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Research on the February 18, 1996 earthquake in the caves of Saint-Paul-de-Fenouillet area (Pyrénées Orientales, France).

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Research on the February 18, 1996 earthquake in the caves of Saint-Paul-de-Fenouillet area (Pyrénées Orientales, France).

Recherches sur le séisme du 18 février 1998 dans les grottes de la région de Saint-Paul-de-Fenouillet (Pyrénées Orientales, France).

RESUME: Afin d'évaluer les effets d'un séisme sur le concrétionnement des grottes, huit cavités ont été visitées en France, dans les Pyrénées Orientales prés de Saint-Paul-de-Fenouillet après le séisme du 18 février 1996. Cet événement de magnitude 5,2 associé au mouvement d'une faille est-ouest à une dizaine de kilomètres de profondeur, a provoqué des dégâts de surface réduits.
Les grottes choisies dans la zone épicentrale n'avaient pas été visitées depuis le séisme. Quelques dégâts y ont été observés. Il s'agit principalement de chutes de fistuleuses et de petits blocs. Parmi les cavités de la zone épicentrale, la plus intéressante est le Barrenc du Paradet qui est aligné sur une faille active récente. Il présente de nombreux dégâts ayant affecté les fistuleuses à la suite du séisme. On y observe aussi de très nombreux dégâts anciens. Parmi eux, des stalagmites cisaillées horizontalement et dont les différents tronçons, restés en place, sont décalés et ont subi une rotation. En l'absence d'autre explication ces formes pourraient être attribuables à des séismes passés.
L'étude des fistuleuses qui sont de véritables pendules naturels peut donner des indications sur la direction et le seuil de l'amplitude du mouvement sismique ayant provoqué leur chute lors d'un séisme, permettant ainsi d'obtenir des informations pour calibrer les dommages engendrés par des séismes anciens. Une étude statistique montre que la direction principale des débris de fistuleuses est est-ouest. L'analyse des enregistrements accélérométriques recueillis au barrage de l'Agly montre une accélération amplifiée dans cette direction. Une modélisation confirme que les fistuleuses sont des objets relativement résistants mais qui peuvent rompre dans certaines conditions pendant un séisme.

MOTS CLES: dégâts, fistuleuse, intensité, séisme, spéléothème

ABSTRACT: Eight caves have been investigated near Saint-Paul-de-Fenouillet after the magnitude 5.2 earthquake of February 1996 which occurred in the Eastern Pyrenees (France) and caused moderate damage at the ground surface. The earthquake has been associated with the movement of a E-W fault. The caves were not visited since the earthquake. Some damage, mainly collapses of soda straws and small rocks, could be attributed to this earthquake. The most interesting cave in the epicentral area is the Paradet cave which is situated on a recently activated fault plane. In this cave, soda straw falls could be assigned to the earthquake, but other more ancient damage were observed also. Analysis of the azimuth of fallen speleothems which are natural pendulums, may indicate the directions and an estimation of their mechanical properties gives the threshold of the seismic ground motion amplitude responsible for their collapse and thus supply information to calibrate damage due to past earthquakes. A statistical study indicates that the main direction of the collapsed soda straws is E-W. Numerical simulations confirm that soda straws are relatively strong objects that may break under certain conditions during earthquakes.

KEY WORDS: damage, earthquake, seismic ground motion, soda straw, speleothem

I. SEISMOTECTONIC CONTEXT

On February 18, 1996 a magnitude 5.2 (Ms) earthquake occurred in the Saint-Paul -de-Fenouillet area, SW France. It was felt over a radius of about 150 km. The earthquake recorded by numerous seismic stations, was followed by hundreds of aftershocks during two months.
The epicentre is located between Saint-Paul-de-Fenouillet et Caramany with an intensity of VI (MSK). This earthquake is one of the most important known of the eastern Pyrenees and of the Aude district where five historical earthquakes (Lambert & Levret, 1996) have induced slight damages in the Fenouillèdes massif (1920, 1922), in the Têt valley (1755, 1922) and in the Corbières (1950). Several major faults with a E-W direction (North Pyrenean Frontal thrust to the north of the epicentre, North Pyrenean fault, Agly fault to the south of the epicentre) exist in the area (figure 1). Moreover, geological investigations have shown several evidences of ground surface ruptures, such as the one of Caramany (Philip et al, 1992).

