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Palaeoseismic investigations in Belgian caves

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Abstract

In some karstic caves, the observation of numerous broken stalagmites may provide potential secondary evidence for intense palaeoearthquakes during recent past times. We have named these morpho-sedimentologic features seismothems. A methodology has been developed to discriminate broken speleothems due to earthquake-induced effects or caused by other mechanisms. A study has been carried out in the Belgian karst areas. In the Vesdre Valley, it seems difficult to find evidence of the well-known Verviers earthquake, probably the most destructive historical earthquake known in Belgium which occurred in 1692 AD. The most important concentration of broken stalagmites was discovered in the caves between Hotton and Han-sur-Lesse. The observations in the cave of Hotton suggest a seismic origin, the other origins can not be the cause of the speleothem break. This result implies a strong earthquake situated close to the cave. A preliminary AMS ^{14}C age suggests a minimum age of 10100 ±1200 cal ^{14}C yr BP. for one stalagmite rupture in the Hotton cave.

Keywords: Belgian karst, broken speleothems, Hotton cave, palaeoearthquakes, seismothems

Introduction

In the low to moderate seismic activity regions, the study of all the deformations, possibly induced by earthquakes, must be considered to assess the seismic hazard. A part of the European project 'Paleosis' focus on the study of the endokarstic deposits as potential seismic recorders. In particular, broken stalagmites, stalactites and soda straws may furnish an indirect evidence of large earthquakes (Gospodaric, 1977; Moser & Geyer, 1979; Forti & Postpischl, 1984; Postpischl et al., 1991; Quinif, 1996; Lemeille et al., 1999; Gilli, 1998; Gilli et al., 1999). The very specific characteristics of the endokarst are advantageous for the study of Plio-Quaternary events, (1) the speleothems are generally well preserved from natural and antropogenic deterioration, (2) speleothems allow absolute chronology with the U/Th decay (Li et al., 1989), ^{14}C method and sequential analysis using the annual lamination (Genty et al., 1996).

We present here a synthesis of the palaeoseismic investigations in Belgian caves. A first part of the study focussed on the methodology by defining usable seismothems. Field observation allowed to set up an inventory of the seismothems and their characteristics in the Belgian karst areas. With this concept, a case study was made in the Hotton cave. Finally dating of the speleothems should help in the elaboration of a chronology of past seismic events.

Methodology

Unbroken speleothems (fig. 1) are generally occurring in the cave environment and therefore indicate stable conditions. However, in other cavities, an important amount of speleothems are fractured, tilted or

Fig. 1. Example of a broken stalagmite from the cave of Hotton with the fallen piece and a new little stalagmite which grows between the stump and the fallen piece. The floor of the gallery is littered with pieces of broken soda straws and stalagmites.

fallen (fig. 1). These anomalies may be caused by many different mechanisms. Stalactites break when their weight overcomes the bonding to the ceiling (e.g. large speleothem, soft, porous or fractured ceiling). Speleothems build upon unconsolidated sediments may topple when the unconsolidated substrate subsides under the increasing load or when the underlying sediments are eroded, for example by a river. Slow tectonic motion may crush a column or provoke some breakdown. Speleothems may also be broken by a violent flood. For example, during bad climate condition, the cave could have been invaded by detrital flow (Quinif & Bastin, 1989). They are actually frequently affected by human depredation (e.g. clumsy cavers, mineral collectors). Frost may cause speleothem breakage, especially near the cave entrance. Finally earthquakes may be responsible for extended speleothem breakage. Speleothem breaks accumulate 'naturally' in older caves due to at least one of the above mentioned origins regarding the time factor. Field observations may help to distinguish among the different origins of speleothem breakage. We define a seismothem as being each speleothem potentially broken by a seismic event (Quinif, 2001).

Mainly stalagmites, stalactites and soda straws are considered in this study. They are particularly usable because they have only one contact point with the substrate (host rock or clastic deposits). Therefore, regional movements such as tectonics or rock decompression will not affect them. Broken stalactites and soda straws are more difficult to interpret because the pronounced influence of the tumble on the orientation of the broken pieces. The ideal shape of the stalagmite is a cylinder with a rather constant diameter and with the centre of gravity above the base of the stalagmite (fig. 1) to eliminate de gravitary effect. The pieces of the broken stalagmite must be soldered on the ground to eliminate recent possibly human depredation. The seismothem must be located in a part of the investigated cave, which must not be perturbed by a detrital or water flow, by frost or by permafrost. It must be located in a horizontal gallery, in order to correctly interpret the orientation of fallen pieces. Breakdowns passages in the cave must be studied with caution since they generally are the expression of a mechanical failure in the surrounding limestone host rock. The cave must contain an important number of broken stalagmites to permit a study on a statistical base. The seismic origin of a speleothem rupture is supported by the spatial extension of speleothem distortion within the cave.

