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Recent active faults in Belgian Ardenne revealed in Rochefort Karstic network (Namur Province, Belgium)

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Abstract

This paper presents observations of recent faulting activity in the karstic network of the Rochefort Cave (Namur Province, Belgium, Europe). The principal recent tectonic features are bedding planes reactivated as normal faults, neo-formatted normal faults in calcite flowstone, fresh scaling, extensional features, fallen blocks and displacement of karstic tube. The seismotectonic aspect is expanded by the presence of fallen blocks where normally the cavity must be very stable and in equilibrium. Three main N 070° fault planes and a minor one affect, at a decimetre scale, the karst features and morphology. The faults are still active because recent fresh scaling and fallen blocks are observable. The breaking of Holocene soda straw stalactites and displacements of artificial features observed since the beginning of the tourist activity, in the last century, also suggest very recent reactivation of these faults. This recent faulting can be correlated to present-day tectonic activity, already evidenced by earthquakes in the neighbouring area. Therefore, karstic caves are favourable sites for the observation and the quantification of recent tectonic activity because they constitute a 3-D framework, protected from erosion. Fault planes with this recent faulting present slickensides. Thus a quantitative analysis in term of stress inversion, with the help of striated faults, has permitted to reconstruct the stress tensor responsible for the brittle deformation. The principal NW-SE extension (σ_3 horizontal) is nearly perpendicular to that of the present regional stress as illustrated by the analysis of the last strong regional earthquake (Roermond, The Netherlands) in 1992. During the Meso-Cenozoic, the main stress tectonics recorded in this part of the European platform is similar to the present one with a NE-SW direction of extension.

The discrepancy between the regional stress field and the local stress in the Rochefort cave can be the result of the inversion of the σ_2 and σ_3 axes of the stress ellipsoid due to its symmetry or of a local modification at the ground surface of the crustal stress field as it has been already observed in active zones.

Keywords: Ardenne, karst, recent faults, Rochefort Cave, stress analysis, tectonics.

Introduction

Into the European platform, the Ardenne massif is often considered as a stable area, without post-Paleozoic tectonic manifestation (Fourmarier, 1954; Michot, 1980). Brittle tectonics analysis (Vandycke, 1992; Vandycke and Bergerat, 1989) and earthquake seismology studies (Camelbeeck, 1994; Camelbeeck and Meghraoui, 1996) prove that a recent and present-day tectonic activity exists, essentially linked to the rifting process of the Lower Rhine graben, but also to the strike-slip movement along a E-W trending axis called Nord Artois Shear Zone (NASZ) (Vandycke et al., 1991), between the French and German border (Fig.1). Although superficial sismo-tectonic manifestations exist along the Rhine Graben and the NASZ (Camelbeeck, 1994), such structures were not known in the Ardenne massif. Also, some structural studies and palaeoseismicity analysis prove present active tectonics with earthquakes and live faults which put out of shape that the Ardenne area (Belgium) is a stable cratonic. However it is difficult to find recent surface faults in near stable craton in which sismo-tectonic activity is low. The marks of present movements are often erased by erosion and masked by thick soils. Moreover, numerous tectonic phenomena like tilt, subsidence or uplift can be measured by either geophysical methods or by geomorphologic marks such as the deformations of rivers terraces (Demoulin, 1989); levels of dry valleys (Vanara et al., 1997), deformations of speleothems and walls in caves (Vanara, 2000). However, geometrical and geo-chronological frameworks are often missing.

Among various record possibilities of recent sismotectonic events, karstic caves are favourable sites to quantify them because they constitute a 3-D framework in which one can easily study the post-genetic deformations provoked by a tectonic activity and earthquakes (Bini et al., 1992; Quinif, 1996; Mocchiutti and Valent, 1998). Caves provide a favourable environment to determine the geometrical and mechanical parameters of seismo-tectonic events and to date them (Bini et al., 1992; Postpischl et al., 1991; Forti and Postpischl, 1984). A gallery can be cut by an active fault; walls can be dislocated; fallen blocks can result from fractures movements, etc. The fillings are also modified. The karstic clastic deposits are not necessarily favourable to preserve post-genetic modifications. Nevertheless, when a gallery is dry, the speleothems (stalagmites, stalactites, flowstones) begin to grow during wet and warm climatic periods (Bastin, 1978; Quinif, 1990; Atkinson et al.1978; Gordon, 1989; Li, 1989; Ivanovitch, 1992; Quinif and Bastin, 1994; Lauritzen, 1995). Afterwards, they can be dislocated by tectonic movements or seismic tremor (Quinif, 1996; Quinif and Genty, 1997; Gilli, 1986; Jeannin, 1990, Vanara, 2000). These speleothems constitute a very good material to study the mechanical modifications inside caves. Furthermore, the perturbed structures and sediments are protected from atmospheric erosion processes. Lastly, present tectonic movements can perturb human works in old tourist caves.

The Cave of Rochefort

The Cave of Rochefort (Namur province, Belgium, Fig.1) constitutes a case study of active faults which deformed the underground forms and deposits. In this cave, recent faults with slipped striated planes are very well visible. They offset and break gallery walls, speleothems and old scenic route features.

Geological and karstic context.

