Paleokarst investigation near Saint-Remèze, Ardèche, France: discovery of an underground river fossilised during the Messinian salinity crisis

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Abstract: A number of paleokarst fillings have been investigated. The most important of them represents an ancient underground river. It appears as a sequence of filled passage segments, which have been de-roofed by karst denudation. These segments are developed at 360 to 380 m above sea level and have been followed for 5.2 km. Three distinct cave fillings were put into evidence: 1) beige micaceous silts and sands which represent exogenic immature alluvials and were dated with rodent bones as Uppermost Miocene; 2) mature red clay and sandstone of local origin, whose age might vary from Uppermost Miocene to Recent; 3) monogenic breccia generated by wall gelifraction during the Pleistocene. The petrographic composition of the immature alluvials is similar to the one of the Ardèche River which flows in the vicinity, but deeply entrenched in a canyon, at the altitude of 60-70 m ASL. Therefore, the paleo-underground river was fed by ponors located on the bank of the Ardèche River, when it was flowing more than 300 m higher than its present bed. The weak variations in elevation of the fossil channel suggest a development within the immediate vicinity of the water table. The biostratigraphic age of the immature alluvials as well as the paleokarstic context suggest that the cave was still active ~5.6 to 5.45 Ma ago. In this timespan falls the drastic dryout of the Mediterranean Sea and the beginning of the incision of the Messinian canyons in this area. In general, this fossil water-table cave is also informative on the morphological evolution of the Ardèche Karst and underline the usefulness of palaeontology in dating speleogenesis.

Key words: paleokarst; Ardèche; fossil underground river; Messinian salinity crisis; rodents.

1. Introduction

The article deals with a number of paleokarst features found and investigated by the author from 2001 to 2004 around the village of Saint Remèze. The main discovery consists of a filled and then de-roofed water-table cave, which could be followed over the unusual length of more than 5 km. It is important for the understanding of the regional morphological evolution, and the frequent occurrence of rodent remnants in the paleokarst fillings was particularly informative for dating the speleogenesis.

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Fig. 1. General situation map.
2. Geological framework and basic geomorphology

The sector under investigation is part of the prestigious caving domain of the “Basse Ardèche” (Figures 1 and 2). Near Saint Remèze, the karst domain is entirely developed within the Urgonian limestone, which is a Barremian to Aptian reef facies, 250-300 m thick, and resting on impervious Neocomian to Barremian marls. This limestone is overlain by Aptian to Miocene marls and sandstones. The Mesozoic strata have been very moderately folded during the Upper Eocene by a northward compression, and then affected by several phases of faulting (Pascal et al., 1989). Further away from the studied area (Fig. 2), the metamorphic Palaeozoic basement crops out to the NW in the Cévennes Mountain Range (Rouire and Chiron, 1980). To the north, the Mesozoic sedimentary strata are disconformably covered by the Coirons Plateau basalts of Upper Miocene age (Fig. 2). In some places, these basalts overlay gravels from a paleo-Ardèche river and fossilise a relatively rugged topography (Grangeon, 1960; Pastre et al., 2004). The Velay volcanic province occurs more to the NW, is also of Upper Miocene age, and comprises basalts, trachytes and phonolites. These volcanics rest directly on the metamorphic basement (Mergoil et al., 1993).

The geomorphology has been studied by several authors (i.e. Cornet, 1988 and Debard, 1997). Its main feature (Fig. 3) is the residual relief of the "Dent de Rez" (719 m), just north of the village of Saint Remèze, which raises above the Saint Remèze-Gras peneplain surface (330-400 m ASL). The latter is part of the "Surface Fondamentale", quoted by many authors, and which is widely developed over a major part of SE France. Its peneplanation is moderate (Figures 2 and 3) and generally accepted as Upper Miocene. South of Saint Remèze another surface, the Malbosc Plateau, is developed at the elevation of 300-320 m ASL. It is roughly triangular, limited to the SW by the Ardèche Canyon and to the SE by an imprecise line passing through Bidon (Fig. 3). Both plateaux are not covered by well-defined alluvial deposits, but by residual “terra rossa”, with some sandy material containing dominantly quartz and minor weathered feldspar and mica. This red clay is filling karst depressions and might evidence the presence of ancient streams.

