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CONTRIBUTION OF A SEDIMENTARY STUDY TO THE CONCEPT OF KARSTIC EVOLUTION OF A CHALK CAVE IN THE WESTERN PARIS BASIN (NORMANDY, FRANCE)

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(7 figures)

ABSTRACT. The Petites Dales cave is a favourable site for studying the sedimentary fill of the karst in the chalk of Normandy. The study of the fill is based on the lithological characterization and mineralogical and chemical comparison between the karstic sediments and the likely sedimentary sources (insoluble residue of chalk, clay-with-flints, loess). Results show that there are three main families of sediment in the Petites Dales karst: brown clayey silts, beige silts, pale beige silts. The karst sediments essentially originate from the mechanical erosion of loess. The insoluble residue of chalk, derived from the weathering of the chalk, is only found in the brown clayey silts, and constitutes a weak amount of this sediment type. According to these results, three conceptual models are proposed for the hydrosedimentary behaviour of the Petites Dales karstic system that could have resulted in such an intra-karstic deposition sequence. The integration of the sedimentary data into the morphological study of the galleries and their arrangement contributes to the conceptualization of an evolutionary pattern of the underground network in its paleogeographic context.

Keywords: karst sediment, Pleistocene evolution, conceptual models.

1. Introduction

Karst filling sediments are well known to offer good information about i) the genesis and the evolution of caves, and ii) the quaternary climatic variations and regional geomorphological and geological evolution. They are better records of depositional conditions than the surface sediments, because they undergo less weathering and disturbance (Ek & Quinif, 1988): karstic deposits are hardly affected by temperature variation, rain, wind, sunlight and bioactivity.

Karstification phenomena are very developed in the chalk of the Paris Basin (Rodet, 1992). In the chalk substratum, surface weathering and karstification are connected. The karstic conduits can either be considered as sites of weathering (Rodet, 1996), as storage volumes for eroded material and also as transit places (Massei *et al.*, 2003).

In the Paris basin, karst was essentially studied under a morphogenetic point of view (Rodet, 1992, 1997a, 1997b), whereas the sedimentary approach of karst deposits was very poorly developed. Karst filled with sediments are difficult, even impossible of access. This explains the rather limited knowledge concerning these deposits. The Petites Dales cave (département Seine Maritime) is a favourable site for studying the sedimentary pile as many speleological investigations (clearing passages for investigation) have been carried out on the site during the past two decades. Hence, the current penetrable part is about 550 m in length and 10 m high, which corresponds to the 13th most important development for a penetrable chalk cavity in the Paris Basin.

This cave is the place of the first analytical study of the sedimentation in the karst of the Paris Basin. In this context, the aims of this work were numerous. First of all, the study consisted to characterize the sediments of the Petites Dales karstic filling from varied lithological analyses (Laignel *et al.*, 2004). Mineralogical and chemical comparisons between the karst sediments and the likely sedimentary sources (insoluble residue of chalk, clay-with-flints, loess) were then carried out to determine the origin of the filling sediments. The results allowed to propose several models of hydrosedimentary functioning of the Petites Dales karst. Finally, the correlation between the filling dynamics and the hydromorphology of the passages gives way to a conceptual model of the cave evolution.

2. Geomorphological and geological contexts of the Petites Dales cave

The entrance of the Petites Dales cave is located in a chalk quarry situated in Petites Dales village (Lambert I coordinates: X 470,17; Y 236,67; Z +30m NGF), near the town of Saint-Martin-aux-Buneaux (Fig. 1). The cave entrance is perpendicular to the East side of the Petites Dales hanging valley above the shoreline. This entrance is situated at about 1.3 km off the coast. The cavity does not present permanent drainage (Rodet & Viard, 1996).

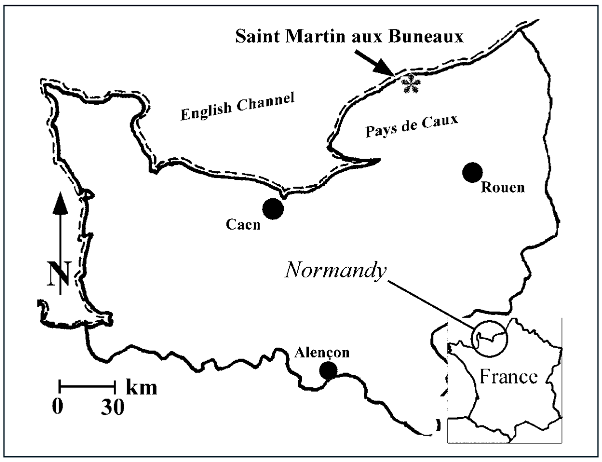

Figure 1. Location map of the 'Petites Dales' area, near the Alabaster Coast, north of the Pays de Caux region.

