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# Defining a Mid-Holocene earthquake through speleoseismological and independent data: constraints for the outer Central Apennines (Italy) seismotectonic framework

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**Abstract.** A speleoseismological study has been conducted in the Cavallone Cave, located in the easternmost carbonate sector of the Central Apennines (Maiella Massif), in a seismically active region interposed between the post-orogenic extensional domain, to the west, and the compressional one, to the east. The occurrence of active "silent normal faults", to the west, close to blind thrust, to the east, raises critical questions about the identification of the true seismogenic sources for this transitional zone. Large ceiling collapses, fractures, broken speleothems with new re-growing stalagmites on their top, preferential orientation of fallen stalagmites and absence of thin and long concretions have been observed in many portions of the conduit and may indicate that the cave suffered of sudden and catastrophic events likely linked to the occurrence of past strong earthquakes. Although controversies exist about the correlation between speleotectonic observations and quantitative modeling, speleotectonic studies, when corroborated by independent data collected outside caves, can play a fundamental role in discovering past earthquakes. Radiocarbon dating and, above all, the surprisingly correspondence with other coeval paleoseismological and geological data collected in surrounding areas outside the cave, provide important constraints for the individuation of a Mid-Holocene paleoearthquake around 4770±30 yr BP and for the identification of the Sulmona normal fault as the most likely causative structure.

## 1 Introduction

In highly seismic active regions characterized by karst environments, where the identification and characterization of the seismogenic sources is poorly constrained both by geological and seismological data, speleoseismology (i.e., the investigation of traces of past earthquakes in caves) represents a potential tool for the improvement of the seismological record and to better understand the seismotectonic framework of an area. Cave environments are, in fact, ideal for paleoseismological investigation because earthquake damages are often fossilized by post-earthquake calcification and preserved from erosion.

Following some pioneering studies at the beginning of the 1990's (see Becker et al., 2006 for a review), many works have focused on the significance of cave damages and their possible correlations with active tectonics and, in particular, with the effects of seismic shaking. These evidence include: broken speleothems and fallen stalactites (e.g., Postpischl et al., 1991;

Ferranti et al., 1997; Lemeille et al., 1999; Delaby, 2001; Kagan et al., 2005; Šebela, 2008; Panno et al., 2009; Bábek et al., 2015; Méjean et al., 2015), blocks and ceilings collapses (e.g., Gilli, 1999; Pérez-López et al., 2009), deformed cave sediments and fault displacements (e.g., Gilli et al., 2010; Babek et al., 2015), speleothems growth anomalies (e.g., Forti et al., 1981; Forti and Postpischl, 1984; Akgöz and Eren, 2015; Rajendran et al., 2015). Although direct observations of cave damages immediately after an earthquake have rarely been observed, "seismothems" (i.e., speleothems potentially broken, or deformed, by a seismic event; Delaby, 2001) have been increasingly recognized in many caves worldwide, allowing the authors to discover past earthquakes (see Becker et al., 2006 for a review). On the other hand, robust evidence and correlations of specific paleoearthquakes in caves with other independent paleoseismic records are very rare in the literature (e.g., Becker et al., 2005).

The analysis of seismothems requires a careful and integrated study approach aimed at the recognition of peculiar structures through the observation of speleothem morphologies. Several typical features can be referred to tectonic coseismic shaking (Forti, 2001). The most characteristic is represented by stalagmites cut along sub-horizontal planes, with the upper parts only translated from their original position but still standing upright or toppled and lying on the floor close to their base, accompanied with new-growing stalagmites covering the rupture surface of the stump (e.g., Postpischl et al., 1991; Delaby, 2001; Kagan et al., 2005). The geometries of the fallen part and the stump must match, allowing the reconstruction of the original speleothem. Another evidence of earthquake-induced phenomena is the presence of specific spatial distribution patterns of fallen concretions, resting on sub-horizontal or slightly inclined cave ground. Collapsed stalagmites toward preferential azimuths may be concordant with the orientation of the earthquake source (e.g., Postpischl et al., 1991; Delaby, 2001; Ferranti et al., 2015; Méjean et al., 2015). More suitable for this kind of observations are fallen stalagmites cemented on the floor to ensure that broken speleothems have maintained their original direction in time (Forti, 2001). These observations have to be strengthened by dating in order to find correlations with past earthquakes. To constrain the age of the damaging event it is necessary to date the oldest layer at the base of the regrowth stalagmite and the youngest layer at the tip of the fallen stalagmite (e.g., Postpischl et al., 1991; Forti, 2001; Kagan et al., 2005). Statistical analyses and comparison with other data (e.g., paleoseismological data collected along neighboring seismogenic sources) are crucial to better constrain the age of a paleoearthquake. On the other hand, some authors have raised the question that seismothems-like features can be induced also by non-seismic processes such as: human and animal presence, shocks due to mine blasting, cryogenic fracturing, gravitational collapses, creep movements of sediments, glacial intrusion and catastrophic floods (e.g., Gilli, 2005; Becker et al., 2012). Therefore, it is fundamental to consider more reasons that can interact and eliminate all other possible non-seismic causative processes.

Finally, controversies exist about the correlation between field observations and quantitative modeling. Some authors sustain that high accelerations are needed to break speleothems and that only thin and long concretions can be damaged following seismic shaking due to "reasonably" strong earthquake ($3 \text{ m/s}^2 < \text{PGA} < 10 \text{ m/s}^2$) (e.g., Cadorin et al. 2001; Lacave et al., 2000; 2004; 2012). Nevertheless, field evidence cannot be neglected and suggest that maybe empirical mechanical relations lack in considering some significant parameters and conditions (Delaby, 2001). Moreover, speleoseismological studies have increased in recent years (e.g., Delaby, 2001; Kagan et al., 2005; Šebela, 2008; Panno et al., 2009; Bábek et al., 2015; Méjean et al., 2015) testifying that caves remain important environments that can contain a great amount of well-preserved geological and seismotectonic information.

Due to the uncertainties affecting this method of analysis, it is fundamental to combine speleoseismological data with independent paleoseismic records in other geological archives outside caves, such as liquefaction evidence within lake and flood-plain deposits, locations of rock falls and coseismic fault displacements (Becker et al., 2005; 2006).

