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SPELEOGENESIS IN REGIONAL GEOLOGICAL EVOLUTION AND ITS ROLE IN KARST HYDROGEOLOGY AND GEOMORPHOLOGY

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BASE LEVEL RISE AND *PER ASCENSUM* MODEL OF SPELEOGENESIS (PAMS). INTERPRETATION OF DEEP PHREATIC KARSTS, VAUCLUSIAN SPRINGS AND CHIMNEY-SHAFTS.

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In Mediterranean karsts, the Messinian Salinity Crisis induced first a deepening of the karst systems, then a flooding after the Pliocene transgression, and finally a reorganization of the drains after this base level rise. This reorganization mainly corresponds to the development of phreatic lifts: the chimney-shafts and the vauclusian springs. Such a *per ascensum* speleogenesis appears with a base level rise, which is caused by eustatism, by fluvial aggradation or valley infilling, or by continental subsidence. Consequently, we explain the origin of most of the deep phreatic cave systems (which are not hypogenic) by a base level rise which flooded the deep karst, producing phreatic lifts connected to vauclusian springs.

1. Introduction

Where no impervious aquiclude is present, cave levels can be correlated to base level (Granger et al. 2001; Anthony & Granger 2004; Häuselmann et al. 2007). Authors generally explain them as the result of descending base level caused by valley incision. Cave levels are implicitly associated with a *per descensum* evolution. Since the ages of cave levels are correlated to successive stages of valley entrenchment, the lowest levels are considered the youngest, and conversely (Palmer 1987). And when a base-level rise is taken into account, its role is generally limited to the flooding and filling of cave systems, without noticeable speleogenesis.

Studies of speleogenesis associated with the Messinian-Pliocene eustatic cycle, i.e., the succession of Messinian Salinity Crisis (MSC) and Pliocene High Stand (PHS), demonstrate the speleogenetic role of base-level rise as a *per ascensum* process, by the formation of phreatic lifts, or "chimney-shafts" (Mocochain et al. 2006). By extension, other contexts of base level rise, mainly caused by fluvial aggradation, produce a similar speleogenesis, making it possible to extend the *Per Ascensum* Model of Speleogenesis (PAMS).

This paper presents our results, carried out first in the French Mediterranean area and associated with the impacts of the MSC. Second, we extrapolate to other contexts of base-level rise that also show a PAMS. Their origin could be eustatic, climatic (transgression or fluvial aggradation), or tectonic (regional subsidence).

2. The PAMS Associated with the Messino-Pliocene Cycle in the Mediterranean

The French Mediterranean periphery displays a cluster of deep phreatic cave systems (Fig. 1). Many authors once interpreted it by the Four State Model (Ford 1977), assigning a bathyphreatic origin with a speleogenesis not influenced by the base-level position. From the 1980s onward, according to concepts developed by Clauzon et al. (1997), the origin of such a deep-phreatic speleogenesis gradually shifted to the MSC. This revision provides conceptual tools based on the influence of large-scale base level changes on deep phreatic cave systems.

Recent studies have identified several types of flooded cave systems (Mocochain 2007; Audra 2007). This typology is built not only on morphological criteria, but also on the elevation of the caves according to the current base-level position. It is possible to distinguish flooded cave systems located mainly below the base level (marine or fluvial), from those currently in the vadose zone but having a phreatic origin.

2.1 Flooded coastal karst, the Port-Miou submarine spring

The Port-Miou submarine spring, near Marseille, is fed by part of the Provence karst (Fig. 1). It has been explored for more than 2 km and down to 179 m depth (Fig. 2). The offshore bathymetry reveals submerged karst features (dolines, poljes, and canyons) (Blanc & Monteau 1988; Collina-Girard 1996). The Cassidaigne Canyon is interpreted as an old pocket valley developed during the Messinian low