The karst developed on the Urgonian limestone is of the fluvial type and thus poor in characteristic surface morphology. This deficiency is compensated by a well-developed endokarst as evidenced by extensive cave...
systems, like Saint Marcel and Foussoubie, as well as by well-known caves such as Aven Orgnac and Grotte Chauvet. Most of the karst springs are located at the level of the Ardèche River, which is deeply entrenched in the Urgonian limestone and flows at the elevations of 80 to 40 m asl. from entry to exit of the karst domain (Fig. 2).

Towards its SE limit, the Malbosc Plateau grades imperceptibly into a structural slope marking the stratigraphic top of the Urgonian limestone and getting progressively steeper down to the alluvial plain of the Rhône River, which roughly limits the karst domain in the East. This alluvial plain is masking thick Pliocene marine sediments (Ballésio, 1972). They fill up the canyon of the Messinian Rhône, whose bottom has been reached in the bore-hole DP 1 of Pierrelatte at the elevation of -236 m below sea level (Demarq, 1960). Originally this canyon reached a depth close to 600 m, cutting through Cretaceous and Miocene strata (Clauzon, 1982; Clauzon et al., 2005). Adjacent canyons developed at the emplacement of the present tributaries of the Rhône River, including the Ardèche River, but they are generally less deeply incised, probably because of less erosional power. These shallower canyons are all developed in karst rock. This characteristic could have fostered the development of endokarst systems, which would have lessened sub-aerial erosion (Mocochain et al., 2005).

3. Description of paleokarst caves

These fossil caves and potholes appear now as filled cavities which have been exhumed as a result of sustained karst dissolution. Most of the time, they are evidenced by boulders of calcitic speleothems, breccia, sandstone, calcified silt and clay, and by rare outcrops of the same lithologies. These boulders are scattered on the ground or removed and piled up on walls in order to make the land amenable to cultivation. It is often not possible to locate their origin with precision (Fig. 4). Other paleo-karst pockets have been located outside the domain covered by the map of Fig. 4, as for instance on the southern slope of the Dent de Rez Massif, but they are small and less significant.

One of these de-roofed caves, the so-called “paleo-underground river”, is obviously more important than the others and therefore has been investigated in detail. It consists of a number of segments mainly developed on the slope marking the transition from the Saint Remèze Plateau to the Malbosc Surface (Fig. 4). The former passage appears as bands and trenches, the floor being covered with soil and limited on both sides by limestone outcrops. Their usual width is 7-8 m, but may vary from 5 to 20 m. Although genuine outcrops of karst filling are rare, they are frequently encountered as thin and discrete coating of calcified sediments and speleothems, which form patches stuck on the paleo-cave walls (Figures 7, 8 and 9). Although under favourable conditions the walls display typical cave morphologies, scallops with unquestionable orientation have not been observed.

Where the paleo-channel disappears, this corresponds to its floor in the lowest elevations and to its ceiling in the highest ones. Therefore on the topographic map (Fig. 4) it is possible to estimate the passage height, which varies from 10 to 30 m. Its length, measured as the crow fly, is 5.2 km, but reaches probably 7 km if the meandering shape is taken into account. Its elevation does not vary much. According to the points corresponding to the ceiling, the elevation rises from 370 m in the Aiguizier segment to 375 m in the Costes Chaudes I, then to a little more than 375 m in those of Rounal I-II and Marzal I, but gets lowered to 375 m in Marzal VII (fig. 4). In contrast, the elevation variations of the floor are more erratic: From 360 m to 350 m in those of Rounal I-II and Marzal I, but gets lowered to 375 m in Marzal VII (Fig. 4). In contrast, the elevation variations of the floor are more erratic: From 360 m to 350 m in the Aiguizier and in the Costes Chaudes, 365 m between Devès III and IV, and 350 m for the southern end of Marzal I. The paleo-karst segments can easily be connected to
each other from the Aiguizier I to the Aven Flahaut, that is over a distance of 4.8 km (Fig. 4). Beyond this point, the layout of the segments is becoming confusing and the connections are uncertain. Moreover, these segments display much less fill remnants and are developed on a relatively flat topography at a generally lower altitude than previously. Some of them give the impression to terminate abruptly at both ends. Although the paleo-karst channel is most often de-roofed or completely filled up to the ceiling, there are exceptions. The most important of them is the Bartade cave, which is, however, only 26 m long (Fig. 10).

The paleo-cave channel cuts through the stratigraphy with an angular disconformity, as evidenced by variations spanning from the base to the middle part of the Urgonian limestone. Moreover the channel intersects major faults three times and does not seem to have been displaced, or at least by not more than a few metres, as a result of post-speleogenetic neotectonics.