The karstic networks of Belgium are developed in Devonian and Carboniferous limestone of the Ardenne Massif which have been folded, faulted and

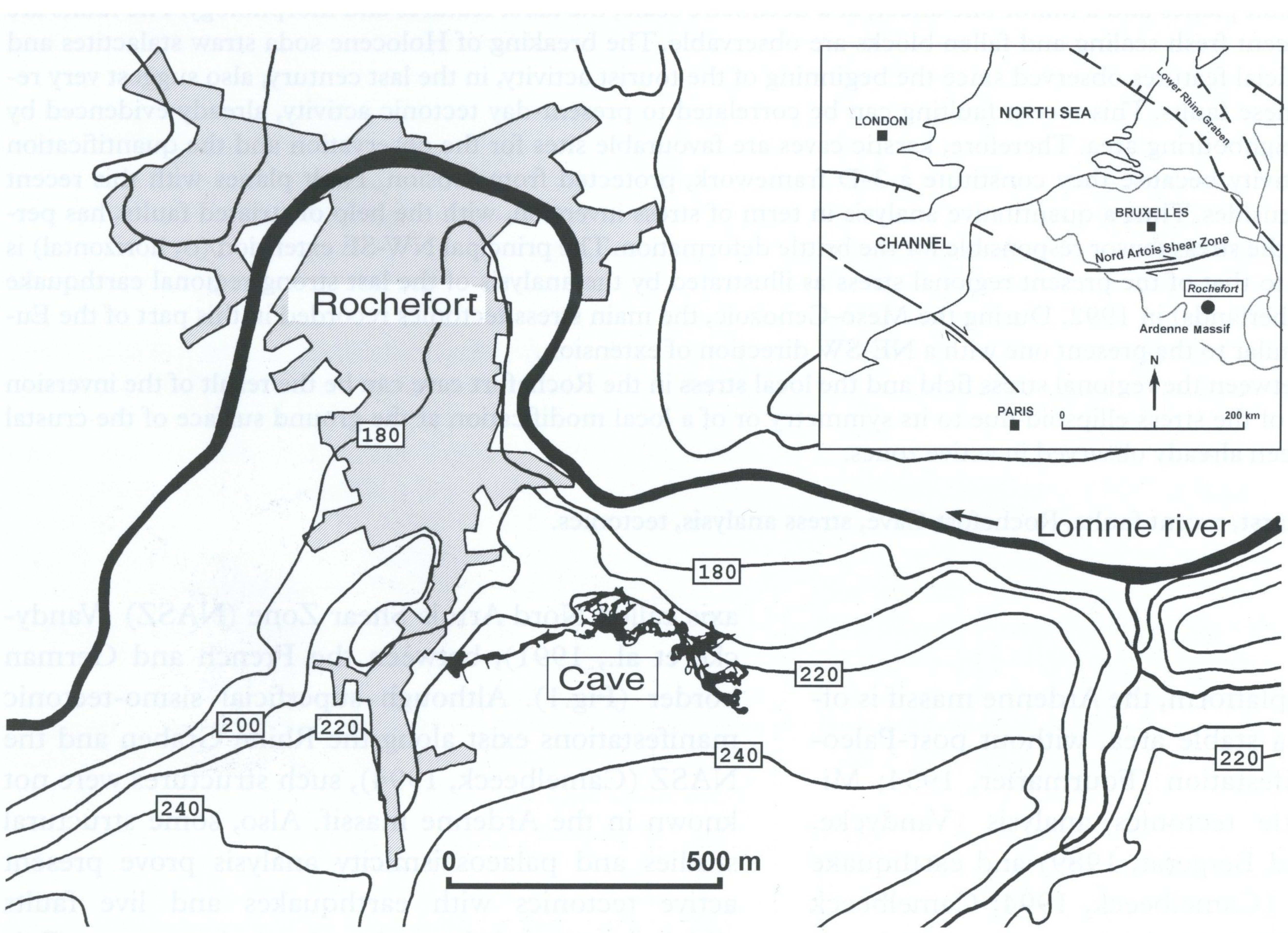

Fig. 1. Localisation of Rochefort site within its geodynamic setting. Rochefort is located in the Belgian Ardenne Massif. The closed principal regional structures recently active in the N-W Europe during the Meso-Cenozoic are the North Artois Shear Zone (NASZ) and the Lower Rhine Graben. The Rochefort Cave is located under the left slope of the Lomme River, near the Rochefort City. The cave belongs to the karstic meander cut-off network of the Lomme River, but is partly disconnected from the hydraulic system.

