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SEISMOTECTONIC AND PALEOSEISMIC STUDIES FROM SPELEOTHEMS: THE STATE OF THE ART

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(12 figures)

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ABSTRACT. The idea that speleothems may record earthquakes is rather old, but it was only after 1950 that systematic studies started on this topic. Presently it's well accepted that karst speleothems (especially stalagmites) can be used as a tool for tectonic and seismic analysis. In the present paper an overview on the state of the art in the seismotectonic and paleoseismic analyses using naturally broken speleothems and/or still growing stalagmites is presented. Specifically they may be important with respect to:
1- location and epicentre of past earthquakes;
2- their relative and absolute dating (within the last 500,000 yr. or so);
3- magnitude of these earthquakes;
4- improvement in the seismic hazard evaluation.

KEYWORDS: speleothems, earthquake, seismic hazard, seismotectonics, paleoseismicity

RESUME. *Etudes sismo-tectoniques et paléosismiques dérivées des concrétions. Etat des connaissances.* L'idée que les concrétions peuvent enregistrer les séismes est plutôt ancienne mais c'est seulement après 1950 qu'ont commencé des études systématiques sur ce sujet. Actuellement on croit que les concrétions karstiques, spécialement les stalagmites, peuvent être utilisées comme des moyens d'analyse des phénomènes sismo-tectoniques.
Ce travail constitue une mise au point des études sismo-tectoniques et paléosismiques qui utilisent des concrétions cassés par des événements naturels et/ou des stalagmites toujours en développement.
Spécifiquement, ces études peuvent être importantes en ce qui concerne la détermination:
1- de la localisation et de l'épicentre des séismes du passé ;
2- de leur datation relative et absolue pendant les derniers 500.000 ans ;
3- de la magnitude de ces séismes ;
4- de l'amélioration de l'évaluation des risques sismiques.

MOT-CLES :
concrétions, séisme, risques sismiques, sismo-tectonique, paléosismicité.

1. Introduction

In the last few decades the importance of cave deposits in geological studies grew enormously in importance and now it's generally accepted that speleothems are amongst the powerful tools to reconstruct the environments of the past 500.000-750.000 yr.

Perhaps one of the most interesting field in which speleothems have been utilised is seismotectonic and paleoseismic research (Forti, 1997).

The idea that speleothems may record earthquakes is rather old: the first paper to deal with relationships between these deposits and earthquakes was that of Becker (1929) in Bing Cave, Germany, and Han-sur-Lesse cave, Belgium. After this, several other authors printed works on the topic. But it was only after 1950 that systematic studies were carried out on broken stalagmites in Postojna Cave, Slovenia, and a few other caves in central Europe (Gospodarich, 1968).

Nevertheless until the 80's geophysicists did not seriously consider the method because it has not been possible to theoretically discriminate between fracturing of speleothems due to earthquake-induced effects and those caused by other mechanisms.

But improvement in sampling, analysis, and statistical techniques (Forti and Postpischl 1980a,b), as well as in theoretical modelling (via computer simulations) (Forti *et al.* 1981), now allows for the evaluation of paleo-earthquakes in karst areas of high seismic activity, using not only broken speleothems but also still active stalagmites.

Presently it's well accepted that karst speleothems (especially stalagmites) can be used as a tool for tectonic and seismic analyses: these analyses permitted the formulation of new hypotheses regarding the activity induced in the superficial faults by deep tectonic systems, as well as the evaluation of main paleoseismic events.

Specifically they may be important with respect to:

1- Location and epicentre of past earthquakes.

2- Their relative and absolute dating (within the last 500,000 yr. or so).

3- Magnitude of these earthquakes.

4- improvement in the seismic hazard evaluation.

In the present paper an overview on the state of the art in the seismotectonic and paleoseismic analyses using naturally broken speleothems and/or still growing stalagmites is presented.

2. Naturally broken speleothems

Caves in seismic areas may contain broken and collapsed speleothems of all types, but most frequently these are stalactites and stalagmites (see Fig. 1). For example, in Gaislochhöhle, Germany, collapsed dripstone represents over 70% of all speleothems in the cave (Moser & Geyer, 1979). However, before it can be stated that broken speleothems are really related to earthquakes, all other possible breakdown factors must be discounted: the more common natural factors causing local breakdown being:

- Weight increase of stalactites growing from porous or highly fractured ceilings
- Sliding of stalagmites, columns and flowstones growing over soft (clay, mud) or unconsolidated (sand, gravels) walls and floors.

Figure 1. Stalagmite breakdown in the Grotta dei Cervi cave, Italy, which has been proved to be caused by seismic shock: the white small stalagmite over the broken one started growing just after the 1456 earthquake.

Figure 1. Rupture de stalagmites dans la "Grotta del Cervo" - Italie: on a démontré que cette rupture a été causée par un choc sismique. La petite stalagmite blanche sur la stalagmite cassée a commencé à se developper après le séisme de 1456.

Beside these factors another natural one has proved to be one of the most important (at least in Central Europe): the presence of ice during the last glaciation. The slow movement of an ice tongue inside the cave has been proved to be responsible for widespread breakdown in caves, even of very large stalagmites and columns (S. Kempe, personal comm.).

Apart the just outlined local natural factors, speleothem, breakdowns are often caused by human activities in caves: this kind of breakage is really widespread and sometimes difficult to be distinguished from those induced by natural mechanisms, including seismic shock.

It is absolutely necessary to make a detailed morphological and lithological analysis of the cave in order to determine if breakage of speleothems is due to earthquakes, or to random events caused by local (natural or anthropic) factors. These analyses allow discounting all those breakdowns, which may have been induced by non-seismic events. Another way to discriminate between seismic and non-seismic collapses of speleothems is to make a statistical analysis on the age of the breakage (Postpischl *et al.*, 1991; Agostini *et al.*, 1994). Earthquake induced breakdowns must be grouped nearly at the same time, while the locally induced ones normally occurs randomly scattered.

