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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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Key-words. – Base level rise, *per ascensum* speleogenesis, Deep phreatic karsts, Vauclusian springs, Chimney-shafts, Messinian salinity crisis

Abstract. – 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.

Le modèle de spéléogenèse *per ascensum* assuré par la remontée du niveau de base. Interprétation des karsts noyés profonds, des sources vauclusiennes et des puits-cheminées

Mots-clés. – Remontée du niveau de base, Spéléogenèse *per ascensum*, Réseaux noyés profonds, Sources vauclusiennes, Puits-cheminées, Crise messinienne de salinité

Résumé. – Dans les karsts méditerranéens, la crise messinienne de salinité s'est traduite d'abord par un enfoncement en profondeur des circulations karstiques, ensuite par un ennoyage lors de la transgression pliocène, et enfin par une restructuration des drains suite à cette remontée du niveau de base. Cette restructuration s'exprime principalement par la formation de conduits ascendants: les puits-cheminées et les sources vauclusiennes. La spéléogenèse *per ascensum* apparaît dès lors qu'une remontée du niveau de base se manifeste, dont la cause peut être eustatique, liée à un colmatage alluvial des vallées, ou à une subsidence continentale. Nous expliquons ainsi l'origine de la plupart des réseaux noyés profonds (non hypogènes) par une remontée du niveau de base ayant ennoyé la base du karst, avec un drainage par des conduits ascendants vers des émergences vauclusiennes.

INTRODUCTION

Where no impervious aquiclude is present, cave levels can be correlated to base level evolution [Granger *et al.,* 2001; Anthony and 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, in this model the lowest levels are considered as the youngest [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 sea level, 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.,* 2006a, b]. 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 relative-base-level rise that also show a PAMS. Their origin could be eustatic, climatic (transgression or fluvial aggradation), or tectonic (regional subsidence).

THE PAMS ASSOCIATED WITH THE MESSINO-PLIOCENE CYCLE IN MEDITERRANEAN

The study of 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

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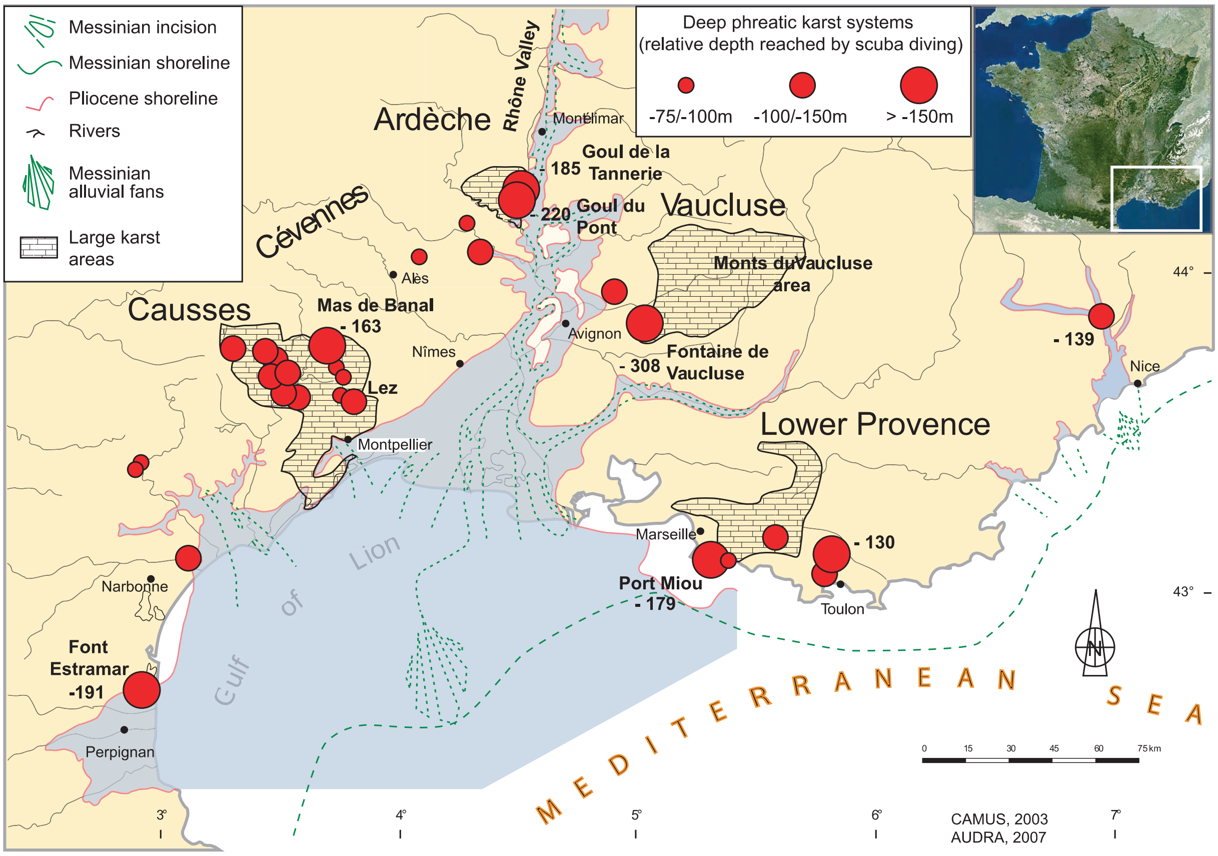

