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CAN BROKEN – AND UNBROKEN – SPELEOTHEMS TELL US SOMETHING ABOUT SEISMIC HISTORY ?

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ABSTRACT

There are many reports about broken speleothems that are interpreted as an indicator of past earthquakes, but little has been done so far to investigate the mechanical behaviour of speleothems during an earthquake. Is it really plausible that earthquakes break speleothems ? Can unbroken speleothems prove that no strong earthquake has ever occurred during a certain period of time ?

The mechanical behaviour of speleothems has been investigated. In situ measurements allowed to determine the range of fundamental natural frequencies of typical speleothems. Static bending tests were also performed on 20 stalactites and 26 soda straws. These tests give an indication not only of the mean tensile resistance, but also – even more important – of its variation. In fact, it is this variation that makes it difficult to estimate the acceleration necessary to break an individual speleothem. That's why a statistical approach is mandatory. Nevertheless, the immediate result of the material tests is that only long and thin speleothems can reasonably be expected to break during an earthquake.

The potentially most vulnerable unbroken stalactites as well as the broken ones were measured in a pilot cave (Milandre) in Switzerland. For each of these specimens, a vulnerability curve (probability of braking as a function of peak ground acceleration) was elaborated by means of a Monte Carlo simulation. Dynamic amplification as well as heterogeneity of tensile resistance within each stalactite were taken into account. Finally, an original statistical approach, valid for incomplete and imprecise data, allowed to estimate the probability that a strong earthquake has occurred during a certain period of time.

Keywords: Paleoseismicity, Speleothem, Stalactites, Long return periods

INTRODUCTION

Many reports that interpret broken speleothems (soda straws, stalactites and stalagmites)as indicators of past earthquakes exist in the literature. A concise overview of what has been published so far can be found in Forti [1] and Forti [2]. Several efforts have been undertaken to date broken speleothems by means of radiometric methods, and relate them to earthquakes (see for example Postpischl et al. [3]). Before broken speleothems can be related to earthquakes, it is obvious that all other possible breakdown causes must be discounted, which is not an easy task, as shown by Delange and Guendon [4], and Gilli [5].

The key question is whether it is really plausible that earthquakes break speleothems. The complementary question is whether unbroken speleothems may prove that no strong earthquake has ever occurred during their lifetime. To the knowledge of the present authors, the publication of Gilli et al. [6] represents the first attempt of looking quantitatively at the mechanical behaviour of speleothems during an earthquake. Cadorin et al. [7] performed static and dynamical bending tests on four broken stalagmites of the Hotton cave in Belgium in order to determine the calcite rupture stress.

The present study is focused on stalactites of a single pilot cave. The first step was to develop vulnerability curves for typical stalactites. To this aim, the bending resistance of 20 stalactites taken from the pilot cave was tested in the laboratory. This resulted in a probability density function for the rupture stress in bending. In the pilot cave, the geometry of many stalactites was measured in situ by photographic means. A simplified numerical model for the dynamic behaviour of the measured stalactites, allowing for geometrical irregularities and uncertainties, was then developed. Finally, a comparison of the stress induced by a seismic event with the rupture stress, by means of a Monte Carlo simulation, lead to a vulnerability curve for each investigated stalactite. The second step was to estimate whether past earthquakes could be identified and quantified for the pilot cave under study. To this aim, an original statistical approach for incomplete inhomogeneous data was developed.

The cave "Milandre" near Porrentruy in the Swiss Jura, was chosen as the pilot cave. This cave is characterised by a wide variety of stalactites, some of them broken. It lies at a low depth (about 40 m) below the surface and is characterised by a sub-horizontal development in Rauracian limestone. There are two entrances to the cave, the downstream entrance, which is natural, and an artificial pit, which was excavated, in the late sixties, at the upstream extremity of the cave. The history of the exploration of Milandre indicates that none of these galleries was visited by human beings before 1964, because of the existence of some siphons along the river, and the great distances from the natural entrance (before the construction of the artificial pit). It is also impossible, for the same reasons, that animals have ever been to these parts of the cave. This makes it clear, at least, that the broken stalactites observed in these galleries are neither broken by human beings (most of them are re-calcified on the floor, which indicates that they have not been broken recently) nor by animals.

LABORATORY RESISTANCE TESTS

In order to preserve the unique cave environment of Milandre, no intact stalactites were broken. Only pieces lying on the ground that were not re-calcified on the floor were collected within the upper part of the cave.