Less speleotectonic studies have been conducted in the high seismically active region of the Apennines (Forti and Postpischl, 1984; Postpischl et al., 1991; Ferranti et al., 1997; 2015). We performed a geological-structural field work, with a paleosesimological approach, in the Cavallone Cave located within the Maiella Massif, in the eastern Central Apennines (Fig. 1). The aim is to find typical earthquake-related structures and, then, to improve the paleoseismological record and the characterization of the seismogenic sources affecting a complex and poorly constrained seismotectonic region such as the easternmost sector of the Central Apennines. The actual configuration of the cave and the presence of structures that can be resembled to seismothems, suggest that the conduit underwent repeated earthquake damages in the past, even more so radiocarbon dating provided important constraints for the individuation of a paleoearthquake. Moreover, an exceptional geological record available from surrounding areas, allowed robustly correlating the recognized paleoearthquake with other independent data (i.e., paleoseismological and geological data outside the cave), suggesting the reliability of speleoseismological studies in discovering past earthquakes.

## 2 Geological and structural setting

The Apennines are a Neogene-Quaternary foreland-verging fold-and-thrust belt showing a complex structural arrangement deriving from the interaction between contractional structures and pre-existing extensional faults (e.g., Calamita and Deiana, 1988; Tavarnelli, 1996; Coward et al., 1999; Scisciani et al., 2001, 2002; Tozer et al., 2002; Butler et al., 2006; Calamita et al., 2009; 2011; Scisciani, 2009; Di Domenica et al., 2014a and b; Pace et al., 2014; Cardello and Doglioni, 2015). The orogenesis involved Triassic-to-Miocene sedimentary successions related to different basin and platform paleogeographic domains of the Adria Mesozoic paleomargin (e.g., Ciarapica and Passeri, 2002; Patacca and Scandone, 2007). Post-orogenic extension affects the Apennine chain and is responsible for the seismicity especially concentrated within the axial part of the belt. This seismicity is related to NW-SE-trending, 15-to-30 km-long Quaternary normal fault systems which are compartmentalized by regional oblique NNE-SSW-trending thrust ramps acting as "persistent structural barriers" and controlling normal fault systems propagation (Fig. 1; e.g., Tavarnelli et al., 2004; Pizzi and Galadini, 2009; Di Domenica et al., 2012). These faults are responsible for high magnitude destructive earthquakes ($M \leq 7$; e.g., Calamita and Pizzi, 1994; Ghisetti and Vezzani, 1999; Galadini and Galli, 2000; Working Group CPTI, 2004; Rovida et al., 2011). On the other hand, so called "silent faults" characterize the easternmost sector of the Apennine chain (e.g., Sulmona fault, Assergi fault, Mt. Vettore fault; Fig. 1). No large-magnitude historical seismic events can be strictly related to these structures which, however, show evidence of Late Pleistocene-Holocene activity (Galadini and Galli, 2000; Papanikolaou et al., 2005 and references therein). Only recently, the II century AD earthquake occurred in central Italy has been associated to the Sulmona fault system through archaeoseismological and paleoseismological evidence (Ceccaroni et al., 2009; Galli et al., 2015). This lack of data could be due to long recurrence intervals (1400-2600 years; Galadini and Galli, 2000) and/or to the incompleteness of the available historical seismic catalogues (e.g., Stucchi et al., 2004), suggesting high seismic hazard levels and raising critical questions about the identification of the seismogenic structures and the true seismic potential of these areas.

The seismotectonic framework of the Central-Northern Apennines is complicated by the occurrence of reverse and strike-slip events delineating an active compressional domain along the peri-Adriatic foredeep-foreland sector that exhibits a moderate and less frequent seismicity with respect to the western extensional one (Fig. 1; e.g., Frepoli and Amato, 1997; Montone et al., 2012; Pondrelli et al., 2006).

The Cavallone Cave is located at 1475 m a.s.l., in the Taranta Valley, a NNW-SSE/NW-SE-trending incision cutting through the Maiella Massif (Figs. 1 and 2). This latter represents the outermost outcropping carbonate anticline of the Central Apennines, involving Early Cretaceous-Miocene carbonate platform and slope-basin successions (e.g., Donzelli, 1969; Patacca and Scandone, 1989; Festa et al., 2014 and references therein). The Maiella anticline is related to the emplacement of a Middle-Late Pliocene NW-SE/NNE-SSW-trending curved frontal thrust, buried beneath Mio-Pliocene siliciclastic deposits and Molise allochthonous Units (e.g., Scisciani et al., 2002; Pizzi, 2003). Given the seismotectonic framework described above, it is clear how the Maiella Massif is interposed between two distinct domains: extensional, to the west, and compressional, to the east (Fig. 1). Although the Sulmona-Maiella area represents the epicentral zone of high magnitude historical earthquakes such as those occurred in the II century AD (Maw = 6.3), in 1706 (Maw = 6.6) and in 1933 (Maw = 5.7) (Working Group CPTI, 2004; Rovida et al., 2011), the identification of the seismogenic source(s) responsible for this seismic activity is poorly constrained (both by geological and seismological data) and still debated.

The most hazardous adjacent seismogenic structures are the Sulmona normal fault (e.g., Galadini and Galli, 2000; Gori et al., 2014; Galli et al., 2015) and the Palena and Western Porrara normal faults (i.e., the southeastward prosecution of the Sulmona fault; Pizzi et al., 2010; Fig. 1). Late Quaternary evidence of faulting have been described for these two latter structures (Pizzi et al., 2010), while paleoseismological studies allowed recognizing four faulting events in the past ~9 ky BP along the Sulmona fault (Galli et al., 2015). Regarding the frontal area of this sector of the chain, less seismological data are available and seismicity could be probably associated to buried Apennine thrust fronts (e.g., Scisciani and Calamita, 2009; de Nardis et al., 2011) such as those activated in the Northern Apennines during the Emilia Romagna 2012 earthquake (e.g., Pizzi and Scisciani, 2012; Govoni et al., 2014 and references therein).

## 3 Method

We performed a careful structural-geological analysis along the main conduit and some lateral branches of the Cavallone Cave (Fig. 2), for a total length of ca. 1 km. The Cavallone Cave has been exposed to human presence since the end of the 1600s and ca. 500 m are still open for touristic purpose. In fact, in the vicinity of the cave entrance and along the touristic path, broken stalagmites may be due to human depredation. Nevertheless, there are portions of the cave, far enough from the entrance and from the touristic path, that allow to exclude the presence of humans and animals in the past (rooms "Sala dei Cristalli" and "Sala dei Merletti" in Fig. 2c). For the speleotectonic analysis, high attention has been paid to distinguish the features described in the literature as earthquake-related structures (e.g., stalagmites cut along sub-horizontal planes, with the upper part lying close to their base and cemented on the floor), according to the indications of Forti (2001).

Measurements of fallen directions, dimensions of speleothems and distribution of speleothem fracturing were collected in the sectors of the cave considered suitable for the study, far enough from possible human disturbance. Only broken stalagmites lying on sub-horizontal or slightly inclined cave ground have been considered for the statistical analysis of the representative azimuths of fallen directions. Careful observations have been also made to eliminate other causes for speleothem damage.

