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The effect of the Messinian Deep Stage on karst development around the Mediterranean Sea. Examples from Southern France

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Abstract

It is difficult to explain the position and behaviour of the main karst springs of southern France without calling on a drop in the water table below those encountered at the lowest levels of Pleistocene glacio-eustatic fluctuations. The principal karst features around the Mediterranean are probably inherited from the Messinian period ("Salinity crisis") when sea level dropped dramatically due to the closing of the Straight of Gibraltar and desiccation of the Mediterranean Sea. Important deep karst systems were formed because the regional ground water dropped and the main valleys were entrenched as canyons. Sea level rise during the Pliocene caused sedimentation in the Messinian canyons and water, under a low hydraulic head, entered the upper cave levels.

The powerful submarine spring of Port-Miou is located south of Marseille in a drowned canyon of the Calanques massif. The main water flow comes from a vertical shaft that extends to a depth of more than 147 m bsl. The close shelf margin comprises a submarine karst plateau cut by a deep canyon whose bottom reaches 1,000 m bsl. The canyon ends upstream in a pocket valley without relation to any important continental valley. This canyon was probably excavated by the underground paleoriver of Port-Miou during the Messinian Salinity Crisis. Currently, seawater mixes with karst water at depth. The crisis also affected inland karst aquifers. The famous spring of Fontaine de Vaucluse was explored by a ROV (remote observation vehicle) to a depth of 308 m, 224 m below current sea level. Flutes observed on the wall of the shaft indicate the spring was formerly an air-filled shaft connected to a deep underground river flowing towards a deep valley. Outcroppings and seismic data confirm the presence of deep paleo-valleys filled with Pliocene sediments in the current Rhône and Durance valleys. In the Ardèche, several vauclusian springs may also be related to the Messinian Rhône canyon, located at about 200 m below present sea level. A Pliocene base level rise resulted in horizontal dry cave levels. In the hinterland of Gulf of Lion, the Cévennes karst margin was drained toward the hydrologic window opened by the Messinian erosional surface on the continental shelf.

Keywords: Messinian Deep Stage; Karst development; French Mediterranean; Deep phreatic cave systems; Coastal karst aquifer

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1. Introduction

During the Messinian (–5.96 to –5.32 Ma) [1, 2], the Mediterranean Sea became isolated from the world's oceans resulting in a large drop in sea-level and widespread deposition of evaporites. The event is partly linked with convergence of Africa and Eurasia. It is one of the most dramatic examples of base-level fluctuations known in the geological record. The sea level drop was reflected several hundred kilometres inland, where deep canyons, linked to the abyssal plain, formed. This drastic drop in base level affected the local karst systems. New karst systems were created and some paleokarst features, such as Cretaceous bauxite-filled fissures and caves, reopened. Julian & Nicod [3], Audra [4] and Clauzon *et al.* [5] pointed out the influence of the Messinian event on French karst. It has also been widely recognised in Italy [6, 7]. Recent research on the Southern France karst provides considerable new information, not only about deep phreatic systems but also about large abandoned cave systems that are indirectly related to the Messinian event.

2. The Messinian Deep Stage Evaporative Basin [8]

2.1. An outstanding eustatic event and its effect on the continental interior

The evolution of karst around the Mediterranean was influenced by eustatic changes in sea level during the Messinian period at the Miocene-Pliocene transition [9, 10, 11]. This cycle is third order TB 3.4/3.5 referring to Vail's curve [12]. Yet, its lowstand was greatly expanded by a sill created West to the Mediterranean straits (Gibraltar) initiating the "**Messinian salinity crisis**", caused by the Mediterranean being isolated from the Atlantic Ocean [13]. During the Messinian, the base level of the Mediterranean area dropped at least 1,500 meters below the level of the Atlantic Ocean [14, 15]. The crisis was responsible for **evaporite** deposition in the abyssal plains and for the development of the **Messinian erosional surface** [16], including the **Messinian canyons** on the continental margins [15, 17, 18, 19, 20]. The Rhône canyon cut down 576 meters into the Cretaceous carbonate platform near the confluence with its tributary the Ardèche. At present the canyon is 1,300 m below the shoreline. Beneath its delta, the floor of the river Nile, is up to 1,900 meters deep [20]. At the end of the crisis, the Gibraltar sill was eroded and the Mediterranean flooded. Flooding took place very quickly, less than twenty years [21] and without any transgressive sedimentary marine fill [19]. The canyons were flooded and filled with terrigenous Gilbert-type fan deltas. These drowned river canyons, formed by a rise in sea level, are called "*rias*". The transgression culminated in the highest sea level high stand of the last ten million years.

Two important surfaces were developed: 1/ the Pliocene diachronous marine/non marine transition, which represents the contemporaneous sea level and 2/ the Pliocene abandonment surface. Altogether this eustatic megacycle provides **four important surfaces** (Figs. 1, 2, 9) **which controlled the morphogenesis of the surrounding karst**:

–the *pre-evaporitic abandonment surface*, at once isochronous and synchronous with the onset of the salinity crisis,
–the *Messinian erosional surface*, formed at the same time as basin flooding in the Early Pliocene,
–the *Pliocene diachronous marine/non marine transition*,
–the *isochronous Pliocene abandonment surface.*

2.2. Changes in the karst aquifers due to the Messinian event

The impact of tectonics on karst is evident but the values collected in Southern France indicate that during the Messinian-Pliocene period, the tectonics events consist mainly in low rates uplifts. Thus tectonics cannot be considered here the fundamental cause of changes in the karst system.

Eustatic changes during the Messinian-Pliocene eustatic cycle (Fig. 2) had three main effects on karst evolution:

–The direct impact of the Messinian base level drop (5.96 to 5.32 Ma) was to cause a drop in the karst base level and an increase in the hydraulic gradient.
–The abrupt Zanclean transgression and the long-lasting sea level high stand flooded the Messinian canyons producing drowned valleys (*rias*) (5.32 to about 3.8 Ma). Deep karst drainage was blocked, forcing the water to rise through vauclusian systems or submarine springs. Water reused older vadose or abandoned dry systems, which offer easy routes for flow, or may have created new passages when no voids were available.
–The drowned valleys were then filled with marine sediments, the fluvial aggradation added to the base level rise (from about 3.8 to about 2 Ma, depending on the areas), and the upward migration of the springs.

A "classical" base level drop produces downcutting and abandoned drains lose their flow, which concentrate at the lowest levels. In contrast, in the case of karst systems influenced by the Pliocene base level rise, a huge thickness of the aquifer became flooded. Several older cave levels were reintegrated in the phreatic zone and reactivated, influencing future hydrology up to the present. The distribution map of deep phreatic systems in France shows that 75% of such systems are linked to the Mediterranean watershed (Fig. 3). Their location clearly shows the link with the Messinian canyons or their second-order tributaries.