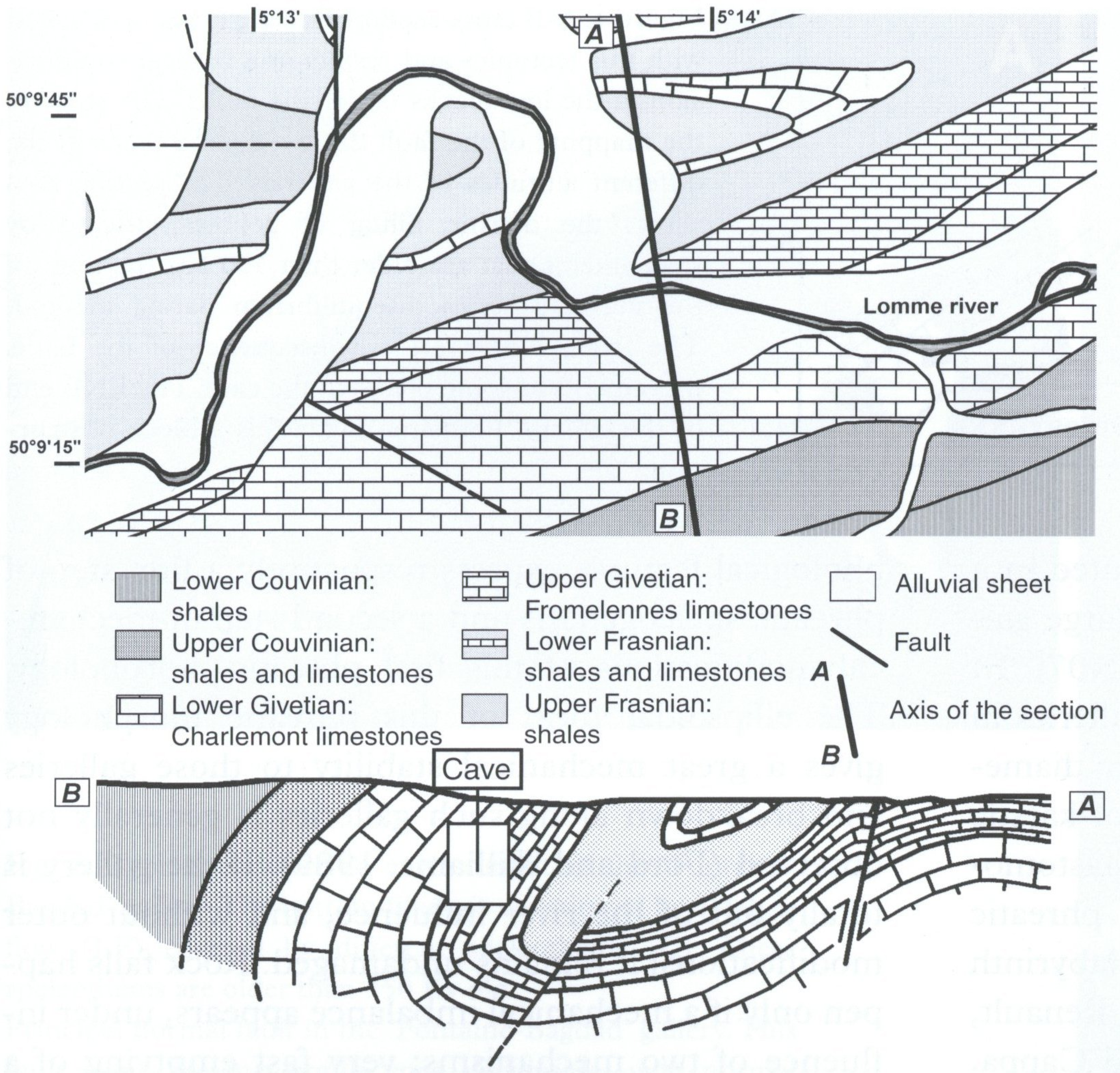

Fig. 2. Geological map and cross-section of the Rochefort site (modified from Delvaux de Fenffe, 1985) The karstic network was built in the Upper Givetian limestone in the inverse side of an overfold. The direction of the beds is around N070°E, which is the general direction of the Hercynian structures.

thrusted during the hercynian orogenesis (Michot, 1980; Van den Broeck, 1910). Caves and underground rivers are the result of the hollowing by major rivers in the Ardenne Paleozoic basement, after the Mesozoic and Tertiary erosions. They date from late Tertiary to Quaternary (Ek, 1976; Quinif, 1977; Quinif, 1984; Quinif, 1989). The Rochefort cave is a piece of the down-cutting of a meander by the river Lomme (Fig.1). It is situated in the Givetian limestone, in the inverse side of an overfold (Fig.2), in an inverse stratigraphic series dipping 55°S. This cave is constituted by great galleries deserted by active hydrologic circulation, and breakdown rooms (Overlau and Quinif, 1979) (Fig.3).

