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Geodynamic evolution of the peri-Mediterranean karst during the Messinian and Pliocen: evidence from the Ardèche and Rhône Valley systems canyons, Southern France

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Abstract.

During the Messinian-Pliocene eustatic cycle, the Mediterranean Sea was characterized by a short lived (5.95-5.32 Ma) sea-level fall, which attained -1500 m in some areas. The study of benchmark levels permits the chronology and dynamics of this event to be established. In the Rhône's middle valley, our investigations allow a new interpretation for the genesis of the Ardèche endokarst. A fall in base-level was responsible for both the incision of the so-called Messinian Canyons as well as a deep karst development. Karst systems were formed in association with the Messinian canyons of the Ardèche and Rhône rivers. During the flooding of the Mediterranean Basin (5.32 Ma), these karst systems were filled by water and plugged by sedimentary infilling of the rias. This mechanism pushed groundwater backward through the karst system, which in turn formed diagnostic "chimney-shafts". These pathways were geometrically connected to the position of the Pliocene benchmark levels. Consequently, the Messinian Salinity Crisis was responsible for two karst responses.

The first was concomitant with the crisis itself and corresponds to the formation of a karst system. The second followed the Messinian Salinity Crisis and corresponds to the adaptation of this karst system in Vauclusian karsts by the formation of "chimney-shafts".

Keywords : Karst; Cave; Speleogenesis; Messinian Salinity Crisis; Benchmark levels; Chimney-shaft.

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1. Introduction

The study area lies (Fig. 1) between the mid-Rhône Valley and the Cévennes Fault (N 50°), which lines the Hercynian basement/Mesozoic cover boundary. The dominant outcropping facies is a thick 200 m lower Cretaceous (Urgonian) carbonate platform incised both by the Rhône river and by its tributary, the Ardèche river. This extensive formation is deeply karstified.

The literature has long focussed on this famous karst (Guérin, 1973; Belleville, 1985; Gombert, 1988; Delannoy et al., 2001; Audra et al., 2004): (1) speleologic investigations concentrated on the organisation of the endokarst caves; and (2) other authors have studied the external morphology of the exokarst (Baulig, 1928; Gombert, 1988; Cornet, 1988). The flat geometry of the internal cave sets were soon identified, but the vertical connections linking these superimposed levels were poorly understood and the genesis of the successive stages was thought to be "*per descensum*", tied to the external fluvial terrace system. Links with the Messinian Salinity Crisis (MSC) or with the Lower Pliocene flooding were ignored.

In a previous work (Mocochain et al, in press), we gave a new interpretation about a karstic network genesis (Saint Marcel cave, Ardèche, France) confronted to important rise of its base level (during the Pliocene Flooding). We conclued with the proposal that a level terracing through a “per ascensum” dynamics was a possibility. This unusual dynamics was controlled by a Pliocene transgression.

This current study widens the field investigation to several local caves which allows us to study formation factors and mechanisms of karstic networks controlled by Messinian Canyon down-cutting (5.6-5.32 Ma).

This study will also tackle the development of these Messinian karsts during the periods following the MSC. As a complement to previous studies, it gives an interpretation about the rising karstic flowpaths similar to the famous Fontaine de Vaucluse (Vaucluse, France). Our interpretation based on the Ardèche karst study provides new insights in order to understand the formation, the age and the development of deep depth Vauclusian karsts wich are quite usual in the areas surrounding the Mediterranean Sea.

In conclusion, this study proposes a formation and development pattern of a karst with direct and differed impacts generated by the MSC, over a period of 6 Ma.

2. Karstic base-level (KBL) variations during the Messinian-Pliocene cycle

2.1. Chronology of the Messinian Salinity Crisis

The MSC (5.95 to 5.32 Ma ; Gautier et al., 1994; Krijgsman et al., 1999) resulted from the drying of the Mediterranean Sea following its isolation from the Atlantic Ocean (Ryan et al., 1973). Two marks resulted from this eustatic event: (1) a sedimentary mark, corresponding to a thick evaporitic layer composed of carbonaceous, sulfate and chloride (Rouchy, 1981); (2) a geomorphological mark at the margins of the Mediterranean Basin, with the incision of deep fluvial canyons. The MSC ended at the beginning of the Pliocene, with the rapid flooding of the Mediterranan Basin (5.32 Ma, see Blanc, 2002).

2.2. The benchmark levels

River processes and response during the Messinian-Pliocene eustatic cycle formed specific sedimentary and morphological records that we call benchmark levels. We have identified four benchmarks levels belonging to this cycle.

The first benchmark level corresponds to the pre-evaporitic abandonment surface (Fig. 2 and 3). Prior to the MSC, the Rhône river deposited a sequence of sediments on the subalpine piedmont plain (Clauzon, 1996). At the beginning of the MSC, the Rhône river incised these sediments and was responsible for the formation of a deep canyon. Therefore, this abandoned surface corresponds to an isochronous benchmark indicating the position of the Rhône river before the MSC. Nowadays, this altitude is 312 m asl (meters above sea level) and is observed 10 km east of the Saint-Remèze plateau (Fig. 1 and 2 ; Clauzon, 1982).

The second benchmark level corresponds to the Messinian Erosional Surface (Fig. 3 and 4). This surface is observed all around the Mediterranean’s margins and is clearly distinguishable on seismic cross-sections from the Gulf of Lion (Lofi et al., 2003). Moving landwards, this benchmark corresponds to the erosional surface of the fluvial canyons. The Messinian canyon of the Rhône river has been observed both on seismic cross-sections and in bore-holes (Clauzon, 1982). Four kilometers east of the present field site, this thalweg has been observed at a depth of – 236 m bsl (meters below sea level; Pierrelatte bore-hole in Fig. 1; Demarcq, 1960) resulting in a 600 meters deep incision in this area during the MSC. The Pliocene transgression flooded this erosional surface and fossilised the Rhône river position at the end of the MSC (Clauzon, 1996; Fig. 4).

The third benchmark level corresponds to the marine/non-marine surface (Fig. 3, 5 and 6). The Pliocene transgression pushed the Rhône river delta 300 km upstream of its present position (Clauzon, 1982). A high-stand sea level at 80 m asl is recorded during the Upper Pliocene (Haq et al., 1987). Sedimentary input from the Rhône river is responsible for the progressive infilling of its ria in a Gilbert type fan delta (Fig. 6 ; Clauzon, 1989). This specific sedimentary architecture is responsible for a sedimentary discontinuity between the continental and marine sediments, and records the altitude of the sea during this infilling phase (Fig. 3). Formation of this benchmark level by progradation is diachronous, occurring during most of the Quaternary (Clauzon, 1996 ; Clauzon and Rubino, 1992; Clauzon et al., 1995). Observations of faunas trapped in several areas along this marine/non marine surface provide an estimate of the velocity of progradation. At Trignan (Fig. 1), the benchmark level lies 130 m asl. This position is 60 m above its initial position, these things have inferred an uplift dynamic since its formation (Clauzon and Mocochain, in Besson et al., 2002; Mocochain and Clauzon, in prep.). These faunas are found upstream (Aguilar *et al.*, 1989) and downstream of that point (Michaux, 1966) and yields a date of 4.7 Ma for the onset of the Rhône progradation front (Fig. 3).

The last benchmark level corresponds to the late Pliocene abandonment surface of the Rhône river (Fig. 3 and 7). In the rias, progradation of the deltas is concomitant with river aggradation (Fig. 3). This sedimentary dynamic is responsible for a rise in river base-level at the end of the Upper Pliocene, approximately 2 Ma (Clauzon, 1996). During the Quaternary, the rivers stopped aggrading and abandoned their high-positions by incising new valleys. Altitude of this 2 Ma old isochronous benchmark level is 200 m asl at the eastern margin of the Saint-Remèze plateau (Fig. 1 and 3).

The position of these four benchmark levels allows the evolution of regional base-level to be reconstructed. This has also been the karst base-level (KBL) during the whole Messinian Pliocene Eustatic Cycle (Fig. 3). Thus, it is possible to demonstrate both a geometrical and a dynamical reconstruction of base-level evolution and the karst development phases in the Ardèche valley.

3. The Ardèche karst

3.1. The surface karst

The Saint-Remèze plateau (Fig. 1) is formed by three planation surfaces (noted S1, S2, and S3). These surfaces truncate a wide branchy anticlinal of faulted Cretaceous carbonates (Baulig, 1928; Guerin, 1973 ; Bellier and Vergely, 1987).

3.1.1. The 400 m surface (S_1)

S1 corresponds to upper surface (400 m) and belongs to a system of intersecting facetted surfaces. The previous surface (S_0) is tilted eastward towards the Molasse Basin of Valréas (Fig. 1). S_0 is partly covered by Burdigalian transgressive deposits indicating that the genesis of S_1 occurred after this cover.

3.1.2. The pre-evaporitic abandonment surface (S_2)

S_2 is cut-and-filled into S_1 and is geometrically related to the position of the Rhône river pre-evaporitic abandonment surface (Fig. 1). It lies between 300 and 330 m (Fig. 1) and contains an alluvial altered deposit. This surface is a benchmark for the position of the Ardèche river prior to the MSC (Martini, in press).

3.1.3. The Pliocene abandonment surface (S_3)

S_3 is cut-and-filled into S_1 and S_2. The extension of S_3 is smaller than the previous one. This surface is well developed upstream and downstream from the Ardèche canyon (Fig. 1), and is geometrically related to the Pliocene abandonment surface of the Rhône river. In the upper part of the canyon, it lies at an altitude of 260 m and decreases to 200 m at the downstream of the canyon. This difference of elevation corresponds to the natural flow slope of the Ardèche river).