Sometimes morphology of the breakage may help to detect those directly induced by earthquakes. In fact several typical breakdowns can be referred only to tectonic stresses (Agostini *et al.*, 1994) (Fig. 2), the more characteristic of which being the perfect cut of stalagmites along sub-horizontal planes close to their connection to the cave floor. Some of these stalagmites have the upper part lying on the floor close to their bases while others have their upper parts only translated, or slightly rotated, from their original position (Gospodaric, 1968, 1977; Moser & Geyer 1979). This peculiar kind of breakage was explained by invoking high-frequency vibration earthquake waves. These waves induced resonance breakage along fiat, horizontal, weakness planes coincident with the c-axes of calcite crystals in the stalagmites (Fig.3). Another evidence of earthquake induced phenomena is the presence of consistent breakage of speleothems in certain directions. The preferential azimuths of the collapsed stalagmites are normally found to be coincident with the main structural directions in the cave area, thus demonstrating the tectonic character of the event(s) that generated the collapse. Anyway, the use of this kind of analysis to detect earthquake-induced collapses is in practice seriously hindered because it is rather impossible to be sure that broken speleothems maintained their original

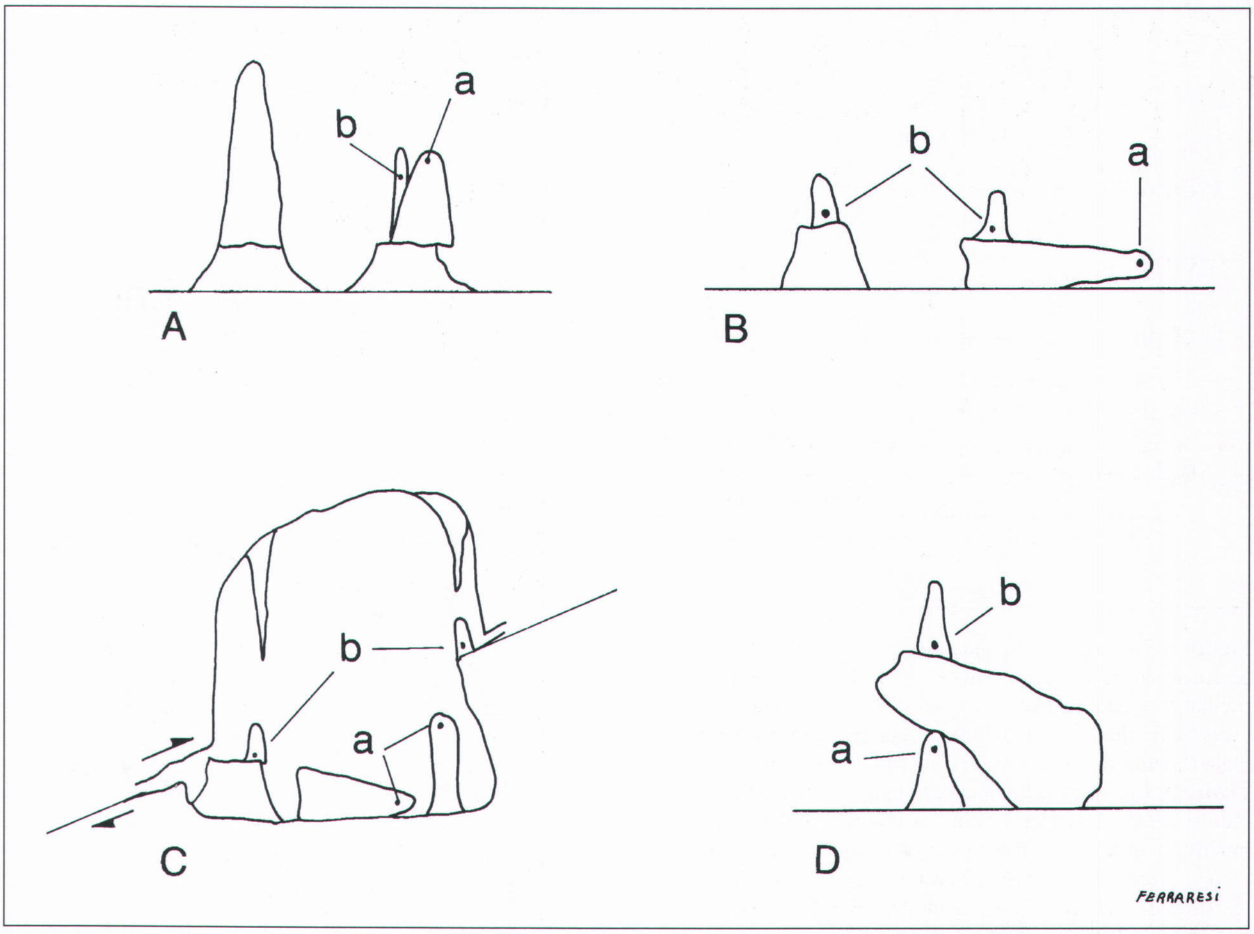


Figure 2. Characteristic breakages of speleothems induced by seismic stress. Resonance induced stalagmite cut along a sub-horizontal plane: (A) the upper part is still standing over its base, being only slightly translated and/or rotated from its original position. (B) the broken upper part lies on the floor close to its base. (C) Stalagmite collapse caused by the displacement of the adjacent wall. (D) New stalagmite growing over a fallen rock, which covered an older stalagmite. Positions (a) and (b) indicate characteristic sampling points for absolute (U/Th and/or 14C dating of deposits which occurred just before (a) or after (b) the seismic event.

Figure 2. Ruptures caractéristiques de concrétions induites par un stress sismique. Rupture causée par résonance le long d'un plan sub-horizontal: (A) la partie supérieure cassée se trouve encore sur sa base en étant seulement deplacée et/ou tournée par rapport à sa position originelle; (B) la partie supérieure rompue est tombée au sol près de sa base; (C) chute de stalagmite causée par le déplacement de la paroi adjacente. (D) Nouvelle stalagmite se developpant sur un rocher qui couvre une stalagmite plus ancienne. Les positions (a) et (b) indiquent des points caractéristiques d'échantillonnage pour une datation absolue (U/Th et/ou ^{14}C) de dépôts formés tout juste avant (a) ou après (b) l'événement sismique.

direction in time if they were not cemented. In fact the human frequentation of caves easily causes displacements of the unconsolidated material over the cave floor. In order to be sure that the whole speleothem breakdowns are unperturbed it should be necessary to take into consideration only caves never visited by man. This was the case of the Grotta del Cervo cave in Central Italy (Fig. 4), the entrance of which was sealed by a landslide as a consequence of the strongest historical earthquake of Italy in 1456. The cave was reopened only in 1986 just to perform scientific research inside (Agostini *et al.*, 1994).