FIG. 1. – Deep-phreatic cave systems in Mediterranean France. All cave systems are connected to the Mediterranean or to the Pliocene rias ["flooded valley"; map after Clauzon *et al.*, 1997; Camus, 2003; caves updated from Audra, 1997].

FIG. 1. – *Localisation des réseaux karstiques noyés profonds sur le pourtour du midi méditerranéen français. L'ensemble de ces réseaux est en relation avec la Méditerranée ou les rias pliocènes [carte d'après Clauzon* et al.*, 1997 ; Camus, 2003 ; karst d'après Audra, 1997].*

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 Messinian salinity crisis (MSC). This revision provides conceptual tools based on the influence of important 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 the flooded cave systems, which are presently located mainly below the base level (marine or fluvial), from the cave systems which are currently in the vadose zone but whose origin is phreatic.

Flooded coastal karst, the Port-Miou submarine spring

The Port-Miou submarine springs near Marseille discharge about 20 m^3/s, originating from a 1000 km^2 large catchment covering a significant part of the Provence karst [Gilli, 2001, Fig. 1]. Upstream of the spring, it has been explored for more than 2 km and down to 179 m depth (fig. 2). Offshore, the submarine landscape displays submerged karst features such as the Cassidaigne canyon. We interpret this canyon as an old pocket valley that was draining karst during the MSC and replaced by the current submarine springs [Blanc and Monteau, 1988; Collina-Girard, 1996]. 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].

Flooded continental karst: the Fontaine de Vaucluse

The Fontaine de Vaucluse is the largest karst spring in France with an average discharge of 23 m^3/s. Its 1130 km^2 large catchment drains the monts de Vaucluse (fig. 1). It is famous for its considerable depth of 308 m, i.e., 224 m below current sea level [Bayle and Graillot, 1987]. Wall karren are developing down to 170 m below sea level. They testify to past epiphreatic conditions by successive flooding and draining. The Fontaine de Vaucluse appeared during the MSC [Martel, 1902a, b; Julian and Nicod, 1984, 1989; Nicod, 1991; Gilli and Audra, 2004]. Seismic investigations reveal a Messinian canyon filled with sediments, located 20 km to the west and originating from the Fontaine de Vaucluse [Schlupp *et al.,* 2001]. 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