3.1.4. The Canyon of the Ardèche river

S_1 to S_3 are down-cutted westward to eastward by the Ardèche canyon. This canyon is 29 km long and its depth can reach 300 meters around the altitude of S_2. At its extremity, this canyon is fossilised by marine Pliocene deposits. The position of the pre-evaporitic abandonment surface (S_2) and the Pliocene sediments suggest the formation of this canyon occurred during the MSC.

However, the Ardèche Canyon is not as deep as the Messinian canyon of with the Rhône river. This is not the only example and indeed a number of other rivers possess shallow Messinian canyons including the Hérault, the Cèze and the Vis rivers to name but a few (e.g., Camus, 2003). These rivers terminate in karstifiable rocks that suggests the formation of a karst below these canyons. The creation of these karsts, systematically observed below these canyons (see Audra *et al*., 2004), would be at the origin of their shallow downcutting during the MSC. This interpretation is confirmed by the existence of deep Messinian canyons in all non-karstifiable (are you sure the term karstifiable is really correct? Please check this point carefully. Yes, this term is correct) formations at the regional scale (for example Tech and Têt rivers in eastern Pyrenean region or the Durance river in the Alpes; Clauzon et al., 1987; Clauzon, 1990, 1996).

3.2. The endokarts

In the studied area, the endokarst is extremely well developed. It exhibits numerous wide karst systems, some of which develop over several kilometers (Saint-Marcel cave, Orgnac cave, Foussoubie cave). The development of this endokarst has resulted from three key controlling parameters, which are: (1) limestone fracturing responsible for permeable pathways facilitating groundwater flow; (2) a karst base-level which determines the slope of groundwater flow and hydraulic head; and finally (3) a topographic gradient which provides potential for the genesis of karst system. This paper is based on geomorphologic and geologic levelling surveys of caves roughly 82 km in the Ardèche plateau. Three representative karst systems are analyzed: the Foussoubie cave, the subterranean Tourne river and the Saint-Marcel cave(see Fig. 1).

3.2.1. The Foussoubie cave

This is a subterranean river 23 km in length and located west of the Ardèche canyon (Fig. 8). The cave is a through-cave and is still active nowadays. The allogenic water comes from the Planche, a small ephemeral creek which drains impermeable rocks (Fig. 8). The sinking stream lies 198 m asl and network's spring is located close of the Ardèche canyon at an altitude of 80 meters. Three other abandoned springs have been observed: the Cordier aven at 140 m, the Event Supérieur aven at 190 m, and the Devès-de-Virac aven at 255 m (Fig. 9).

3.2.2. The subterranean Tourne river

This karstic network is composed of the Perte -86 cave, Pascaloune cave and Tourne springs (Fig. 10 and 11). Links have been shown to exist between Pascaloune cave (alt. 260 m) and the Tourne springs (alt. 55 m; Belleville, 1985). The caves of Pascaloune and Perte -86 (Fig. 11) correspond to sinking streams of water from the Rimouren river, feeded by a deep phreatic network. Exploration by scuba diving of this karst system has reached a level of –154 m bsl in the Tannerie spring (see S. Redoutey; http://www.plongeesout.com/explorations/france/goul%20tannerie/goul%20tannerie%20recit%20redoutey%202004.htm) and – 98 m bsl in the Pont spring (explored by X. Méniscus.(http://www.plongeesout.com/explorations/france/goul%20du%20pont/goul%20du%20pont% 20recit%202003.htm; Fig. 11). These explorations have yet to reach the bottom of the system. Consequently, from the system's recharge to discharge areas, groundwater flows in a karstic system several kilometers long, with roots well below the present altitude of the Rhône river (50 m), before coming up in its vicinity.

Darbousset is an abandoned cave (200 m asl; Fig. 10 and 11) located close to Tourne springs and its karstic phreatic features suggest that it belongs to the subterranean Tourne river. It could be, as shown above, an abandoned spring of this karst system.

3.2.3. The Saint-Marcel cave

Saint-Marcel cave is located on the northern side of the Ardèche canyon, 3 km from its termination (Fig. 1). This 55 km long cave manifests three terraced draining levels (Belleville, 1985; Mocochain et al, in press); the lower level is active and is partly developed into a karstic phreatic zone (50 m asl to - 10 m bsl), the middle (100 to 130 m asl) and upper levels (170 to 200 m asl) are abandoned (Fig. 12). Each level is connected to the two other levels by chimney-shaft drains (Fig. 12). Their vertical conduits exhibit water drainage in an upward direction (Camus, 2003; Mocochain et al., in press).

4. Cave development dynamic during the Messinian Salinity Crisis

The deep stage associated with the MSC occurred later in time (Clauzon et al., 1996). The down-cutting of the canyons by some rivers was a relatively short 0.3 Ma event between 5.6 and 5.32 Ma. The fall in karst base-level (KBL) in response to the canyon incision that occurred during this period. Thus, the consequences of the MSC on the KBL decreased both in duration and in strength as we move further back the Mediterranean Sea. In the study area, down-cutting is estimated to be 600 m (Clauzon, 1982) for a duration lower than 0.3 Ma.

4.1. The formation of the Foussoubie cave

The Foussoubie cave corresponds to a karstic bypass of the Planche river in the direction of its base-level that corresponds to the Ardèche river. The galleries show a steady flow slope (see profile in Fig. 9). This is structured by a gravitational flow, with an associated spring near the Ardèche river (Fig. 9, altitude of 85 m asl). This is the consequence of a very stong topographic gradient between the deep of the Ardèche canyon and the Saint Remèze plateau.

Nowadays, the Ardèche river occupies the canyon bed incised during the MSC (Section 3.1). Thus, these observations suggest two possible periods for the formation of this cave: during the MSC or the Quaternary. Between these two periods, the formation of this cave was not possible because the Ardèche canyon was filled by Pliocene deposits (175 m in depth; Section 2.2). Foussoubie cave exhibits abandoned springs whose study allows to the establish the period of cave formation (Section 6.1).

4.2. The formation of the subterranean Tourne river

The downstream part of this system lies below the present position of the Rhône river and is consequently filled with water. Between the two outlets of this system at Pont spring and Tannerie spring, scuba diving explorations have reached a depth of – 154 m bsl (Tannerie spring) (Fig. 11).

The upstream part of the system manifests a sinking-stream physiography subjected to a gravitational flow (Perte – 86 cave, Fig. 11). The strong flow slope of this network and the depth of its downstream part suggest a link with the Messinian canyon of the Rhône river (Fig. 13). As in the previous example, the base-level down-cutting of the canyon is responsible for a very strong topographic gradient (600 m for the Rhône river). The Rimouren river probably used this topographic gradient to flow through the karst before to get back to the Messinian Rhône river. Investigations at – 154 m bsl allow an estimation of the position of the Messinian spring of groundwater. It could be located between – 154 m bsl and – 236 m bsl which corresponds to the final position of the Rhône river during the MSC. On the opposite side of Foussoubie cave, the subterranean Tourne river cannot use its Messinian spring at present. Indeed, this spring is plugged by 200 m of Pliocene deposits (Fig. 13). To remain active, this system must therefore use an open spring (Section 5.3).

4.3. The formation of the Saint-Marcel cave

The lower level of the Saint-Marcel cave (Fig. 12) occurs between 50 m asl and – 10 m bsl. This system drains the polje of Bidon at 330 m asl (unpublished dye tracing; Fig. 1). Three types of features are present in this system: (1) Features of the karst phreatic zone which were formed when the system was flooded. During these events, erosion was active in all the caves and was responsible for scallops or ceiling pockets (Slabe, 1995); (2) Features associated with the temporary phreatic zone. During the fall, water streamed along the cavity walls and was responsible for flute-type erosional features (rock rill); (3) Vadose features. During the low water level, flow incised channel in the floor of gallery.

These three types of features can be used to reconstruct the way in which the subterranean river operates under an episodic flood regime. The network's flow profile lies beneath the present position of the Ardèche river and goes down to a depth of –10 m bsl. The downstream portion of this network is therefore phreatic, although it retains the same physiography as the upstream section. Such an observation proves that the formation of this level was dependent upon the position of a base- level located at least 60 meters below the present day base-level. This base-level cannot be associated with the position of the Messinian Rhône river. In the downstream part of the network, ascending-shafts are well developed and linked to the Ardèche canyon.

The physiography of this subterranean river, its downstream depth under the present day level of the Ardèche river and the existence of these ascending shafts suggest two flow rates: (1) during low flow, the lower level drains towards the Messinian Rhône river, (2) during flood periods, this drainage is partly blocked because it reaches its saturation point. The lower level is put under pressure and ascending-shafts drain off the additional water towards the Ardèche river. This explains the presence of features typical of the vadose and temporary phreatic zones under the present position of Ardèche river. Thus, the lower level of Saint-Marcel cave has two flow rates: (1) a low flow rate, dependant on the subterranean Ardèche river which flows near the Messinian Rhône river (2) and a high flow rate, tributary of the Ardèche canyon. This specific architecture of this level is similar to the karst drainage model of the epi-phreatic zone described by Audra (1994) and Häuselmann et al. (2003).

During the MSC, down-cutting of the Rhône canyon was responsible for a karstification potential and a 600 m strong topographic gradient, over a short period of time inferior to 0.3 Ma. The examples described in this paper show that the karst development syn-crisis depends on the seepage of important allogenic streams into the karst (from a river or a polje). These streams require enough energy to compensate for the short duration of the crisis. This idea suggests a minimum energy threshold under which the genesis of the karst is not possible over a certain timescale. Dreybrodt (1996) has identified such a karstification process in a somewhat different context. He analyzed the very efficient formation of flooded karst systems associated with the seepage of important streams related to the creation of dams. In this situation, the karst fractures are flooded under an imoprtant thickness of water. This effect on limestones generates a fast dissolution. In conclusion, the injection of a high-energy stream into karst fractures, leads very quickly to the development of a karst drainage system. In this example, energy stream results of pressure exerted by an important thickness of water. In the Ardèche karst this energy stream results from an important topographic gradient linked with an important rate of flow water.