The laboratory tests were made on 20 stalactite specimens. This gave 20 bending tensile rupture stresses, henceforth called rupture stress, for the calcite material (Table 1). Based on these 20 values, a distribution of the rupture stress was estimated (Figure 1). A parameter free kernel estimation of densities (Silverman [8]) was used that does not need any a priori for a particular distribution shape.

TABLE 1

RUPTURE STRESS OBTAINED FROM LABORATORY TESTS ON 20 STALACTITE SPECIMENS

N°	VV1	VV2	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18
MPa	3.3	7.0	6.2	4.3	3.0	3.3	2.8	7.7	2.9	2.6	5.6	4.0	2.0	4.5	2.6	2.7	3.5	6.1	7.0	4.0

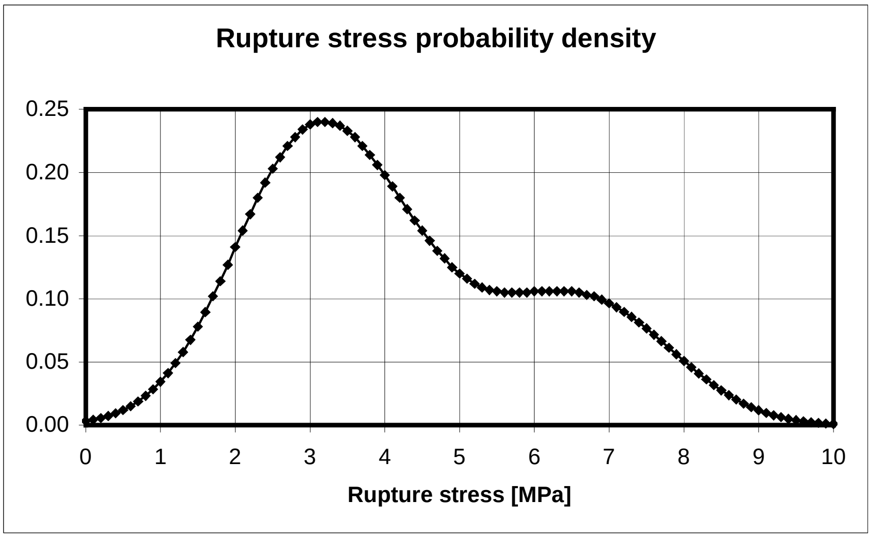

Figure 1 : Rupture stress probability density obtained with a kernel estimation of density from the results of the laboratory tests

MEASUREMENTS OF THE STALACTITES

The geometry of a large population of stalactites was measured – as precisely as possible – by means of numerical photography. The length and the development of the diameter along the stalactite's axis were determined. All sections were assumed to be circles. Figure 2 shows a schematic shape of a typical stalactite. Obviously, the measurements are characterised by a certain amount of uncertainty. Typically, a standard deviation of 1 mm, supposing a normal distribution, was estimated for the measurements of the diameters.

MODELLING OF THE MECHANICAL BEHAVIOUR OF STALACTITES

In a previous study (Cadorin et al. [7], Delaby and Quinif [9]), the acceleration necessary to break stalagmites was estimated, modelling them as rigid homogeneous perfect cylinders. In the present study, the assumption of homogeneous resistance was dropped. Furthermore, the stalactite deformation, with the possibility of dynamic amplification, was taken into account.

Resistance heterogeneity

Both in caves and in the material tests, it was observed that only few speleothems break at their base (where they would break if they were homogeneous). This implies that the possibility of a stalactite to break at any section of possible weakness has to be accounted for. It is therefore necessary to model the material resistance heterogeneity along the stalactites.

For the present study, it was assumed that the rupture stress within two different stalactite cross sections are as uncorrelated as they would be for different stalactites of the same cave – provided that the cross sections are sufficiently distant from each other. Unfortunately, it is not known how much "sufficiently distant" is. On the one hand, the local size of the crystals, usually of the order of 1 or 2 mm, might represent a minimum. On the other hand, a distance of the order of the diameter, thus a few centimetres, might be an upper bound. A value of $l^* = 10\ mm$ was assumed throughout this study. Obviously, the smaller l^* is, the more independent values of rupture stress can be found within a given stalactite. And since rupture stress is assumed to be a random variable with a probability distribution as given in Figure 1, the smaller l^*, the higher the probability that weak sections exist, and therefore, the higher the vulnerability of a given stalactite.