A preferential orientation of the fallen pieces is a strong indication for the seismic origin of stalagmite rupture. During an earthquake speleothems may break, more specifically by the vertical and horizontal acceleration of the ground during the passage of a seismic wave. The horizontal component of the acceleration may be responsible for part of the horizontal displacement. The orientation of the fallen pieces is a characteristic, which was already used by other authors to suggest a seismic origin of speleothem rupture (Postpischl et al. 1991; Gilli et al. 1999). In own study, we also measured the displacement vector (fig. 2), which is characterised by (1) the distance between the remaining stumps and the fallen pieces and by (2) the direction of the displacement.

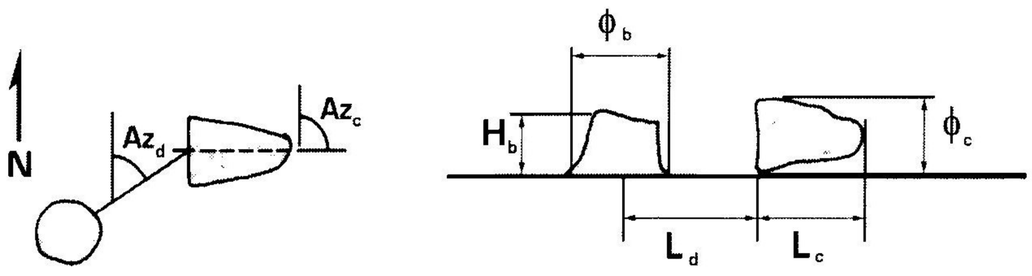

Fig. 2. Measured parameters such as (1) the remaining stump: Hb (height of the stump above the floor), Φb (diameter of the base stump) (2) the fallen piece: Az_c (direction of the fallen), Lc (length), Φc (diameter) (3) such as the displacement vector Az_d (direction of the displacement) Ld (length of the displacement).

The possibility to date the speleothems allows a chronological reconstruction of the rupture. A broken stalagmite on which a new stalagmite develops is a very good morphologic disposition. By dating the youngest part of the fallen stalagmite and the oldest part of the new intact stalagmite, which grows on the stump, a maximum and minimum age for the stalagmite rupture can be estimated. Analyses of an important number of seismothem are necessary to perform the chronological study on a statistical base. The same specific ages of the breaks obtained from different seismothems may indicate the chronology of seismic events in the region. This chronology has a double interest. (1) If several seismic crises are recorded by the speleothems, the return period of large earthquakes may be estimated. In this context, the seismic hazard assessment of the area can be based from long-term seismicity, back to 350,000 yr BP. (2) An occurrence of repetitive ages is indicative of a seismic origin for stalagmite rupture.

Applying the methodology described above, we realised a geo-referenced inventory of seismothems in the Belgian karst areas. This implied (1) a precise cartography of the selected galleries; (2) the 'piecing together' and the counting of the broken stalagmites; (3) the measurement of the length, the diameter, the displacement and of the orientation of selected broken stalagmites (fig. 2); (4) the sampling of some selected seismothems for alpha spectrometric U/Th and *AMS* ^{14}C dating and (5) the sampling of some selected speleothems for the analysis concerning the mechanical properties of these deposits such as their natural frequencies, tensile failure stress and the ground acceleration necessary for their rupture (Cadorin et al., 2001). We concentrated our study in two specific regions (fig. 3), the caves of the Vesdre valley and the caves between Hotton and Han-sur-Lesse.