For a detailed paleoseismic interpretation, AMS Radiocarbon dating of damaged speleothems has been performed (by Beta Analyitc Radiocarbon Dating Laboratory, Florida, USA).

## 4 Speleoseismological analysis

The cave mainly develops in a N-S direction within the Paleocene-Upper Oligocene calcarenite and cherty limestone of the Maiella carbonate slope-basin succession (Fig. 2). Within the cave, patches of both fine- and coarse-grained deposits are preserved. In the majority of cases, these latter represent collapsed material over which new generations of concretions have grown up.

The cave shows many concretions, especially stalagmites. Near the entrance, the biggest stalagmites (more than 2 m-high) are preserved. In an exposed longitudinal section of one of these speleothems, it is clear how the concretion has grown onto ca. 2 m-thick chaotic material, originated after repeated collapse events, involving also big portion of stalagmites and draped by flowstone deposits (Fig. 3a, 3b and 3c). Similarly, great stalagmites (more than 3 m-high, with diameter of 30-50 cm) are preserved within the first eastern branch of the cave, named "Galleria della Devastazione", that cannot be visited by tourists (Fig. 2c). Here, stalagmites rest tilted converging toward the central axis of the conduit and some of them are broken (Fig. 3d). The big dimensions of the speleothems may indicate that these first sectors of the cave represent the most ancient ones. Evidence of falls and collapses, moreover, testify that the cave underwent several catastrophic events (probably of different origin) during its development. Nevertheless, at least for the "Galleria della Devastazione", earthquake-induced damages are difficult to be invoked as the main cause of the present-day configuration of the conduit, since too strong seismic events should have been occurred to break so big concretions (e.g., Cadorin et al. 2001; Lacave et al., 2000; 2004; 2012). A strong influence, instead, could have been exerted by gravitational processes, that maybe caused the floor sinking (Fig. 3e), probably related to the collapse of a deeper karst network, although it cannot be excluded that also this collapse could have been triggered by a strong seismic event.

Apart from these first meters of the cave, stalagmites found in the rest of the conduit do not exceed one and, exceptionally, two meters in height and have diameters ranging between 10 cm and 30 cm, on average. Stalagmites showing these dimensions, however, are very scarce and are preserved only in restricted portion of the conduit, while the most abundant stalagmites do not exceed 20 cm in height. Regarding the stalactites, those appearing well-developed (more than 1 meter long and with a diameter of a ten of centimeters) result broken in the majority of cases. On the other hand, where the stalactites are entirely preserved they show uniform lengths that not exceed some tens of centimeters (Fig. 4a). From a general point of view, therefore, the Cavallone Cave lacks in intact long and thin speleothems. This is an interesting question because it is known that long and thin concretions are the first to be destroyed during an earthquake and in the literature it is generally accepted that soda straws damage are reliable indicators of co-seismic shacking (e.g., Lacave et al., 2004; Becker et al., 2006). The actual configuration of the Cavallone Cave, therefore, cannot be the result of a gradual process, but it can be probably associated to sudden events, among which seismic shaking can be invoked.

Ceiling collapses are, moreover, widespread and testified by the presence of piles of collapsed materials in many points along the conduit. On top of these piles, little stalagmites, from few centimeters up to 20 cm-high at most, can be observed (Fig. 4c). Often the floor of the conduit shows centimetric-wide sub-vertical open fractures that affect concretions (Fig. 4b) running at the base of the cave walls, probably suggesting the interplay of different processes, from gravitational to seismic.

Especially in the rooms “Sala dei Cristalli” and “Sala dei Merletti” (see Figure 2c for the location), typical features that are associated in the literature to earthquake damages can be observed. These are represented by fractured stalagmites showing sub-horizontal cut planes located in the lower third of their height. Where it was possible to observe both the stumps and the fallen portion of the speleothems that underwent this kind of damages, the concretions show diameters of 10-15 cm and original lengths of 40-100 cm, on average. The upper parts of these broken speleothems are standing upright, only translated on the fracture plane (Fig. 4d) or are fallen and cemented on the floor (Fig. 5b), lying close to their corresponding stumps. Most of the examples of these stalagmites were found remaining on sub-horizontal or slightly-inclined cave ground. The cut planes of the broken speleothems are often covered by new-growing stalagmites, few centimeters high (2-5 cm), analogous to those found on top of collapsed materials. The analysis of the orientation of the fallen stalagmites cemented on the floor reveals two preferential trends: NNW-SSE and ENE-WSW (Fig. 5a), respectively parallel and perpendicular to the strike of the main seismogenic normal faults in the extensional domain to the west of the cave (e.g., Sulmona, Palena and Western Porrara normal faults), whereas, to the east of the cave, the thrust planes generally strike ca. N-S (i.e., parallel to the Sangro-Volturno thrust zone; see Fig. 1). The preferential orientation of broken speleothems has been widely considered as seismic-related and often found as concordant with the orientation of the seismogenic causative faults (e.g., Delaby, 2001; Forti, 2001; Postpischl et al., 1991; Kagan et al., 2005; Ferranti et al., 2015).

In the cave we found peculiar examples of features similar to that showed in Figure 5b. The two parts of the broken speleothem perfectly match and a new generation of concretion, with dimension analogous to other stalagmites regrowth on broken speleothems and collapsed materials (2-5 cm-high), can be found on top of the cut plane. All these data and observations likely suggest that the cave could have recorded a strong past earthquake responsible for diffuse toppling of stalagmites and ceiling collapses. According to the available literature (e.g., Forti, 2001), the speleothem of Figure 5b can be resembled to a “seismothem” (Delaby, 2001), hence we chose it for our paleoseismological analysis also considering that this kind of feature is optimal to conduct radiocarbon dating. A sample of the tip of the upper part of the broken stalagmite and a sample of the base of the little stalagmite growing on top of the stump have been collected. The AMS (Accelerator

Mass Spectrometry) analysis has been performed (by Beta Analyitc Radiocarbon Dating Laboratory, Florida, USA) on the youngest layer of the broken stalagmite (sample "GC/1"; likely pre-seismic) and on the oldest layer of the new-growing stalagmite, as close as possible to its mutual contact with the cut plane of the stump (sample "GC/2"; likely post-seismic; Figs. 5b and 6a). The age of the possible paleoearthquake should be more recent than the age of the tip of the broken stalagmite and more ancient than the base of the new stalagmite growing on the stump. The break and the start of the regrowth of the stalagmites should be assumed as instantaneous and simultaneous events. In fact, the results of both samples are highly comparable and indicate a time span that extends from 4840 yr BP to 4525 yr BP (2σ cal. age) (Fig. 6b). As sample "GC/1" belongs to a stalagmite older than sample "GC/2", we can strengthen our chronological constraint considering only the intervals within which the dating of the two samples overlaps. In this way, we can obtain an average age of 4730±85 yr BP for the paleoearthquake (Fig. 6c).

