The effect of river dynamics induced by the Messinian Salinity Crisis on karst landscape and caves: Example of the Lower Ardèche river (mid Rhône valley)

Ludovic Mocochain [a,b,*], Philippe Audra [c], Georges Clauzon [a], Olivier Bellier [a], Jean-Yves Bigot [d], Olivier Parize [e], Philippe Monteil [f]

[a] CEREGE, Aix-Marseille Université, CNRS, IRD, Collège de France, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence, Cedex 4, France
[b] Aix-Marseille Université, Centre de Sédimentologie — Paléontologie «Géologie des systèmes carbonatés». 13331 Marseille, Cedex 03, France
[c] Polytech'Nice Sophia, Engineering School of Nice — Sophia Antipolis University, 1645 route des Lucioles, 06410 BIOT, France
[d] Les 7 portes, 04400 Barcelonnette, France
[e] AREVA, 1 place de la Coupole, 92084, Paris La Défense, France
[f] Buisson Barbier, 42520 Roisey, France

ARTICLE INFO

ABSTRACT

The karstic canyon of Lower Ardèche is located in the Middle Rhône valley, which is directly tributary to the Mediterranean Sea. The Rhône River is emblematic of the Messinian Salinity Crisis (MSC) impact on landscape morphology. Along the edge of the Saint-Remèze Plateau, the Rhône valley displays four benchmark levels generated by the MSC: the Pre-evaporitic abandonment surface (1), the Messinian erosional surface (2), the Marine/non-marine surface of the Pliocene ria (3) and the Pliocene abandonment surface (4).

The study of these benchmark levels allows us to reconstruct the evolution of the regional base level over the last 6 Ma. We obtain a curve for base-level evolution that provides a geodynamic reference, which is used to investigate the morphogenesis of the Saint-Remèze karstic plateau.

The Ardèche River downcuts the Saint-Remèze Plateau in a deep canyon, from Vallon-Pont-d'Arc to the West, to its confluence with the Rhône to the East. Several abandoned valleys are present along the western edge of the Saint-Remèze Plateau at the inlet of the Ardèche canyon. In these abandoned valleys, the fluvial deposits are related to several periods, from the Pliocene onwards. They provide important insights into the fluvial dynamics: a 160 m-thick aggradation sequence infilled the Ardèche canyon during the Pliocene. This aggrading river caused the first lateral shifting, as an aggradation epigenesis. This first infilling shows that the Ardèche canyon already existed before the Pliocene. Secondly, it has been demonstrated that the Ardèche Canyon is downcut into the Pre-evaporitic surface of the Saint-Remèze Plateau, dated to 5.45 Ma [Martini, J., 2005. Etude des paléokarsts des environs de Saint-Remèze (Ardèche, France): mise en évidence d'une rivière souterraine fossilisée durant la crise de salinité messinienne. Karstologia 45–46, 1–18]. Consequently, the canyon downcutting is entirely due to the MSC, and occurred during a time span of only 100 000 years. Based on these observations, it is possible to elucidate the curve of the regional base-level evolution. Hence, we are able to propose a new interpretation of the geomorphological evolution of the Saint-Remèze karstic plateau and its cave levels for the last 6 Ma. The cave levels consist in underground short-cuts of the surface meanders. They mainly developed during the Pliocene aggradation cycle. The Chauvet Cave, famous for its Palaeolithic paintings, corresponds to one of these underground short-cuts. The aggradation period ends at the end of the Pliocene with long high-level riverbed stability. It favours the development of large low gradient surfaces as pediments.

The complete Messinian–Pliocene eustatic cycle is responsible for the downcutting of the Ardèche canyon and its infilling during the Pliocene. Consequently, karst developed according to the base-level oscillations, as low gradient surfaces and as cave levels. For the study of the peri-Mediterranean caves and karst areas, we propose to apply the Lower Ardèche valley evolution model, based on the base-level oscillations during and after the MSC.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Many karst areas around the Mediterranean have been subject to massive changes of base level since the Late Miocene (Messinian) salinity crisis that desiccated the Mediterranean Sea basin and had profound effects on base levels provided by the major river systems flowing into the Mediterranean. One such area, where evidence of such changes is preserved, and where there is evidence of prolonged and varying interactions between karst and fluvial processes, is the limestone Ardèche Canyon, a tributary to the river Rhône in Mediterranean France.

* Corresponding author. Aix-Marseille Université, CEREGE, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence, Cedex 4, France.
E-mail address: ludomocochain@gmail.com (L. Mocochain).

Pliocene marine sediments are present in a paleotalweg currently located at the outlet of the Ardèche canyon (Fontannes, 1882; Baulig, 1928; Denizot, 1952; Ballesio, 1972; Blanc, 1976; Belleville, 1985). This outcrop allows us to ascribe the downcutting of the Ardèche canyon to the Miocene, and possibly to the Messinian period. However, the dating of the canyon incision phases has remained, until now, an open question because consistent observations could only be obtained in the outlet of the Ardèche canyon. This question regarding the age of Ardèche canyon downcutting provoked debate, especially regarding the interpretation and ages of speleogenetic phases, which are connected to the evolution of the Ardèche base level.

Numerous studies have attempted to explain the existence of cave levels along the edge of the canyon (Labrousse, 1977; Belleville, 1985; Pascal et al., 1989; Debard, 1997). At present, discussion centres on the chronology of the speleogenetic phases. According to some authors (Debard, 1997; Delannoy et al., 2001a,b, 2004), genesis of the cave levels resulted from downcutting stages that can partly be ascribed to the Messinian Salinity Crisis (MSC) and partly to the glacial cycles of the Pleistocene.

Martini (2005) has demonstrated that the Ardèche flowed over the Pre-evaporitic surface of the Saint-Remèze Plateau, at 5.45 Ma. Since the Ardèche is cut into this surface, it is obviously younger. Mocochain et al. (2006a) have ascribed the canyon downcutting entirely to the MSC. This hypothesis was based on the 'per ascensum' cave level genesis over a 200 m elevation, from the bottom of the Messinian canyon up to the top of the Pliocene filling of the valleys. The 'per ascensum' speleogenesis is related to the rising of the base level during the Pliocene (phase 1: rewatering of the Mediterranean Sea; phase 2: river aggradation).

In this paper, we provide a new hypothesis to account for the downcutting of the Ardèche Canyon, due entirely to the MSC. Dating of the Ardèche canyon incision can be obtained by studying the deflections of the river at the canyon inlet, near Vallon-Pont-d'Arc (Figs. 1 and 2). A 'self-piracy' phenomenon (a meander cut-off) produced the Estre "cirque" during the Upper Pleistocene, as indicated by the age of the last fluvial sediments (Fza_1 of the geological map; Pascal et al., 1989). One kilometre upstream, in the vicinity of Vallon-Pont-d'Arc, our field work has identified several additional deflections of the Ardèche. The relative chronology of these deflections allows us to propose a new interpretation for the age of the Ardèche canyon downcutting and its subsequent evolution.

This renewed interpretation of the direct and delayed impacts of the MSC allows us to define a new model for the geomorphological evolution of the Saint-Remèze Plateau, with implications both for surface landscapes and for the genesis of the cave levels. This methodological framework will help the reassessment of all karst areas that surround the
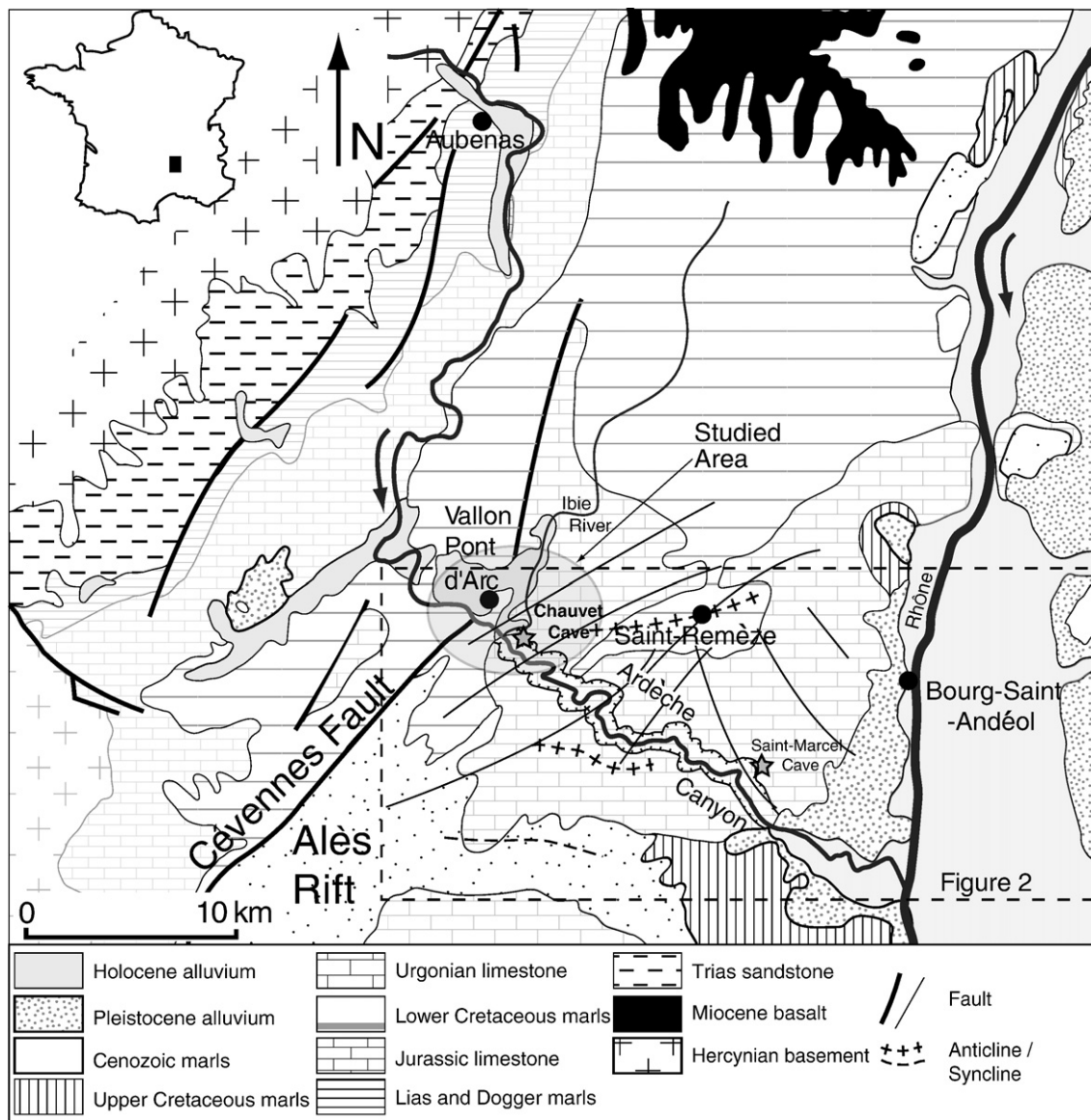
Fig. 1. Geological map of the Middle and Lower Ardèche.
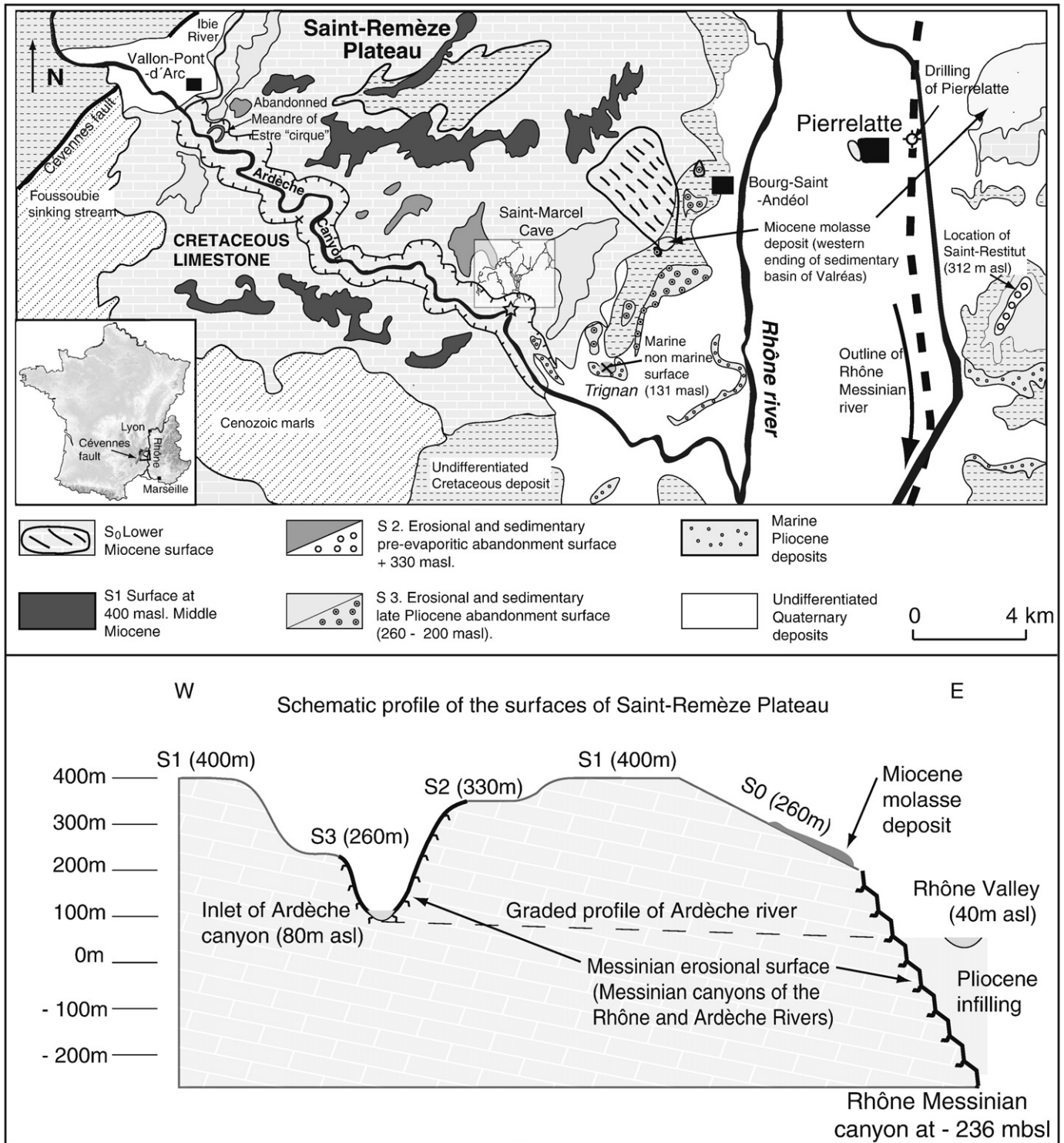
Fig. 2. Geomorphological and structural setting of the Saint-Remèze Plateau and its surrounding (after Mocochain et al., 2006a).