5. Dynamic of cave adaptation during the Pliocene (5.32 – 2 Ma)

The down-cutting of the canyons was stopped by their flooding at the beginning of the Pliocene (Clauzon, 1996) and the sea finally occupied the rias at 80 m asl (Haq et al., 1987). Base-level, which had been fluvial until that time, became marine and changed from – 236 m bsl to 80 m asl. This transgression certainly affected the canyon of the Ardèche river, as indicated by Pliocene deposits in its downstream part.

The Messinian springs were flooded because they lie below Pliocene sea level. This context favoured a forcing back of the springs in the karst system. The origin of the first KBL rise stage is eustatic. It replaces a second phase of sedimentary origin. This second phase corresponds to the aggradation of the rivers that filled the rias in a Gilbert type fan delta (Section 2.2; Fig. 6) This stage rose the KBL by 70 meters and ended during the Upper Pliocene. It is marked by position of the Pliocene abandonment surface. Consequently, the KBL was submitted to two rises during the Pliocene times (Fig. 3) which were responsible for a *per ascensum* adaptation of the Messinian karst drainages as for instance in the Saint-Marcel cave (Mocochain et al., in press).

5.1. Evolution of the Foussoubie cave

The different features in Foussoubie cave indicate dynamics associated with two flow rates: (1) low flow rate during low water level period (vadose features); and (2) high flow rate during flood perid (epi-phreatic features). In the downstream part of cave, a chimney-shaft system develops from the gallery and exits above the level of the Ardèche river (Fig. 9). The slope of this cave shows a break along the chimney-shafts. Therefore, genesis of these shafts occurred after formation of initial gallery (Fig. 14).

These abandoned shafts manifest phreatic morphologies. These features indicate a permanent phreatic hydrodynamic situation over a height of 100 m. Formation of these chimney-shafts could only have occurred if they had been associated with a pronounced increase KBL. During this period, the Foussoubie cave was permanently flooded and fonctionned in Vauclusian karst. Chimney-shafts are the conduits that worked in the springs (Camus, 2003; Mocochain et al., in press). Terracing of three chimney-shaft springs suggests a rise of KBL in several stages. A geometrical correlation exists between the Pliocene benchmark levels and these chimney-shafts. The Cordier aven (alt. 145 m asl) is very close to the marine/non- marine surface (altitude of 131 m asl; Section 2.2). The Devès-de-Virac aven (alt. 255 m) lies very close to the Pliocene abandonment surface of the Ardèche river (Fig. 3 and 9; Section 3.1.3). Thus, the first base-level rise induced by the Pliocene transgression formed the Cordier aven and the second rise, generated by aggradation of the Ardèche river, is at the origin of the Devès-de-Virac aven. This idea suggests a Messinian age for the intial conduit (Section 4.1). Indeed, during the Quaternary, base-level had a downslope behaviour induced by the glaciation cycles. This *per descensum* dynamic is therefore non-compatible with the development of these ascending shafts. From this perspective, the position of Event Supérieur aven at 190 m asl could correspond to a stabilization of the Ardèche river, between the beginning and the end of its aggradation (from 4.7 to 2 Ma). This 190 m bsl level is observed in other caves on the north side of the Ardèche canyon.

5.2. The caves associated with the 190 m base level

The Chauvet cave is a famous prehistoric cave. This cave has developed along a horizontal level during a period of base-level stability. A geomorphological study (see Delannoy et al., 2001; 2004) has shown that this cave is pre-Quaternary. Formation of the cave could not have occurred before the MSC because it is located 150 m below the pre-evaporitic abandonment surface (Section 2.2). The Chauvet cave is probably of Pliocene age linked to a high position of the Ardèche river at 190 m asl.

The Plaine-des-Gras cave (250 m, Fig. 8 and 15) begins with a shaft which is connected to a horizontal gallery located at 190 m asl. This gallery carries scallops indicating a flood direction (Fig. 15). On the gallery floor, an allogenic fluvial stand can be observed (Fig. 15). Therefore, the position of this gallery at 190 m asl, the flow-direction and the external stand indicate a subterranean bypass of the Ardèche river (Fig. 8). This cave is a benchmark of the Ardèche river at 190 m asl. The gallery floor has no feature characteristic of the vadose zone, therefore the cave was not formed during an episode of base-level fall (down-cutting river dynamic).

These observations suggest that the formation of Plaine-des-Gras cave did not occur during the Quaternary and the Messinian periods. The position of its horizontal gallery, 150 m below the pre-evaporitic surface, suggests that its genesis most probably occurred during the Pliocene, in the same context as the Event Supérieur aven (part of theFoussoubie cave) and the Chauvet cave. In addition, its geographical setting corresponds to the phreatic and epiphreatic features observed in all of the Plaine des Gras cave. These features are the result of Ardèche river floods.

5.3. Evolution of the subterranean Tourne river

The layout of the Tourne river network is similar to that of the Foussoubie cave, but its present dynamics is different. Indeed, the position of its Messinian spring is located below the position of its base-level which corresponds to the Messinian Rhône river. This assumed spring is covered by a thick layer of Pliocene deposits (< 200 m; Fig. 13). The present functioning of this system is Vauclusian karst (spring feeded by a deep flooded karstic network). With the initial spring being blocked, water flow uses two chimney-shafts (the Pont and Tannerie springs) to exit at the level of the Rhône river. These chimney-shafts also indicate a break with the initial flow slope system (profile). Their formation is therefore more recent and occurred during the Lower Pliocene, and could correspond to a "*per ascensum"* adaptation of the subterranean Tourne river during the Pliocene transgression. The Darbousset cave lies at the same altitude as the Pliocene abandonment surface of the Rhône river (200 m asl; Fig. 1 and 13). This cave also presents the typical feature of a chimney-shaft. These observations suggest that Darbousset cave was a spring of the subterranean Tourne river during the Upper Pliocene.

Correlation between the springs of these chimney-shafts and the Pliocene benchmark levels provides additional confirmation for the Messinian age of this network.

5.4. Evolution of the Saint-Marcel cave

Following its rise, the base-level stabilized for a long period which corresponds to the Pliocene high stand sea level (TB 3.4 cycle of Haq et al., 1987) and to the end of the aggradation phase (Fig. 3). In the Saint-Marcel cave, these periods of base-level stability were responsible for the development of two distinct speleogenesis stages. Each stage developed at the same altitude that Pliocene benchmark level:

- the Lower Pliocene, middle level is associated with the position of the marine/non-marine surface at 130 m asl,
- the upper level of Upper Pliocene age is associated with the position of the Pliocene abandonment surface (200 m asl; Mocochain et al., in press).

This *per ascensum* speleogenesis dynamic is associated with the formation of chimney-shafts, which interconnected each superimposed level. They allow an upward flow dynamic from one level to the other (Mocochain et al., in press). Therefore, when the base-level rises and then stabilizes, a chimney-shaft is formed between the concealed level and the new level (Fig. 16). During the Upper Pliocene, the Saint-Marcel cave had three draining levels. Thus, each cave level corresponds to a base-level position: (1) the lower level is consistent with the Messinian base-level position at a minimum elevation of 10 m bsl, (2) the middle level corresponds to the position of the Lower Pliocene marine/non-marine surface, (3) the upper level corresponds to the position of Pliocene abandonment surface.

6. Conclusion

In our opinion, the deep karst development of the Ardèche plateau is the direct result of the MSC. This conclusion results from two observations: (1) The karst systems manifest flowing slopes directly controlled by the Messinian canyons. The features of these systems indicate their functioning in terms of free gravitational flow. (2) These systems systematically have one or several chimney-shafts. The conduit landforms of these conduits reveal upward groundwater flow. This flow uses the chimney-shaft towards the position of the Pliocene benchmark levels.

These observations allow us to explain the formation of the Ardèche karst system by two karst models (Fig. 17).

- The Foussoubie cave model (Fig. 17). This includes the Foussoubie cave and the subterranean Tourne river. The formation of these two caves depends on river absorption by a swallow hole. Their initial springs are close to the bottom of the Messinian canyons. Subsequently, these caves acquired spring chimney-shafts associated with the Pliocene benchmark levels and were converted into Vauclusian karsts. There chimney-shafts very often come out onto the canyonside that is never linked to surface flow. Consequently it seems difficult to make these karstic flowbaths work in absortion at a given time of their genesis. This rise in flowpath formation can only be contemporary with a rising of base level and can only have a rising hydrodynamic function. In the areas surrounding the Mediterranean Sea, Vauclusian karsts are common, and our interpretation sheds light on their process of formation.

- The Saint-Marcel cave model (Fig. 17). The Saint-Marcel cave shows three terraced draining levels. Each draining levels are associated with a position of the base level. The development of the first level during the MSC is similar to the Foussoubie model. However, during the Pliocene there is a *per ascensum* speleogenesis in two karstification stages (Mocochain et al., in press). As with the Foussoubie model, rising base-level dynamics generated chimney-shafts. In the Saint-Marcel model, these chimney-shafts are not connected to the ground surface but interconnected with the three horizontal cave levels.

The factual chronology for the genesis of the Ardèche karst may be summarised as follows (Fig. 17):

(1) The first period corresponds to the MSC: deep down-cutting of the limestone plateau by the Rhône and the Ardèche rivers was responsible for a strong topographic gradient. Only a strong allogenic input could have produced speleogenesis. This was a consequence of the short duration of the MSC in this area.