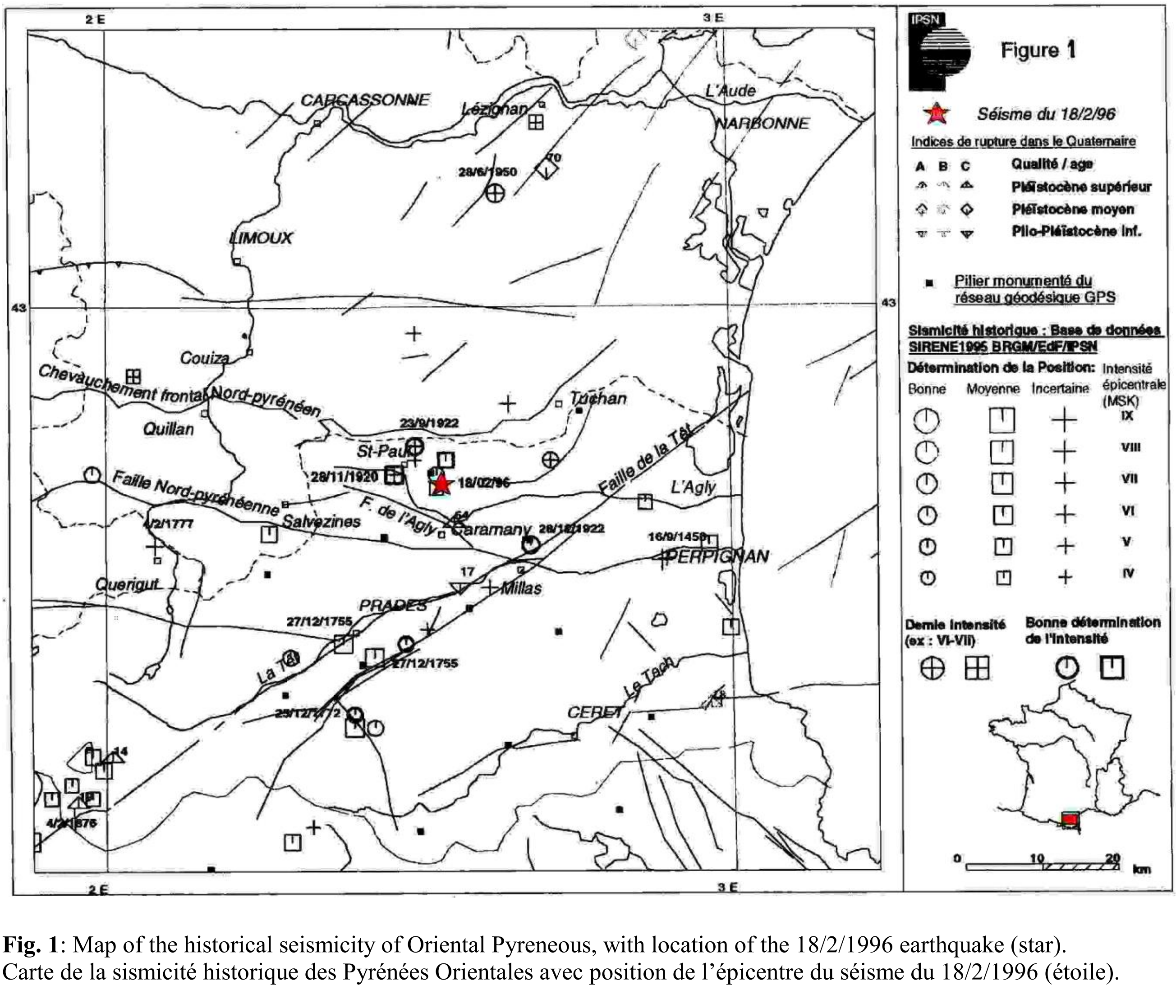


Fig. 1: Map of the historical seismicity of Oriental Pyreneous, with location of the 18/2/1996 earthquake (star).
Carte de la sismicité historique des Pyrénées Orientales avec position de l'épicentre du séisme du 18/2/1996 (étoile).

The interpretation (Rigo et al., 1997) of the numerous records of the main shock gives a precise determination of the epicentre location: 42° 47.81' N, 2° 32.30' E and a focal depth in the range of 6 to 11 km depending on the observatories. It is therefore located at 8 km north of the North Pyrenean fault, inside the strongly fractured Agly massif. A published focal mechanism study (Rigo et al., 1997) shows an E-W or N-S, left-lateral strike-slip fault plane solution. The most significant aftershocks recorded during two months following the main shock, cluster within the Agly massif, immediately south of the main shock, with depths ranging from 0 to 11 km. To reach a magnitude of 5.2, a rupture plane of about 25 km^2 (5 km x 5 km) is required (Kanamori et Anderson, 1975). Such a vertical fault plane oriented E-W, crossing the aftershock cluster, exists in the Agly massif (figure 2).

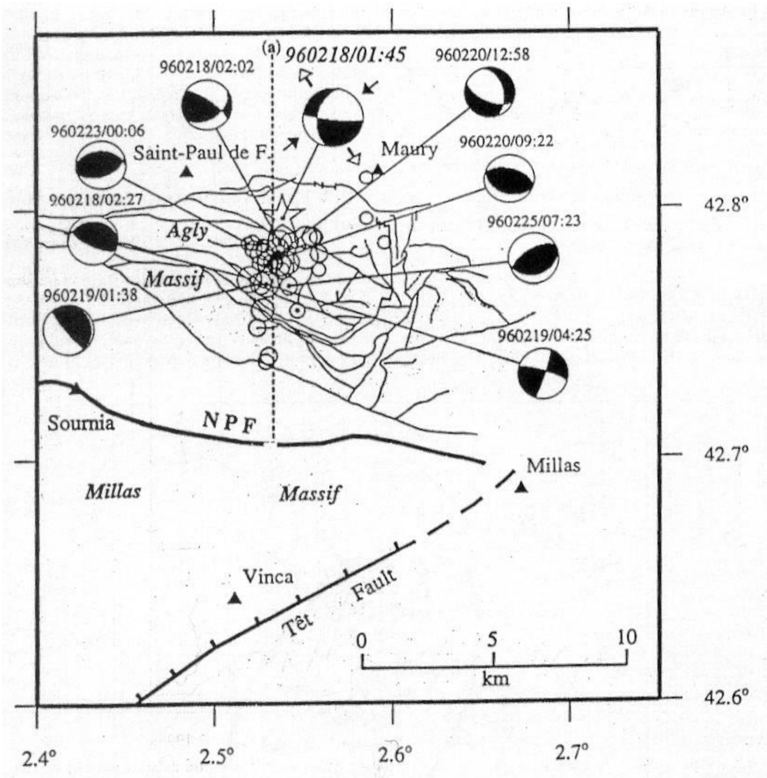


Fig. 2: Epicentral locations and fault plane solutions (lower hemisphere) of the 18 february, 1996 main shock and of the aftershocks. The locations are given for the 37 aftershocks of magnitude of duration M_l above 1.8. The shaded fault plane solutions are determined with at least one P polarity of the temporary stations and the black fault plane solutions are determined without data from the temporary network, not yet installed. Compressional (P-) and extensional (T-) axes for the main shock are shown as black and white arrows respectively.