Finally, some of the seismically induced breakage may also provide data to evaluate the earthquake accelerations, thus allowing, at least theoretically, to define the epicentre and magnitude of the event by the use of broken formations from different caves in the same area. Only the stalagmites broken along flat subhorizontal planes are suitable for such a study.

The method to determine the epicentre and the magnitude of a seismic event from stalagmites is similar to that used by geophysicists in studying the effect of earthquakes on tombstones (Moser and Geyer, 1979; Postpischl *et al.* 1991). The stalagmite is considered as a homogeneous cylinder perfectly connected to the floor. Its collapse is therefore caused by resonance-induced earthquake waves and the ratio of the diameter versus height of the collapsed stalagmite is related to the horizontal acceleration of the waves (which, in turn, is related to distance from the epicentre and magnitude). Thus the measure of the geometric parameters (diameter and

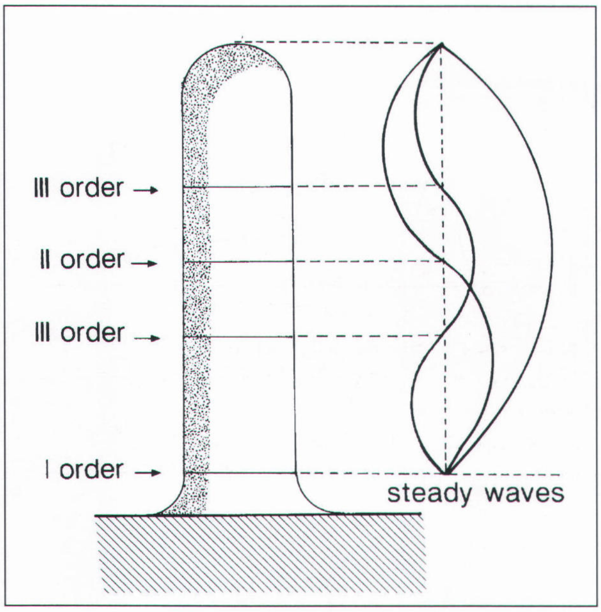


Figure 3. The horizontal planes along which a stalagmite may be fractured by a seismic shock are defined by the possible oscillation modes for that speleothem. The first oscillation mode (a) is by far the most probable one, but even those induced by higher modes (b, c) have been sometimes observed in caves.

Figure 3. Les plans horizontaux le long desquels une stalagmite peut être cassée par un choc sismique sont définis par les modes possibles d'oscillation de cette concrétion. Le premier mode d'oscillation (a) est de beaucoup le plus probable, mais les fractures induites par les modes plus hauts (b, c) ont quelquefois été observées dans les grottes.

height) of the broken stalagmite allows to evaluate the modes of possible oscillation, while the mechanical tests give at least a rough idea of the accelerations the stalagmite underwent.

Although simple from a theoretical point of view, the actual execution of such a study is very complex and impractical because:

1 - Real stalagmites are far different from perfect homogeneous cylinders ideally connected to a rock floor.

2 - A large number of stalagmites must be sampled in order to obtain reliable results.

3. Still growing stalagmites

In addition to the seismic data derived from broken speleothems, caves may supply seismotectonic information through still growing stalagmites. Schillat (1977) considered the stalactite-dripping-stalagmite system to be a "recording pendulum", in which the stalagmite with its successive growth layers acts as the recorder of the "actual verticality". A polished section along the growing axis of a stalagmite normally shows well-marked, symmetrical growth layers. Ideally, this axis records the vertical direction, which, if stable over time, would be a rectilinear segment. In reality, progressive and/or sudden variations in the growing axis can be found in many stalagmites, which variations are either associated to local facts, or may record tectonic events.

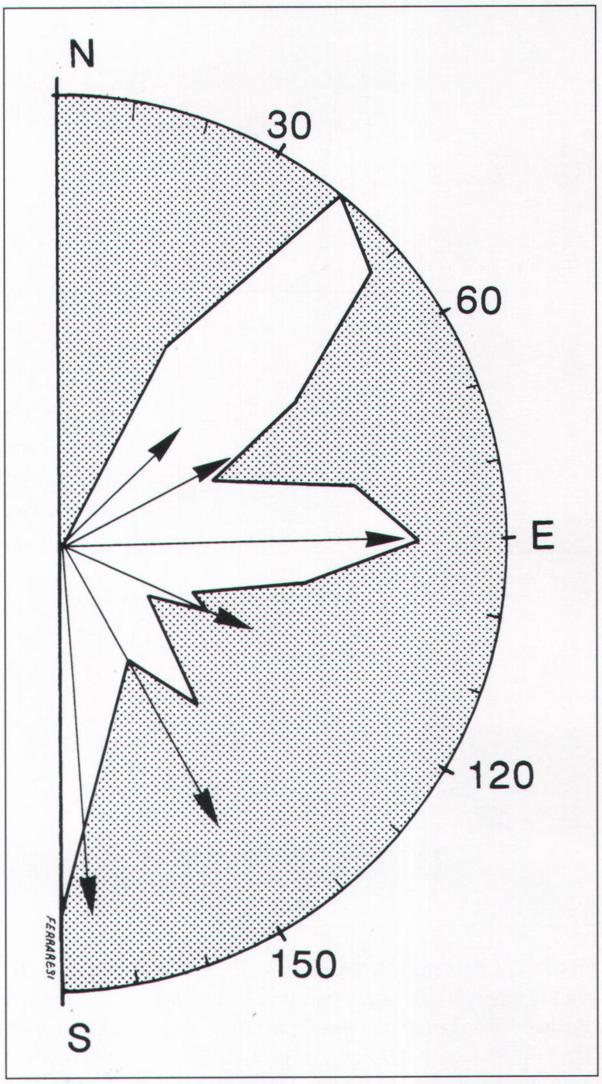


Figure 4. Diagram showing the azimuths of the 45 collapsed stalagmites (arrows) and those of the 745 main discontinuities in the stalagmite growing axis in the Grotta del Cervo cave, Italy. They are rather coincident and clearly grouped along directions corresponding to the main structural planes present in the cave area (after Agostini et al., 1991).