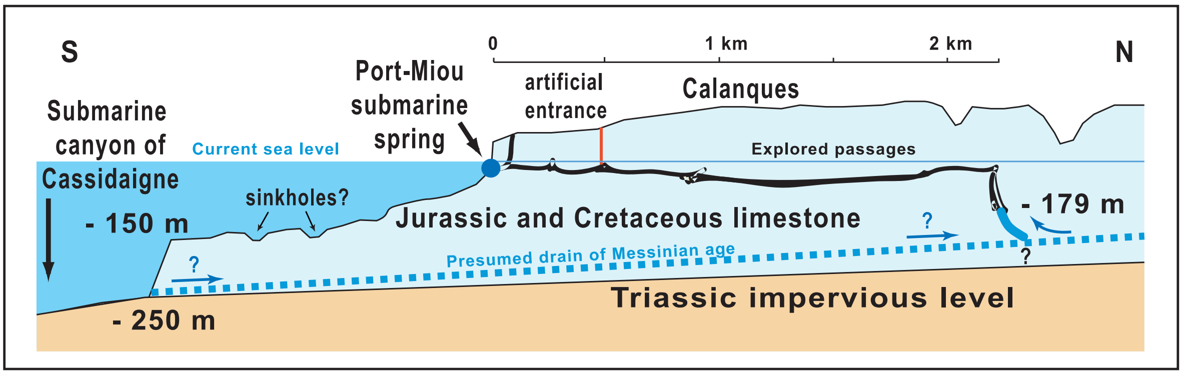

FIG. 2. – Port-Miou submarine spring. In the Messinian drain, opening offshore at the head of the Cassidaigne canyon, the water is blocked by the density of the salt water. The underground flow follows a phreatic lift connected to the submarine spring [Blavoux *et al*., 2004; survey after Douchet and Fage, 1993].
FIG. 2. – *Réseau de Port-Miou (Calanques de Cassis, Bouches du Rhône, France). Le réseau messinien est raccordé en profondeur à l'ancienne reculée du canyon de la Cassidaigne, actuellement ce réseau est bloqué par le barrage d'eau salée. Le drainage de l'eau douce est assuré par un conduit ascendant qui se raccorde à l'émergence littorale [Blavoux* et al., *2004 ; topographie d'après Douchet et Fage, 1993].*

past overflow route as a perennial spring. The lowest part of the karst is flooded to a great depth.

A similar evolution occurred upstream in the Rhône valley, at the Saint-Remèze Plateau (Ardèche), where the Goul du Pont and Goul de la Tannerie springs have been explored by scuba divers down to –220 m (figs. 1 and 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.

In the upper part of Ardèche canyon, 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 canyon. Above the resurgence are vertical series with phreatic features that 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 (fig. 4) [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 has been entirely exhumed by clearing away of the Pliocene filling: Foussoubie chimney-shafts became dry, 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 remain dry (Foussoubie type).

In turn, the chimney-shafts are interpreted as a record of the PAMS, which originates from a base-level rise.