A peculiarity of the analyzed concretions is the presence of so called "macroholes", i.e., millimetric to centimetric-size cavities which can determine significant secondary porosity of the speleothem (Shtober-Zisu et al., 2012). These holes can develop parallel to the growth axis of the stalagmite ("axial holes") causing the characteristic antiformal shape of the surrounding growth layers which are bent downward towards the holes (Fig. 6a). The origin of the axial holes has been linked to syn-depositional slow rate of calcite accumulation and falling drop erosion. Also "off-axis holes" can occur and they are related to post-depositional calcite corrosion, possibly controlled by bacterial activity (Shtober-Zisu et al., 2014).

## 5 Correlation with independent geological records

In order to constrain the seismic origin of the broken speleothem dated in the Cavallone cave and the age of the related paleoearthquake, we searched for other synchronous and independent evidence outside the cave. We found that the result of the radiocarbon dating matches with other geological evidence and data collected in surrounding areas, in particular along the Sulmona fault and near the Lettopalena village (Figs. 1 and 2).

The SW-dipping Sulmona fault represents the most important active normal fault in the vicinity of the Maiella Massif. Along its prosecution, toward the SE, detailed geological analyses have revealed a recent activity also for the so called "Western Porrara Fault" and the "Palena Fault" (Fig. 1; Pizzi et al., 2010). Paleoseismological trenches performed along the northwestern portion of the Sulmona fault system allowed the recognition of four paleoearthquakes (Galli et al., 2015). One of them is testified in two trenches by the presence of a faulted colluvium. The age of the involved material is included within the interval 5580-3370 yr BP. Mediating and overlapping the dating coming from the two trenches, the authors fix the event around 4500 yr BP (Galli et al., 2015; Fig. 7a).

The Lettopalena village is located at the base of the Maiella forelimb, few kilometers to the south of the Taranta Valley, and rises on top of chaotic rockslide avalanche deposits (Fig. 2a). The involved rock mass volume is in the order of 106 m3 and includes meter-scale angular-shaped rock blocks, with sandy matrix, arranged in a chaotic texture and an inverse grading (Paolucci et al., 2001; Di Luzio et al., 2004; Bianchi Fasani et al., 2014). The origin of the Lettopalena rock avalanche has been linked to deep-seated gravitational slope deformation (Bianchi Fasani et al., 2014; Di Luzio et al., 2004) or to earthquake triggering, as initially proposed by Paolucci et al. (2001) who reproduced the rockslide considering a M 5.5 event. Thanks to the presence of a buried wood within the landslide body, Paolucci et al. (2001) determined a radiocarbon age of 4800±60 yr BP for the Lettopalena rock avalanche.

Therefore, the dating of both the paleoevent recognized in the trench along the Sulmona fault (Galli et al., 2015) and the Lettopalena rock avalanche match with the age indicated by the seismothem found in the Cavallone Cave constraining the age of a Mid-Holocene earthquake around 4770±30 yr BP, likely associated to the Sulmona normal fault seismogenic source. This surprisingly correspondence strengths the paleoseismological significance of earthquake-induced-like features recorded in the cave and corroborates also the hypothesis that the Lettopalena rock avalanche was triggered by a Mid-Holocene earthquake.

## 6 Discussion and conclusions

The use of speleotectonics for the recognition of paleoearthquakes is highly debated in the literature both because there are many possible breakdown causes that must be discounted (e.g., Gilli, 2005) and because it is still unclear if it is really plausible that earthquake can break speleothems (e.g., Cadorin et al., 2001; Lacave et al., 2004). On the other hand, peculiar features, recognized in many caves worldwide, have been often connected to earthquake damages (e.g., Postpischl et al., 1991; Ferranti et al., 1997; Lemeille et al., 1999; Delaby, 2001; Forti, 2001; Kagan et al., 2005; Šebela, 2008; Panno et al., 2009; Bábek et al., 2015; Méjean et al., 2015).

We perform a speleotectonic analysis within the Cavallone Cave located in the most external portion of the Central Apennines. The seismic history of this region and the characterization of possible seismogenic sources are poorly constrained, even more so that the study area remains interposed between two seismotectonic domains (extensional to the west and compressional to the east).

Many interesting features that can be associated to sudden and catastrophic events have been recognized in the cave. Anyway, because we cannot select only one cause for the analyzed broken speleothem, we must eliminate all other possibilities.

Large glacial intrusions in the Cavallone Cave can be excluded since the climate around 4500-5000 yr BP is considered a warm period (e.g., Walker et al., 2012 and references therein) as also suggested by the presence of Quercus ilex discovered within the Lettopalena rock avalanche deposit dated by Paolucci et al. (2001), indicating the presence of an evergreen oak forest and mediterranean climate conditions in the cave surroundings. Moreover, the dated stalagmite is located quite far from the entrance of the cave where the ice could not have been acted.

Fracturing due to catastrophic floods can also be excluded because there is no evidence of impacts on the concretions and related deposits. Moreover, the fallen parts of the stalagmites match with the stumps and lay uphill in their vicinity suggesting the absence of transport linked to hydrodynamic floods or ice.

Most examples of the standing broken stalagmites were found on sub-horizontal cave ground, suggesting that their deformation is not related to slope instability or sediment creep. An exception can be found within the first branch of the conduit (Galleria della Devastazione) where the presence of meter-scale broken concretions, resting tilted toward the axis of the conduit, suggests the gravitational collapse of the floor (Fig. 3d and 3e) which in turn could also have been triggered by a seismic event.

As the entrance of the cave is located in correspondence of a near vertical cliff, more than 100 m-high, human and animal access seems to be unlikely at the time of the dating event. Even if it could have been possible, human and animal disturbance can be excluded for the portions of the conduit where the paleoseismological analysis has been performed. These sectors, in fact, are too far from the entrance (~ 1 km) and they would have been too hard to reach also because of the articulate morphology of the cave ground (Fig. 2c).