Position des épicentres et des plans de failles déduits (hémisphére inferieure) de la secousse principale et des répliques de l'épisode du 18 février 1996.

In contrast with the main shock, the aftershock mechanisms indicate reverse faulting with a predominantly right lateral component. This is consistent with the complexity of the structures in the Agly massif and the reactivation by the main shock of several smaller structures (Rigo et al., 1997).
The slight damage observed between Saint-Paul-de-Fenouillet and l'Ille-sur-Têt: widening of preexisting cracks and new cracks in old masonry walls, cracks in ceilings, fall of large pieces of plaster, particularly in the church of Saint-Paul-de-Fenouillet are of a degree VI on the MSK intensity scale. The vibration was felt over a radius of about 150 km as far as Auch to the east, Villefranche-de-Rouergue to the north, Montpellier to the west and Barcelone to the south (figure 3) indicating a focus relatively deep (Levret et al., 1994).

The damage area covers a surface of a mean radius of 10 km from north to south in a karstic area that motivated the investigation of potential damage inside the caves. Eight caves situated between 2 and 10 km from the epicenter have been investigated (figure 4).

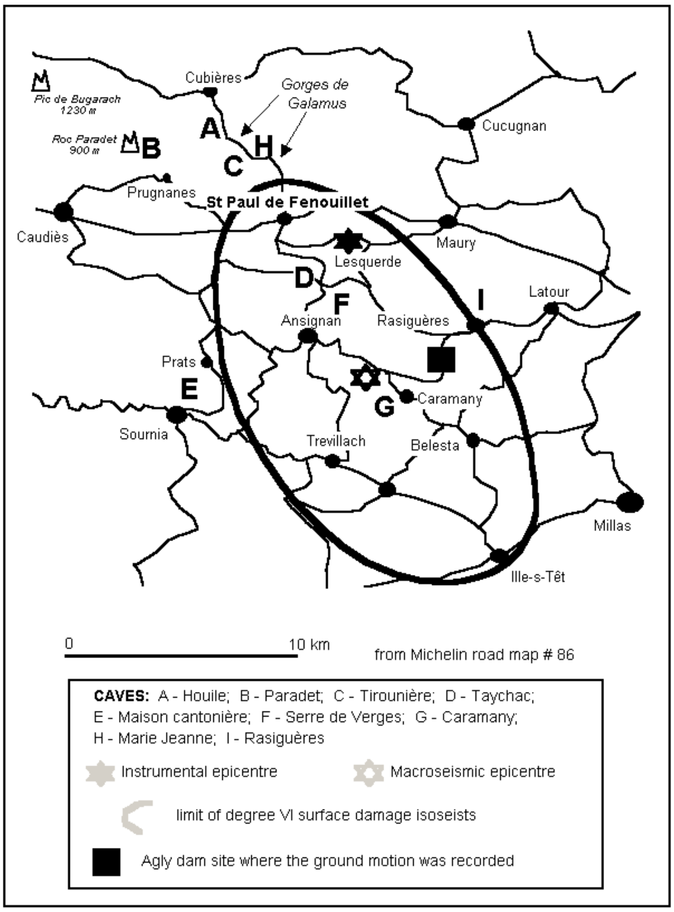


Fig. 3: Main caves around the epicentre of the 18 february, 1996 earthquake.
Principales cavités signalées autour de l'épicentre du séisme du 18 février 1996.

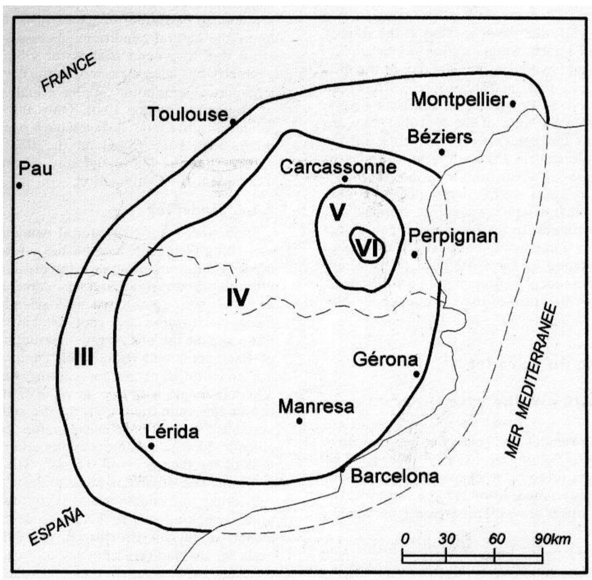


Fig. 4: Isoseismal map of the 18 february, 1996 earthquake in Saint Paul de Fenouillet (Pyrénées Orientales, France).
Carte des isoséistes du séisme du 18 février 1996 à Saint Paul de Fenouillet (Pyrénées Orientales, France).

II. METHOD AND FIRST RESULTS:

A. Damage scale

We have defined a scale for underground damages (Gilli, 1996)

Tableau 1 : underground seismic or tectonic damage scale.

degree	damage
0	no visible damage
1	broken soda straws, fall of dust
2	broken stalactites, collapse of stalagmites on clay, collapse of rocks
3	broken stalagmites, collapse of parts of the roof
4	decimetric to metric displacement of gallery sections
5	destruction of cave

The caves had not been explored since the earthquake. To make the difference between natural damages and human caused ones, we have mainly looked for fragments of soda straws coming from places situated out of the reach of cavers: niches difficult of access or roofs several meters high.