3. Changes to the karst drainage depending on distance from the Mediterranean

The differences in the duration and the amplitude of the base level drop, and the differences in the geological and structural environments do not make it possible to apply a simplistic model for the response of the karst systems to the

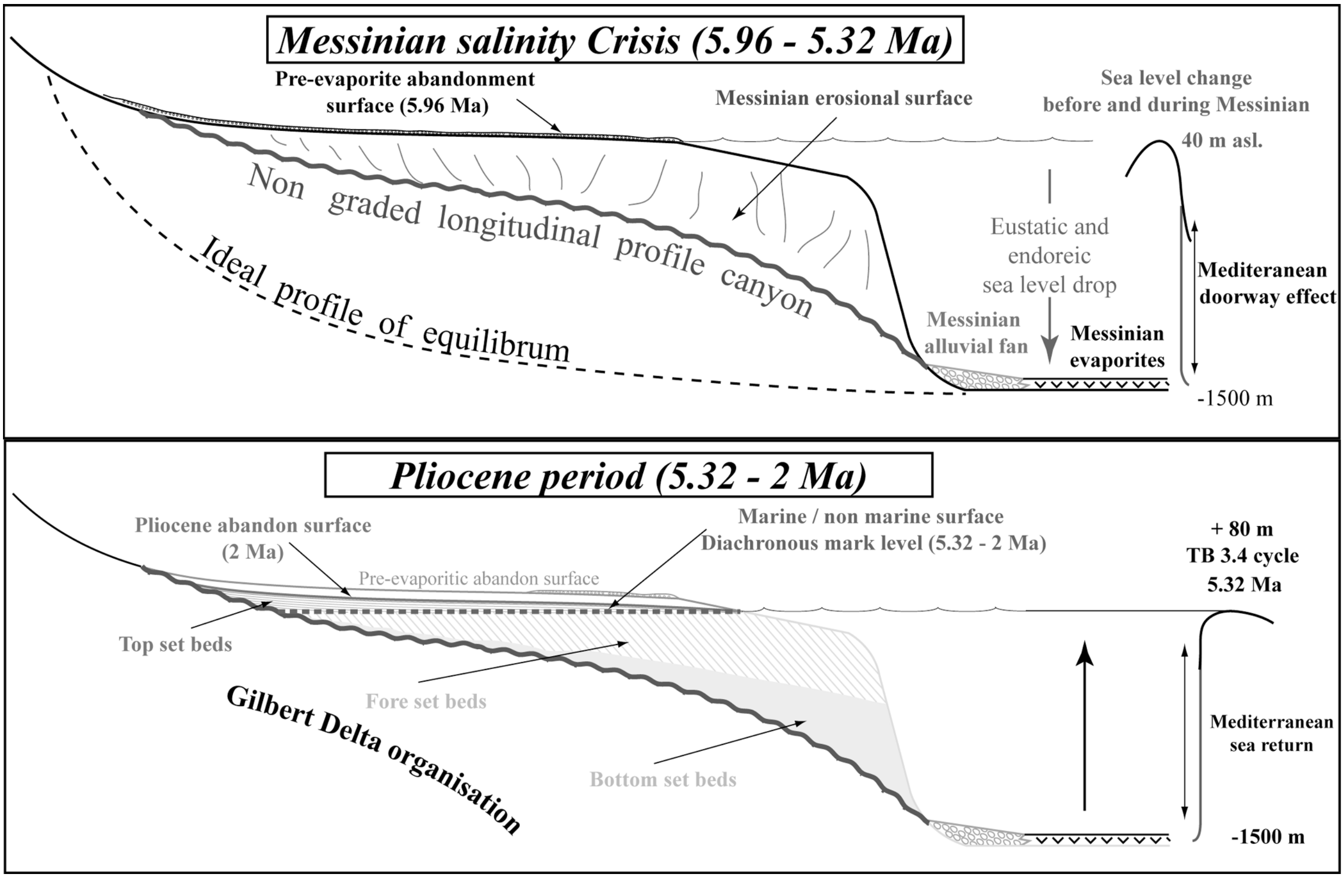

Fig. 1 The effect of eustacy on the Messinian canyons and the Gilbert deltas filling the Pliocene *rias.*

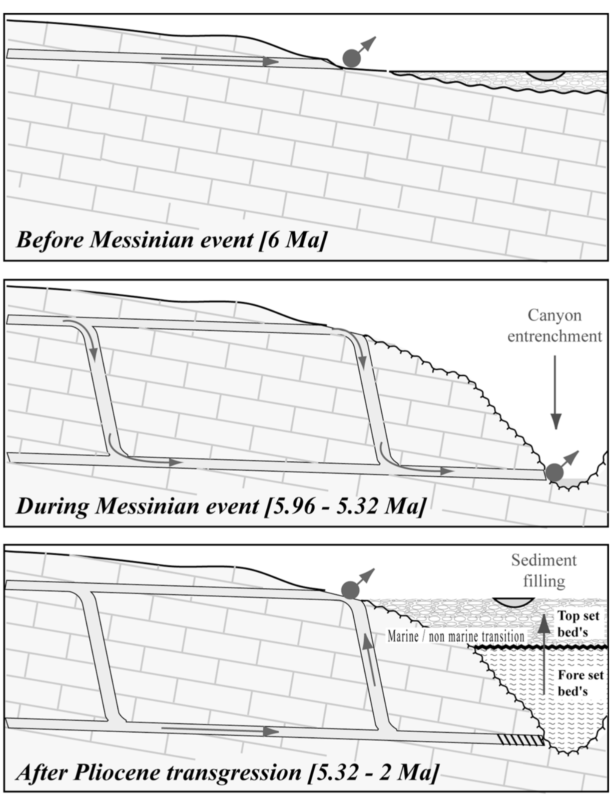

Fig. 2 Diagrammatic model of karst drainage evolution corresponding to the Messino-Pliocene eustatic impulse.

Messinian event. This paper proposes three completely different types of drainage development, based on the distance of karst from the Mediterranean 1) next to the present Mediterranean shoreline; 2) linked to the Messinian canyons that drained into the deep stage Mediterranean; 3) inland remote karsts having hydrogeologic deep connection with continental shelf and discharging at a place now located offshore where the aquifer is locally breached by the messinian erosional surface.

