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# Evaluation of the seismogenic potential in key areas of the central and southern Apennines through analysis of speleothem vulnerability

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***Abstract:*** *We used speleothem vulnerability for assessing the seismic ground shaking threshold probably experienced or not in caves located within Apennines seismogenic areas. On the southern flank of the Pollino Range, which is considered a current seismic gap, cave observations suggest the lack of significant earthquake-related deformation in the last ~5-7 ka, but the widespread occurrence of creep. In the central Apennines, homogenously-trending collapses within the Grotta Cola (Petrella Liri, AQ) evidence a significant co-seismic deformation event radiometrically bracketed at ~4-5 ka. We supplemented the cave observations with numerical modeling and static test analysis of the speleothem mechanical behaviour to stipulate probability density functions for the bending stress leading to rupture, and established different vulnerability curves for speleothems according to their shapes. Model results are consistent with the co-seismic deformation at Grotta Cola as being caused by the Liri or by the Velino fault. On the other hand, unbroken speleothems in the Pollino area were used to define an upper limit of the "strength" for earthquakes that could have occurred during the speleothems' lifetime.*

***Key words:*** *Seismic Hazard, Speleothem vulnerability, Seismic ground motion threshold, central and southern Apennines.*

## INTRODUCTION

Earthquake forecast and seismic hazard models are generally based on historical and instrumental seismicity. However, in regions characterized by moderate strain rates and by strong earthquakes with recurrence longer than the time span covered by historical catalogues, such as in many parts of the Apennines, different approaches are desirable to provide an independent test of seismologically-based models.

We used non-conventional methods, such as the so-called "Fragile Geological Features" (FGFs), and in particular cave speleothems, for assessing and improving existing paleoseismological databases and seismic hazard models for selected areas of the Apennines.

The analysis of speleothem deformation (breakage or offset) is part of speleoseismological studies, which seek for evidence of past earthquake within the cave archive (Forti, 2001; Becker et al., 2006). Radiometric dating of the deformation events can be performed with relative ease and thus "speleoseismic" events can be compared to historical seismicity catalogues (e. g. Forti & Postpischl, 1984), or be used to extend back in time the paleoseismological record (e. g. Delaby, 2001; Becker et al., 2005; Kagan et al., 2005).

The underlying idea is based on the stalactite-stalagmite oscillatory system which represents the vertical datum. Provided that other sources are excluded (e. g. landslide, flooding, animal or men passage), the deviation from the vertical of the growth axis, and the speleothem breakage, is evidence for shaking of the cave walls (Forti & Postpischl, 1984; Kagan et al., 2005). However, the difficulty in quantitative modeling of the observed deformation, and its direct attribution to a geometrically-constrained seismogenic source is a major issue (Lacave et al., 2004; Becker et al., 2006).

Lacave et al. (2000) investigated the range of fundamental natural frequencies and the damping of speleothems, and established that most of the broken speleothems are a direct indicator of the peak ground acceleration (PGA) during past earthquakes. Based on the analysis of the mechanical behaviour of speleothems through static tests, Lacave et al. (2004) stipulated the PDF (probability density functions) for the bending stress leading to rupture, and established different vulnerability curves (probability of breaking as a function of PGA) for speleothems according to their shapes. On the other hand, unbroken speleothems may be used to define an upper limit of the "strength" for earthquakes that could have ever occurred during the speleothems' lifetime. This approach was applied by Lacave et al. (2012) to two pilot caves in Lebanon.

Based on these results, we started developing speleothem-based vulnerability curves for selected areas within the axial seismogenic belt of the Apennines. The study area in southern Italy is in northern Calabria (Pollino Range), and represents a gap in the belt of active faults and current seismicity, but, based on paleoseismological data, it is thought to host seismogenic faults (Cinti et al., 2002). Our previous work on broken speleothems from caves distributed around suspect active faults established past episodes of speleothem deformation, tentatively related to

earthquakes (Ferranti et al., 1997; Ferranti and Maschio, 2007), but no investigation on vulnerability was carried.
The study area in central Apennines is located ~10 km west of the Fucino Plain, one of the largest tectonic basin of the Apennines, affected by the large 1915 earthquake (M=7). In detail, the cave is located close to the Liri fault, a ~42 km long and southwest dipping normal fault, considered by some authors (e.g. Roberts & Michetti, 2004) active and seismogenic.