Mediterranean basin, which were influenced by sea-level changes, and notably the MSC.

2. Geological and morphotectonic context

2.1. Geological context in the region of Vallon-Pont-d'Arc

The study region constitutes a regional carbonate plateau affected by a major NE-trending fault system, the Cévennes fault system, which was emplaced during a late Hercynian event and reactivated during the Cenozoic tectonic phases (Bellier and Vergeley, 1987). During the Eocene, the Pyrenean tectonic phase produced wide E-striking folds and reactivated a NE-trending major fault system (Cévennes Fault) by a left-lateral movement (Fig. 1; e.g., Bellier and Vergeley, 1987; Pascal et al., 1989; Martin and Bergerat, 1996). The Oligocene extension in relation to the regional rifting reactivated the Cévennes fault and its conjugate fractures (N 140°) by normal faulting. These tectonics produced the Alès rift (e.g., Sanchis and Séranne, 2000). After the Oligocene, the present

geological structure was acquired. From the Oligocene onwards, no activity is recorded along major structures, even if Bellier and Vergeley (1987) mentioned E-trending compression mainly registered by micro-structures. Tectonics only occurred during the Upper Miocene and Quaternary with a regional uplift of about 250 m, as shown by the Pre-evaporitic surface S_1, which remained perfectly horizontal (Clauzon et al., 1990; Clauzon and Mocochain, 2002; Gargani, 2004).

The Middle Ardèche area corresponds to the Mesozoic and Cenozoic cover of the Cévennes basement, tilted eastward to the Rhône valley (Fig. 1). The Ardèche flows out of the Cévennes at Aubenas and then crosses southward through Jurassic rocks. At Vallon-Pont-d'Arc, the Ardèche enters a wide depression into the Valanginian marls, corresponding to the northern part of the Alès rift. Downstream to Vallon-Pont-d'Arc, the Ardèche turns again eastwards and crosses the Urgonian Cretaceous limestones, as a 300 m-deep and 29 km-long meandering canyon.

The studied area is located around Vallon-Pont-d'Arc, at the inlet of the Ardèche canyon, where it receives a left bank tributary, the Ibie River, the catchment of which is entirely in Mesozoic outcrops (Fig. 1).

During the Miocene the Saint-Remèze Plateau evolved as an erosional surface (Baulig, 1928; Cornet, 1988; Mocochain et al., 2006a). The MSC triggered considerable changes in the predominant horizontal landscape by downcutting the Messinian canyons.

2.2. Sequence of the Messinian–Pliocene eustatic cycle in the Mediterranean Sea

The MSC results from an amplification of the onset caused by endoreic drainage of the Mediterranean during the TB 3.4 3rd order eustatic cycle (Haq et al., 1987). This collapse, produced by the drying out of the basin, is responsible for a double imprint:

– The deposition of a thick evaporite layer in the Abyssal plains under shallow water;
– The shaping of an erosional surface on the emerged margins prolonged by canyons along the rivers. On the north Mediterranean edge, the Rhône canyon that extends up to the Jura (Clauzon, 1999) constitutes the most significant morphological evidence for the Messinian event (Clauzon, 1982). At the latitude of Pierrelatte (Fig. 2), near its confluence with the Ardèche, the Messinian Rhône talweg is situated at −236 m below sea level (bsl) (Demarcq, 1960a; Clauzon, 1982).

The MSC ends with the transgression of the Mediterranean basin which occurred during the high-stand sea level of the TB 3.4 3rd order eustatic cycle (5.32 to 3.8 Ma; Haq et al., 1987; Lourens et al., 2004). During this high-stand sea level the delayed impact of the MSC took place firstly with the submersion of the Messinian canyons transformed into rias and secondly with the '*Gilbert type fan delta*' infilling of the rias (Clauzon et al., 1995, 1996).

2.3. Stratigraphic benchmarks and base-level evolution in the Rhône Mid-valley

Global and Mediterranean sea-level changes are well constrained (Haq et al., 1987; Hardenbol et al. 1998; Clauzon et al., 2004). During the Messinian–Pliocene cycle, these sea-level changes have been recorded as four stratigraphic benchmarks (i.e. Clauzon, 1996). Any altimetric change in relation to their initial position allows us to quantify the uplift. In this area, we identify a 200 m uplift during the MSC, and 50 m during the Quaternary (Clauzon et al., 1990; Clauzon and Mocochain, 2002); similar values have been obtained by modelling (Gargani, 2004). From a morphological point of view, during the MSC, the eustatic drop and the tectonic uplift provoked the incision of the Messinian canyons. During the Pliocene, sea-level rise and the long-term high stand induced the infilling of the canyons. During the Pleistocene, glacio-eustatic sea-level

oscillations, combined with a recurrence of uplift provoked renewed downcutting of the valleys and the terracing of the Pleistocene alluvial sequences.

Consequently, the elevation of each benchmark results from both tectonics and eustacy.

2.3.1. The Pre-evaporitic abandonment surface

The Pre-evaporitic abandonment surface corresponds to the Rhône and Ardèche alluvial plains just before the MSC, at 5.95 Ma (Clauzon, 1982, 1996; Martini, 2005; Mocochain et al., 2006a). The MSC triggered a series of regressive erosional processes along the hydrographic network. Messinian canyons abruptly downcut the former alluvial plains. Consequently, the Pre-evaporitic abandonment surface constitutes an isochronous benchmark level (Clauzon, 1996). The Pre-evaporitic abandonment surface appears to be extensively degraded in the landscape. It is still preserved on the left bank of the Rhône, close to Bollène city, at the Saint-Restitut Belvedere, 312 m above sea level (asl). It comprises a layer of residual gravels composed of reddened silicate pebbles (Fig. 2) (Denizot, 1934, 1952; Demarcq, 1960b; Bonnet, 1963; Clauzon, 1982). Along the left bank of the Ardèche River, the Pre-evaporitic abandonment surface is at an elevation of 330 masl. It is composed of gravels of a similar petrography that veneer the fluviokarstic surface (Mocochain et al., 2006a,c; Fig. 2). A recent study, based on micro-mammal dating of fluvial cave sediments, established that 5.45 Ma ago, just before the downcutting of the canyon, the altitude of the Ardèche River was 360 masl (Martini, 2005). This accuracy enables us to calculate the thinning (30 m) of the Pre-evaporitic alluvial deposits by weathering. Since the Ardèche Canyon is downcut into the Pre-evaporitic abandonment surface, it is obviously younger than 5.45 Ma.

2.3.2. Messinian canyons of the Rhône and Ardèche at 5.32 Ma

The bottom of the Messinian canyons marks the maximal down-cutting at the end of the MSC, just before their submersion by the Pliocene transgression at 5.32 Ma (Clauzon, 1996). In the Rhône valley, the Pierrelatte drilling cut through Rhône gravel down to the bottom of the Messinian canyon at a depth of −236 m below sea level (bsl) (Demarcq, 1960a; Clauzon, 1982) (Fig. 2). According to a Pre-evaporitic surface at 342 masl (312 m currently+30 m of weathering), the benchmark level of Messinian canyon at −236 m bsl indicates that the Rhône cut down about 580 m during the MSC (Clauzon, 1982). The outlet of the current Ardèche canyon corresponds to the bottom of its Messinian canyon, located at 50 masl. Thus, the Ardèche Messinian canyon was perched about 300 m above its confluence with the Rhône.

The Pliocene transgression of the Mediterranean Basin submerged the canyons and abruptly stopped their downcutting. The Messinian erosional surface was suddenly transformed into a fossil surface. This second benchmark level is thus isochronous (Clauzon, 1996).

2.3.3. Marine/non-marine Pliocene surface

The Pliocene transgression forced the rivers to deposit their load at the uppermost part of the rias. The fluvial sediments infilled the rias downwards due to the rapid progradation of their deltaic cones, the Gilbert-type-fan-deltas (Clauzon et al., 1995, 1996). They constitute marine subaqueous deposits (fore-set and bottom-set beds), overlain by fluvial sediments (top-set beds). Thus, this filling process progresses firstly forwards by deltaic progradation and subsequently upwards by fluvial aggradation. The two different filling facies of marine and fluvial sediments are separated by a clear sedimentologic discontinuity, the marine/non-marine surface. This facies discontinuity developed according to the progressive forwards progradation of the Gilbert-deltas, during the period of the rias' infilling. Consequently, this benchmark is diachronous (Clauzon et al., 1995; Clauzon, 1996). Close to the Saint-Remèze Plateau, the marine/non-marine surface is visible at Trignan, at 130 masl (Fig. 2). Since it precisely records the elevation of Pliocene sea level, which was 80 m above the current one (Haq et al., 1987), it shows that the marine/non-marine transition has been uplifted by 50 m after

its deposition, mainly during the Quaternary (Clauzon et al., 1990; Mocochain, 2002; Clauzon and Mocochain, 2002; Clauzon et al., 2004).