3.1. Coastal aquifers: the submarine springs of Marseille (Port-Miou and Bestouan)

In the *Calanques* ("drowned canyon") of Cassis, close to Marseille, the submarine karst springs of Port-Miou and Bestouan discharge from submarine solution galleries (Fig. 3). The water is brackish and not suitable as a water supply. The salinity, between 10 and 20 $g.l^{-1}$, was first believed to be due to seawater injection into the submarine entrance and two dams were built to prevent contamination. Salinity never fell below 3 $g.l^{-1}$ [22]. In Port-Miou, scuba divers reached a remote point, in 1993, situated 2,200 m from the entrance and 147 m below sea level [23]. The cave continues further and deeper, as an inclined, large gallery (Fig. 4). A sample collected at this remote part of the cave was still brackish with a salinity of 6.6 $g.l^{-1}$ [23]. The Br^-/Cl^- ratio of water sampled at different depths in the main gallery

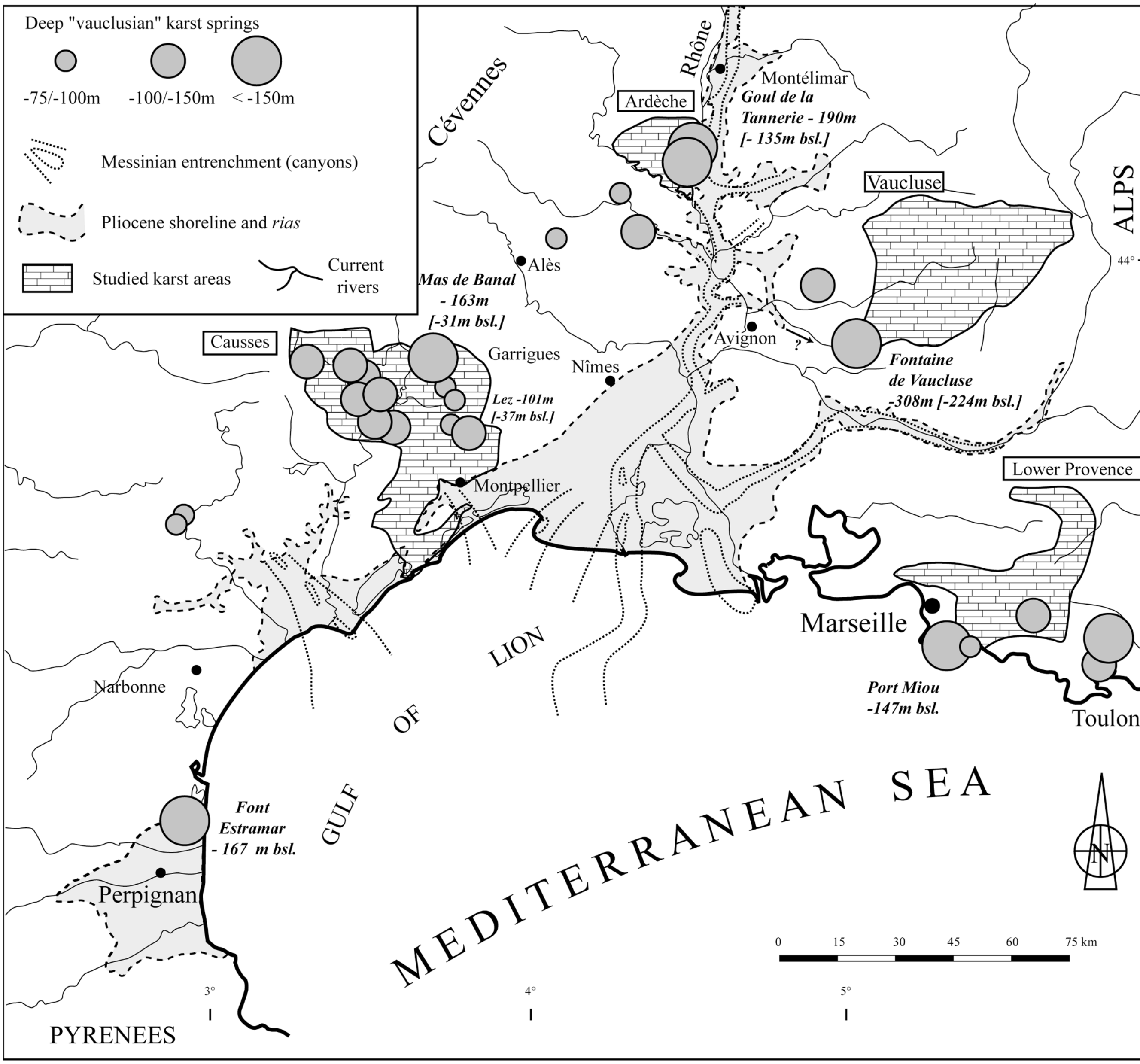

Fig. 3 Location of deep phreatic systems in Southern France compared to Messinian canyons and the Pliocene *rias* shoreline [after 5, 40].

proves a marine origin. Thus the salinity of the spring comes not only from seawater injection at the entrance but also from the deeper reaches of the cave. Values of Cl^-, Na^+, SO_4^{2-}, Mg^{2+} and K^+, indicate that 13 to 15% seawater mixes with karst freshwater in the deep karst system.

3.1.1. Inferred watershed

The extent of the Port-Miou watershed is unknown. One usually assigns it to the Urgonian belt of the structural unit of the Beausset but some authors invoke a larger area [24]. During the 70's, before and immediately after the construction of the dams, the discharge of the both brackish springs (Port-Miou and Bestouan) was gauged at between 3 and 160 $m^3 . s^{-1}$ with an average of 7 to 8 $m^3 . s^{-1}$ [25, 26]. As 15% of the water is sea water, and according to the respective salinities of the sea water and cavewater, we assume an average discharge of about 6 $m^3 . s^{-1}$ of freshwater from the karst system of Port-Miou. To explain such values and the inertia of the springs it is necessary to have a very large watershed. A regional balance, including rainfall, infiltration, discharge of Lower Provence springs and rivers, suggests the catchment area should be increased to 1,200 km^2 [27]. An isotopic study (^{18}O) supports this hypothesis indicating that the water came from an average altitude of 480 m asl. [28], which can include an important part of Western Lower Provence.