Although gravitational processes can play an important role in defining the stability and configuration of the cave (as in the case of the “Galleria della Devastazione”; Figs. 3d and 3e), ceiling collapses, broken speleothems (of both stalactites and stalagmites), preferential orientation of fallen stalagmites and the absence of thin and long concretions, observed in many portions of the conduit, may indicate that the cave also suffered of sudden and catastrophic events likely linked to the occurrence of earthquakes. Two preferential trends of the fallen tips of broken stalagmites result to be parallel and perpendicular to the main known NW-SE-trending normal faults affecting this area of the Central Apennines. Moreover, a lot of stalagmites cut along sub-horizontal planes with the upper part lying close to their base and cemented on the floor and with a new speleothem generation re-growing onto the stumps have been recognized and can be resembled to seismothems (Delaby, 2001; Forti, 2001). Few centimeters-high stalagmites are widespread in the cave, raising also both on top of collapsed deposits and broken speleothems likely suggesting the occurrence of a sudden event after which concretions started to regrow. One of these seismothems has been chosen for dating (Fig. 5b), sampling the oldest layer at the base of the regrowth stalagmite (likely post-seismic) and the youngest layer at the tip of the fallen stalagmite (likely pre-seismic). We obtained an average age for the possible paleoearthquake of 4730±85 yr BP (Fig. 6). Moreover, dating indicates an interval age of 4840-4645 yr BP for the base of the re-growing stalagmite. Considering an average age of ca. 4700 yr BP and the height of the new stalagmite of ca. 1.5 cm, we can estimate a growth rate of 0.003 mm/y for the new stalagmite generation. The obtained value is quite different from the mean rates recognized in the literature that vary between 0.015 e 0.37 mm/y (e.g., White, 2007; Akgöz and Eren, 2015 and references therein). This may be explained by variations in the growth rate of stalagmites, as well as by complexities in their structure, texture, and chemical composition (e.g., Akgöz and Eren, 2015) or by peculiar processes governing the cave environment. The observed evidence of surface erosion and internal cavities in several stalagmites, moreover, strongly suggests the occurrence of periods with slow rate of calcite accumulation and falling drop erosion.

Empirical relations and quantitative modeling linking dimensions of speleothems and peak ground accelerations (e.g., Cadorin et al., 2001; Lacave et al., 2004) are difficult to be applied for the dated stalagmite, as too high accelerations ($3\ m/s^2 < PGA < 10\ m/s^2$) would have needed to break it. The answer to this question can be found considering that these correlations do not take into account some parameters and conditions such as: structural and chemical compositional variability, presence of pre-existing discontinuities and/or anomalies within the concretions, seismic site response, etc. (e.g., Delaby, 2001; Kagan et al., 2005), which can significantly influence the mechanic behavior and the strength of the material. In our case, indeed, the analyzed stalagmites show a peculiar porous inner structure due to the presence of millimetric to centimetric-size holes (macroholes in Fig. 6a; Shtober-Zisu et al., 2012). We believe that the widespread distribution of these voids within a concretion makes it weaker and then more susceptible to rupture during seismic shaking. Therefore, the ways through which speleothems convey seismic shaking need to be still understood and more in situ and laboratory studies are needed to evaluate ground peak accelerations required to break porous speleothems.

In summary, all the data collected within the Cavallone Cave allow considering plausible the occurrence of past earthquakes. In this kind of studies, the correlation of speleoseismological data with independent geological data collected outside the cave represents the key to constrain the results (Becker et al., 2005; 2006). In our case, the dating of the seismothem analyzed in the Cavallone Cave finds surprisingly correlation with other two independent phenomena occurred in surrounding areas. Both the coseismic faulting along the Sulmona normal fault (Galli et al., 2015) and the rock-avalanche affecting the Lettopalena village, to the south of the Taranta Valley (Paolucci et al., 2001), show radiocarbon ages around 4500-4800 yr BP, on average, that are strictly comparable with the dating performed on the broken stalagmite (Fig. 7a). This robust matching confirms that the Cavallone Cave has recorded a Mid-Holocene paleoearthquake around 4770±30 yr BP for which the Sulmona normal fault likely represents the causative structure which also triggered the Lettopalena rock-avalanche.

In this perspective, according to Galli et al. (2015), the 4770±30 yr BP earthquake can be considered the penultimate event for the Sulmona seismogenic structure, where the last one is represented by the II century AD. Our study, however, provides some evidence that the 4770±30 yr BP earthquake may have been even stronger than the Maw 6.3 II century earthquake. No other comparable large rock avalanche, indeed, are known to have occurred after the 4770±30 yr BP event along the same southeastern slope of the Maiella massif, characterized by a near uniform morpho-structural setting (i.e., ca. 30-40°-dipping forelimb), even during the more recent stronger earthquakes recorded in 1706 (Maw 6.6) and in 1933 (Maw 5.9). Furthermore, many studies indicate that more than 40% of worldwide rock avalanches that dammed streams (as in the case of the Lettopalena landslide with respect to the Aventino River; Fig. 2) were caused by earthquake shaking (Costa and Schuster, 1991; Jibson, 1996) and have been associated, in New Zealand area, to $M \geq 6.5$ earthquakes (Perrin and Hancox, 1992). According to scaling relationships relating surface rupture length vs magnitude (e.g., Wells and Coppersmith, 1994), a magnitude of about 7 could be reasonably hypothesized for the 4770±30 yr BP earthquake considering a synchronous activation of the Sulmona fault segment together with the Western Porrara and Palena faults segment, for a total length of about 40 km (up to the intersection with the Sangro-Volturno thrust zone; Fig. 1). This synchronous activation of these two adjacent segments, may explain both the higher magnitude of the resulting earthquake and why large effects have been recorded in the southern Maiella area (i.e., Lettopalena rock avalanche and broken stalagmites observed at the Cavallone cave). In case of activation of the Western Porrara and Palena segments, in fact, this area results much closer to the trace of the possible seismogenic source (ca. 8-10 km), with respect to the case of the sole activation of the Sulmona fault segment (ca. 20 km; Fig. 7b). Nevertheless, further paleoseismological studies are needed to constrain the exact length of the surface rupture trace and the magnitude associate to the 4770±30 yr BP event.

In conclusion, this study indicates that major coseismic secondary effects recorded in the external zone of the Central Apennine chain (i.e., at the transition zone between inner post-orogenic extension and outer chain/foreland deformation) have to be ascribed to seismogenic normal faults which are capable to produce M ≤ 7 earthquakes, instead of compressive structures capable of M ≤ 6 events, as testified by the Central-Northern Apennines historic seismicity (e.g., Working Group CPTI, 2004; Rovida et al., 2011). Nevertheless, further studies are needed to constrain both the seismogenic structures responsible for other events, such as the 1706 and the 1933, and the seismic hazard associated to this transitional zone.