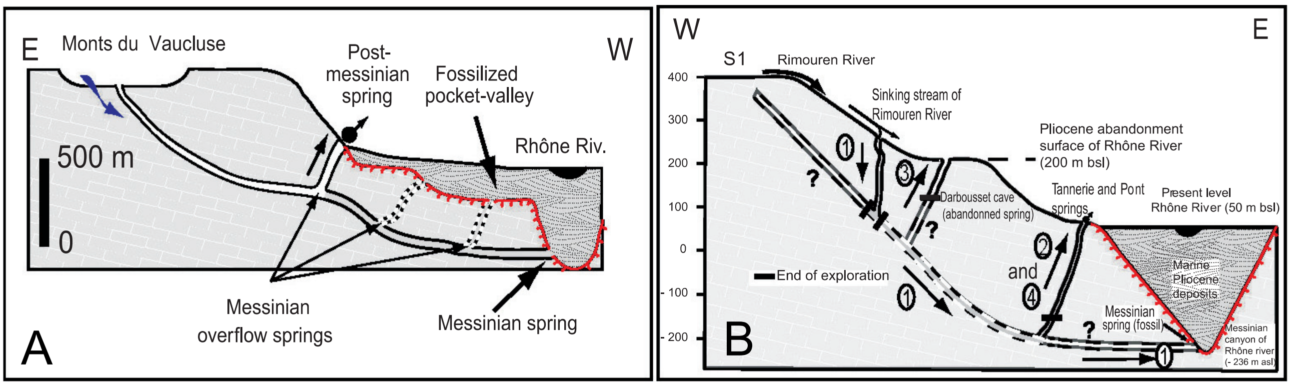

FIG. 3. – Speleogenetic model of the Vaucluse karst.
A : The Messinian canyon of the Rhône river is filled with Pliocene deposits. Its bottom is at 900 m below current sea level. The Messinian cave system, which was probably connected to this canyon, has been flooded and filled with sediment during the Pliocene. Since that time, the underground flow has used a chimney-shaft opening to the current base level at the Fontaine de Vaucluse.
B : Along the Rhône river, the Ardèche karst with the underground river of the Tourne system displays a similar structure.
FIG. 3. – *Modèle de spéléogenèse du karst de Vaucluse. Le canyon messinien du Rhône, à -900 m NGF est fossilisé par les dépôts pliocènes. Le réseau messinien profond qui s'y raccordait s'est trouvé ennoyé puis colmaté. Le drainage utilise actuellement un puits-cheminée débouchant au niveau de base actuel, la fontaine de Vaucluse.*

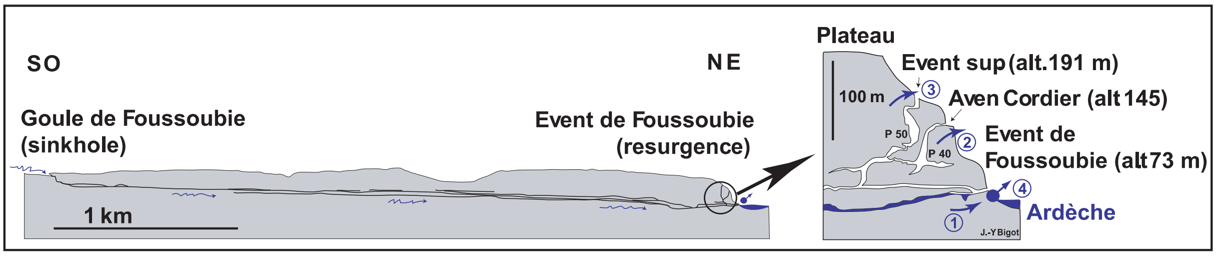

FIG. 4. – PAMS in the Foussoubie cave system, Ardèche. The phreatic lifts resurge at vauclusian springs connected to the higher base-level positions corresponding to the Pliocene filling. During the Pleistocene, the Messinian canyon was exhumed and cleared of its Pliocene fill down to its bottom. Current drainage reuses the deep Messinian drain. The Pliocene phreatic lifts are abandoned as fossil "chimney-shafts" [Bigot, 2002; Mocochain, 2007; Mocochain *et al.*, 2006a, b].

FIG. 4. – *Modèle de spéléogenèse du karst de l'Ardèche, exemple du système de Foussoubie. Le canyon messinien des gorges de l'Ardèche à 80 m NGF a été exhumé et vidé de ses dépôts pliocènes. Le réseau messinien profond, toujours utilisé par les écoulements torrentiels actuels, est complètement dénoyé. Les conduits ascendants, raccordés aux positions successives du remplissage pliocène, fonctionnaient alors en émergences vauclusiennes. Ils sont depuis abandonnés en puits-cheminées « fossiles » [Bigot, 2002 ; Mocochain, 2007 ; Mocochain* et al.*, 2006a, b].*

Consequently, a base-level rise is interpreted to be a founder speleogenetic event. Besides the Messinian-Pliocene eustatic cycle, other causes of base-level rise also produce *per ascensum* speleogenesis and the development of chimney-shafts (fig. 6).

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 (fig. 6) [Mocochain *et al.,* 2006a, b]. 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, 8).

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 geodynamic driving force could be eustatic (transgression), tectonic (subsidence) and climatic (clearing of slopes soils, glacial advance).

The Miocene eustatic cycles

In the Rhodanian-Provence foreland basin between the Fontaine de Vaucluse and the Rhône, the marine molasses record several eustatic cycles during the Miocene (Aquitanian, Burdigalian). The regression, which is linked with tectonic uplift, follows valley entrenchment up to 100 m deep, with eventual flooding and filling with sediments by transgressions [Besson, 2005; 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 molasses.