The cave is developed in chalk with flints of Coniacian age (Breton *et al.*, 1993). This lithological unit is succeeded by chalk with flints of Santonian age, which locally terminates the Cretaceous sedimentary series. The chalks are covered by a clay-with-flints deposit, produced by atmospheric weathering of the chalk and dated Pliocene-Quaternary (Laignel *et al.*, 1999; Quesnel *et al.*, 2000). Finally, Quaternary loess, an eolian periglacial deposit (Lautridou, 1985), is draped over the clay-with-flints and some residual Caenozoic deposits (pebble beds attributed to the Thanetian). This succession represents the typical geological section of the northwestern Paris Basin. The Petites Dales cave is a karst with alterites coverage according to Nicod's classification (1992).

According to Rodet (1997a), the subterranean network corresponds to the paragenetic model described by Renault (1967), commonly observed in the caves of the western Paris Basin: the formation process of the karst conduits goes bottoms up, building progressively on the previously deposited sediments (Rodet *et al.*, 1995).

The Petites Dales cave, described by Rodet & Viard (1996), consists of a main gallery, explored over 440 m of lateral development, for 10 m height (according to borehole cores in the sedimentary fill) and 2 to 5 m width (with maximal width observed at the cave entrance and in the 'Espace des Six' chamber), with two small tributary passages, giving a total development of 550 m (Fig. 2). It is the most important cave of the département Seine Maritime (Rodet, 1997b). The main axis shows a succession of rectilinear and sinuous sections. In the

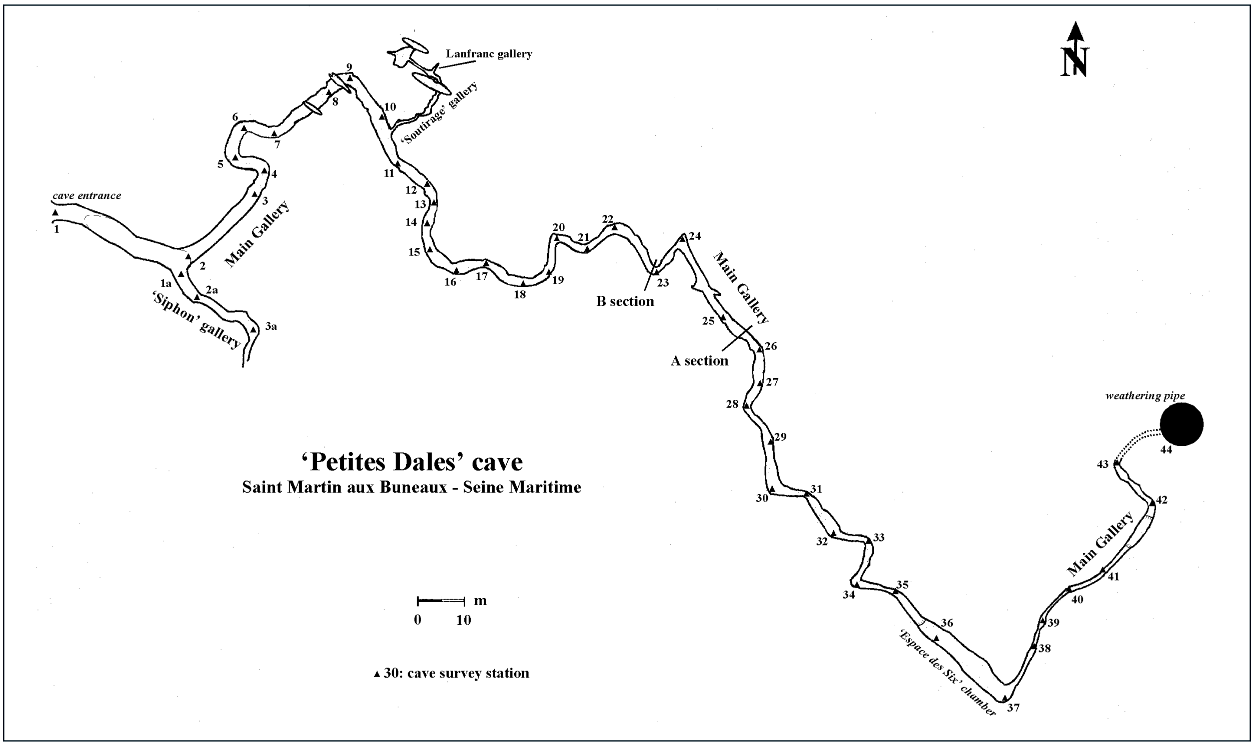

Figure 2: 'Petites Dales' cave survey (after Viard, 2004).

downstream part of this axis, two secondary drains join the main one. The drain morphology gives evidence of an evolution from an anastomosed network, which became reduced to a main collector by concentration of drainage (Coquerel *et al.*, 1993).

3. Lithological characterization of the Petites Dales cave filling

The Petites Dales cave is the most important investigated karstic network of the littoral valleys of the chalk areas along the English Channel borders. Sections of 2 m high at the top of the sedimentary filling are visible in continuity all along the main gallery. Methodology and results were developed by Laignel *et al.* (2004).

3.1. Methodology

3.1.1. Sections survey

Two sections A and B were studied in the upper two metres of the sedimentary filling. The distance between the 2 sections is 21,6 m (Fig. 2). Observations consisted then in noting thickness, colour and texture of the sediments. A sampling was then carried out according to the different observed sedimentological facies.