4. Nature of the filling

It is possible to distinguish four types of filling: 1) immature alluvials; 2) mature alluvials and colluvials; 3) breccia; 4) speleothems.

4.1. Immature alluvials

This is a peculiar facies, exclusively observed along the long fossil channel from Aiguizier I to Marzal V and in the parallel segment of Devès V. It is very likely that the latter, which has been intersected by the vertical shaft of the “Aven du Devès de Reynaud”, corresponds to a diffusional from the main channel (Fig. 4). Generally the sediments appear as beige silt and fine micaceous sand, often irregularly hardened by calcification. Usually the hardened form is observed in outcrops or in dumps left after stone clearing. Coarser materials, with grains over 2 mm in size, are more rare and only observed as thin and lenticular layers. A characteristic nature of the sandstone is a glittering facies due to cleavages in large calcite crystals (up to 3 cm) forming the matrix and filling the voids between detrital grains (=poilcilitic texture). This facies suggests a good graded bedding, as well as absence of finer detrital matrix.

Fig. 4. Map of paleo-karst fillings. 1) Segment of unroofed cave passage; 2) inferred route of paleo-cave under Urgonian roof; 3) flow direction (where the passage is eroded away); 4) punctual paleo-karst filling; 5) paleo-karst filling with no definite location; 6) pothole; 7) immature silt and sand (outcrops and loose blocks); 8) mature red clay, silt and sand; 9) micro-mammal deposit; 10) “low-grade” vertebrate occurrence. Names of segment groups are underlined and individual segments are marked with roman numbers.
An exceptional conglomerate outcrop was observed at Costes Chaudes II (Figures 7 and 11), which proved amenable to petrographic analysis (Fig. 12). It underlines the immature nature of the detritals. There is abundance of quartzo-feldspathic rocks (granite, gneiss and leptynite), of low-grade metamorphic rocks (micaschist) and of volcanic rocks. The latter are always deeply affected by a post-sedimentation alteration, with development of clay minerals (kaolinite or smectites), but most of them can easily be identified as basalt by their palimpsests of intersertal microlithic texture and by very fine magnetite inclusions, which make them magnetic. Rare elements displaying a similar texture, but leucocratic and magnetite-free, could possibly be related to trachyte or phonolite. The kaolinisation of quartzo-feldspathic rocks is less pronounced and grades from complete to practically nil. In Fig. 12, the petrographic pie diagram of Costes Chaudes II is compared with one of Upper Pleistocene alluvium of the Ardèche River, sampled downstream of Pont d’Arc (Fig. 3), on a Wurmian terrace. In both cases, the origin of the detritic grains is identical. They were dominantly transported from the Cévennes metamorphic-granitic basement and from the

Fig. 7. Map of segments I to III of the Costes Chaudes. 1) Urgonian limestone outcrop; 2) exposed cave wall; 3) inferred cave wall; 4) rocky ledge in paleo-cave; 5) block from ceiling breakdown; 6) large flowstone block, more or less in situ; 7) constructed wall; 8) point of elevation, in metres; Gp = Immature sandstone; Gq = mature sandstone; Ac = calcified red clay; Li = ferruginous crust; Br = breccia; Cc = calcite; V = vertebrates. Underlined symbols mean that they were observed in situ, the others as blocks displaced onto constructed walls.
Upper Miocene volcanics (Fig. 1). Their immature nature indicates that they have been eroded from unweathered outcrops in rugged terrains.

In finer detrital rocks, for example in coarse sandstone, quartz grains are angular, which suggests transport in torrential streams and crushing by large pebbles. As in the conglomerates, the feldspars are irregularly kaolinitized. The feldspars, as well as the basaltic rocks, must have been unaltered at the onset, otherwise they could not have survived torrential transport. In sandstone, mica is particularly abundant, consisting mainly of biotite, which is generally altered into vermiculite. It appears frequently as elongated prismatic piles of flakes.

Beside these elements, which are exogenic with respect to the karst domain, endogenic fragments are also present and are classified under "various" in the pie diagrams of Fig. 12. In the coarse sandstone, their content is variable, but does not seem to rise above 20%. They include limestone and calcite rods from speleothems which are recognisable by a reddish banding perpendicular to the c-axis. Corroded quartz grains with a red coating, ferruginous debris, silicified fragments from Mesozoic fossils, and soft red clay flakes are present and possibly also of endogenic origin. In this category one may perhaps include a few well-rounded and polished quartz grains, sometimes resembling water drops.

