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The Charente karst basin of the Touvre: alteration of the Jurassic series and speleogenesis by ghost-rock process

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ABSTRACT: The Jurassic limestone of the North-eastern part of the Aquitain Basin (Angoulême, Charente, France) provide evidence of the prominent role of the ghost-rock process from the study of three quarries, drillings and the discovering of a young cave called "La Fuie" (Chasseneuil-sur-Bonnieure). This alteration process explains the genesis of maze caves and also the complexity of the Touvre aquifer which supplies the city of Angoulême. Indeed the large water reserve is situated into the porous rock (slow drainage) constituted by ghost-rocks while a small part is drained by the karst conduits (fast drainage coming from river losses). Moreover, for the first time a speleogenesis by ghost-rock process is demonstrated in a young and active subterranean network in Charente. La Fuie Cave, discovered during road works, was used as subterranean laboratory. Analysis of ascending collapse chimney and the discovery of ghost-rock combined with the study of piezometric level variations, recorded by a Luirograph, allowed to highlight a new way to drain residual deposits by flooding / dewatering of pseudo-galleries from ghost-rocks in cave system. At the same time, the piezometric level variations in the epiphreatic zone are the cause of a partial filling of the galleries.

KEYWORDS: Speleo-karstology, Ghost-rock weathering, SW France, Cave infillings, Piezometric level variations, Porous aquifer tank.

Introduction

In the context of the "Climanthrope" ANR program we led a PhD thesis (Dandurand, 2011) concerning caves and subterranean karst infillings deposits from the large karstic basin of the Touvre springs (Charente, France). Several studies have been devoted to La Rochefoucauld karst area concerning geomorphology (Enjalbert, 1947), hydrogeology (Rouiller, 1987; Larocque, 1997) and archeology (Debénath, 1974). But no speleological study had been conducted yet on one of the largest French karst basins. Considering the current knowledge regarding the alteration of carbonate platform and new approaches to scientific speleology, it was decided to clarify this general problem in the light of new facts that are part of the long geological time. These facts are first based on observations of quarries that demonstrate the existence of isovolumic weathering processes like « ghost-rock » as it was observed in quarries near Tournai city in Hainaut province, Belgium (Vergari, 1998; Quinif, 2010). This discovery answers a question that we asked about the origin of maze caves clogged of mud of Charente. Many of these cavities allow having a look on the water-table that fluctuates of several meters between periods of low and high waters. The classical speleogenesis schema by a progressive physicochemical dissolution along joints, cracks and fractures is questioned. The aim of this article is to demonstrate the prominent role of the ghost-rock process during the long geological time of Lower Cretaceous (45 Ma). We here provide a multidisciplinary approach to discuss the results in terms of regional palaeogeography and karstic evolution.

Geographical and geomorphological setting

The karst of La Rochefoucauld (Angoumois, Charente, SW France) is one of the largest French karst areas (550 km²). It develops on the North-eastern part of the Aquitaine Basin at the contact with western edge of the Massif Central (Fig. 1). It is structured by a series of three stepped low plateaus at altitudes decreasing westward between 120 and 250 m elevation. The only outlet known is the Touvre springs, the second biggest French resurgence (13 m³/s) after the Fontaine of Vaucluse (SE France).

The catchment, where three rivers converge, the Bonnieure, the Tardoire and the Bandiat, tributaries of the Charente river, lies mainly in the oolithic limestones of the Middle and Upper Jurassic (Fig. 1). The stratigraphy sequence is nearly uninterrupted from Aalenian-Bajocian to Kimmeridgian (Fig. 2). It is formed by micritic oolith cimented by sparitic crystallization. The sequence is characterized by a main lacuna during the Lower Cretaceous (45 Ma). Our hypothesis is that this period may have been conducive to carbonate platform weathering at depth. The region would have evolved under continental conditions. Then the Upper Cretaceous is separate from the Lower Cretaceous by a major lacuna. The Cretaceous formations are mainly composed of black clays, sands and glauconitic sandstone and argillaceous limestone. The maximum extension of the eastern deposits is unknown. But it seems unlikely that it was limited to the western