Two sites of the marine/non-marine surface, dated by fauna, are known upstream and downstream along the Rhône valley, respectively at Péage-du-Roussillon (Aguilar et al., 1989) and at Saze — Mas Soulet (Clauzon et al., 1995). By interpolation, the age of the marine/non-marine surface at Trignan is estimated at 4.7 Ma (Mocochain et al., 2006b).

2.3.4. The Pliocene abandonment surface at about 2 Ma

The Pliocene abandonment surface marks the end of the complete infilling of the Ardèche and Rhône rias around 2 Ma. This last benchmark level is a large alluvial plain abandoned by a new downcutting phase due to the Pleistocene glacio-eustatic sea-level fall (Clauzon, 1996). The Pliocene abandonment surface lies at about 200 masl at the Ardèche/Rhône confluence (Mocochain, 2002; Mocochain et al., 2006a). It is characterized by large surfaces composed of reddened quartz and quartzite pebbles.

During the Pleistocene, the climatic-induced cycles produced successive phases of downcutting and partial exhumation of the valleys. They are recorded as alluvial terraces, stepped downwards from the Pliocene abandonment surface at 200 m to the current level of the Rhône River at 44 masl.

From the Neogene onwards, the studied area is only affected by epirogenic uplift, without any local displacement. Consequently, we can use the elevation of the Messinian–Pliocene benchmark levels as reliable altimetric markers. As a result, the identification of four benchmark levels allows us to reconstruct the evolution of the base level during the last 6 Ma (Fig. 3).

Around 6 Ma, the Ardèche and the Rhône flowed at an elevation of 340/360 m, slightly above the present weathered Pre-evaporitic abandonment surface. The triggering of the MSC provoked the Rhône and Ardèche canyon downcutting. This process was ended at 5.32 Ma by the Pliocene flooding, when the Rhône and Ardèche canyons were at −236 m bsl and 50 masl, respectively. The base level abruptly rose to 80 masl, following the sudden transgression of the Mediterranean basin. This level remained stable until the formation of the Rhône _Gilbert delta_ that marks the beginning of the rivers' aggradation at about 4.7 Ma. The marine/non-marine surface is presently located at 130 masl, recording a post-sedimentary uplift of 50 m.

During the Pliocene (from 4.7 to 2 Ma), the aggradation of the rivers slowly raised the regional base level to 200 masl. Finally, during the Pleistocene, the rivers re-incised their valleys in successive steps, washing away their Pliocene infills, and depositing stepped terraces between 200 m and 50 masl.

3. Geomorphology along the western edge of the Saint-Remèze Plateau

3.1. The surfaces of the Saint-Remèze Plateau

The Urgonian plateau forms a brachyanticline. It displays classical karstic features, such as poljes, dolines, shafts and karren fields. Moreover, four generations of surfaces have cut through the structure (Fig. 2) (Mocochain et al., 2006a).

Surface S_0. The oldest surface forms a talus which is cut by small gullies. During the Lower Miocene, onlap occurred onto a transgression surface which is recognized on the whole periphery of the Alpine foreland basin. The marine molasses that fossilized the surface are still present at the contact between the Saint-Remèze Plateau and the Rhône valley. This surface is now tilted eastward, towards the Rhône valley and the Miocene foreland basin. The foreland subsidence was responsible for the tilting of the S_0 surface, before the formation of surface S_1.
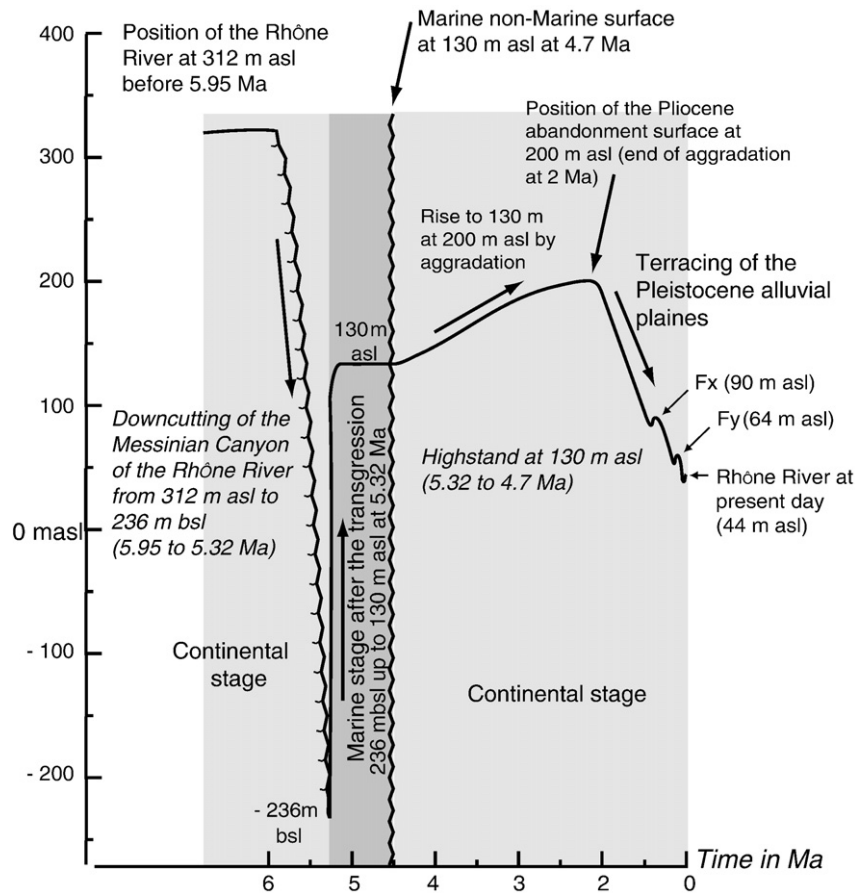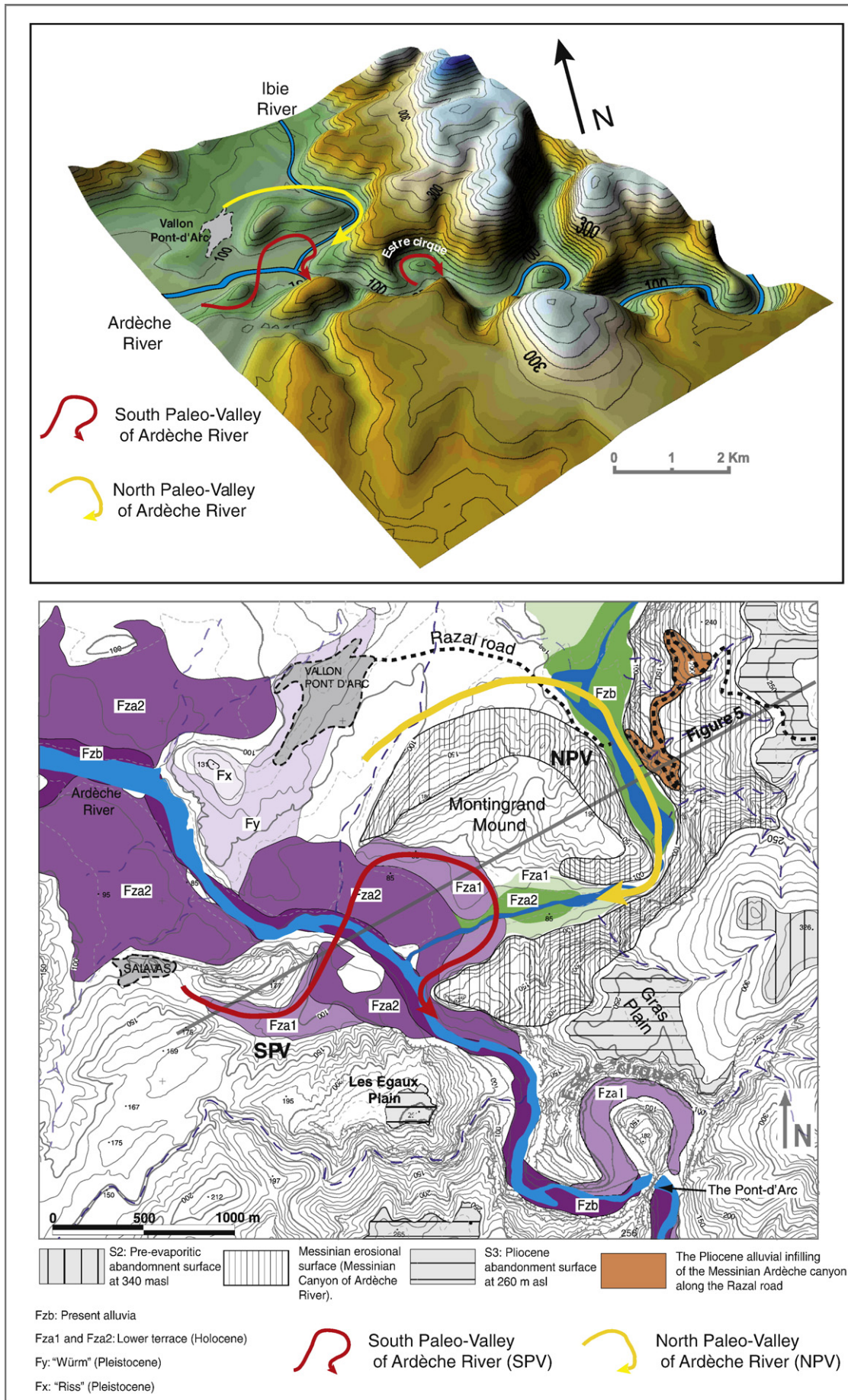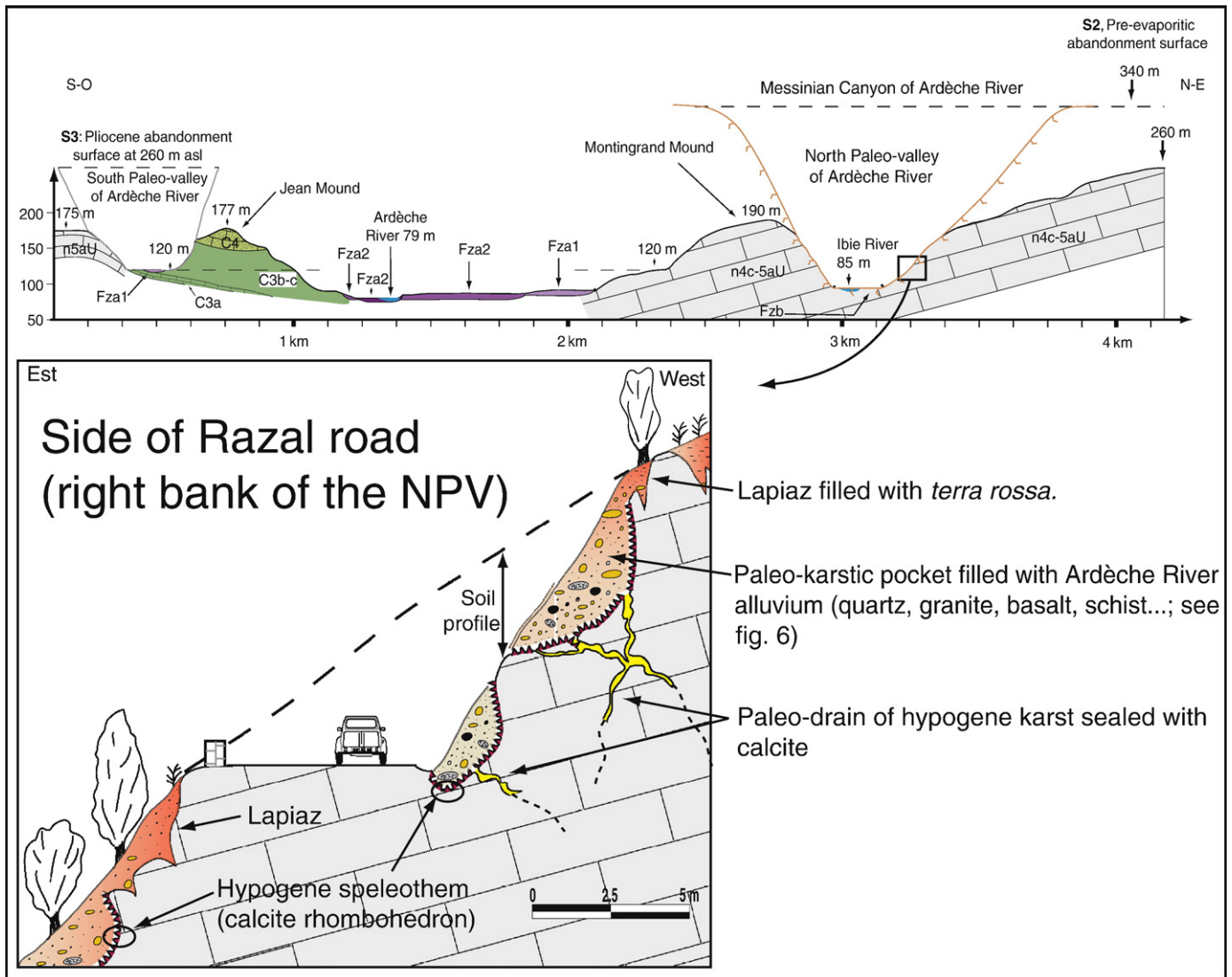

