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Tectonics

Review on the use of natural cave speleothems as palaeoseismic or neotectonics indicators

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Abstract

Collapses that affect cave speleothems have frequently been attributed to earthquakes, although this has not been proved. Observations after an earthquake and laboratory tests indicate that only slender speleothems break under coseismic solicitation. Other causes as subsidence, decompression and creeping of ice or cave sediments explain most of the breaks. Tectonics is also a major cause of speleothems breakages and it is possible to detect minute movements of faults. It seems possible to make the difference between brutal coseismic movements and aseismic slow ones. However, the interpretation is often difficult, as the damage can also be caused by gravity tectonics or glacitectonics. ***To cite this article: É. Gilli, C. R. Geoscience 337 (2005).***

Résumé

Point sur l'utilisation des spéléothèmes comme indicateurs de paléosismicité ou de néotectonique. Les chutes de concrétions des grottes ont souvent été attribuées à des tremblements de terre, sans qu'aucune preuve ne soit apportée. Les observations effectuées consécutivement aux séismes et les essais en laboratoire montrent que les dégâts cosismiques se résument au bris de très fines concrétions. D'autres causes, comme la subsidence, la décompression, le fluage de glace ou de sédiments, expliquent la majorité des ruptures observées. La tectonique active est aussi une cause importante de rupture de concrétions, et même de très faibles mouvements de failles peuvent être mis en évidence. Il semble parfois possible de différencier des mouvements rapides, qui pourraient être cosismiques, de mouvements lents asismiques. Cependant, leur interprétation est souvent difficile, car ces phénomènes peuvent aussi être gravitaires ou glaciotectoniques. ***Pour citer cet article : É. Gilli, C. R. Geoscience 337 (2005).***

Keywords: Gravity; Ice; Karst; Seism; Speleothem; Tectonics

Mots-clés : Gravité ; Glace ; Karst ; Séisme ; Spéléothème ; Tectonique

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1. Introduction

Les sédiments endokarstiques, protégés de l'érosion, sont de remarquables enregistreurs de paléoenvironnements. Les spéléothèmes brisés ou déplacés sont fréquents dans les grottes et l'origine de ces dégâts a très souvent été attribuée à des séismes. De nombreuses études sur ce thème laissent entrevoir d'intéressantes perspectives dans l'utilisation des grottes comme enregistreurs naturels de paléoséismes [1,2,6,20,22,23]. Cependant, l'analyse de la bibliographie récente relative aux cavités naturelles, des enquêtes et des observations de terrain montrent que cette méthode doit être abordée avec prudence.

2. Causes principales de rupture des concrétions

Avant d'attribuer une origine cosismique à des dégâts souterrains, il faut pouvoir éliminer les autres causes de rupture, qui peuvent relever de nombreux mécanismes : vandalisme, subsidence, décompression, mouvements de sédiments. Une cause majeure est l'intrusion de glace dans les réseaux (Fig. 1). Ce phénomène a été observé au niveau du glacier souterrain de Snezna jama (Slovénie) [13] et peut vraisemblablement être évoqué pour expliquer des ruptures décrites en Suisse [19] (Fig. 2) et en Belgique [5]. De nouvelles observations dans certaines des cavités étudiées précédemment ont permis de confirmer que les dommages les plus importants résultaient de ce dernier mécanisme et n'étaient donc pas cosismiques [13,15,16,20] (Fig. 1).

3. Dégâts provoqués par des mouvements de faille

Les dégâts souterrains peuvent résulter de mouvements récents de failles, liés à une tectonique active. Des exemples spectaculaires ont été décrits en Italie [3]. L'étude de différentes cavités dans le Sud-Est de la France a permis l'observation de mouvements tectoniques caractéristiques. Dans la grotte des Deux-Gourdes, un mouvement de faille a brisé des concrétions à différentes périodes (Fig. 3) [9]. Dans les gouffres du Calernaum et de l'Aven Abel, le mouvement des plans de chevauchement a brisé de nombreuses concrétions [10,12] et provoqué la naissance de fistuleuses courbes (Fig. 4).