3.1.2. Granulometric analysis

The grain-size distribution is studied by means of two methods: 1) Coulter Counter Multisizer (Lafite, 1995; Lacroix *et al.,* 1998) for the fraction of size < 50 µm; 2) classic sieving for the fraction > 50 µm. Results are expressed in 5 granulometric fractions: clay and fine silt: d < 10 µm, medium and coarse silt: 10 ≤ d < 50 µm, fine sand: 50 ≤ d < 100 µm, medium sand: 100 ≤ d < 500 µm, coarse sand: d ≥ 500 µm (d: particle diameter).

3.1.3. Mineralogy by X-ray diffraction

The clayey and non clayey minerals were studied by diffraction of X-rays (DRX) on the <50 µm and < 2 µm fractions of sediment (Brindley & Brown, 1980; Holtzapffel, 1985).

3.1.4. Chemical analyses

The major chemical elements in < 2 mm material were determined by gravimetry after alcaline fusion for SiO_2, colorimetry for Al_2O_3 and TiO_2, atomic absorption spectrometry for CaO, MgO, MnO and Fe_2O_3, and emission atomic absorption for Na_2O and K_2O. The precision of results is 2 %.

3.2. Results

3.2.1. Observations

Three main families of sediments where distinguished: brown silty clays (A4, A7, A10, B3, B5, B8 and B13), beige silts (A1, A2, A6, A11, B1, B9, B11 and B14) and pale beige silts (A12, B10 and B12). A5, A8, A9, B4, B6 and B7 are beige silts containing millimetric beds of brown silty clays (rather numerous for B4 and A5 and little numerous for the other sub-units); A3 and B2 are a marker bed of calcite. These sediments get organized under the shape of beds of various thicknesses (0,1 in 20 cms) showing a rythmicity to the different scale (centimetric or millimetric). These beds can be regrouped in two complexes showing so a third scale of rythmicity (decimetric).

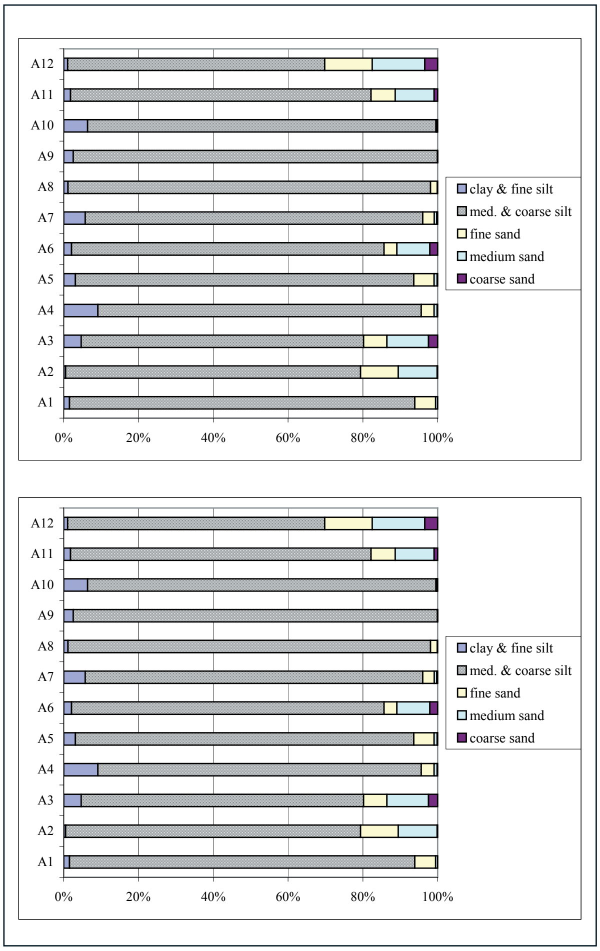

Figure 3. Grain size distribution of sediments sampled on the section A and B of sedimentary fillings of the 'petites Dales' cave. Clay & fine silt: < 10 µm; med. & coarse silt: 10-<50 µm; fine sand: 50-<100µm;medium sand: 100-<500 µm; coarse sand: 500 µm-2 mm (after Laignel *et al.*, 2004).

3.2.2. Grain-size distribution

The sediments of sections A and B are very widely dominated by the 10-50 µm fraction (medium and coarse silts ≥ 70 %) (Fig. 3). Granulometric analyses show that there is a relative sedimentary homogeneity between sections A and B and we find systematically, in agreement with observations, 3 main families of sediments (brown clayey silts, beige silts, pale beige silts), to which one can add the marker bed of calcite. For this reason we chose only the samples of the section B to define more exactly the mineralogical and geochemical characteristics of sediments.

3.2.3. Mineralogical Characterization

For all families of sediments (with the exception of a calcite bed), the non-clayey minerals are largely dominated by quartz, which represents more than 90 %. Feldspars are also observed (2-6 %), and four samples contain not more than 1 % of dolomite and calcite. Only the calcite bed is different from the other sediments, with 8 % of quartz and 92 % of calcite. The clayey minerals are smectite (39 to 76 %), kaolinite (16 to 38 %) and illite (7 to 31 %).