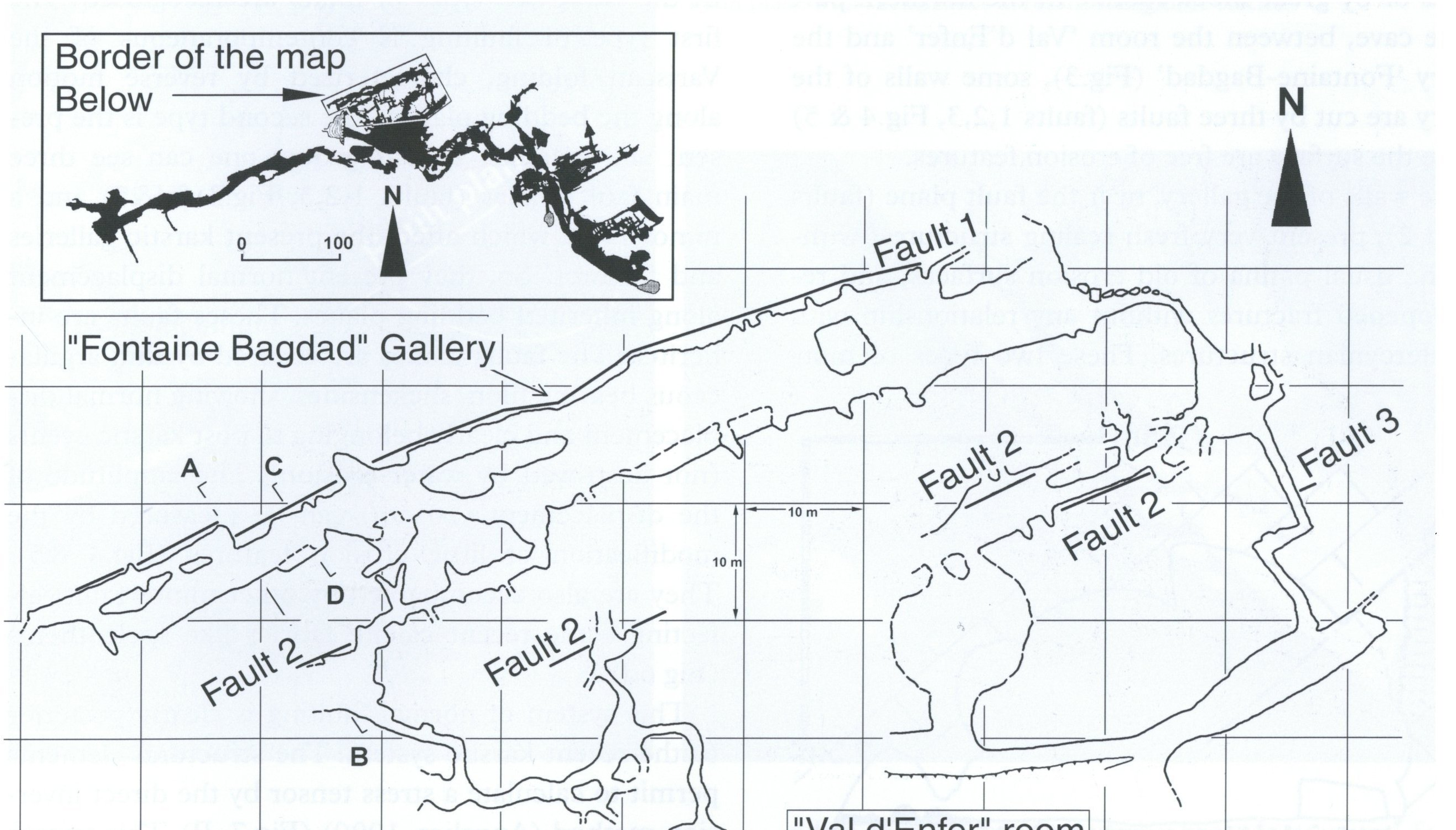

Fig. 3. Detailed topographic map of the part of the Rochefort Cave where the recent faults were discovered. The section A-B and C-D cross the main three recent faults. The direction of the faults is the direction of the Hercynian structures. Their movements act on inherited structures, but the present tectonic stress tensor is different from that during the Hercynian.

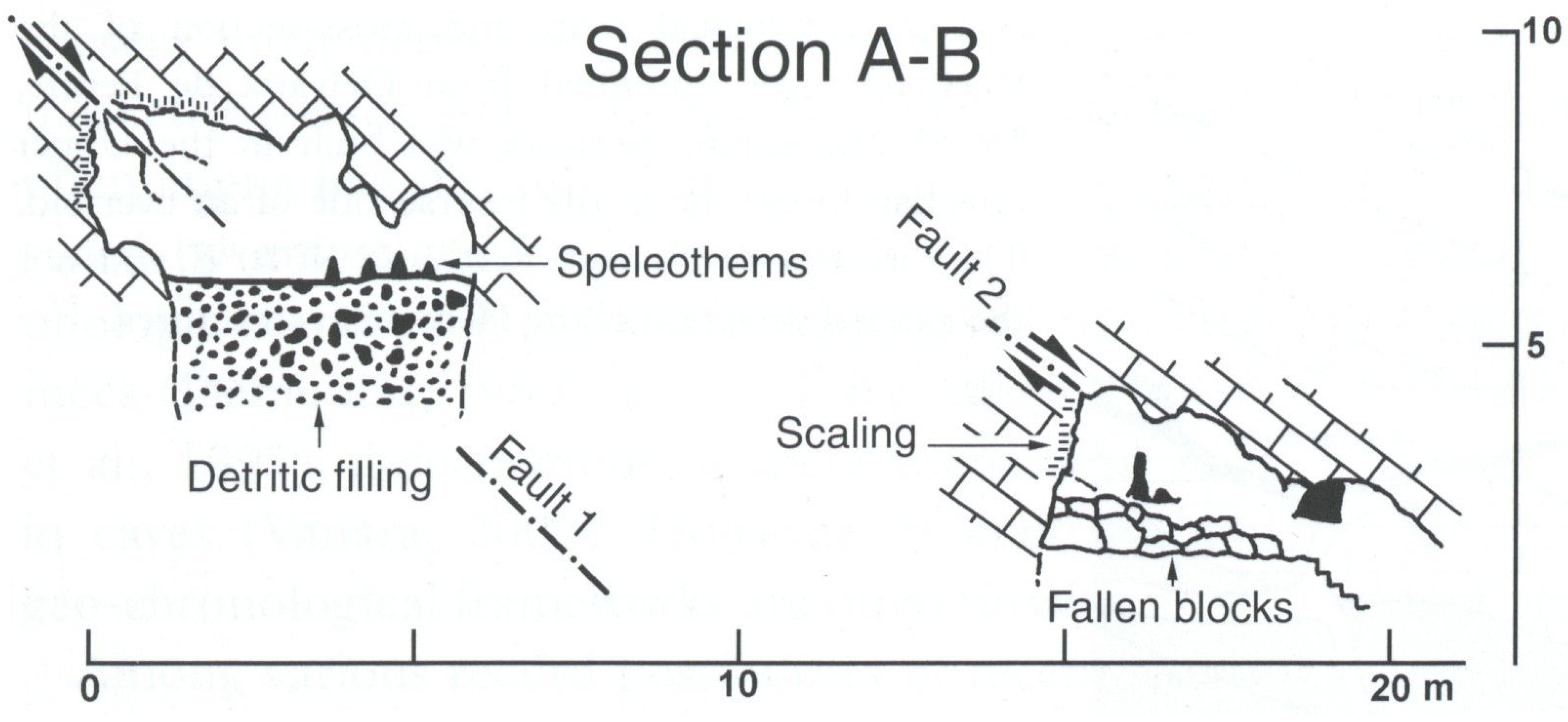

Figure 4. A-B cross-section. Scaling is also associated with this tectonics and results of a vertical compression in the low blocks under the faults. The steps in the mapping of the fault 2 are a consequence of the different altitudes of the galleries. The section A-B shows the detritic filling of pebbles covered by speleothems that are older than 350 Ky, the limit of the uranium series disequilibrium dating method. The fallen blocks are a consequence of the faults movements at some places in the cave. The ENE end of the gallery 'Fontaine-Bagdad' is a block obstruction.