An unusual facies has been observed at the end of the Bartade Cave. It consists of an alternation of red clay and beige silt laminae, which are very finely micaceous (Figures 10 and 13). This material completely fills a

Fig. 8. Map of the central part of the Devès III segment. 1) Stone dump; 2) top soil; 3) in situ breccia; 4) in situ flowstone; 5) outcropping mature sandstone; 6) fine micaceous sandstone, cropping out (solid lines) and inferred (broken lines); 7) Urgonian limestone; 8) cave wall; 9) inferred cave wall; 10) edge of rocky ledge in paleo-cave; 11) constructed wall; 12) point of elevation, in metres; Gp = immature sandstone; Gq = mature sandstone; Ac = calcified red clay; Br = breccia; Cc = calcite; V = vertebrates. Underlined symbols mean outcrop, otherwise loose blocks.

Fig. 9. Map of the Rounal I segment. 1) outcrop of Urgonian limestone; 2) cave wall; 3) inferred cave wall; 4) outcropping calcite; 5) outcropping breccia; 6) sub-outcropping silt and fine grained micaceous sandstone; 7) sub-outcropping coarse fossiliferous sandstone; 8) escarpment limiting southward extension of immature sediments under top soil cover; 9) stone dump; 10) stone wall; 11) point of relative elevation; Gp = immature sandstone; Gq = mature sandstone; Ac = calcified red clay; Br = breccia; Cc = calcite; V = vertebrates. Underlined symbols mean outcrop, otherwise loose blocks.
4.2. Mature alluvials and colluvials

They have been observed over the entire length of the fossil channel as well as in most of the other paleokarst pockets in the Saint Remèze surroundings (Fig. 4). This deposit consists of more or less silty red clay and of fine to coarse sandstone, but with a clayish matrix. Calcification is not producing the glittering facies observed in the immature sandstone, but, in the red clay, produces nodules displaying a typical radiating structure. In some rare instances the red clay had been bleached by iron reduction and leaching, probably on account of organic matter originally present in the sediment.

Detritic elements in sand and sandstone reveal only minerals resistant to weathering, mainly quartz, chalcedony and goethite. These minerals are comparable to the endogenic material described in the previous section. They probably originate from the same metamorphic basement as the immature sediments, but were subject to long periods of weathering in soil and several reworkings (Camus, 2001). The elements sensitive to weathering, like quartzo-feldspathic and volcanic rocks, disappeared. An unusual abundance of very fine-grained magnetite appearing in pan concentrates, however, suggests that basalt might have been present at the onset. The elements originating from the Mesozoic sequences comprise diagenetic silicifications and other chalcedonic fragments. The well-poled quartz grains reported above in the immature sandstone are also present, sometimes abundantly, like in the Cheyrol and Beauregard fillings (Fig. 4). These grains might have formed in the cave itself or perhaps have originated from the erosion of ancient marine beaches (Lower Miocene), which might have been present on the Saint Remèze Plateau. The pie diagram of Fig. 12 exemplifies a mature assemblage, in which the three most common elements are well represented.
Elsewhere the proportions may vary considerably, in particular with the dominance to the quasi absence of ferruginous grains. This phenomenon is certainly due to mechanical separation by density (placer effect).

4.3. Breccias

They are composed of very angular fragments, fine to coarse in size, and almost exclusively consisting of Urgonian limestone. The fragments can often be supported by a beige or red calcified silt-clay matrix, or by speleothem calcite, or they can be only partly consolidated, thus leaving interstitial voids. They have been observed practically over the entire length of the fossil channel. The origin is very certainly from wall and ceiling gelifraction.

4.4. Speleothems

They represent the most frequent paleokarst exposures and debris. It is easy to identify stalactites and stalagmites, as well as blocks of calcite from flowstone. On these, micro-rimpool dams are commonly developed, especially in the Costes Chaudes and Devès segments (Fig. 5). Cave pearls, fossilised in an ancient pool, have been observed in Roual I and in one of the small paleokarst fillings of the southern slope of the “Serre de Barre”, N of Saint Remèze (outside Fig. 4). Speleothem calcite is generally largely crystallised and red to white. It can also be finely crystalline and then forms popcorn, which is often characteristic of deposition under variable humidity and temperature, like for instance in the proximity of cave entrances. This latter type has been observed in Devès II and in the highest parts of Marzal I.