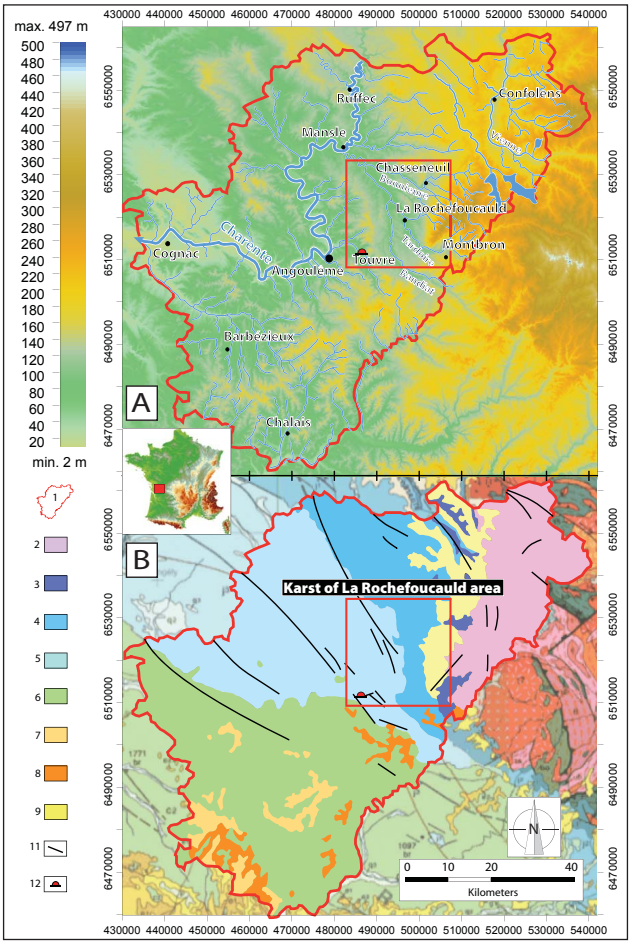

Figure 1. (A) The topography of northern Aquitaine basin constructed using IGN data from the BDTOPO_16 Charente (1: regional administrative limits). (B) Simplified regional geology constructed using BRGM data (2: Devonian granitic rock; 3: Early Jurassic limestone; 4: Middle Jurassic oolitic limestone; 5: Late Jurassic limestone; 6: Late Cretaceous marly limestone; 7-8: Palaeogene formation (undifferentiated); 9: Neogene; 11: Main faults; 12: Touvre springs).

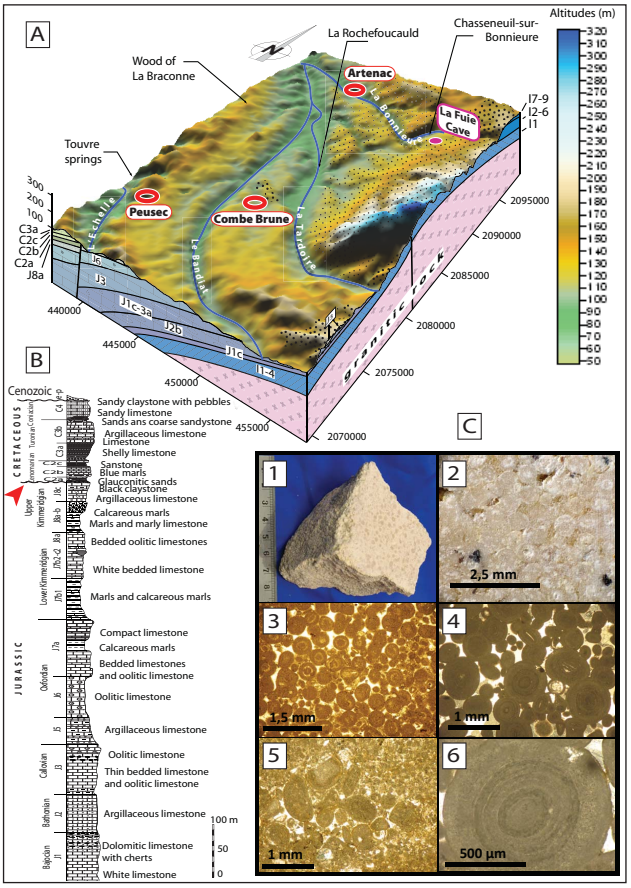

Figure 2. (A) 3D diagram (digital terrain model) of the karts of La Rochefoucauld area allows situating the three quarries and the La Fuie Cave. Drillings were performed just near the cave. The junction between the Massif Central and the sedimentary basin appears clearly as morphological structuring units (I1-I9: Lias dolomite and marls; J1-J8: Jurassic limestones; C2-C3: Late Cretaceous marls and limestones). (B) Litho-stratigraphic column (inspired from Gabilly & Cariou, 2007). The red arrow points to the main lacuna where the ghost-rock has developed. (C) Petrography of a typical oolitic limestone from "unweathered" rocks (1-2: white oxfordian oolitic limestone; 3-4-5: oolites with sparitic cimentation; 6: structure of an oolite).

part of the basin of La Rochefoucauld. The sedimentation would have extended more to the east, stopped by the foothills of the Massif Central.