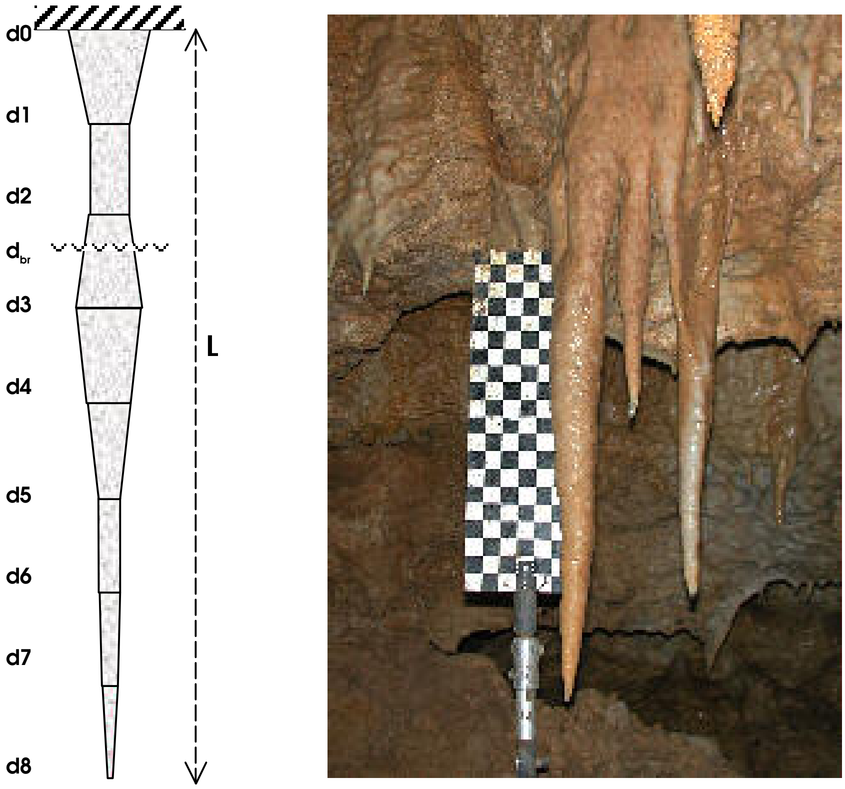

Figure 2 : Left : description of the modelled geometry of stalactites ; right : photo of a stalactite with the measuring scale (each square is 20 mm x 20 mm)

Modelling of breaking: vulnerability curves for rigid stalactites

Here, a vulnerability curve is understood as being the probability of breaking as a function of peak ground acceleration (PGA). Such curves are sometimes also called "fragility" curves in the literature. PGA was chosen as the parameter describing the "strength" of the earthquake since most stalactites – the ones with fundamental frequencies above the seismic excitation range – undergo stresses directly proportional to PGA. Vulnerability curves were calculated with the aid of Monte Carlo simulations. All variations of variables (in statistical language: all realisations of random variables) were done with the aid of "stratified" sampling, called "Latin Hypercube Sampling" (McKay et al. [10], McKay [11]).

The vulnerability curves were obtained in the following way: The probability of breaking of a given stalactite was calculated for different PGA's, performing $N = 1000$ Monte Carlo simulations per investigated stalactite and per PGA value. The goal of each simulation was to test whether the stalactite would break or not. Summing up all simulations that ended with breaking, divided by N, gave the probability of breaking, a number between 0 and 1.

Elastic stalactites: dynamic amplification

In situ measurements of the natural frequencies and damping of speleothems (Lacave et al. [12]) allowed to estimate the approximate natural frequency for different types of stalactites. As a result it appeared that the fundamental natural frequencies of most stalactites are well above the range of seismic excitation (usually supposed to be limited to f < ~ 30 Hz). The consequence is that there would be no dynamic amplification of the movement of the speleothem with respect to its base, i.e. the speleothem would follow the earthquake ground motion as a rigid body. However, since the long and slender speleothems, those with natural frequencies within the seismic frequency range, are those with the highest probability of breaking, the vulnerability of a large part of the speleothems that break would be significantly underestimated if dynamic amplification were neglected.