Fig. 3. Reconstruction of the Rhône base-level evolution since 6 Ma based on the Messinian–Pliocene benchmark levels (after Mocochain et al., 2006b).

Fig. 4. Physiography and location of the Ardèche valley and the alluvial sediments around Vallon-Pont-d'Arc.

Fig. 5. a. Geological cross-section (located in Fig. 4) across the North Paleo-Valley (NPV), the South Paleo-Valley (SPV) and the present Ardèche valley. b. Detail of the left flank of the NPV and its paleokarst filled with fluvial material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Surface S₁ forms the largest part of the Saint-Remèze Plateau at an average elevation of 400 m. In contrast to surface S_0, the S_1 surface does not exhibit any correlative deposits. Around the Alpine foreland, the S_1 extent is so considerable, and its planarity so remarkable, that it is considered to be a wave-cut platform, developed during the Middle Miocene (Besson, 2005). Surfaces S_0 and S_1 form a system of faceted surfaces (Baulig, 1956), whose genesis was controlled by the geodynamics of the Alpine foreland basin (Mocochain et al., 2006a).

Surface S₂ is smaller; it is encased in S_1 and lines the median section of the Ardèche Canyon, predominantly on the left bank. Recent studies of the unroofed cave systems have shown that the S_2 surface corresponds to the Pre-evaporitic abandonment surface (Martini, 2005; Mocochain et al., 2006a). Surface S_2 is presently degraded and located at elevations ranging between 300 and 330 m. It is a low gradient surface that was generated by the Ardèche River itself. Consequently, S_2 develops along the edge of the canyon as a narrow belt, and is veneered by scarce fluvial pebbles. Only quartz and quartzite pebbles remain after the intense weathering of this old Ardèche alluvial plain.

Surface S₃ is small. It only extends to the upstream and downstream sections of the canyon. It gradually connects with the Pliocene abandonment surface of the Rhône and Ardèche rias. Upstream, near Vallon-Pont-d'Arc, S_3 cuts through the Urgonian anticline on both sides of the canyon at 260 masl. Downstream of the Ardèche canyon, S_3 develops
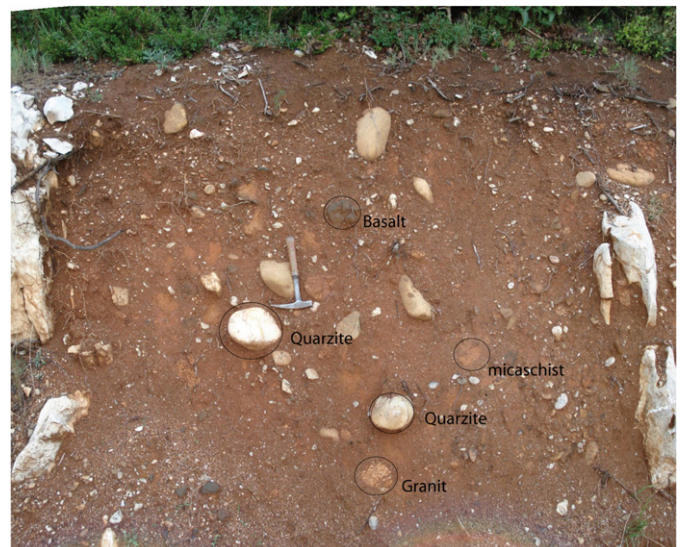
Fig. 6. The weathered infilling of the paleokarst along Razal road, showing allogenic fluvial material from the Pliocene Ardèche, mixed with karstic *terra-rossa*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

around 220 masl. This topographic gradient corresponds to the graded profile of the old Ardèche valley, which is similar to the current one at the bottom of the canyon. This S_3 erosional surface (cut through the limestone plateau), which connects with the alluvial Pliocene abandonment surface, is a valuable benchmark level, since it allows correlations to be made between fluvial filling, erosional surfaces and cave systems.

3.2. The successive Ardèche valleys around Vallon-Pont-d'Arc

Around Vallon-Pont-d'Arc, the study of the landscape, the topography, and the fluvial formations allows us to identify three successive valleys for the Ardèche: the present valley, a dead canyon to the south, and a paleo-canyon to the north, wherein the Ibie River presently flows (Figs. 4 and 5).

The modern Ardèche valley is straight, oriented NW–SE. It crosses perpendicularly through the geological structures in a non-readjusted course. The second valley, called the South Paleo-Valley (SPV), is a succession of two abandoned meanders located at each extremity of the modern valley. The first meander is an abandoned gorge. The valley is about 60 m deep and is located immediately to the south of the present valley. The village of Salavas marks the inlet of the first meander downcut at the contact between the Cretaceous sandstone and the Urgonian limestone. The SPV continues towards the north and forms a meander that has reshaped the south flank of the Montingrand Hill. The SPV alluvial sequence has been called the "Terrace Fza1" by Pascal et al. (1989).

The third valley of the Ardèche, called the North Paleo-Valley (NPV) is located further north. It forms a short canyon between Montingrand Hill on the right bank and the talus of the Saint-Remèze Plateau on the left bank. The Ibie River flows through this canyon, upstream from its confluence with the Ardèche River.

Paleokarst outcrops on the left bank of the NPV, along the Razal road (Fig. 5). This paleokarst develops along the Cévennes fault system. These faults were originally karstified by hypogenic processes (i.e., ascribed to a thermo-mineral ascending flow), long before the NPV itself. The subsequent erosion opened these paleokarsts, making their filling possible.
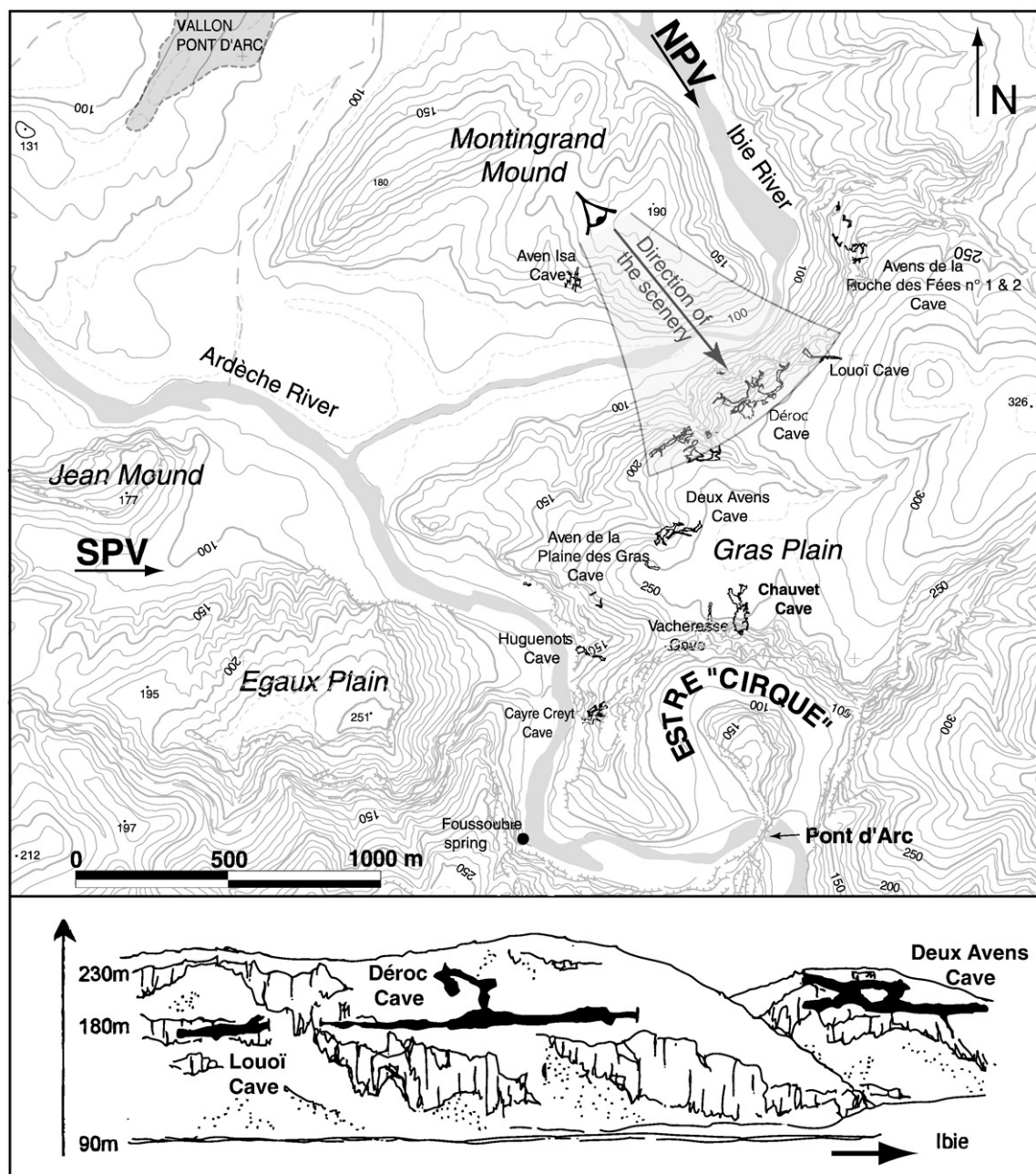

Fig. 7. Location map and schematic view of the main caves of the Plaine des Gras along of the Ibie valley (after Monteil, 1998).

Fig. 8. The allogenic fluvial infilling that plugs Déroc cave. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The paleokarst infilling is made of pebbles of quartz, basalt, granite, gneiss, micaschist, and quartzite, some of them being up to 30 cm long (Fig. 6). Such a petrography is similar to the recent Ardèche terraces, which are fed by an allogenic catchment from the Cévennes (Fig. 1). In contrast, the Ibie alluvial sediments are fed by a catchment entirely in sedimentary rocks, where no crystalline pebble has been mentioned up to now. Consequently, the NPV was first downcut by the Ardèche River, then abandoned, and finally re-used by the Ibie River.