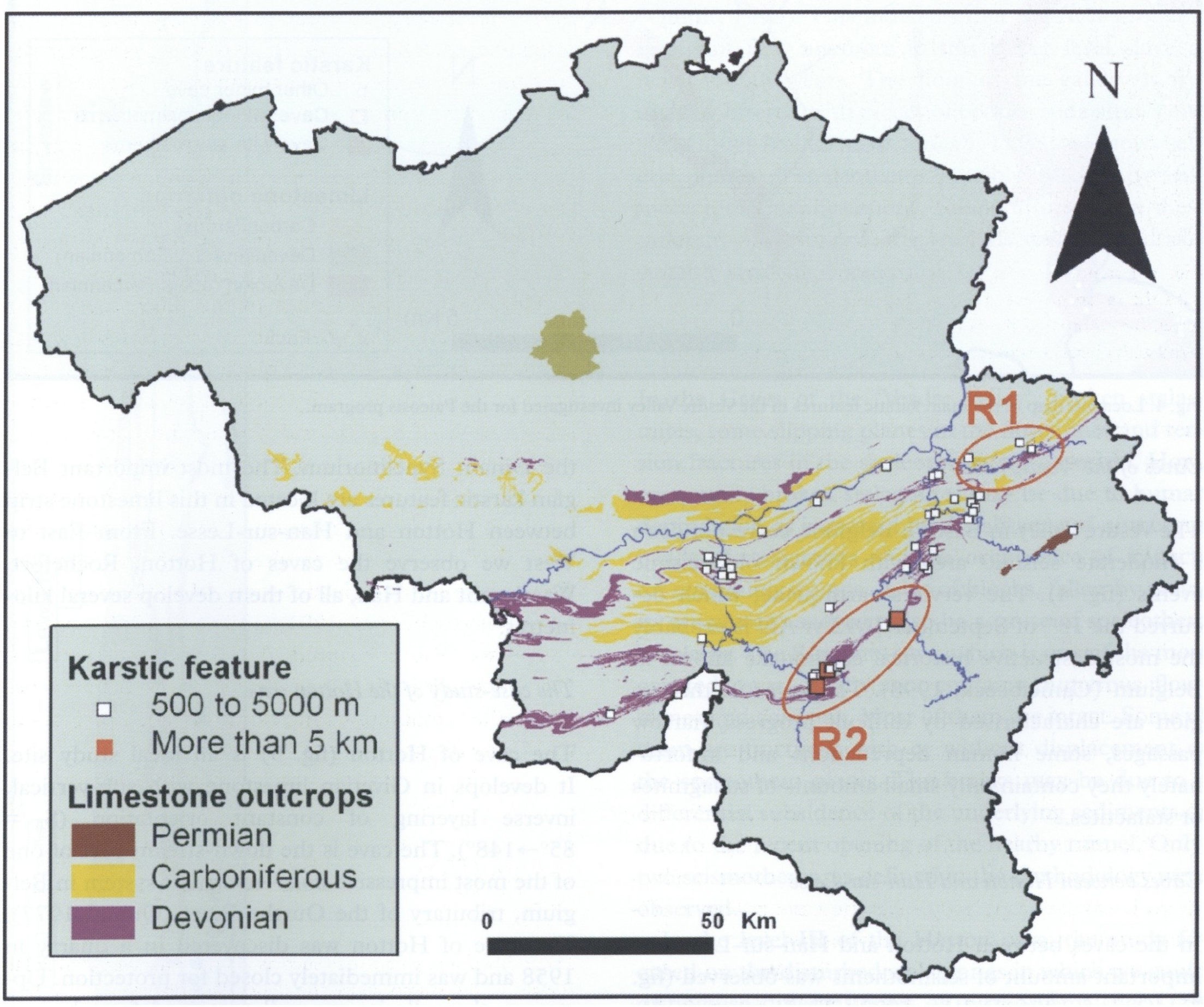

Fig. 3. Location map of the limestone outcrop and the main Belgian karstic features. The southern band of Devonian limestone, also called Calestienne, contain the majority of the bigger cave. The two investigated regions for this study is the Eastern Belgium (R1) and the caves between Hotton and Han-sur-Lesse (R2).