The Rochefort cave studied area is constituted by a network of two principal types of galleries: large galleries along the stratigraphic direction (N070°E) (some meters large and high) and smaller galleries in the dip direction (often less than one meter diameter). The morphology includes two classes of karstic features. First, ceiling pockets, joint plane anastomosis, ceiling anastomosis are the result of phreatic chemical erosion, which has also induced a labyrinth network structure in the cave (Bretz, 1942; Renault, 1958; Renault, 1968; Quinif, 1973; Bini and Cappa, 1978; White, 1988). Second, perturbed features resulting from younger activities like debris flow are preserved on the floor on the gallery.

Recent fractured features

Some galleries are sometimes stopped by fallen blocks or by great shock rooms. In the northern part of the cave, between the room 'Val d'Enfer' and the gallery 'Fontaine-Bagdad' (Fig.3), some walls of the gallery are cut by three faults (faults 1,2,3, Fig.4 & 5) whose the surface are free of erosion features.

The walls of the gallery, near the fault plane (faults 1 and 2), present very fresh scaling structures, without the usual patina of old erosion surfaces, and recent opened fractures without any relationship with the Hercynian structures. These two types of morphological features express respectively a first step of phreatic speleogenesis and a second step of mechanical modifications of this first phreatic morphology. The ellipsoïdal form of this phreatic morphology gives a great mechanical stability to those galleries and breakdown along such galleries is generally not observed (Ford and Williams, 1989). If the gallery is totally out of the river influence, and without outer modifications, it remains undamaged. Rock falls happen only if a mechanical imbalance appears, under influence of two mechanisms: very fast emptying of a total filling or tectonics influence. Here, the movement of faults causes these perturbations.