(2) The second period corresponds to the beginning of the Pliocene, when the Pliocene transgression flooded the canyons and karst systems. In these systems, forcing back formed chimney-shafts which allowed water circulation around the raised base-level.

(3) The third period is contemporaneous with the Pliocene aggradation of the river filled the first generation of chimney-shafts. This new forcing back facilitated the formation of a second generation of chimney-shafts near the Pliocene abandonment surface.

(4) The last phase occurred during the Quaternary: the cyclic occurrence of glaciations generated new down-cutting of the rivers in several steps. The rivers eroded the Pliocene deposits and successively unblocked the springs filled during the Pliocene. The present base-level position suggests that the caves of Saint-Marcel and Foussoubie were functional during the Messinian, and that the subterranean river of Tourne operated during the Pliocene.

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Figure caption

Figure 1. Geological setting and location of the caves and benchmark levels in the study area.

Figure 2. Sketch of the three-dimensional representation of the study area showing the pre-evaporitic situation.

Figure 3. Reconstruction of the base-level evolution since 6 Ma by the use of Messinian Pliocene benchmark levels.

Figure 4. Sketch of the three-dimensional representation of the study area during the Messinian Salinity Crisis.

Figure 5. Sketch of the three-dimensional representation of the study area during the Pliocene transgression.

Figure 6. Sketch of the three-dimensional representation of the study area during the Pliocene and the contemporaneous sedimentary structuring of a Gilbert type fan delta.

Figure 7. Sketch of the three-dimensional representation of the study area: at the end of Pliocene and the contemporaneous structuring of the Pliocene abandonment surface.

Figure 8. Location of the Foussoubie cave and the Plaine-des-Gras cave in these geological setting.

Figure 9. Profile of the Foussoubie cave and associated springs.

Figure 10. Geological setting and localisation of the subterranean river of the Tourne system.

Figure 11. Profiles parts of subterranean Tourne river (Perte – 86 cave, Pascaloune cave, Darbousset cave, Pont and Tannerie springs).

Figure 12. Map of three levels of the Saint-Marcel cave and location of the chimney-shafts.

Figure 13. E/W schematic profile of the subterranean Tourne river.

Figure 14. Sketch of the genesis of chimney-shaft spring by rise of base-level.

Figure 15. Profile of the Plaine-des-Gras cave.

Figure 16. Sketch of the representation of the terracing dynamic of a karstic drainage and genesis of chimney-shafts during a stage of base- level rise.

Figure 17. Synthesis. Evolution of two karstic models since 6 Ma.

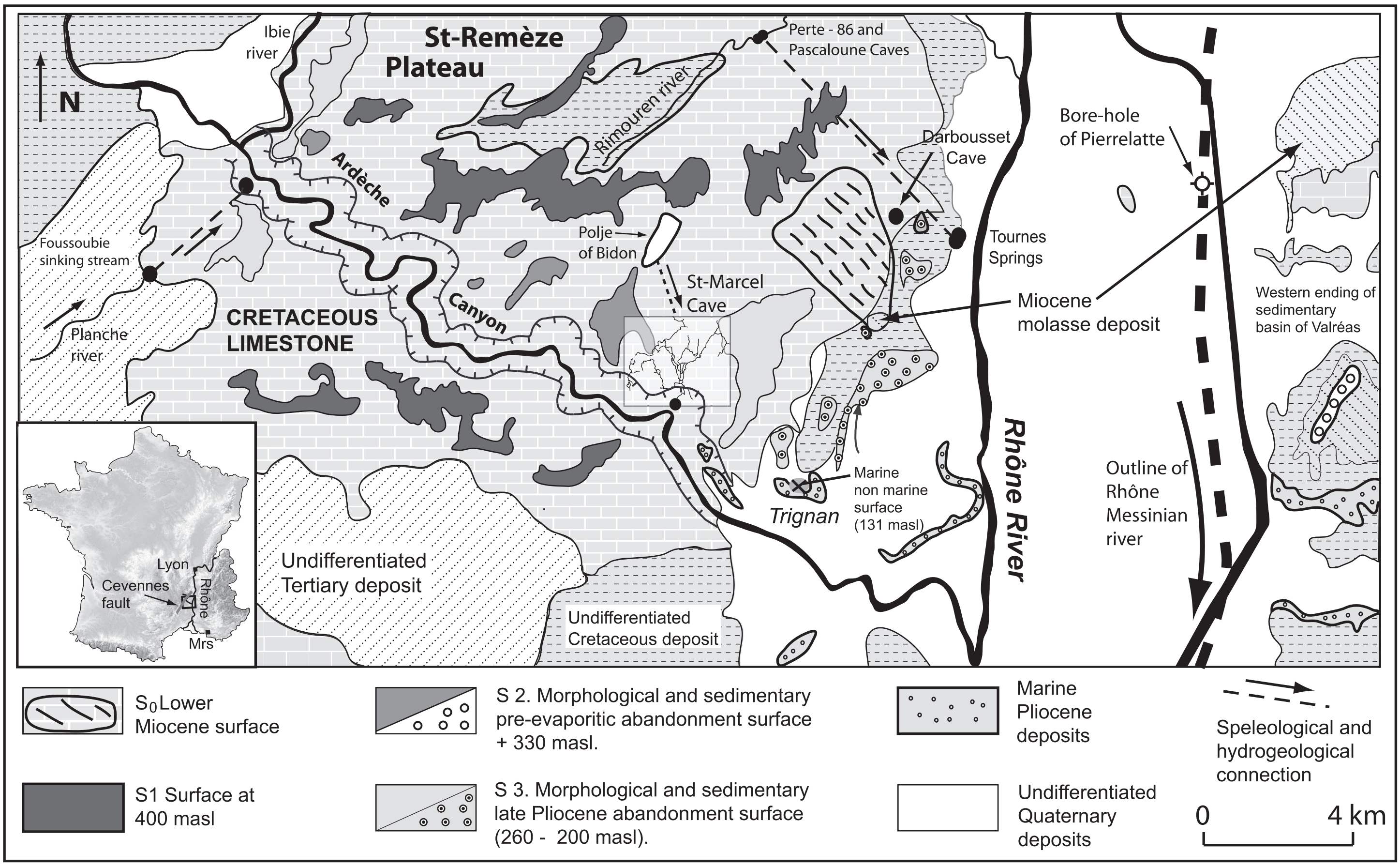

N
Ibie river
St-Remèze Plateau
Perte - 86 and Pascaloune Caves
Rimouren river
Ardèche
Canyon
Darbousset Cave
Tournes Springs
Bore-hole of Pierrelatte
Foussoubie sinking stream
Planche river
CRETACEOUS LIMESTONE
Polje of Bidon
St-Marcel Cave
Miocene molasse deposit
Western ending of sedimentary basin of Valréas
Marine non marine surface (131 masl)
Trignan
Rhône River
Outline of Rhône Messinian river
Undifferentiated Tertiary deposit
Undifferentiated Cretaceous deposit
Lyon
Cevennes fault
Rhône
Mrs
S0 Lower Miocene surface
S1 Surface at 400 masl
S 2. Morphological and sedimentary pre-evaporitic abandonment surface + 330 masl.
S 3. Morphological and sedimentary late Pliocene abandonment surface (260 - 200 masl).
Marine Pliocene deposits
Undifferentiated Quaternary deposits
Speleological and hydrogeological connection
0
4 km

Figure 1

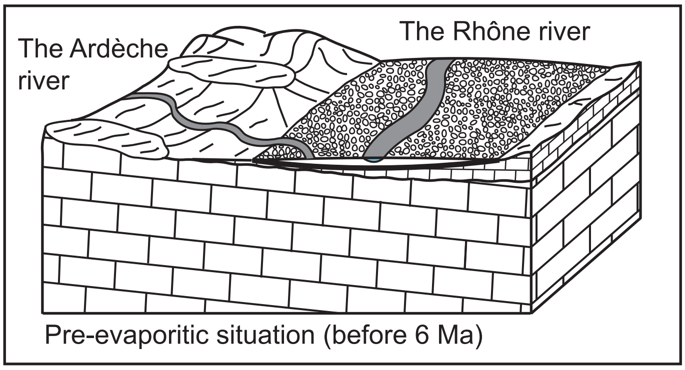

The Ardèche river
The Rhône river
Pre-evaporitic situation (before 6 Ma)