Dans la grotte des Deux-Gourdes, située dans les gorges de la Vésubie, zone de sismicité faible à moyenne, la présence de fistuleuses brisées permet d'évoquer un mouvement de faille brutal, d'origine sismique. Les deux autres cavités sont en zone réputée asismique et un mouvement lent des chevauchements est probable. Un mécanisme en faille inverse permet d'éliminer un phénomène gravitaire.

4. Dégâts cosismiques

Les deux principaux effets supposés d'un séisme sous terre sont, d'une part, les chutes de stalactites et stalagmites sous l'effet des vibrations ou des accélérations et, d'autre part, les ruptures de spéléothèmes provoquées par des mouvements de failles. Compte tenu de la sismicité moyenne de la France, des recherches ont été menées au Costa Rica [11] et en Grèce pour valider la méthode. Elles ont permis d'observer des mouvements de faille affectant les concrétions sur les parois et le sol des grottes, mais aucune chute de concrétions, cosismique, n'a pu être mise en évidence.

De même, une enquête auprès de la communauté spéléologique internationale a permis de recueillir des témoignages de spéléologues témoins de séismes dans des grottes. Là aussi, aucune chute de concrétion n'a été signalée.

En février 1996, un séisme de magnitude 5,2 a secoué la région de Saint-Paul-de-Fenouillet (France). Une dizaine de cavités ont été inspectées quelques jours après le séisme, ce qui a permis de constater que cet épisode avait provoqué des chutes de fistuleuses (très fines stalactites) dans le gouffre du Paradet (Fig. 5) [14]. En certains points, des débris anciens, soudés au sol, peuvent être attribués au séisme de 1921, comparable à celui de 1996. Des dégâts plus importants ont aussi été observés dans cette même cavité. Ils résultent principalement d'intrusion de glace [13], mais aussi du mouvement de la faille sur laquelle est alignée la cavité (Fig. 6). La juxtaposition de trois phénomènes – séisme, mouvement de faille et intrusion de glace – rend les interprétations complexes.

5. Comportement mécanique des concrétions

Des essais in situ et en laboratoire, ainsi que des modélisations [4,14,17], ont été réalisés récemment pour vérifier que les propriétés mécaniques des spéléothèmes permettent leur rupture lors d'un séisme. Ces essais montrent que les concrétions des grottes ne peuvent pas se briser, sauf les plus fines et les plus élancées [18]. Ceci confirme les données de terrain et montre que l'observation éventuelle de dégâts souterrains cosismiques, principalement des chutes de fistuleuses, traduirait l'existence d'importants séismes.

6. Conclusion

Les séismes ne peuvent briser dans les grottes que les stalagmites élancées et les fistuleuses. L'analyse des chutes de ces dernières pourrait constituer un intéressant marqueur de paléosismicité et la simplicité de ces objets pourrait permettre une approche quantitative.

Des dommages liés à des mouvements de failles peuvent aussi être mis en évidence. Certains pourraient être cosismiques ; il est parfois possible de les différencier de ceux résultant d'un processus tectonique lent, mais l'interprétation est généralement complexe, car les mouvements peuvent résulter d'un processus gravitaire ou d'un phénomène glaciotectonique.

1. Introduction

Cave sediments are often well preserved against erosion for hundred of thousands of years. Their study provides information on paleoenvironments and, as caves may be a few millions years old, it is possible to collect data for very long periods. These properties of preservation could find interesting applications in palaeoseismology, as caves often contain a great number of broken speleothems (cave formations) whose aspect suggests a coseismic origin. Several studies propose to use caves as natural recorders of palaeoearthquakes [1,2,7] and for some authors it is even possible to quantify previous seisms by measuring the direction and the size of the collapsed objects [6,20,22,23]. Their use as indicators of palaeoseismicity opens up a large field of studies, subject to the elimination of the several non-coseismic causes that can break speleothems, but the mechanisms of speleogenesis are complex and their misappreciation may lead to premature conclusions. Thus this approach has to be used with care.