3.2.4. Chemical characterization

The three major constituents are SiO_2 (67 to 85 %), Al_2O_3 (6 to 13 %), and Fe_2O_3 (2 to 5 %).

3.2.5. Lithological synthesis

The lithological characterization of sediments from the Petites Dales cave shows that the cave fill is mainly composed of silts rich in smectite and SiO_2, and poor in kaolinite, Al_2O_3 and Fe_2O_3. However, it is possible to distinguish three main families of sediments: (1) brown clayey silts relatively rich in smectite, Al_2O_3 and Fe_2O_3, and poor in kaolinite and SiO_2; (2) pale beige silts relatively poor in smectite, Al_2O_3 and Fe_2O_3, and rich in kaolinite, illite and SiO_2; (3) beige silts, with an intermediate mineralogical composition between the brown clayey silts and pale beige silts and chemical composition identical to that of the pale beige silts.

4. Sediments origin of the Petites Dales cave filling

According to the geological context, three sources are possible for the Petites Dales cave sediments: loess and/or clay-with-flints, by way of mechanical erosion, or the insoluble residues of chalk, by way of chalk weathering. Data acquired on the karstic sediments were compared with the bibliographical data of the likely sources: loess (Lautridou, 1985), surrounding chalk and clay-with-flints (CWF) (Laignel, 1997; Laignel *et al.*, 1998a, 1998b, 2002). Once deposited in the karst, the insoluble residues of the chalk are considered as autochtonous or endogenous deposits and loesses or CWF as allochtonous or exogenous deposits. Terms endogenous and exogenous are used in the sense of Ford & Cullingford's English classification (1976) in Ek & Quinif (1988).

4.1. Sediments origin - granulometric evidence

The grain-size distribution of the karstic sediments is widely dominated by the medium to coarse silt fraction (10-50 µm). Among the three sediment sources, loess is consisting predominantly of particles ranging in size between 10 and 50 µm (Lautridou, 1985). This is a first argument indicating that the karstic sediments origin is mainly loess.

4.2. Sediments origin - geochemical evidence

To compare sources and sediments of the karstic fill, we expressed graphically the quantities of Al_2O_3, Fe_2O_3 and SiO_2 (Fig. 4). The graphic representation of % Al_2O_3 = f (% SiO_2) indicates that the karstic sediments are very

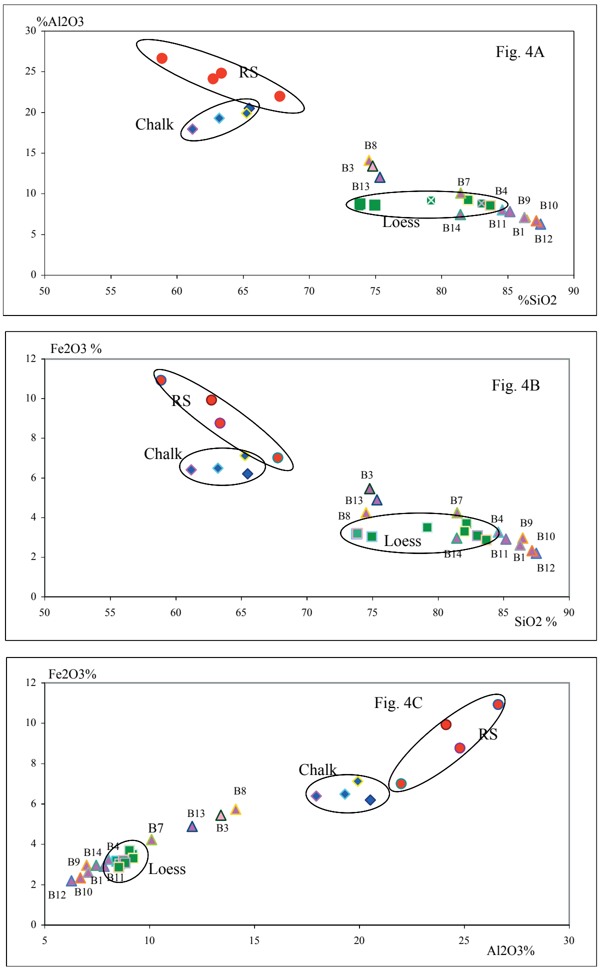

Figure 4. Comparison of SiO_2, AlO_3 and Fe_2O_3 contents between the karstic sediments of 'Petites Dales' cave and the potential sedimentary sources (insoluble residue of chalk, clay-with-flints, loess). RS: clay-with-flints or CWF, B: karstic sediments sampled in the B section (after Laignel *et al.*, 2004).

close to the plot of loess (Fig. 4A). The karstic filling has so an obvious loessic component. The graphic representation of % Fe_2O_3 = f (% SiO_2) confirms the previous one (Fig. 4B). The graphic representation of % Al_2O_3 = f (% Fe_2O_3) confirms also the previous ones (Fig. 4C).
Chemical comparisons show that the sediments origin of the Petites Dales karstic filling is mainly loessic. However, in detail, there are two scenarios: (1) brown clayey silts consist of a mixture of loess and insoluble residue of chalk and\or CWF, loess representing dominant phase; (2) silts consist only of loess. However, some silts, notably the most pale, are enriched in SiO_2 and reduced in Al_2O_3 and Fe_2O_3 with regard to the loess, credibly interpreted as a washing out of the fine fraction < 10µm.

