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CONSTRAINTS ON LONG-TERM SEISMIC HAZARD FROM VULNERABLE STALAGMITES FOR THE SURROUNDINGS OF KATERLOCH CAVE, AUSTRIA

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Abstract: The examination of a stalagmite in the Katerloch Cave (Austria) allows estimating an upper limit for horizontal peak ground acceleration generated by paleoearthquakes. The geometrical dimensions and the eigenfrequencies of an intact stalagmite were determined by in situ observations. The value of horizontal ground acceleration resulting in failure and the eigenfrequencies were assessed by theoretical calculations as well. The acceleration level determined by our study for the territory of Katerloch Cave is much lower than the PGA value interval (from 0.075 g to 0.1 g, in case of arithmetic mean, 85% fragile, rock type) determined by probabilistic seismic hazard calculation (SHARE Model) for a 475-year recurrence time (in 50 years with 10% probability of exceedance).

Keywords: *Speleothem, stalagmite, prehistoric earthquake, peak ground acceleration, seismic hazard*

1. INTRODUCTION

Earthquakes hit urban centers in Europe infrequently, but occasionally with disastrous effects. Obtaining an unbiased view of seismic hazard (and risk) is therefore very important. The main motivation for study vulnerable stalagmites in Katerloch Cave comes from the wish to better understand seismic hazard, a problem with important social and economic implications.

The occurrence of strong earthquakes at many plate boundaries is well-known, but in intraplate regions the seismicity rate can be low. Recurrence intervals of large earthquakes can be as long as 10,000 years [1] and may thus be overlooked [2]. In such areas, the missing long-term information about past earthquakes makes it very difficult to estimate the seismic hazard. Long-term information of earthquakes in Central Europe is missing, since the instrumental seismic records go back only for about a century and even the historical reports generally provide too short and incomplete a coverage of the past [3], [4]. In principle, such long-term information may be gained from the traces of strong palaeoearthquakes that pre-date the available catalog information or from the absence of such traces. The latter may be established by the continued existence of speleothems that are still intact in the pertaining region, indicating a lack of earthquakes strong enough to destroy them [5–12]. For stalagmites that have survived, we are able to estimate the horizontal ground acceleration that would have made them fail at different stages of their growth. It can then be concluded that the ground acceleration has not exceeded the estimated value ever since the growth stage for which it was computed. Such information can be crucial for properly estimating the seismic hazard.

There are some recently published papers on the topic of vulnerable stalagmites for estimating seismic hazard. The study of Bednárik [13] provides a thorough guidance to the construction of a geometrically and physically realistic (anisotropic in both elasticity and fracture, and comprising data-based frequency-dependent attenuation) quantitative model of any calcite speleothem and its seismic motion, with particular focus on tubular stalactites (soda straws). Bottelin et al. [14] investigated the motion and maximal tensile stress of soda straws excited by nearby rock blasting vibrations through laboratory and field tests. Two years ago Mendeczki and Szczygiel [15] published a speleoseismological study. One of the most important outcomes of their study is the potential for estimation of the minimum magnitude of an earthquake required for destruction in a cave at a given distance from its source. Natural frequencies of vulnerable stalagmites were calculated with the finite element method (FEM) by Martin et al. [16] and Bonkowski et al. [17]. Their simulations used the real 3D shape model of the intact stalagmites produced by in situ laser scanning. Zhao et al. [18] have conducted a large number of investigations at over a dozen cave sites along the Longmen Shan fault zone of the eastern Qinghai-Tibet Plateau in order to assess the damage inflicted on speleothems by the 2008 Mw7.9 Wenchuan earthquake, China. Kagan et al. [19] investigated broken speleothems in Northern Calabria, Italy and found previously unrevealed Holocene and Late Pleistocene paleoearthquakes. Ferranti et al. [20] carried out a speleoseismological study in the Pollino Range (Calabria, southern Italy) and have placed constraints on the recurrence of $M > 6$ earthquakes, on the expected ground shaking threshold and on definition of seismogenic sources in that region. Pace et al. [21] modeled the collapse of a tall (173 cm high) stalagmite in Cola Cave, Central Apennines (Italy), in order to find a causative association of this event with one of the potential seismogenic sources. They defined the uniform hazard spectrum for each seismogenic source at the site, and they used the calculated spectra in a deterministic approach to study the behavior of the speleothem through numerical finite element modeling (FEM).