2. Main causes for speleothems breakage

Subsidence, decompression, vandalism are well known causes for speleothems breakage. They are usually easy to characterise, but other mechanisms are more complex. Recent articles on natural caves and field observations indicate that underground damage is frequently caused by ice intrusion or movements of sediments in cave [13]. The present action of ice on cave formations was studied in the cave of Snezna jama (Luce, Slovenia) and new observations were conducted in caves where potential coseismic damage was previously described [13]. In Gaislochhöle (Germany), where most of the speleothems are broken [20], underground moraine has recently been discovered, proving a glacial origin for the breaks [13]. Similar breakages were observed in Postojna cave [15] but in a recent study, the damage is attributed to the ice [16]. In our latitudes, during glacial periods, ice that filled several caves may also have broken even large speleothems (Fig. 1). This is a main cause of ruptures and the breaks or rock collapses described in Swiss [19] (Fig. 2) or Belgian [5] caves have certainly been caused by such a mechanism, as their latitude or altitude is high. However, some examples show that a seismotectonic origin is supported.

3. Breakages caused by fault movements

The movements of joints, cracks or faults in limestone blocks are frequent causes of speleothems rupture. They may be caused by tectonics or gravity. Spectacular examples are described in Monte Campo dei Fiori caves (Italy), where indisputable tectonic movements have deformed galleries and provoked breakages of speleothems [3]. The study of different caves in southeastern France made it possible to observe many signs primarily attributable to tectonic movements. In the cave of Deux-Gourdes (Alpes-Maritimes), the movement of a fault (with a reverse

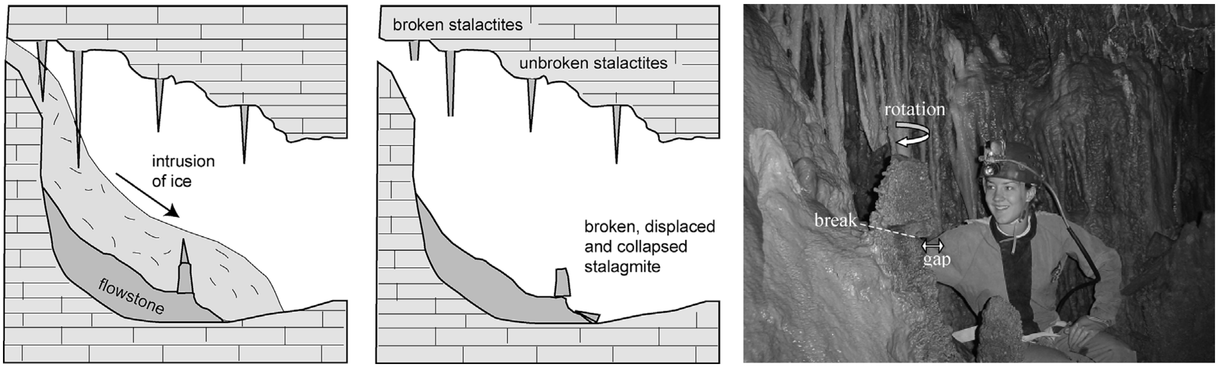

Fig. 1. Principle of the breaking of speleothems by a glacial filling as observed in Snezna jama (Slovenia) and in the shaft of Haut Paradet (photography) [13].

Fig. 1. Mécanisme de rupture de concrétions par un remplissage de glace, tel qu'il a été observé à Snezna jama (Slovénie) et dans le Barrenc du haut Paradet (photographie) [13].