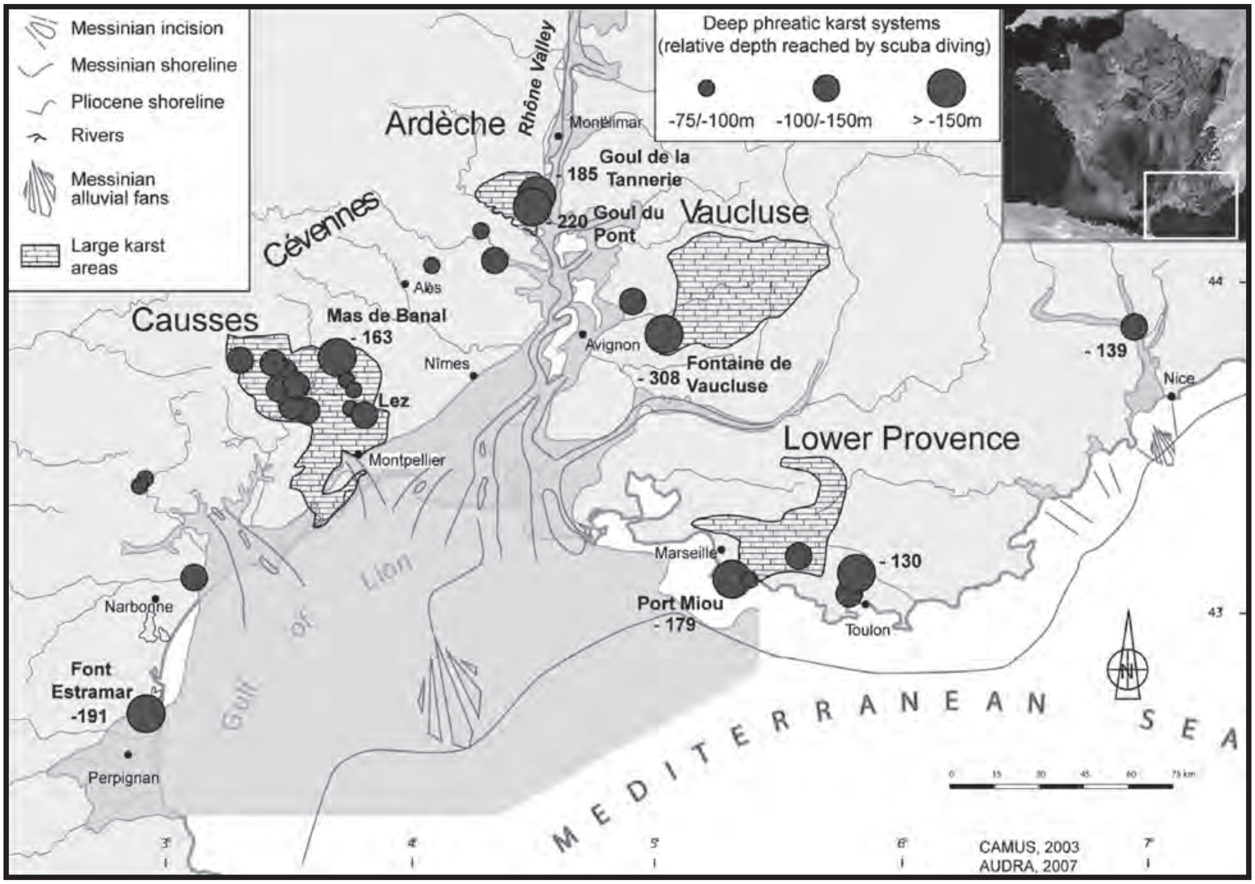

Figure 1: Deep-phreatic cave systems in Mediterranean France. All cave systems are connected to the Mediterranean or to the Pliocene rias ("flooded valley") (map after Clauzon et al. 1997; Camus 2003; caves updated from Audra 1997).

sea level. Since the Pliocene transgression, the deep karst has been flooded. Sea water enters several kilometers into the aquifers through the old Messinian drains. This intrusion is responsible for the salinity of the spring (Gilli 2001; Blavoux et al. 2004; Cavalera 2007).