4.3. Sediments origin - mineralogical (clayey fraction) evidence

A smectite-kaolinite-illite diagram was performed so as to compare the proportions of these three minerals between sources and sediments of the karstic fill (Fig. 5). As for the results of the chemical analyses, the various populations of sediments form several groups on the diagram. The CWF is relatively rich in kaolinite whereas chalks, loess and karstic sediments are more close to the smectite pole. With regard to chemical comparison, this allows to exclude the CWF as possible origin of the karstic fill. The karstic sediments are situated near the plot of loess, showing that their origin is mainly loess.

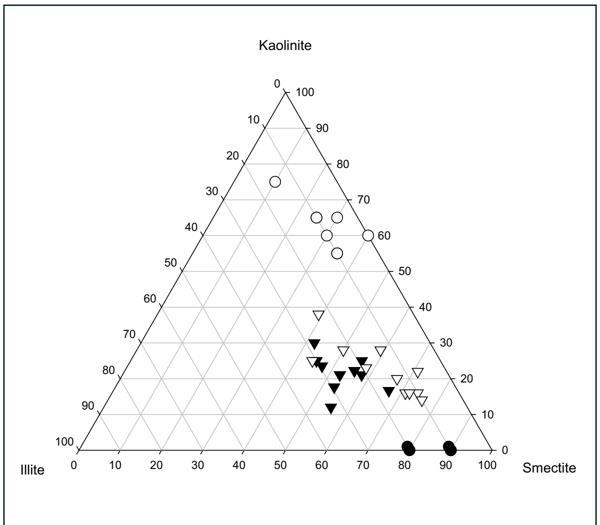

Figure 5. Comparison of clay mineralogy between the karstic sediments of 'Petites Dales' cave and the potential sedimentary sources (insoluble residue of chalk, clay-with-flints, loess). Craie: chalk, RS: CWF or clay-with-flints (after Laignel *et al.*, 2004).

4.4. Synthesis on the sources of the sediment

The sediments origin of the Petites Dales karstic fill is essentially loess. Loess is eroded at the surface by the mechanical effect of the runoff or by suffosion, a frequent sub-surface erosion process in loess (Pellegrin & Salomon, 2001). The loess particles are transported in suspension by flowing water, entering into the karst through sinkholes, and deposited within the karst aquifer. The insoluble residue of chalk is weakly represented, mixed in small quantity with particles of loess. Furthermore, it was demonstrated that there were no contribution of the CWF, according to Reams (1968), for whom the clay of karsts can have two possible origins: the limestones weathering; and sediment inputs from the surface by mechanical erosion. These results do not follow those of Sweeting (1973).
The absence of allochtonous karstic deposits (from the CWF) could be surprising if one considers the important coverage of alterites and numerous dissolution vertical pipes filled with CWF in the Pays de Caux county. The discovery of a vertical pipe (about 430 m upstream from the cave entrance) connected to the main gallery would imply the existence of karst deposits originating from the clay-with-flints at the bottom of the fill. As no CWF has been observed at the top of the fill, we can suggest the following hypothesis: the vertical pipe establishes a connection between the plateau and the endokarst. Thanks to this connection with the endokarstic horizontal network, the sedimentary content of the pipe (essentially CWF and loess at the top) is drawn downwards. Once the CWF within the pipe section has been displaced, only loess would be eroded at the surface in an area draining into the pipe, transported downwards through the pipe and deposited in the karst. Indeed, it is proved that the unconsolidated loess cover is particularly sensitive to erosion (notably for the current period: Le Bissonnais, 1988), whereas the CWF cover is often compared to concrete, highly resisting to erosion (Callot & Pédro, 1977a, 1977b ; Laignel, 1997 ; Quesnel, 1997). Such a hypothesis supposes the presence of CWF-derived sediments at the base of the fill. However, only the upper two metres were effectively studied whereas the total thickness of karstic deposits is of the order of 8 to 10 m. To check this hypothesis, it is necessary to get to the bottom of the fill with a borehole, down to the contact between the chalk substratum and the fill. It is so verified that the sedimentary budget offered to the karstic domain is mainly of superficial origin (Lacroix *et al.*, 2000). The surface behaves as a sedimentary stock, the infiltration zones are especially transit zones and the karst is a sedimentation environment.