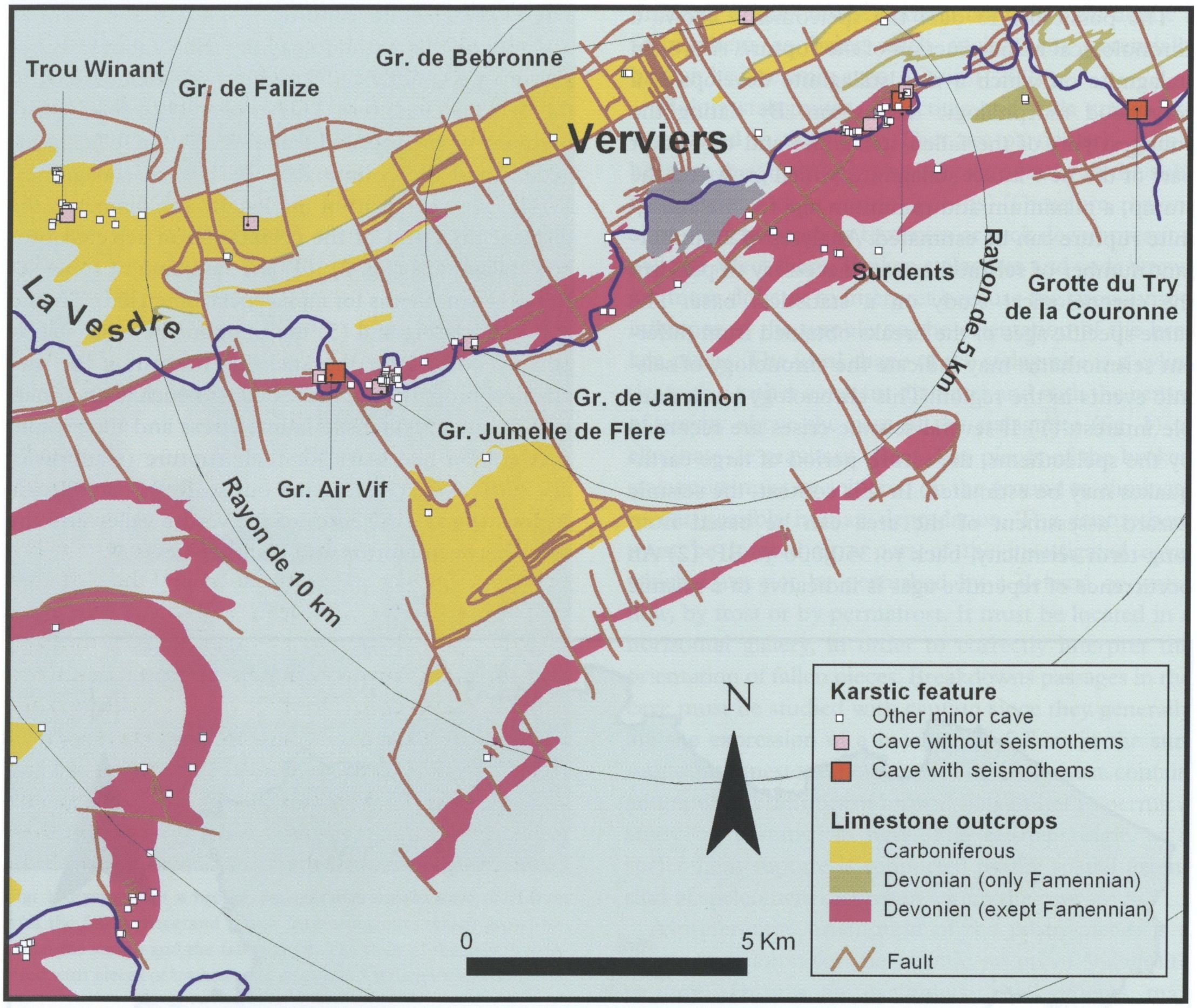

Fig. 4. Location map of the main karstic features in the Vesdre Valley investigated for the Paleosis program.

Caves of the 'Vesdre Valley'

The Vesdre Valley in Eastern Belgium, corresponds to a moderate seismic area with known old seismic events (fig. 4). The Verviers earthquake, which occurred the 18th of September 1692 yr AD is probably the most destructive historical earthquake known in Belgium (Camelbeeck, 1998). The caves in this region are characterised by difficult progress, narrow passages, some human depredations and unfortunately they contain only small amounts of stalagmites or stalactites.

Caves between Hotton and Han-sur-Lesse

In the caves between Hotton and Han-sur-Lesse, an important amount of seismothems was observed (fig. 3), (Quinif, 1996; Delaby, 1999). These caves are located in a Givetian and Frasnian limestone band, known as the 'Calestienne' at the Southern border of the Dinant Synclinorium. The most important Belgian karstic features are located in this limestone strip between Hotton and Han-sur-Lesse. From East to West we observe the caves of Hotton, Rochefort, Waerimont and Han, all of them develop several kilometres.

The case-study of the Hotton cave

The cave of Hotton (fig. 5) is an ideal study site. It develops in Givetian limestone with sub-vertical, inverse layering of constant orientation (S_0 = 85°→148°). The cave is the down-stream part of one of the most impressive *sink – resurgence* system in Belgium, tributary of the Ourthe River (Quinif, 1977). The cave of Hotton was discovered in a quarry in 1958 and was immediately closed for protection. Upstream, the galleries are well preserved from human or animal depredation by a number of doors and sumps. The cave of Hotton is a typical example of a

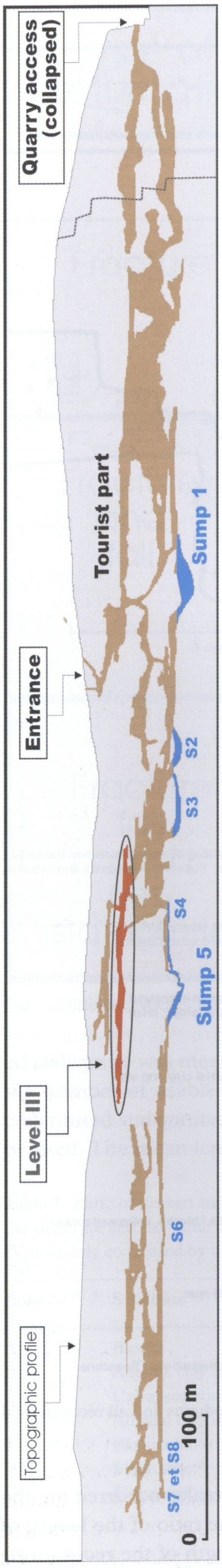

Fig. 5. Schematic longitudinal profile of the main galleries in the Hotton cave. The level III is encircled.

