Relationships between fluvial evolution and karstification related to climatic, tectonic and eustatic forcing in temperate regions

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Abstract

This paper reviews the diversity of relationships between river evolution and karstogenesis. It also underlines the fundamental role of numerical dating methods (e.g. cosmogenic nuclides) applied to sedimentary sequences in tiered cave passages as they have provided new insights into these complex interactions. Although karst terrain is widespread worldwide, we focus on European karst catchments, where the sedimentary records are especially well preserved. We review the recent dating of fluvial sediments and speleothems, to examine the timing of karstification, incision and deposition in cave levels. The most complete alluvial records occur in tectonically uplifted high mountains where some of the oldest sediment fills date to the Miocene. Evidence indicates that not only uplift, but also climatic conditions and fluvial dynamics (e.g. knickpoint retreat, increased channel flow and/or sediment load, and stream piracies) can play a major role in speleogenesis and geomorphological evolution. In evaporite rocks, speleogenesis is characterized by rapid dissolution and subsidence. In European catchments, gypsum cave development largely occurred during cold climate periods, while limestone caves formed during warm interglacial or interstadial phases. Our synthesis is used to propose four models of fluvial and karst evolution, and highlight perspectives for further research.

Keys words: karst, speleogenesis, valley incision, aggradation, base level, cave level, phreatic cave, cosmogenic nuclide dating

1. Introduction: links between karst and fluvial systems

1.1. Conditions and processes of karstification

Karst terrain is characterised by underground drainage networks and (sub)surface features such as dolines, poljes, sinkholes, and caves (Palmer, 2007). It is typical of regions of limestone, evaporite and marble bedrock, but also develops in siliceous (sandstones and quartzites) and other metamorphic rocks (Ford & Williams, 1989; Bigot & Audra, 2010). According to Ford and Williams (1989), karst is globally present in all climate domains, but the widest areas of karstified terrain are in the limestone and evaporite regions of Europe and Asia (Figure 1). Karstification is the process of water infiltration and dissolution, mainly through chemical mechanisms, involving the presence of water and carbonic acid. This definition implies strong links between karst and fluvial activity, especially for epigenetic speleogenesis which involves the vertical organization of 'three karstic horizons' (Mangin, 1975; Audra & Palmer, 2013): the infiltration of water at the surface; the flow of water through karstified limestones or evaporites; and the emergence of water from karst conduits at the valley bottom (Ek, 1961; Delannoy, 1997; Audra, 2010, Figure 2A, 2B). Water flow, and resulting sediment transport, along the three 'karstic horizons' (Mangin, 1975) means that subaerial fluvial forms such as terraces, often contain only generalized records of palaeo-base and cave levels. Therefore, the core topic of this contribution focuses on the combined analysis of surface alluvial sequences and subterranean (endokarst) geomorphology and sediment fills, which produces more complete reconstructions of palaeofluvial activity in karst settings.

In karst regions, alluvium is often well-preserved in endokarstic cavities. The most distinctive endokarstic features are the horizontal tubes that form in the saturated zone: syngenetic and paragenetic galleries, the latter of which form upward to the water table (e.g. Ford & Williams, 1989; Quinif, 1989). These features correspond to periods of base level stability in the fluvial system. In contrast, meandering canyons and vadose shafts form in the unsaturated zone, and may be correlated to incision in the adjacent valleys (Audra & Palmer, 2011). The transition from phreatic to vadose conditions produces keyhole (T-form) features, and the reshaping of previously enlarged passages and narrow and deep underground canyons during river entrenchment phases.

In limestone karst, cave formation occurs due to the dissolution of bedrock by unsaturated water containing carbonic acid (from CO_2) (Palmer, 1991). The maximal denudation rates in the temperate zone occur in the wetter oceanic regions (even in wet subarctic areas), such as in Chilean Patagonia (100 mm/ka, Hobléa *et al.,* 2001) or in the Vercors, French subalpine chains (120-170 mm/ka, Delannoy, 1982), and primarily depend on the amount of precipitation (Palmer, 1991). Under interglacial and interstadial conditions, forest soils are well-developed, and these can be an especially aggressive dissolution agent (Ford & Williams, 1989; Quinif, 2006). White (1988) highlighted the existence of thresholds in the development of cave passages. First, a laminar flow regime produces micro-caves (diameter: 5-10 mm) during an initiation phase of 3-5 ka. Then, turbulent flow can shape 1-3 m conduits within a few thousand years during a phase of enlargement. In high alpine mountains, where high precipitation and acidic forest soils mean that cave development can be especially rapid, wide conduits (from 1 to 10 m) can appear in a few hundred years (Ford & Williams, 1989).

The propagation of groundwater through a karst system is largely determined by its structural framework (Ford & Williams, 1989). In limestone, only planes of penetrable fissures (e.g. bedding planes, stratification joints, faults) have sufficient permeability. In rocks with greater fracturation, permeability is higher due to decreased anisotropy (Bazalgette & Petit, 2005). For example, in folded rocks that have been subjected to tectonic stresses, fissure frequency and therefore permeability, is generally higher (Ford & Williams, 1989). Fissure frequency also increases over time, in relation to solvent water infiltration (Gabrovšek et *al.,* 2014) and rock decompression due to valley entrenchment. These structural controls on subterranean morphology also explain the existence of caves in non karstified areas: opened faults, underground collapse structures, or caves shaped in impervious rocks. For example, the Verna cave (Pyrenees, the biggest cave chamber in France), is mainly situated in Carboniferous sandstone and shales (Gilli, 2010). In general, geomorphological maps of karstified areas show parallel horizontal passages, aligned with the main regional fractures (Losson, 2003) and, sometimes, a gridded cave network of intersecting, fracture-controlled fissures (Palmer, 1991; Audra & Palmer, 2011). However, fluvial geometry can develop independently of structural controls, such as in the Eastern Paris Basin, where rivers are superimposed on the Mesozoic strata (Le Roux & Harmand, 1998, 2003).

1.2. Types of cave sedimentary fill

Cave deposits are highly variable in their origin and characteristics, and include allochthonous and autochthonous sediments which can be broadly categorized as coarse and fine-grained clastic sediments, and carbonate precipitates. The most common cave formations are the coarse clastic deposits of the entrance facies. In the glaciated parts of Europe and North America much of this clastic material is derived from glacial till and deglacial sediments (Granger *et al.,* 2001). In non–glaciated areas, clastic deposits are the result of bedrock breakdown and decompression close to the valley sides as well as cryoclastic processes at the cave entrance (Campy, 1982). Cryoclastic sediments can include palaeontological and/or archaeological remains, such as in the "Belle-Roche" cave, developed in the Carboniferous limestone of the Amblève valley (Ardenne massif, E. Belgium; Cordy *et al.,* 1993; Rixhon *et al.,* 2014). There, the archaeo-palaeotolongical layers overlie basal Amblève gravels, indicative of a palaeovalley floor position (Rixhon & Demoulin, 2010). The presence of such coarse sediments, deposited by high energy flows, generally indicate a period of enhanced fluvial activity in the cave environment (Ford & Williams, 1989).

Secondary carbonates are formed by the dissolution of calcium carbonate in the karst bedrock and its reprecipitation, producing features such as tufa, travertine, and speleothems (Couchoud, 2008). These precipitates develop in association with prevailing environmental conditions, and reflect changes in water percolation, evaporation and degassing. They can therefore provide valuable records of palaeoclimate, palaeoecology, and palaeogeomorphology – since tufa and travertine cap palaeoland surfaces. Moreover, they can be dated by radiocarbon (^{14}C) and Uranium-series (U-series) methods. Speleothems in particular can provide very high temporal resolution palaeoclimatic data due to their banded nature. Tufa and travertine *(sensu lato)* are more complex, and can form in multiple, superimposed horizons or tiered steps of different ages (Ford & Williams, 1989).

1.3. Markers of Pleistocene valleys evolution

Many studies have thoroughly discussed the relationships between karst terrain and catchment sediment flux, incision and aggradation (Benito *et al.,* 1998, 2010; Granger & Palmer, 2001; Jaillet *et al.,* 2004; Mocochain *et al.,* 2009; Audra & Palmer, 2011; Guifang *et al.,* 2011; Calvet *et al.,* 2015; Columbu *et al.,* 2015). During the Pleistocene, karst evolution was conditioned by climatically-driven cycles of river incision and aggradation, operating over 41 ka and 100 ka timescales (Bridgland & Westaway, 2007). In most cases, cave levels formed following entrenchment of rivers into limestone rocks, lowering the piezometric level. Incision into preexisting alluvium and the substratum occurred either during warm–cold (e.g. karst of N France; Antoine, 1994) or cold–warm transitional periods (e.g. British karst; Bridgland & Westaway, 2007; Lewin & Gibbard, 2010). Aggradation occurred chiefly during cold periods, characterised by massive deposition of gravel and sand,. Evidence of other cold climate indicators, such as ice-rafted blocks, ice wedges, and cryoturbation, have also been identified in karst alluvial sequences. River gravels at the valley bottom (e.g. Antoine *et al.,* 2006) or terraces (e.g. Bridgland *et al.,* 2009) are sometimes covered by interglacial or interstadial alluvial silt, soils, peat, and tufa.

Evidence of progressive stacking of alluvial sequences indicates the raising of cave level (Audra & Palmer, 2011), while fill-in-fill terraces imply a succession of lowering and raising of base and caves levels. At the valley scale, Pleistocene uplift generates tiered terraces provided that progressive vertical fluvial incision was accompanied by lateral erosion due to channel migration (Lewin & Gibbard, 2010). In karst areas where only few remnants of strath terraces are preserved along deeply-incised canyons, only infilled caves can be used to precisely reconstruct the evolution of Pleistocene valley entrenchment (Audra *et al.,* 2001).

In karstic fluvial settings, sediment sources, transportation and deposition characteristics vary in accordance with Quaternary environmental changes. On the one hand during glacial and periglacial periods, enhanced sediment mobilization means that clastic sediment can become trapped in caves and karst depressions (Audra *et al.,* 2001; Audra, Ed, 2010; Rixhon *et al.*, 2014; Calvet *et al.,* 2015). In areas covered by ice-sheets, sedimentation ceases. On the other hand, during interstadial, interglacial, and postglacial climates, tufa, travertine, and speleothems generally developed as a result of prolonged valley floor stability (Delannoy, 1997; Frank *et al.,* 2006; Limondin-Lozouet *et al.,* 2006; Couchoud, 2008).