2.2 Flooded continental karst: the Fontaine de Vaucluse

The Fontaine de Vaucluse drains the largest karst area of France (1130 km^2, Q = 23 m^3/s; Fig. 1). It is famous for its considerable depth of 308 m, i.e., 224 m below current sea level (Bayle & Graillot 1987). Wall karren are developing down to 170m below sea level. They testify to past epiphreatic conditions by successive flooding and draining. The Fontaine de Vaucluse appeared during the MSC (Gilli & Audra 2004). Seismic investigations reveal

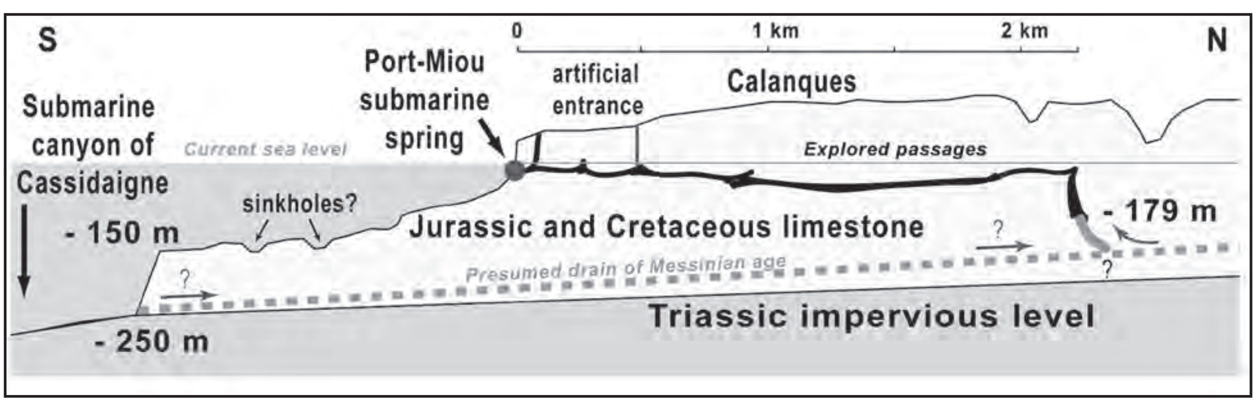

Figure 2: Port-Miou submarine spring. In the Messinian drain, opening offshore at the head of the Cassidaigne Canyon, the water is blocked by the density of the salt water. The underground flow follows a phreatic lift connected to the submarine spring (Blavoux et al. 2004; survey after Douchet & Fage 1993).

a Messinian canyon filled with sediments, located 20 km to the west and originating from the Fontaine de Vaucluse (Schlupp et al. 1997). This pocket valley has been filled during the Pliocene (Fig. 3). The fill blocked the canyon at depth and forced the flow upward and to use the past overflow route as a perennial spring. The lowest part of the karst is flooded to a great depth. A similar evolution occurred in Ardèche, where the Goul du Pont and Goul de la Tannerie springs have been explored by scuba divers down to -220 m (Fig. 1).

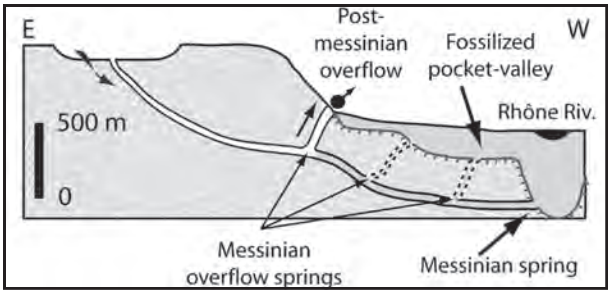

Figure 3: Speleogenetic model of the Vaucluse karst. The Messinian canyon of the Rhône River is filled with Pliocene deposits. Its bottom is at 900 m below current sea level. The Messinian cave system, which was probably connected to this canyon, has been flooded and filled with sediment during the Pliocene. Since that time, the underground flow has used a chimney-shaft opening to the current base level at the Fontaine de Vaucluse.