Figure 2

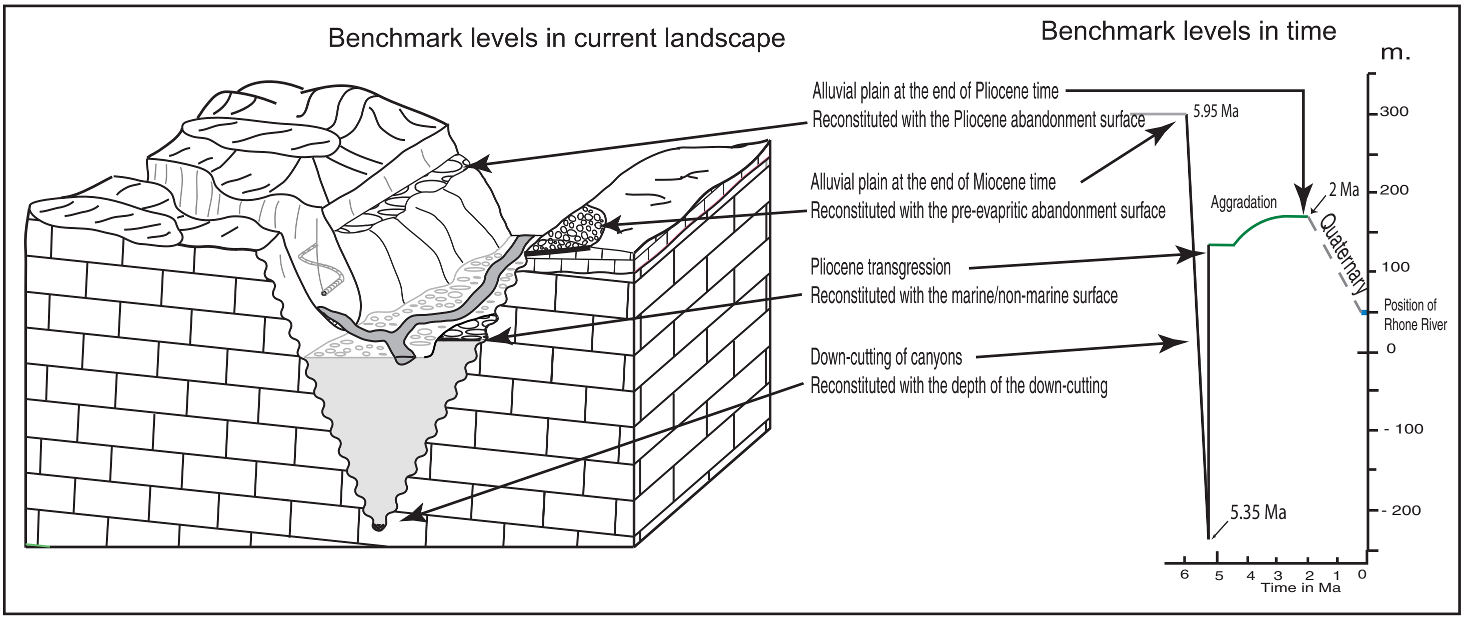
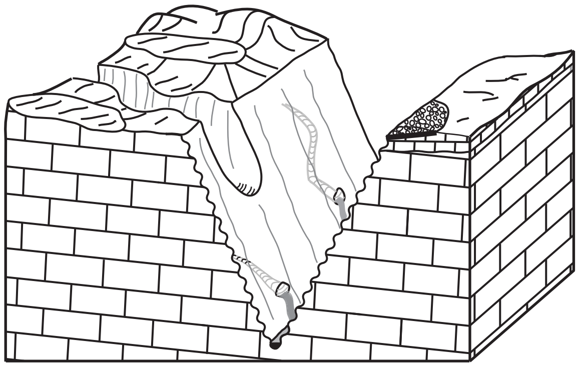
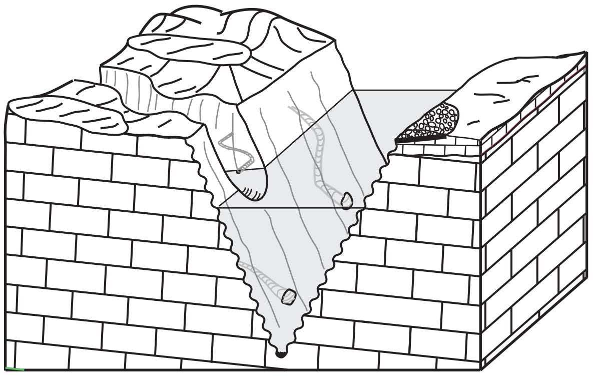

Benchmark levels in current landscape
Benchmark levels in time
m.
Alluvial plain at the end of Pliocene time
Reconstituted with the Pliocene abandonment surface
5.95 Ma
300
Alluvial plain at the end of Miocene time
Reconstituted with the pre-evapritic abandonment surface
Aggradation
2 Ma
200
Quaternary
Pliocene transgression
Reconstituted with the marine/non-marine surface
100
Position of Rhone River
0
Down-cutting of canyons
Reconstituted with the depth of the down-cutting
- 100
5.35 Ma
- 200
6
5
4
3
2
1
0
Time in Ma

Figure 3



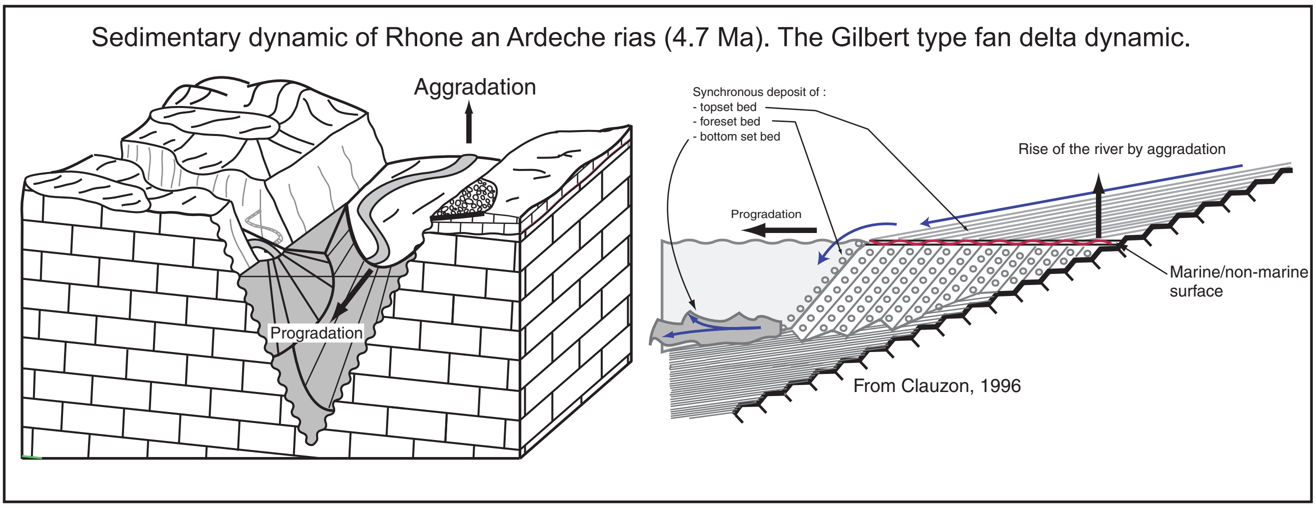
Situation during the Messinian Crisis (5.95 - 5.32 Ma)

Figure 4



Situation during the Pliocene transgression (5.32 Ma)

Figure 5



Sedimentary dynamic of Rhone an Ardeche rias (4.7 Ma). The Gilbert type fan delta dynamic.

From Clauzon, 1996

Figure 6

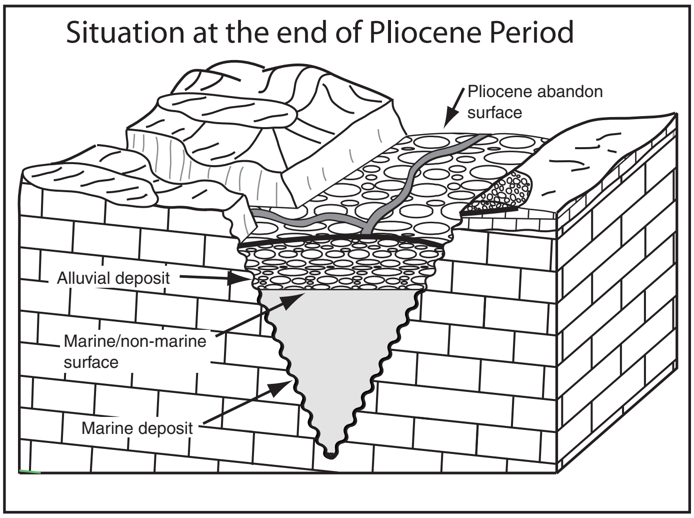

Situation at the end of Pliocene Period
Pliocene abandon surface
Alluvial deposit
Marine/non-marine surface
Marine deposit