5. Hydrosedimentary behaviour of the Petites Dales karst

In order to assess hydrodynamic conditions during the settling of intra-karstic sediments, we calculated the percentile d_{95} of the grain-size distribution of the various samples of karstic sediments taken from section B. The values obtained were then reported on a Hjulström's diagram (Dercourt & Paquet, 1995), according to the method of Renault (1967) and Bögli (1980). For the totality of the sediments of the Petites Dales cave, the flow velocity values are weak, ranging from 0,4 to 1,6 cm/s. According to the flow velocity, Renault (1967) distinguishes two categories of galleries: syngenetic galleries with a velocity > 10 cm/s and paragenetic galleries with velocity < 10 cm/s. The low flow velocities, found here, confirm the works of Rodet (1992), Rodet *et al.* (1995) and Rodet & Viard (1996): the Petites Dales karstic system is a paragenetic cave with a continuous sedimentation. Corrosion occured only at the roof, contrary to syngenetic galleries where it occured on all the gallery section (Renault, 1958, 1967).

More precisely, the brown clayey silts would have settled for flow velocity of 0,4 - 0,5 cm/s. The beige silts would have settled for flow velocity of 0,9 - 1,1 cm/s and the pale beige silts with flow velocity of 1 - 1,6 cm/s. The entire range would then correspond to about 15 to 60 m/h: it would correspond approximatively to what is observed in functional karst systems (70 to 200 m/h). The calculated values of flow velocities are nevertheless lower than those measured at functional sites. It is probably due to the uncertainty of such a method of calculation. However, they correspond more or less to the same order of magnitude and are quite representative of conduit-system flow.

Finally, the results allow to propose three conceptual models of hydrosedimentary behaviour of the Petites Dales karst (Fig. 6).

The brown clayey silts (mix loess-insoluble residue of chalk) are characterized by a non negligible < 10 µm granulometric fraction and a quasi-absence of > 50 µm-particles. This absence might be explained by a size-sorting at the surface during the erosion of loess: only particles < 50 µm would have been transported consequently to surface erosion. Furthermore, < 10 µm-particles enrichment would result from decalcification of the surrounding chalk (chemical weathering), led to an increase of smectite concentration and to an enrichment in Al_2O_3 and Fe_2O_3 in the deposit. This supposes a low

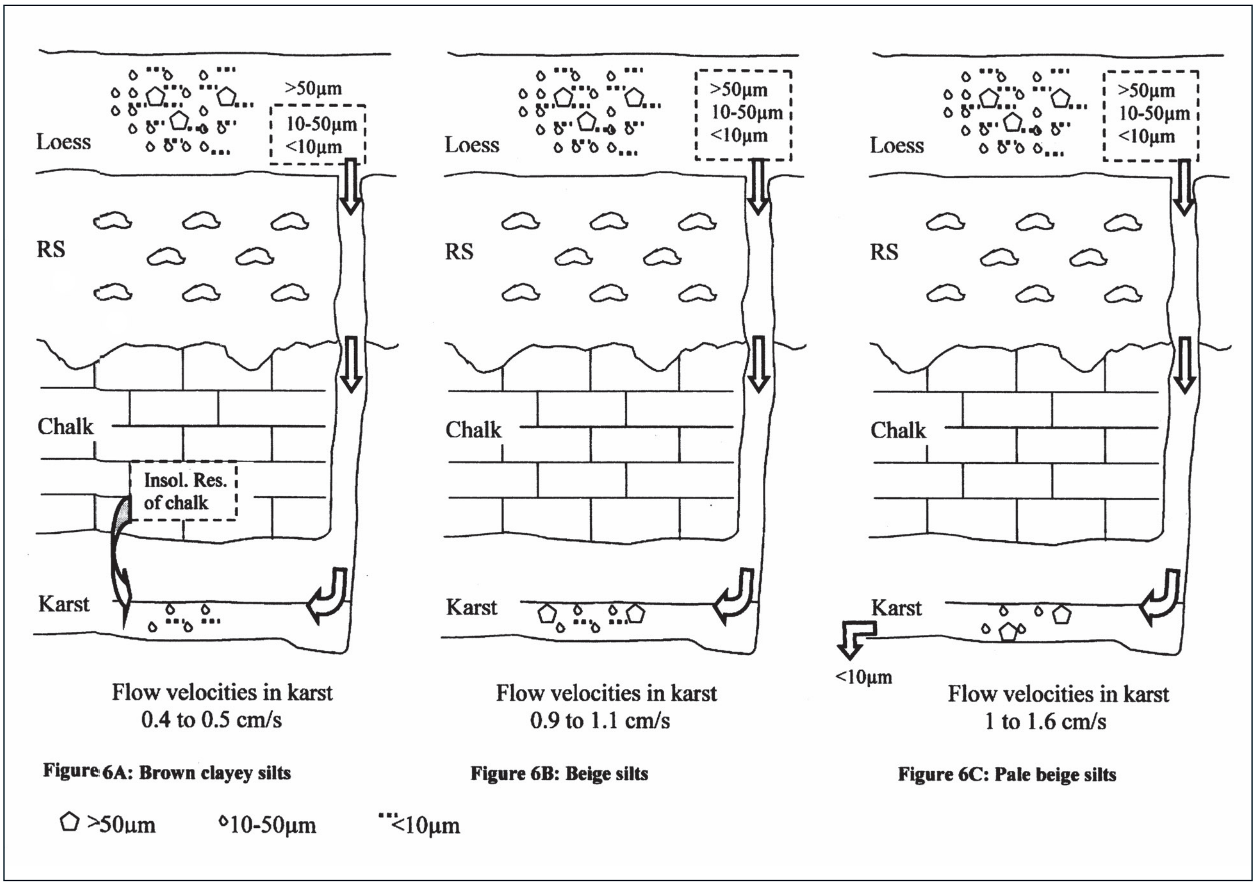

Figure 6. Conceptual models of hydrodynamical behaviour of Petites Dales karstic system (after Laignel *et al.*, 2004). RS: clay-with-flints or CWF. 6A: conceptual model of hydrodynamical behaviour of the brown clayey silts deposition. 6B: conceptual model of hydrodynamical behaviour of the beige silts deposition. 6C: conceptual model of hydrodynamical behaviour of the pale beige silts deposition.