B. Results of caves visits (figure. 3)

The different caves show variability in the intensity ot the present damage, but also ancient ones. The most interesting phenomena was found in the Barrenc du Paradet, (B on the map) where many soda straw collapses and massive speleothem destructions are observed. This cave, the highest one, is located on a limestone crest. This led us to suppose a site effect that could have amplified the ground motion, augmenting the damages.

Tableau 2: Quantification of the underground evidences

name	epicenter distance	altitude	degree of damage	intensity	notes
	km	m	present	ancients	
D - Taychac	2	430	0	0	few speleothems
C - Tirounière	6	320	0	2	
A - Houile	7	470	0	1	
H - Marie Jeanne	7	350	0	2	
I - Rasiguères	8	140	1	3	
G - Caramany	9	500	1	2	
B. du Paradet	10	840	2	3 - 4	
E - Maison Cantonière	10	400	0	0	no speleothem

C. Earthquake study from the macroseismic observations.

The macroseismic inquery following the earthquake gathered more than 850 observations spread over France and Spain, from which isoseismals separating areas whom intensity vary of one degree, have been drawn (figure 4). The intensity VI epicentral area is spread over a mean radius of 10 km and the vibration was felt over a radius of about 150 km as far as Auch to the east, Villefranche de Rouergue to the north, Montpellier to the west and Barcelone to the south.

From the spatial distribution of macroseismic intensities, the earthquake characteristics can be determined (Levret et al., 1994). The macroseismic epicenter which corresponds to the barycentre of the maximal intensity area, is located slightly to the north of Caramany (42°45' N, 2°34’ E) at 6 km south of the instrumental epicenter (figure 3). The decreasing intensity with distance (Sponheuer relationship) allows the focal depth to be calculated. The great spreading of the effects indicates a focus relatively deep of 5 to 10 km consistent with the values given by the analysis of the records. The magnitude has been calculated from a correlation (Levret et al., 1994) based on 140 earthquakes which occurred in France for which the macroseismic intensity and the instrumental magnitude are known: $M = 0.44\, I + 1.48 \log R + 0.48$ linking the magnitude (M) with the focal distance (R in km) of the isoseismal mean radius of intensity I (on MSK scale). This correlation applied to the February 18 earthquake isoseismals yields the following results:

Tableau 3: macroseismic intensities and magnitudes

Intensité (MSK)	Rayon moyen (km)	Distance focale (km)	Magnitude
VI	10	14	4.8
V	30	32	4.9
IV	106	107	5.2
III	147	147.5	5

The mean value is: M = 5, consistent with the instrumental value (Rigo et al., 1997).
The February 18 earthquake for which moderate damages have been observed on the ground surface (new cracks, widening of old cracks) generated very slight effects in the caves. The main damages have been observed in one cave (Barrenc du Paradet) situated at 840 m height, while the caves located at the foot of the relief remained intact. Amplification of the underground damage must have been induced due to the altitude of the cave. In fact, at the ground surface, no damage is produced at, Prugnanes, Camps-sur-l'Agly, Cubières-sur-Cinoble, in spite of the fact that they are the closest ones to the epicenter. Presumably, the reason could be that they are situated in the valleys at altitudes less than 400 m (figure 3). Site amplifications on top of steep slops of rocky spurs are, frequently, observed. One explanation (Bard, 1982) is that seismic waves are trapped and this effect is strongest in the presence of geological layers with strong impedance contrast. Similar site effects can be observed on the isoseismal maps where the Miocene and Oligocene sedimentary are responsible for the NE-SW direction of the earthquake isoseismals (figure 4).

III. THE BARRENC DU PARADET

A. The cave characteristics (figure. 5)

The Barrence du Paradet is a shaft that begins with a narrow 26 m deep pit giving access to a succession of 3 inclined rooms up 60 m deep. The cave is well decorated and rarely visited, allowing precise observations as cave formations are well preserved from human damages.
An accurate survey of the cave, as well as inside and outside observations, indicate that the Barrenc du Paradet is a tectonic cavity. It is organized on an active fault zone that cuts the North-Pyrenean Thrust fault in Chaînon de Galamus area. Its direction is roughly N40°. The space in which we circulate has been created by the relative displacement of the fault edges. This accident has moved during Holocene causing the breakage of speleothems.
In the entire cave, places with soda straws show broken fragments on the floor (phot. 1). Some fragments that we observed last year, are now soldered to the floor by an imperceptible calcite cloak which is probably about 0.01 mm thick..
Except these numerous collapses of soda straws, the Barrenc du Roc Paradet presents also many big speleothems breakdowns, rocks collapses, and stalagmites ruptures. A human cause is impossible due to the importance of the calcite shield that covers these evidences. Moreover, the entrance of the Barrenc du Paradet is a vertical narrow pit.
These ancient phenomena have not been dated.