Figure 4. Diagramme des azimuts de 45 stalagmites tombées et des azimuts de 745 pincipales discontinuités des axes de croissance de stalagmites dans la grotte "del Cervo" (Italie). Ces azimuts coïncident assez bien et sont clairement regroupés le long des directions correspondants aux principaux plans structuraux présents dans l'aire de la grotte, (selon Agostini et. al., 1991).

Many local factors may perturb the stalagmite growing axis, such as:

- Permanent air currents, which deflects the dripping
- Migration of the dripping point along a fracture on the ceiling
- Gravity sliding of the stalagmite, growing on unstable material (mud, sand, gravel).

Figure 5. Grotta del Cervo cave: the azimuth of the principal dislocations in the growing axis of a stalagmite is measured by using a specific instrument (Fig. 6).

Figure 5. Grotta del Cervo: l'azimut des principales discontinuités de l'axe de développement d'une stalagmite est mesuré en utilisant un appareil particulier (Fig. 6).

In order to rule out local effects, it is necessary to perform a statistical analysis on a wide number of stalagmites (Forti & Postpischl, 1984). The systematic observation of a given vertical displacement in the growing axis is considered indicative of a tectonic movement, whereas factors of local perturbation would introduce random behaviour.

The statistical analyses of the main stalagmite anomalies led to the formulation of new hypotheses regarding the activity induced in superficial faults by deep tectonic systems, which were not observed with normal analytical methods (Forti & Postpischl, 1980a). This study has been carried out in several different karst systems of Italy (Forti & Postpischl, 1984): in each of them all the large axis dislocations in the speleothems have been measured inside the cave using a specific instrument (Figs. 5 and 6).

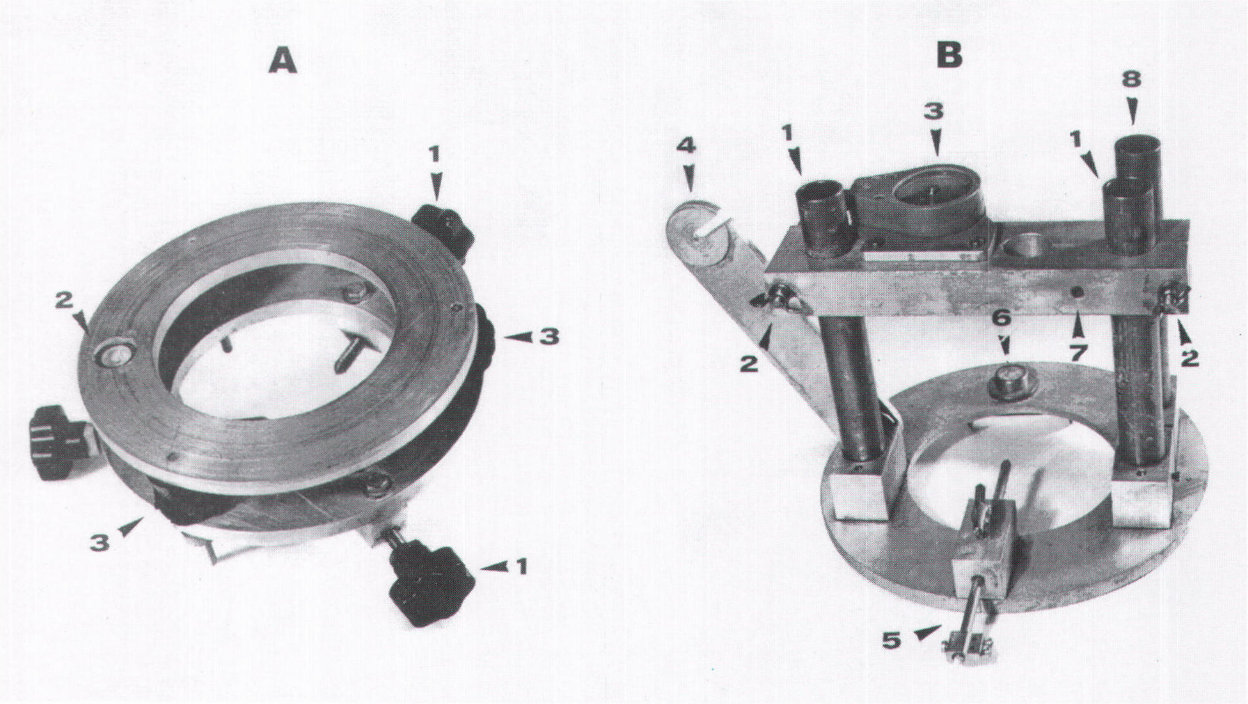


Figure 6. The instrument to define the spatial position of a stalagmite inside the cave. A- lower part: 1) screws to fix the instrument onto the stalagmite; 2) spirit level; 3) levelling screws. B-Upper part: 1) sliders, for the compass; 2) screws to fix the compass on the vertical slider; 3) compass; 4) arm to fix the vertical plane; 5) awl to trace the horizontal plane; 6) spirit level; 7) hole to trace the vertical plane; 8) slider to trace the vertical plane.

Fig. 6. Instrument pour définir la position spatiale d'une stalagmite à l'intérieur de la grotte.
A-Partie inférieure: 1) Vis pour fixer l'instrument sur la stalagmite; 2) Niveau à bulle; 3) Vis de nivellement. B-Partie supérieure: 1) Curseur pour la boussole; 2) Vis pour fixer la boussole sur le curseur vertical; 3) Boussole; 4) Bras pour fixer le plan vertical; 5) Pointeau pour tracer le plan horizontal; 6) Niveau à bulle; 7) Trou pour tracer le plan vertical; 8) Curseur pour tracer le plan vertical.

Figure 7. determining the spatial parameters of a stalagmite before cutting.

Figure 7. Détermination des paramètres spatiaux d'une stalagmite avant le découpage.

All the considered karst systems evidenced well defined directional preference for the displacements, which are the same for caves in the same area and correspond to all its principal tectonic lineaments. Any attempt to isolate the different directions chronologically has given negative results.

These results are an experimental proof that every time a deep displacement takes place it induces movements of the entire mosaic of the superficial blocks, which constitute the karst system. The possibility of such superficial movements will strictly be controlled by the geometry of the blocks, which in turn depends on the structural settlement of the area. In other words a major tectonic dislocation is always associated with movements of the whole small superficial blocks resulting by the intersection of all the pre-existing faults and fractures.