In this paper we focus on a case study from the Katerloch Cave, close to the city of Graz, Austria. Specially-shaped (candle stick style: high, slim, and more or less cylindrical) intact and vulnerable stalagmites (IVSTM), were examined in 2013 and 2014. This type of IVSTM is suitable for estimating the upper limit for horizontal peak ground acceleration generated by pre-historic earthquakes, and we have extensive information about ages for this cave (e.g. [5], [22], [23]).

2. THE LOCATION OF KATERLOCH CAVE IN SOUTHEASTERN AUSTRIA

Katerloch Cave is located in Sattelberg, in the Grazer Bergland of Austria (in the province of Styria, *Figure 1*). This cave is close to the town of Graz (24 km to the northeast) and Weiz (at 7.5 km distance). This cave has many intact candlestick-type stalagmites (STM); among them the most vulnerable (the longest one with small average diameter) is the 8.7 m long one (STM8.7m, *Figure 2*).

In this study we try to find the answer to the questions: What is the upper limit of the size of earthquakes occurring in the surroundings of the cave? In other words: What is the highest ground motion that this tall and vulnerable STM8.7m can survive?

3. THE INVESTIGATION METHOD OF STALAGMITES

The method of our investigation is the same as in previous studies [6], [7], [8], [9], [10], [11]:

- the eigenfrequencies and the geometrical dimension of the intact STM8.7m were determined by in situ non-destructive observations;
- the density, the dynamic Young's modulus and the tensile failure stress of broken stalagmite samples were measured in a mechanical laboratory;
- the value of horizontal ground acceleration resulting in failure and the theoretical natural frequency of STM8.7m were assessed by theoretical calculations in a static case, resonance (dynamic amplification) was not taken into account [24], [26];
- age determination.

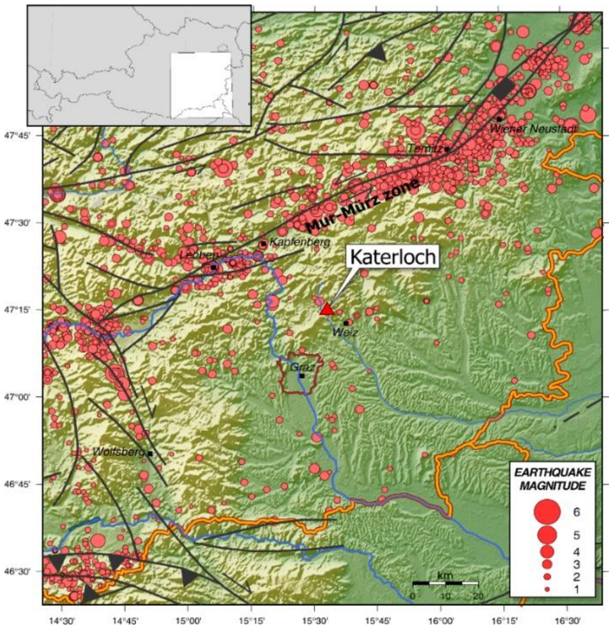

Figure 1

The location of the investigated cave, Katerloch in Sattelberg, Austria, near the town of Graz and Weiz, the active faults [25] *and seismicity of the area*

Figure 2

The 8.7 m high stalagmite in Zauberreich, Katerloch Cave, Sattelberg, Austria

4. NON-DESTRUCTIVE IN SITU EXAMINATIONS OF THE STALAGMITE

Considering that in situ measurements of slim and high stalagmites had to be done non-destructively, we confined ourselves only to determining their geometrical dimensions *(Table 1)* and the natural frequency and harmonic oscillations (eigenfrequencies) *(Table 2)*. If the investigated STM is slim enough, a resonance effect can occur during an earthquake [26]. In order to measure the natural frequency and harmonic oscillations of SMT8.7m, horizontal LF-24 geophones were fastened on the stalagmites; they were excited by low amplitude forced vibration obtained by a gentle hit *(Figure 3)* and the oscillation was recorded *(Figure 4)*.