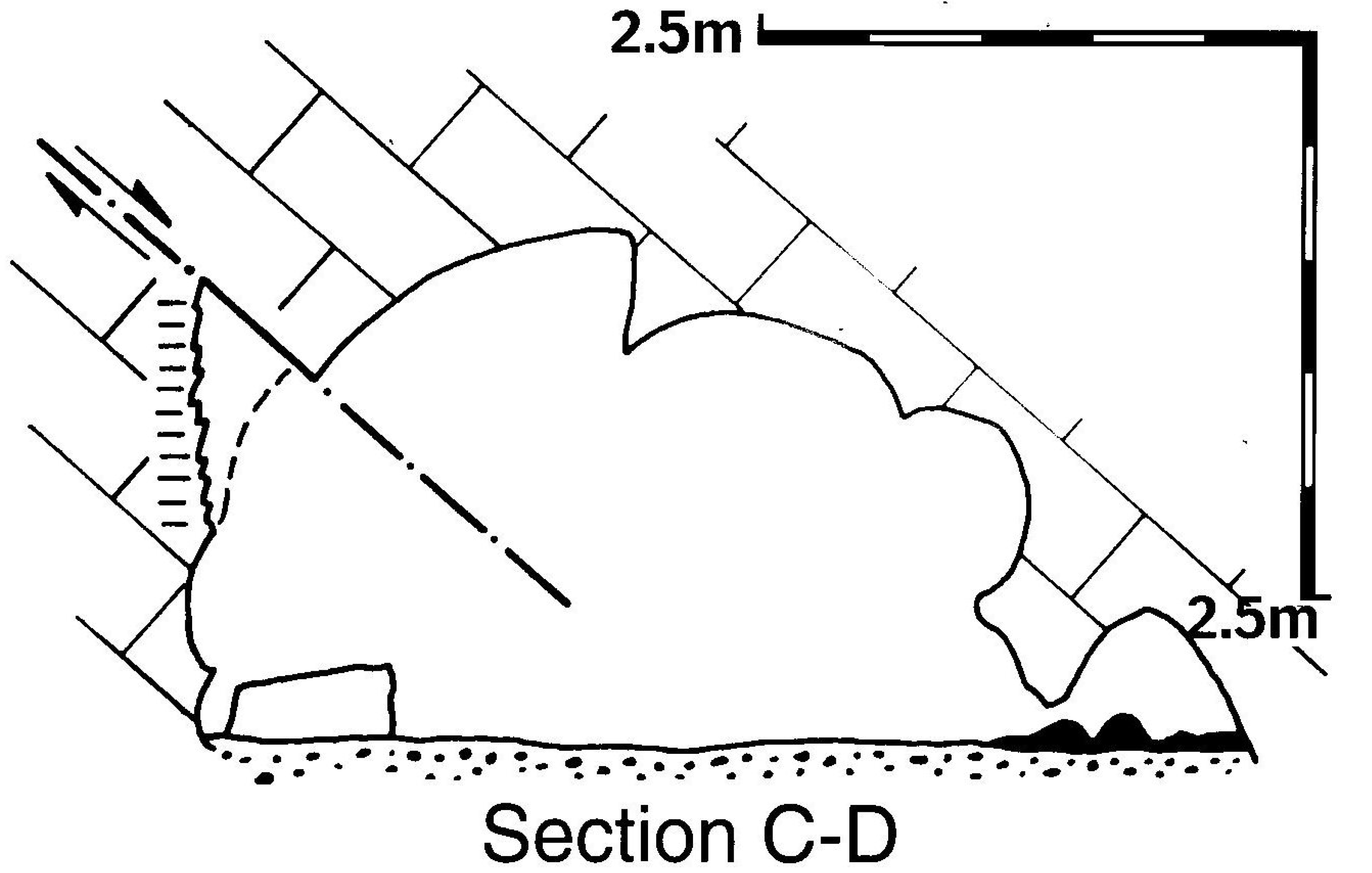

Fig. 5. C-D cross-section with fault 1 and 'Fontaine-Bagdad' gallery morphology.

Neotectonics activity

Brittle and stress analysis

In the cave, two types of faults are recognised. The first type of faulting is contemporaneous of the Variscan folding, characterized by reverse motion along the bedding planes. The second type is the present active faults. In this group, one can see three main fault planes (faults 1,2,3, Fig.3 &4&5) and a minor fault, which affect the present karstic galleries and features. So, they present normal displacement along inherited bedding planes. Theses faults are inherited. The faults planes are covered by thin argillaceous bearing filon, slickensides, showing normal displacement and clearly belonging to post karstic events (not destroyed by water erosion). The amplitude of the displacement (20 cm) can be measured by the modification of little erosion features (Fig.4 &5). They are also accompanied by other minor faults affecting some recent calcite fabrics like speleothems (Fig 6d).

This system of normal faulting is clearly posterior to the recent karstic system. The structural elements permit to calculate a stress tensor by the direct inversion method (Angelier, 1990) (Fig.7, B). This system is characterized by an extensional main axis (σ_3) trending NW-SE.