Finally, the red sandy clay with cherts cover which outcrops northeast of the basin is usually associated with the Oligo-Pliocene "*sidérolithique*" formation (Dubreuilh & Platel, 1982). But in fact it could be related to the alteration of the Cretaceous cover, as shown Alabouvette et al. (1984), Astruc (1988), Simon-Coinçon & Astruc (1992), Platel (1996), Bruxelles (2001), Thiry et al. (2006), and Bruxelles et al. (2006) concerning the Quercy province (SW Massif Central, France).

Methods and materials

The field observations focused on investigating the link that exists between the altered limestone and the formation of caves. First of all, three quarries were studied (Fig. 2). The selection of sites focused on their distribution across the karst basin of the Touvre. Field observations helped highlight common points between the three sites. We could also benefit from the results of drilling conducted by the Centre for the Study of Technology and Equipment of Bordeaux (CETE, resp. F. Clément) between

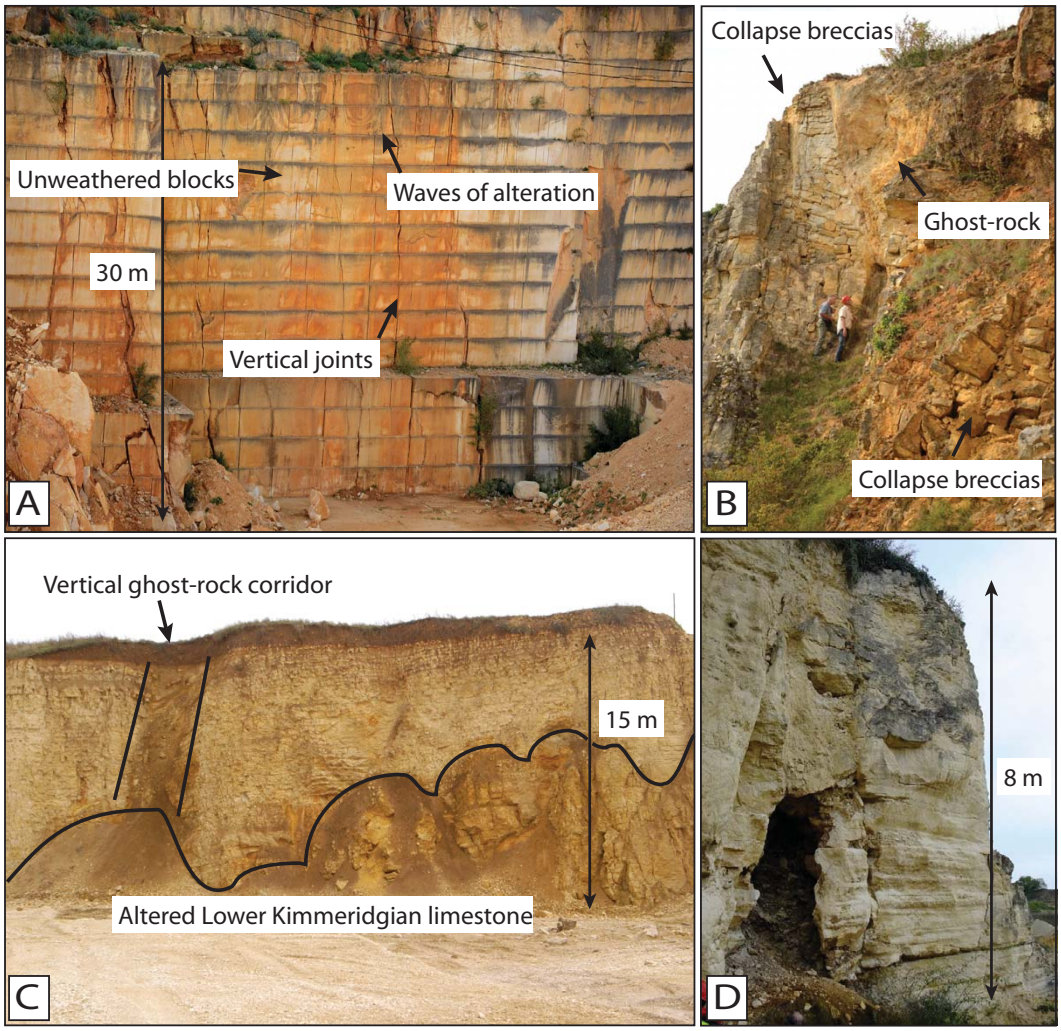

Figure 3. The three quarries studied. (A) The quarry of Combe Brune. It should be noted that the alteration waves isolated a fresh unweathered block. (B) The quarry of Artenac. Note the link between ghost-rock and the collapse breccias. (C) The quarry of Peusec. The lower part of the Kimmeridgian formation is entirely weathered. Note the ghost-rock corridor cutting the whole series till the erosion surface. (D) Cave cutted by the quarry. The petrographic examination reveals a weathered zone on the left side of the photo linked with a vertical fracture and collapses breccias. The filling corresponds to a debris flow with heterometric sub-rounded blocks of porous limestone and at the lower level the fine glauconitic sandy loam is assigned to the Cenomanian.