2.3 Drained karst: the Ardèche

The canyons were deeply entrenched during the Messinian and then filled with sediments during the Pliocene, causing a base-level rise of similar amplitude. This rise first occurred by flooding of the valleys during the Pliocene transgression, then by fluvial aggradation through to the end of the Pliocene (Fig. 4). Cave levels are correlated with the successive positions of the base level during the Messinian-Pliocene cycle.

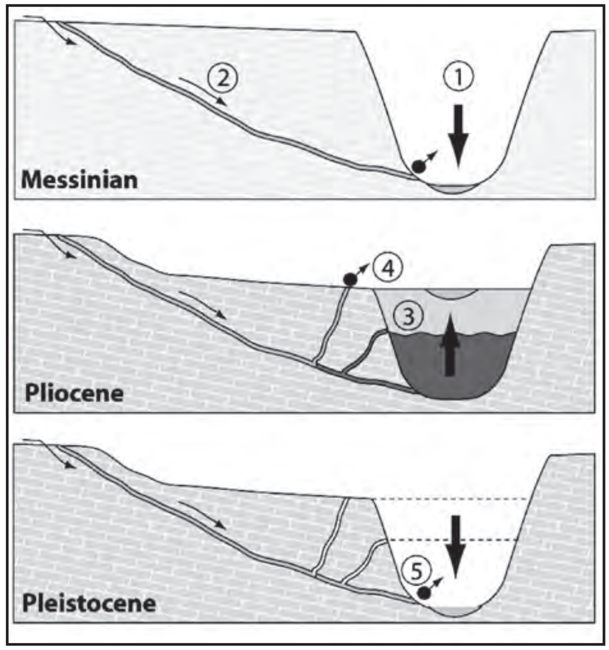

Figure 4: PAMS during the Messinian-Pliocene cycle. Left: Messinian canyon entrenchment caused the deepening of karst drainage. Center: Pliocene base level rise occurred in two steps – by marine ingression as ria (dark gray), then by fluvial aggradation (light gray). Deep drainage uses phreatic lifts to emerge as vauclusian springs, recording successive positions of the base level. If the Messinian canyon is located below the current base level, it remains fossil; the karst remains flooded and discharges by a vauclusian spring (fontaine de Vaucluse type). Right: if the Messinian canyon is located above the current base level, the canyon is exhumed and the karst is drained. The current drainage uses the deep Messinian drain; the Pliocene phreatic lifts are abandoned as fossil "chimney-shafts".

Foussoubie is a 25-km long cave system with a main drain displaying a regular gradient (2.5%) between the sinkhole and the resurgence in the Ardèche Gorge (Fig. 5). Above the resurgence are vertical series with phreatic features that

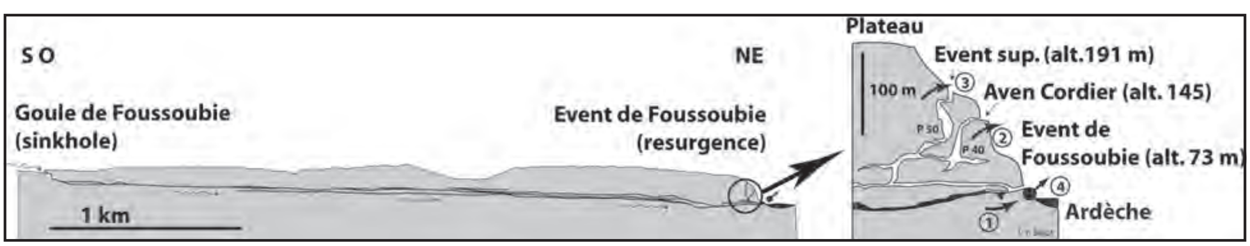

Figure 5: PAMS in the Foussoubie Cave System, Ardèche. The phreatic lifts resurge at vauclusian springs connected to the higher base-level positions corresponding to the Pliocene filling. During the Pleistocene, the Messinian canyon was exhumed and cleared of its Pliocene fill down to its bottom. Current drainage reuses the deep Messinian drain. The Pliocene phreatic lifts are abandoned as fossil "chimney-shafts" (Bigot 2002; Mocochain 2007; Mocochain et al. 2006, 2008).