3.1.2. Origin and evolution of the karst system

The existence of a large karst aquifer in Lower Provence is difficult to imagine today because of the present very low

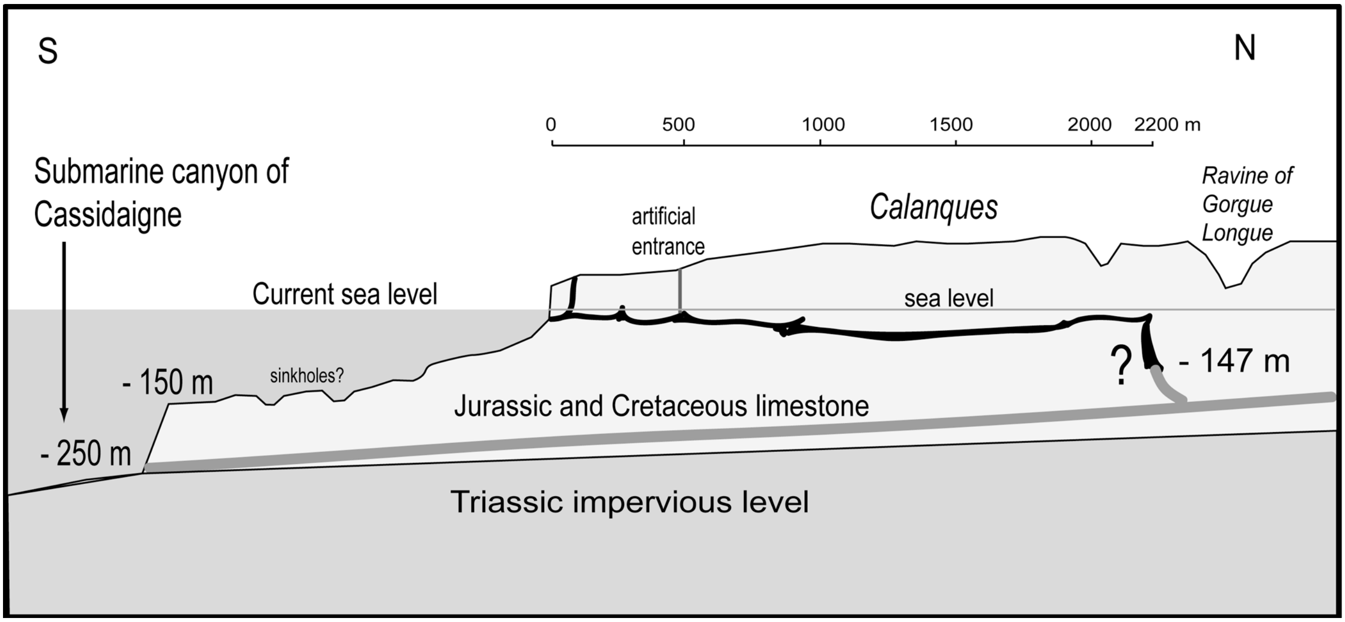

Fig. 4 The Port-Miou submarine spring. Cross-section showing the surveyed part (black line) and the hypothetical Messinian section (grey line) discharging at the base of the Cassidaigne submarine canyon, which is incised into a karst plateau [survey after 23].

hydraulic gradient. It is possible that the system owes its development to the drop in sea level during the Messinian [29]. Evidence includes the 147 m depth reached by scuba divers, which is deeper than depths reached by sea level fluctuations during the Quaternary. A bathymetric study by Collina-Girard [30] reveals the existence of a karst plateau that extends a few kilometres south of the *Calanques*, with dolines at a depth of 150 m below present sea level (Fig. 5). The submarine blind canyon of Cassidaigne whose base is at a depth of 1,000 m cuts this plateau. This canyon looks like a karst pocket valley ("*reculée*"), which is not continuation of a continental valley. We suggest that the underground river of Port-Miou, which at the time flowed several hundreds meters below its current position, excavated the canyon. At the end of the Messinian crisis, the system was flooded by seawater. The karst water now flows through an upper gallery. The presence of a paleo-drain filled by seawater explains a deep marine introduction into the karst system.

3.2. Aquifers connected to Messinian canyons and Pliocene drowned river valleys

Downcutting of Mediterranean tributary rivers into deep canyons during the Messinian induced entrenchment of inland karst systems. Pliocene transgression and fluvial aggradation affected the karst in several ways.

3.2.1. The very deep phreatic system of the Fontaine de Vaucluse

The Fontaine de Vaucluse is among the deepest known phreatic systems in the world (–308 m depth, 224 m below present sea level). It gave its name to the adjective "vauclusian" that describes a spring fed by rising phreatic water. Its watershed (about 1,100 km^2) consists of the Vaucluse mountains where numerous deep shafts occur [31]. At 750 m depth, the Souffleur shaft reaches the phreatic zone at the same elevation as the Fontaine de Vaucluse [32]. A deep valley, presently filled with hundreds of meters of Pliocene sediments is recognised from well logs [5]. This Rhône tributary used to be fed by the Vaucluse aquifer and is evidence that the deep karst system formed during the Messinian (Fig. 3). Following the Pliocene transgression, the karst was flooded. The spring was plugged and water found a new discharge point at the Fontaine de Vaucluse (Fig. 6). Images brought back by the Remote Operative Vehicle (ROV) show peculiar features, interpreted as wall karren, which developed down to –200 m (100 m below sea level). If confirmed, it could demonstrate that this part of the system evolved in epiphreatic conditions during the Messinian (Fig. 7) [33].

3.2.2. The upward development of horizontal levels in the Ardèche karst [34]

The Ardèche river is a right bank tributary of the Rhône (Fig. 8). At the Ardèche outlet, close to the Rhône confluence, the current canyon is fossilised by pliocene marine deposits. Rhône and Ardèche messinian canyons show a difference in entrenchment depth of about 300 m (Rhône: –236 m bsl. in a borehole located 10 km upstream from the confluence; Ardèche: +50 m asl. at the confluence), showing a hanging position for the Ardèche Messinian canyon. Numerous vauclusian springs are found along the Ardèche canyon (Fig. 8). Scuba divers exploring the flooded karst found evidence for vadose or epiphreatic features –50 m below the Ardèche river (torrential entrenchment, potholes, wall flutes…) [Brunet Ph. 1999, oral comm.]. These flooded torrential features are related to the Messinian salinity crisis, when the water of the surface rivers infiltrated into the lime-