These paleokarst forms outcrop along Razal road, from the bottom of the NPV at about 100 masl, up to 215 masl. On the lower part of the slope, the fluvial material is fresh. Upslope, its weathering gradually increases. On the highest part of the slope only small quartz almonds, up to 2 cm, remain. They are mixed with beige clay originating from the weathering of the phyllosilicates and the basalts. Close to the surface, the fluvial material is mixed with *terra rossa*. The *terra rossa* formation, which is ubiquitous on the karst surface, has been washed into the paleokarst pockets during the Pleistocene (Blanc, 1964).

In places, recent road work has completely destroyed the paleokarst and its infilling. It shows that this infilling is spread out as a thin veneer along the slope. From this, we deduce that the present NPV slope corresponds to the original slope of the valley with its alluvial infilling protected in shallow paleokarstic pockets (Figs. 4 and 5).

3.3. Cave levels around the Plaine des Gras

The evolution of the base level is the main factor that determines the organisation of the karst drainage, and consequently of the cave levels (Palmer, 1987). The base-level curve is the referential used in this paper to constrain the evolution of both karst and surficial geomorphology.

The region of Vallon-Pont-d'Arc, and more particularly the Plaine des Gras area, presents a considerable number of caves and karstic formations amongst which the Chauvet Cave, famous for its Palaeolithic paintings (Fig. 7). Most of the caves are located along the edge of the Ardèche and Ibie valleys, such as Chauvet, Déroc, and Louoï caves, as well as the Deux Avens cave. These caves are short (less than 500 m), because of calcite deposits or flowstone filling. The caves display large horizontal drains, often more than 10 m wide, mainly located at about 190 m elevation, such as Déroc, Louoï, Chauvet, and Deux Avens caves, and also the Plaine des Gras Aven. Because these cave levels cut through the folded structures, and since they are not related to any impervious basement, they can be considered as good indicators of their contemporaneous base level.

Three sediment facies are present: (1) The alluvial facies has an allogenic petrography, similar to the fluvial filling of the Razal road paleokarsts (Fig. 8). Although buried and thus preserved from erosion, this infilling is weathered: limestone pebbles have disappeared; granite pebbles are weathered and only a few remains of them can be found; (2) The second facies is composed of yellow sand with fine quartz grains and mica flakes; (3) The third facies is made of fine beige silt and clay, rich in mica. This last facies is common in the Saint-Remèze Plateau caves. It indicates an environment characterized by non-turbulent flow and buried deposits (Mylroie and Sasowsky, 2004). The first two facies are similar to the Ardèche alluvium. It shows that the Ardèche River played an important role in the development of the caves around Vallon-Pont-d'Arc.

Paragenetic features, formed by solution along walls and ceilings, are frequent. They also record the progressive filling of the caves by the fluvial sediments.

4. Chronology and dynamic of the Ardèche valley around Vallon-Pont-d'Arc

4.1. The South Paleo-Valley (SPV) and the present Ardèche valley

The presence of three successive valleys in the vicinity of Vallon-Pont-d'Arc raises the question of the deflection mechanism that is responsible for the shifting of the Ardèche River course from one valley to another. The process of self-piracy caused by meander cut-offs explains the abandonment of the first meander of the SPV resulting in the course of the current Ardèche (Figs. 4 and 9). When the cut-off occurred, the river was translated towards the south by avulsion, a process that was responsible for the second meander abandonment. This interpretation is mainly supported by the cartography of the terraces Fza_1 and Fza_2. The deposit Fza_1 corresponds to the course of the Ardèche in the SPV whereas the deposit Fza_2 corresponds to the course after the cut-off (Fig. 4). These two successive terraces mark a two-phase evolution of the self-piracy, a mechanism which is concurrent with the stepping dynamic of the Pleistocene terraces. It implicitly suggests that the downcutting of the NPV occurred prior to the SPV downcutting.

4.2. The North Paleo-Valley (NPV)

Although the North Paleo-Valley is the most ancient valley, its talweg at 100 masl, is lower than the talweg of the SPV (130 masl). This implies that the deflection process between the NPV and the SPV necessarily follows an infilling phase of the NPV (Fig. 9).

Fluvial formations trapped on NPV bank (paleokarst and caves) are continuous over a 115 m vertical range and are in primary position. This setting cannot be interpreted as a part of the succession of Pleistocene terraces, since they never exceed a thickness of 20 m in the area (Labrousse, 1977). Thus, the deposit trapped in the Razal road paleokarst is therefore not correlative with the NPV downcutting but might rather correspond to the Ardèche infilling by aggradation. This suggests that the downcutting of two successive valleys by the Ardèche is separated by an important phase of infilling. This infilling would therefore have provoked the aggradation epigenesis responsible for the shift of the Ardèche from the NPV to the SPV.

The mechanism of aggradation epigenesis corresponds to a general process of river rise that enables streams to be upraised above their valley bottoms and even above their interfluves, resulting in the subsequent change of their course. Baulig (1928) detailed this deflection mechanism. Clauzon (Clauzon and Beaudoin, 1994; Clauzon et al., 1995; Clauzon, 1996; Clauzon and Rubino, 2001; Clauzon et al., 2004) already attributed this mechanism to the infilling of the Messinian canyons

Fig. 9. Reconstruction of the paleogeographic evolution of the Ardèche-Ibie confluence for the last 6 Ma. The main part of the Ardèche evolution occurs at the left side of the cross-section, in a wide alluvial plain. Horizontal distances are not to scale.

Stage 1: During the MSC

Downcutting of the Messinian canyon of the Ardèche and Ibie Rivers.

Stage 2: Lower Pliocene

First stage of aggradation at 190 m asl.

Underground shortcuts of meanders.

Stage 3: Pliocene

Base level lowering

Caves are drained and calcite deposits.

Stage 4: Upper Pliocene

Aggradation restarts, fills the Messinian canyons, and stabilises at 260 m asl

Ardèche abandons the North Paleo-Valley.

Pediments extend laterally.

Stage 5: Pleistocene

New phase of downcutting.

Cleaning of Pliocene filling.

Ardèche cuts down the South Paleo-valley.

Ibie exhumes the North Paleo-Valley

Stage 6: Upper Pleistocene

Auto-piracy of the Ardèche meanders.

The South Paleo-Valley is abandoned

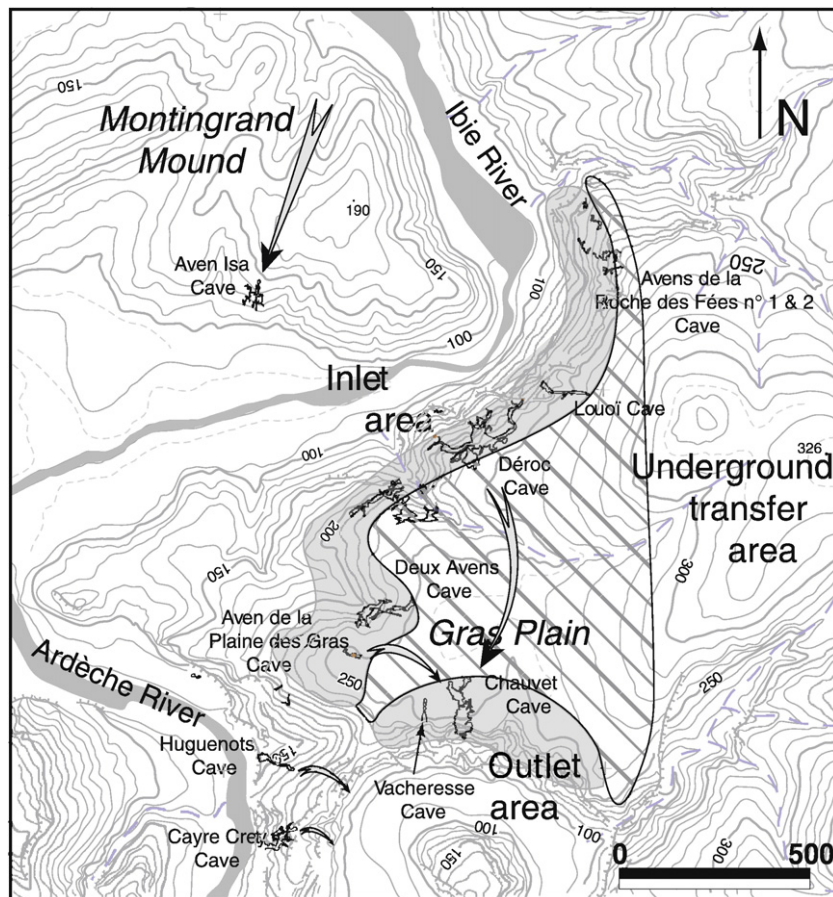The Pont d'Arc shortcuts the Cirque d'Estre.

Fig. 10. Dynamics of the meander short-cut through the Plaine des Gras caves (*aven* means "shaft"). Vertical scale: m asl.

during the Pliocene. More generally, this mechanism allows the quasi-systematic identification of the fossil Messinian canyons that have been totally infilled by the Pliocene fluvial processes.

Thus, the Ardèche abandoned its NPV first due to the infilling process, and then underwent a lateral displacement towards the south. During a second incision phase, the Ardèche downcut the SPV (Fig. 9). The Ibie, which is an Ardèche tributary, must have flowed just above the NPV at the end of the infilling process, before its exhumation during the second downcutting phase.

The two deflections observed around Vallon-Pont-d'Arc allow us to propose the interpretation that the MSC triggered the downcutting of the NPV from the Pre-evaporitic abandonment surface (360 masl; Martini, 2005) down to a depth of 100 masl. During the Pliocene, the Ardèche Messinian canyon, which was under the control of the Rhône aggradation, underwent the same infilling process as attested by the presence of Ardèche alluvium trapped in the Razal road paleokarst and caves. The aggradation reached 260 masl, the level of the Pliocene abandonment surface around Vallon-Pont-d'Arc (Mocochain et al., 2006a). Having left its Messinian canyon (the NPV), the Ardèche flowed onto the Pliocene abandonment surface and migrated laterally by avulsion towards the south. This lateral displacement resulted in a second downcutting of the Ardèche (the SPV) during the Pleistocene, while the Ibie River excavated the NPV (Messinian canyon of the Ardèche River; Fig. 9).

5. Discussion: deflection impacts on the karst

5.1. Fluvio-karst genesis for the Plaine des Gras caves

The 190 masl cave level was connected to an ancient base level of the Ardèche River (Fig. 7). This well-marked level, allied with the size of the galleries, corresponds to a long period of base-level stability. The Ardèche river brought allogenic fluvial material into swallow holes, eventually filling the caves (Fig. 8). Furthermore, the distribution of the caves on both left banks of the meander neck suggests the presence of an underground short-cut through the Plaine des Gras area. The inlets of this underground meander short-cut were in the NPV, whereas Chauvet Cave, located in the meander of the Estre "cirque", would have been the outlet (Figs. 7 and 10).

This interpretation explains the presence of allogenic infilling that characterizes the local caves, their location, and their dimensions (Ferrier et al., 2005; Mocochain et al., 2006a). Only a swallowing allogenic river (Palmer, 2001), such as the Ardèche, could represent an erosional agent capable of generating such large cave systems and subsequently of filling them.

Their underground short-cuts could therefore not have been set up during the Pleistocene (Mocochain et al., 2006a), because at this time the Ardèche had already left the NPV after the aggradation epigenesis. A major portion of the Vallon-Pont-d'Arc caves is characterized by typical flooded morphologies, displaying widespread paragenetic features. Considering the connection of these caves with the Ardèche valley, these flooded features could potentially have been formed during river flooding. However, these features are sometimes observed at considerable elevations of 120 m, largely exceeding the water height that the Ardèche can reach during a flood. The vertical distribution of these features suggests a permanent flooding of the karst due to a base-level rise: i.e. the Ardèche River aggradation. As a consequence, the caves of the Plaine des Gras could have only been set up during the Pliocene when the Ardèche River infilled its canyon. A Messinian age for the underground short-cuts is unlikely, because during the MSC, caves developed vertically according to the deepening of the base level and display torrential features.