clearly show a rising flow. The rectilinear long profile shows that the main drain developed during the Messinian, at a base level at the bottom of the Ardèche Canyon (Bigot 2002; Mocochain 2007). Filling of the canyon causes the development of resurgences as phreatic lifts, or "chimney-shafts". The elevations of resurgences record the stages of base-level rise due to Pliocene fluvial aggradation. During the Pleistocene, the Messinian canyon of the Ardèche was exhumed by clearing away of the Pliocene filling: Foussoubie chimney-shafts became fossil, and the Messinian drain returned to a vadose flow (Figs. 4, 5).

In partly exhumed canyons, the lower part of the karst has remained flooded since the beginning of the Pliocene, and they discharge as vauclusian springs (Fontaine de Vaucluse type). In the entirely exhumed canyons, the karst is drained and the chimney-shafts are fossil (Foussoubie type). In turn, the chimney-shafts, which are systematically associated with paragenesis, are interpreted as a **record of the PAMS**, which originates from a base-level rise. Consequently, a base-level rise is interpreted to be a founder speleogenetic event. Besides the Messinian-Pliocene cycle, other causes of base-level rise also produce *per ascensum* speleogenesis and the development of chimney-shafts.

3. Extrapolation of the PAMS to Other Causes of Base-Level Rise

The speleogenetic role of the Messinian-Pliocene cycle could be attributed to a dramatic base-level drop that allowed a deepening of karst drainage, followed by a base-level rise of similar magnitude. This base-level rise flooded the deep drainage and developed chimney-shafts, sometimes associated with new horizontal cave levels, as in Saint-Marcel Cave, Ardèche (Mocochain et al. 2006). The occurrence of deep phreatic karsts, vauclusian springs, and chimney shafts all around the Mediterranean is a consequence of speleogenesis during the Messinian-Pliocene cycle (Figs. 1, 7).

Besides the Messino-Pliocene cycle, the PAMS applies to every kind of base-level rise (following a low base-level position). A base-level rise is shown by filling of the lowest parts of valleys by water, ice, or sediment. The driving force could be eustatic (transgression), tectonic (subsidence), climatic (clearing of slopes soils, glacial advance), or even anthropic (e.g., man-made dams).

3.1 The Miocene eustatic cycles

In the Rhodanian-Provence foreland basin between the Fontaine de Vaucluse and the Rhône, the marine molasse records several eustatic cycles during the Miocene (Aquitanian, Burdigalian). The regression, which is linked with tectonic uplift, follows valley entrenchment up to 100m-deep, with eventual flooding and filling with sediments by transgressions (Besson et al. 2005a, 2005b; Parize et al. 1997). Near the Fontaine de Vaucluse, a fossil pocket-valley ends exactly at the Valescure Shaft, which displays characteristic chimney-shaft features. The Valescure Shaft used to be a vauclusian spring during the Burdigalian, following the filling of the pocket-valley with the molasse. An earlier outflow should exist, buried beneath the molasse sediments.