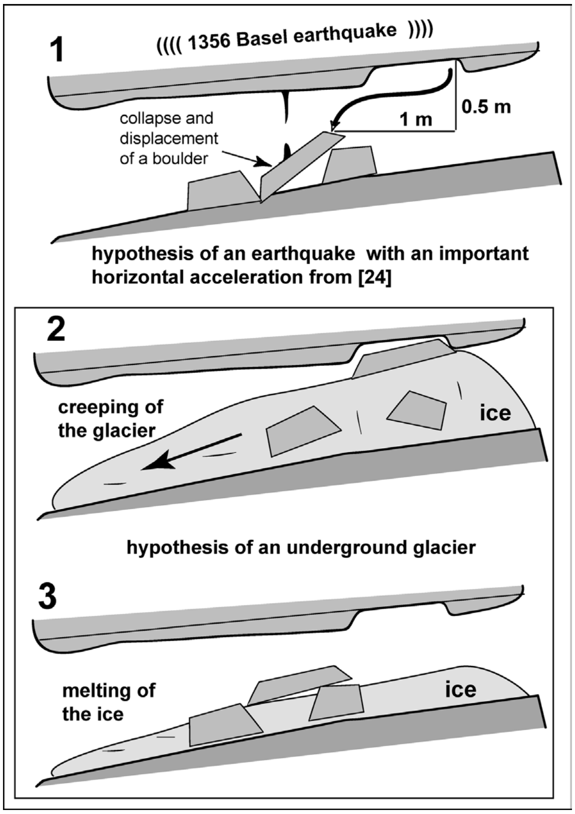

Fig. 2. Collapse and displacement of a slab in Bättlerloch cave (Switzerland). A coseismic origin (1356 Basel earthquake) was proposed [19], but a glacial cause is more likely.

Fig. 2. Effondrement et déplacement d'un bloc dans la grotte de Bättlerloch (Suisse). Une origine co-sismique (séisme de Bâle en 1356) a été proposée [19], mais une cause glaciaire est plus probable.

component) has fractured several speleothems at different periods of time (Fig. 3) [9].

In the shaft of Aven Abel and in the shaft of Calernaum, the movement of thrust faults towards the south has caused the breakage of many speleothems [10,12]. In the former cave, this has caused some soda straws to be curved (Fig. 4). They are fixed to a rock that has rotated due to the movement of the fault. Close to this area, the soda straws that are not fixed to the rock are still vertical and this excludes a curvature caused by an air current. Their study could give good indications on the dynamics of the overthrust faulting. In these two examples, the reverse movement excludes a gravity origin, but in some cases the latter explanation is possible.

If active tectonics is the cause of the underground damage, one difficulty is to evaluate whether the movement was a slow one or a sudden one caused by a seism. The cave of Deux-Gourdes is located in the Vésubie valley, an area characterized by a present low to medium seismicity. The presence of fragments of soda straws in the cave supports a damage caused by important vibrations. Their localisation behind a barrier of unbroken speleothems excludes vandalism or ice intrusion, thus it is possible that the fault moved during an earthquake and caused the breakage. A gauge was installed on the fault in 1986. It had recorded no movement in 2000 and this tends to turn down the hypothesis of a movement caused by gravity.

In the shaft of Aven Abel, the regular curvature of the soda straws supports a slow movement. A similar