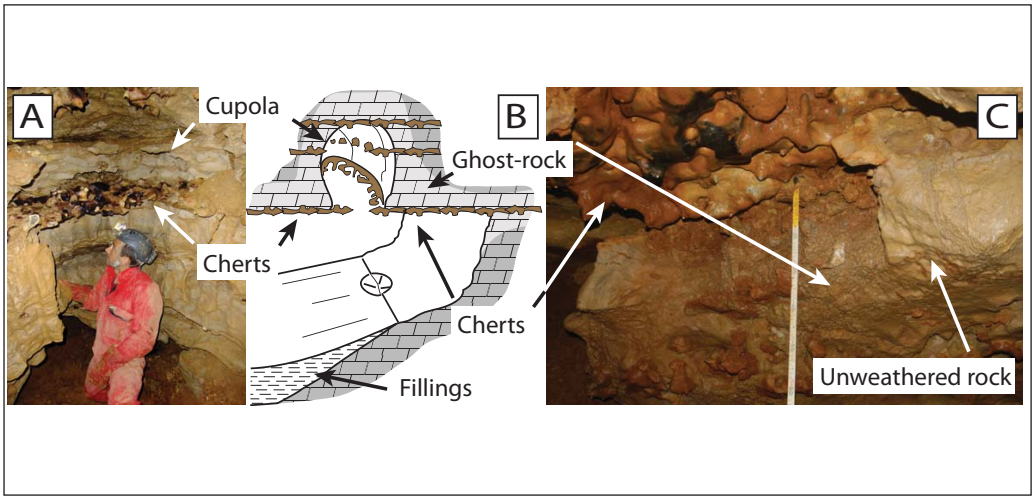

Figure 4. Ascending collapse chimney: example of some typical underground morphologies observed in La Fuie Cave. (A) It should be noticed from the picture the horizontal level of cherts still in place. (B) From the bottom of the cupola, we can observe the ghost-rock *in situ*. (C) The contact between ghost-rock and "fresh" dolomitic limestone is abrupt. The weathering front is linear and continuous. It seems that ghost-rock developed preferentially in dolomite and furthermore between interbedded nearest cherts levels.

2002 and 2007. These observations were supplemented by laboratory analyses comprised density analyses, mineralogy of heavy elements, and micromorphology. Finally, the discovery, exploration and monitoring of the cave of La Fuie allowed linking the ghost-rock process of the Jurassic series and speleogenesis of caves in Charente. Fluctuations of the water-table were recorded by a "*luirograph*", corresponding to an independent cell that records heights and water flow rates (Morel, 1996).

Results

4.1. Field observations

The first quarry we studied, called Combe Brune, develops in the Bathonian limestone (Fig. 3, A). The cutting face highlights the weathering profile which progresses along vertical and horizontal joints and extends laterally in the heart of the carbonate platform. The altered bedrock contains also isolated unaltered or less altered "corestones". We observed from the cutting face the "waves" of alteration that radiate from a fresh limestone block "floating" isolated in an altered mass.

The quarry of Artenac is the second site that we studied (Fig. 3, B). This old quarry is a very famous archaeological site (Delagnes et al., 1999), exploited until the middle of the 20th century into the Callovian limestone. We discovered on the right part of the site a very porous texture limestone. The junction between the fresh and the weathered rock (powdered limestone facies) is gradational. The weathering front is characterized by Liesegang rings which are generally developed in vadose context with redox processes. We also remark from the cutting face that the altered rock is often in connexion with collapse breccias collateral related to the reactivation of the ghost-rock. Breccias are constituted by porous and friable reworked heterometric blocks developed vertically. The voids between the blocks are filled in with coarse glauconitic sands corresponding to the base of the coastline Cenomanian formation.