Millimetric to centimetric thick crusts of goethite have been noticed coating the paleo-cave walls and boulders. They developed from primary or secondary reduction of iron, probably under the detrital filling, later followed by migration, oxidation and re-precipitation in contact with limestone.

5. Palaeontology and biostratigraphy

Micro-mammal remnants have been identified in eleven sites (Fig. 4). Eight of them proved to be rich enough to provide age information for the karst filling. Four are located on the long paleo-cave channel. Detailed description of the palaeontological material and discussion about their biostratigraphic significance have been given elsewhere (Martini, 2005).

5.1. Roual I deposit

The fossiliferous horizon consists of lenses of coarse sandstone and sand belonging to the immature type. The lenses extend for a few metres only. They are not thicker than 25 cm and are inter-stratified in beige silt and fine micaceous sand (Fig. 9). Although vertebrate remnants have been observed in material collected in situ, most of the former originate from 6 loose boulders. The identified species are as follows:

- Occitanomys adroveri
- Stephanomys dubari
- Paraethomys cf meini
- Apodemus cf gudrunae
- Apodemus cf gorajensis
- Apodemus cf jeanteti
- Aporcricetus barrierei
- Neocricetodon cf polonicus

This fauna is characteristic of the upper part of the biozone MN 13 (Upper Miocene). Furthermore, by combining the palaeontological data with the karst and general morphological context, it was concluded (Martini 2005), that the age of the immature filling was comprised between 5.8 and 5.33 Ma, perhaps even younger, that is 5.52 to 5.33 Ma.

5.2. Costes Chaudes II deposit

This fossiliferous deposit consists of red sandstone boulders derived from mature coarse alluvials. The material was found stacked on a wall, but was not observed in situ (Figures 4 and 7). The following species have been identified:

- Stephanomys donnezani
- Apodemus jeanteti
- Apodemus gorajensis
- Apodemus dominans
- Rhagapodemus frequens
- Occitanomys cf brailloni
- Occitanomys cf ellenbergeri
- Aporcricetus sp
- Dolomys occitanus
- Trilophomys sp
- Glis cf sackdilingensis
- Eliomys intermedius

The Costes Chaudes II fauna is characteristic of the upper biostratigraphic zone, that is an age approximately comprised between 3.6 and 3.0 Ma.

5.3. Rodent remnants in the breccia facies

Along the paleo-channel, rodents were found in breccia at two places. In the first one, which is located in the Costes Chaudes II segment (Figures 4 and 7), a breccia in a matrix of speleogenic calcite revealed an Apodemus of the sylvaticus-flavicollis type and a rootless arvicolidae. The second one, located in the NW end of the Marzal I segment (Fig. 4) and in a similar breccia, yielded the same Apodemus and arvicolidae plus Allocricetus bursae. These two animals indicate a Pleistocene age for the breccia facies. This age is also supported by the gelifracted nature of the breccia.
5.4. Arredons W deposit

This deposit is situated outside the long unroofed cave (Fig. 4). The richly fossiliferous material is reduced to five small fragments of red argillaceous mature sandstone, which were collected on a stone wall. The primary deposit has not been found, but should occur in the immediate vicinity, as the fragments were observed well grouped on the wall. The following species were identified:

- Occitanomys adroveri
- Paraethomys meini
- Apodemus cf jeanteti
- Apocricetus barrierei
- Neocricetodon polonicus

This fauna shows similarities with the species found in Rounal I and in particular with the great dominance of O. adroveri in both deposits. The most obvious difference is the absence of Stephanomys in the Arredons W deposit. If this absence is due to a local ecological cause, the occurrence could be contemporaneous with Rounal I, but in mature facies. If on the contrary this absence is due to the local "extinction" described north of the Pyrénées Range (Aguilar et al. 1991), the age would be Lower Pliocene (MN14 zone).

5.5. Arredons E deposit

A few fragments of fossiliferous sandstone and breccia have been collected on stone dumps left after land clearing (Fig. 4). The most significant material originates from a small piece of calcite breccia in red hard clay matrix. The latter yielded Apodemus angustidens and Stephanomys cf donnezani. This association suggests the MN15 zone in the Pliocene.