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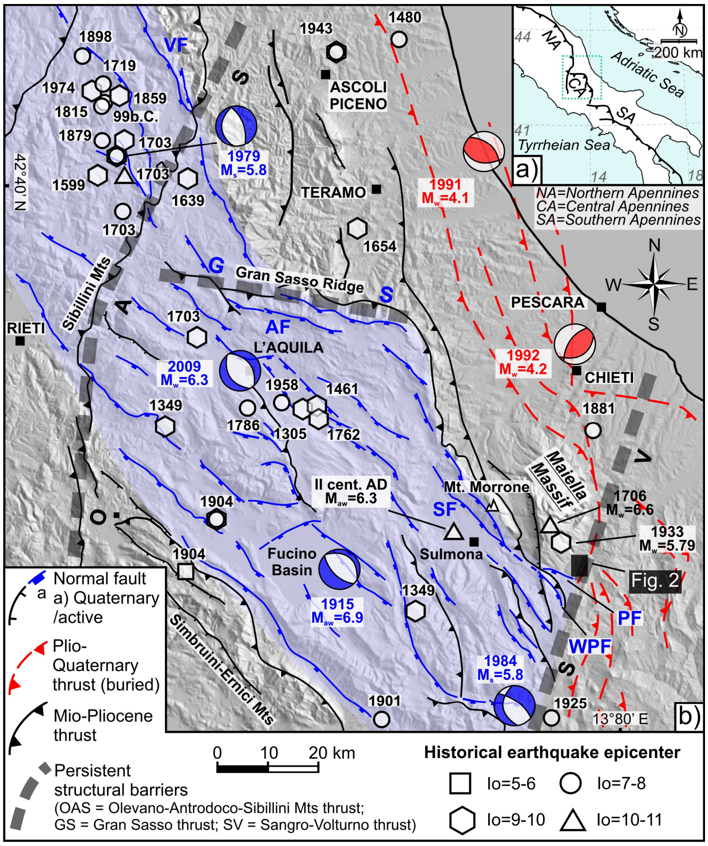


**Figure 1: a) The three major arcs of the Apennine chain. b) Simplified structural map of the Central Apennines and related seismicity (modified from Pizzi et al., 2010; de Nardis et al., 2011). To the west (axial zone of the chain) major Quaternary/active post-orogenic normal faults, superposed onto the Neogene thrusts, define the intra-Apennine extensional domain (light blue band) testified by focal solutions of recent earthquakes. Compressive or strike-slip tectonics prevails in the Adriatic foreland area, to the east. Epicenters location and macroseismic intensity (Io), or equivalent moment magnitude (Maw) and moment magnitude (Mw), of historical and recent earthquakes (Working Group CPTI, 2004; Rovida et al., 2011; Ceccaroni et al., 2009 for the II century AD earthquake) indicate stronger seismicity within the inner extensional domain and only moderate events in the outer compressional zone. Some events, such as the 1706 and 1933, localized in the Maiella Massif (i.e., at the extension/compression transitional domain), still have an uncertain source and kinematics. Persistent structural barriers, oblique to the main trend of the normal fault systems, control the propagation of the Quaternary/active normal faults (e.g., Pizzi and Galadini, 2009). AF = Assergi Fault, SF = Sulmona Fault, PF = Palena Fault, WPF = Western Porrara Fault, VF = Mt. Vettore Fault.**

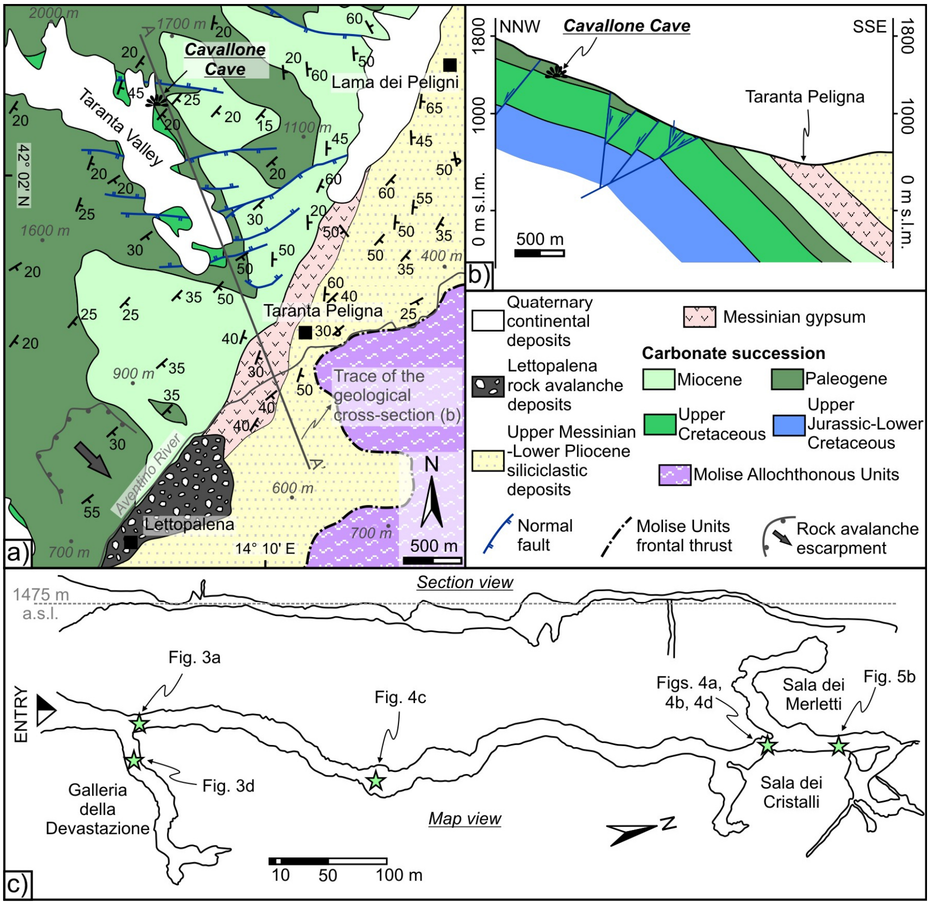


**Figure 2: Schematic geological map of the study area (a) (simplified from Accotto et al., 2014; see Fig. 1 for the location) and geological cross-section along the Taranta Valley (b) showing SE-dipping Meso-Cenozoic carbonate strata, passing to Mio-Pliocene gypsum and siliciclastic deposits, describing the forelimb of the Maiella anticline. The Cavallone Cave is located along the cliffs of the Taranta Valley, in the southeastern portion of the Maiella Massif; to the south, the Lettopalena village rises on top of rock avalanche deposits. c) Section and map views of the Cavallone Cave showing the articulate morphology of the cave ground.**