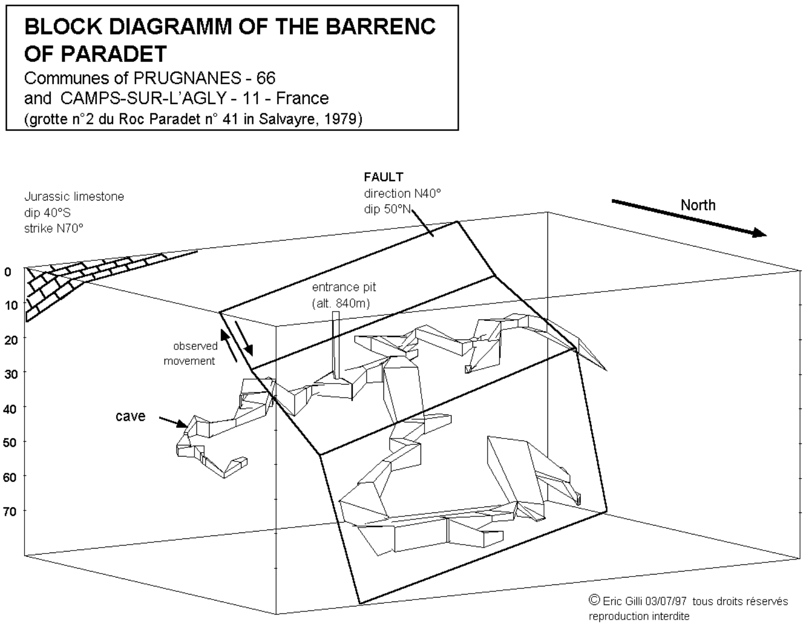


Fig. 5: Block diagramm of the Barrenc du Paradet and its geological environment. The shaft is aligned on a N40° tear fault .
Bloc diagramme du Barrenc du Paradet et de son environnement géologique. Le gouffre est aligné sur un décrochement N40°.

B. Sodastraws study

a.- *in situ*. study

Due to the importance of underground damage, the Barrenc de Paradet is an excellent place to study the mechanical behavior of soda straws . It is interesting to know the natural conditions necessary to break a soda straw due to ground shaking or vibration. Soda straw geometry has been measured in the cave to give data for a numerical simulation. We have analyzed the directions of fragments on the floor. Only the objects that had fallen on horizontal surfaces have been measured. The others may have rolled on the floor or are inclined according to the soil topography. Figure 6 clearly shows a preferential E-W orientation.

Phot. 1: Aspect of the floor of Barrenc du Paradet after the 1996 seism. Note the recent soda straw fragments (white) and the several older collapsed objects (right up corner).
Aspect du plancher du Barrenc du Paradet après le séisme de 1996. Noter les fragments récents de fistuleuses et les nombreux objets plus anciens tombés (coin en haut à droite).

Orientation in degrees		Number
0	to 10	4
10	20	3
20	30	3
30	40	4
40	50	2
50	60	2
60	70	2
70	80	3
80	90	13
90	100	2
100	110	4
110	120	4
120	130	7
130	140	2
140	150	4
150	160	4
160	170	1
170	180	6

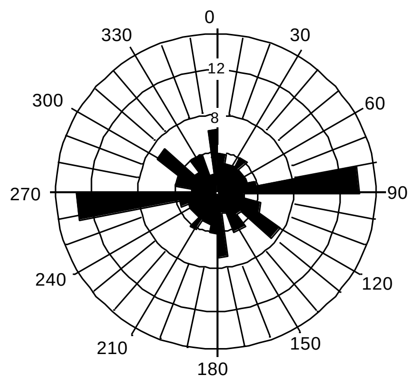


Fig. 6: Directions of soda straws fragments collapsed on horizontal surfaces in the Barrenc du Paradet (Pyrénées Orientales, France).
Direction des fragments de fistuleuses tombés sur des surfaces horizontales dans le Barrenc du Paradet (Pyrénées Orientales, France).

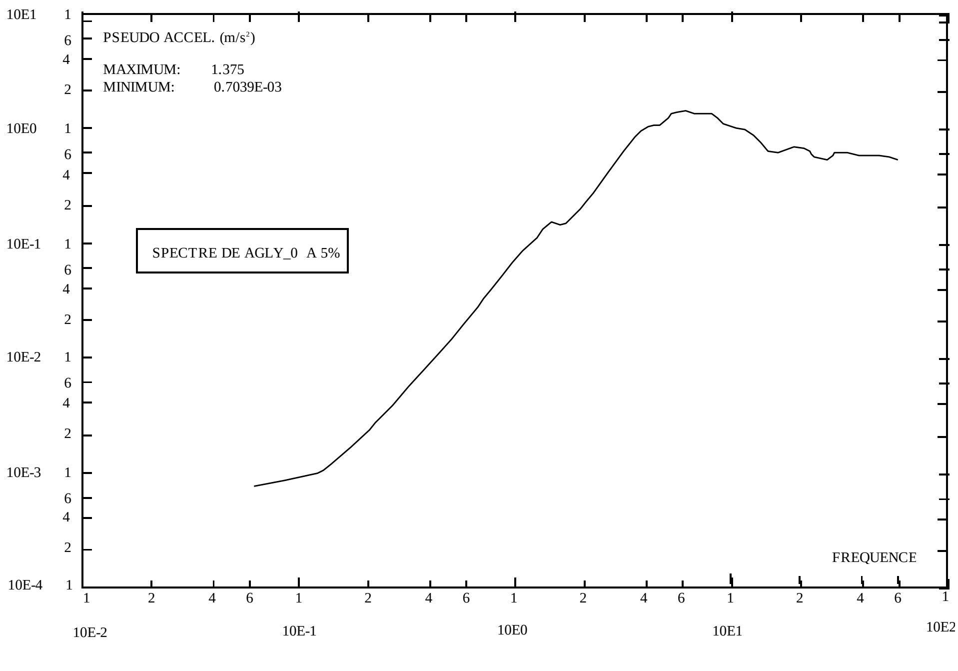


Fig. 7: 5% damping response spectrum of the horizontal ground motion componante measured in Agly dam site.
Spectre de réponse avec un amortissement de 5% du signal horizontal mesuré au barrage de l'Agly (Pyrénées Orientales, France)