energy hydrodynamic conditions with slow flow (flow velocities: 0,4 to 0,5 cm/s), which allowed a rather long residence time of waters within the chalk aquifer, and not led sorting in the karst (the totality of sediments eroded in surface settles in the karst, as well as the products of the chalk decalcification).

To obtain the beige silts, a complete erosion of loess at the surface is needed. There is any sorting at the surface. Furthermore, the residence time of water in contact with the surrounding chalk is reduced, so that there is no chemical weathering of the chalk, or enrichment in fine particles. The hydrodynamic conditions are weak because there is practically no sorting, but they are yet stronger than in the previous case.

Finally, the pale beige silts, corresponding to the deposits of "leached loess" type, also suppose a complete transport of eroded loess without any size-sorting at the surface. However, the particles < 10 µm are almost not represented in these deposits. This absence shows that there is no decalcification of the surrounding chalk and furthermore the underground flow operated some sorting of the transported sediments.

6. Conceptual model of the Petites Dales karst evolution

The cave with over 550 m of explored galleries, is the main chalk karst feature of the Paris Basin. As it became accessible first in 1991, the explored length is still increasing steadily. The cave offers a simple organization pattern, composed by a long main conduit ten metres high, filled before the speleological excavations, with only a couple of 3 m high, wholly infilled and fossilized tributaries joining at the main gallery base. Along the 450 m of the main gallery, we noted several geomorphological features.

The first observation is at the entrance section which is 30 m long and 5 m high and wide. This section is really bigger and wider than the main gallery upstream, and an attentive study of the walls demonstrates that the roof is not made by the main gallery but by a 30° inclined uplifted 'Siphon' tributary, representing a 0,5 m step with the main gallery's roof.

The second observation is the contact with the 'Soutirage' tributary, by a 6 m vertical shaft through the terrigeneous infill. This morphological specificity results from a different hydrodynamic evolution from the Siphon's tributary.

6.1. Conceptual evolution model

Six chronological stages were identified for the network evolution (Fig. 7):

1- Within the chalk aquifer, a very anastomosed pattern of small karstic tubes is created. This is the complex inception stage, including the early weathering genesis, but we did not identify specific elements of this period.

2- As a result of coalescence processes, an important stage of water concentration organizes the karstic network into several collectors which connect to a main gallery.

3- The main gallery become the only draining collector, the other galleries are disconnected and fossilized. The main gallery evolutes upward over its fill til 10 m high.

4- The upstream part of the 'Siphon' tributary (2nd stage) is breached by the dale opening which uses it like a bypass,