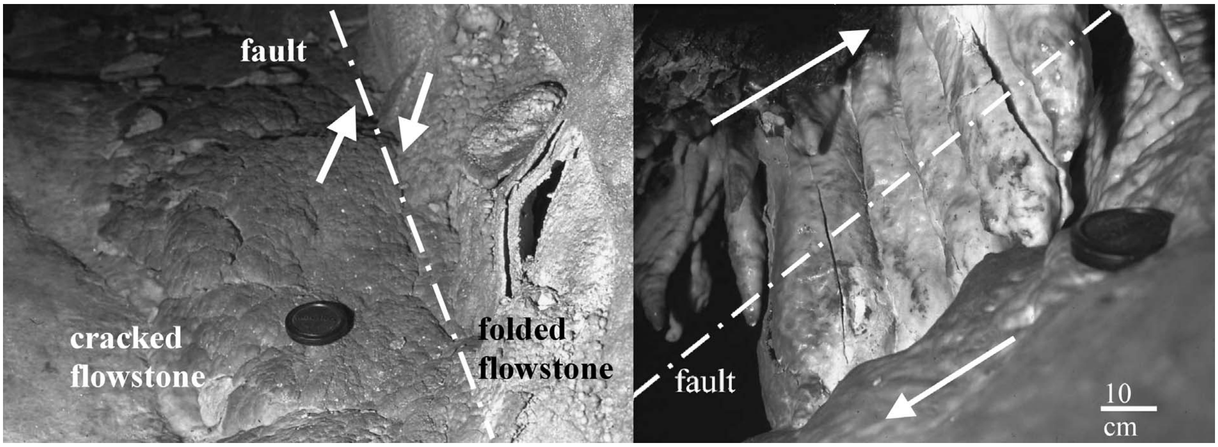

Fig. 3. Damage to a flowstone and stalagmites caused by a fault movement in the cave of Deux-Gourdes (Le Suquet, Alpes-Maritimes, France).

Fig. 3. Dégâts affectant un plancher stalagmitique et des stalagmites, provoqués par un mouvement de faille dans la grotte des Deux-Gourdes (Le Suquet, Alpes-Maritimes, France).

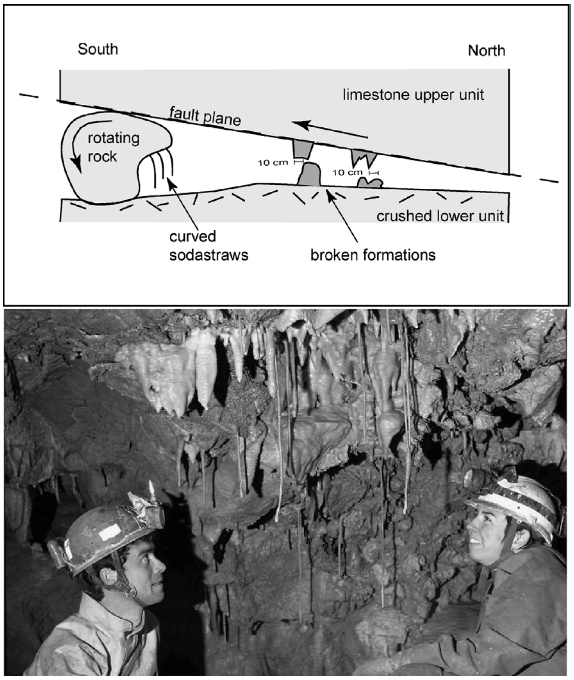

Fig. 4. Damage and curved soda straws due to the movement of a thrust fault observed in the shaft of Aven Abel (Saint-Vallier-de-Thiey, Alpes-Maritimes, France). The curvature is not caused by an air current but by the movement of the overthrusting fault.

Fig. 4. Dégâts et courbure de fistuleuses, provoqués par un mouvement du plan de chevauchement dans l'Aven Abel (Saint-Vallier-de-Thiey, Alpes-Maritimes, France). La courbure n'est pas liée à un courant d'air, mais au rejeu de la faille.

observation was conducted in the shaft of Calernaum, where no significative movement was recorded by a data logger installed for one year on a fault plane. In both areas, the present seismicity is very low.

4. Field observation of coseismic breakages

A naturalist approach was conducted to try to characterize the action of seisms on speleothems. Two possible effects of an earthquake in a cave are the collapses of speleothems and the breakages caused by a coseismic fault movement. The difficulties in finding seismic evidence in France where the seismicity is low, led us to study caves in Costa Rica, where more than ten $Ms > 7$ earthquakes took place since 1940 at depths between 10 to 40 km. Many cracks affecting the flowstones were detected in the caves situated in the most seismic places. The damage was mainly caused by a tectonic uplift of the limestone blocks (up to 6 $m\,kyr^{-1}$ [7]), but no evidence of collapsed speleothems was observed [11]. Studies in the island of Kefalonia (Greece), where a massive destructive earthquake occurred in 1953, did not reveal any signs of collapses in the caves.