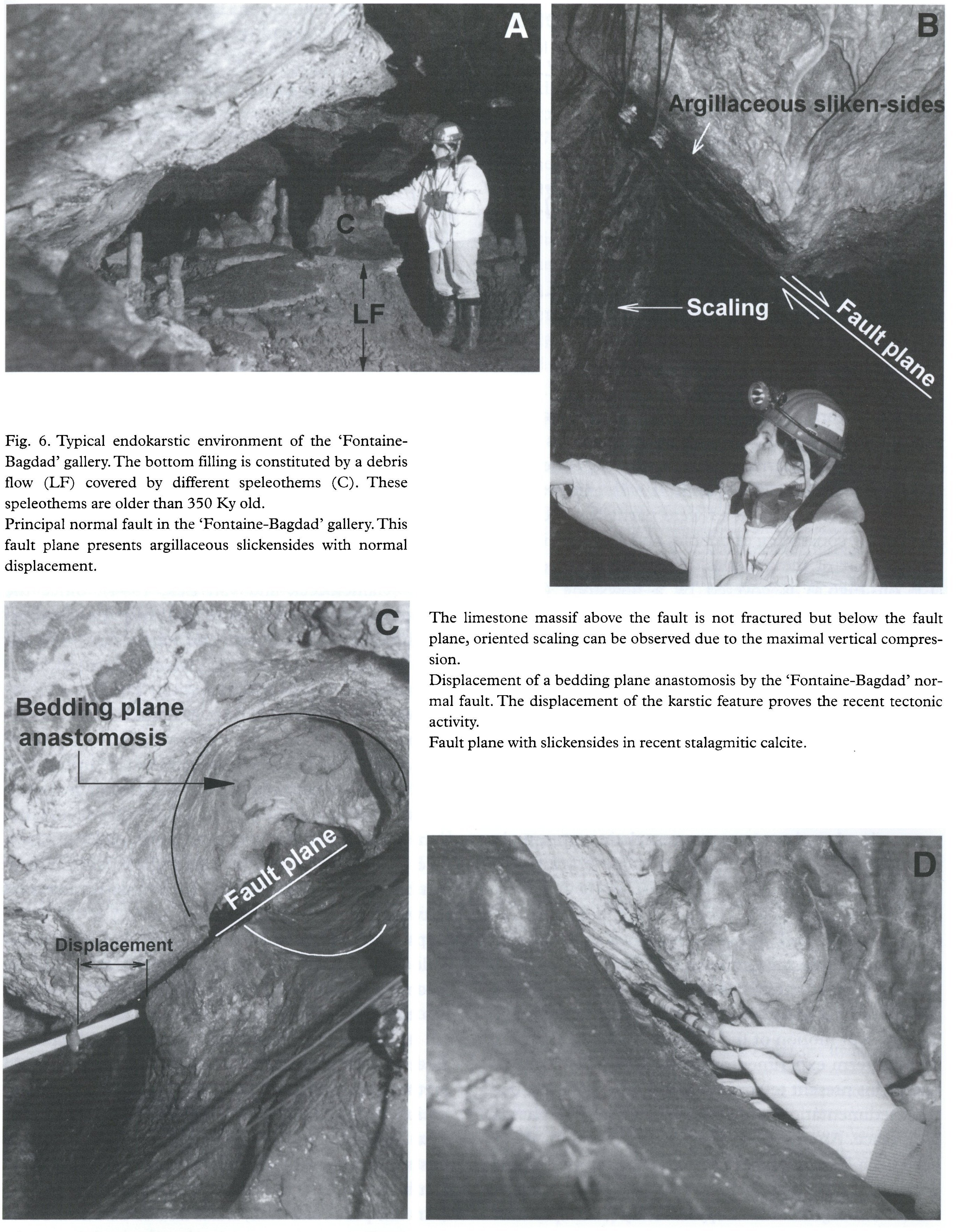

Fig. 6. Typical endokarstic environment of the 'Fontaine-Bagdad' gallery. The bottom filling is constituted by a debris flow (LF) covered by different speleothems (C). These speleothems are older than 350 Ky old.
Principal normal fault in the 'Fontaine-Bagdad' gallery. This fault plane presents argillaceous slickensides with normal displacement.
The limestone massif above the fault is not fractured but below the fault plane, oriented scaling can be observed due to the maximal vertical compression.
Displacement of a bedding plane anastomosis by the 'Fontaine-Bagdad' normal fault. The displacement of the karstic feature proves the recent tectonic activity.
Fault plane with slickensides in recent stalagmitic calcite.

Dating.

The tectonic features in the karstic cavities are well integrated into the evolution of the cave. The knowledge of the evolution of the karst is essential for the understanding and the dating of these recent tectonic events. In the example of Rochefort, what is the evolution of the galleries and its chronology? Rochefort

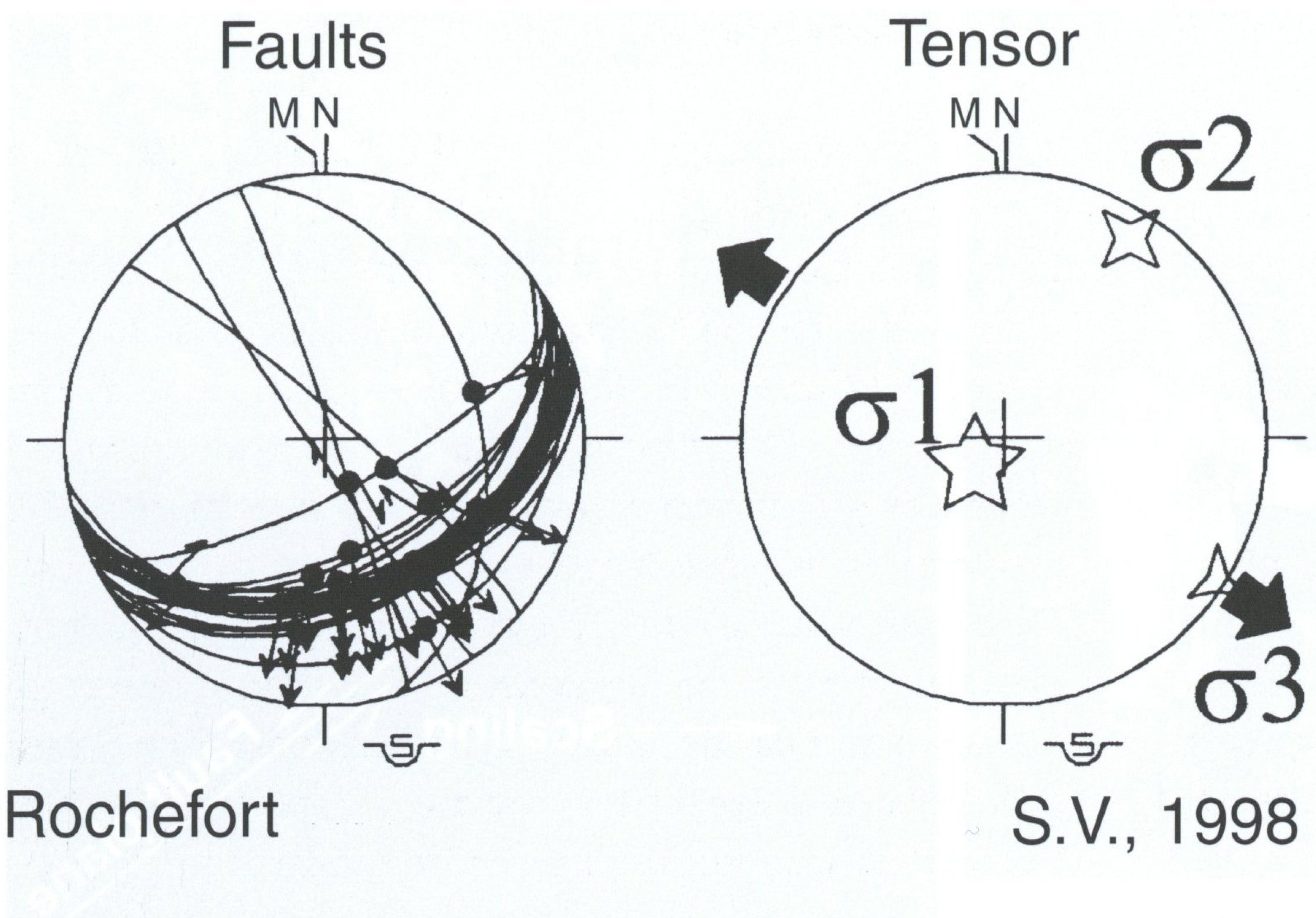

Fig. 7. Paleostress analysis of the recent faults affecting the Rochefort karstic network. The first diagram is the stereographic projection (Lower Schmidt hemisphere) of normal faults. The arrows represent the sliken-sides and the direction of movement. The second diagram represents the stereographic projection of the main axis of the stress ellipsoid. σ_1, σ_2, σ_3 are respectively represented by 5,4,3 stars. The side of the stars corresponds to the relative value of the f factor. σ_1 is the principal vertical axis. σ_2 and σ_3 are similar in magnitude and the principal extension NW-SE is shown by σ_3. The stress tensor is calculated by the direct inversion method (Angelier, 1990). ($\sigma_1>\sigma_2>\sigma_3$; σ_1=228°/77°, σ_2 = 032°/12°, σ_3 = 123°/03°, F = $(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ = 0.25, average angle a = 18° and the RUP is 38%, Angelier 1994.).