The statistical analyses of the major displacement in the stalagmite axis carried out inside the cave allow also choosing those stalagmites suitable to be further studied

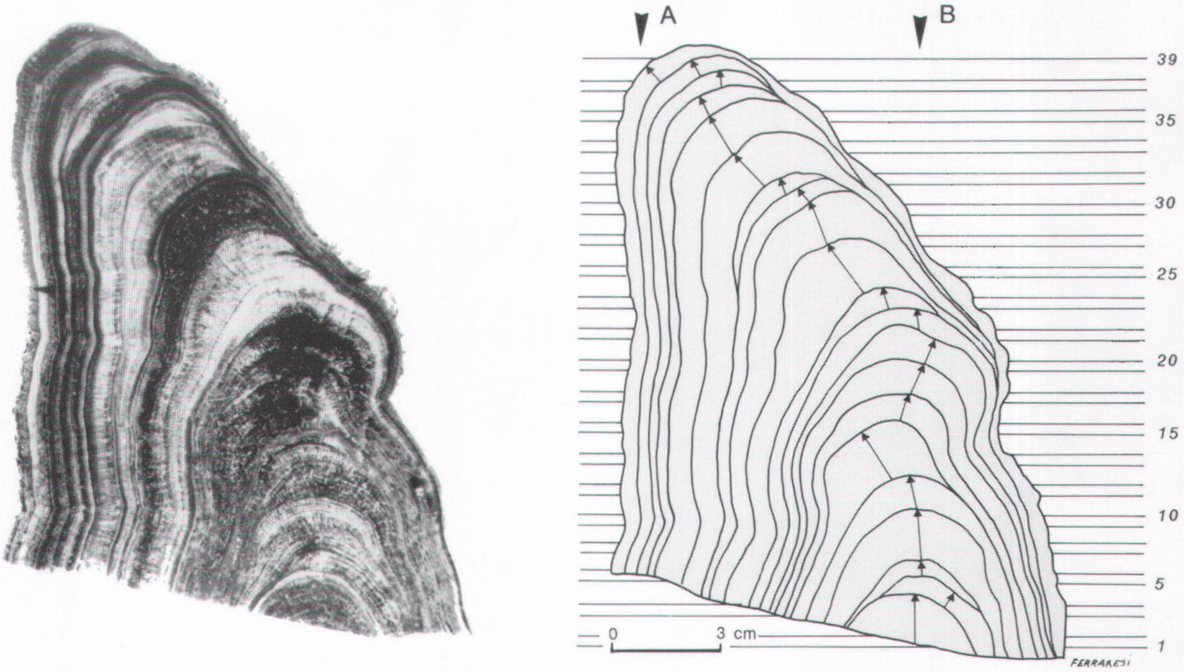


Figure 8. Photo of a polished vertical section of a stalagmite made along an axial plane defined inside the cave and its graphical restitution: A- final and B- starting position for the dripping impact on the stalagmite. The number on the right indicates the trace of all the horizontal sections utilised for the 3-dimensional reconstruction of the movements the stalagmite underwent.

Figure 8. Photo d'une section verticale de stalagmite le long d'un plan axial défini à l'intérieur de la grotte et sa restitution graphique. Position finale (A) et initiale (B) du point d'impact des gouttes sur la stalagmite. Le nombre sur la droite indique la trace de toutes les sections horizontales utilisées pour la reconstitution tridimensionnelle des mouvements subis par la stalagmite.

in order to define the movements of the related block quantitatively and chronologically. Before to cut the chosen speleothems it is necessary (Fig. 7) to define inside the cave:

- The geometric parameters of the pendulum made up of the stalactite-dripping-stalagmite to relate the recorded displacements inside the stalagmite to the movements of the block
- The orientation in the space of the stalagmite to define the azimuths and the change in the horizontality for all the displacements the stalagmite axis underwent
- The physico-chemical parameters of the dripping to evaluate the velocity of vertical growth of the stalagmite.

The analyses of the stalagmite growing axis is then made on a polished vertical section of the stalagmite chosen to contain its major discontinuities (Fig. 8). Anyway the study of the single vertical section is not enough allowing only a two dimensional analysis. In order to obtain the three dimensional quantitative reconstruction of tectonic movements experienced by the block hosting the stalagmite, the information obtained from as much as possible horizontal sections is needed too (Forti & Postpischl 1984).

Proper computer calculations then permit a univocal tracing of the deviations of the stalagmite axis in their sequential order, which may easily be transformed in chronological by means of absolute dating.

Not every tectonic movement is recorded by the stalagmite (Fig. 9A): in fact those occurring along the vertical, unchanging the dripping impact on top of the stalagmite, cannot be recorded in the growing axis.

Sub-horizontal displacements and swinging may produce an identical variation on the stalagmite axis, nevertheless it is possible to distinguish them because the shape of the resulting growing layer is different (see Fig. 9 B-C).