Endokarstic alluvial deposits thus have the potential to offer a valuable record of Quaternary river system evolution. However, fragmentary nature of endokarstic deposits, and their integration with other sedimentary records over different timescales are two key issues that need to be addressed. Can endokarstic fluvial deposits be reliably integrated with other alluvial records to produce a model of Quaternary valley evolution? Can we combine records from fragmentary time slices into the same landscape evolution model (valley terraces, isolated endokarstic remnants, tiered passages in karst massifs)?

This paper presents a synthesis of recent research in European karst river systems (where appropriate, we also refer to well-studied non-European karst settings), developed within the modern temperate climate zone (Fig.1). It considers multiple spatial scales, from localized cave deposits to regional palaeoenvironmental reconstructions. It also discusses climatic, glacial, tectonic, isostatic, and eustatic forcing on karstogenesis (lowered sea level causes rejuvenation of karst processes, and subsequent raised sea level generates successive cave levels in systems fluvially linked to coastal locations), as well as the increasing application of dating methods on alluvial sediments in karst terrains, such as U-series, terrestrial cosmogenic nuclide (TCN) and ^{14}C. We establish a typology of the relationships between speleogenesis and fluvial incision/aggradation. Finally, we propose four conceptual models of karstic fluvial development based on the reviewed literature.

We examine their Quaternary development which is influenced by periglacial and glacial processes in mountain settings. In glaciated areas, fluvial discharge would have been directly linked to glacier mass balance (see 4.3). In periglacial settings, river flow regime would have been strongly influenced by precipitation and temperature variability.

2. Dating methods in karstic environments

Until the 1980s and 1990s, relative dating techniques (notably palynology and palaeomagnetism) were the primary methods used to estimate the age of fluvial deposits in karst terrain (Ford & Williams, 1989). Several numerical dating methods, such as thermoluminescence (TL, Huxtable and Aitken, 1991), uncalibrated radiocarbon (^{14}C, Bastin & Gewelt, 1986) and Uranium-series (U-series) in caves and river terrace calcrete were also used (Ambert & Ambert, 1995). Advances in numerical dating methods during the last two decades have allowed more robust chronologies to be developed (Couchoud, 2008; Richard *et al.,* 2015; Rixhon *et al.*, 2016). Calibrated radiocarbon ages (cal ^{14}C), optically stimulated luminescence (OSL, e. g. Vernet *et al.,* 2008), and electron spin resonance (ESR, e. g. Moreno *et al.,* 2012) techniques have become more widely applied. Terrestrial cosmogenic nuclide (TCN) dating of karst environments, especially burial dating, has also greatly enhanced the understanding of complex interactions between karst and fluvial systems (Granger *et al.,* 1997).

2.1. Numerical methods to date tufa, travertine and fluvial calcrete

Secondary carbonates, such as tufa, travertine, calcrete and speleothem, have been widely used to date landscape change in karst environments, most commonly using U-series methods (^{230}Th/U, ^{231}Pa/^{238}U, ^{234}U/^{238}U, ^{206}Pb/^{238} U). At Pierre-la-Treiche, located along the entrenched Mosel valley into the Bajocian limestones (NE France), U-series ages of speleothems in fossil caves indicated that their growth was correlated to marine isotope stage (MIS) 6.5, 5.3, 3.3, 3.1, and 1 (Losson *et al.,* 2006). The U-series ages were used to identify several abrupt warming phases during MIS 3 - a cold period recorded in the Greenland ice cores and in the Grande Pile peat record from the Southern Vosges mountains, NE France (Pons-Branchu *et al.,* 2010). U-series analysis of pedogenic and groundwater calcrete horizons has also been used to constrain the timing of fluvial aggradation in karst settings such as the Sorbas basin of SE Spain (Candy *et al.,* 2015) and the limestone Orjen massif, western Montenegro (Adamson *et al.,* 2014), respectively.

A chronology based on multiple dating methods allows us to rigorously examine the relationships between fluvial evolution and karstification, where tiered travertine steps increase coherently with terrace age, or if there is a more complex terracing history involving cut-and-fil terraces, for example. A good example is the Tarn valley, near Millau (S France), where the dating framework has been a matter of debate (Ambert & Ambert, 1995). Based on the presumed ages of the travertine steps, the rate of incision of the Tarn Canyon was thought to be very low. However, recent OSL dating as well as palaeoecological and palaeontological analyses showed that the majority of travertine steps (Peyre) formed during MIS 5e-5b (Vernet *et al.,* 2008). This indicates that the incision rate in the Tarn valley has reached >30 cm/ka since the deposition of the ~75 ka-old terrace 3 (MIS 5b-5a), located 25 m above the valley floor. Secondary carbonate-based chronologies can be used alongside stable oxygen (δ^{18}O) and carbon (δ^{13}C) isotope ratio analysis to provide a record of interglacial climatic changes (Dabkowski *et al.,* 2011, 2016), such as interglacial tufas in France (e.g. La-Celle-sur-Seine, Paris Region: MIS 11 and Caours, Somme Basin: MIS 5e) and pedogenic calcretes in Southeast Spain (Adamson *et al.,* 2015; Gázquez *et al.,* 2016).

2.2. $^{26}Al/^{10}Be$ burial dating of cave-deposited alluvium

Burial dating is based on the differential decay of at least two cosmogenic nuclides (Granger and Muzikar, 2001). Amongst them, the pair $^{26}Al/^{10}Be$ is very well suited because: 1) both nuclides are produced in quartz, 2) their production ratio is fundamentally independent of latitude and altitude, and 3) it varies only slightly with depth (Dunai, 2010). Burial dating is useful in those settings where previously exposed quartz-bearing material (i.e. for $^{26}Al/^{10}Be$) becomes shielded from cosmic rays. Two basic assumptions must be fulfilled for a fast and complete burial (Granger and Muzikar, 2001). First, the time span over which incomplete shielding occurs is much shorter than the subsequent burial duration. Second, shielded sediments are buried deeply enough, i.e. in practice ≥30 m (rock equivalent mass), implying an insignificant production through muons at depth. We refer to the comprehensive works of Granger and Muzikar (2001), Dunai (2010) and Granger (2014) for further information about the basic principles of burial dating, including mathematical developments.

In the fluvio-karstic context, the burial event is achieved when river sediments, formerly exposed to cosmic rays at the Earth surface during hillslope denudation and fluvial transport, are washed into an underground system. The two aforementioned prerequisites are frequently met for in-cave deposited alluvium; the study of Granger *et al.* (2001) in Mammoth cave (i.e. the longest cave system known in the world, developed in Mississipian limestones in the Kentucky Appalachian Plateau) is one of the first successful applications of burial dating to such sediments. Since then, quartz-bearing material deposited into different multi-level cave systems by streams or rivers flowing into the sub-surface has been dated in a range of tectonically-active (e.g. Stock *et al.,* 2004) or moderately-uplifted (e.g. Anthony and Granger, 2007) settings. Inferring long-term river incision rates in these environments relies on the key assumption that the alluvium deposited in a horizontal, hydrologically abandoned, phreatic tube represents the last time the passage was at the local water table (Anthony and Granger, 2007). The selection of suitable sampling sites should ensure that abandoned and alluvium-filled phreatic tubes were not contaminated by any reworked material from an older (or younger) depositional episode (Dunai, 2010). It is therefore recommended to sample sediment layers displaying fluvial features or structures (Anthony and Granger, 2007) and/or where other material allows a cross-check with an independent dating method (e.g. U-series dating of a speleothem/flowstone sealing the fluvial sequence; Stock *et al.,* 2005).

In Europe, this approach, sometimes used in combination with paleomagnetism and U-series dating, was mostly applied to cave systems of mountainous environments: both in the Eastern (Wagner *et al.,* 2010; Häuselmann *et al.,* 2015) and the Western Alps (Häuselmann *et al.,* 2007; Hobléa *et al.,* 2011), and in the Pyrenees (Calvet *et al.,* 2015). Three case studies exemplify the value of burial dating of in-cave deposited alluvium to unravel long-term landscape evolution in diverse karstic environments (Fig. 2). First, the Têt valley (Eastern Pyrennées, France) shows nine karst levels, between 1400 to 400 m a.s.l., along its epigenetic fluvial gorge cut into the Devonian limestones of Villefranche de Conflent, with caves filled by sand and siliceous pebbles (Calvet *et al.,* 2015). Level 5 was dated from the lower Pliocene and level 3 from the Early Pleistocene, allowing an estimate of an incision rate of ~52 m/Ma, with a clear acceleration to 90 m/Ma for the last Ma. Level 3 is clearly linked to the upper terrace of the Têt valley and all the lower cave levels and sublevels strongly correlate to the younger terrace levels. Second, burial ages from different speleogenetic levels of the Siebenhengste-Hohgant cave system (Aare catchment, Switzerland) revealed a remarkable increase of glacial valley lowering since the beginning of the Middle Pleistocene, which substantially postdates the onset of glaciation in this region (Häuselmann *et al.,* 2007). This might be related to a considerable lowering of the equilibrium line altitude and the transgression of threshold conditions beyond which increase in glacial downcutting rates becomes nonlinear (Brocklehurst and Whipple, 2004). Third, burial ages coupled with magnetostratigraphy in multi-level cave systems along the Ardèche valley indicated a stepwise karst genesis during the Plio-Pleistocene, consistent with the *per ascensum* model of Mocochain *et al.* (2009), after the Messinian salinity crisis (Tassy *et al.,* 2013) especially, during the rise of sea level in the Lower Pliocene. These data also highlighted an uplift rate of ~30 mm/ka since 1.8 Ma in the lower Ardèche area.