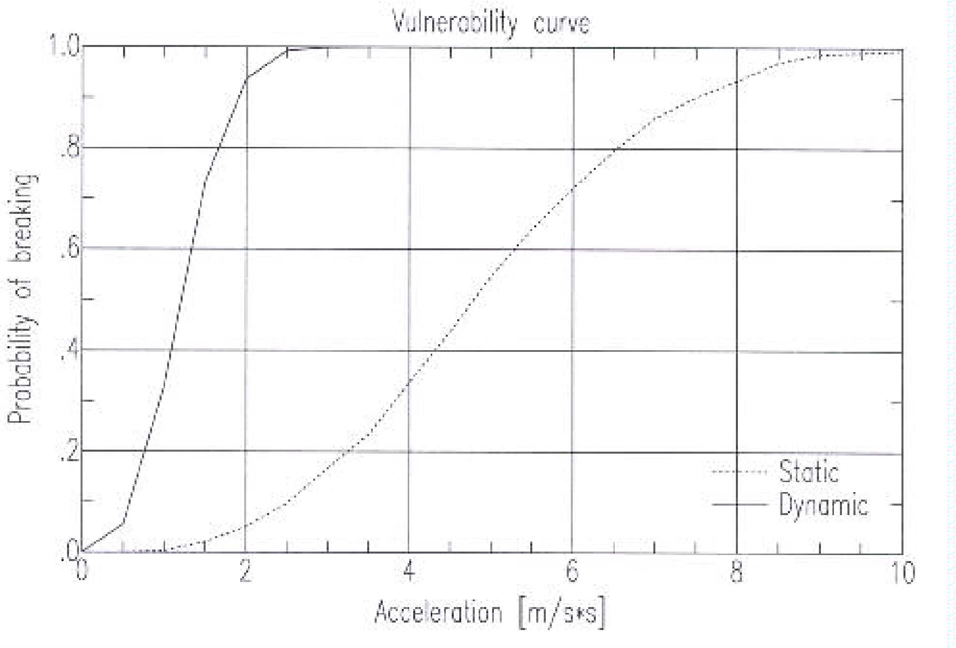

Figure 3 : Vulnerability curves for a test stalactite (L about 80 cm and average D of 2 cm), under the hypothesis of a rigid body (dashed line) or accounting for full dynamic amplification of the motion (solid line)

For the present study, a very simplified approach was adopted. It was assumed that any stalactite with estimated natural frequency f_o < 25 Hz would undergo full dynamic amplification according to the "plateau" value of a typical response spectrum. This amplification factor was assumed to be as high as 4.5 since the damping of speleothems is of the order of 0.1 % of critical damping. Figure 3 shows the vulnerability curve for a test stalactite, once without dynamic amplification (rigid case) and once with dynamic amplification of the earthquake motion. It becomes clear that – for speleothems that have natural frequencies in the frequency range of seismic excitation – neglecting dynamic amplification would lead to a drastic underestimation of the vulnerability.

Resulting vulnerability curves

The vulnerability curves for ten stalactites of various type and shape were calculated. The results reveal that it is indeed possible that earthquakes break stalactites – at least long and slender ones. For example, the most vulnerable stalactites are broken with 90% probability at an acceleration of 2 m/s^2 (0.2 g) and 50% of some less vulnerable ones are broken for an acceleration of about 3 m/s^2 (0.3 g). Long and slender stalactites are the most vulnerable ones for three concurrent reasons :

- the purely geometrical influence: the longer the stalactite, the greater the lever of the inertia forces and herewith the bending moment, and the smaller the diameter, the higher the maximum tensile bending stress for a given bending moment,
- the dynamic amplification, since sufficiently long and slender stalactites have their fundamental natural frequencies within the frequency range of seismic excitation,
- the longer the stalactites, the higher the probability that they contain a weak section, i.e. an internal structural irregularity with a low rupture stress.

In view of the large uncertainties associated with the modelling of the stalactite's mechanical behaviour, it would not make sense to measure hundreds of stalactites in detail and to calculate their vulnerability curves individually. Therefore, it was decided to define four classes of vulnerability (associated vulnerability curves are shown on Figure 4) for the statistical analysis of the pilot cave:

– class 1 : very vulnerable (e.g. L=80cm, D=2cm)
– class 2 : vulnerable (e.g. L=50cm, D=1.5cm)
– class 3 : slightly vulnerable (e.g. L=126cm, D=7cm)
– class 4 : not vulnerable (e.g. L=37cm, D=1cm).