5.6. Cheyrol deposit

1.7 km to the SE of Saint Remèze, a relatively large filled paleo-cave has been intersected by a road cut (Fig. 4). Like the two previous occurrences, it does not seem to be part of the main paleo-cave channel described above. The filling is well exposed and consists of several metres of alluvial sediments grading from sand to clay, which are typically mature. The fossiliferous horizon consists of a 20-30 cm thick bed of yellow sand, exhibiting channelling structures, clay pebbles and particularly well-polished quartz grains. It yielded:

- Apodemus jeanteti
- Apodemus dominans
- Stephanomys cf donnezani
- Paraethomys sp
- Neocricetodon cf intermedius
- Mimomys sp

Like in the case of the Costes Chaudes II, this small fauna suggest the upper MN15 biostratigraphic zone.

6. Distribution, stratigraphy and sedimentology

Although good outcrops of the main paleokarst filling are rare, it is nevertheless possible to propose a stratigraphic model (Fig. 14). Because of the loose boulders, we assume that the four facies should be present over nearly the entire length and elevation of this karst channel. It appears, however, that these fragments are more abundant in the high parts of the channel, with the exception of speleothem calcite, which remains relatively frequent at any elevation. The largest part of the outcropping detritic sediments have also been noted in the highest elevations. The immature sediments seem to have filled the cave over heights not exceeding 13 m below the ceiling, as observed in the Aiguizier and Marzal I segments. If there is no evidence that the lower parts of the channel have been filled by these sediments, nevertheless they might be present, but concealed under recent soil. In this case this would mean that the calcification of the filling, a phenomenon producing boulders after erosion, is essentially developed in the highest parts and would be related to a large abundance of overlaying speleothems.

The mature sediments also seem to be located in the top parts. Calcified silt and clay forming coats on the wall, however, have been observed as low as 13 m below the top (Devès I and II). In Rounal I, red clay rests disconformably on immature sand and silt (Fig. 9). This suggests that the mature facies can be substantially more recent, which is also supported by the palaeontological age from the Costes Chaudes II, which is here 1.5-2.0 Ma younger than the immature facies. This younger age is not a rule, however, since in the terminal alluvial filling of Bartade Cave immature and mature sediments form alternating laminations (Figures 10 and 13) and thus indicate synchronous deposition. It is logic that both exogenic and endogenic sedimentation could have been concomitant: the karst context suggests that fill originating from surficial residual cover could have been introduced into the endokarst continuously up to the present. Moreover, this variable age is supported by the palaeontological deposit of Arredons W (MN biozone 14 or even perhaps 13), contained in mature sandstone.

Pleistocene gelification breccia have also been generally observed in the high parts of the paleo-karst channel (Bartade Cave, Devès III, Rounal I, and Marzal I: Figures 8, 9 and 10), except in Devès II (Fig. 4), where an outcrop is located 12 m under the top. The breccia probably developed when the filled passage was intersected by the surface as a result of denudation, dissolution and erosion. Then short caves were opened by gravity sliding and creeping of soft material, then were again more or less filled by gelifracts and calcite speleothems. Like the immature sediments, telescoping with older fillings occurred. Although the two observed palaeontological ages are Pleistocene, it remains possible that older breccias (ex. Lower Villafrancian) developed, but were later eroded away as a result of denudation progress.
Speleothem calcite is associated with all the detrital sediments described above and, although predominating in the highest parts, it has been observed practically over the entire height and length of the paleo-channel. Interesting cases are where it is associated with the immature facies. In the Devès III top zone, an in-situ stalagmite shows a zoning underlined by thin micaceous seams, which suggests that the calcite has been deposited between periodical flooding. Similar zonings have been noted in boulders in Devès II and IV. In Devès III a loose block grouping 3 stalactites was coated with fine micaceous sand, even on the detachment surface. This indicates that it fell from the ceiling into immature sediments. As the speleothem-immature sediments deposition is concomitant and therefore suggests a vadose flow, this supports the denomination of “underground river” for this fossil channel. It is nevertheless not excluded that shallow phreatic segments (sumps) existed.

Relatively recent erosion and weathering of the paleokarst filling produced a residual soil. Within it, epikarstic dissolution under cover was certainly enhanced by concentration and accumulation of surficial water. The effect was post-speleogenetic deepening of the trenches marking the paleo-channel (= “doline effect”). Recent dissolution and reworking is evidenced by detrital accumulations into younger cavities (Fig. 14). This phenomenon is observed in the Aven Flahaut (Fig. 4), a pothole in which immature sandstone has been incorporated with an archaeological breccia of Middle Pleistocene to Holocene age (Debard, 1997).