The caves at 190 masl are underground meander short-cuts of the Ardèche developed during a prolonged period of base-level stability. This phase of relative stability corresponds to a break between two aggradation phases. Such a condition only occurred during the Pliocene, after infilling of the first part of the Ardèche NPV.

In several caves at 190 m elevation (Déroc and Louoï caves; Fig. 7), we observed intensively corroded flowstones, covered with fine-clay and more recent calcite. Similar observations were made both in the caves of the Estre "cirque" (Delannoy et al., 2001b; Ferrier et al., 2005) and in those located downstream of the Ardèche canyon (Mocochain et al., 2006b). The calcite deposition occurred during a draining phase of the caves, induced by a drop of the Ardèche River base-level. This draining phase was followed by a second flooding phase that corroded the flowstones and filled the caves with fine clay and alluvial material. Both draining and flooding phases are incompatible with the Pleistocene period as stated previously by Delannoy et al. (2001b). Consequently, they could only have occurred during the Pliocene (Mocochain et al., 2006c).

The study of the benchmark levels of the Rhône valley enables us to draw a curve for the evolution of the regional base level (Fig. 3). Conversely, the smallest base-level oscillations have only been recorded in the caves that can preserve the imprints of events that usually left no traces on the surface. Studying the endokarst has therefore yielded additional information to improve the regional base-level evolution curve during the Pliocene aggradation cycle (Fig. 11).

5.2. Speleogenesis along the Ardèche canyon

Several caves along the Ardèche canyon correspond to short gallery segments which are consequently difficult to access. However, their study has revealed sedimentological and morphological characteristics similar to those of the caves of the Vallon-Pont-d'Arc area. We have drawn up an inventory of the caves based on three criteria representative of the underground meander short-cuts: a geographical positioning of the caves compatible with an underground short-cut, the presence of allogenic fluvial infilling, and the development of large underground voids. This inventory was then compared with the base-level evolution curve (Appendix 1; Fig. 11). It reveals a strong correlation between the elevation of the cave levels and the elevation of the Ardèche stability

phases. The speleogenetical stages that are best recorded are those found: a) at 130 masl, downstream of the canyon (Saint-Marcel cave), which is correlated with the Pliocene sea-level high-stand (Marine/non-marine surface); b) at 190 masl in the upstream part of the canyon (Déroc and Chauvet Caves, Plaine des Gras Aven), which are correlated with the intermediate phase of the Pliocene valley filling; c) around 220 masl (Saint-Marcel cave, Neuf Gorges cave, etc.), which are consistent with the Pliocene abandonment surface (Appendix 1; Fig. 11); and d) at 330 masl, correlated with the Pre-evaporitic abandonment surface (Bartade cave, Aiguèze cave; Fig. 12).

Underground meander short-cuts are present everywhere in the Ardèche canyon, from the Pre-evaporitic abandonment surface down to the current Ardèche River level (Fig. 12). The correlation drawn between the meander short-cut elevations and the base-level evolution shows that the predominant speleogenetic process in Saint-Remèze Plateau stretches over a period of more than 4 Ma (between 6 and 2 Ma), and preferentially during aggradation phases of the river (Fig. 11).

5.3. The karstic pediments around Vallon-Pont-d'Arc

Around Vallon-Pont-d'Arc, the fluvial Pliocene abandonment surface extends into the S_3 low gradient surface (Fig. 2). It is situated at the inlet of the canyon on the right bank of the so-called 'Egaux Plain', and on the left bank of the Plaine des Gras (Fig. 4). The size of the Plaine des Gras is not very extensive (1.5 km^2) and it ends with an important knick point (Fig. 13). The transversal profile of this low-gradient surface shows a gentle slope. The slope and the direction of S3 surface result from processes along slopes and not at the level of the alluvial plain; consequently, an abrasion terrace made by river erosion or a lateral corrosion is unlikely. Its transverse profile is characteristic of pediment. If pediments are usually described in arid and semi-arid areas, such features are also frequent in karst environment, especially in Southern France (Nicod, 1985). This surface covers a large area along the edge of the left bank of the Ibie valley such that the whole western edge of the plateau is affected (Fig. 2). This morphological unit always shows the same transversal profile. The abrupt slope of the Ibie valley is broken at its junction with the surface S_3 that has a gentle slope. S_3 is interrupted thereafter by a knick that marks the foot of a particularly regular slope (Fig. 13).
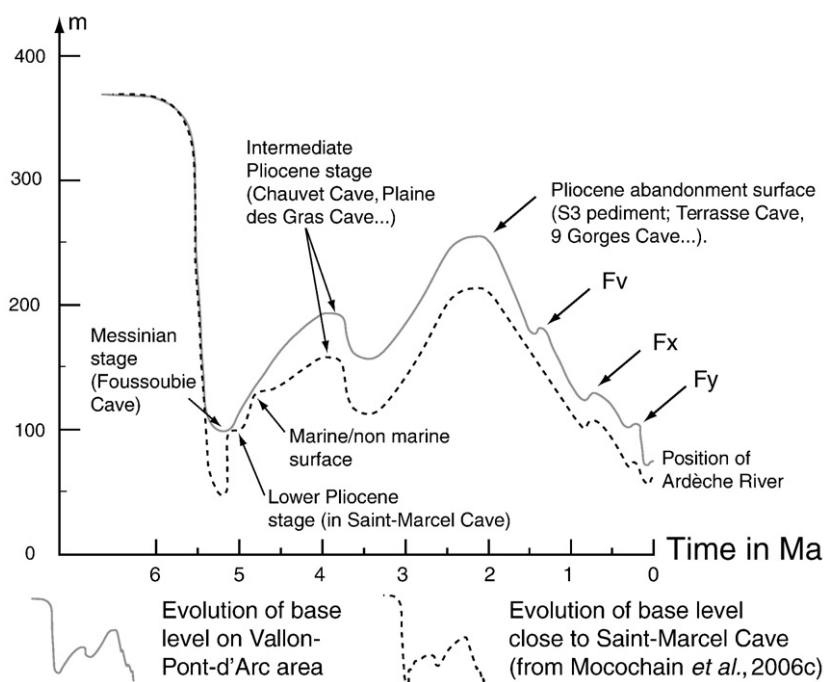

Fig. 11. Base-level evolution curve based on the Messino-Pliocene benchmark levels in the Middle Rhône valley, coupled with the level of the cave.

Meanders short-cuts in the Ardèche Canyon

2,5km

N

Ibie

Vallon-Pont-d'Arc

Aven Isa Cave

Montingrand Mound

Déroc Cave

Ardèche

Chauvet Cave

Plaine des Gras Cave

Pont d'Arc

Le Tiourre

Saint-Remèze

Cayre-Crêt and Huguenot Caves

Moine Rock

Ibie Sping

Underground Paleo-River of Saint-Remèze

Karstic water of the plateau

Foussoubie Spring

Pas de Mousse

Bartade Cave

Bidon

Ebbou Cave

Canyon of Ardèche River

Polje of Bidon

Gaud sinking steam

Cirque Cave

Goule de Virac sinking stream

Dragonnière sinking stream

Mourre de la Tour

RichemaleSpring

Resquilladou Cave

Aven de la Rouvière Cave

Parapluie Spring

Combe Vieille

Malbosc Plain

Guigonne Spring

Aven Noël Cave

Baume d'OullinsCave

La Flassade

La Rouvière

Saint-Marcel Cave

Aven des Neuf Gorges Cave

Aven des Templiers Cave

Ecluse and Bateau Springs

Midroï Cave

Madeleine Cave

Aven de laTerrasse Cave

Cadière sinking steam

La Cadière

Ribeyrol

Aven Rochas Cave

Aven d'Aiguèze Cave

Copains d'Abord Cave

Underground stream

- ⋯▶ Old meander short-cut (pre-Messinian)
- ⋯▶ Abandoned meander short-cut (Pliocene)
- ⋯▶ Abandoned meander short-cut (Upper Pliocene)
- ⋯▶ Active meander short-cut
- ⋯▶ Autogenic karstic water

Rivers

- —— Present course
- ---- Abandoned course

Abandoned karst

- ▼ Abandoned sinking stream
- ▼ Abandoned drain
- ● Abandoned spring

Active karst

- ⌒ Sinking stream on the plateau
- ▼ Sinkhole in Ardèche River
- ▼ Active drain
- ● Spring in Ardèche River
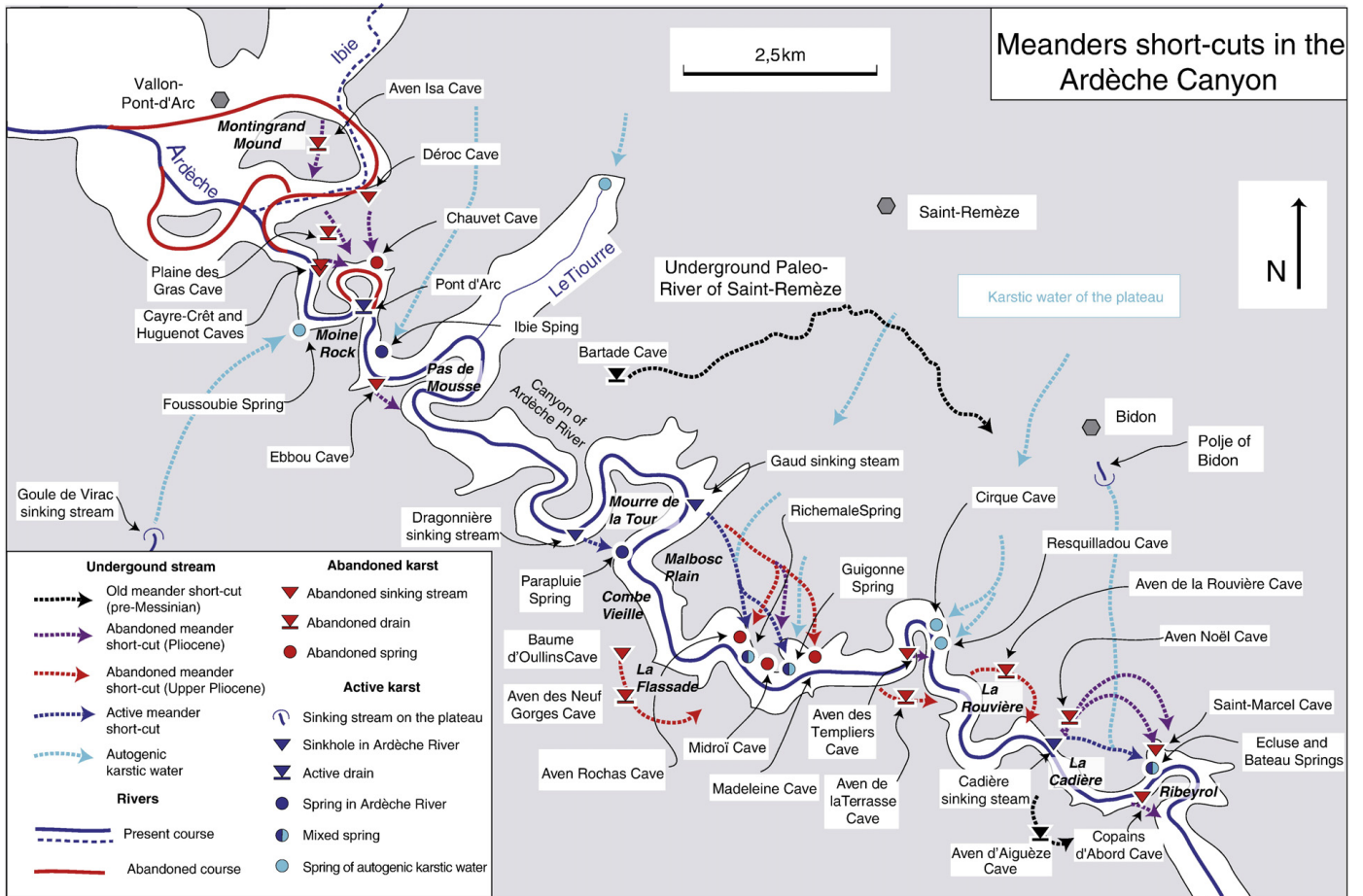- ◗ Mixed spring
- ● Spring of autogenic karstic water