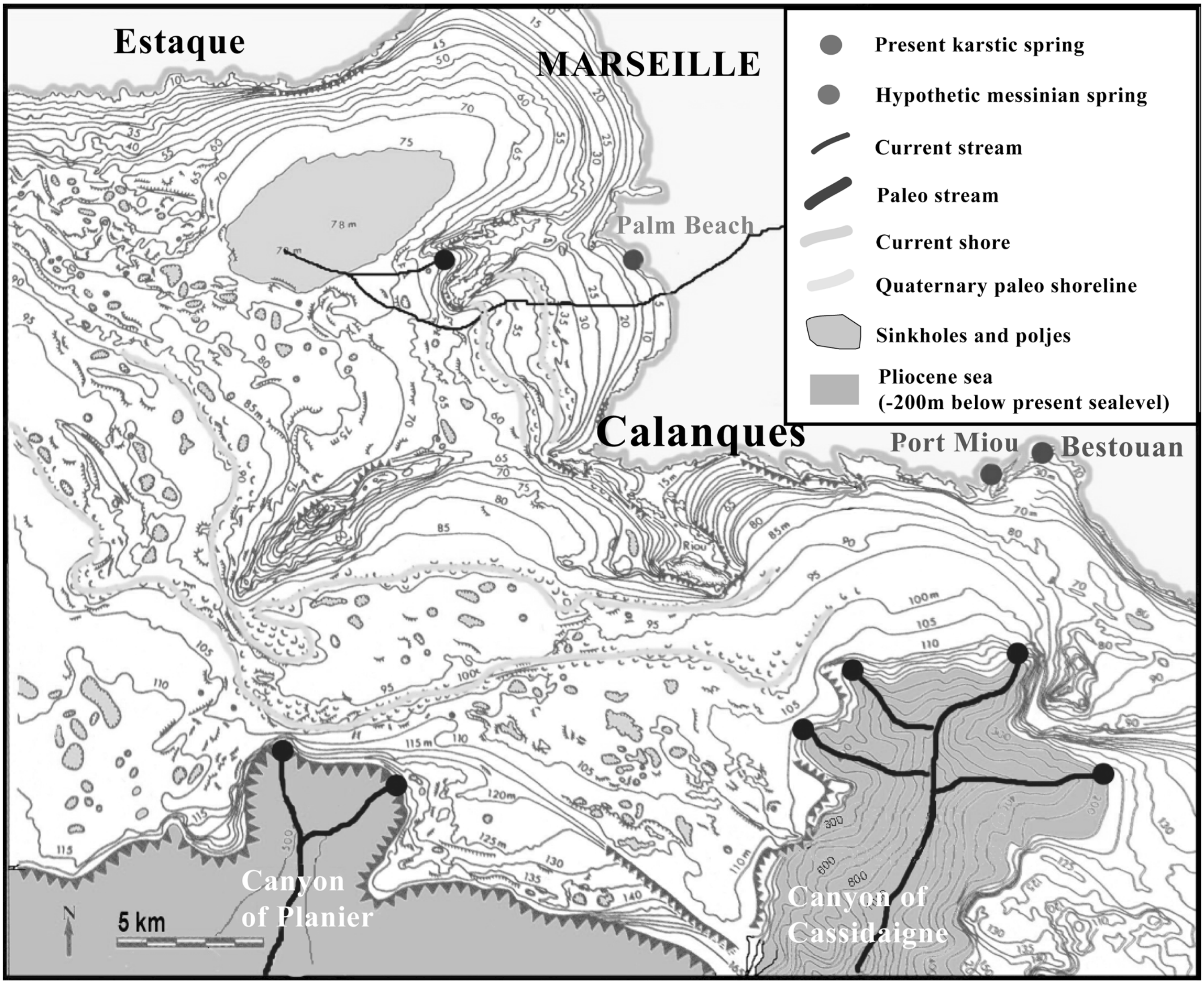

Fig. 5 Bathymetric map of the *Calanques* area [after 30]. A large plateau with closed depressions developed to –150 m bsl. Deep canyons (Cassidaigne) corresponding to pocket valleys are downcut and join abyssal plains. They correspond to discharge points during the Messinian.

stone to feed the deep aquifer. The surface river was bypassed by underground passages pouring out downstream of its canyon, inside the deep entrenched Rhône canyon. Such a high hydraulic gradient induced deepening of the streamways beneath the Ardèche river whereas the Ardèche valley remained perched (Fig. 9A). Similar features are observed at the Ardèche/Rhône confluence where two vauclusian systems (Pont and Tannerie) go down to –150 m and –120 m below present sea level. In these springs divers have found speleothems at –90 m below the entrance (that is –30 m below present sea level and also below any Pleistocene Rhône talweg). Ardèche karst also displays horizontal systems like the Cave of Saint-Marcel. This comprises three horizontal tiers connected by vertical shafts, which show phreatic features and indications of rising flow (Fig. 9). The lowermost level (1) corresponds to the flooded one whilst the uppermost levels (2 and 3) develop at about 130 m and 190 m asl. respectively. As the Mediterranean sea level rose, the Rhône and Ardèche canyons were flooded forming *rias* and the springs were sealed by pliocene sediments (Fig. 9b). The upper karstlevels are closely correlated to pliocene stratigraphic reference levels (see § 2.1 and Fig. 1). Cave level 2 fits with the "marine/continental transition" corresponding to the Lower Pliocene high stand sea level; cave level 3 corresponds to the Upper Pliocene "abandonment surface" of Ardèche's Gilbert delta. Such altitude correlation implies an internal/external coupling. The abrupt sea level rise for level 2, and slow and regular fluvial aggradation for level 3, created the hydraulic driving force necessary for generating the connection shafts which acted as phreatic lifts (Figs. 9B, 9C). During base level rising, the two successive still stands corresponding to respective Pliocene stratigraphic reference levels induced the development of the 2 and 3 horizontal cave levels. Correlations to other periods are excluded due to the fact that base level was higher before Messinian and lower after Pliocene [34]. Cosmogenic isotopes dating (in progress) confirm these stratigraphic correlations.