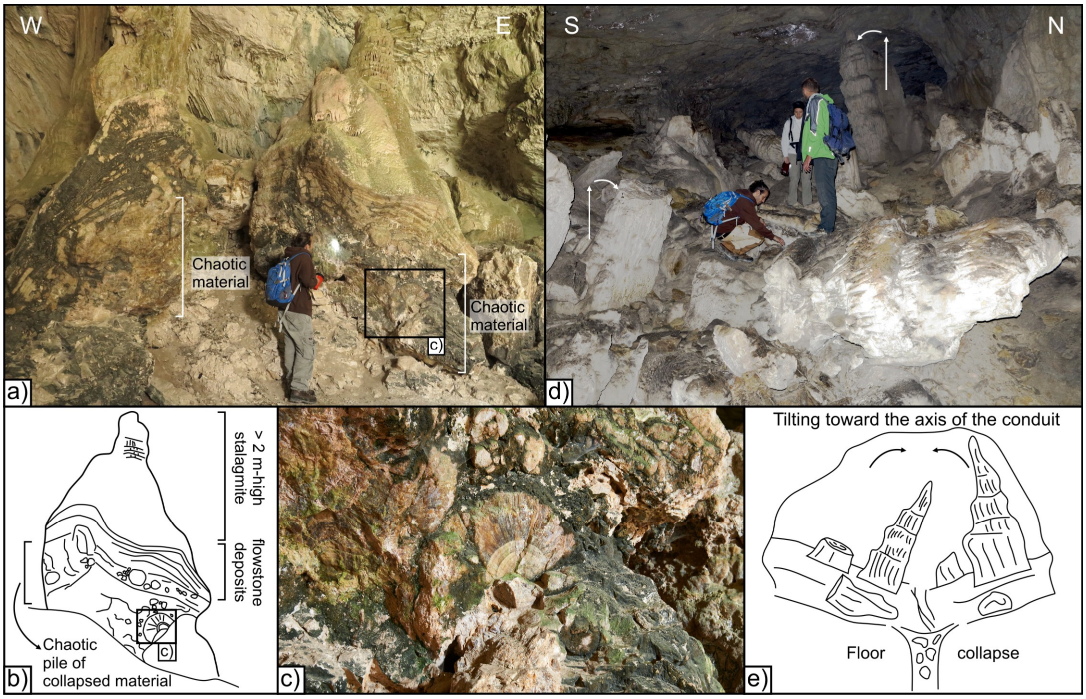


**Figure 3: a) Superposed multiple phases of large collapses and concretions near the entrance of the cave. Meter-scale large stalagmites grew on top of thick piles of chaotic materials, draped by flowstone deposits (sketch of Fig. 3b), within which big portions of tens of centimeters-large concretions are involved (close-up of Fig. 3c). d) Great collapses involving meter-scale large stalagmites in the Galleria della Devastazione". Stalagmites still standing upright show a clear tilting toward the axis of the conduit, probably as a consequence of floor sinking (Fig. 3e). See Figure 2c for sites location.**

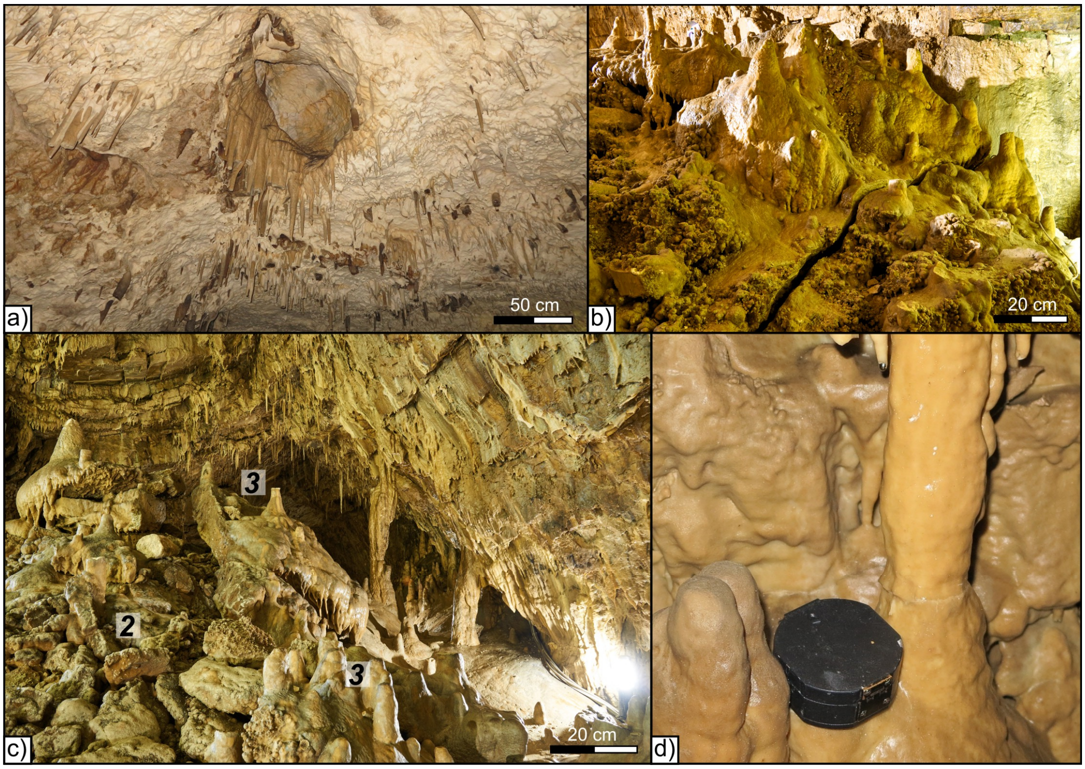


**Figure 4: a) Typical setting of the cave ceilings where originally "long" stalactites (probably more than 1 meter) are all truncated at the same point. Only short stalactites (tens of centimeters-long) are entirely preserved. b) Centimetric-wide sub-vertical open fractures frequently affecting flowstones, running at the base of the cave walls. c) Centimetric to decimetric-high stalagmites growing on top of collapsed materials: 1- ceiling rejuvenated by collapses; 2- blocks from the collapsed ceiling; 3- stalagmites growth after the ceiling collapse. d) Speleothem cuts along a sub-horizontal plane, with the upper part only translated from their original position but still standing upright. See Figure 2c for sites location.**