Figure 3

The owner of Katerloch Cave, F. Geissler, knocking the 8.7m high stalagmite in order to record its vibration

Table 1

Results of non-destructive in situ examination: dimensions

Name	**Place**	**Height (m)**	**Diameter (cm)**	**Height/ Diameter**
STM8.7m	Katerloch, Zauberreich	8.7	average: 7.5	116

Table 2

Results of non-destructive in situ examination: calculated and measured natural frequencies and harmonic oscillations of STM8.7m

Name	**Place**	**f_0 (Hz)**	**f_0 (Hz)**	**f_0 (Hz)**	**f_0 (Hz)**	**f_0 (Hz)**
STM8.7m	Katerloch, Zauberreich	0.7 calculated	4.1	11.5	22.5	37.2

5. CALCULATION OF THE EIGENFREQUENCY OF STM8.7M

The eigenfrequency of STM8.7m is so low that it was impossible to measure it wih our equipment (we were unable to precisely determine its value); therefore, we calculated it by the following method.

We used the relation between the different harmonic oscillations of a beam's eigenfrequency [27]:

$$\frac{f_i}{f_0} = \left(\frac{k_i}{k_0}\right)^2 \tag{1}$$

where f_i is the frequency of i-th harmonic oscillation and k_i is the solution of the resonance equation. The first 5 solutions of different k_i values [27] are: $k_0 = 1.875$, $k_1 = 4.694$, $k_2 = 7.855$, $k_3 = 10.996$, $k_4 = 14.137$.

The different f_i values that we measured for STM8.7m are given in Table 2: ~4Hz; 11.5Hz; 22.5Hz; ~37Hz. By using the measured and visible values in Fig. 4, the natural frequency of STM8.7m (f_0 = 0.7 Hz) can be identified with the aid of the columns in Table 3. Table 3 shows the harmonic oscillation values in different cases taking into account the value 11.5 Hz. Different cases mean that 11.5 Hz is equal to different f_i values. The red column shows the appropriate result.

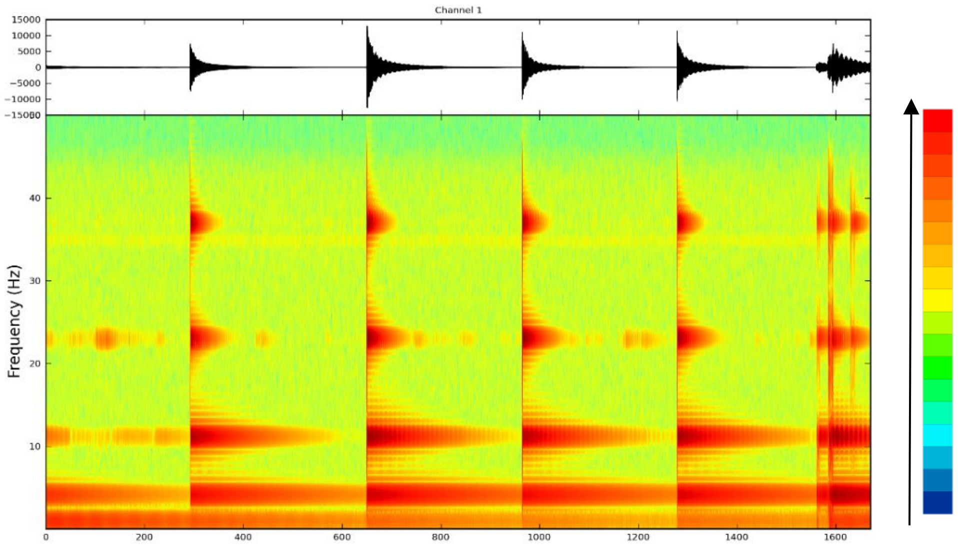

Figure 4

The oscillation and power spectral density as a spectrogram showing repeated excitation by a gentle knock on STM8.7m along the recorded signal of the excited stalagmite

It can be seen in *Table 3*, red column that the three lowest natural frequencies of STMs are below 20 Hz. This means that they fall into the frequency range of nearby earthquakes. If the natural frequency of the stalagmite is below 20 Hz then resonance can occur.