multilevel cave. The different levels of the cave are linked with the evolution of the Ourthe Valley. The lowest level, where the actual underground river flows, is called level I. It contains a lot of fluvial sediments and nearly no speleothems. The upper or relict levels, from II to V, have more less the same characteristics, but till now only the third level was observed. Level III situated approximately 25 meters above the river (base level) is one of the oldest level. The original shape of the gallery due to the karstic erosion is well preserved, indicating stable mechanical conditions of the surrounding limestone host rock. Collapses are concentrated on the junction points between the several levels. There is no active fault directly visible in the cave and at regional scale (Vandycke & al, 2001). The endokarstic deposit is composed of fluvial sediments covered by a stalagmitic complex i.e. flowstones and stalagmites. The youngest speleothems are Holocene (Genty, 2001) and the oldest are older than 350000 year, the limit of the U/Th method (Quinif, 1993). This indicates that the river probably does not flow anymore in this upper level since at least 350000 years. The floor of the gallery is frequently littered with pieces of broken soda straws and stalagmites (called 'cemeteries'). This level shows several phases of speleothems possibly affected by seismotectonic manifestations. Taking into account these different observations, the level III was selected as a suitable area (fig. 5 and 6).

Results

In the Caves of the 'Vesdre Valley', broken stalagmites, some slipping planes in the flowstones and tension fractures in the speleothems are observed. However, many broken stalagmites may be due to human depredation as indicated by the absence of numerous heads of stalagmites and the occurrence of impacts on remaining stumps. A lot of blocks, fallen by gravity, are present and may also be a cause of speleothem breakage. The Surdents cave, which is one of the most ornated caves of this area contains numerous flowstones and columns. Most of them are intact. Some of them are fractured with or without displacement of the speleothem pieces. The breaks may be due to a differential subsidence of the underlying sediments or due to the recent opening of the nearby tunnel. Only, two seismothems, as defined in the methodology were observed.

In the level III of the Hotton cave, the study focused on the disturbed stalagmites in which we could distinguish different types of seismothems (fig. 7). A total of 236 broken stalagmites were counted. The ratio of broken stalagmites over total stalagmites is