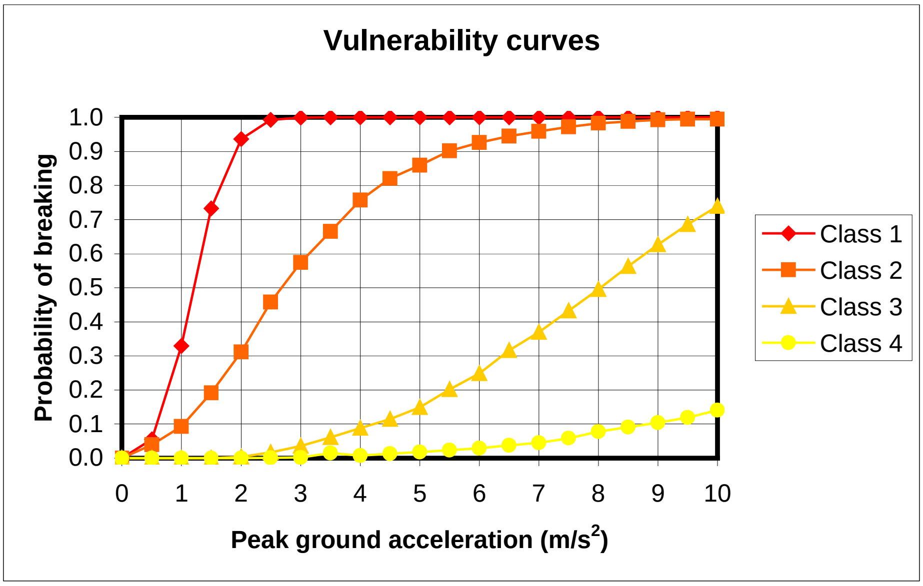

Figure 4 : Vulnerability curves for the four vulnerability classes of stalactites

STATISTICAL ANALYSIS OF THE CAVE

The final objective is to find out whether past earthquakes can be identified and quantified for the pilot cave under study, and whether an upper limit of acceleration can be estimated which has never been exceeded during the stalactite's life time with a certain probability. To answer these questions, an original statistical approach for incomplete inhomogeneous data was developed. Since the theory of this approach is far from being elementary and will be published elsewhere, only the underlying hypothesis, the results and their interpretation are given here.

So far, the statistical analysis has been done only in a time independent way. This means that the stalactite's growth over time has not been explicitly considered. This important aspect would have to be treated in a later study. In this study, the observed stalactites, with their present shape, are simply assumed to have a certain age, henceforth referred to as "observation time". A value of 5000 years has been used for the statistical evaluations. Furthermore, it is assumed that seismic events that produce a PGA in the cave of less than $\alpha_0 = 0.5$ m/s^2 cannot be identified, since they would hardly break any stalactite. Therefore, "seismic events", by definition, are only events that exceed this threshold.

Prior information

The statistical approach is mainly based on Bayesian statistics. That is why it asks for an a priori knowledge of the result, called "prior". If nothing is known a priori, the prior can be kept non-informative, and the final result is only influenced by the observed data.

In the present case, the subjective evaluation of the cave is that "probably at least one event has occurred in the last 1000 years over the absolute threshold of PGA"; this absolute threshold was set to 0.5 m/s^2. This impression is based on the fact that the cave is situated in a moderately seismic region and that fault mirrors exist in the cave. Therefore, a probability of 70% for one event or more, and 30% for no seismic event during the last 1000 years was chosen as a prior for the main statistical analysis (run 1 of the statistics programme). Sample data confirmed this impression since otherwise, the 54 stalactites observed as broken would have had to be broken by non-seismic reasons.

In order to test the importance of this prior in the present context, an additional statistical analysis was done with a prior assuming a probability of 100% that no seismic event has occurred in the last 1000 years (run 2 of the statistics programme). In both runs, a value of 2 m/s^2 was chosen as a surely attainable level of acceleration (PGA). A value of 15 m/s^2 PGA was assumed to be attainable with a probability less than 10^{-7}.