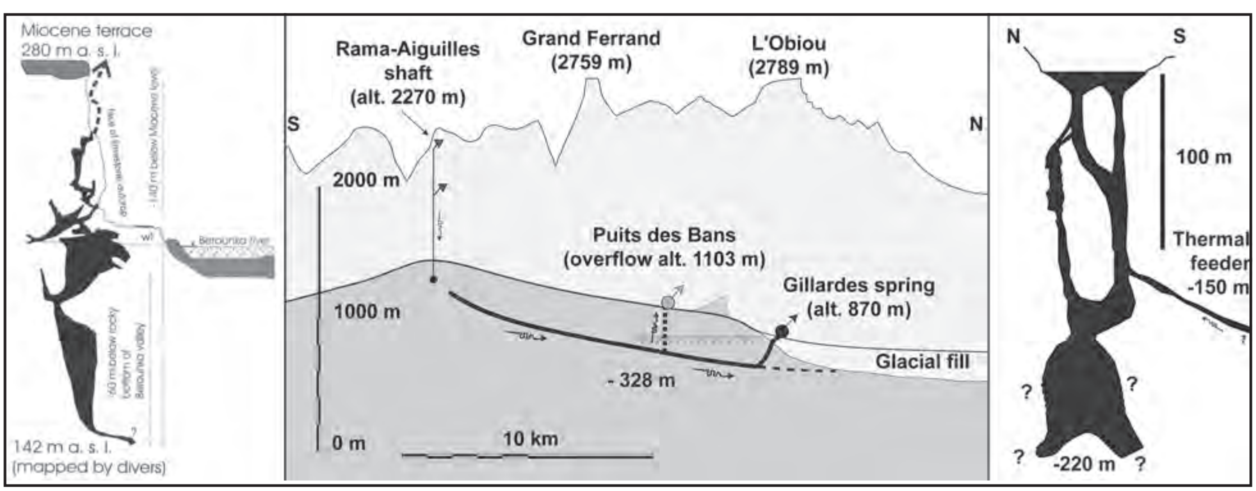

Figure 6: Left: Podtraťová jeskyně, Moravian karst, Czech Republic, a 140-m high chimney-shaft, the lowest part of which is flooded below the Beroukna valley (Bruthans & Zeman 2003). It could show a record of the base-level rise of the hydrologic network after pre-Badenian entrenchment. Center: the Puits des Bans and the Gillardes Spring (French Alps). The basin fill (glacial, lacustrine, and fluvio-glacial) has blocked the Gillardes Spring. In high water, the Puits des Bans, a 300m-high chimney-shaft, floods and overflows. Right: Lagoa Misteriosa (Brazil), a 200-m deep phreatic shaft, a window in a karst aquifer flooded after the continent subsidence (survey by G. Menezes).

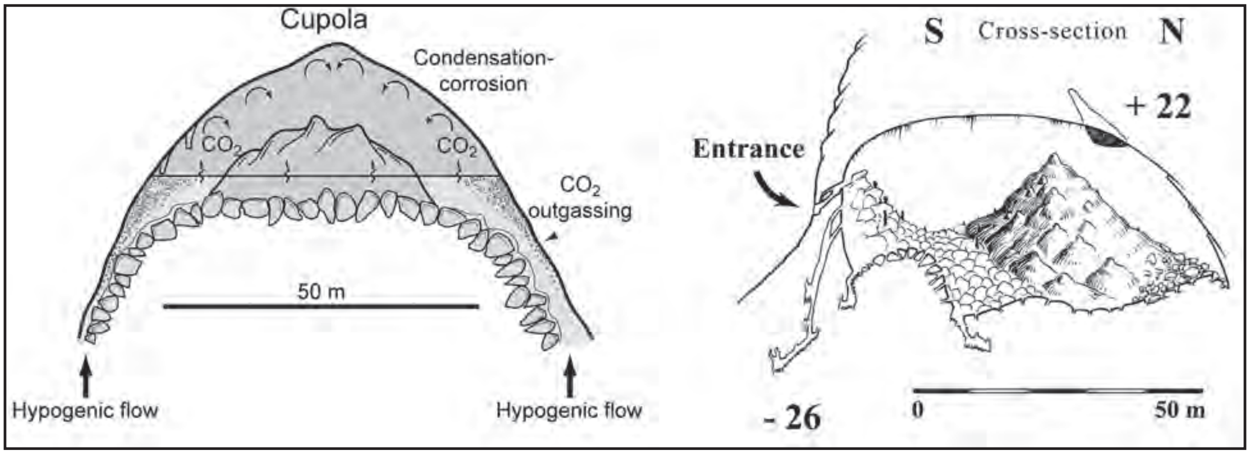

Figure 7: Distribution and origin of the deepest phreatic cave systems in the world.