Figure 7

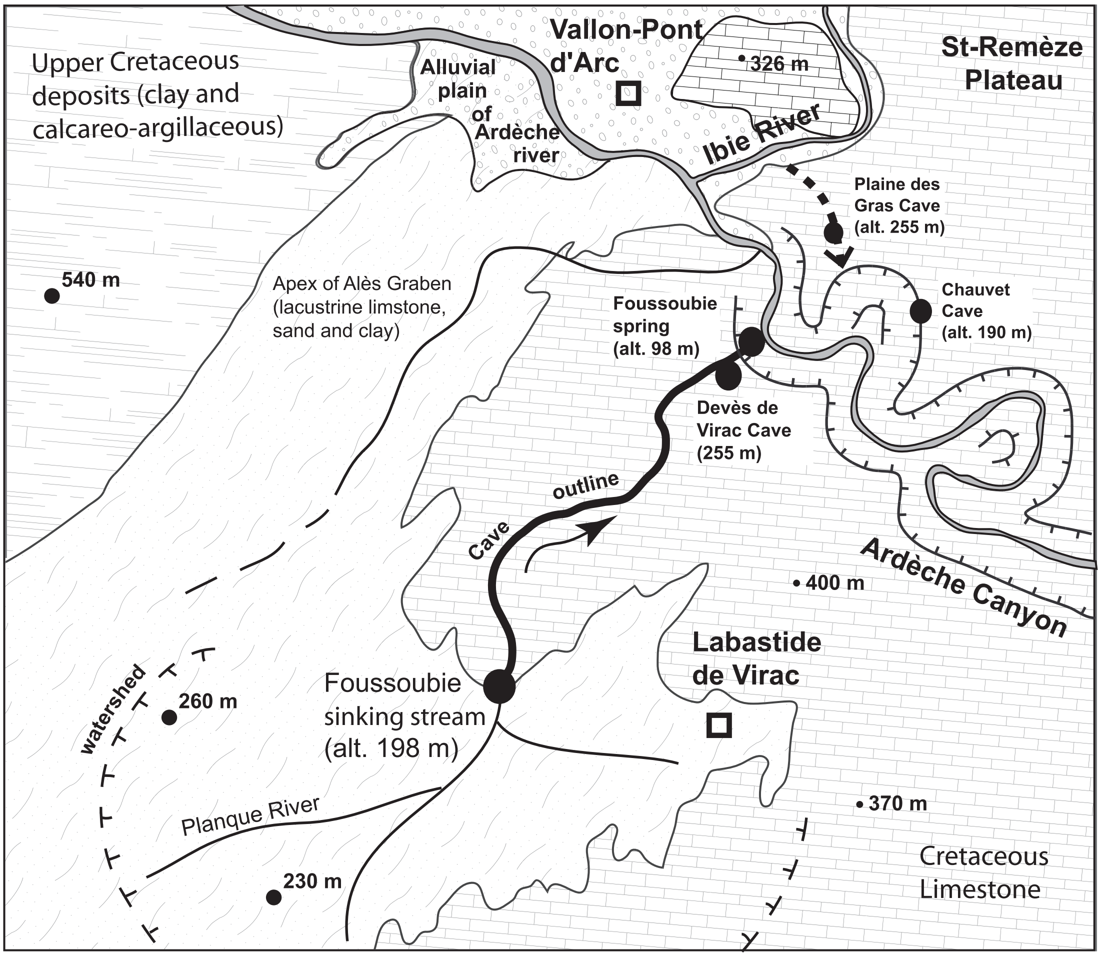

Upper Cretaceous deposits (clay and calcareo-argillaceous)
Alluvial plain of Ardèche river
Vallon-Pont d'Arc
326 m
St-Remèze Plateau
Ibie River
Plaine des Gras Cave (alt. 255 m)
540 m
Apex of Alès Graben (lacustrine limstone, sand and clay)
Foussoubie spring (alt. 98 m)
Chauvet Cave (alt. 190 m)
Devès de Virac Cave (255 m)
Cave outline
Ardèche Canyon
400 m
Labastide de Virac
watershed
260 m
Foussoubie sinking stream (alt. 198 m)
370 m
Planque River
230 m
Cretaceous Limestone

Figure 8

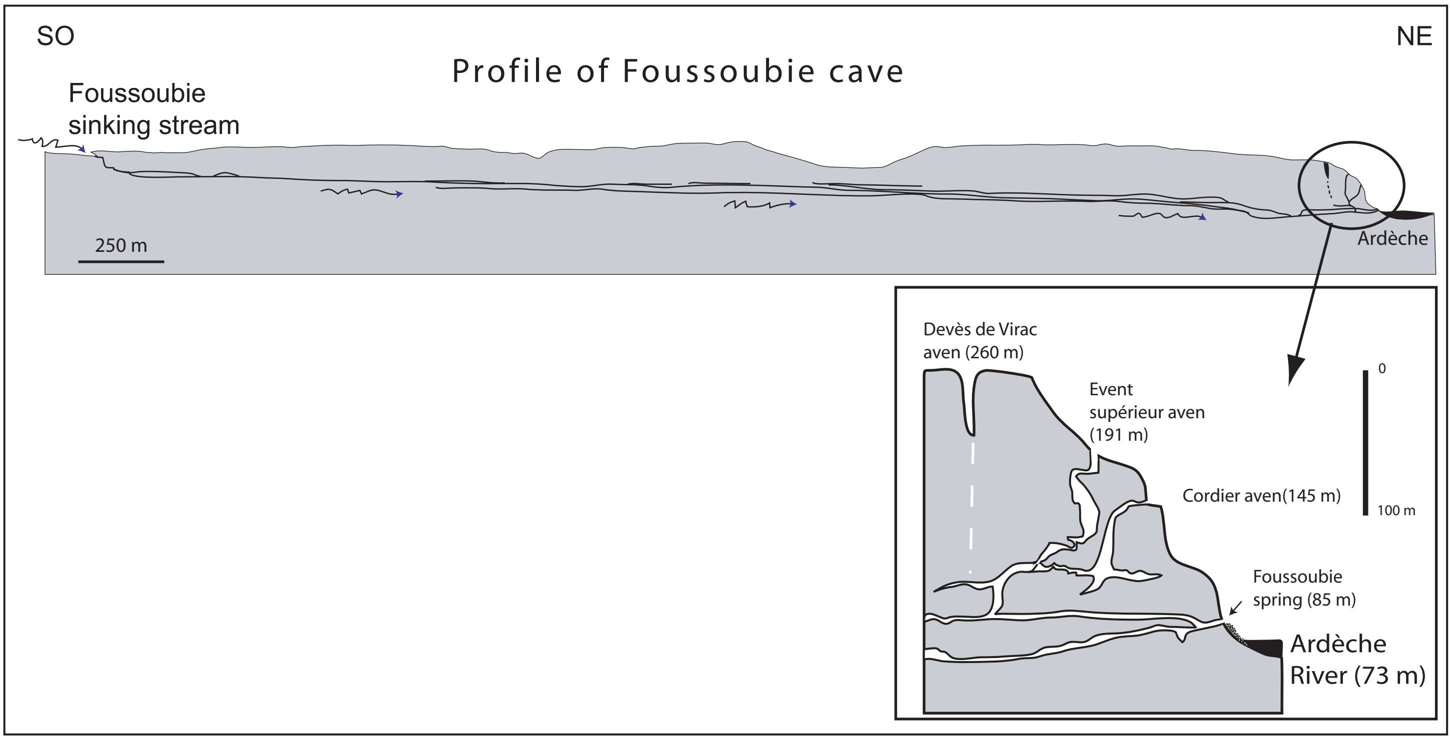

SO
NE
Profile of Foussoubie cave
Foussoubie sinking stream
250 m
Ardèche
Devès de Virac aven (260 m)
Event supérieur aven (191 m)
Cordier aven(145 m)
0
100 m
Foussoubie spring (85 m)
Ardèche River (73 m)

Figure 9

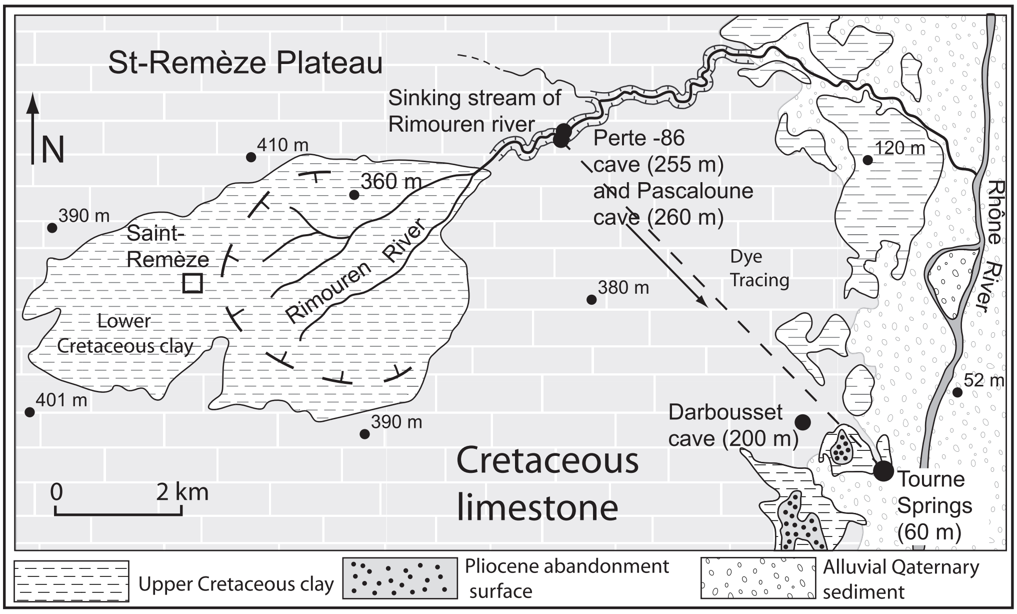

St-Remèze Plateau
N
Sinking stream of Rimouren river
Perte -86 cave (255 m) and Pascaloune cave (260 m)
410 m
360 m
390 m
Saint-Remèze
Rimouren River
Lower Cretaceous clay
401 m
390 m
380 m
Dye Tracing
120 m
Rhône River
52 m
Darbousset cave (200 m)
Tourne Springs (60 m)
Cretaceous limestone
0
2 km
Upper Cretaceous clay
Pliocene abandonment surface
Alluvial Qaternary sediment