In third place, the quarry of Peusec (near the Touvre springs) presents the morphologies the most accomplished in relation with weathered processes that we can observed in surface. This quarry develops in the Kimmeridgian limestone. The cutting face shown that the lower bedding plane of the kimmeridgian limestone is deeply altered (Fig. 3, C). Vertical ghost-rock corridors have been observed cutting the whole kimmeridgian series. Ghost-rocks with gallery architecture have been observed (Fig. 3, D). Roof arch like structure, cupolas and lateral limit bench were observed too. The galleries are partially filled by debris flow containing sub-rounded bloc of altered limestone. Thin silt and glauconitic sandy layers have been recognized in some galleries interpreted as Cenomanian formation (see Rouiller, 1987, p. 31).

4.2. Drilling results

Drillings made by the CETE in the northern part of the study area during roadwork have intersected altered levels between 11 and 18 m below the 10 m thick tertiary cover of sandy clays with chert nodules. Altered levels are characterized by decalcified clays and altered chert nodules comprised in a reddish silty clay matrix. At about 18 m deep the boreholes intersected the unaltered Bajocian dolomitic limestone with chert nodules and beds in position of unconformity with the tertiary cover attesting to the Cretaceous erosion surface. The bevelled bedding planes of the Jurassic transgressive deposits also attest to the importance of erosion and weathering during the Late Cretaceous. And at 20 m depth, the cave of La Fuie was intersected.

4.3. Speleological observations

The young and active La Fuie Cave was used as subterranean laboratory. It expands horizontally over one kilometer into

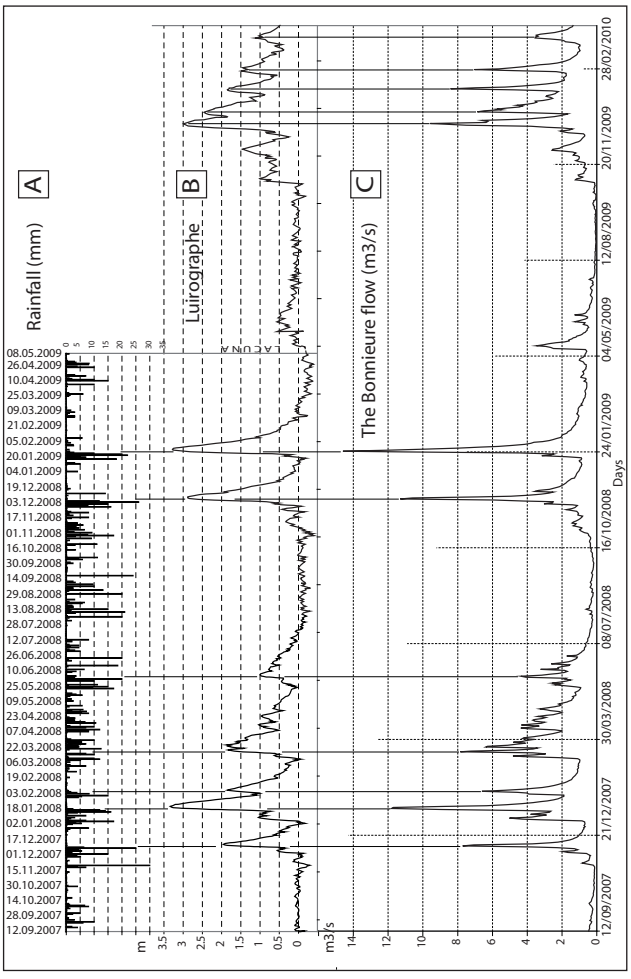

Figure 5. Comparison between (A) the histogram of daily rainfall (station Chasseneuil, MeteoFrance data), (B) water levels recorded by the *luirographe* in La Fuie Cave, and (C) the flow of the Bonnieure river (station of Saint-Ciers) allow us to have a better understanding of the work of the cave.