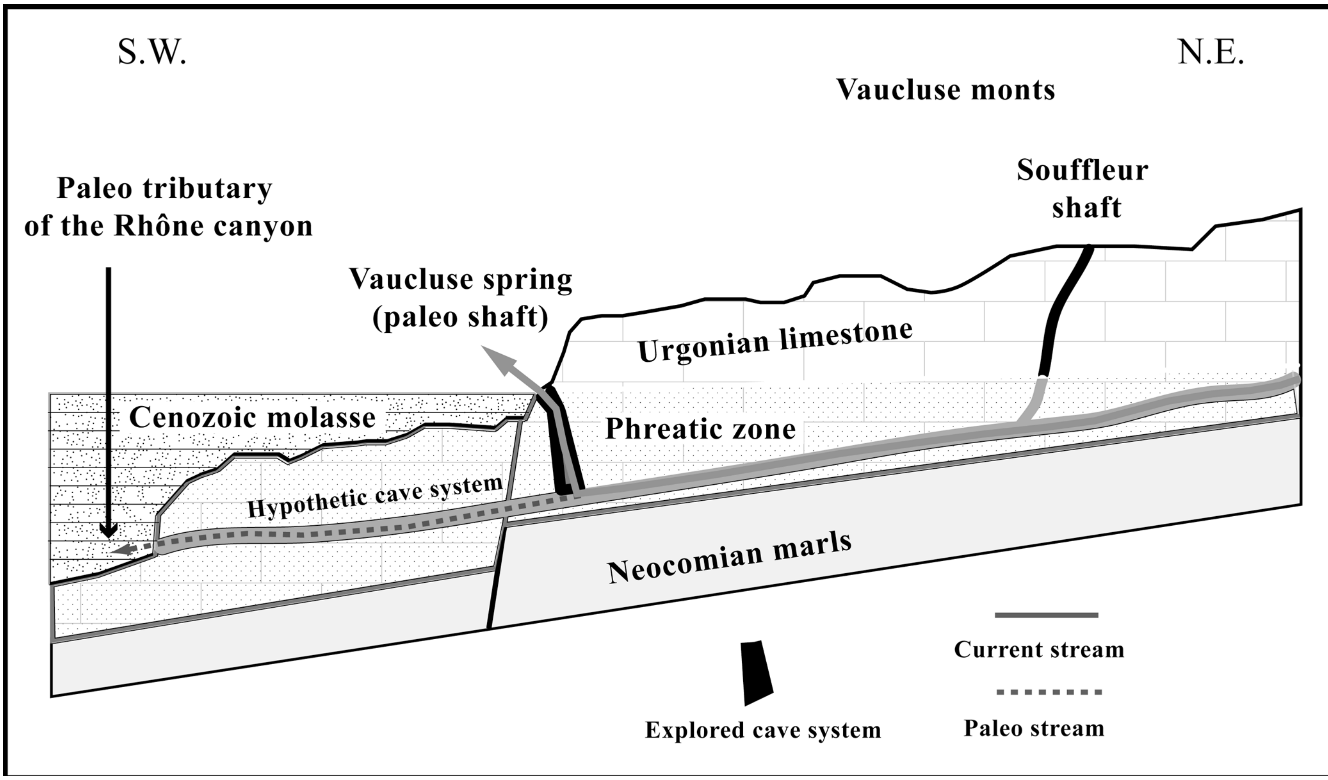

Fig. 6 Today the Fontaine de Vaucluse drains the Vaucluse mounts. A deep system drained by Messinian canyons is now flooded below several hundreds of meters of water.

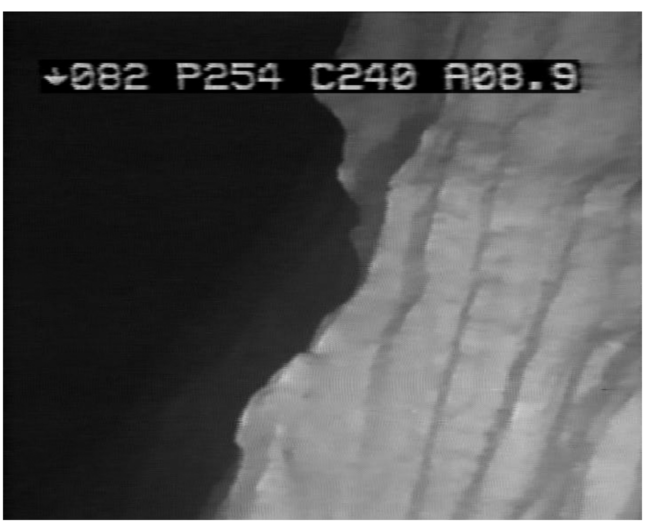

Fig. 7 Solutional wall features developed down to –200 m in Fontaine de Vaucluse (100 m below present sea level). They were formed in the epiphreatic zone during the Messinian. Image from ROV at about 120 m depth (1988).

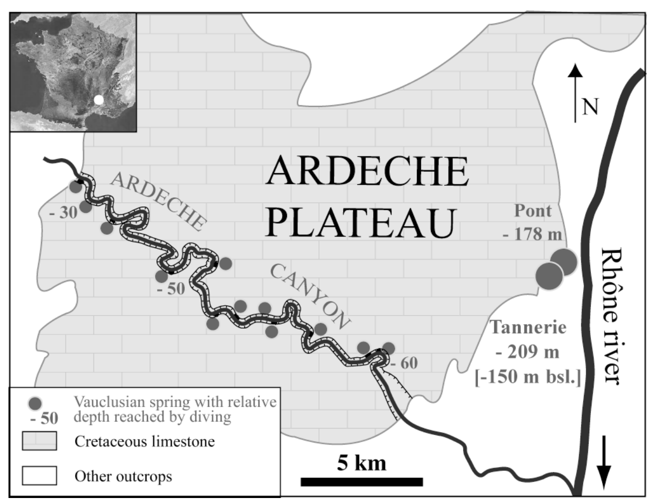

Fig. 8 Location of deep phreatic karst systems in Ardèche.

In summary, after a period of abrupt base level drops during the Messinian salinity crisis (5.96 – 5.32 Ma), cave systems developed upward and were controlled by the step-like rise in base level that occurred over more than 3 Ma up to the end of the Pliocene (1.8 Ma). This organisation of cave systems shows that the influence of the Messinian salinity crisis on karst development was not restricted to the crisis period but prolonged its effects over the whole Pliocene period. The impacts that occurred during or after the salinity crisis lasted 4 My, from 5.96 to 2 Ma.

3.3. Continental aquifers of the Mediterranean Causses

The Causses and Garrigues karsts extend between the Hercynian basement of the Cévennes to the north and the Gulf of Lion to the South (Fig. 3). Three main rivers drain this area: Hérault in the west, Vidourle in the east and Lez in the central part (Fig. 10). This area has a high density of vauclusian springs and includes 65% of the French deep phreatic karst systems (between –100 and –160 m deep).