karstic network is linked by the evolution of the Lomme valley (Fig.2). Usually, this evolution is related to the Plio-Quaternary surrection of Ardenne massif (de Heinzelin, 1963; Quinif, 1997). After a first phreatic phase, the galleries were partially filled by a debris flow constisting of pebbles and clay matrix. So, on the floor of the galleries, the filling with pebbles (LF on Fig6.a) is covered by a flowstone (C on Fig.6a) and speleothems which are older than the limit of uranium series disequilibrium dating method (350 Ky). At this stage, it is not possible to precise the age of these karstic features. But, it is yet remarkable that the motion of the faults has affected recent soda straws still active. Thus, the recent tectonic or seismotectonic activity is very young because these active soda straw stalactites are broken along extension fissures. These stalactites are still active with flowing of water droplet; in consequence, their rupture is younger than the nineteenth century. During the tourist activity of the cave (in the last century), guides of the cave have taken broken stalagmites and put them on a big block, between this block and the roof. At present, these stalagmites are wedged. It is impossible to extract them. Column and fault basement present scaling as a consequence of the fault pressure. The present motion of the faults is currently analysed by long-term experiments (Quinif & al., 1997b). Between this present tectonic expression and the last detritic sedimentation, some speleothems growth phases took place. Among these speleothems, some of them have been broken and are sealed in flowstones. Thus, it can be noted that there is a succession of seismotectonic manifestations separated by calm periods. Maybe this is the expression of a geodynamics evolution with seismo-tectonic crisis separated by more or less long calm periods.

Discussion and Conclusion

The principal extension direction NW-SE obtained by inversion of recent faults of the Rochefort Cave is nearly perpendicular to that of the actual stress field (Müller et al., 1992) and also to that of the mechanism of the last regional earthquake of Roermond in 1992 (Camelbeeck and van Eck, 1994). Since the Cretaceous (Vandycke, 1992) and in particular during the Quaternary (Bevan and Hancock, 1986), the NW European platform was also influenced by a stress regime in NE-SW extension. The NE-SW extension was also derived from earthquake focal mechanisms in the Rhine Graben where, as in this case study, the deviatoric components of σ_1 and σ_3 are nearly of the same order of magnitude but have opposite signs (Plenefisch and Bonjer, 1994). An explanation of the discrepancy between the regional stress field and that observed locally in the Rochefort cave can be that they are related to each other by inversion of two of the three main axis (σ_2 and σ_3) of the stress ellipsoid (Angelier and Bergerat, 1983). Another possible explanation can be that the faults in the Rochefort cave move in response to a local stress as it has been already observed for earthquakes, for example in Iceland (Bergerat & al., 1998). In this specific case, a correlation has been established between earthquakes and fault structures resulting from tectonic stresses acting in a direction perpendicular to that corresponding to the earthquake. We favoured this second hypothesis, which nevertheless has to be confirmed by other field evidence.

In this particular case, it has also to take in account that the faults are inherited (Angelier, 1994) and use the previous bedding planes. In the cave of Rochefort, we provide evidence that, after the Hercynian tectonics and the karstic development of the cave, there is successive expression of brittle damage. In this folding Hercynian structure, the recent deformation is low in magnitude and the stress has to use the minimum energy to produce these present brittle structures. In this context, minor faults in the speleothems with oblique slickenside on fault plane are observed (Fig. 6d, Fig.7). These striated faults in the calcite flowstone are also evidence of post karstic and recent tectonic activity.

In the NW European Quaternary context, data concerning the recent tectonic activity are punctual, anecdotal and exceptional: stratigraphic structures are very diversified and most of the NW European Quaternary sediments are incompetent in terms of mechanical analysis (lack of visible striated faults). In addition, the recent continental sedimentary series are often discontinuous and it is very hard to date them. In this poor informant context, the observations provided by the Rochefort cave are very interesting. The properties of many palaeo-environmental parameters recorded by the karst are now well known: structure of the karstic network, morphological features, the endokarstic sediments have characteristics which are function of the evolution of relief, palaeo-climates, tectonics and mechanical behaviour of the massif. Because of the quasi lack of erosion in the dry galleries, karstic morphological features are conserved. Adding by the fact that it is possible in favourable cases to date speleothems by uranium series disequilibrium, caves are a favoured field investigation to constraint recent tectonic and paleoseismic activities. Of course, now, the behaviour of the cavities in relation to the regional constraint is poorly known. Nevertheless, structural features (faults, joints, scaling, etc..) in this study are the classical marks of the tectonics and are thus easily used. This tectonic context is a particular case of the interaction, which exists between karstification and brittle tectonics (Quinif et al., 1997 a) since it is here a tectonic record after its formation. Our observations provide evidence that these tectonic features are very recent and are always active. In the NW Europe, some crustal structures areas are active during the Holocene (NASZ, Lower Rhine Graben) and show continuity in their dynamics. Thus, it is very important to know their influence in the neighbour areas, which are generally considered stable and non-interactive. It has been shown here that the recent tectonics has been superimposed to the existing tectonic structures. In Ardenne Massif, karst allows the study of these inherited and new tectonic structures. Particular and original morphologies in caves are very good witnesses of recording post-genetic modifications like tectonic movements and earthquakes consequences.

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