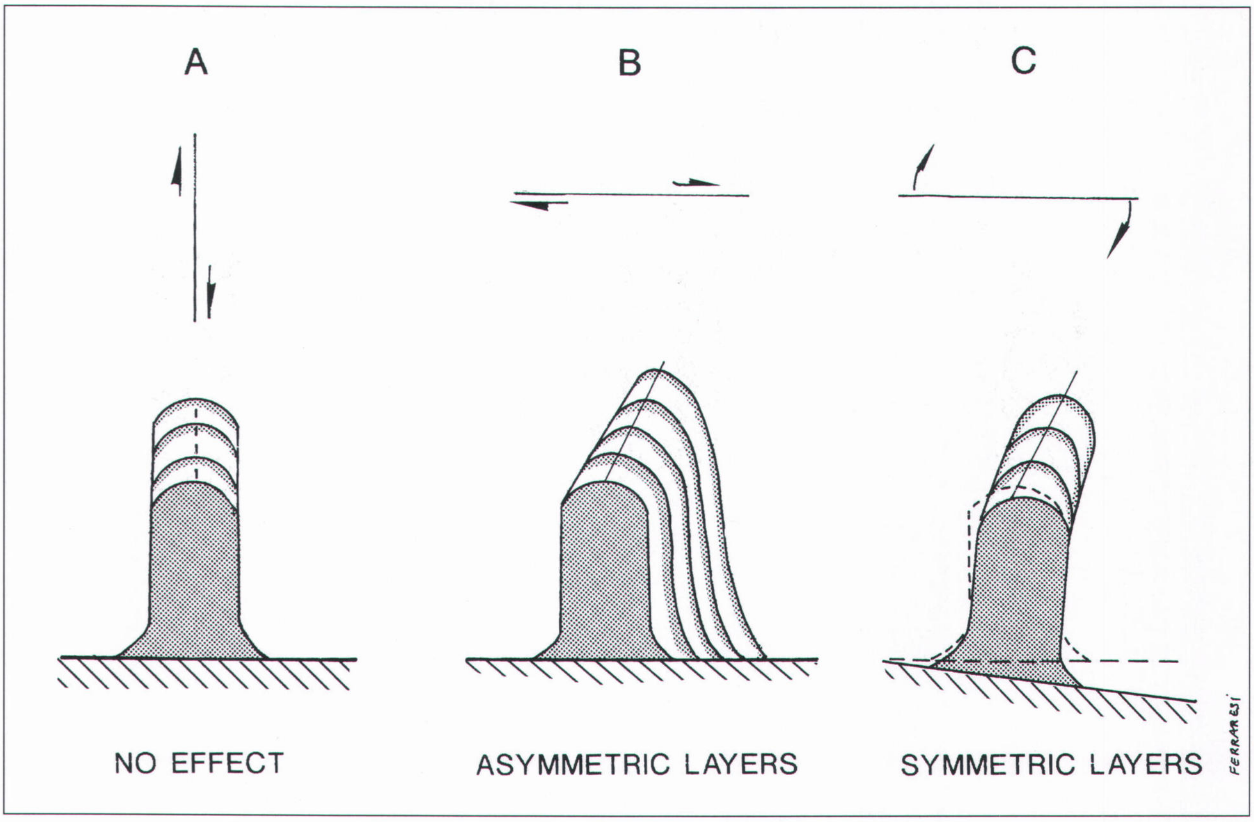
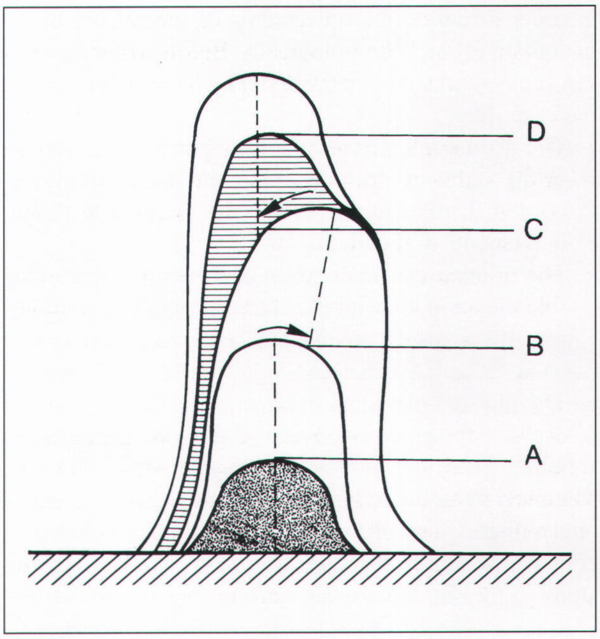


Figure 9. Different tectonic movements and their effect on stalagmites. A- vertical displacement: no effect because the dripping impact on the stalagmite remain the same; B- horizontal displacement: migration of the dripping point on the ceiling with consequent progressive displacement of the splash point on the stalagmite. This movement leads to the evolution of asymmetric growing layers in the direction of the displacements; C- swing: change of the actual verticality with no change in the dripping point. The effect is the displacement of the stalagmite axis with the evolution of symmetric growing layers.

Figure 9. Différents mouvements tectoniques et leurs effets sur les stalagmites . A- Déplacement vertical: aucun effet parce que le point d'impact de la goutte reste le même; B- Déplacement horizontal: migration du point d'écoulement sur la vo°te avec un déplacement progressif du point d'impact sur la stalagmite. Ce mouvement détermine l'évolution de couches qui grandissent asymétriquement dans la direction des déplacements. C- Oscillation: changement de la verticalité effective sans aucun changement dans le point d'ecoulement. L'effet est le déplacement de l'axe de la stalagmite avec une évolution des couches à croissance symétrique.

Figure 10. Evidences of earthquakes in the inner structure of a stalagmite: sudden and sharp vertical changes in the stalagmite axis (B & C) and abrupt variations in the texture, colour and chemical composition of the growing layers (A, C, D) may be induced by seismic shocks.

Figure 10. Témoignages de séismes dans la structure intérieure d'une stalagmite: les soudains et brusques changements dans l'axe de croissance de la stalagmite (B & C) et les soudaines variations de la texture, la couleur et composition chimique des couches d'accroissement (A, C, D) peuvent être induits par des chocs sismiques.