2.3. Strengths and weaknesses of dating methods

Each numerical dating technique has an upper age limit (e.g. U-series: c. 350 ka; OSL: c. 150-200 ka; $^{26}Al/^{10}Be$ burial dating: c. 5.5 Ma) and associated analytical uncertainties. Ages obtained from adjacent karstic areas, or even within the same valley, can vary considerably. For example, in the Sierra of Atapuerca and the Arlanzón Valley (Moreno *et al.,* 2012) and in the upper Mosel catchment (Harmand & Cordier, 2012), TL, IRSL, ESR and U-series ages provided divergent results. In such instances, different ages may reliably represent spatial variations in uplift rates, river incision and karstification. However, it must be borne in mind that these dating methods provide age information about different processes of landscape evolution. Whereas burial ages give constraints about the last time the phreatic passage was at the local water table, U-series ages date the timing of calcite formation and thereby provide minimum ages of sediment deposition. A clear understanding of the chronostratigraphic framework is therefore essential. Detailed geochronological studies, using multiple dating methods, are required to reliably quantify rates of incision and karstification.

3. Approaches for examining drainage evolution in karstic terrains

The relationship between valley incision and karstification are summarized in Figure 3. Much research has focused on the impacts of valley entrenchment on karst development, which can in turn provide important insights into fluvial evolution. However, karst development can occur independently of valley evolution, especially when dealing with the ghost-rock process (i.e. rock transformation by self-volume chemical dissolution; Vergari & Quinif, 1997) or hypogene karstification (i.e. dissolution and crystallization along ascending, often hydrothermal, flows; Hill, 1987). A number of studies have highlighted the influence of karst terrain on valley incision (Figure 3).

Analysis of the relationship between fluvial evolution and karstification requires a multiscale approach, evolving from the valley bottom to the karst, and from the karst to the valley. This review proposes a typology of relationships between karst and valley, depending on morphostructural framework, lithology, base level change, and climatic fluctuations (emphasizing the role of glaciers).

3.1. From the valley bottom to the karst: relationships between karst cave level and valley base level

Many studies have highlighted the relationships between base level or cave level and the regional evolution of river systems controlled by climatic, tectonic and/or eustatic forcing (Ambert & Ambert, 1995; Jaillet, 2000; Audra *et al.,* 2001; Losson, 2003; Harmand *et al.,* 2004; Wang *et al.,* 2004; Mocochain *et al.,* 2009; Guifang *et al.,* 2011; Ortega *et al.,* 2013; Tassy *et al.,* 2013). As a result, it is well-established that karstic levels can provide valuable altitudinal markers, or 'dip sticks' for river incision. This is especially effective in mountain massifs where local relief can exceed several kilometers, and multiple cave levels exist, therefore providing long-term records of fluvial evolution since the Plio-Pleistocene.

Karst plays a major role in the formation and preservation of the fluvial sedimentary record. Where alluvial sediments accumulated in karst depressions, they became more immune to subsequent erosion and reworking (Delannoy, 1997; Audra *et al.,* 2001). Ancient alluvium is reported to have been preserved within karst settings since the Early Pleistocene (Wagner *et al.,* 2010; Adamson *et al.,* 2014; 2016); the Neogene (Hobléa *et al.,* 2011; Calvet *et al.,* 2015), the Paleogene (Bruxelles *et al.,* 2013) and even the Mesozoic (Vergari & Quinif, 1997), Palaeozoic (Osborne, 2007) and Precambrian (Buffard & Fischer, 1993). The excellent preservation potential of these records means that they are valuable archives of landscape change. This is especially the case where palaeovalleys or alluvial terraces are not well-preserved at the surface, when karstic cavities are disconnected from adjacent valleys, due to headward erosion (Enjalbert, 1967*, in* Nicod, 2010); or when there have been changes to drainage patterns (Adamson *et al.,* 2014). However, correlations between cave deposits and valley fills at the surface are sometimes difficult when karstic sediments are present only in isolated fragments, due to erosion and reworking of the exposed sediments (Quinif & Maire, 1998).

3.2. From the karst to the valley: Base level controls on the geometrical organization of karst drainage networks

Assuming that initial cave development occurs along the water table, Ford and Ewers (1978) proposed a conceptual framework called the "four-state model". In this model, different types of caves evolve depending on increasing fissure frequency through time: 1) bathyphreatic caves, with a few deep phreatic loops (Figure 2B.a, c, d); 2) phreatic caves with multiple and shallower loops (Audra & Palmer, 2011); 3) caves with a mixture of phreatic and water table-levelled components; and 4) an idealised water table cave without loops, formed as a result of high fissure frequency. The four-state model has been reinterpreted by Häuselmann (2002), Audra & Palmer (2011) and Gabrovšek *et al.* (2014) who pointed out two main controls in relation to valley incision: 1) The recharge control occurs in dammed aquifers, when recharge is fairly regular. Thus, the main endokarstic drain is established at the water table at the same altitude as the valley bottom (Figure 2B.b). When an irregular recharge occurs, looping tubes develop throughout the epiphreatic zone (Figure 2B.a). 2) The base-level control corresponds to the development of perched cave levels. Base level lowering is common in most temperate climate karstic areas, especially mountainous regions, due to uplift of the continental crust and associated river incision (Figure 2A, Fig. 2B.c). In contrast, base-level rise produces flooded cave levels and Vauclusian springs, when water ascends (Figure 2B.c). Deep-phreatic cave systems, for instance, are located around the Mediterranean Sea, as a result of the Messinian marine regression and near instantaneous Pliocene flooding (Mocochain *et al.,* 2009).

3.3. A multi-scale approach

To effectively capture the complexity of karst evolution, and securely identify the relationships between fluvial activity and karstification, multi-scale analysis should be used to combine large-scale studies of karstified massifs and entrenched valleys, and local-scale analysis of individual karst drains and sediment fills. In valleys entrenched up to several hundred meters deep, numerous studies (Webb *et al.,* 1992; Audra *et al.,* 2001; Losson *et al.,* 2006; Guifang *et al.,* 2011; Rixhon *et al.,* 2014) have highlighted the altitudinal relationship between karstic passages and stepped terraces (Figure 2A). At the valley scale, establishing the elevation of alluvial terraces and karstic drains to within a few metres is sufficient for reliable geomorphological reconstructions. For example, in the Sierra de Atapuerca and the Arlanzón valley (Iberian Chain, Eastern Burgos, Spain), geomorphological analysis was combined with archaeology, palaeomagnetics, TL, IRSL, U-series and ESR dating to develop a chronostratigraphical framework of fluvial incision and speleogenesis of karst caves during the Lower and Middle Pleistocene (Moreno *et al.,* 2012; Ortega *et al.,* 2013).

At even larger spatial scales, across the Mediterranean basin for example, karstic and palaeovalley features suggest a common regional pattern of geomorphological evolution. At the Mediterranean coast, such as the South-East of France, Messinian canyons and Pliocene rias, among other features, demonstrate that sea level change has had a major influence on karstification (Audra *et al.,* 2004). Late Miocene base-level fall was followed by rising base-level in the Pliocene, which flooded lower endokarstic levels, and karst waters discharged as Vauclusian springs. In this system, higher elevation karst horizons are more recent forms, as indicated by *per ascensum* speleogenesis.

At smaller spatial scales, in individual caves or valleys, high-resolution analysis is essential when caves are disconnected from neighbouring valleys – due to erosion of the limestone valley sides or of terrace remains. For example, in the Pierre-Saint-Martin cave, Pleistocene deposits of the Aranzadi gallery recorded a succession of depositional and entrenchment phases (Quinif & Maire, 1998). Three groups of speleothems situated between the detrital units highlighted the succession of several interglacial or interstadial stages allowing the precipitation of carbonate. U-series dating showed that speleothem growth occurred during MIS 9, 7 and earlyMIS 6. In the Têt river basin, recent research has provided precise correlations between aggradation and incision phases in each glacial cycle (Hez *et al.,* 2015; see section 5 for discussion).

4. A typology of the relationship between fluvial evolution and karstification

As outlined above, fluvial incision and karstification in limestones or evaporite rocks are driven by a number of factors. The most central are: eustasy, isostasy, climate and tectonics. Here we discuss the relationships between valley evolution and speleogenesis using examples from across Europe, as well as key studies in Australia, North America, and the Tibetan Plateau. Four models of valley evolution and karstification are proposed.

4.1. Karstification in association with base and cave level lowering

A number of karst systems have horizontal tubes and vertical conduits which reflect stability and incision in the neighbouring valleys, respectively. These valleys often contain stepped alluvial terraces associated with aggradation/incision cycles. Generally, epigenetic speleogenesis of limestone massifs and the succession of valley incision and aggradation are largely associated with strong isostatic or tectonic uplift. Climatic forcings have also played a key role, especially at the onset of the Quaternary, and during the Mid-Pleistocene Revolution at the onset of the 100 ka Milankovitch cycles (Bridgland *et al.,* 2009). Four types of geomorphological evolution are distinguished in the following discussion, based on the relief energy/topography of the karstified region.

4.1.1. Karstification in low elevation and very stable cratonic area

The Devonian limestone region of Buchan (South-East Australia) is a valuable example of slow, long-term incision and speleogenesis. Three fluvial terraces and epiphreatic cave levels have developed below a height of 30 m above the adjacent river (Webb *et al.,* 1992). Geomorphological evidence and palaeomagnetic dating indicate that these formed before 780 ka, giving a maximum incision rate of 38.5 mm/ka. The Buchan area has experienced only 4-5 m incision over the last 40 Ma (i.e. 0.1–0.125 mm/ka), 2-3 m of this has occurred over the last 730 ka (i.e. 2.7–4.1 mm/ka).

4.1.2. Karstification on low altitude plateaus (<500 m a.s.l.)

4.1.2.1. General cases

There are many examples of epigenetic speleogenesis and fluvial incision as a result of moderate (up to 10 mm/ka) uplift in cratonic areas, sedimentary basins, and low-altitude (<500 m-a.s.l.) basement plateaus, such as in the Paris, Aquitaine basins (Bridgland *et al.,* 2009; see *in* Audra, Ed., 2010) or British karst (Waltham *et al.,* 1997). In North America, the karst evolution of the Kentucky Appalachian Plateau has been dated in detail using TCN ages (Granger *et al.,* 2001). These karstic areas broadly correspond to one of two morphostructural settings. 1) Extended horizontal or monoclinal strata of Palaeozoic age (e.g. the Kentucky Plateau, USA: Granger *et al.,* 2001), Mesozoic or Cenozoic karstified rocks (e.g. in the plateaus of the Eastern Paris Basin, France; Jaillet, 2000; Losson, 2003; Devos *et al.,* 2007). 2) Folded strata in Alpine or older (e.g. Appalachian) structures. In most cases the caves are located in narrow outcrops of limestone, such as the Devonian and Carboniferous rocks of the Ardenne massif, Belgium (Quinif, 1999, 2006).