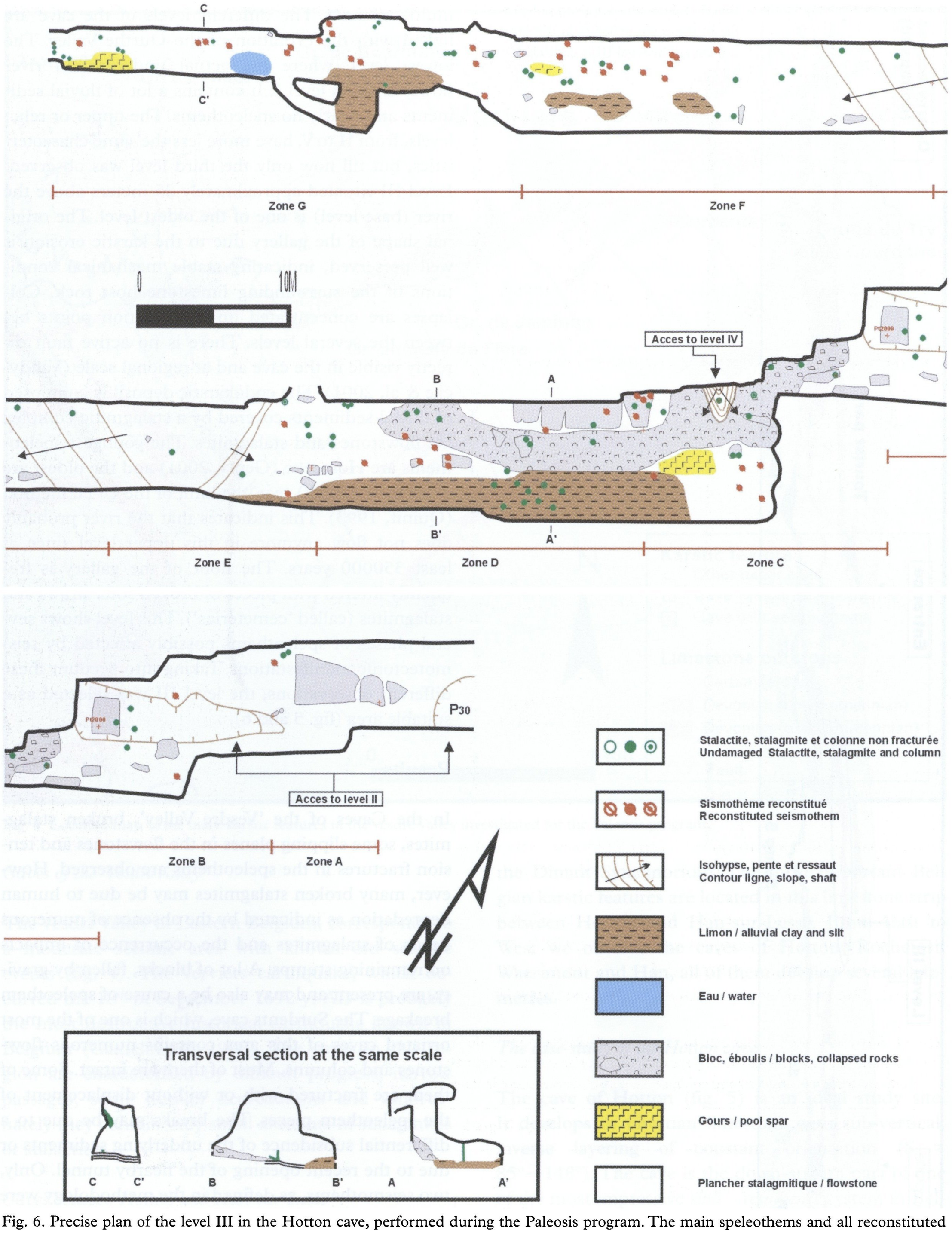

Fig. 6. Precise plan of the level III in the Hotton cave, performed during the Paleosis program. The main speleothems and all reconstituted seismothems are localised on this map. The nature of the cave bottom is represented.

40%. It varies between 23% and 52% in the different parts of the gallery. This ratio does not depend on the substrate or on the slope of the gallery (tab. 1). Nearly all the observed stalagmite breaks occurred in the lower half of the stalagmite. The ratio of the length of the remaining stump to the length of the reconstitut-

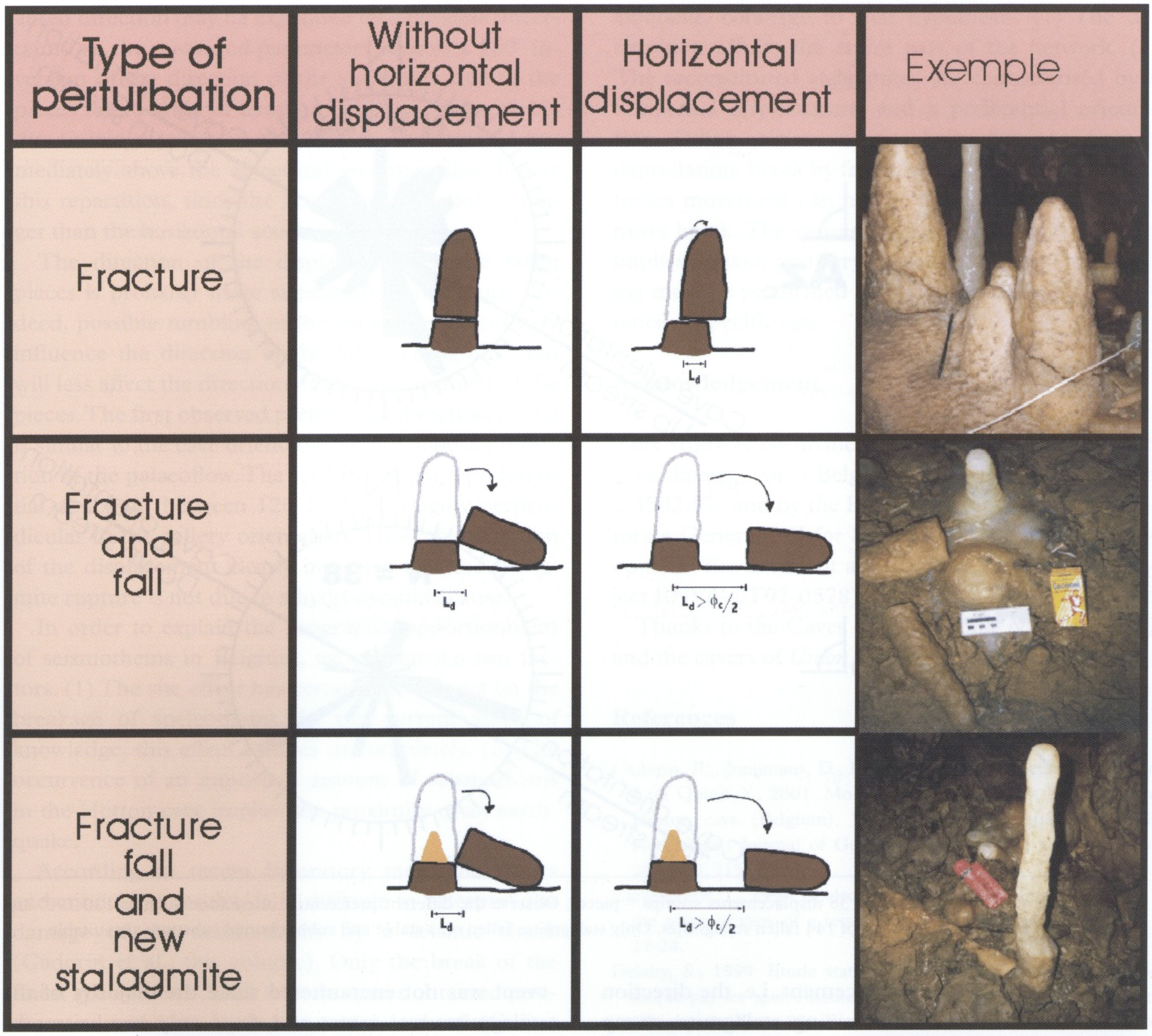

Fig. 7. Different types of perturbation of candle shaped stalagmites found in the Hotton cave

ed stalagmite was measured for 38 stalagmites. This is the number of usable samples since only entirely reconstituted stalagmites (stump and fallen pieces) may be used. The mean length of the remaining stumps (8 cm) is 20% of the mean length of the reconstituted stalagmites (38 cm) (Tab. 1). The measured directions of 144 fallen stalagmite pieces (fig. 8) do not display well-individualised directions. Measurements