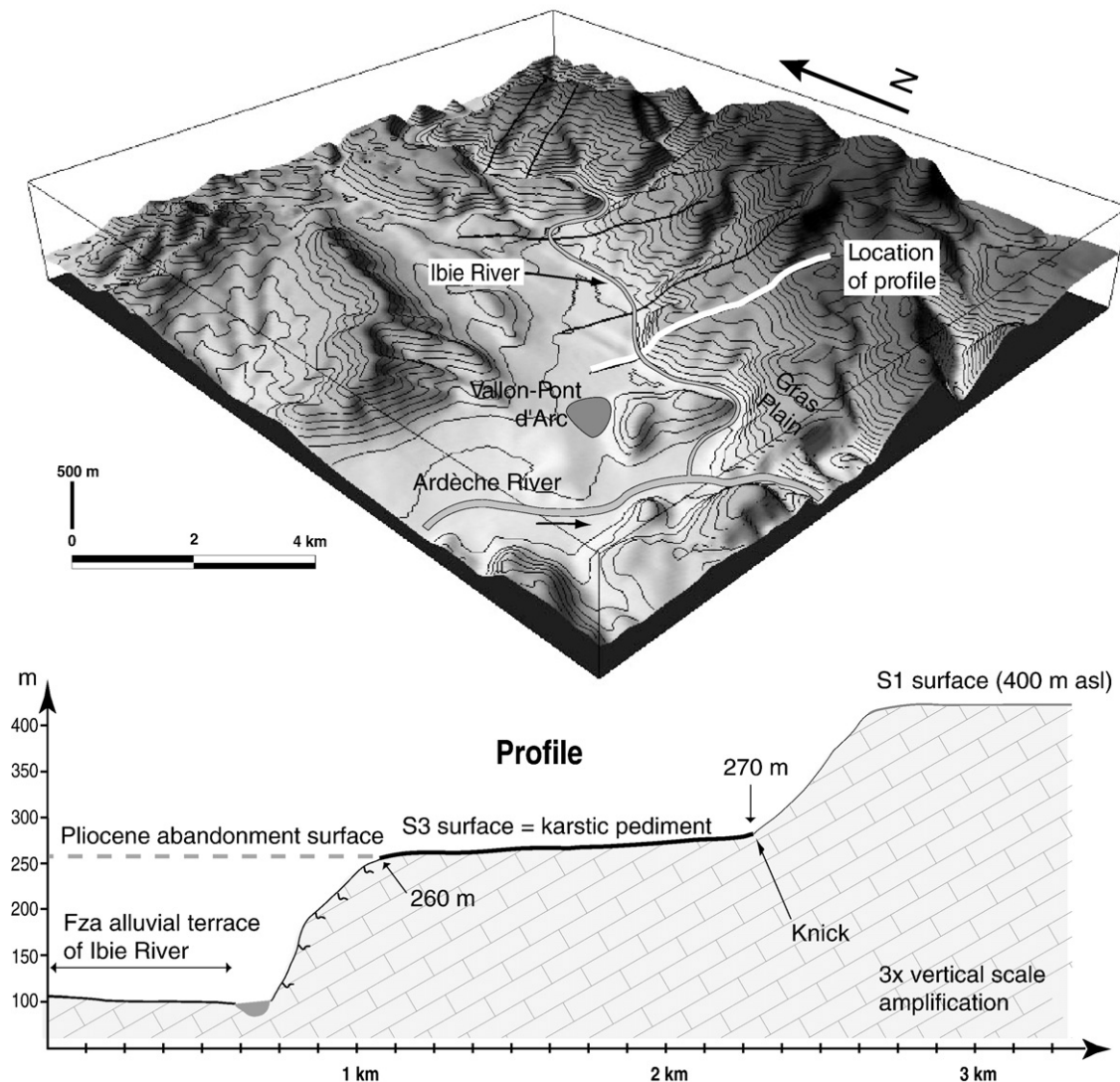**Fig. 12.** Map of the main underground short-cut along the Ardèche gorges (*aven* means "shaft").

Fig. 13. Topographical section of the low gradient surface S₃ along the Ibie valley.

In the landscape, the pediment is connected to the Pliocene abandonment surface. Thus, the abandonment surface was the base level of a very active morphogenetic process that has reshaped both the eastern and western slopes of the Saint-Remèze Plateau. Corrosion is the principal geomorphic mechanism for the origin of this pediment (Corbel, 1963; Nicod, 1985). Under present conditions, the infiltration of water in the karst would prevent any relief morphogenesis; this is the so-called principle of 'karstic immunity'. The pediment development along the edge of the Ibie valley (S₃) was possible only because the cave system disfunctioned, or was maybe blocked, at the end of the Pliocene period following the aggradation of the Ardèche and Ibie.

The blocking of cave systems induced a reactivation of the morphogenesis onto the surface. Furthermore, the development of the pediments with pronounced impact on the landscape could only happen during a prolonged period of stability. Such stability of the rivers at higher elevation is undoubtedly the result of the extension of a graded long profile resulting in river stability and the progressive cessation of the aggradation.

Finally there is a zonal relationship between the pediments and the uppermost stage of the cave systems. No pediment at all occurs in the median segment of the Ardèche valley, however a cave level related to the Pliocene abandonment surface is present (Appendix 1; Fig. 12). Conversely, no cave system close to the Pliocene abandonment surface could be found close to the pediment zones. Therefore, it seems that the development of either of these two morphological features prevents the other from developing. They simply correspond to opposite types of flow which cannot act simultaneously, either at depth or on the surface.

6. Conclusion

The middle Rhône valley presents five attributes allowing us to consider that the Saint-Remèze Plateau is a reference site for the Mediterranean basin: (1) it is developed on a limestone substratum; (2) it is close to the Mediterranean Sea; (3) it is downcut by the Messinian canyon of the Rhône; (4) it is intensely karstified both on the surface and at depth; and finally (5) the four benchmark levels of the MSC are present on the edge of the Plateau.

Due to their morphology and the nature of their alluvial sediment, the abandoned valleys of the Ardèche River around Vallon-Pont-d'Arc exhibit diachronism in their incision that is related to the considerable Pliocene infilling. In fact, the bottom of the Messinian canyon of the Ardèche has been identified, thus revealing that the whole downcutting only occurred during the MSC. Moreover, since the Saint-Remèze surface where the Ardèche canyon is downcut has been dated to 5.45 Ma (Martini, 2005), and since the MSC ended at 5.32 Ma, we argue that the Ardèche canyon downcutting occurred during a time span of only 100,000 years. The chronology of the Messinian–Pliocene cycle events has been reconstructed by the study of benchmark levels. Notably, the identification of

the Ardèche Messinian canyon has enabled us to propose a new interpretation for the mechanisms of speleogenesis. Large underground meander short-cuts were formed in the Pliocene during the phases of relative stability of the Ardèche River between two aggradation periods.

The dynamics and amplitude of the river aggradation during the Pliocene are responsible for the blocking of the endokarst. It has favoured the restarting of surface morphogenesis by developing karstic pediments that have reshaped the edges of the Saint-Remèze Plateau.

From a geodynamic and chronological point of view, the model we present does not agree with previous interpretations that postulated a stepping *per descensum* of both surficial landforms and caves. This model proposes a better understanding of peri-Mediterranean karst genesis and demonstrates that the MSC's impact on the karst is not limited to the Messinian episode alone, but that its impact transcends the Pliocene.

Acknowledgements

Appendix A. Characteristics of the short-cut meanders of the Ardèche River

Cave	Name of meander	Alt. of entrance cave	Alt. of cave development	Correlation with a bench mark level or a recognized Ardèche level	Morphological observation	Sedimentary observation
Bartade Cave	Saint-Remèze plateau	360	360	Pre-evaporitic abandonment surface	Dry flowpath with feature of the phreatic zone.	Allochthonous fluvial sand and crystalline pebbles.
Aven d'Aigèze Cave	Ribeyrol	380	350	Pre-evaporitic abandonment surface	Dry flowpath with feature of the phreatic zone.	
Aven des Neuf Gorges Cave	La Flassade	320	240	Pliocene abandonment surface of Ardèche River	Dry flowpath with feature of the phreatic zone.	Allocthonous fluvial sand
Rochas–Midroï Caves	Mal Bosc Plain	260 (Rochas) 85 (Midroï)	240	Pliocene abandonment surface of Ardèche River	Network formed by large flowpath stepped with phreatic features.	Allochthonous fluvial sand, white sands and black magnetic particles
Terrasse Cave	La Maladrerie des Templiers	275	230	Pliocene abandonment surface of Ardèche River	Large dry flowpath with phreatic features. Flowpath infilled by calcite deposit.	Allochthonous fluvial sand
Baume d'Oullins Cave	Combe Vieille	230	230	Pliocene abandonment surface of Ardèche River	Dry flowpath with feature of the phreatic zone.	Allochthonous fluvial sand and crystalline pebbles.
Aven de la Rouvière	La Rouvière	260	230	Pliocene abandonment surface of Ardèche River	Dry flowpath with feature of the phreatic zone. Flowpath infilled by calcite deposit.	Allochthonous fluvial sand
Saint-Marcel Cave		50/100/260	50/100/130/160/220	50: present position of Ardèche River. 100: Lower Pliocene stage. 130: marine/no marine surface. 220: Pliocene abandonment surface	Flowpaths network abandoned or actives according to its elevation between the base level. Three underground short-cut meanders: Boucle Active by Cadière sinking stream (alt. 50); Boucle Cristalline (alt. 130) and the Grande Boucle (alt. 160 m).	Allochthonous fluvial sand and crystalline pebbles.
Plaine des Gras Cave	Gras Plain	255	190	Intermediate Pliocene stade (fig. 9)	Dry flowpath with feature of the phreatic zone.	Allochthonous fluvial sand
Chauvet Cave	Gras Plain	190	190	Intermediate Pliocene stade	Dry flowpath with feature of the phreatic zone.	Allochthonous fluvial sand
Déroc Cave	Gras Plain	190	190	Intermediate Pliocene stade	Dry flowpath with feature of the phreatic zone.	Crystalline pebbles.
Madelaine Cave	La Madeleine	230/190/145	170	Intermediate Pliocene stade (fig. 9)	Network formed by large flowpath stepped with phreatic features.	White sands and black magnetic particles
Aven Isa Cave	Mound of Montingrand	141	120	No	Dry flowpath with feature of the phreatic zone.	Crystalline pebbles
Cayre-Crêt Cave	Cayre-Crêt Rock	90	120	No	Dry flowpath with feature of the phreatic zone.	Allochthonous fluvial sand
Copains d'Abord Cave	Ribeyrol	100	100	Lower Pliocene stage (Fig. 9)	Dry flowpaths with features of the phreatic zone.	Crystalline pebbles.
Huguenots Cave	Cayre-Crêt Rock	90	100	No	Dry flowpath with feature of the phreatic zone.	
Ebbou Cave	Pas de Mousse	80	80	No	Dry flowpath with feature of the phreatic zone.	Allocthonous fluvial sand
Pont d'Arc Cave	Moine Rock	70	70	Present position of Ardèche River	Arch vast	Alluvium of Ardèche River
Templiers Cave	La Maladrerie des Templiers	90	70	No	Small dry flowpath with phreatic features.	Allochthonous fluvial sand
Parapluie Spring	Mourre de la Tour	63	65	Present position of Ardèche River	Flowpath periodically flooded by the Ardèche river.	Allochthonous fluvial sand
Dragonnière sinking stream	Mourre de la Tour	65	60	Present position of Ardèche River	Flooded flowpath.	
Sinking stream of Gaud meander Guigonne–Richmale Springs	Mal Bosc Plain	60	60	Present position of Ardèche River	Flowpath periodically flooded by the Ardèche river.	
Cadière sinking stream–Saint-Marcel Cave–Ecluse/Bateau Springs	La Cadière	48 (Cadière) 46 (Ecluse/Bateau)	50	Present position of Ardèche River	Flowpath periodically flooded by the Ardèche river. Active short-cut meander.	