Our theoretical calculations (equations using cantilever beam theory, see "Oscillation of stalagmites theoretical calculations" below) did not take into consideration the phenomenon of resonance, which means that in reality the STMs would have broken at a lower value of horizontal acceleration than the computed values.

Table 3

Calculated potential eigenfrequencies for STM8.7m and the best fit (red)

i-th harmonic oscillation	**if 11.5 Hz is the eigen-frequency of STM8.7m, zero-th harmonic oscillation (Hz)**	**if 11.5 Hz is the first harmonic oscillation of STM8.7m (Hz)**	**if 11.5 Hz is the second harmonic oscillation of STM8.7m (Hz)**	**if 11.5 Hz is the third harmonic oscillation of STM8.7m (Hz)**
f_0	11.5	1.8	0.7	0.3
f_1	72.1	11.5	4.1	2.1
f_2	202.3	32.3	11.5	5.9
f_3	395.4	63.1	22.5	11.5
f_4	653.7	104.3	37.2	19.0

6. MECHANICAL PROPERTIES OF STALAGMITES

Since it was not permitted to collect broken samples from the Katerloch Cave for mechanical laboratory measurements (MLM), therefore we used the results of MLM from Baradla Cave, Hungary in our calculations (eigenfrequency and horizontal ground acceleration equations). This gives a conservative estimation, since the STM8.7m would have broken under the influence of higher horizontal acceleration values. [Among our earlier results of MLM, the highest tensile failure stress (σ_u) and the lowest dynamic Young's modulus (E) values were determined in case of samples from Baradla Cave, compared to our other MLM results.]

Table 4

Results of mechanical laboratory measurements of stalagmites from Baradla Cave, Hungary

	density, ρ [kg/m3]	**dynamic Young's-modulus, E [MPa]**	**tensile failure stress, σ_u [MPa]**
Baradla Cave	2 394 ± 155	20 813 ± 5 921	1.62 ± 0.48

7. OSCILLATION OF STALAGMITES BY THEORETICAL CALCULATIONS

In order to calculate the natural frequency of STM8.7m and the horizontal ground acceleration that would result in failure of STM8.7m we used the following equations:

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

$$a_g = \frac{D\sigma_u}{4\rho H^2}, \tag{3}$$

where D is the diameter, H is the height of stalagmite, ρ is the mass density of the stalagmite, E is the dynamic Young's modulus and σ_u is the tensile failure stress.

Table 5 shows the results of eigenfrequency calculations and the results of critical horizontal ground acceleration calculations for three different cases: (1) for the ground of the cave at this time, (2) for the ground of the cave 500 years ago, and (3) for the surface (above the cave) 500 years ago.

Table 5

Measured and calculated natural frequencies and horizontal ground accelerations resulting in failure, obtained by theoretical calculations at two time points (for this time and for 500 years ago)

Name	**measured f_0 (Hz)**	**theoretical f_0 (Hz)**	**theoretical a_g (m/s^2)**	**theoretical a_g (m/s^2)**	**theoretical a_g (m/s^2)**
STM8.7m	0.7	0.4	0.167 for 8.7m height in the cave	0.176 for 8.5m height in the cave, 500 years ago	0.439 for 8.5m height at the surface, 500 years ago

8. DEPTH OF THE CAVE

For this kind of study (seismic hazard estimation by using intact, very vulnerable stalagmites) the stalagmites that are the most suitable are those located in caves at shallow depth, since seismic waves are progressively attenuated with depth (or on the contrary, the seismic waves amplitudes amplify from the cave's ground to the surface). The maximum known vertical depth from the cave entrance is about 135 m in Katerloch Cave. The rock cover above the cavities typically ranges from 100 to 200 m, depending on the position in the cave [5] *(Figure 5)*. At this depth the seismic waves can be attenuated by a factor of ~2.5–3 compared to the surface [28].