There have been several studies of Pleistocene sedimentary sequences from caves and river terraces formed on low-level plateaus (Losson, 2003; Jaillet *et al.,* 2004). These studies show that Pleistocene incision rates were low, and reached up to 100 mm/ka in the Mosel catchment (Harmand and Cordier, 2012). On low-elevation karst plateau, there is evidence for Quaternary rejuvenation of older palaeo-karsts or crypto-karsts, such as the Belgian Ardenne, Eastern Paris Basin, and Quercy plateaus (Bruxelles *et al.,* 2013; Vergari and Quinif, 1997; Harmand *et al.,* 2004). At Poissons (Eastern Paris Basin, France), Pleistocene incision of the upper Marne reached 42 mm/ka to 58 mm/ka, and extended below the base of the palaeokarstic wells, which were filled with continental Infra-Cretaceous (Wealdian) ferruginous deposits (Harmand *et al.,* 2004). However, the presence of Late Pleistocene fauna and MIS 6 speleothems in the sediment fill (Jaillet, 2000) was indicative of a Quaternary karstification of the older palaeo-karsts.

4.1.2.2. The relations between rivers, aquifers and karst in the Eastern Paris basin

In the Eastern Paris Basin, epigenetic speleogenesis and fluvial incision is linked to the structural framework of the basin and entrenchment of the main valley into the alternating marl and limestone strata (Losson, 2003; Devos *et al.,* 2009, 2015). The main feature is the position of the river with regard to the water table. Four situations can be distinguished (Figure 4A). 1) When perched rivers are entrenched into limestone above the saturated zone, infiltration occurs into and under the valley from local or allochtonous flows (Jaillet, 2000; Losson, 2003; Devos *et al.,* 2009, 2015; Figure 4A level a). 2) When the surface river channel is in contact with the water table of the saturated zone, the lack of hydraulic gradient induces a ghost rock process around the fractures of the valley floor (Quinif, 2010, Devos *et al.,* 2011; Figure.4A level b). In contrast, lowering of the piezometric level, due to fluvial incision, causes the discharge of residual deposits of the ghost rocks and the creation of conduits in the epiphreatic zone. 3) When the surface river channel is strongly entrenched into the limestone substratum, and drains the flooded karst zone, a thin piezometric horizon develops (Figure 4A level c). 4) If fluvial incision occurs in the marls or clays situated below the saturated zone, the perched karstified zone is disconnected from the river (Figure 4A level d) and the flooded zone drains into low flow springs (Devos *et al.,* 2015). However, as shown in Figure 4B, it is important to remember that the faulted tectonic basement can produce structural and aquifer compartments which control the hydraulic gradient between aquifers and rivers (Devos *et al.,* 2007).This can have major impacts on the hydrological and geomorphological connectivity, between karst and subaerial fluvial drainage networks.

4.1.3. Relationships between fluvial incision/aggradation and karstification on high altitude plateaus and low mountain ranges (500 – 2,000 a.s.l.)

In low mountain ranges and high plateaus, a moderate uplift rate (up to 100-200 mm/ka) commonly causes deep fluvial incision and epigenetic speleogenesis in thick limestone strata. On some high plateaus, geomorphological processes have continuously shaped the landscape since the Neogene. In the Southern part of the Causse of Larzac, four stages of speleogenesis were identified from the Middle Miocene until the Pliocene (Camus, 1997, 2010). Even during the Pleistocene, there is evidence of phases of incision and karstification in many regions, such as the Sierra de Atapuerca and the Arlanzón valley (Moreno *et al.,* 2012; Ortega *et al.,* 2013), the Languedocian plateaus (Audra *et al.,* 2001) or the Swabian Alb (Abel *et al.,* 2002). These speleogenetic phases occurred in response to base-level and cave-level lowering, due to tectonic uplift and glacially-driven sea level change. During Pleistocene glacial stages, sea level fell by up to 140 m below modern levels (Rohling *et al.,* 2009). In some settings, such as the Arlanzón and Ardèche valleys, incision has reached over 100 m deep since the Lower Pleistocene. The number of terrace levels varies between the narrow middle Ardèche valley (4) and the wide Arlanzón valley (14), but the karstified massifs exhibit only 2 or 3 cave levels, respectively (Audra *et al.,* 2001; Moreno *et al.,* 2012; Ortega *et al.,* 2013).

4.1.4. Long-term records of fluvial incision and karstification in high mountain regions (>2,000 m a.s.l.)

Many high altitude limestone mountains contain horizontal cave networks at elevations exceeding 2,000 m a.s.l. (Feichtnerschacht, Austrian Alps: 2,000 m; French subalpine chains: 2,300 m; Dolomites, northeastern Italy: 2,775 m; Siebenhengste-Hohgant-Höhle, Berner Oberland, Switzerland >2,000 m; Häuselmann and Granger, 2005; Audra *et al.,* 2007; Wagner *et al.*, 2010, Hoblea *et al.*, 2011; Figure 5A). Many of these mountains contain thick horizons of karstified rock that extend vertically for up to 1 km, and are characterized by cave to rock ratios as high as 1.3 m^3 per 1000 m^3. Some high mountains also contain long karstic cavities (up to 90 km in the Granier massif, Grande Chartreuse, France, Hoblea *et al.,* 2011) and many cave levels (9 in the Têt catchment; 14 in the Siebenhengste; Calvet *et al.,* 2015; Häuselmann, 2002). These stacked caves indicate numerous speleogenetic phases and strong uplift trends. Where these endokarstic galleries contain alluvial sedimentary sequences, they have the potential to record long-term fluvial evolution. Key examples include the European Alps (Styrian Alps: Wagner *et al.,* 2010; Grande Chartreuse massif: Hoblea *et al.* 2011), the Alpi Apuane, Italy (Piccini *et al.,* 2011), the Sierra Nevada, California (Stock *et al.,* 2004, 2005), and the Hengduan Shan, Tibet (McPhillips *et al.,* 2016).

In the Alps and Pyrenees, TCN burial dating of sediment infills from the highest cave levels frequently yielded Pliocene ages (Häuselmann and Granger, 2005; Wagner *et al.,* 2010; Hoblea *et al.,* 2011; Calvet *et al.,* 2015). The same method, based on the ^{10}Be and ^{21}Ne isotope pair, revealed a Lower Miocene karstification age at the Southeast margin of the Tibetan Plateau at the First Bend (McPhillips *et al.,* 2016). Valley incision and karstification continued during the Quaternary period in European karst regions (Häuselmann and Granger, 2005; Wagner *et al.,* 2010; Calvet *et al.,* 2015), and in China (Qinling: Wang *et al.,* 2004; Northwestern Hunan: Guifang *et al.,* 2011; Guizhou plateau: Liu *et al.,* 2013).

Many high altitude karstified massifs, including the limestone mountains of Europe (e.g. Hughes *et al.,* 2010) and North America (Palmer and Palmer, 1993), were glaciated during Pleistocene cold stages, including MIS 12, 6, and the Younger Dryas. As a result, they evolved into a distinctive 'glaciokarst' landscape (See section 4.3).

4.2. Karstification in association with rising base and cave level

The *per ascensum* model of speleogenesis is initiated by eustasy and climatically-driven aggradation and subsidence (Audra *et al.,* 2001; Figure 5B). The influence of eustatic base level does not typically extend more than 200 km inland (Antoine *et al.,* 2000). In Europe, one of the most significant examples of rising base level and its impacts on terrestrial landscape change is the Pliocene transgression after the Messinian regression of the Mediterranean basin (e.g. Clauzon, 1978; Audra *et al.,* 2004).

The Languedocian plateaus, incised by the Lower Ardèche canyon (at Saint-Remèze), present a record of rising base and cave level since the Messinian. TCN dating combined with magnetostratigraphy revealed that, following an early phase of karstification during the Messinian regression, subsequent phases of speleogenesis took place during marine and continental aggradation in the Pliocene rias (Mocochain *et al.,* 2009; Tassy *et al.,* 2013, 2014). Rising base level caused flooding of the lower cave levels, which discharged as Vauclusian springs. Pleistocene valley incision led to the progressive draining of horizons situated above base level and the reactivation of caves at the same altitude as the river.

Other cases of base and cave level fluctuations follow a similar evolutionary model (Bruthans and Zeman, 2003; Audra and Palmer, 2011). Several cases of *per ascensum* speleogenesis by fluvial (or glacial) aggradation occur in Europe, including Podtraťová jeskyně in the Moravian karst (Czech Republic, Bruthans and Zeman, 2003) and in the Devoluy mountains, France (Audra & Palmer, 2011). In the Devoluy chain, the Pleistocene glacial, lacustrine, and glaciofluvial sediment fill increased the elevation of the Gillardes karst springs, and caused the 300 m high chimney shaft at Puits de Bans to overflow.

4.3. Pleistocene incision and karstification in association with glaciation

Broadly, there are three mechanisms through which Pleistocene glacial activity influenced karst areas. First, in non-glaciated mountains or plateaus areas, incision and karstification were indirectly conditioned by glacial activity, such as the Kentucky Appalachian Plateau (Palmer and Palmer, 1993). Second, in glaciated mountain regions, such as parts of the Dinaric Alps in Montenegro (Hughes *et al.,* 2010; 2011; Adamson *et al.,* 2014), and the Pindus mountains in Greece (Hughes *et al.,* 2006; Woodward *et al.,* 2008), fluvial evolution and karstification were directly influenced by glaciers. Third, some karst areas were covered by ice sheets up to 3 km thick that developed across much of Northern Eurasia (Eurasian Ice Sheet) and North America (Laurentide Ice Sheet) during Pleistocene glacial phases. The erosional effects of the ice sheets on karst and non-karst landforms and deglacial speleogenesis, are beyond the scope of this paper, which concentrates on karst geomorphology south of the major ice-sheets, and downstream of ice caps and valley glaciers (mechanisms one and two outlined above).