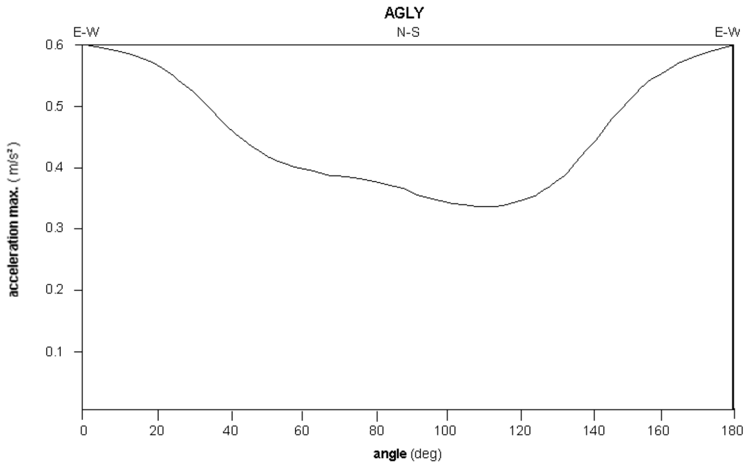


Fig. 8: Amplitude of horizontal acceleration measured in Agly dam site for different directions, 0 = East-West; 90 = North-South.
Amplitude de l'accélération horizontale mesurée au barrage de l'Agly pour différentes directions, 0 = est-ouest; 90 = nord-sud.

b.- Modeling.

Sodastraws are like natural pendulums. A mechanical modeling of their behaviour has allowed to evaluate the conditions necessary for breaking under seismic vibration. Soda straws are considered as beams working in breaking and solicited by a seismic motion at their fixing point to the cave roof. We have essentially taken into account the soda straw measurements in the caves of Rasiguères and Barrenc du Paradet. The stalactites are constituted of a root whose length varies between 3 cm to 30 cm with a mean value of 10 cm, Beyond the soda straw cylindrical body begins with a variable length. A mean value of 20 cm can be considered. The section is empty and the average thickness of the face is about 0.5 mm. The outside diameter is 5 mm. The density is close to 2.5.

In order to evaluate the sensitivity of soda straws to ground shaking, we first have to determine the fundamental frequency. Blevins (1986) gives the following formula for the natural frequency of a cantilever beam:

$$f = \frac{3{,}52}{\pi .\ L^2} \sqrt{\frac{E.I}{\overline{m}}}$$

where f, is the frequency
L, is the length of the beam
E, is the Young modulus
I, is the section inertia of the beam
m, is the mass per unit length

The formula applies for a elastic material which can be assumed in order to appreciate the sensitivity to earthquake loads. In the formula all the parameters are known for a given geometry, except the Young modulus. It is shown that the frequency is proportional to the square root of the Young modulus. It was not possible to measure the calcite elasticity Young modulus on the available samples. Therefore, we have used, in this preliminary study, an approximate value: E = 400 MPa, which is one per cent of the concrete value. This value has been assumed by judgment, and is considered as lower bound. An *in situ* investigation is in progress to precise the Young modulus of

the calcite.
We obtained the frequency of the fundamental mode at 7.8 Hz, which is right in the middle of the amplification range of seismic motion. As shown on figure 7, the 5% damping response spectrum of the horizontal ground motion component measured in Agly dam site, during the Saint-Paul-de-Fenouillet earthquake, presents a peak between 4 and 10 Hz with a maximum acceleration of 1,37 m/s^2. Moreover, the frequency is inversely proportional to the square length and proportional to the square Young modulus, this allows to extrapolate to other values.
Another result obtained from this elementary analysis is that the place where the bending force is the most important, is the soda straw root, and this for all modes. The fractures should be observed there, for an homogeneous soda straw. Other fractures may result from structural anomalies.
The other important parameter to quantify seismic behavior is the rupture stress of calcitic stalactites. Some tests have been realized at the laboratory of Ecole des Mines de Paris on some samples. They give values between 0.93 et 2.8 MPa but on a few samples. With a minimum value of 0.9 MPa it is possible to define the following points:

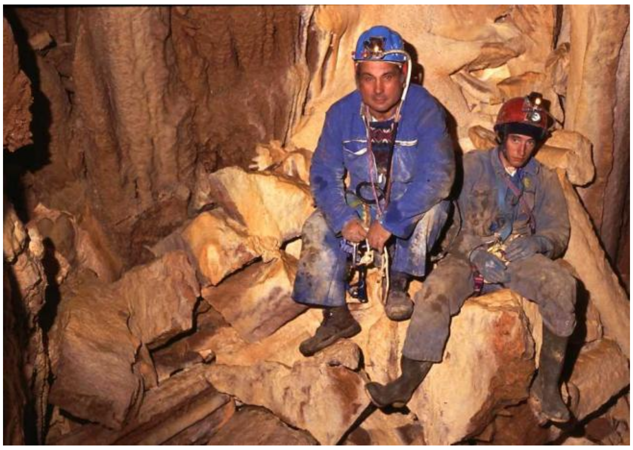
- to break under its proper weight a soda straw must have more than 20 m of length;
- to break in bending during an earthquake the spectral acceleration must be close to 7 m/s^2.