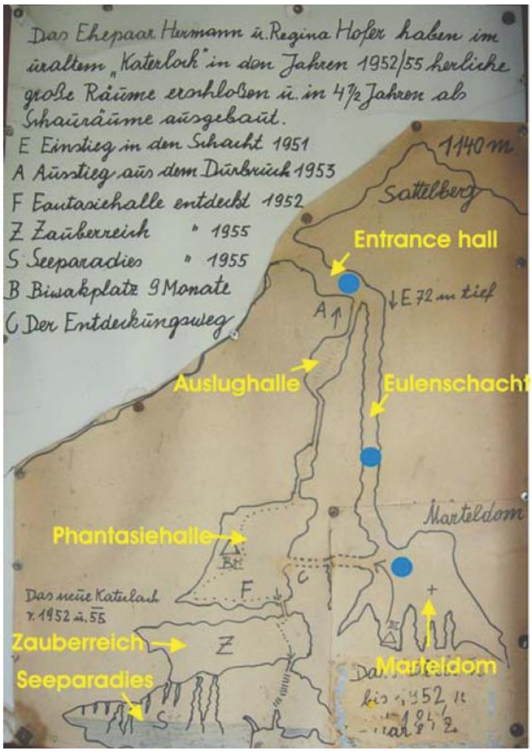

Figure 5
Historic schematic cross section of Katerloch Cave [5]

9. AGE DETERMINATION

Boch et al. [5], [22], [23] determined the age and the growth rate of 8 stalagmites located in the Katerloch Cave by U/Th ICP-MS technique. They concluded that the growth rate bias is between 0.2–0.7 mm/yrs. Assuming an average 0.4 mm/yr growth rate, the STM8.7m were about 8.5 m high 500 years ago and horizontal peak ground acceleration which could have broken the stalagmite 500 years ago (STM8.5m) was 0.176 m/s^2 at the ground of the cave and 0.439 m/s^2 at the surface, since the seismic wave amplitudes amplify from the cave's ground to the surface (the last two columns in *Table 5* and the section "Depth of the cave").

10. CONCLUSIONS

Stalagmites are useful for giving upper bounds of maximum credible earthquakes in the present and the past.

Our investigation determined much lower values for critical horizontal ground acceleration (CHGA) (0.439 m/s^2) than the SHARE model for 10% probability of exceedance in 50 years (from 0.075 g to 0.1 g, in case of arithmetic mean, 85% fragile, rock type [29]). Furthermore, the same conclusion (CHGA values determined by using the vulnerable stalagmite are lower than the values of SHARE model) can also be gained for 5% and 2% probability of exceedance in 50 years.

The approach used in our study yields significant new constraints on seismic hazard, as the intactness of the stalagmites suggests that tectonic structures close to Katerloch Cave, i.e. the Mur-Mürz fault, did not generate very strong paleoearthquakes in the last few thousand years. This study is particularly important for understanding the seismic hazard associated with the town of Graz.

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REFERENCES

[1] Scholz, H. (1990). *The Mechanics of Earthquakes and Faulting*. Cambridge: Cambridge University Press, p. 467.

[2] Calais, E., Camelbeeck, T., Stein, S., Liu, M., Craig, T. J. (2016). A new paradigm for large earthquakes in stable continental plate interiors. *Geophysical Research Letters*, 43, pp. 10621–10637, https://doi.org/10.1002/2016gl070815.

[3] Zsíros, T. (2000). *The seismicity and seismic hazard of Carpathian basin: Hungarian earthquake catalog. (456–1995)* (in Hungarian). MTA GGKI Szeizmológiai Obszervatórium, p. 482.

[4] Tóth, L., Mónus, P., Zsíros, T., Bondár, I., Bus, Z., Kosztyu, Z., Kiszely, M., Wéber, Z., Czifra, T. (1996–2014). *Hungarian Earthquake Bulletin, 1995–2013*. MTA GGKI és Georisk Kft, Budapest.