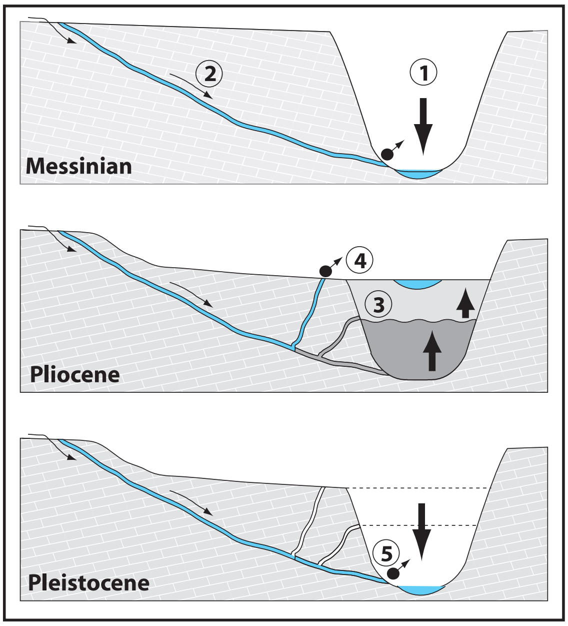

FIG. 5. – PAMS during the Messinian-Pliocene cycle. High: Messinian canyon entrenchment caused the deepening of karst drainage. Center: Pliocene base level rise occurred in two steps – by marine ingression as ria (dark gray), then by fluvial aggradation (light gray). Deep drainage uses phreatic lifts 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). Low: 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".

FIG. 5. – *Modèle général de spéléogenèse per ascensum lors du cycle messino-pliocène.*

Haut : le surcreusement du canyon messinien provoque un enfoncement du drainage karstique,

Milieu : la remontée du niveau de base au Pliocène s'effectue en deux temps ; par ingression marine en ria (gris foncé), puis par aggradation fluviatile (gris clair). Le drainage profond utilise des conduits ascendants noyés permettant aux eaux d'émarger par des sources vauclusiennes. L'étagement de ces sources marquent les positions successives de stationnement du niveau de base. Lorsque le canyon messinien est situé sous le niveau de base actuel, il demeure enfoui ; le karst reste noyé, il est alors drainé par une émergence vauclusienne.

Bas : Lorsque le canyon messinien est situé au-dessus du niveau de base actuel, il est exhumé et le karst est dénoyé. Le drainage actuel utilise le réseau profond messinien, les conduits ascendants pliocènes sont abandonnés en puits-cheminées « fossiles ».

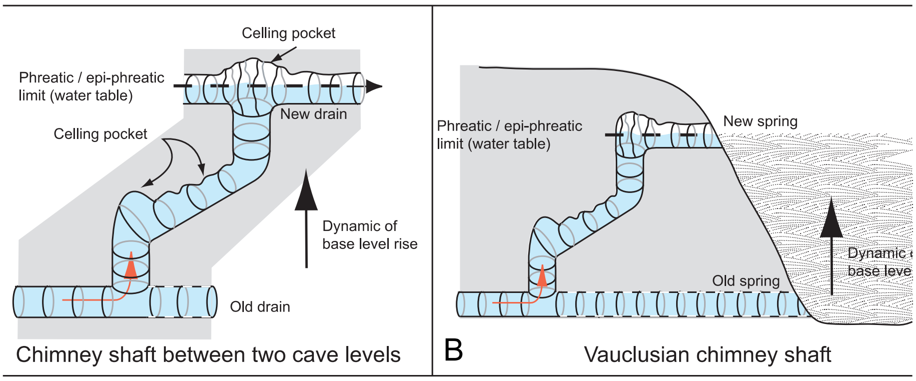

FIG. 6. – Two types of chimney-shafts.
A: Development of a chimney-shaft between two horizontal levels after a base level rise.
B: Development of a chimney-shaft making a vauclusian spring after a base level rise.
FIG. 6. – *Les deux types de puits-cheminées*
A*: développement d'un puits-cheminée entre deux niveaux horizontaux suite à une remontée du niveau de base,*
B*: développement d'un puits-cheminée de type source vauclusienne creusé sous l'impulsion d'une remontée du niveau de base. Dans cet exemple, il s'agit d'un comblement de vallée par aggradation alluviale.*

An earlier outflow should exist, buried beneath the molasses sediments [Parize *et al.,* 1997; Besson, 2005].