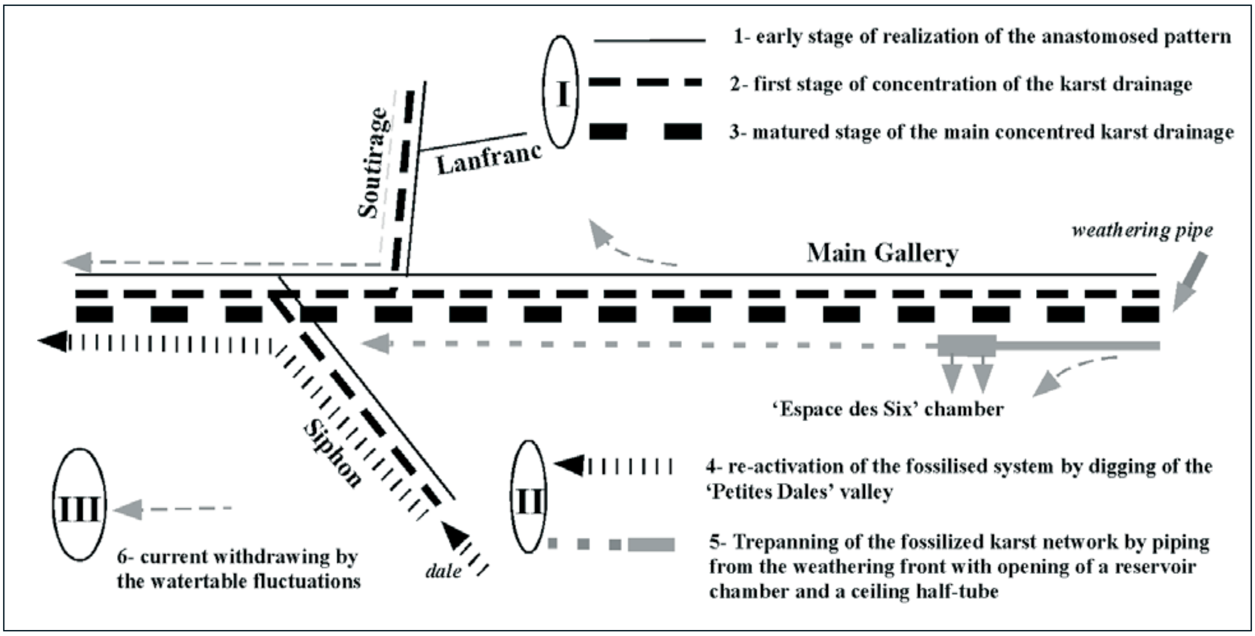

Figure 7. Conceptual model for the karst network evolution of 'Petites Dales' cave. I: the sea is far from the cave (several kilometres), II: the approach of the sea border (few kilometres) results in the valley excavation, III: the current shore line is resulting in a hanging valley (1.3 km far from the cave entrance).

calibrating it until the junction with the Main Gallery which presents morphological adaptations in the entrance part. The resurgence gallery is lost because of the quarry activity on the dale border.

5- The breaching of a weathering pipe upstream in the Main Gallery allows an important influx of water and heterogeneous sediment, part of which is produced by the chalk weathering but the main part coming from the surface (loess). This input mechanism happened several times which resulted in surface ablation and massive underground deposits. We can attribute the visible adaptation morphologies in the Main Gallery to the pipe functioning: oblique top conduit near the breach, opening of the penetrable roof half tube (medium section: 1 m large, 2 m high), opening of an equilibrium chimney with lateral water leaks in the 'Espace des Six' chamber, opening of a small roof half-tube with a decreasing size downstream from the chamber until the 'Siphon' confluence.

6- The withdrawal created by high water level stages flooding the cave lower conduits, is an ongoing mechanism observed in 1995 and 2001. In spite of the absence of a direct observation, it seems evident than such flooding can be more abundant and could flow out by the cave entrance in the valley, but it cannot be demonstrated that this phenomenon is fossil (Holocene) or actual.

6.2. Relations with the regional Quaternary evolution and essay of datation

A three stage regional evolution can be proposed:

I- The first regional geomorphological period concerns a continental karst pattern, far from the sea border, developed in three steps from an anastomosed karst network to just one collector, passing through a complex concentration stage of the water drainage growing every time bigger with less numerous drains. Geomorphological data should prove that the cave started to develop before the valley incised. The Early to Middle Pleistocene is the assumed age for this important first karst stage; the sea coast is several (tens) kilometres far from the present shoreline. None element due to a littoral influence has been identified.

II- The second geomorphological period is a fossilized karst network cut by the 'Petites Dales' valley. The morphological incidence of the downcut is visible in the 'Siphon' gallery used as a bypass for the valley's drainage, which calibrated the conduit. As the passage develops several metres under the actual top of the Main Gallery, the exogeneous flow opened an important half-tube of the gallery's size, with reversed-sloping (30°) roof, which also calibrated the Main Gallery after the confluence. That explains the exceptional size of the section, both of the 'Siphon' gallery and of the Main Gallery downstream of the confluence, and the section size contrast between the upstream part and the downstream part of the Main Gallery. The opening of the Petites Dales valley is due to the partitioning of the continental groundwater basin by the approaching shoreline. This stage is supposed to have happened during the Middle Pleistocene, and the hanging valley's position over the present shoreline is consistent with an Eemian age. The upstream cutoff of the Main Gallery by a weathering pit could have happened during this period, but after the valley's opening, because the development of the 'Espace des Six' chamber seems to be connected with a tributary dale.

III- The third geomorphological period is the Present: the shoreline has come to 1,3 km from the cave entrance, but 30 metres lower. The cave and the valley do not offer any geomorphological element due to the proximity of the shoreline that demonstrates those features were fossilized before the sea arrived in its present place. This stage is Late Pleistocene/Holocene. The only appreciable activity of the cave is the watertable fluctuation which could result in flooding the basal conduits, creating erosion gullies in the filling and perhaps sediment removal from the cave entrance. This ultimate function, demonstrated by the filling morphology between the 'Soutirage' gallery and the cave entrance, has never been witnessed.

7. Conclusion

The 'Petites Dales' cave is an important site for karst study in the western Paris Basin. The lithological characterization of the sediments of the Petites Dales karstic filling showed that they are essentially composed of silts. Nevertheless, it is possible to distinguish three main families of sediments, which present a rythmicity at several scales. For the first time in chalk karst, cave fill characteristics are related to their geomorphological context, allowing the construction of a conceptual model. The dating of the Petites Dales karst is difficult, as no speleothems could be found in the cave. Nevertheless, the presence of loess in the karst suggests that filling started during the Quaternary, more exactly during the Pleistocene, because of its relation to the time of loess deposits on the plateaus of the western Paris Basin. The method used in this study can be applied to other sedimentary fills of cryptokarsts, especially in the English-Parisian chalk basin.

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