4.3.1. Indirect impacts of glaciation: the Appalachian plateau of Kentucky, USA

The Kentucky Appalachian Plateau (c. 2,000 m a.s.l.) is a vast karstified area that contains an extensive sinkhole plain (Pennyroyal Plateau) and the Mammoth Cave Plateau where the famous cave provides a well-preserved example of the indirect influence of glaciers on Plio-Quaternary morphologic evolution (Palmer and Palmer, 1993). TCN (^{26}Al and ^{10}Be) dating of sediments in the five levels of Mammoth Cave, as well as vertical vadose passages, is in accordance with the timing of Pliocene and Pleistocene glaciations of North America (Granger *et al.,* 2001). Major aggradational phases occurred at c. 3.2, 2.3 and 0.8 Ma, when large volumes of sediment would have been produced by the ice sheet and delivered downstream via meltwater channels. A major incision phase occurred at c. 1.39 Ma in relation to a drainage change towards the Mississipi catchment when the Ohio river formed along the Southern North-American ice-sheet margin.

4.3.2. Direct impacts of glaciation: Glaciated limestone mountains: examples from the Dinaric Alps

Limestone mountains that were glaciated by ice caps or valley glaciers during Pleistocene cold stages, such as the Dinaric Alps, are characterized by a distinctive ‘glaciokarst’ terrain, which displays features including limestone pavements and bare bedrock surfaces. The presence of glaciers in karst environments can have major impacts on glaciofluvial drainage pathways, and subsequent karst drainage evolution. On the Orjen massif in western Montenegro, a large ice cap developed during the Pleistocene (MIS 12, 6, 5d-2 and the Younger Dryas, Hughes *et al.,* 2010). The configuration of the Orjen massif, with its high altitude (c. 1,800 m a.s.l.) ice accumulation zone, and surrounding depocentres (such as valleys, poljes and dolines), meant that during the major ice advance of MIS 12, ice extended over the plateau, and likely plugged the surface of karst depressions and conduits. Meltwater was delivered directly downstream and largely flowed at the land surface. This is evidenced by the presence of large volumes of glaciofluvial sediments that have been deposited and preserved in large poljes, as terraced valley fills, and as alluvial fans at the margins of the plateau (Adamson *et al.,* 2014; 2016a). One of these alluvial fans, the Lipci fan, extends offshore into the Bay of Kotor. It was deposited subaerially at the southern margins of the Orjen massif during the major glacial phase of MIS 12, when sea level in this part of the Mediterranean was up to 140 m lower than present, and the Bay of Kotor was exposed subaerially (Adamson *et al.,* 2016b). U-series ages of the alluvial deposits at Orjen are consistent with the timing of glacial activity (Hughes *et al.,* 2010). During subsequent cold stages (MIS 6, 5d-2, and the Younger Dryas), the ice cap did not advance beyond the plateau. During these periods, large areas of karst were exposed on the plateau, and meltwater was channeled into subterranean cavities (Adamson *et al.,* 2014). There is only limited evidence of post-MIS 12 alluvium preserved at the surface of the Orjen massif, and incision into the sediment fills is negligible. As a consequence, the oldest (Middle Pleistocene) part of the alluvial record is exceptionally well-preserved, but the youngest archives are not accessible at the surface. The interactions between glacial activity, karst terrain, and fluvial pathways, can therefore be a major control on the Quaternary sedimentary record in such glaciated regions (Stepišnik *et al*., 2009; Adamson *et al.,* 2014).

4.4. The particular case of karstified evaporites

In evaporite rocks, karst systems are sparser and tend to be restricted to relatively drier climate regions due to the restricted availability of moisture. However, in such environments the preservation potential of karst systems is much higher. In some regions of evaporitic bedrock, most commonly gypsum, climate forcing in uplifting areas generates cave levels associated with patterns of river incision and aggradation. In the Northern Apennines, Italy, especially in the region of Emilia Romagna, the Re Tiberio cave system is hosted in Messinian gypsum (Columbu *et al.,* 2015). Gypsum is much more soluble than limestone, and cave levels form very rapidly.

Two significant examples of karstified evaporites also exist in Spain, in the Sorbas basin, Southeastern Spain, and in the Gállego valley, in the central Ebro Basin, with cave levels and subsidence areas respectively (Calaforra and Pulido-Bosch, 2003).

4.4.1. Cave levels in karstified evaporites

The Sorbas basin, Southeast Spain, contains an interstratal karst system formed within intercalated Messinian gypsum and marls (Calaforra & Pulido-Bosch, 2003; Figure 6A). At first, the gypsum karst evolved under phreatic conditions during the early Pleistocene, enabling the formation of small conduits. Subsequently, mechanical erosion occurred under vadose conditions. Increased incision, as a consequence of rapid Plio-Pleistocene uplift (>80-160 mm/ka; Mather, 2000) allowed an eastward capture of the Upper Aguas river system at c. 70 ka (based on U series dating of river terrace calcretes, Candy et al., 2005, Harvey *et al.,* 2014). Dated pre-capture terraces represent the former southern drainage system of the Rio Aguas, prior to the river capture event, enabling incision rates to be calculated (Stokes *et al.,* 2002). In fact, the capture leads to a 10 fold increase in incision rates, driven by the ~90m base level drop that it initiated (Stokes *et al.,* 2002). This incision led to the development of further cave levels. Karst tributaries that were connected to the Aguas channel at the surface, were protected from enhanced incision due to the development of the cave network (Mather 2000). Headward incision in the Upper Aguas catchment induced a lowering of the piezometric level in the Sorbas basin. Subterranean erosion processes, largely concentrated into the marl strata, occurred under vadose conditions (Calaforra & Pulido-Bosch, 2003), and these processes continue at the present day.

4.4.2. Subsidence in evaporite rock areas

Bruthans and Zeman (2003) identified a suit of features typical of salt karst terrain, including broad and low caves shaped by subterranean meandering streams, and the development of large subterranean alluvial fans, due to the high solubility of salt (NaCl). Apart from these forms, a key feature of evaporite karst (e.g. gypsum karst) is the incomplete record of valley evolution due to high solubility and enhanced dissolution and subsidence. A number of examples exist worldwide, most notably in Spain (Benito *et al.,* 1998, 2010; Figure 6B). In the Gállego valley, in the central Ebro Basin, Northern Zaragoza, 12 stepped terraces (2-5 m thick) were mapped upstream of Zuera. Downstream, the complex of alluvial formations is over 100 m thick. This downstream thickening of the alluvial formations, as well as multi-scale karstic depressions and syn- and post-sedimentary deformations, such as collapses, reverse faults, and marl-clay diapiric structures, reflect the dissolution of Cenozoic evaporitic bedrock. Palaeomagnetic and OSL dating revealed two main periods of subsidence and associated alluvial aggradation: the first (represented by terraces T2, T3, and T4) began in the Early Pleistocene (Benito *et al.,* 1998). The second occurred during MIS 6, primarily when glaciers were present in the Pyrenees. A later phase also occurred during the Warthe Advance, a later part of MIS 6 (155-140 ka), as a result of high discharge delivered by the upper catchment of the Gállego River (Benito *et al.,* 2010).

In the Eastern Cinca and Segre catchments of the Ebro Basin, Lucha *et al.* (2012) identified a phase of dissolution subsidence and halokinetic uplift along the evaporitic core of the Barbastro–Balaguer Anticline. Eight of the nine fluvial terraces were affected by dissolution-induced synsedimentary subsidence, by dissolution-induced post-sedimentary subsidence, or by deformation due to salt flow, especially the upper Pleistocene terrace 4 of the Cinca River. OSL ages obtained in the alluvial sediments of this backtilted terrace indicated a minimum uplift rate of 0.3 mm/a (Lucha *et al.*, 2012). Moreover, deposits of the highest terrace levels reach over 100 m thickness in the Segre catchment, in basins generated by dissolution-induced synsedimentary subsidence.

5. Discussion

5.1. Variability of incision rates in karst fluvial systems

Based on chronological evidence from karstic fluvial sedimentary fills and secondary carbonate forms, such as travertine and calcrete, long-term regional incision rates can be securely constrained. In fact, numerical dating highlights the variability in space and time of river incision rates. Incision rates are highest in high mountains (>2,000 m a.s.l.), exceeding 100 mm/ka in the Alps (Hobléa *et al.,* 2011; Häuselmann & Granger, 2005; Wagner *et al.,* 2010) or in China (especially on the southeast margin of the Tibetan Plateau, McPhillips *et al.,* 2016). Incision rates are lower (<100 mm/ka) in the plateaus and low mountain range areas (200-2,000 m a.s.l.), such as the Eastern Paris Basin (Harmand & Cordier, 2012), the Languedocian plateaus (Ambert & Ambert, 1995; Camus, 1997; Audra *et al.,* 2001), the Duero basin (Moreno *et al.,* 2012; Ortega *et al.,* 2013), Swabian Alps (Abel *et al.,* 2002), or the Eastern Pyrenees

(Calvet *et al.,* 2015). The lowest incision rates (typically <10 mm/ka) are measured in Palaeozoic crustal provinces, such as the Southeastern part of Australia (Webb *et al.,* 1992) or on the Appalachian plateau (Granger *et al.,* 2001).

Most of the time, higher incision rates are related to periods of stronger uplift, such as in the Styrian Alps or the Western American Sierra Nevada, where Miocene uplift rates reached 140 mm/ka (Stock *et al.,* 2005; Wagner *et al.,* 2010). Where karstification and fluvial dynamics have been studied in particular detail, it is possible to identify multiple uplift phases during the Cenozoic era. This is the case in the Languedocian plateaus where karstic and valley evolution corresponded to several uplift pulses since the Cretaceous period (Séranne *et al.,* 2002); the last pulse occurring during the Middle to Late Miocene. The onset of accelerated incision is related to Pliocene and Pleistocene tectonic uplift and climate change, in the Sierra Nevada (from 3 and 1.5 Ma; Stock *et al.,* 2005), in the middle Ardèche valley (since 2 Ma; Audra *et al.,* 2001) or in the Eastern Pyrenees (since the beginning of the Pleistocene; Calvet *et al.,* 2015). Variations in tectonically- and climatically-driven incision rates are conditioned locally by geomorphology and fluvial behavior, such as river capture. In the Styrian Alps, strong incision of the Mur River, from 4 to 2.5 Ma was connected with an extension of the Mur catchment following river drainage change (Wagner *et al.*, 2010). Decreased incision during the Quaternary corresponded to fluvial aggradation during Pleistocene cold periods and reduced potential for bedrock entrenchment. Short-term increase in incision rate in the Siebenhengste at 800 ka has been related to a change in flow direction from the Eriz valley to the south, to the Aare valley in the north (Häuselmann & Granger, 2005). Similar short-term changes in incision rate are evident in the Mammoth Cave record, where an incision event at c. 1.4 Ma has been correlated with headward erosion in the Green River valley, after the formation of the Ohio River, at the end of an ice-sheet advance (Granger *et al.,* 2001).