This value is 5 times higher than the one observed on the spectrum (figure 7), with a 5% damping, but a smaller damping tends to increase the spectral acceleration. Nevertheless, this value may be achieved with moderate size earthquakes where site effects may increase the movements up to 10 times more. For such event (magnitude 5 and a distance of 10 km), accelerations up to 3 to 4 m/s^2 are commonly observed with a 5% damping and more with a smaller damping.
It could be possible to get these stresses for longer soda straws, as moment varies with the square length, but frequency will decrease in the same way. A more accurate estimate of Young modulus and a better statistical knowledge of calcite rupture stress would be interesting.
With this model we confirm the extreme fragility of a soda straw when a static charge is applied at its end and also the relative resistance concerning the action of lateral winds.
In order to explain the preferential direction E-W of the stalactite falls observed in the cave of Barrenc du Paradet (figure 6), the seismic ground motion and its response spectrum have been calculated in different directions (each 22°5 from 0° = E-W to -90° = N-S). The maximum ground acceleration is in the direction E-W (angle 0° and 180° and the minimum near the N-S direction (figure 8). This directivity of the maximum ground motion could explain the preferential E-W fall of the soda straws.
In conclusion, these preliminary calculations indicate that soda straws are not breakable under the effect of their proper weight or with strains caused by a lateral wind. If they are homogeneous, they need an important acceleration (7 $m/s^{2)}$ to break during an earthquake, but such a value is not far from the maximum spectral accelerations observed for similar earthquakes and soda straws are rarely homogeneous. The break of soda straws observed in the Barrenc du Paradet situated at 840 m height could be explained by an amplification of the seismic ground motion or/and by structural anomalies in the sodastraw body as it can be deduced from the modeling.
It is interesting to note that only some soda straws were broken in the Barrenc du Paradet, probably the ones with structural anomalies.
To confirm these results we need more complete information concerning the Young modulus, the damping, and more accurate statistics on rupture stresses. A more precise modeling could be done using these new data, associated with a seismic ground motion analysis it would allow a more complete quantification of the effects observed.

C. Description of old damage

In several parts of the cave, we observe soda straw fragments that are cemented with calcite. Due to the thin layer of calcite, they could be attributed to the 1922 earthquake (phot 2). As a matter of fact, they are small objects and the calcite coating thickness is reduced, about 1 mm. Now we have seen that during one year, a coating of probably 0.01 mm had been deposed on the 1997 fragments, 1 mm of calcite could represent 100 years. Even without accurate measures we remain in a time scale which is compatible with the 1922 earthquake.

Phot. 2: Two fragments of soda straws in the Barrenc du Paradet. The upper one has collapsed during 1996 seism. The lower one, now covered with calcite is probably from 1922 earthquake.
Deux débris de fistuleuses dans le Barrenc du Paradet. Celui du dessus est tombé pendant le séisme de 1996, l'autre remonte probablement au séisme de 1922.



Phot. 3: Old massive speleothems collapsed in the Barrenc du Paradet.
Concrétions anciennes et massives effondrées dans le Barrenc du Paradet.

Much more important damage are visible in the whole cave (phot.3) :

- Type A (figure 9) : objects in touch with the walls are crushed or sheared. This implies a subvertical movement of the fault. Some features are very spectacular (stalactite that vertically penetrates its facing stalagmite, causing its breakage; stalagmite embedded into the roof) (phot.4).

- Type B (figure 10) : speleothems are broken without any contact with the wall or a rock (phot.5). The surface of the speleothems is free of impact. The most interesting are stalagmites that are horizontally broken at different levels. The broken parts remain in place with a displacement and a rotation. These signs are similar to the ones observed on tomb stones or antique columns after an earthquake. An important shake or a vibration are the only explanations for such forms in a cave.

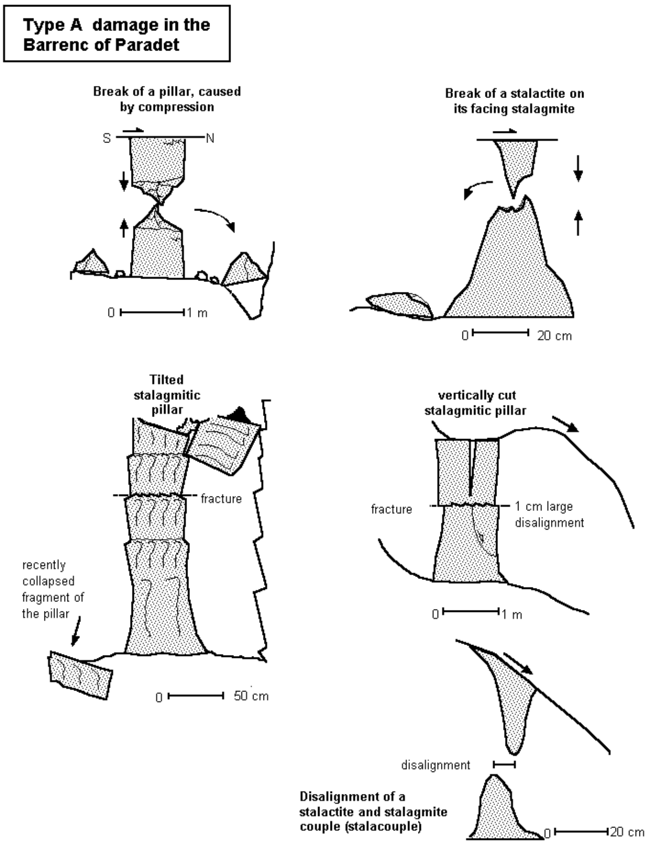


Fig. 9: Some type A ancient damage observed in Barrenc du Paradet. The speleothems are in contact with the walls or the roof.
Quelques dégâts anciens de type A observés dans le Barrenc du Paradet. Les concrétions sont en contact avec le plafond ou les parois.

Phot. 4: A speleothem pillar broken by a recent movement of the fault in the Barrenc du Paradet (Pyrénées Orientales, France).
Un pilier stalagmitique brisé par un récent mouvement de la faille du Barrenc du Paradet (Pyrénées Orientales, France).