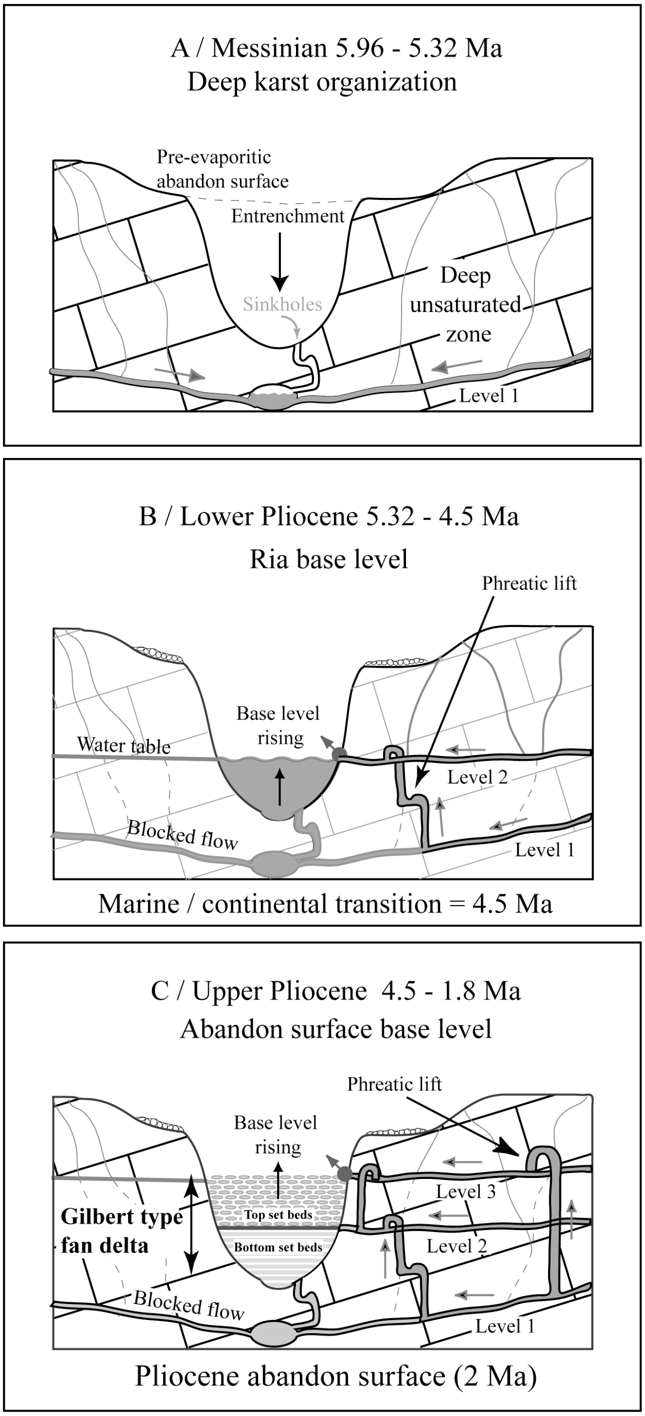

Fig. 9 Model of the Saint-Marcel Cave system. A/ Downward evolution related to the Messinian drop in base level in the Ardèche. B-C/ Upward evolution related to the Pliocene rise in base level in the Ardèche.

Some of these are over a kilometer in length; others are vertically developed. Some springs are located in the thalweg of the karst canyon of the Hérault River and its tributary, the Vis River. In the past, these springs acted as swallow holes, as attested by underwater travertine formations, flutes and vadose solution features located –50 m below the present thalweg [35, 36].

Offshore, continental Pliocene alluvial deposits overlie the Messinian erosion surface. In profile, this surface can be extrapolated inlandward to the Hérault canyon at about 150 m asl. [36, 37]. This also shows that the Hérault Messinian paleovalley was perched during the Messinian Crisis. Due to this perched position, both Hérault and Vidourle valleys were drained by streams, sinking while crossing limestone outcrops. The underground bypasses were connected at depth to the Lez karst aquifer that drained the whole area at this time.

Currently, the Lez aquifer is bounded downstream and laterally by three impervious dams (Fig. 10): (1) To the south, an impervious 1,000 m–deep dam continues offshore along the transcurrent fault of Sète; (2) to the east, the 4,500 m–deep syn-rift Vistrenque Basin, above which the Vidourle River flows [38]; (3) and to the west, the impervious deposits of a 1,600 m thick Tertiary syn-rift basin that the Hérault River crosses before reaching the Mediterranean Sea [39]. The only way the Lez aquifer could discharge at the Mediterranean base level during the Messinian low sea level was through a hydrogeologic watergap in the eastern part of the anticline of the Montpellier thrust (including limestones of the Gardiole massif; Figs. 10, 11). Offshore, the Messinian erosional surface cut across the Jurassic limestones and breached the aquifer. Water emerging from these windows formed blind canyons, which are not the continuation of any continental valley. The paleo-springs where the Lez aquifer could discharge may be located at three points along this blind canyon (Figs. 10, 11): 1) at the foot of the Montpellier karst close to –300 m bsl.; 2) below the present shoreline close to the fault bordering the Gardiole Massif at –500 m bsl.; 3) at –1,000 m, that is the base of a small Oligocene basin.

After the subsequent Pliocene sea level rise (Fig. 1), the entire karst system was sealed (Figs. 2, 12). Below the Pliocene water table, the former karst system was flooded, resulting in the high density of deep phreatic systems. Above the water table, the former karst systems were partially or totally filled with sediments (Fig. 12). The location of these filled systems fits with that of the vauclusian springs because they were initially part of the same Messinian karst system.

4. Conclusions

Technological advances in cave diving have permitted the study of the geometry of deep phreatic zones in cave systems. Observations in Ardèche, Causses, Vaucluse and Port-Miou reveal that there are several levels of galleries present in the different karst systems; above and below the present water table. The depths and altitudes of these galleries are not consistent with the Quaternary glacio-eustatic levels. They can, however, be matched to erosional features observed during the Miocene and the Pliocene.

A karst spring is the terminal point of a system of galleries that drain the karst aquifer. Circulation of water through