Delayed response between tectonic uplift and resulting fluvial incision can also be discerned from the karst-fluvial archive. This is the case in the Ardenne massif where ^{10}Be dating highlighted diachronous river incision from the lower Meuse valley at the northern rim of the Ardenne to its intra-massif (sub–) tributaries, i.e. Belle-Roche in the Amblève valley (Rixhon *et al.*, 2011, 2014). However, rates of knickpoint retreat are variable, and depend on many factors, including climate, discharge, lithology, tectonics and time (Whittaker & Boulton, 2012). These controls are translated into the morphosedimentary record as spatial variations in the timing of uplift, valley incision, aggradation, and karstification. In the Upper Yangzi catchment, cosmogenic nuclide ages suggest a considerably delayed response (c. 20 Ma) between Late Eocene uplift (Hoke *et al.,* 2014) and Miocene incision (from 18 to 9 Ma), such that valley incision is not a useful proxy for surface uplift (McPhillips *et al.*, 2016).

5.2. Models of valley evolution and karstification

At the regional scale (e.g. across the Mediterranean basin), eustatic, isostatic, tectonic and climatic factors, largely explain the rise or fall of base and cave levels. These drivers do not influence hypogenic caves and ghost rocks (isovolumetric weathering with very low flow) because these types of speleogenesis are not connected to a fluvial base level. However, uplifted hypogenic and ghost rock karsts can be reactivated, as cryptokarsts (when karstification occurs under an impervious sedimentary cover) or palaeokarsts, when they can be influenced by base and cave level change (e.g. Wealdian: continental Infra-Cretaceous (Vergari & Quinif, 1997; Jaillet *et al.,* 2004). In most karst regions, geomorphological evolution consists of valley incision and *per descensum* speleogenesis. Over Quaternary timescales, this model is underpinned by climate change, since tectonic uplift and subsidence change over much longer geological time spans. Thus, Quaternary glacial and interglacial cycles are recorded in terraces and caves by aggradation, incision, or concretion phases (Antoine, 1994; Quinif, 2006; Columbu *et al.,* 2015).

At the catchment scale, Pleistocene climatic cycles and geomorphological factors influenced fluvial and karstic environments. In many catchments, river incision chiefly occurs during cold-to-warm or warm-to-cold climatic transitions, in accordance with regional climate change (Antoine, 1994; Bridgland *et al.,* 2009). Underground streams adjust to falling base level by incising new passages. However, there is evidence that *per descensum* speleogenesis also depends on the timing of valley incision, as well as geological factors such as (i) the degree of bedrock karstification (Abel *et al.,* 2002), (ii) alternating pervious and impervious strata causing perched karsts (Devos *et al.,* 2015, Figure 4A level a) and iii) underground karstic flows towards a lower elevation river in a neighbouring hydrographic basin or in the downstream position of the same river (Losson, 2003). As a consequence, numerous interactions between fluvial evolution and karstification can exist. We therefore propose four local to regional models of Quaternary geomorphological evolution from different settings: 1) Eastern Pyrenees, in limestone rocks, 2 and 3) low limestone plateaus of the Eastern Paris Basin and 4) a rapidly-uplifted gypsum area in the Northern Apennines, Italy (Losson, 2003; Antoine *et al.,* 2006; Hez *et al.,* 2015; Colombu *et al.,* 2015).

5.2.1 A conceptual model of valley scale karstic and fluvial development: river terrace records in the Têt basin (Eastern French Pyrenees)

On the basis of river terrace records from the Eastern French Pyrenees (Calvet *et al.,* 2015; Hez *et al.,* 2015), a valley-scale conceptual model of karst drainage evolution is presented in Figure 7. This reflects changes in karst genesis, evolution, and abandonment as well as fluvial incision into bedrock, sediment aggradation, and terrace incision/abandonment. This model is based on cavities in the Têt basin, especially in the Devonian limestones syncline of Villefranche, where nine horizontal conduits exist up to 1,000 m above the present valley floor (Hez *et al.,* 2015; Calvet *et al.,* 2015). The two lowest karstic tubes contain rich morphologies of sediment fill and corrosion forms, which can be explained by the succession of three genetic karstic phases (Figure 7A, C). In phase 1, the presence of phreatic caves indicates syngenetic karstification below base level during or after valley incision. In phase 2, bench walls and the corroded ceiling of the horizontal conduit indicate aggradation at the valley bottom leading to progressive and synchronous base-level rise during a paragenetic phase. During phase 3, funnel shaped conduits cutting down into the horizontal tubes highlight a period of renewed incision ("trepanning", Jaillet *et al.*, 2004). This suggests a diachronic evolution of the caves with: a) lowering of the base-level inducing downstream incision of the paragenetic stage sediments. Thus, ancient horizontal conduits shaped in the flooded zone evolve downstream in the vadose zone where the cave deposits are partially reworked (see phase 1); b) formation of bench walls in the middle part of the galleries; and c) deposition of a cave fan delta upstream. Indeed, a strong hydraulic gradient (1/1000) and flooding on the perched valley floor causes upstream transport and deposition of coarse alluvium in karstic caves. In a last stage d), headward erosion along the valley axis induces fluvial incision of the alluvial plain and underlying bedrock, and entrenchment of the cave fill. Beneath the valley floor, a karstic drain is initiated in the flooded zone (Figure 7B).

One must note that this model of karstic drain evolution and the relationships between valley and karstic development during a Pleistocene climatic cycle is not valid when underground flow is diverted to stream capture or piracy (see below, Figure 8B). Thus, in the capture area of the

Moselle river by the Meurthe (Losson, 2003), the caves of Pierre-la-Treiche show that the endokarstic networks are not correlated in elevation with the Moselle terraces.

5.2.2. Two conceptual models of regional karstic and fluvial development in low limestone plateaus: cave records

In limestone plateaus, alluvial stepped terraces and tiered cave infills record successive Milankovitch cycles of palaeoenvironmental change (Figure 8). In both models (Figure 8A and 8B), two positions are distinguished based to the type of speleogenesis. Figure 8A shows the evolution of a plateau karst where the caves are in connection with the valley bottom. Figure 8B presents a valley karst. The lower caves, situated below the water table, are in connection with the base level of another valley which is located below the water table, as in Pierre-la-Treiche (Losson *et al.,* 2006). Figure 8B3 presents a valley karst where underground flows occur between zones of karstic losses and resurgences along the same valley, such as the upper Meuse upstream of Neufchâteau, Eastern Paris basin (Losson, 2003).

In both models, stage 1 corresponds to an interglacial period with pedogenesis and silt deposition in river systems and caves. Biological CO_2 allows speleothem, travertine and tufa growth, especially in warm environments or in chalk Cretaceous catchments where thick tufa deposits occur (Antoine *et al.,* 2006, Figure 8A). During stage 2, at the onset of climate cooling, the progressive disappearance of forests leads to soil erosion on the slopes, lateral erosion in the meandering valleys, and headward erosion of the steep slopes of the karstic massif (Antoine, 1994). As a consequence, cave entrances become disconnected from the valley bottom in a plateau karst (Figure 8A). There is little or no speleothem growth in vadose caves and fine clastic deposits (from soil erosion) are deposed in flooded cavities. Lower flooded caves are situated below the water table in relation to neighbouring valley (such as the Palaeo-Meurthe valley, Figure 8B). In the cold period (stage 3), for example in the Moselle valley (Figure 8B), the river entrenches into the bedrock, above the former flooded caves connected with the Palaeo-Meurthe river. In stage 4, during full glacial conditions (such as the Last Glacial Maximum, MIS 2), coarse alluvium, originating from the glaciated Vosges massif, was deposited by a braided river in the valley bottom. This material was also deposited in the lower elevation flooded or vadose caves (Losson *et al.,* 2006). In fact, glaciated karst regions where a major glacial advance occurs generates large volumes of sediment that are deposited in karst cavities at the surface and subsurface, leading to major phases of aggradation (e.g. Lewin & Woodward, 2009; Adamson *et al.,* 2014, 2016a and b). No speleothem formation occurs during full glacial conditions (Fairchild and Baker, 2012).

When large volumes of alluvium are deposited on the valley floor, they can fill caves that are situated (almost) at the same altitude as the river (Figure 8A), such as the Middle Pleistocene filling of the Belle-Roche cave in the Ardenne massif (Rixhon *et al.,* 2014). Some authors have highlighted the difference between wet glacial periods characterized by sediment-laden rivers, and dry cold periods with reworked loess, for example in Belgian caves, close to the former margins of the Fennoscandian ice sheet (Quinif, 2006). Where caves have become filled, they display evidence of a complex geomorphological evolution, with successive phases of aggradation and incision (Quinif & Maire, 1998).

The wide caves of Pierre-la-Treiche, filled with coarse grained alluvium (Figure 8B) indicate a speleogenetic phase during an interglacial period, before the deposition of alluvium in the subsequent glaciation. However, the horizontal cave levels of the (epi)phreatic zone, which correspond to stable base levels without tectonic uplift, require a minimum formation time by solutional processes of 10-40 ka (Ford & Williams, 1989). The time period between two Quaternary glaciations (MIS 5e, c, a) is thus long enough for dissolution processes to excavate the horizontal tubes. During the subsequent interglacial, new flooded caves were formed at the bottom of the valley where tufa deposits can develop (Antoine *et al.,* 2006; Dabkowski *et al.,* 2011; Figure 8A). Today, at Pierre-la-Treiche, the entrenched valley of the Moselle is situated below the vadose caves (Losson, 2003; Cordier *et al.,* 2006) where speleothems have grown since 300 ka, spanning several interglacial and interstadial periods (Losson, 2003, Losson *et al.,* 2006; Pons-Branchu *et al.,* 2010).