Figure 10

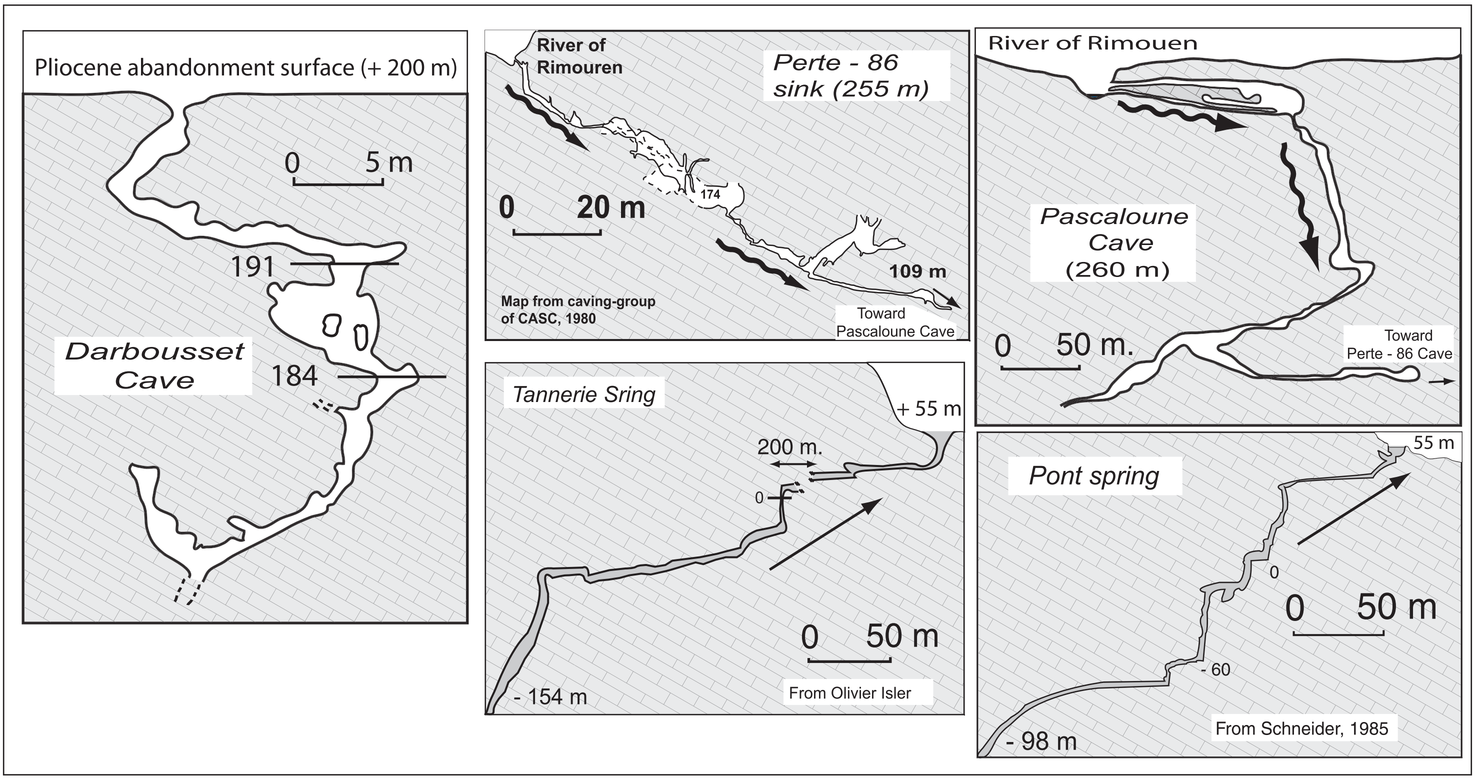

Pliocene abandonment surface (+ 200 m)
0 5 m
191
Darbousset Cave
184
River of Rimouren
Perte - 86 sink (255 m)
0 20 m
174
109 m
Map from caving-group of CASC, 1980
Toward Pascaloune Cave
River of Rimouen
Pascaloune Cave (260 m)
0 50 m.
Toward Perte - 86 Cave
Tannerie Sring
+ 55 m
200 m.
0
0 50 m
- 154 m
From Olivier Isler
Pont spring
55 m
0
0 50 m
- 60
- 98 m
From Schneider, 1985

Figure 11

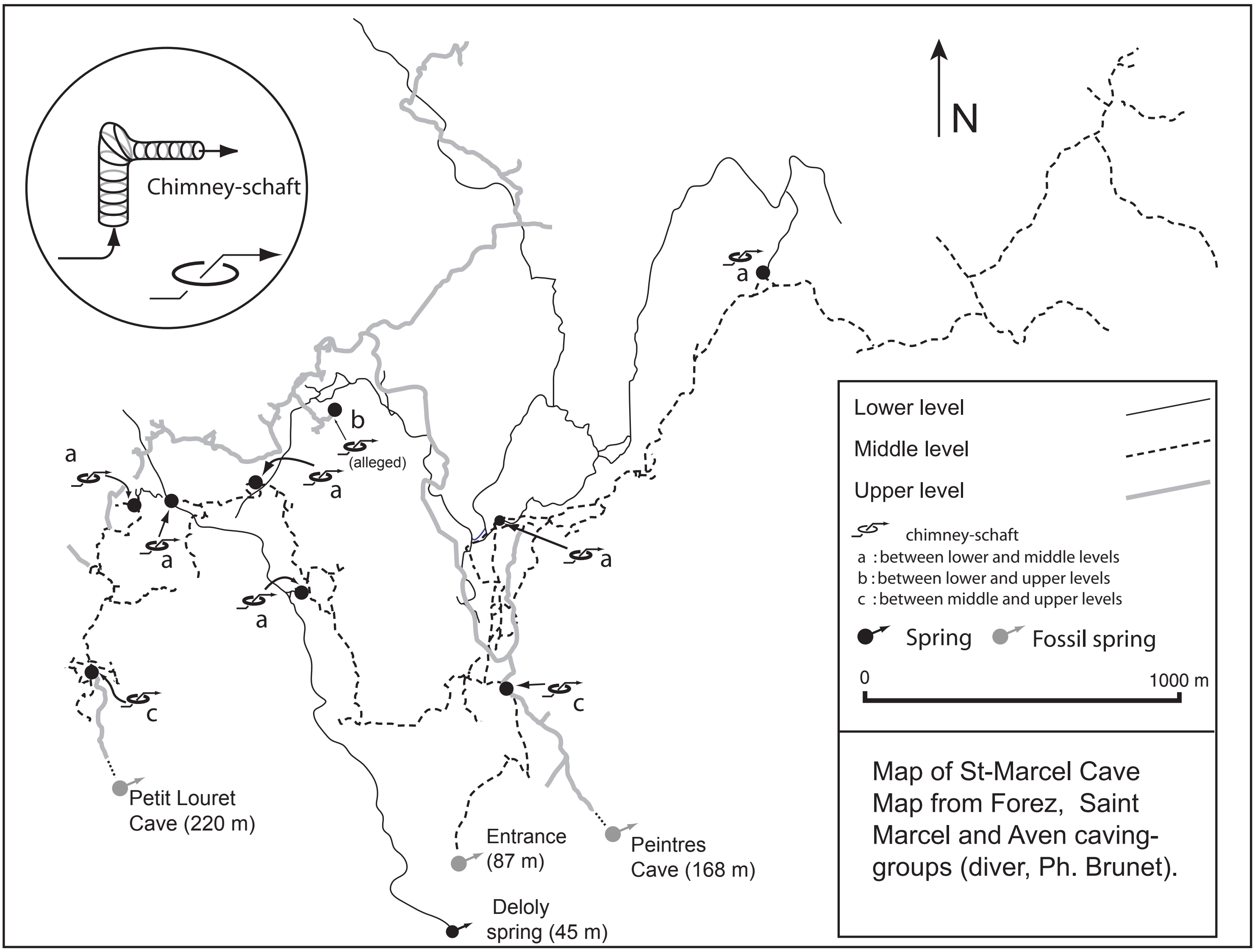

Chimney-schaft
N
a
a
b
(alleged)
a
a
a
a
a
c
c
Petit Louret
Cave (220 m)
Entrance
(87 m)
Peintres
Cave (168 m)
Deloly
spring (45 m)
Lower level
Middle level
Upper level
chimney-schaft
a : between lower and middle levels
b : between lower and upper levels
c : between middle and upper levels
Spring
Fossil spring
0
1000 m
Map of St-Marcel Cave
Map from Forez, Saint
Marcel and Aven caving-
groups (diver, Ph. Brunet).

Figure 12

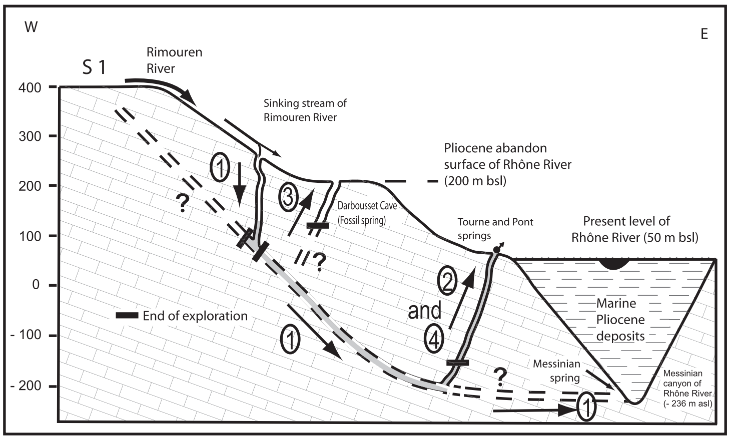
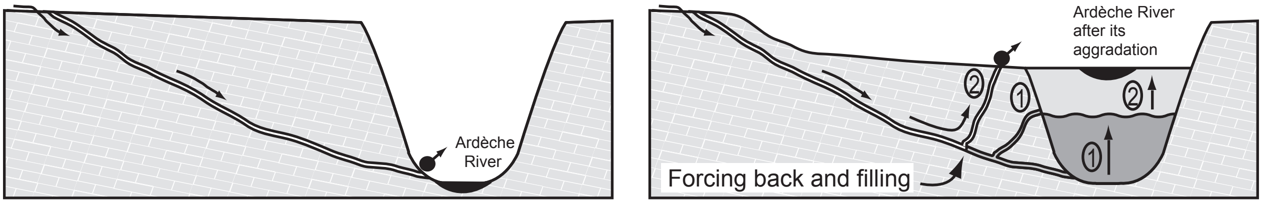

W
E
S 1
Rimouren River
400
300
200
100
0
- 100
- 200
Sinking stream of Rimouren River
Pliocene abandon surface of Rhône River (200 m bsl)
①
③
?
Darbousset Cave (Fossil spring)
//?
Tourne and Pont springs
Present level of Rhône River (50 m bsl)
②
and
④
Marine Pliocene deposits
End of exploration
①
?
Messinian spring
Messinian canyon of Rhône River (- 236 m asl)
①

Figure 13



Formation of the initial drainage during the douwn-cutting of the river.