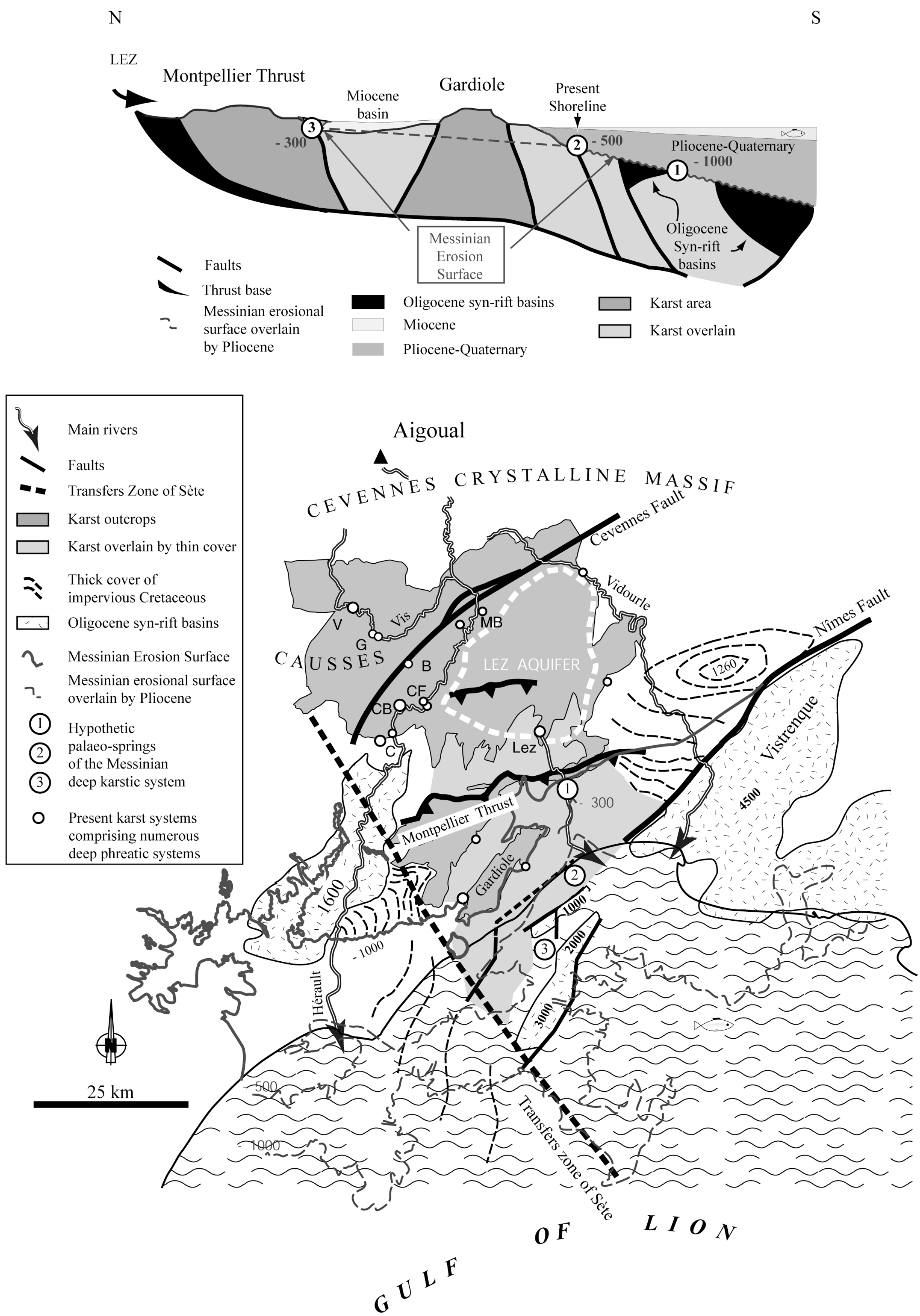

Fig. 10 The carbonate recharge area bordering the Gulf of Lion during the Messinian. Cross-section showing the relationship between geological structure and the karst systems.

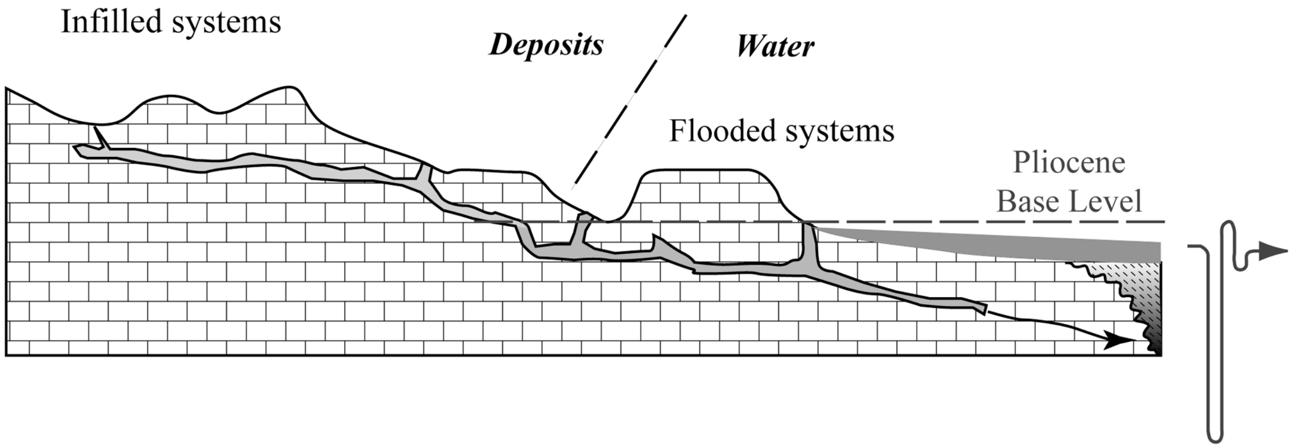

Fig. 11 Diagrammatic cross section of Mediterranean Causses karst systems inherited from the Messinian Deep Sea Stage. Today the part below the former Pliocene sea level is flooded forming deep phreatic systems. The upper part above the former Pliocene sea level is partially filled with sediment.

a limestone block depends on the hydraulic gradient generating a current and the permeability of the limestone which regulates the discharge. If the permeability is homogeneous, a preferential current establishes at the upper part of the aquifer, enlarges the discontinuities and increases the permeability. Thus, most karst systems are drained by galleries that are close to the top of the aquifer. The height of the water table determines their average level (sea, stream, river or lake). If the permeability is heterogeneous, water may flow in deeper zones, thus, allowing for deep dissolution galleries to be created. Two primary causes define the permeability and the possible location of the drains: the nature of the limestone itself and the density of the discontinuities (cracks, joints and faults). The presence of karst paleogalleries offers a possible third cause by making high permeability zones possible in any part of the limestone blocks. Karst palaeogalleries are inherited from past karstic erosional periods. As the areas under study reveal few lithologic differences and contain high densities of discontinuities, we assume that the presence of the deepest passages is mainly caused by the existence of such paleogalleries that form zones of high permeability in the deep aquifers. Within Europe, the speleological features described are only observed in regions in the Mediterranean watershed. All the features can be ascribed to one original cause. The Messinian model, with a huge lowering of the water table due to the desiccation of the Mediterranean Sea, followed by a fast Pliocene transgression, is the most coherent explanation. It provoked the deepening of the main streams, their tributaries and the aquifers that drained toward them, and it accounts for the existence of the deepest drains. These drains, however, may predate the Messinian stage; they may have formed during the Cretaceous or the Tertiary, filled with sediments and then be washed out and returned to service by Messinian water.

The model implicates the presence of deep vadose zones before the Pliocene transgression. Evidence for these former vadose zones has been found at 90 m below sea level, in the form of speleotherms observed by divers in Ardèche. Research, including new exploration and dating, is still in progress to consolidate the Messinian model but both the depth and length of the flooded cave systems limits human access, making the use of a ROVs necessary.

An important implication of our model is the availability of water resources at greater depths than previously anticipated. The Messinian model predicts that zones with an important permeability are present at unusual depths in the karst aquifers. These zones, that drain large proportions of the aquifers, are the best places for water capture and could be reached by deep wells. A good example of this is the present water supply system of the city of Montpellier. At the karst spring of the Lez, two pumps are installed in a natural gallery that penetrates deep into the karst aquifer. This catchment system allows the lowering of the water table, of the whole aquifer, down to 40 meters below the spring level [41]. The success of this system is considered to be related to an exceptional hydrogeological environment but the Messinian model postulates that this kind of environment, with deep drains, is common in the Mediterranean watershed and could be developed in several other places.

Further examples are provided by submarine springs. Today, the Mediterranean coastal zone is characterised by a high population density and large exposures of karst. Fresh water is scarce in most places but many brackish coastal or submarine springs, similar to the one at Port-Miou, are present on the Mediterranean sea shore. They could feed an important population but the attempts to use this water have very often failed, due to the difficulty of resolving the issue of residual salinity. At the Almyros of Heraklion (Crete), the hydrogeological model predicts a mixing of sea and fresh waters, in a large gallery at depths to –450 m [42]. The Messinian model easily explains the origin of the salinity and gives new ideas as to sourcing the water before it is salt contaminated.

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