5.2.3. Model of climate-driven speleogenesis of gypsum caves

Figure 9 presents a model of climate-driven river incision and karstification based on the multi-level gypsum cave systems of the Re Tiberio (Fig. 1) situated in the moderately-rapidly uplifted Northern Apennines, Italy (Columbu *et al.,* 2015). This Italian karstified area presents a more relevant model than the Spanish karsts, where the subsidence is irregular in time and space (Gállego valley) or where the geomorphological evolution is accelerated by a river capture event (Rio Aguas, Sorbas basin, see 4.4). Mostly, in the Re Tiberio valley, dating speleothems provide a more precise chronological framework (Columbu *et al.,* 2015). U-series ages of calcite speleothems from the three cave levels, situated at 340, 215, and 190 m a.s.l., revealed growth phases during the MIS 5e, MIS 5d-c (Dansgaard-Oeschger cycle 24) and MIS 5b-a (D-O cycles 22 to 20), respectively. The ages suggest rapid entrenchment during cold periods, because uplift rates had reached c. 1 mm/yr since the end of the Middle Pleistocene (Columbu *et al.,* 2015).

This model presents significant differences with previous conceptual models (see Figs 7 and 8), because horizontal cave levels formed during cold periods. Karst evolution was rapid, especially during wetter phases, due to increased bedload (Figure 9B2, 9B3, 9B4). Valley aggradation led to the infilling of cave passages and a paragenetic karstification due to slowly rising base level. During the subsequent warm period, decreased bedload initiated incision into the cave sediments, but karstification was slow (Figure 9A, 9B5). The key similarities with the models presented in Figures 7 and 8, are that carbonate speleothems grew during wet and warm interglacials or interstadials (MIS 5e, 5d-a, 5b-a, figure 9A, 9B1) and valley incision occurred at cooling transitions due to high stream discharge and low bedload concentrations (figure 9B2).

5.2.4. Diverse models of karstic and valley evolution

The four models outlined above present idealised scenarios, based on existing evidence, but more complex models of fluvial and karstic evolution can occur in response to local to regional conditions. Thus, successive aggradation or erosion phases can occur over multiple cold periods. These can be recorded in the same cave level, as in the Pierre-Saint-Martin caves in the French Pyrenees (Quinif & Maire, 1998). On the other hand, tiered caves can be filled with deposits of the same age, as in the Mammoth cave, USA (Granger *et al.,* 2001). Establishing the model of karst and valley evolution in different settings relies on the number of cave levels and river terrace surfaces in a connected valley. However, the number of cave passage levels present in karst landscapes is commonly lower than the number of 100 ka cycles that have occurred over the last 1 Ma of the Quaternary. This suggests that karst-fluvial systems might record only the major climate changes (‘supercycles’ of Kukla, 2005; Bridgland *et al.,* 2009) or/and variations in uplift rate.

6. Conclusion

For two decades, analysis of river systems in karstic areas, including the wider application of dating methods, such as cosmogenic nuclide dating of cave infills, have provided a better understanding of geomorphological evolution over the Cenozoic era, especially during the Quaternary. Alluvial records in karst terrain, especially in European karst catchments, where the sedimentary records are particularly well preserved compared to their sub-aerial counterparts, now provide a reliable record of landscape evolution that can be effectively tied to wider, regional morphosedimentary archives.

Evidence indicates that many factors, including uplift, eustatic fluctuations, climatic conditions and fluvial dynamics (e.g. knickpoint retreat, increased channel flow and/or sediment load, and stream piracies), can play a major role in speleogenesis and geomorphological evolution. Data reviewed here have allowed us to propose a four-fold typology of the relationship between fluvial evolution and karstification: 1) karstification in association with base and cave level lowering, i) in low elevation and tectonically-stable cratonic area, ii) on low altitude plateaus (<500 m a.s.l.), iii) on high altitude plateaus and low mountain ranges (500 – 2,000 a.s.l.), where long-term records of fluvial incision and karstification are present; iv) in high mountain regions (>2,000 m a.s.l.), 2) karstification in association with rising base and cave level, 3) Pleistocene incision and karstification in association with glaciation, and 4) the particular case of karstified evaporites. In, gypsum and salt speleogenesis is characterized by rapid dissolution and subsidence. In European catchments, gypsum cave enlargement has occurred during cold climate periods, while limestone caves formed during warm interglacial or interstadial phases. However, in limestone rocks, the bulk of karstic cave fills correspond to cold periods, with thick, clastic sediments deposited under glacial conditions. Speleothems and tufa deposits are formed chiefly during interglacial periods. This demonstrates that, over Quaternary timescales, climate plays an important role in karst processes. The regional and local setting determines the modes of valley evolution and karstification, and the geomorphological framework plays a triggering factor to initiate speleogenesis.

In addition, our synthesis is used to propose four models of fluvial and karst evolution, from different settings: 1) in the Eastern Pyrenees, in limestone rocks, 2 and 3) in low elevation limestone plateaus of the Eastern Paris Basin, and 4) a rapidly-uplifted gypsum area in the Northern Apennines, Italy.

Future research should focus on improved reliability and application of dating methods, because in many cases, numerical dating is not possible, due to a lack of alluvial sequences such as fluvial terraces or sedimentary fills within karstic caves and surface depressions (such as poljes and dolines). Even if alluvium is preserved in karstic terrain, it may not contain sufficient siliceous content for OSL dating, or secondary carbonate concretions, such as travertine or calcrete, for U-series dating. Moreover, U-series dating is further complicated by the ingrowth of younger calcite into pre-existing sediments. Alluvial sequences might also bear the imprint of sediment reworking, meaning that the sedimentary sequence is not indicative of primary formation mechanisms. Further research should also include other karstic regions, especially low latitude regions, as well as arid regions, around the Mediterranean Sea, to enhance our understanding of karstic processes in other global regions.

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Figures

Figure 1: Location map of the karstic areas discussed in the text.

Figure 2: Schematic diagrams of the relationships between valley evolution and karstification: A) The concept of correlation between surface features (alluvial terraces) and subsurface karstification levels (caves) (modified from Abel *et al.,* 2002); B) Different types of cave profile

development, constrained by recharge (a and b) and base-level controls (c and d) (after Audra & Palmer, 2011).

Figure 3: Typology of the relationships between karst and valley incision, demonstrating the type of speleogenesis, characteristic morphologies, and examples (after Losson, unpublished)

Figure 4: Karst and entrenched valleys in the Eastern Paris Basin: A) Typology of the relations between karstification and valley evolution; B) hydraulic gradient between aquifer compartments and rivers (after Devos, unpublished).

Figure 5: Idealised models of *per descensum* (A) and *per ascensum* (B) speleogenesis using examples from the Vercors Subalpine Chain (A) and the Lower Ardèche River (B).

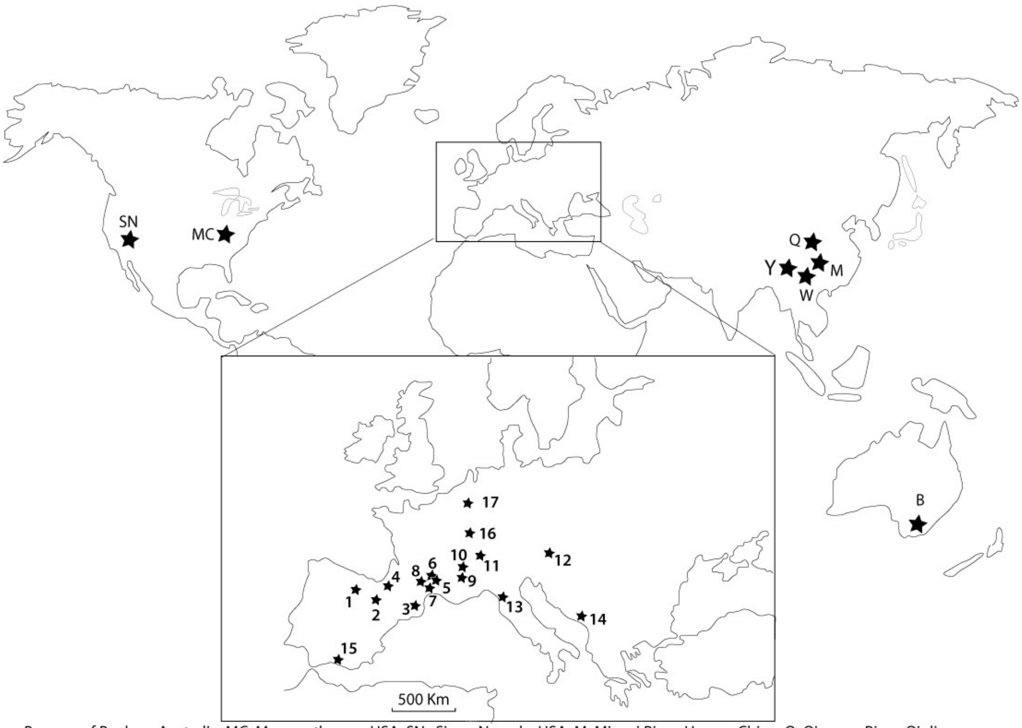
Figure 6: Two conceptual models of gypsum karst: A: interstratal karstification with contemporary underground erosion processes (after Calaforra & Pulido-Bosch, 2003); B: karst subsidence and accelerated fluvial aggradation (after Benito *et al.,* 2010)

Figure 7: A conceptual model of valley scale karstic and fluvial development in relation to river terrace records: A) successive stages of evolution of a karstic drain and a valley floor, B) schematic cross-section of relationships between cave passage and valley terrace during phase 4 (upstream part); C) Model elevation / time of the hydrographic network and the cave passage (Jaillet, unpublished)

Figure 8: Valley entrenchment during a Pleistocene glacial-interglacial cycle in limestone areas. A: connected cave and base levels of a same valley (plateau karst); B) speleogenesis in connection with an neighbouring valley (valley karst) (after Antoine, 1994; Losson, 2003; Antoine *et al.,* 2006; Quinif, 2006)