Evolution of drainaige after a rise of base-level. Each base-level rise generates a chimney-shaft spring.

Figure 14

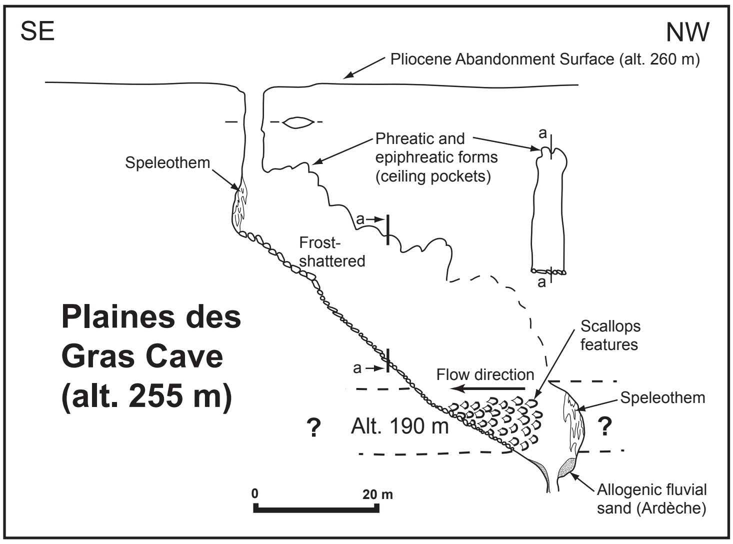

SE
NW
Pliocene Abandonment Surface (alt. 260 m)
Phreatic and epiphreatic forms (ceiling pockets)
a
Speleothem
a
Frost-shattered
a
a
Plaines des Gras Cave (alt. 255 m)
Scallops features
Flow direction
Speleothem
?
Alt. 190 m
?
0
20 m
Allogenic fluvial sand (Ardèche)

Figure 15

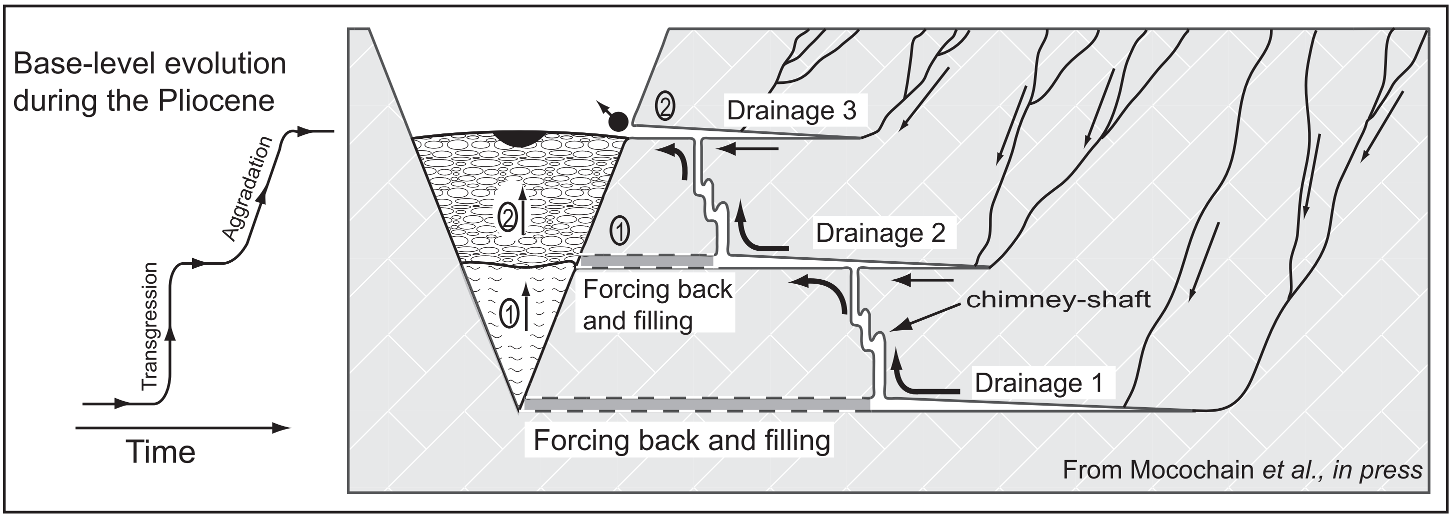
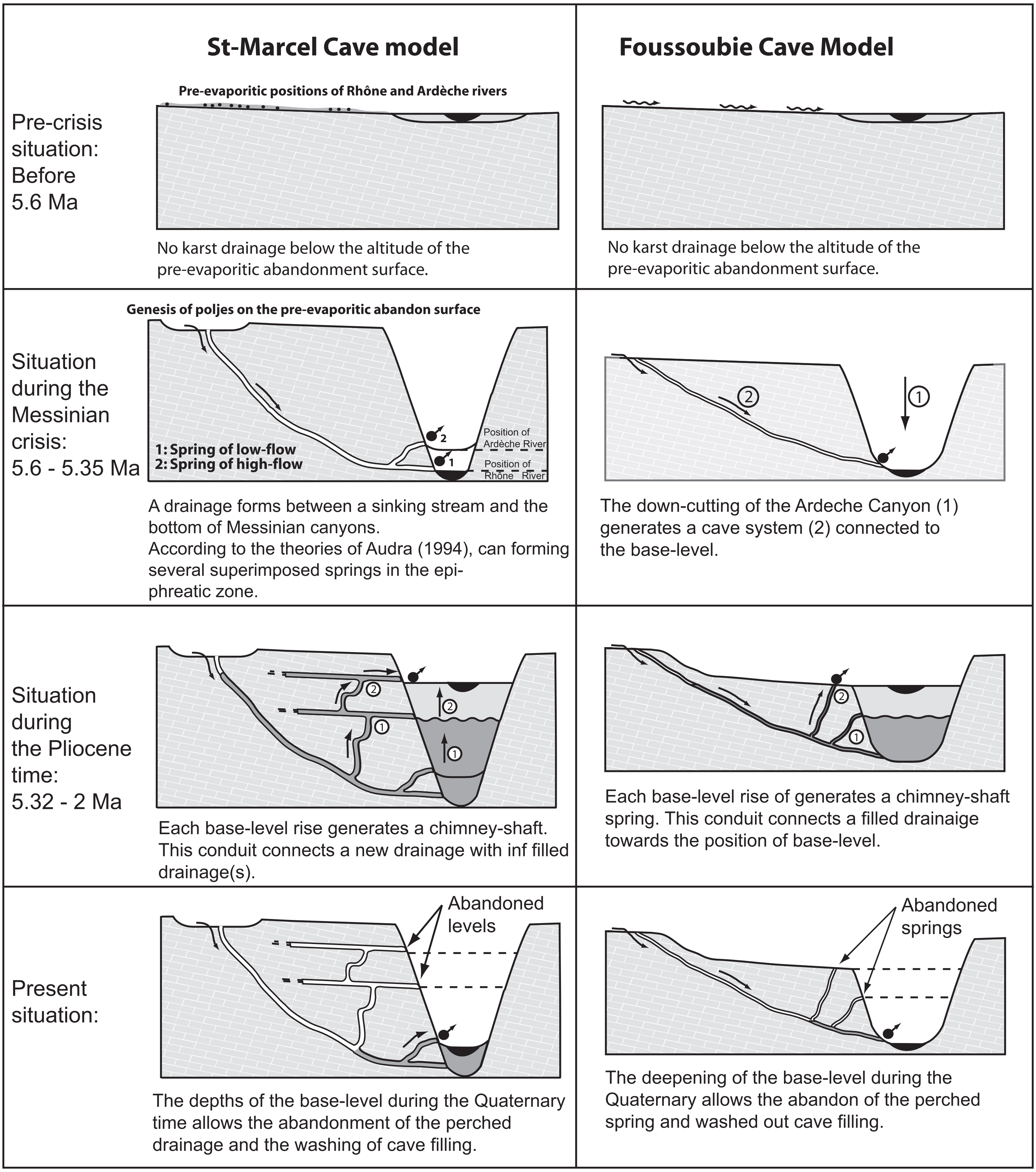

Base-level evolution
during the Pliocene
Transgression
Aggradation
Time
②
Drainage 3
②
①
Drainage 2
①
Forcing back
and filling
chimney-shaft
Drainage 1
Forcing back and filling
From Mocochain *et al., in press*

Figure 16



St-Marcel Cave model

Foussoubie Cave Model

Pre-crisis situation: Before 5.6 Ma

No karst drainage below the altitude of the pre-evaporitic abandonment surface.

No karst drainage below the altitude of the pre-evaporitic abandonment surface.

Situation during the Messinian crisis: 5.6 - 5.35 Ma

A drainage forms between a sinking stream and the bottom of Messinian canyons.
According to the theories of Audra (1994), can forming several superimposed springs in the epiphreatic zone.

The down-cutting of the Ardeche Canyon (1) generates a cave system (2) connected to the base-level.

Situation during the Pliocene time: 5.32 - 2 Ma

Each base-level rise generates a chimney-shaft. This conduit connects a new drainage with inf filled drainage(s).

Each base-level rise of generates a chimney-shaft spring. This conduit connects a filled drainaige towards the position of base-level.

Present situation:

The depths of the base-level during the Quaternary time allows the abandonment of the perched drainage and the washing of cave filling.

The deepening of the base-level during the Quaternary allows the abandon of the perched spring and washed out cave filling.

Figure 17