Table 1. Ratio of broken stalagmites to the total stalagmites in the different zones of the level III as represented in the figure 6. The nature of the substrate and the value of the slope are indicated. The global ratio is 40% of broken stalagmites. The zone C situated bellow access of level IV, is mainly composed by a strong collapse. In consequence, there is no value associated to this zone.

Zone	Substrate	Slope in grads.	Broken stalagmites	Total stalagmites	Ratio in %
A	Blocks	5	20	65	31
B	Alluvial clay and silt, blocks	5	15	50	30
C	Collapsed rocks	6 to 41	NA	NA	NA
D	Alluvial clay and silt, blocks, flowstone	–6	50	145	34
E	Flowstone	12	15	55	27
F	Flowstone	–3.5	90	170	53
G	Flowstone	1.5	46	106	43
Total			236	591	40

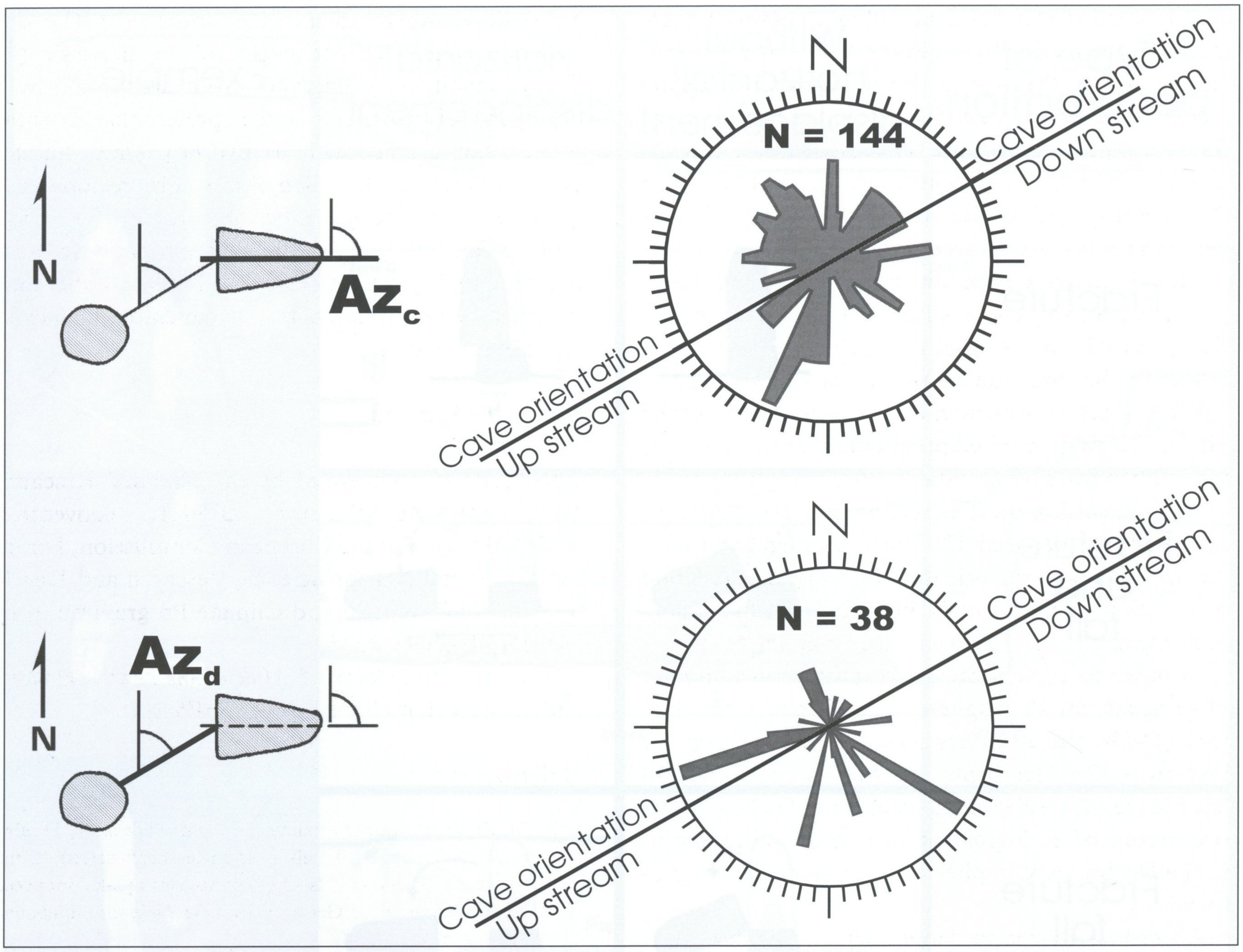

Fig. 8. (A) Rose of the direction of 38 displacements stumps – pieces. Observe the different preferential orientation such as 120-190° and 255-260°. (B) Rose of the direction of 144 fallen stalagmites. Only stalagmites fallen on a stable and subhorizontal substrate are suitable.