We conclude that after the initial filling of the channel by alluvium from the Ardèche River, several vadose speleogenetic phases intersected and partly eroded the immature sediments. The resulting cavities were later filled by mature sediment or breccia, thus inducing facies telescoping (Fig. 14). During these renewals of speleogenesis, vadose activity might have deepened the old riverbeds over some lengths which probably did not exceed a few hundred metres. This subsequent erosion, plus the “doline effect” under soil cover, could explain the unusual low altitude of the “paleo-riverbed”, as observed in certain “blind” segments near Marzal (Fig. 4). In this case, one may perhaps speak of palimpsests of the original channel. This model is explicitly illustrated in Fig. 14. It is also necessary to point out that the model is provisional and in the future should be checked by geophysics, trenches and boreholes.

7. Speleogenesis and impact on the regional karst and morphological evolution

The paleo-underground river was certainly fed from at least two ponors on the bank of the Ardèche River (Fig. 4), as it is suggested by the petrography of the immature sediments. The weak gradient of the channel, as a matter of fact not measurable on the field with certainty, plus its disconformable relationship with the limestone strata, indicates that it developed in the immediate vicinity of the water table. These observations allow estimating the position of the ponors at elevations of 360-380 m at the end of the Miocene. The altitude of the channel ceiling, which is increasing from up- to downstream (about 370 m at the Aiguizier to more than 380 m at Marzal I) could be explained by the position of the initial phreatic channel. Sustained speleogenesis could have shaped it into a vadose passage. Alternatively the obsequent gradient could be explained by gentle post-speleogenetic structural deformation, although this does not seem likely in this region (Schlupp et al., 2001).

Only partial flow losses of the Ardèche into ponors, as it is observed today on the bank of this river (Pascal et al., 1989), should have been responsible for the development of this system. Indeed a total engulfing of the river would have excavated a much more voluminous tunnel, which would have rapidly collapsed into a canyon (Nicod, 1997), if one refers to the present flow which can reach 7000 m$^3$/sec. At the ponors, the Ardèche was probably flowing not far away from its present course. Further downstream, the river should have deviated to the East and should have been flowing above the Malbosc Plateau (Figures 2 and 3), that is about 60 m higher than this surface. Considering that the relative elevation of the underground river remained unchanged, this implies a lowering of the plateau of 11 m/Ma. This figure seems somewhat low, when compared with the 15-25 m/Ma proposed by Gombert (1995) for
the present regional denudation, even if assuming that 80% of this value represents the proper lowering of the surface. 11 m/ Ma remain acceptable, however, if it is considered that under Uppermost Pliocene and Pleistocene peri-glacial climate the denudation could have been reduced (White, 2000). For these speculations, it was assumed that the lowering of the Malbosc Surface was entirely due to karst denudation. Indeed fluvial erosion would have lowered it much more. This suggests that shortly after the filling of the paleo-channel, the Ardèche was shifted to the approximate position of its present course.

The paleo-underground river was mainly active before the alluvial filling started, an antiquity which probably did not exceed a few 10^5 years, referring to the average rate of erosion of the streams after having entered the endokarst (White, 2000). If it is accepted that the elevation of the paleo-channel was controlled by the water-table, it appears that this system could have been active only before the rapid lowering of the karst aquifer, which was triggered by deep incision of canyons during the Messinian salinity crisis (Clauzon, 1982; Clauzon et al., 2005). Such a rapid lowering has been observed in the Far West Rand, South Africa, where a deep karst aquifer has been punctured by mining activity at more than 1000 m below the water-table (Kleywegt and Pike, 1982). It was also theoretically shown that speleogenesis can rapidly develop in such cases (Dreybrodt, 1996).

One may visualise the position of the resurgence of this underground river by virtual restoration of the strata eroded since the deep salinity crisis. At that time the non-karstic Upper Cretaceous, Oligocene and Miocene sedimentary cover was more extensive to the NW (Fig. 3) and consequently the karst surface was proportionally reduced. This extent to the NW of the sedimentary cover suggests that the water was returned to the Ardèche via a resurgence positioned where the limestone disappeared under the impervious terrain (Figures 3 and 15). Implicitly it appears that the average slope of the underground river should have been about the same as the Messinian Ardèche. Furthermore one may assume that this gradient was the same than today, that is 1.56 m/km, measured as the crow flies from its confluence with the Ibie to its confluence with the Rhône. If one takes into account the rectilinear distance of 24.5 km between the ponors and Bois Redon, where a small alluvial outlier marking the abandonment surface of the Messinian Rhône is located, one obtains the altitudes of 332-342 m for the paleo-Rhône position at the brink of the deep salinity crisis (Fig. 15). This position has been estimated by Clauzon (1982) at 340 m, a value approximately in agreement with the former figures.