## RESEARCH STRATEGY

The starting step of the research was to select within the target areas the caves with required features (concretions within near-surface rooms, wide range of speleothem shapes, easy access, and so on). We visited four caves scattered on a ~20 km stretch on the southern flank of the Pollino Range, and one cave in Abruzzi. In both settings, caves are in the immediate footwall of suspect active normal faults (Pollino-Castrovillari, and Liri faults, respectively). The shape of speleothems was recorded by measuring length and diameter of intact and deformed speleothems. Care was taken in distinguishing within the speleothem data the subset related to non-seismogenic deformation (e. g. creep, manifested in quasi-continuous change of the growth axis), and to seismic processes (speleothem breakage and fall, discrete change of growth axis), respectively. Vulnerability analysis of the speleothem population based on the length and diameter ratio was initially carried according to published curves (Lacave et al., 2012).
In a following step, we performed static tests on a representative speleothem population from the different settings in order to correctly define the speleothem vulnerability curves (in terms of probability to be broken), and thus past PGA thresholds, for each investigated area.
In addition, we performed theoretical and numerical modelling in order to estimate the values of the horizontal ground acceleration required to failure the speleothems. In particular we used a finite element method (FEM), with the SAP200 software, starting from the detailed geometry of the speleothems and their mechanical properties.
Laboratory analysis included radiometric dating of the speleothem deformation events in order to define, for each area, the paleoseismological frame. For unbroken speleothems, dating of the most recent speleothem layer was used to define the time interval of the limited PGA threshold experienced by speleothems.
The speleothem-based estimate was then compared with the acceleration predicted by the national seismic hazard model (MPS04, 2004).

## DISCUSSION

In the Pollino area, we found a good chronological correlation between deformation events recorded by single speleothems of comparable size from an individual cave. At a larger scale, type and age correlation of events among different caves located along a ~20 km stretch of the southern flank of the range led to identification of a well-constrained, regional collapse event at ~5-7 ka, and a previous similar event at ~23 ka. Because these events are recorded by speleothem with moderate vulnerability, we regard them as related to strong, but infrequent earthquakes. Conversely, we did not found evidence of significant seismic shacking between ~40-23 ka, ~23-7 ka, and after~5-7 ka, for this latter time frame even for more vulnerable speleothems. Instead, we observed the widespread existence of “slow” deformation events that we relate to creeping.
Laboratory tests on a representative Pollino speleothem population documented P-wave velocities ranging from 3 to (mostly) 5-6 km/s and an inverse correlation between velocity and porosity. Preliminary results of static uniaxial tests show instead a more complex relation between deviatoric stress and deformation. Broadly, samples with higher P-wave velocity and lower porosity show a higher deviatoric stress reached at a lower deformation amount when compared to slower and more porous samples. Although not yet completed, these tests are being used to build dedicated vulnerability curves for the Pollino caves.
Within the Grotta Cola in central Italy, on the other hand, we found evidence of significant co-seismic deformation, represented by near similar-sized speleothem concretions on collapsed speleothems. This deformation event, which is recorded in several rooms of the cave, is characterized by a consistent direction of stalagmite collapse toward N330°±10°. Such collapse direction is expected for seismic wave propagation along a NNW-SSE striking causative fault, consistent with the strike of either the Liri fault, mapped at the foot of the range hosting Grotta Cola (Roberts & Michetti, 2004), and of the Velino fault, located further northeast and having the Grotta Cola in its hanging-wall (Schlagenhauf et al., 2011). We dated the deformation at between ~4.2-5.8 cal ka. Taking into account an up to 20% correction to account for the age contamination due to water circulation into the Mesozoic carbonate reservoir (Alessio et al., 1991), an ~4-5 ka age for this event is estimated. Although we do not provide dates, observations are consistent with more than a single event recorded in the cave.
Laboratory measurements were performed on Grotta Cola speleothem samples in order to characterize their mechanical properties. The obtained values of density, Young’s modulus and tensile failure stress, both from broken and unbroken speleothems, have been used as input data for theoretical calculations and numerical modelling of the main collapsed speleothem. The horizontal ground acceleration resulting in failure and the natural frequency of the speleothem were assessed by the FEM modelling. The results suggest either the Liri or the Velino fault as the most probable causative fault of the cave speleothem collapses recorded ~4-5 ka ago. Noteworthy, the time range bracketed for the speleothem deformation is well consistent with a period of clustered slip recorded by cosmogenic dating of the Velino-Magnola fault scarp (Schlagenhauf et al., 2011).

In summary, our research contributes to assess the existence or lack of past earthquakes within the axial seismogenic belt of the Apennines. As a matter of fact, the Grotta Cola lies just west of the Fucino plain, where historical and modern seismic deformation of the central Apennines seismic belt has concentrated. Similarly, the Pollino region is at the transition between southern Apennines and Calabria seismogenic provinces, where a marked decrease in seismic and geodetic deformation occurs (Totaro et al., 2013; Ferranti et al., 2014). Definition of the upper threshold for seismic shaking, as in the case for the recent behaviour of the Pollino region, can help reducing overestimated risks and calls for a fault-based revision of seismic hazard maps.

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