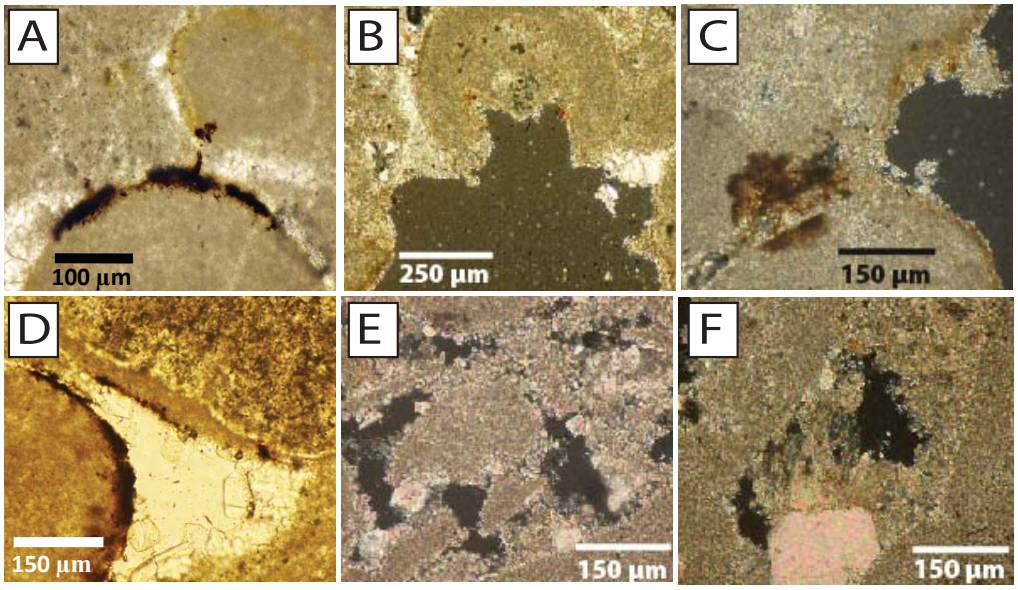

Figure 6. Micromorphology features (polarized light) showing the development of porosity of ghost-rock weathered limestone from Combe Brune quarry (A-B-C-D) – it should be noticed that alteration leads to many pores which affect first sparitic inter-oolites structure but also the intra-oolites micrite. Thin sections (polarized light) of core samples from plateau of the wood of Braconne (E-F) show alteration of the micritic background and diagenetic recrystallization phenomena with budding aragonite.

the dolomitic limestone with chert nodules of the Bajocian. The epiphreatic zone is organized on a main drain formed by the galleries of the Ammonites and Belemnites less than 10 m below the surface. The lower levels are completely filled by clay deposits under the water table. In the higher level, morphological observations have led to indentify a number of indicators showing walls alteration in depth like semi-liquid creeping rock, the chimneys ascending collapse, and the alterated interbedded plans.

In several places into the cave the weathered rock is creeping, because it is saturated forming micro-gours, and micro-pipes <2 mm wide. In addition, some morphology of ascending collapse chimney has been recognized in the whole subterranean network (Fig. 4). The loose material comes directly from a higher weathered level identified by the drillings. The study of collapses has identified *in situ* dark gray and soft texture of the altered limestone on the footwalls. Chert nodules and beds into the ghost-rock are recognisable from the unweathered limestone in continuity with bedding planes (Fig. 4, C). It is frequently possible to trace geological features from unaltered to altered limestone without interruption (e.g. calcite veins, chert bedding, geodes of chalcedony, ferro-manganic veins), and fossils of belemnite rostrum which is a proof of their Jurassic origin. At last, ghost-rock of 1m thick have been found in many rooms and interbedded between chert levels.

Fluctuations of the water-table recorded by a "*luirograph*" in the Gallery of the Belemnites highlighted the very high amplitude of the epiphreatic zone (Fig. 5). The chronic raw data reveal

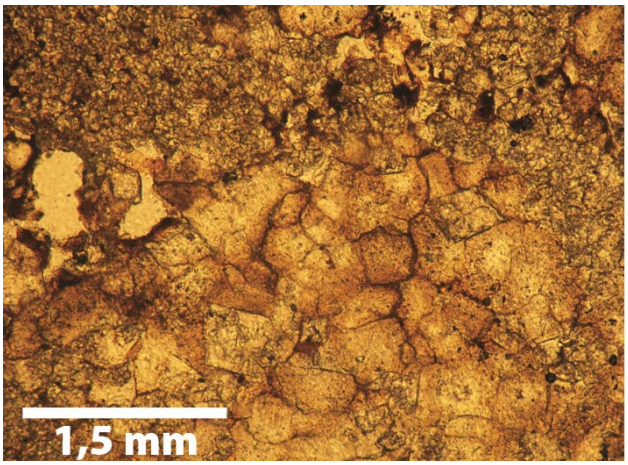

Figure 7. Thin section (polarized light) of ghost-rock weathered dolosparite with micropores between crystals sparitiques taken from La Fuie Cave walls.

significant variations in water level in the cave with maximum height of 3.30 m, corresponding to the maximum height of the vault, in January 2008 and February 2009. The high water period is between November and March. There is a phase shift, variable from 15 days to one month between rainfall events of November 2007 and 2008 and the first flood. In contrast, the reaction is faster, about a week between rainfall events of January 2009 and the rising waters. The slow reactivity in late autumn in 2007 and 2008 is probably due to the recharge of the aquifer. In general, the effects of infiltration are weak, due to the filter effect played by the tertiary cover in surface.