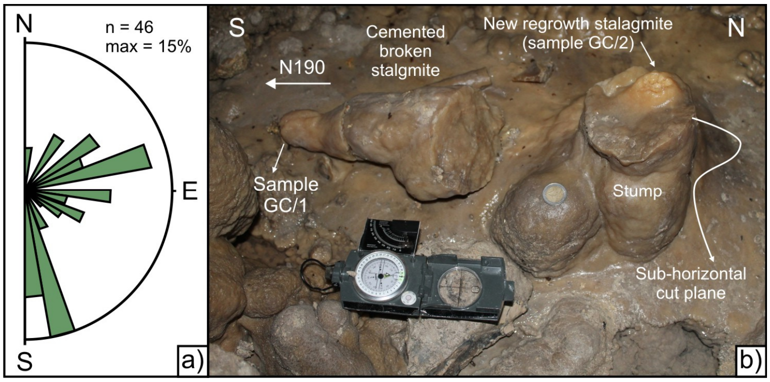
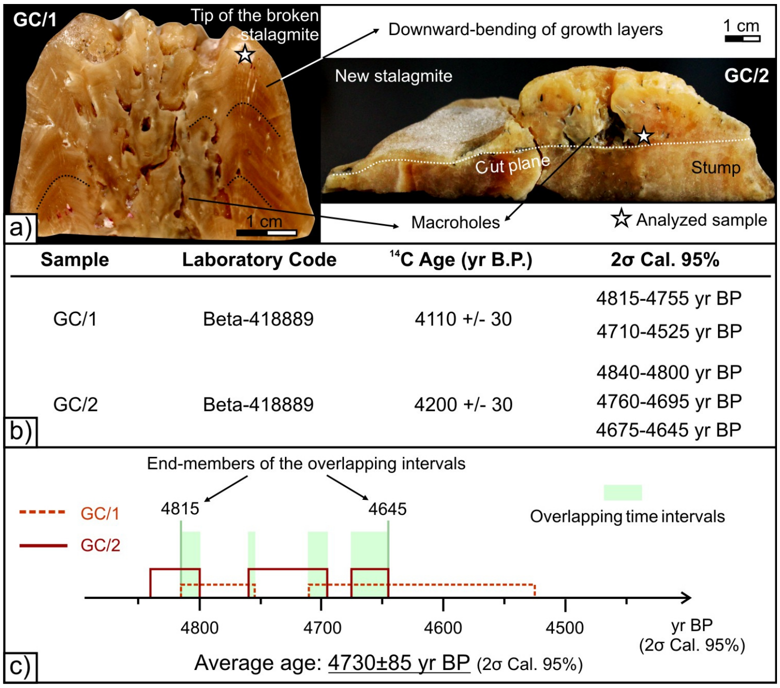


**Figure 5: a) Rose diagram of the measured orientations of fallen stalagmites cemented on the floor. Two main trends can be recognized: ENE-WSW and NNW-SSE, respectively orthogonal and parallel to the main active normal faults of the area. b) Seismothem-like feature chosen for radiocarbon dating: stalagmite (originally ~40 cm-high) broken along a sub-horizontal plane, fell toward N190 and resting cemented on the floor (see Fig. 2c for the location). On the stump surface a ca. 2 cm-high new stalagmite is growing.**



| Sample | Laboratory Code | $^{14}$C Age (yr B.P.) | 2σ Cal. 95% |
|---|---|---|---|
| GC/1 | Beta-418889 | 4110 +/- 30 | 4815-4755 yr BP<br>4710-4525 yr BP |
| GC/2 | Beta-418889 | 4200 +/- 30 | 4840-4800 yr BP<br>4760-4695 yr BP<br>4675-4645 yr BP |

Average age: 4730±85 yr BP (2σ Cal. 95%)

**Figure 6: a) Images of the analyzed samples "GC/1" (tip of the broken stalagmite, likely pre-seismic) and "GC/2" (new stalagmite growing on the stump, likely post-seismic), see samples location in Fig. 5b. The axial section of the two samples shows a characteristic internal porous structure due to the presence of widespread syn-genetic "macroholes" (Shtober-Zisu et al., 2012) which are also responsible for the downward-bending of the growth layers (marked with dotted lines in "a"). White stars indicate the points where the material has been collected for radiocarbon dating. b) 2σ calibrated ages with 95% of probability found for the two samples through AMS analysis. c) Overlapping time intervals that allow restricting the paleoearthquake dating to 4730±85 yr BP.**

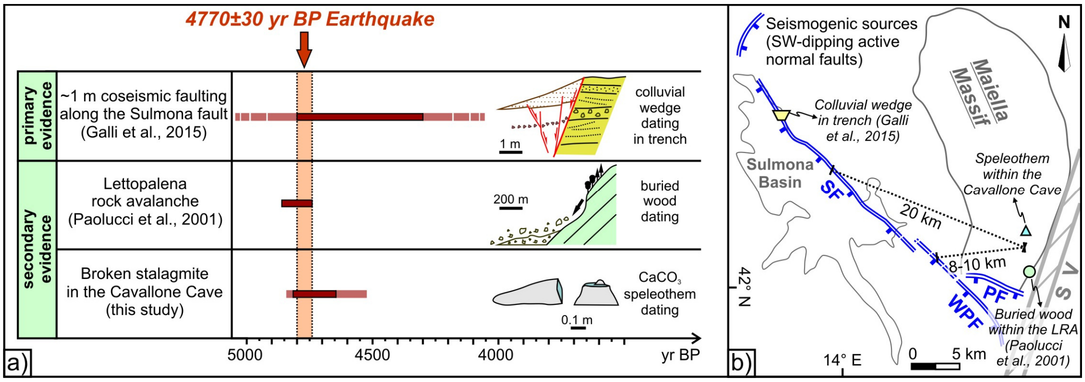


**Figure 7: a) Comparison between the ages resulting from radiocarbon dating of different paleoseismic records studied in the Maiella surroundings. The wood found within the Lettopalena rock avalanche provides a restricted interval age of 4800±60 yr BP. The faulted colluvial wedge deposits along the Sulmona fault reveal an event around 4500 yr BP (dark bar indicates a more plausible age resulting from mediating data; Galli et al., 2015). Dating performed in this study in the Cavallone Cave (light bar) on the broken stalagmite and the new re-growing one, overlap in the range included between 4815 and 4645 yr BP (dark bar). All these available dating match around 4770±30 yr BP constraining the age of a Mid-Holocene paleoearthquake likely associated to the Sulmona seismogenic source. b) Planimetric distance between the Cavallone Cave and Lettopalena Rock Avalanche (LRA) area and the center of the Sulmona Fault (SF) trace (20 km) or the overlap zone between the Sulmona Fault and the Western Porrara Fault (WPF) traces (8-10 km). The localization of major coseismic damages in the southern sector of the Maiella Massif possibly suggests an epicentral area shifted toward the overlap zone between the SF and the WPF. See the text for further explanation. (PF = Palena Fault; SV = Sangro-Volturno persistent structural barrier).**