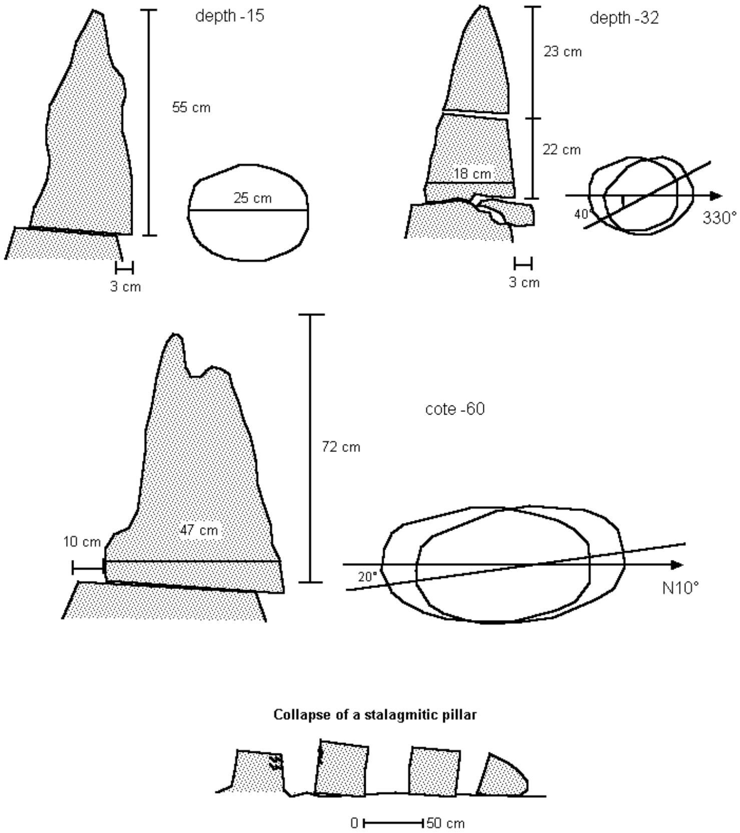


Fig. 10: Some type B ancient damage observed in Barrenc du Paradet. The stalagmites are not in contact with the walls or the roof.
Quelques dégâts anciens de type B observés dans le Barrenc du Paradet. Les stalagmites ne sont pas en contact avec le plafond ou les parois.

Phot. 5: A stalagmite broken without contact with walls or roof in the Barrenc du Paradet (Pyrénées Orientales, France).
Une stalagmite brisée sans contact avec les parois ni le plafond dans le Barrenc du Paradet (Pyrénées Orientales, France).

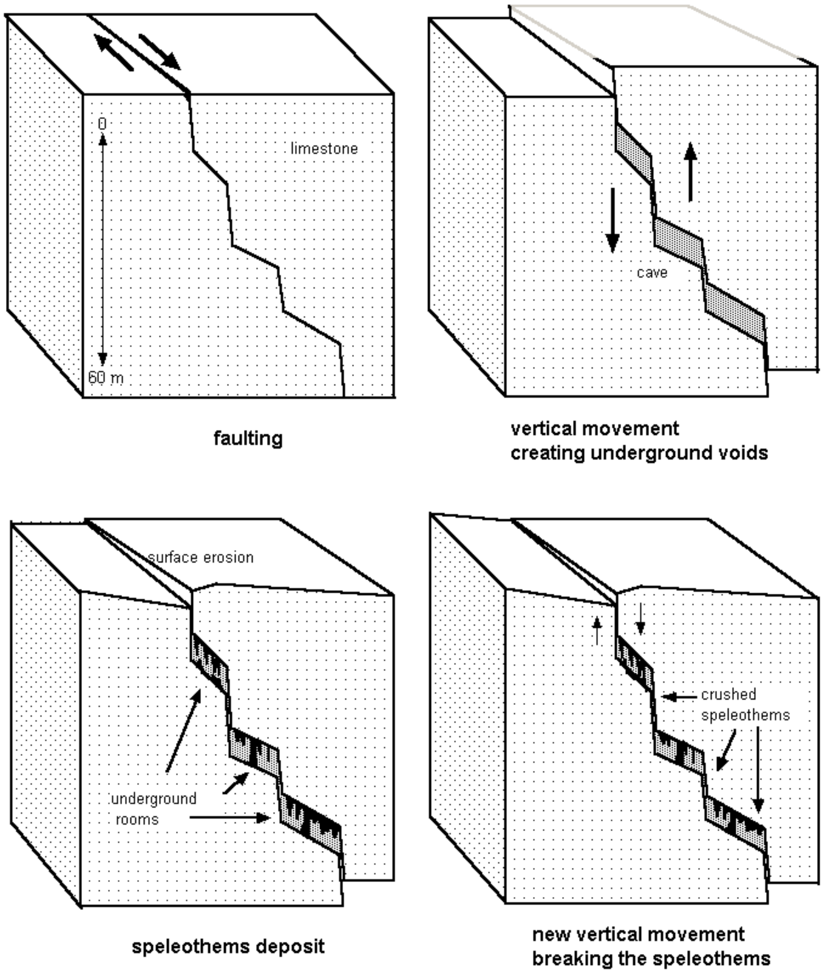


Fig. 11: Origin of type A damage in the Barrenc of Paradet.
Origine des dégâts de type A dans le Barrenc du Paradet

IV. CONCLUSION

This study shows that a 5.2 earthquake causes only few underground damage in the caves located in the epicentral area. A special attention should be given to soda straws. They are simple objects easy to model under seismic solicitation. The first results of the calculation are consistent with the observed effects.

The Barrenc de Paradet that shows modern and ancient damage, is a very interesting cave for quantitative and qualitative analysis of seismotectonic movements that cause disorders in this area. The comparison with other caves in the same area, shows the importance of site effects. The damage have now to be dated and quantified.

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