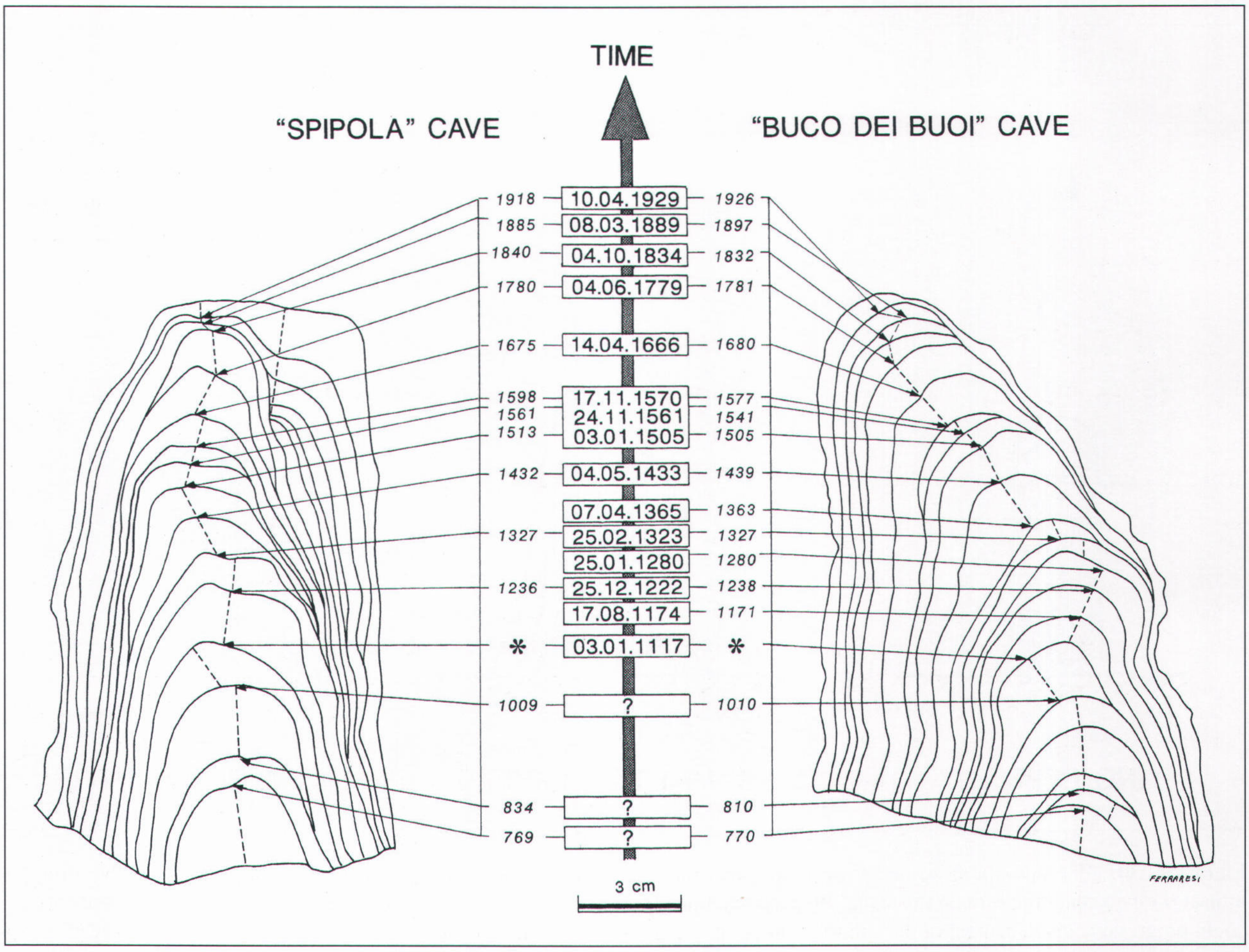


Figure 11. Sections of two stalagmites taken from two caves in the Gessi Bolognesi karst area (Italy). The main discontinuities in the growing axis and/or in texture and colour of the growing layers have been dated and correlated with those of the historical earthquakes which hit the area with an intensity I° _ VI. The fitting was 98% with an average error lower than 11 yr.

Figure 11. Section de deux stalagmites de deux grottes de la zone karstique des Gessi Bolognesi (Italie). Les principales irrégularités dans l'axe de croissance et/ou dans la texture et la couleur des couches d'accroissement ont été datées et mises en corrélation avec les séismes historiques qui ont frappé la zone avec une intensité _ VI. La correlation est de 98 % avec un écart moyen inférieur à 11 ans.

The stalagmite of fig.8 has undergone both these movements in different time periods. In fact, the deviations of its axis up to the 21st level are mainly induced by swing, as the growing layers are sufficiently symmetric with respect to the axis. Above the 21st level a translational movement started, which led to the migration of the splash point from 1 to 2 and correspondingly the growing layers become asymmetric in the same direction.

A computer analysis (Forti and Postpischl 1980b) of the relative shapes of the layers allow to quantitatively determine what kind of movements the stalagmite has undergone; thus the movements of the supporting block are univocally defined.

The just outlined data on superficial blocks movements induced by active fault are not the single information, which can be obtained by the analysis of the stalagmites: in fact, these speleothems may also provide records of the major earthquakes which hit the cave area.

In many cases the study of the vertical polished section of a stalagmite has shown some clear discontinuities in the growth axis (Fig. 10). Such discontinuities indicate moments of abrupt vertical variation and therefore reveal the occurrence of a seismic phenomenon if local factors can be excluded.

Another parameter, which has to be taken into account to define the seismic history of a karst area, is the colour and/or texture of the stalagmite layers (Fig. 10). In fact it has been evidenced that a seismic event may lead not only to abrupt deviation of the stalagmite axis but also to sharp variations in the colour and/or texture of the growth layers (Forti and Postpischl, 1986). The variation in colour and texture being a consequence of the change of water supply and/or of the chemistry of the seeping water induced by the seismic shock.

By using both the deviations in the growth axis and the sharp variation in colour and texture of calcite stalagmites in two different gypsum caves of Bologna (Italy), Postpischl *et al.* (1991) reconstructed the seismic history of the Bologna region (Italy) over the last 1200 yr. The starting hypothesis was that the strongest historical event must correspond to the greatest discontinuity inside the stalagmites. The statistical fit between seismic activity with an intensity larger than VI and speleothem evidence for that activity was determined to be 98%, with an average error in the date of each earthquake over the 1200 yr. period being lower than 11 yr. (Fig. 11).

Therefore the study, besides confirming its validity, extended also the seismic records for area of Bologna 400 yr. back with respect to the historical earthquake catalogue with the detection of three new seismic event with an intensity I° _ VI.

4. Seismic hazard

The evaluation of the seismic hazard for a given area is normally based on its seismic history, which rarely extends over the past two thousands years. Clearly this span of time is too short to ensure that the strongest possible earthquake hit the region under examination, and therefore the achieved result on the seismic risk may result greatly underestimated.

By using the just outlined seismic analyses over broken speleothems and/or still growing stalagmites it is possible to recognise and date strong paleo-earthquakes up to the limit of the radiometric dating of cave formations, which presently is 500.000 yr. BP or even more (Gospodarich 1977; Postpishl *et al.* 1991).

The hypothesis that in such a period a given seismogenetic structure has experienced the maximum earthquake possible is reasonable.

Up to present only a cave has been studied from the seismotectonic and paleoseismic point of view by using all the just outlined analysis on broken speleothems and still growing stalagmites: the Grotta del Cervo in Central Italy (Agostini *et al.* 1994). This cavity is located not far from the epicentre of the strongest historical earthquake of Italy, which occurred in December 1456.