4.4. Laboratory analyses

Microscopic study of thin-sections of samples taken from the three quarries showed micromorphological similarities for the different ghost-rocks. Firstly, porosity results from an attack of inter-oolites sparitic and microsparitic structures which then progresses in micritic oolites (Fig. 6). There is also a concentration of iron oxides on the edge of oolites and sometimes even within oolites. The origin of this ferruginisation is not yet clear. Bacteria probably play a role in the formation of ferric microspheres particularly on the edge of oolites. Microscopic observations also show that the micrite is "eaten" by gray "spots" kinds of particles we can interpreted as iron associated with manganese. These "spots" are probably in the ferrous state (FeO). The same spots become reddish under the effect of oxidation. There would be a transition from FeO to Fe_2O_3. Bacteria activities seem to be conducive to oxidation (Y. Quinif, Barton H.A., pers. comm.). We also observe diagenetic phenomena with recrystallization of aragonite budding (Fig. 6, F). Microscopic examination of ghost-rock taken from La Fuie Cave reveals a dolosparite structure with micropores between sparitic crystals (Fig. 7). And the study of heavy minerals shows slurry of carbonate particles 10 to 100 µm grains mixed with some dark ferruginous probably from cover filling.

The analyses of density were undertaken on several samples from surface and caves. Calculations of density of 6 samples in La Fuie Cave showed losses of more than 25% (density 2.15 g/cm³) compared with the fresh bedrock (density 2.68 g/cm³). For samples collected in Peusec and Artenac quarries (12 samples), the results provide losses of 30 to 40% (density < 2 g/cm³).

Discussion

5.1. Speleogenesis of La Fuie Cave

Analysis of ascending collapse chimney and the discovery of ghost-rocks combined with the study of piezometric level variations, recorded by a "*luirograph*", allowed to highlight a new way to drain residual deposits by flooding / dewatering of galleries in cave system. But at the same time, the piezometric

level variations in the epiphreatic zone are the cause of a partial filling of the galleries. Speleogenesis of la Fuie Cave can be summarized in three chronologic steps. The first phase or stage of inception corresponds to isovolumic alteration of horizontal and vertical levels that occurs during long period of emersion that started in the Early Cretaceous and has lasted for 45 Ma. The regolith were not removed because of the absence of an hydraulic gradient important enough in a context of low-lying carbonate platform. The second phase resulted on a removal of ghost rock according to the hydraulic potential which allows the transport of weathered particles. The process corresponds to a particular type of regressive erosion since the internal water transits through the ghost-porous rock and carries out gradually carbonate particles. This regressive erosion has been observed in real time in The Quentin Cave, Belgium, formed in only two years (Quinif, 2010). This more recent stage is correlated to the erosion of Cenozoic surface coverage in connection with the lowering of drainage during the Early Pleistocene and the surrection of the Massif Central implying a relative lowering of the regional base level. The third stage (current stage) corresponds to mechanical erosion when the ghost-rock passes from the phreatic zone into the vadose zone in a context of the water-table fluctuations.

The main gallery (galleries of Ammonites and Belemnites) becomes the most important drain collector in which the fluctuations of the water-table promote the removal of the ghost-rock. This formation of horizontal pipes induces the down withdrawal of alteration products derived from the weathered higher levels recognized by drillings. This dewatering may be conditioned by an opening hydrological window (Valley of the Bonnieure) which causes a lowering of the local groundwater level. So, La Fuie Cave appears such as a natural model as well as the Quentin Cave, Belgium, to understand the geomorphological evolution and the genesis of a maze cave in its early youth located in the north-eastern part of the Aquitaine Basin. The age of the cave remains unclear due to the missing of speleothems.

5.2. Role of tertiary coverage in the alteration of Jurassic limestones and karstification

One of the parameters controlling the karstification is the establishment of the Tertiary cover of loose material (Jaillet, 2005). The ghost-rocks have been "sealed" by the unconformable cover trapped in the depressions. Then, in a second time, the erosion of the loose material cover combined with the uplift of the Massif Central has driven an original deep karstification. Indeed, the infiltration of surface water by stripping the cover has permitted the appearance of a hydrodynamic energy and new underground fluviatile circulations which have preferentially disaggregated the ghost-rock formation. It is now clear that this type of karstification differs from "normal" karstification which itself is linked to the total removal of material (solutes and insoluble) by progressive dissolution of the walls of joints and fractures in the tectonic context of distension (Quinif, 2010).