of the direction of the displacement, i.e. the direction measured between the remaining stalagmite stump and the fallen stalagmite piece, were done on the 38 reconstituted stalagmites. Results indicate that (1) the average of the displacement length is about 10 centimetres and (2) the rose-diagram of displacement directions clearly displays some preferential directions (fig. 8) one at 255° and one between 120-190°.

AMS ^{14}C dating was performed on the new stalagmite growing on the remaining stump from the Hotton cave. Results and methodology are detailed in Genty (2001). The AMS ^{14}C ages are given, corrected for 11.2% dead carbon proportion (Genty et al, 1998) and calibrated against atmospheric ^{14}C variability (Struiver & Kra, 1986). Linear interpolation of the ^{14}C ages suggests that the break occurred before 10100 ± 1200 cal ^{14}C yr BP.

Interpretation and discussion

In the Surdents cave, the spatial extension of speleothem breakage, which suggests a wide-scale event was not encountered since the majority of the stalagmites was intact and since only two seismothems were observed. Therefore, at this point, the presence of seismothems only suggests a possible seismic origin for the speleothem breaks in the Surdents cave but the lack of spatial extension of speleothem breaks enables us to confirm this hypothesis.

In the level III of the Hotton cave, the high ratio of broken stalagmites over total stalagmites (40%) proves a global perturbation in the cave. Since the gallery remained very stable (see methodology), falling blocks may not be the cause of the stalagmite breaks. Since level III is located approximately 25 meter under the surface and since the cave was very confined till its discovery, it seems very unlikely that the cave was affected by frost or permafrost. This is confirmed by the total absence of cryo-clastic features in the surrounding limestone host rock. Frost would probably cause the stalagmite to crumble while the observed breaks are very clean and occur in the lower half of the stalagmite.

In the Hotton cave, the absence of a well-individu-

alised direction may be explained by a possible uncertainty on the measured parameters such as a 180° inversion of the direction of the stalagmite due to the pieces found without head or tumbling of the pieces due to irregularities on the floor. A cave situated immediately above the epicentral area may also display this repartition, since the vertical acceleration is bigger than the horizontal acceleration.

The direction of the displacement of the fallen pieces is probably more significant in this study. Indeed, possible tumbling of the stalagmite pieces may influence the direction of the fallen stalagmites but will less affect the direction of the displacement of the pieces. The first observed preferential direction (255°) is similar to the cave orientation in the opposite direction of the palaeoflow. The second observed preferential direction (between 120-190°) is roughly perpendicular to the gallery orientation. Thus, the direction of the displacement clearly indicates that the stalagmite rupture is not due to a hydrodynamic cause.

In order to explain the geographic apportionment of seismothems in Belgium, we can invoke two factors. (1) The site effect has certainly an impact on the breakage of speleothems. In the current stage of knowledge, this effect escapes us completely. (2) The occurrence of an important amount of seismothems in the Hotton cave implies the proximity of an earthquake.

According to recent laboratory mechanical tests and modelling results, it is difficult to interpret the damage of the seismothems by a seismic shock (Cadorin et al., this volume). Only the break of the finest speleothems, such as soda straws obtained positive results and can be due to a seismic shock (Gilli et al., 1999; Lacave et al., 2000). The field observations in the Hotton cave, however, strongly suggest a seismic origin for several broken stalagmites. Therefore, it is likely that important parameters are forgotten in the modelling e.g. structural anomalies in the speleothems. One of the future research efforts will be to understand the origin of this discrepancy.

Chronological study on a statistical base was not encountered, till now only one seismothem was successfully dated. A specific age was not yet obtained in order to confirm a seismic origin.

Conclusion

The study objective was to obtain some convincing signs about the seismic origin of most speleothem breakage present in the Belgian karst. The Vesdre Valley presents only few seismothems due to the poor number of speleothems present in this area. The results from Hotton cave, even if they are not yet quite eloquent, converge to that hypothesis. (1) The destruction affects the entire part of the network. (2) The reconstituted stalagmites are characterised by a horizontal displacement and a preferential orientation. Other origins such as hydrodynamic, human depredation, break by fallen blocks or by regional tectonics movement can not be the cause of the stalagmites break. The cause of damage, probably seismic, implies a major and very close earthquake. Other dating must be performed before to conclude of an existence of specific age.

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