Observation of the stalactite population
The stalactites were sampled in the most exhaustive way possible, by photographic means. This sampling was limited to the parts of the cave with the most dense stalactite population. The sampled stalactite population was divided into the four vulnerability classes defined in Figure 4. Furthermore, two groups of stalactites are considered : the unbroken and the broken ones. It is not obvious to determine to which vulnerability class belongs a stalactite by only looking at its geometry. This is the reason why, for each class of stalactites, a probability is given that an individual stalactite associated to this class would actually belong to another class (the total probability of the 4 classes being 100%). Table 2 shows this probabilistic classification of the unbroken stalactites (total number 324).

The broken stalactites (total number 54) were also investigated, and for each of them, a probability of belonging to class 1 to 4 was given. Furthermore, it is taken into account that some of the apparently unbroken stalactites might in fact have been broken, but no visible traces are present today (broken section fully hidden by new calcification). In an analogous way, stalactites observed as seismically broken can be broken by something else than an earthquake or can actually be unbroken (sudden change in growth rate or type). These uncertainties are also taken into account.

TABLE 2

CLASSIFICATION OF THE UNBROKEN STALACTITE POPULATION

class 1	class 2	class 3	class 4	Number of specimens with this distribution
90%	10%	0%	0%	14
15%	70%	15%	0%	54
0%	20%	60%	20%	68
0%	0%	10%	90%	188

Results: probably attained PGA in the cave
The main result of the statistical analysis is the estimation of the probability of occurrence of 0 events over a given threshold PGA in an also given period of time; in this case 5000 years .

Figure 5 shows such results for run 1 and run 2. Both prior and posterior are shown. A comparison of both prior results points out that, in fact, prior information was different. For low thresholds (0.5 up to 3.5 m/s^2) run 1 prior predicted more probability of 0 events than run 2 prior. The role is inverted for higher thresholds and finally both converge to 1.0 near the considered most upper limit 20 m/s^2. After Bayesian updating, these probabilities maintain the mentioned features and shapes but the probabilities have been increased, slightly more in run 1 than in run 2. This is due to the fact that in run 1 prior information agrees with the data (one event or more), but in run 2, data (probably one event or more in 5000 years) do not match the prior (probably 0 events in 1000 years) : the longer time observation dominates the result.

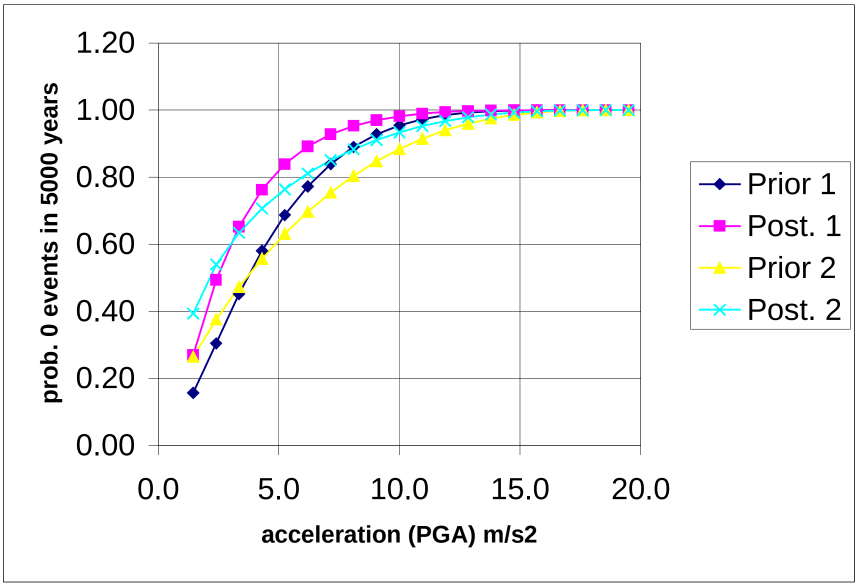

Figure 5 : Probability of occurrence of 0 events over a given threshold in a given period of time (5000 years). Both prior and posterior are shown for each run (1 and 2)