The study reconstructed the seismic history of the cave up to >350.000 yr. BP (Fig. 12), showing that during that period 4 macro-seismic events led to breakdown of speleothems, to sudden deflection of stalagmite axes and to sharp variation of the texture and composition of growing layers of speleothems.

Analyses of the broken stalagmites allowed to reconstruct, though only approximately, the relative strength of the 4 earthquakes, proving that the single historical event was far weaker than those occurred about 100.000 yr. and >350.000 yr. BP (Fig. 12).

The Grotta del Cervo case study confirms the importance of extending the seismic history of a given area far beyond the historical time in order to make a correct evaluation of the seismic hazard. Therefore, in the near future, the seismic data from speleothems should become a fundamental tool for the studies oriented to the definition of the seismic hazard for a given area.

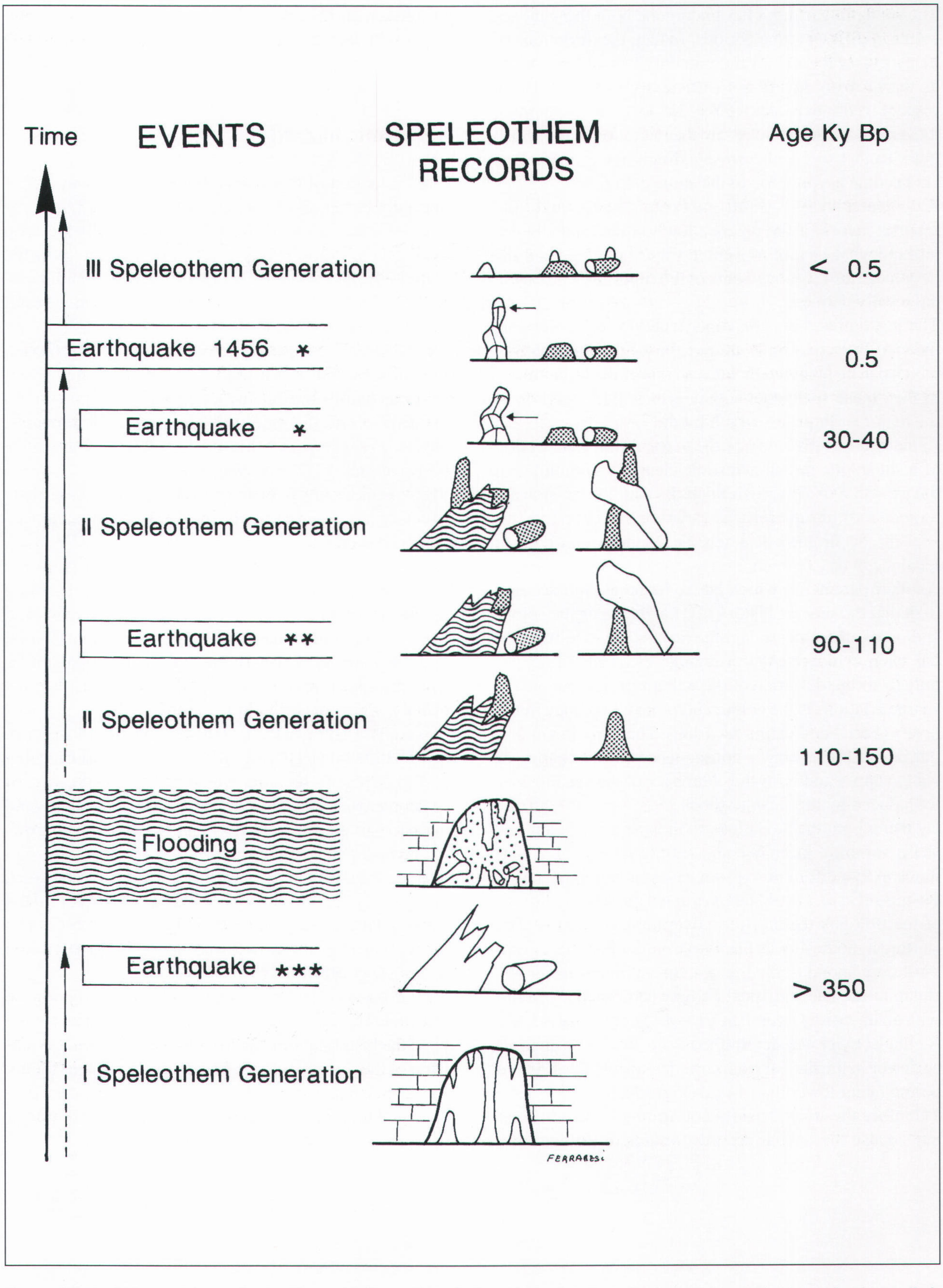


Figure 12. Evolutionary history for the Grotta del Cervo Cave, Italy with the 4 major seismic events recorded by speleothems, their radiometric dating and relative intensities (*).

Figure 12. Histoire évolutive de la "Grotta del Cervi" (Italie) avec les quatre principaux évènements sismiques enregistrés par des concrétions, leur datation radiométrique et les intensités relatives (*).

5. Final remarks

The seismotectonic and paleoseismic research performed inside the cave during the last two decades proved that broken speleothems and still growing stalagmites may result amongst the most powerful tools for the quantitative and chronological reconstruction of seismotectonic events over the past half million years or more. In fact they may supply data which should be impossible to obtain by means of the traditional seismotectonic analyses: in particular they improve our knowledge on intensity and epicentre of the stronger prehistoric earthquakes thus allowing for a better definition of the seismic hazard.
Anyway there are still some hard problems to be solved in order to transform the just outlined method of investigation into a widespread and standardised analytical protocol.
In the near future the scientific research must improve those aspects of this method that still hinder its easy and widespread application , the most of them important being:

- Detection of the effects of locally induced (non seismotectonic) events by improving morphological and statistical analyses in order to be sure to rule out all the whole of them
- Chronology of the seismotectonic events by improving: 1- the comparisons of the results obtained in cave with the available data from the earthquake catalogue; 2- the method of dating of speleothem samples to obtain more reliable data over a longer span of time
- Definition of the intensity of the event by improving the mechanical tests on broken stalagmites and the theoretical approach to the model

Moreover it would be important to test the method in as many as possible karst areas of the world interested by strong seismic activity.

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