In the Rhodanian-Provence basin, the speleogenetic influence of the Miocene eustatic cycles is partly hidden by the imprint of the younger Messinian-Pliocene eustatic cycle. On the contrary, the Paratethys molassic basin of central Europe, at least in its northern part (Czech Republic, Slovakia, Poland, etc.), has not been affected by Messinian entrenchment. Consequently, the oldest eustatic cycles are better recorded. The transgressions of the Carpathian (i.e., Burdigalian) and especially of the Middle-Badenian (i.e., Langhian-Serravalian) follow continental erosional phases, which deepened valleys as much as 150-200 m, and which were later fossilized. Pre-Badenian karsts are well-known: tower karst in Zbrasov (Czech Republic) partly exhumed from the molasse; caves filled with molasse in Bohemian; caves and fluviokarst morphologies in the Moravian karst (Kadlek et al., 2001). In the Bohemian karst, the Podtraťová jeskyně (cave) is a chimney-shaft partly drained and more than 100 m deep (Fig. 6). It is developed below the Beroukna Valley, which was entrenched before the Burdigalian and then exhumed during the Pleistocene (Bruthans & Zeman 2003, Fig. 6). If some caves in this area have a hypogenic origin, its chimney-shaft features would have recorded the Miocene base-level rise by *per ascensum* speleogenesis.

3.2 Glacio-eustatic transgression

Post-glacial sea-level rises have flooded the coastal karsts (Fig. 7), including the cave systems developed during previous low sea levels. It is evidenced by submerged speleothems, which have been observed down to -120m, around the Gulf of Mexico: Yucatan Peninsula, Bahamian blue holes, Wakula Spring in Florida, etc. Such types of karst discharge through vauclusian springs at the mouths of phreatic lifts. In French Normandy, Pleistocene sea-level changes are well recorded in cave systems developed in chalk. The high conductivity of the chalk allows cave systems to adapt precisely to the slightest base-level changes, with chimney-shafts less than 10 m high (Rodet 1991; Rodet et al. 2001).

3.3 Fluvio-glacial flooding

Glacial retreat leaves moraine dams across valleys. Behind them, lacustrine and fluvio-glacial sedimentation occurs, sometimes up to several hundred meters high. Cave outlets connected to the valley bottom become plugged. Some chimney-shafts are still developing, allowing phreatic lifts from deep passages up to the uplifted base level. The height of the chimney-shafts corresponds to the height of the base level rise. The Puits des Bans (French Alps), is a 300-m high chimney-shaft (Fig. 6).

3.4 Base-level rise after continental subsidence

In Brazil, the Lagoa Misteriosa is a deep-phreatic shaft explored to -220 m by scuba divers (Fig. 6). Regional subsidence (communication from A. Auler) can be considered a relative base-level rise that has flooded the karst.

4. Conclusion

Studies of the Messinian-Pliocene eustatic cycle in the Mediterranean allow us to design a model of karst adaptation to major oscillations of base level. Pliocene base-level rise has flooded the karst and systematically produced phreatic lifts – chimney shafts – which feed vauclusian springs. Some cave systems remain flooded, and others have been partly or entirely drained after Pleistocene re-entrenchment of the valleys. Other causes of base-level rise (eustacy, fluvial aggradation, continental subsidence), less significant in amplitude, have the same effect on PAMS. Consequently, there should be a global genetic model for most deep-phreatic systems (Fig. 7). Some of them have a hypogenic origin (e.g., in South Africa, North America, etc.)

(Audra 2007). However, most of them could correspond to a base-level rise inducing the PAMS, which first flooded the karst and then allowed the development of phreatic lifts, chimney-shafts, and of vauclusian springs,

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