A worldwide enquiry on the web, amongst the international speleological community provided interesting data concerning the effects of tremors in caves during Ms 5 or 6 earthquakes. No collapse was related

Fig. 5. Two ages of collapse of soda straws in the 'Barrenc du haut Paradet' (Prugnanes, Pyrénées-Orientales, France). The white fragment is related to the 1996 earthquake, the lower one is probably related to the 1920 earthquake.

Fig. 5. Deux épisodes de chutes de fistuleuses, observés dans le Barrenc du haut Paradet (Prugnanes, Pyrénées-Orientales, France). Le fragment blanc correspond au séisme de 1996, celui du dessous est probablement lié au séisme de 1920.

but loud noises were often described. In most cases, a total absence of underground effect is described.

On 18 February 1996, a magnitude 5.2 earthquake occurred in the Saint-Paul-de-Fenouillet area, southwestern France. The focal depth was close to 6 km and intensity VI damage (on MSK scale) was observed in the epicentral area. This earthquake is one of the most important of the eastern Pyrenees. The slight damage observed in that karstic area, motivated the investigation of potential damage inside the caves, a few days after the earthquake [14]. Many coseismic collapses of soda straws were observed in the Barrenc (shaft) du haut Paradet. It is situated at an altitude of 840 m and the action of the earthquake was probably amplified by a topographical effect. In several places, two generations of collapse were present. The recent fragments were just layed on the soil and the older ones were covered with calcite. A similar earthquake occurred in the same area in 1921 and we suppose that this older collapse was caused by this seism (Fig. 5). In the same cave, the orientation of the fragments was measured on the horizontal areas. A preferential east–west direction was observed, which is concordant with the data recorded by the Agly dam accelerometer (epicentre, shaft and dam are aligned). The study of the aforementioned cave shows that an Ms 5.2 earthquake only causes light underground damage in the caves located in the epicentre area: collapse of soda straws, collapse of small rocks and presence of dust [14].

In the same cave, breakages affecting large speleothems are also observed. They were mainly caused by ice intrusion [13], but in several places the damage was caused by a fault movement. This cave is close to the North Pyrenean Fault and has a tectonic origin. It is aligned on a fault whose movements have caused the existence of underground voids subsequently filled with speleothems (Fig. 6). Thus, in that example, ice intrusion, movements of the fault and earthquake have caused speleothems to break at different time periods and it is sometimes difficult to distinguish between the different causes. These causes are also subject to discussion: was the movement of the normal fault caused by a slow tectonic movement, an important earthquake or the weight of ice on the limestone block? Dating, local tectonics analysis and palaeogeography studies are necessary to go further.

5. Study of the mechanical behaviour of speleothems

An important question was to be sure that speleothems may break during an earthquake. The two potential causes for coseismic breakage of speleothems are vibrations and accelerations. Thus it was necessary to study the behaviour of speleothems, and to compare the results with the data recorded during seisms.

Observations and laboratory tests were conducted:

– theoretical modelling by the Saclay Mechanics and Technology Department of CEA (France) [14];
– laboratory tests of rupture at the University of Liege (Belgium) [4];
– in situ measuring of vibrations in Switzerland [17].

These three different approaches give close results that tend to prove the impossibility of a collapse during an important earthquake for most of the samples, except for slender or fragile speleothems [18].

