EVALUATION OF THE SEISMOGENIC POTENTIAL IN KEY AREAS OF THE CENTRAL AND SOUTHERN APENNINES THROUGH ANALYSIS OF SPELEOTHEM VULNERABILITY

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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 nonconventional 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 and 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). However, the difficulty in quantitative modelling 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 behavior 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. 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. Previous works 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 and 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. 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 modeling 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 U/Th and 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 span there are no evidence even for more vulnerable speleothems).

Within the Grotta Cola, in central Italy, we found evidence of significant coseismic 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 and 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. 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. 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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