The underground river could have been still active during the deep salinity crisis (5.52-5.33 Ma), for instance around 5.45 Ma. In this case the “Waterfalls of the Rhône”, that is the front of the regressive erosion, could already have reached the latitude of the paleo-Ardèche. As the latter river had a lesser erosion power than the Rhône, this front might not have reached the karst domain yet. This delay time could have allowed the underground river to be still active. This is the youngest possible model (Fig. 15). The channel fill could be accounted to the beginning of the lowering of the paleo-Ardèche riverbed, but when this river was still able to reach the cave during flooding time. This lowering could have resulted from the first effects of the regressive erosion due to the drying out of the Mediterranean Sea.

Alternatively another model could assume that the filling of the cave was the result of an accretion period for the riverbeds. This could have been related to a rise of the Mediterranean Sea just before the salinity crisis, during the deposition of a “lago mare”. This period would have taken place immediately before the formation of the canyons, that is between the deposition of the upper and the lower evaporites (from 5.64 to 5.52 Ma, Clauzon et al., 2005). This accretion phase is suggested by the alluvial gravel of the Bois Redon, which might have reached an original thickness of at least 50 m, according to a virtual restoration of the weathered and eroded part (Clauzon, 1982).

Fig. 15. Possible Uppermost Messinian morphology compared with the present topography. Geology and topography are simplified. Note the erosional surfaces (5.64 and 5.45 Ma) and the paleo-Rhône abandonment surface (5.52 Ma), which all three may have played a role in the genesis and the evolution of the paleo-underground river. 1) Rhône River alluviums; 2) Lower Pliocene marine sediments filling the Messinian canyon; 3) largely non-karstic terrains (Cretaceous to Miocene); 4) Urgonian limestone.
8. Conclusion

Evidencing a paleo-cave controlled by the water table during, or just before, the deep salinity crisis, contributes to fix the altitude of the pre-evaporitic abandonment surface of the Rhône River and supports the model of Clauzon (1982). Also, the coincidence of the paleo-channel with the altitude of the Saint Remèze-Gras Plateau (= the “Surface fondamentale”) during, or just before, the deep salinity crisis, contributes to fix the altitude of the pre-evaporitic abandonment surface of the Saint Remèze-Gras Plateau (= the “Surface fondamentale”) appears. Indeed this surface should have been situated 50 to 70 m higher 5.5 Ma ago, if the karst denudation is taken into consideration. The hypothesis of a more or less continuous uplift since at least 8 Ma seems to be also confirmed, as already suggested by the relief and immature alluvial covered by the Coiron basalts (Grangeon, 1960; Serranne et al., 2002; Pastre et al., 2004).

On the eve of the crisis, it seems that the Ardèche Canyon was not well materialised yet. The river was probably only flowing in a broad valley bordered with hills not higher than 100 m (Fig. 2). Therefore the major part of the canyon development appears posterior to at least 5.8 Ma and perhaps even less (5.45 Ma), as suggested by palaeontology. Slightly different conclusions were obtained for the Tarn Canyon, which is disposed symmetrically with respect to the Ardèche, but which flows westwards on the Atlantic slope of the Cévennes Mountains. At the same period, half of the Tarn Canyon was already excavated (Ambert and Ambert, 1995; Serranne et al., 2002). It appears that this symmetry is more morphological than chronological.

This water-table channel also suggests that the majority of the important regional caves, which are developed at lower altitudes (Orgnac, Chauvet, etc), are younger. Their speleogenesis took place during the Pliocene and the Pleistocene, although they have certainly been initiated already during the Messinian salinity crisis (Mocochain et al., 2005). It appears also that the voluminous caverns in the region could have rapidly formed by absorption of important surface streams into the endokarst. This process could represent an alternative to the hypothesis of a speleogenesis under ancient warm climate, as suggested previously (p. ex. Blanc, 1997).

Eventually, the common occurrence of a number of fossiliferous paleo-karst fillings over a relatively small surface around Saint Remèze suggests that elsewhere similar deposits might also be widespread. This palaeontological approach appears very promising, and for karstologists, it could become a routine method.

References