This recent mechanical data is very interesting as it confirms the field observations:

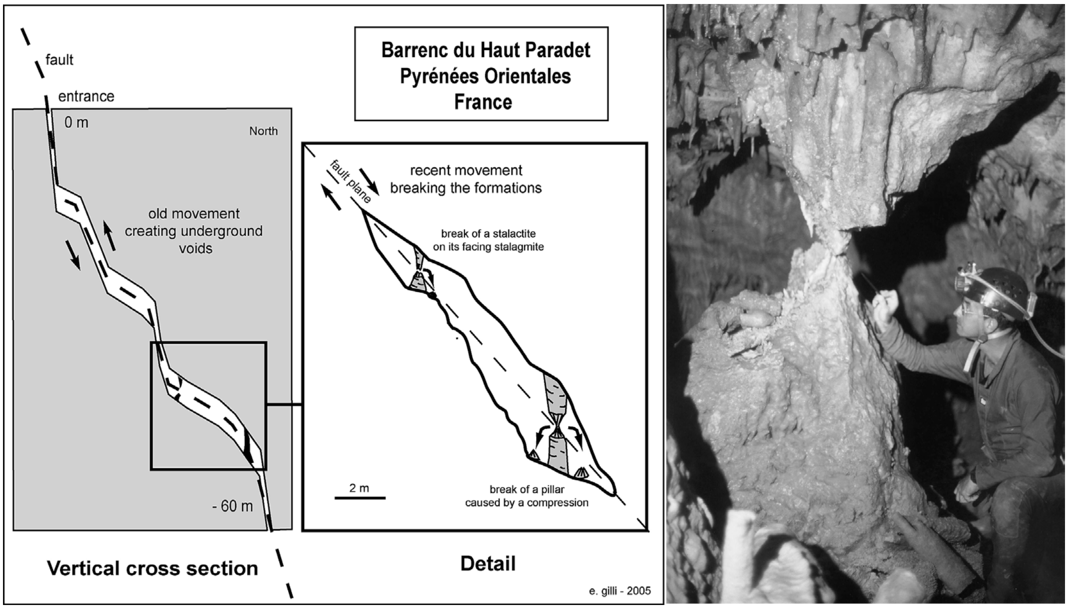

Fig. 6. Scheme of the shaft of 'Barrenc du haut Paradet' (Prugnanes, Pyrénées-Orientales, France), position and photography of the speleothems broken by the movement of the fault.

Fig. 6. Coupe schématique du Barrenc du haut Paradet (Prugnanes, Pyrénées-Orientales, France) avec emplacement et photographie des concrétions brisées par le mouvement de la faille.

– most of the collapses of speleothems have other causes than seisms,
– soda straws may suffer from an earthquake.

It is now possible to acknowledge that the possible observation of seismic damage in caves, mainly collapses of soda straws or slender stalagmites, could be representative of important earthquakes.

6. Conclusion

Protected from erosion and exempt of vegetation, the endokarst is an interesting place to observe damage that affect speleothems in natural caves, but their interpretation is often difficult. Several causes may explain breakages: tectonics, gravity, thermo-hydromechanics, vandalism... A coseismic origin has frequently been suggested, but the absence of damage during recent earthquakes, the existence of well ornamented caves in seismic zones and the laboratory tests, show the strength of cave formations. This tends to prove that large speleothems do not usually suffer from earthquakes. The coseismic origin of massive collapses is doubtful and other mechanisms such as sediment or ice creeping, explain more easily most of the ruptures. However, very elongated stalagmites or soda straws remain interesting tools for studies of palaeoseismicity, as several methods exist to date recent calcite [8,21]. Their mechanical behaviour is compatible with coseismic breaks and collapses were observed in the 'Barrenc du haut Paradet' after the 1996 earthquake. The observation of levels of broken soda straws in cave sediments could be representative of important seisms. As they are very simple objects, a modelling is possible and quantitative data (magnitude, orientation) could be deduced from their study. The research of fault movements caused by seisms is also a possibility for studies of palaeoseismicity in caves. It is possible to detect minute movements that affect faults when a sealing layer of calcite is broken but the main difficulty is to characterize the speed of the movement and to exclude other mechanisms as gravity, decompression or glacitectonics.

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