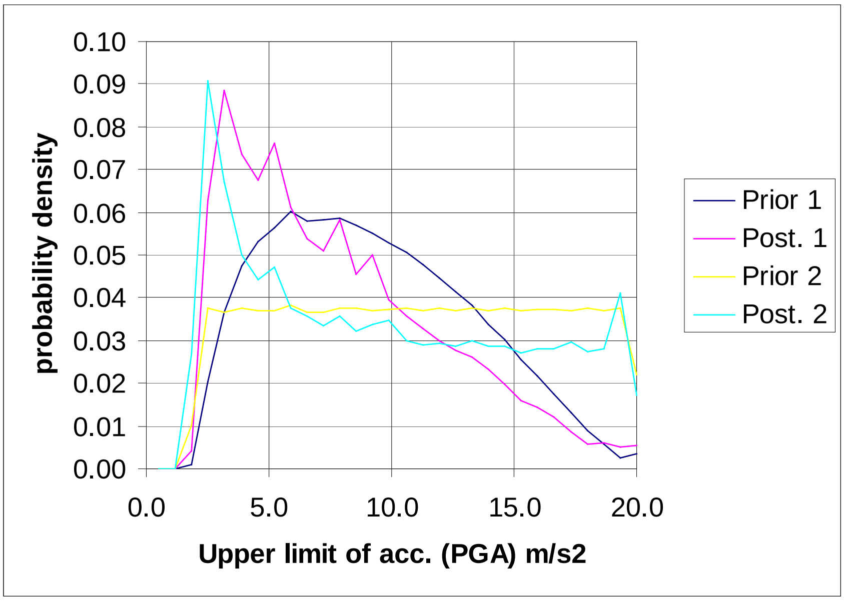

Figure 6 : Probability density of the upper limit of the acceleration (PGA) for both runs and for prior and posterior

Figure 6 shows a secondary but intuitive result. The probability density of the upper limit of the acceleration (PGA) is shown for both runs and for prior and posterior. Run 1 prior shows a preference of an upper limit of the PGA between, say, 5 and 8 m/s^2, whereas run 2 prior shows no preference between the absolute threshold (0.5 m/s^2) and the maximum admissible value (20 m/s^2). After Bayesian updating, both posterior densities show that the more likely values of the upper limit of the PGA are less than, say, 6 m/s^2. This clearly points out :

- the data were informative as both priors were changed in the same direction ;
- probably, no really strong event occurred and, also probably, a moderate event with PGA between 0.5 and 2.5 m/s^2 occurred, with the most likely upper limit of the PGA at about 2.5 m/s^2 (posterior 2) or 3 m/s^2 (posterior 1).

DISCUSSION AND CONCLUSIONS

It is interesting to compare the results obtained with the history of regional seismicity that is known – as far as strong events are concerned – for about 700 years. In fact, the only strong event known for that period is the 1356 Basel earthquake. Its epicentre was about 40 km away from the Milandre cave, and its magnitude (M_s) was probably between 6.5 and 7. According to Ambraseys et al. [13], a mean value for the larger component of the horizontal PGA of 0.7 m/s^2 ($M_s = 6.75$) would be expected in this case on rock outcrop. Since the Milandre cave is situated about 40 m below ground level only, this value would also approximately be valid in the cave. Since the standard deviation of the PGA attenuation law is a factor of 1.8, the actually occurred PGA value may have been also significantly higher. This is even probable. It is known from both Mayer-Rosa and Cadiot [14] as well as from Levret et al. [15] that the isoseismal counters were elongated in the direction from the epicentre to the region of Milandre, i.e. the attenuation in this direction was significantly less than the mean. Furthermore, both publications show Milandre within the I_{MSK} = VIII isoseismal counter. This makes a PGA-value of 1 m/s^2 and even 1.5 m/s^2 much more probable than a value of 0.7 m/s^2.

The main tentative conclusions that can be drawn so far are:

- Most of the existing stalactites (and stalagmites), except long and slender ones, hardly break during realistic earthquakes, say with PGA < 1 g.
- There are many broken stalactites present in the pilot cave where low or very low seismic vulnerability is inferred for their estimated unbroken shape. It seems therefore improbable that the majority of them broke during a seismic event.
- Most of the long and slender stalactites are expected to break during a "reasonably" strong earthquake, say with 0.3 g < PGA < 1 g.
- The observed data nevertheless indicate that probably at least one seismic event has occurred. (As long as no datation of the broken stalactites is undertaken, multiple events cannot be distinguished from a single event.) The most probably attained PGA was of the order of 1 to 2 m/s^2. However, this statement must be understood as a rather "weak" information.

The co-existence of intact, but vulnerable stalactites with broken ones of very low vulnerability is not necessarily a contradiction. As long as no datation has been undertaken, it is possible that the unbroken vulnerable stalactites are younger than the last strong earthquake that had broken the less vulnerable ones.

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