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 molasses; caves filled with molasses in Bohemian;

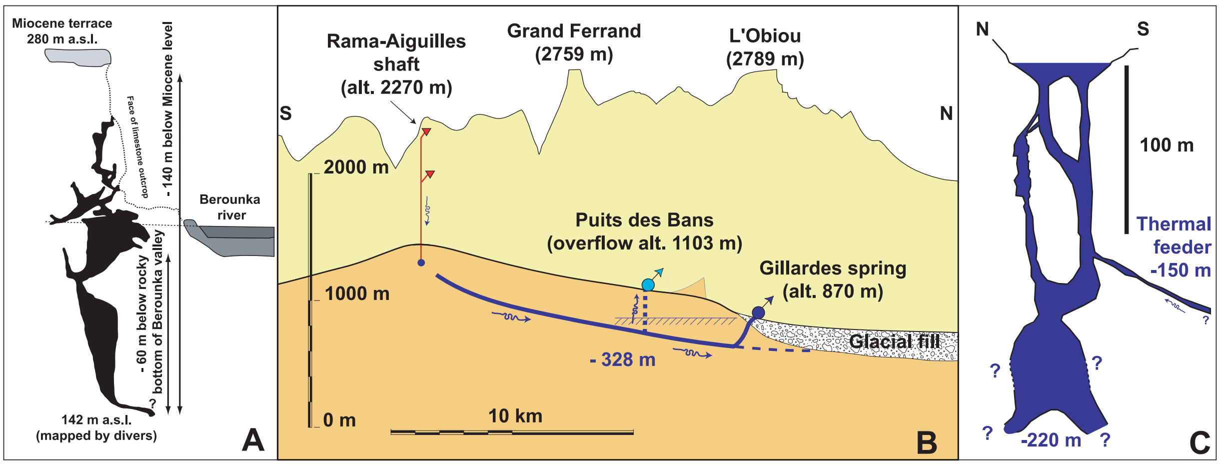

FIG. 7. – Three types of chimney-shafts development induced by different geodynamic context.
A: Podtrat'ová jeskyně, Moravian karst, Czech Republic, a 140 m high chimney-shaft, the lowest part of which is flooded below the Beroukna valley [Bruthans and Zeman, 2003]. It could show a record of the base-level rise of the hydrologic network after pre-Badenian entrenchment.
B: 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 300 m high chimney-shaft, floods and overflows.
C: Lagoa Misteriosa (Brazil), a 200 m deep phreatic shaft, a window in a karst aquifer flooded after the continent subsidence (survey by G. Menezes).
FIG. 7. – *Gauche : Podtrat'ová jeskyně (karst de Moravie, République Tchèque) : puits-cheminée de 140 m de hauteur dont 68 m noyés sous le niveau de la vallée de la Beroukna [Bruthans et Zeman, 2003]. Il s'agit d'un conduit creusé sous l'effet d'une remontée du niveau de base par aggradation alluviale faisant suite à un creusement profond de la vallée dès le Burdigalien.*
Milieu : Mise en place de puits-cheminées débouchant sur des émergences vauclusiennes sous l'effet de la remontée du niveau de base par colmatage fluvio-glaciaire des vallées ; le puits des Bans et les sources des Gillardes (Dévoluy, Hautes-Alpes et Isère). Le colmatage de la dépression du Trièves par des dépôts glaciaires et fluvio-glaciaires a bloqué l'émergence des Gillardes provoquant le fonctionnement du puits des Bans en émergence vauclusienne lorsque le réseau est en crue. Les eaux du réseau se déversent dans la vallée de la Souloise en empruntant un puits-cheminée de plus de 300 m de dénivellation. Actuellement, l'obstruction de la source des Gillardes par des dépôts de versant maintient le fonctionnement du puits des Bans en trop-plein occasionnel (schéma J.-Y. Bigot et Ph. Bertochio).
Droite : Lagoa Misteriosa (Brésil) : un puits noyé géant de plus de 200 m de profondeur. Il constitue un regard sur un karst ennoyé par la subsidence régionale (topographie G. Menezes).