5.3. Karstic evolution and palaeogeography

Ghost-rocks were formed during a long and flat relief period linked to a low hydrodynamic energy and an extensional tectonic

Geochronology	Eustatic variations	Tectonic	Erosion et sedimentation	Ghost-rock weathering and karstification	Morphologies et deposits
Jurassic 180-135 Ma	Major marine transgression	-	Implementation of the carbonate platform	-	-
Early Cretaceous 135-96 Ma	Marine regression, 1st continental period	Rifting	1st erosion surface	Slow and deep isovolumic ghost-rock biochemical weathering (inception phase) + 1st caves	Roots of weathering, corridor of ghost-rock and ghost-rock interbedded
					Collapses breccias + wall smooth morphologies
Late Cretaceous 96-65 Ma	2nd major marine transgression	-	Terrigenous deposits mixed marine sedimentation (type lagoon)	Infillings into the caves	Glauconitic sandy marine deposits and debris-flow. 1st removal of ghost-rock (maze caves)
Cenozoic 65-2,6 Ma	2nd continental period	Pyrenean orogeny => Compression	Exhumation of Jurassic sub-structural surface (2nd erosion surface)	Fossilization of the karst	Infillings into depressions and caves
Quaternary 2,6 Ma	Base level variation associated with climate fluctuations	Uplift of the Massif Central	Lowering of the drainage network + Regressive erosion of the Tertiary cover	Removal of ghost-rock weathering + Formation of the Touvre aquifer (losses + fluctuation of the phreatic levels aquifer and regressive erosion from the Touvre springs.	Syngenetic infillings in the lower part of the caves from the plateau of the wood of la Braconne.
				Mechanical erosion (current stage)	young maze endokarstic network under tertiary cover

Table 1. Paleogeographic and geodynamic evolution of the North Aquitaine carbonate platform in relation with speleogenesis.

context. The ghost-rock is prior to the upper Cretaceaous transgressive marine cover (Table 1). The soil activity in terms biostasic conditions (see Erhart, 1955) was amplified by penetrating deep into the limestone mass as roots alteration to a very slow rate (a few µm/year?) during 45 Ma.

The petrographic examination and microscopy of a silicified rock with iron oxides crusts sampled from the quarry of Peusec allowed to date the main phase of alteration karst. Indeed, the silica deposition dating from Late Cretaceous and Cenozoic period lies in all the pores of the rock. So the alteration is earlier. The working hypothesis is that the phase of ghost-rock weathering occurred during the Early Cretaceous. The paleokarst of the Peusec Quarry, not far from the Touvre springs, testifies to the long phase of incipient ghost-rock weathering that has spread throughout the Cretaceous and the surface erosion surface is also a privileged witness. Consequently the ghost-rock weathering has determined the later karstification when the carbonate platform was in a topographic conducive position: Plio-Quaternary surrection, lowering of valleys, erosion the detrital tertiary mantle, losses in valleys, diffuse infiltration, and partial removal of the residual alterite creating maze cave systems. The sandy deposits of the Upper Cretaceous and debris flow indicate that the subterranean network already acquired its morphologies at the end of the Early Cretaceous and allowed the sedimentary trapping during the marine transgressions of the Cenomanian. The quarry of Peusec allows us to make the link between the ghost-rock weathering of the Jurassic series and the speleogenesis of the Charente karst basin of the Touvre.

Conclusion

The prominent role of the ghost-rock process during the long geological time of Lower Cretaceous (45 Ma) was demonstrated by the study of three quarries, drilling and the young cave of La Fuie. The surface morphological examinations and microscopic clarified weathering processes and link them to regional karstogensesis. The ghost-rock weathering explains the genesis of maze caves and also the complexity of the Touvre aquifer which supplies the city of Angoulême. Indeed the large water reserve is situated into the porous rock (slow drainage) while a small part is drained by the karst conduits (fast drainage coming from river losses). The combined action of bacteria and the water table fluctuations explains the alteration of the entire series of the Jurassic limestone and the very special karst morphologies.

The International Symposium on Karst held in Malaga gathered 60% of communications in hydrogeology (Andreo et al. Ed., 2010). The formula of Maillet is usually used to emphasize the state of karstification, that is to say the state of organization of the system of subterranean galleries and microconduits (Castany, 1963). This formula analyzes the long recession curves built from porous aquifers and interpreted as poor karstified aquifers (Mangin, 1975). However, no communication considers ghost-rock weathering to explain the nature of poor karstified tanks considered as porous aquifers. In this case, and since the discovery of ghost-rock weathering connected to speleogenesis, it seems necessary to check if we are dealing with a porous type ghost-rock aquifer as in the basin of the Touvre.

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