[5] Boch, R. (2008). *Stalagmites from Katerloch Cave, Austria: Growth dynamics and high-resolution records of climate change.* PhD Thesis, Leopold-Franzens-Universität Innsbruck, Austria.

[6] Szeidovitz, G., Paskaleva, I., Gribovszki, K., Kostov, K., Surányi, G., Varga, P., Nikolov, G. (2008). Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in caves situated at the western part of Balkan mountain range. *Acta Geodaetica et Geophysica Hungarica,* 43, pp. 249–266.

[7] Szeidovitz, G., Surányi, G., Gribovszki, K., Bus, Z., Leél-Őssy, S., Varga, Z. (2008). Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in Hungarian caves. *Journal of Seismology,* 12, pp. 21–33.

[8] Gribovszki, K., Paskaleva, I., Kostov, K., Varga, P., Nikolov, G. (2008). Estimating an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in caves in southwestern Bulgaria. In: Zaicenco, A., Craifaleanu, I., Paskaleva, I. (eds.). *Harmonization of seismic Hazard in Vrancea Zone with Special Emphasis on Seismic Risk Reduction*. NATO Science for Peace and Security, Series C: Environmental Security, Dordrecht, pp. 287–308.

[9] Gribovszki, K., Kovács, K., Mónus, P., Shen, C.-C., Török, Á., Brimich, L. (2013). Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact stalagmites and the mechanical properties of broken stalagmites in Domica cave, Slovakia. *Slovensky kras. Acta Carsologica Slovaca,* 51 (1), pp. 5–14.

[10] Gribovszki, K., Bokelmann, G., Szeidovitz, G., Varga, P., Paskaleva, I., Brimich, L., Kovács, K. (2013). Comprehensive investigation of intact, vulnerable stalagmites to estimate an upper limit on prehistoric ground acceleration. In: *Proceedings of the Vienna Congress on Recent Advanced in Earthquake Engineering and Structural Dynamics & 13. D-A-CH Tagung,* Vienna, Paper No. 445, p. 10.

[11] Gribovszki, K., Kovács, K., Mónus, P., Bokelmann, G., Konecny, P., Lednicka, M., Moseley, G., Spötl, C., Edwards, R. L., Bednárik, M., Brimich, L., Tóth, L. (2017). Estimating the upper limit of prehistoric peak ground acceleration using an in situ, intact and vulnerable stalagmite from Plavecka´

priepast cave (Detrekői-zsomboly), Little Carpathians, Slovakia—first results. *Journal of Seismology*, 21 (5), pp. 1111–1130, https://doi.org/10.1007/s10950-017-9655-3.

[12] Gribovszki, K., Esterhazy, S., Bokelmann, G. (2018). Numerical modeling of stalagmite vibrations. *Pure and Applied Geophysics*, 175, pp. 4501–4514, http://link.springer.com/article/10.1007/s00024-018-1952-4.

[13] Bednárik, M. (2009). *Seismometric portrayal of calcite tubular stalactites – modeller´s guide.* PhD Thesis. Bratislava, Geophysical Institute of the Slovak Academy of Sciences, p. 147.

[14] Bottelin, P., Baillet, L., Mathy, A., Garnier, L., Cadet, H., Brenguier, O. (2020). Seismic study of soda straws exposed to nearby blasting vibrations. *Journal of Seismology*, 24, pp. 573–593, https://doi.org/10.1007/s10950-020-09922-7.

[15] Mendecki, M., Szczygieł, J. (2019). Physical constraints on speleothem deformations caused by earthquakes, seen from a new perspective: Implications for paleoseismology. *Journal of Structural Geology*, 126, pp. 146–155.

[16] Martin, A., Lecocq, T., Hinzen, K.-G., Camelbeeck, T., Quinif, Y., Fagel, N. (2020). Characterizing Stalagmites' Eigenfrequencies by Combining In Situ Vibration Measurements and Finite Element Modeling Based on 3D Scans. *Geosciences*, 10 (10), pp. 418, https://doi.org/10.3390/geosciences10100418.