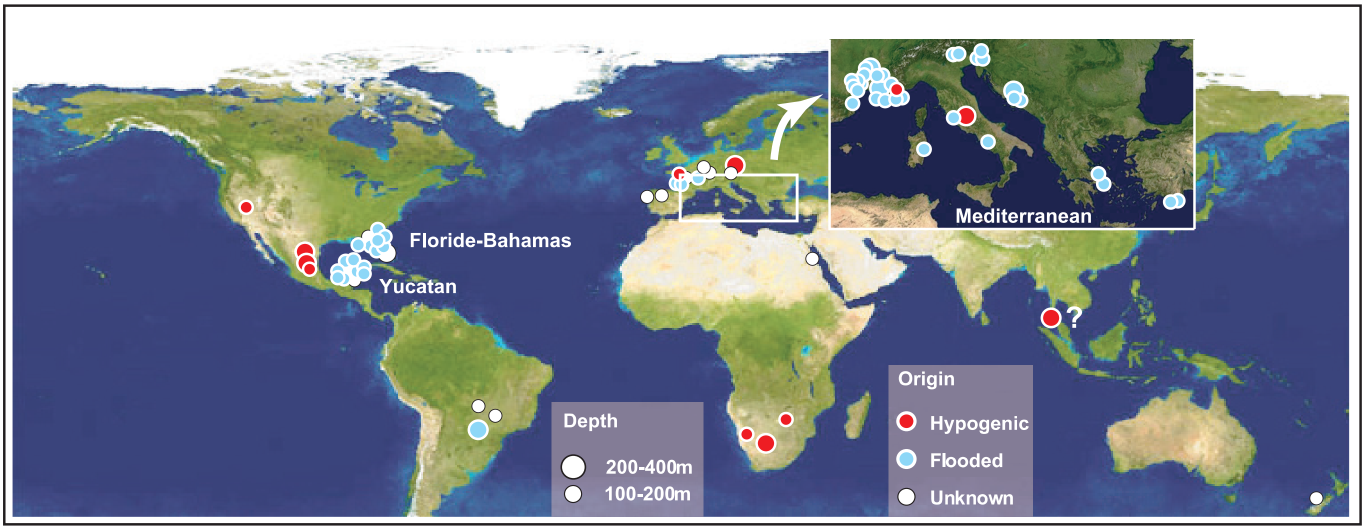

FIG. 8. – Distribution and origin of the deepest phreatic cave systems in the world.
FIG. 8. – *Répartition et typologie des karsts noyés profonds dans le monde.*

caves and fluviokarst morphologies in the Moravian karst [Kadlek *et al.,* 2001]. In the Bohemian karst, the Podtratová jeskyne (cave) is a chimney-shaft partly drained and more than 100 m deep (fig. 7). It is developed below the Beroukna valley, which was entrenched before the Burdigalian and then exhumed during the Pleistocene [Bruthans and Zeman, 2003, fig. 7]. 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.

Glacio-eustatic cycle

Post-glacial sea-level rises have flooded the coastal karsts (fig. 8), including the cave systems developed during previous low sea levels. It is evidenced by submerged speleothems, which have been observed down to –120 m, 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 and Lautridou, 2003].

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. 7).

Base-level rise after continental subsidence

In Brazil, the Lagoa Misteriosa is a deep-phreatic shaft explored to –220 m by scuba divers (fig. 7). Regional subsidence [Auler, 2009] can be considered a relative base-level rise that has flooded the karst.

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. 8). 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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