References

Aguilar, J.-P., Clauzon, G., Michaux, J., 1989. limite Mio-Pliocène dans le Sud de la France d'après les faunes de rongeurs: état de la question et remarques sur les datations à l'aide de rongeurs. Boll. Soc. Paleontol. Ital. (Bologna) 28, 137–145.

Ballesio, R., 1972. Etude stratigraphique du Pliocène rhodanien. Doc. Lab. Géol. Fac. Sci. (Lyon) 53 333 pp.

Baulig, H., 1928. Le plateau central de la France et sa bordure méditerranéenne. Armand Colin, Paris.

Baulig, H., 1956. Vocabulaire franco-anglo-allemand de géomorphologie. Ed. Ophrys, Paris.

Belleville, L., 1985. Hydrologie karstique: géométrie, fonctionnement et karstogenèse des systèmes karstiques des gorges de l'Ardèche. PhD Thesis, Univ. Sc. Med, Grenoble, 228 pp.

Bellier, O., Vergeley, P., 1987. Etats de contraintes et tectogenèse cénozoïque du plateau calcaire de basse Ardèche (France). C. R. Acad. Sci. Paris 305, 1379–1382.

Besson, D., 2005. Architecture du bassin rhodano-provençal miocène (Alpes, SE France). Relations entre déformation, physiographie et sédimentation dans un bassin molassique d'avant-pays. Ph. D. Thesis. Ecole des Mines de Paris, 358 pp.

Blanc, J.-J., 1964. Recherches sur les sédiments argileux des grottes dans le Sud-Est de la France. Bull. Mus. Anthropol. Prehist. Monaco 11, 5–36.

Blanc, J.-J., 1976. Recherches géologiques à la grotte de Saint-Marcel-d'Ardèche (Ardèche, France). Géol. Méditerr. III (4), 227–236.

Bonnet, A., 1963. Nouvel essai de corrélation des terrasses rhodaniennes. Bull. Soc. Géol. Fr. 7, 543–554.

Clauzon, G., 1982. Le canyon messinien du Rhône: une preuve décisive du "*Desiccated deep-basin model*" (Hsu, Cita, Ryan, 1973). Bull. Soc. Géol. Fr. 24, 597–610.

Clauzon, G., 1996. Limites de séquences et évolution géodynamique. Géomorphologie 1, 3–22.

Clauzon, G., 1999. L'impact des variations eustatiques du Bassin de Méditerranée occidentale sur l'orogène alpin depuis 20 Ma. Actes du colloque: la montagne méditerranéenne. Etud. Géogr. Phys. 28, 33–40.

Clauzon, G., Beaudoin, B., 1994. La mémoire du fleuve. Chronique du Var depuis 6 Ma. Archive ANDRA.

Clauzon, G., Mocochain, L., 2002. Saint-Restitut Belvédère. In: Besson, D., Clauzon, G., Coueffe, R., Dexcote, Y., Ferry, S., Gonzalo, J., Mocochain, L., Parize, O., Rubino, J.L., Suc, J.P., Tessier, B. (Eds.), Le Néogène de bassin d'avant pays rhodano-provençal, Livret guide de l'excursion Strati 2002, pp. 142–145.

Clauzon, G., Rubino, J.-L., 2001. La crise de salinité messinienne et les Gilbert-deltas pliocènes, marqueurs de l'évolution géodynamique du Roussillon et du Conflent. Livret guide de l'excursion GDR-Marges Atelier messinien. 24 pp.

Clauzon, G., Mandier, P., Aguilar, J.-P., Delannoy, J.-J., Guendon, J.-L., Klein, C., Michaux, J., Rubino, J.-L., Vaudour, J., 1990. Genèse et évolution du piémont néogène subalpin du Bas-Dauphiné. Livret guide excursion préforum du 3° Forum National de Géomorphologie, Aix en Provence, Trav. URA 903 du CNRS, XIX. 71 pp.

Clauzon, G., Rubino, J.-L., Savoye, B., 1995. Marine Pliocene Gilbert-type fan deltas along the French Mediterranean coast. Livret guide de l'excursion de l'ASF 23, 145–222.

Clauzon, G., Rubino, J.-L., Suc, J.-P., 1996. Les rias pliocènes du Var et de Ligure: comblement sédimentaire et évolution géodynamique. Livret-guide de l'excursion commune du Groupe Français d'Etude du Néogène et du Groupe Français de Géomorphologie, 6 au 8 septembre 1996. 111 pp.

Clauzon, G., Fleury, J., Schlupp, A., 2004. Evolution géodynamique du Bas-Rhône (section Orange/Beaucaire) depuis 6 Ma. Apport de la méthode des niveaux repères messiniens ainsi que des terrasses quaternaires intégrés à l'outil SIG. Rapport CEA/CEREGE. 90 pp.

Corbel, J., 1963. Pédiments d'Arizona. Mém. Doc. CNRS 9, 33–95.

Cornet, C., 1988. Evolution géomorphologique et néo-tectonique du Vivarais calcaire au Pontien à l'infra-Quaternaire. Géol. Fr. 4, 55–66.

Debard, E., 1997. Les remplissages karstiques du Bas-Vivarais: karstogenèse, sédimentogenèse et archéologie. Quaternaire 8, 305–317.

Delannoy, J.-J., Debard, E., Ferrier, C., Kervazo, B., Perrette, Y., 2001a. Contribution de la cartographie morphologique souterraine dans l'étude spéléogénétique de la grotte ChauvetPremiers éléments spéléogéniques et implications paléogéographiques, préhistoriques et paléontologiques. Quaternaire 12, 235–248.

Delannoy, J.-J., Debard, E., Ferrier, C., Kervazo, B., Perrette, Y., 2001b. La grotte dans son cadre. In: Clottes, J. (Ed.), La grotte Chauvet, l'art des origines. Seuil, Paris, pp. 16–26.

Delannoy, J.-J., Perette, Y., Debard, E., Ferrier, C., Kervazo, B., Perroux, A.-S., Jaillet, S., Quinif, Y., 2004. Intérêt de l'approche morphogénique pour la compréhension globale d'une grotte à haute valeur patrimoniale: la grotte Chauvet (Ardèche, France). Karstologia 44, 25–42.

Demarcq, G., 1960a. Observations à propos de la série pliocène du sondage de Pierrelatte (Drôme). C. R. Acad. Sci. Paris 250, 4013–4015.

Demarcq, G., 1960b. Observations et hypothèses à propos des cailloutis élevés de Saint-Restitut (Drôme) et de la Caume (Alpilles, Bouches du Rhône). Bull. Soc. Géol. Fr. 7, 741–746.

Denizot, G., 1934. Note sur l'extension des cailloutis pliocènes dans le Sud-Est de la France. Bull. Soc. Géol. Fr. 5, 613–647.

Denizot, G., 1952. Le Pliocène dans la vallée du Rhône. Rev. Géogr. Lyon 27 (4), 327–357.

Ferrier, C., Debard, E., Kervazo, B., Perroux, A.-S., Delannoy, J.-J., Perrette, Y., 2005. Grotte Chauvet, salle Hilaire et salle du Crâne: contexte sédimentologique des vestiges d'origine humaine et animale. Karstologia mémoires 11, 35–42.

Fontannes, F., 1882. Note sur l'extension de la faune de la mer pliocène dans le Sud-Est de la France. Bull. Soc. Géol. Fr. 11, 103–141.

Gargani, J., 2004. Eustatisme, érosion et isostasie flexurale: modélisation numérique appliquée au Rhône messinien. C.R. Geosci. 336, 901–907.

Haq, B.-U., Hardenbol, J., Vail, P., 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). Science 235, 1156–1167.

Hardenbol, J., Thierry, J., Farley, M.B., de Graciansky, P.C., Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: de Graciansky, P.C., Hardenbol, J., Thierry, J., Vail, P.R. (Eds.), Mesozoic and Cenozoic sequence stratigraphy of European basins. SEPM Special Publication, vol. 60, pp. 3–13.

Labrousse, B., 1977. Altération des terrasses anciennes de l'Ardèche. PhD Thesis, Université de Marseille St-Charles, France, 125 pp.

Lourens, L., Hilgen, F.J., Laskar, J., Shackleton, N.J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F., Ogg, J., Smith, A. (Eds.) (2005), A Geologic Time Scale. Cambridge Univ. Press, pp. 403–440.

Martin, P., Bergerat, F., 1996. Palaeo-stresses inferred from macro- and microfractures in the Balazuc-1 borehole (GPF programme). Contribution to the tectonic evolution of the Cevennes border of the SE Basin of France. Marine and Petroleum Geology 13, 671–684.

Martini, J., 2005. Etude des paléokarsts des environs de Saint-Remèze (Ardèche, France): mise en évidence d'une rivière souterraine fossilisée durant la crise de salinité messinienne. Karstologia 45–46, 1–18.

Mocochain, L., 2002. Utilisation des marqueurs chronostratigraphiques miocènes et pliocènes pour l'étude karstologique et hydrogéologique du Bas-Vivarais (Ardèche, France). Mémoire de DEA. Univ. Provence, Aix-en-Provence. 43 pp.

Mocochain, L., Clauzon, G., Bigot, J.-Y., Brunet, P., 2006a. Geodynamic evolution of the peri-Mediterranean karst during the Messinian and the Pliocene: evidence from the Ardèche and Rhône Valley systems canyons, Southern France. Sediment. Geol. 188–189, 219–233.

Mocochain, L., Clauzon, G., Bigot, J.-Y., 2006b. Réponses de l'endokarst ardéchois aux variations eustatiques générées par la crise messinienne. Bull. Soc. Géol. Fr. 177 (1), 27–36.

Mocochain, L., Bigot, J.-Y., Clauzon, G., Faverjon, M., Brunet, P., 2006c. La grotte de Saint-Marcel (Ardèche): un référentiel pour l'évolution des endokarsts méditerranéens depuis 6 Ma. Karstologia 48, 33–50.

Monteil, P., 1998. Grotte du Déroc. Une salle dans un étonnant remplissage. Bull. Com. Dép. Spéléol. Loire-La Botte 17, 62–63.

Mylroie, J., Sasowsky, I.D. (Eds.), 2004. Studies of Cave Sediments: Physical and Chemical Records of Paleoclimate. Kluwer Academic, New York.

Nicod, J., 1985. Les cônes rocheux en Provence et dans quelques régions de comparaison. Rapports avec les surfaces de corrosion des plojés. Mémoires et Documents de Géographie. CNRS, Paris, pp. 107–117.

Palmer, A.N., 1987. Cave levels and their interpretation. Natl. Speleol. Soc. Bull. 49, 50–66.

Palmer, A.N., 2001. Dynamics of cave development by allogenic water. Acta Carsol. 30 (2), 14–32.

Pascal, M., Lafarge, D., Chedhomme, J., Glintzbaeckel, C., 1989. Notice explicative, carte géologique de la France (1/50.000), feuille Bourg-Saint-Andéol (889). B.R.G.M., Orléans, 67 p. Geological map by Pascal M., Elmi S., Busnardo R., Lafarge D., Truc G., Valleron M., Chedhomme J., Combier J. (1989).

Sanchis, E., Séranne, M., 2000. Structural style and tectonic evolution of a polyphase extensional basin of the Gulf of Lion passive margin: the Tertiary Alès Basin, southern France. Tectonophysics 322, 243–264.