[17] Bońkowski, P., Zembaty, Z., Bobra, P., Gribovszki, K. (2020). Modeling seismic capacity of stalagmites. In: Montanari, A., Buiter, S. (eds.). *EGU General Assembly 2020: Sharing Geoscience*. Online (#shareEGU20), EGU2020-20575, https://doi.org/10.5194/egusphere-egu2020-20575.

[18] Zhao, X., Wang, F., Verheyden, S., Liu-zeng, J., Zhang, G. (2020). Earthquake-related speleothem damages: observations from the 2008 Mw 7.9 Wenchuan, China. *Geomorphology*, 358, 107103, https://doi.org/10.1016/j.geomorph.2020.107130.

[19] Kagan, E. J., Cinti, F. R., Alfonsi, L., Civico, R., Bar-Matthews, M. (2017). Broken speleothems reveal Holocene and Late Pleistocene paleoearthquakes in Northern Calabria, Italy. *Quaternary International*, 451, pp. 176–184, https://doi.org/10.1016/j.quaint.2016.10.023

[20] Ferranti, L., Pace, B., Valentini, A., Montagna, P., Pons-Branchu, E., Tisnérat-Laborde, N., Maschio, L. (2019). Speleoseismological constraints on ground shaking threshold and seismogenic sources in the Pollino Range (Calabria, southern Italy). *Journal of Geophysical Research: Solid Earth*, 124, https://doi.org/10.1029/2018JB017000.

[21] Pace, B., Valentini, A., Ferranti, L., Vasta, M., Vassallo, M., Montagna, P., Colella, A., Pons-Branchu, E. (2020). A large paleoearthquake in the Central

Apennines, Italy, recorded by the collapse of a cave speleothem. *Tectonics*, 39, e2020TC006289, https://doi.org/10.1029/2020TC006289.

[22] Boch, R., Spötl, C., Kramers, J. (2006). The age of stalagmites from Katerloch Cave (2833/59, Styria): first Uranium/Thorium dating results. *Die Höhle*, 57 (1–4), pp. 57–62.

[23] Boch, R., Spötl, C., Kramers, J. (2010). Growth phases of stalagmites from Katerloch (2833/59). *Die Höhle*, 61 (1–4), pp. 48–56.

[24] Cadorin, J., Jongmans, D., Plumier, A., Camelbeeck, T., Delaby, S., Quinif, Y. (2001). Modelling of speleothems failure in the Hotton cave (Belgium). Is the failure earthquake induced? *Netherlands Journal of Geosciences*, 80 (3–4), pp. 315–321.

[25] Horváth, F., Bada, G., Windhoffer, G., Csontos, L., Dövényi, P., Fodor, L., Grenerczy, Gy., Sikhegyi, F., Szafián, P., Székely, B., Timár, G., Tóth, L., Tóth, T. (2004). *Atlas of the Present-day Geodynamics of the Pannonian Basin: Euroconform Maps with Explanatory Text*. http://geophysics.elte.hu/atlas/geodin_atlas.htm.

[26] Lacave, C., Levret, A., Koller, M. (2000). Measurements of natural frequencies and damping of speleothems. *Proc. of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 30 January–4 February, 2000, No. 2118.

[27] Kong, S., Zhou, S., Nie, Z., Wang, K. (2008). The size-dependent natural frequency of Bernoulli-Euler micro-beams. *International Journal of Engineering Science*, 46 (5), pp. 427–437.

[28] Shimizu, I., Osawa, H., Seo, T., Yasuike, S., Sasaki, S. (1996). Earthquake-related ground motion and groundwater pressure change at the Kamaishi Mine. *Engineering Geology*, 43, pp. 107–118.

[29] Giardini, D. et al. (2013). *Seismic Hazard Harmonization in Europe (SHARE)*. Online Data Resource, DOI: 10.12686/SED-00000001-SHARE, http://www.share-eu.org/node/6.html.