8) significantly exceeds the computed a_g ground acceleration value. This phenomenon is in agreement with the solution of the equation of motion.

Based on Table 1, we can conclude that, for the investigated speleothems in the Baradla and

Hajnóczy caves, the horizontal acceleration values needed to break them are between 0.05 and 0.24 g.

7 Sampling and age determination

We took samples from the stalagmite of 5.1 m high (Fig. 5) in the Olimposz hall of Baradla cave (Speleothem N° 6) at different heights to determine its age and rate of growth.

Due to its geometry, sampling was a very difficult task. To avoid breaking the stalagmite, we tied it to a frame at several points. The 3–4 g of samples necessary for alpha spectrometric measurements was taken from four locations at different heights with the help of a core sampler (the diameter of the sample core was 12 mm).

The samples were examined and measured in the Radiometric Laboratory of the Geophysics and Environmental Physics Research Group of the Hungarian Academy of Sciences at the Loránd Eötvös University and in ICP-MS Laboratory of the Institute of Isotopes, Hungarian Academy of Sciences. After the dissolution of the sample with dilute hydrochloric acid, uranium and thorium were pre-concentrated with iron hydroxide followed by their extraction chromatographic separation using UTEVA resin. Alpha source preparation was carried out by micro-co-precipitation using NdF_3. The sources were counted by low-background alpha-spectrometers (Canberra); the duration of measurement was 8–10 days. The ICP-MS analysis was carried out using an ELEMENT2 ICP-MS (Thermo Corp., Bremen, Germany) with stable sample introduction system (Elemental Scientific Inc.). Measurement and data acquisition parameters were optimised before the analysis. The obtained raw data were corrected for the method blank and instrumental mass bias.

The applied tracer was ^{232}U in equilibrium with ^{228}Th daughter in alpha spectrometry and mixed ^{229}Th/^{233}U/^{236}U tracer in ICP-MS analysis, respectively; the chemical recovery varied between 65–95%. The measurements were processed by our own assessment procedure based on the Monte Carlo method. The results of the measurements carried out are presented in Table 2.

The high variation of the measurements in the case of alpha spectrometry was due to the low uranium content and low mass of the samples available; in the case of ICP-MS, it was due to the inaccuracy of the available tracer.

Our measurements show that, below the height of 390 cm (measured from the bottom of the speleothem), the ages become younger with the increasing height of the sample origin; therefore, the dating results are in good agreement with the formation mechanism of the stalagmites. However, the age of the sample originating from 476 cm height contradicts the previous statement, as it is older than the samples from lower positions according to both the alpha spectrometric and ICP-MS measurements. This result cannot be explained by the simple hypothesis of steadily growing stalagmite. It is noteworthy that similar controversial age data have been observed (Siklósi, personal communication) in the Trió cave in the Mecsek Mountains (Hungary).

Table 2 Ages measured at different heights for the stalagmite of 5.1 m high (Speleothem N° 6) in the Olimposz hall of the Baradla cave

Height of sampling point (cm)	Cored interval (mm)	Age (year)	Error (year) (confidence level of 95%)	U-content (ppm)	Method
476	19–39	124,000	+19,500/−17,000	0.038	ICP-MS
476	19–39	140,000	+29,000/−24,000	0.034	Alpha spec.
390	19–39	70,800	+7,000/−6,800	0.025	ICP-MS
287	22–43	102,500	+22,500/−19,000	0.020	Alpha spec.
287	3–22	102,500	+36,000/−28,000	0.020	Alpha spec.
16	36–47	132,000	+14,000/−12,500	0.052	ICP-MS

The reason for the controversial nature of the results for the sample at the height of 476 cm was not found after repeated checking of the measurements and assessment. Cross contamination and ^{232}Th-contamination have been excluded by repeating the analysis. The uranium content of the paint on the sampling drill was suspected, but after 5 days of control measurements, the paint did not show alpha radiation; furthermore, most of the paint had been removed earlier.

However, a possible explanation can be given. The speleothems in the Olimposz hall contain numerous small diameter cavities (their size is in the order of millimetres), which are interconnected by hairline cracks. According to our assumption, the dripping water seeped through the pore space, and calcite filling accumulated gradually over time. As this deposit can be considerably younger than the primary material of the speleothem, the more recent radiometric age of the middle part of the stalagmite (i.e. the controversial age data) can be explained by this mechanism, namely, the dating method measures the "average" of the old and new ages. Beyond that, this process of recrystallisation made the original laminae hard to observe.

The recrystallisation completely ruined the traceability of the growth of the speleothem by rejuvenating the radiometric age of the samples. Therefore, we cannot deduce how its shape changed during the times. If we do not want to erroneously underestimate the level of seismic hazard, or in other words, we want to give the most conservative estimation, we have no other choice but to use the youngest age data we measured on the samples.

This is why we suppose that Speleothem N° 6 has not been changed significantly during the past 70,000 years, and we made the calculations using the current shape of the stalagmite.

A conceivable hypothesis for the stopped growth of the stalagmite is that the clayey solution residue of the rock blocked the fissures through which the growing speleothem got the water supply or it can be the consequence of surface climate change. By all means, at the present time, no trace of dropping can be seen in the neighbourhood of this stalagmite. The same process of stopped growth has already been observed in the Baradla cave (Lauritzen and Leél-Őssy 1999).

8 Conclusions

Speleothems with large height/diameter ratio (H/D>40) have been found in two Hungarian caves. We determined by in situ measurements the natural frequency of seven speleothems of the Baradla and Hajnóczy caves, and in laboratory, the material properties (the density, the Young's modulus and the tensile failure stress) of a speleothem specimen have been measured. The inner friction coefficient for a speleothem was calculated, as well. Based on a simple mechanical model, the theoretical natural frequency (f_0) and the horizontal ground acceleration values resulting in failure (a_g) have been calculated for the stalagmites.

The measured natural frequencies of the investigated speleothems fall in the range of 1.4–27.9 Hz. The theoretical frequencies for the stalagmites differ, of course, from the measured ones. In the worst case, the observed natural frequency is 2.5 times greater than the theoretical one (Speleothem N° 7). We obtained the best result for Speleothem N° 6, where the difference is smaller than 8%.

The computed a_g values for the studied stalagmites fall in the range of 0.05 and 0.24 g, which can arise even in the case of moderate sized earthquakes. As in most cases, the natural frequency of these stalagmites is in the frequency range of nearby earthquakes; the failure acceleration can be even smaller because of the resonance effect.

As the modelling of the 5.1 m high stalagmite in Olimposz hall of Baradla cave (Speleothem N°6) was remarkably successful concerning the f_0 value, in our opinion, the resulting $a_g = 0.05$ g acceleration value can be considered reliable, as well.

This agreement, together with the results of age determination, allows us to estimate an upper limit on prehistoric PGA. On the basis of our measurements and theoretical calculations, we can assume that the geological structures close the Baradla cave (Fig. 1) did not generate paleoearthquakes producing a horizontal ground acceleration larger than 0.05 g in the last 70,000 years.

This acceleration level is lower than the PGA value determined by Tóth et al. (2006) for a much shorter period of time, and evidently, the expected

PGA would be even greater for a 70,000-year interval. At the present time, it is not possible to reveal the cause of this discrepancy. We must take into consideration, however, that the PGA was determined during a regional study and a more detailed investigation focusing on the territory of Baradla cave (which is anyway one of the least seismically active regions of the country) may modify the result.

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