Figure 9: Conceptual model of climate-driven speleogenesis of gypsum cave systems in relation with valley incision and aggradation in moderately and rapid uptlifted gypsum area: A) climate-driven speleogenesis of epigenic gypsum cave systems, B) evolution of river valleys and adjacent gypsum cave systems (based on the Northern Apennines after Colombu *et al.,* 2015)

Figure 1



B: caves of Buchan, Australia; MC: Mammoth cave, USA; SN : Sierra Nevada, USA; M: Miaoxi River, Hunan, China; Q: Qianyou River, Qinling mountains, China; W: Wujiang River, Guizhou, China; Y: Yangzi Gorge,Yunnan, China; Europe: 1: Arlanzón, Spain; 2: Gállego River, Spain; 3: Têt valley, Eastern Pyrenees, France; 4: Pierre-Saint-Martin, Western Pyrenees, France; 5: Lower Ardèche valley, France; 6: Middle Ardèche valley, France; 7: Southern Larzac plateau, Grands Causses, France; 8: Tarn valley at Millau, Grands Causses, France; 9: Vercors, subalpine massif, France; 10: Mont Granier, Grande Chartreuse, subalpine massif, France; 11: Siebenhengste, Switzerland; 12: Mur valley, Eastern Alps, Austria; 13: Monte Corcia, Alpi Apuane, Italy; 14: Mount Orjen, Montenegro; 15: Gypsum karst of Sorbas, Spain; 16: Caves of Pierre-la-Treiche, Eastern Paris Basin, France; 17: Cave of Belle-Roche, Ardenne massif, Belgium

Figure 2

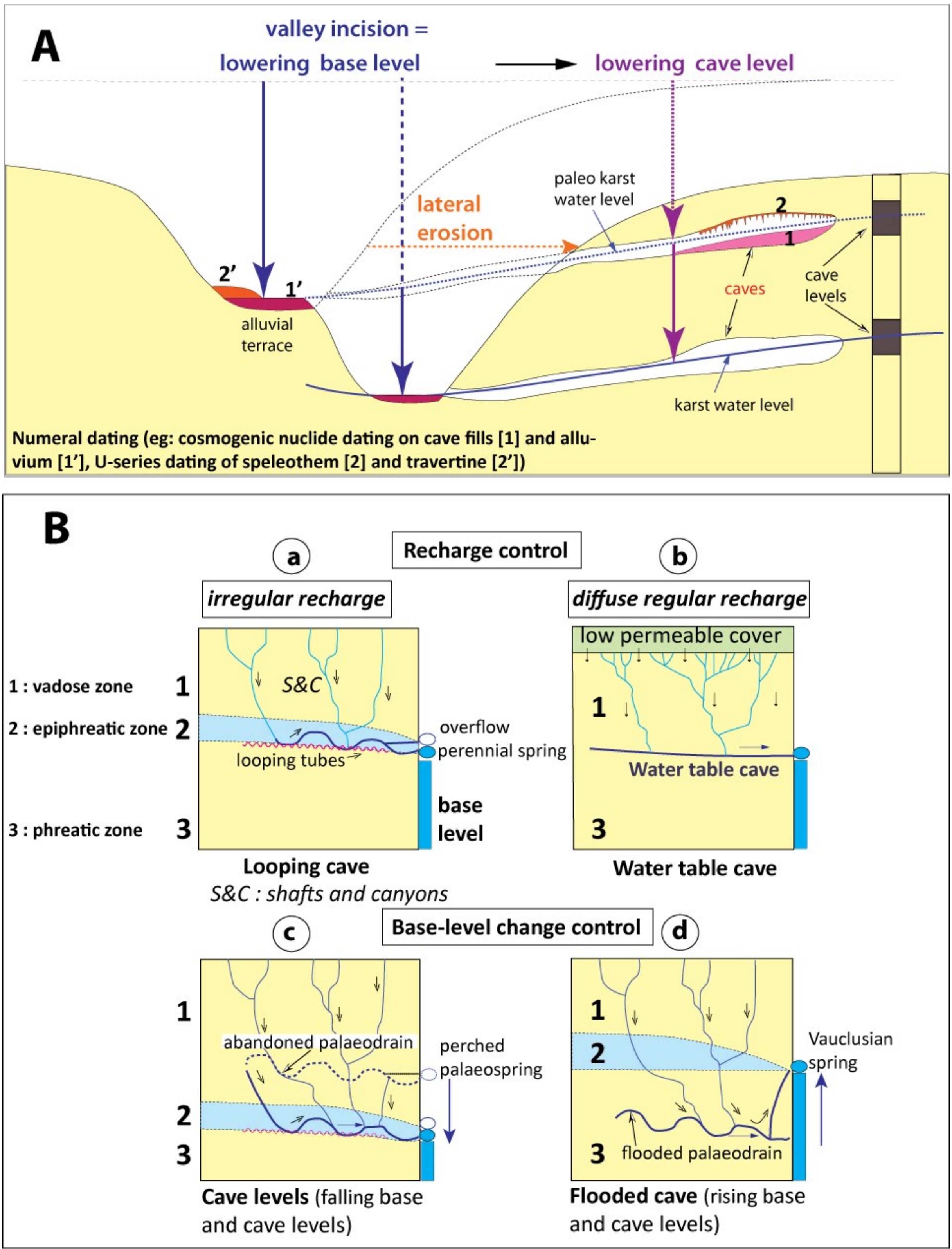

A
valley incision =
lowering base level
lowering cave level
lateral
erosion
paleo karst
water level
2
1
2'
1'
alluvial
terrace
caves
cave
levels
karst water level
Numeral dating (eg: cosmogenic nuclide dating on cave fills [1] and allu-
vium [1'], U-series dating of speleothem [2] and travertine [2'])
B
Recharge control
a
b
irregular recharge
diffuse regular recharge
low permeable cover
1 : vadose zone
2 : epiphreatic zone
3 : phreatic zone
S&C
overflow
perennial spring
looping tubes
base
level
Water table cave
Looping cave
S&C : shafts and canyons
Water table cave
Base-level change control
c
d
abandoned palaeodrain
perched
palaeospring
Vauclusian
spring
flooded palaeodrain
Cave levels (falling base
and cave levels)
Flooded cave (rising base
and cave levels)

Figure 3

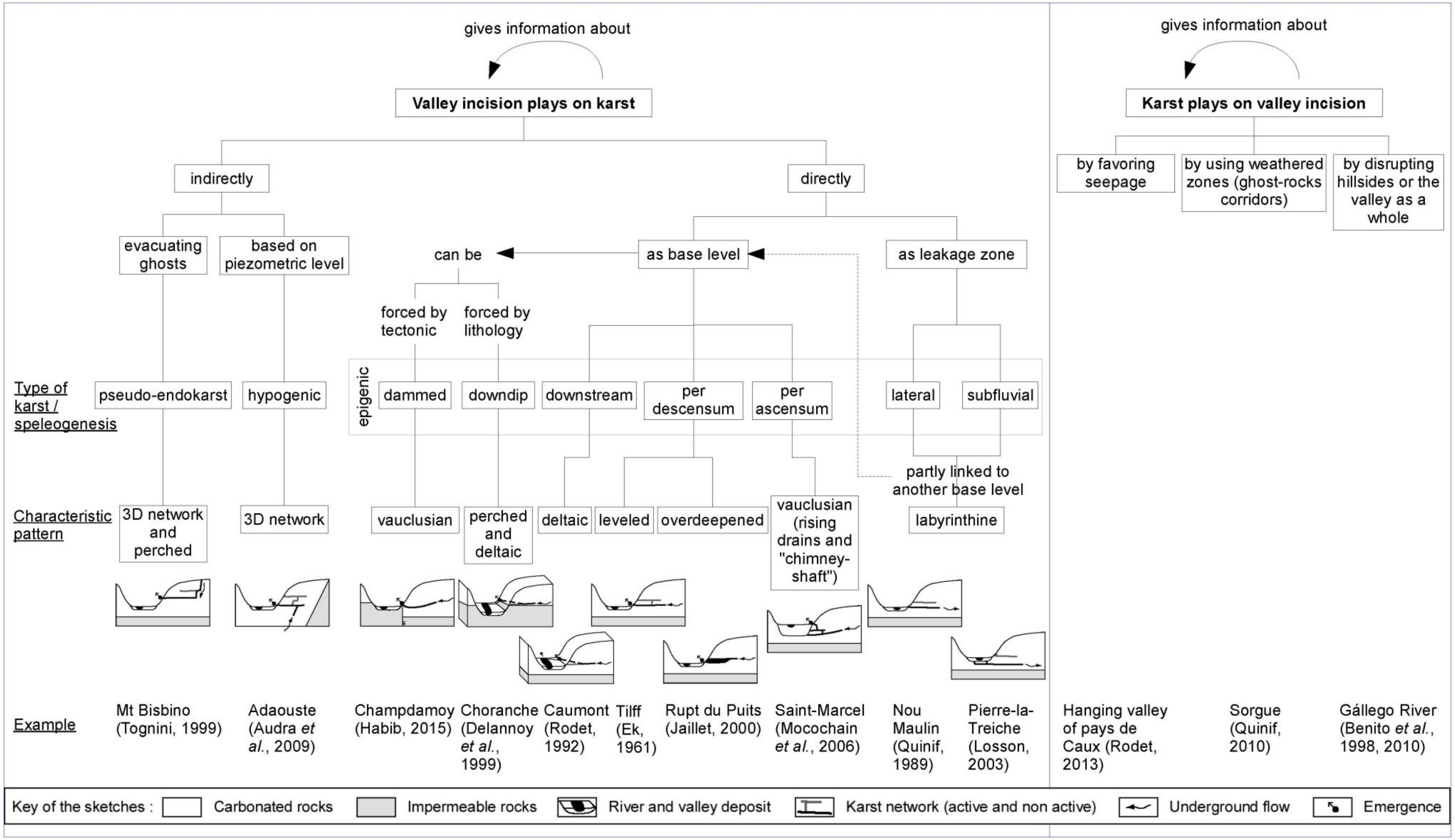
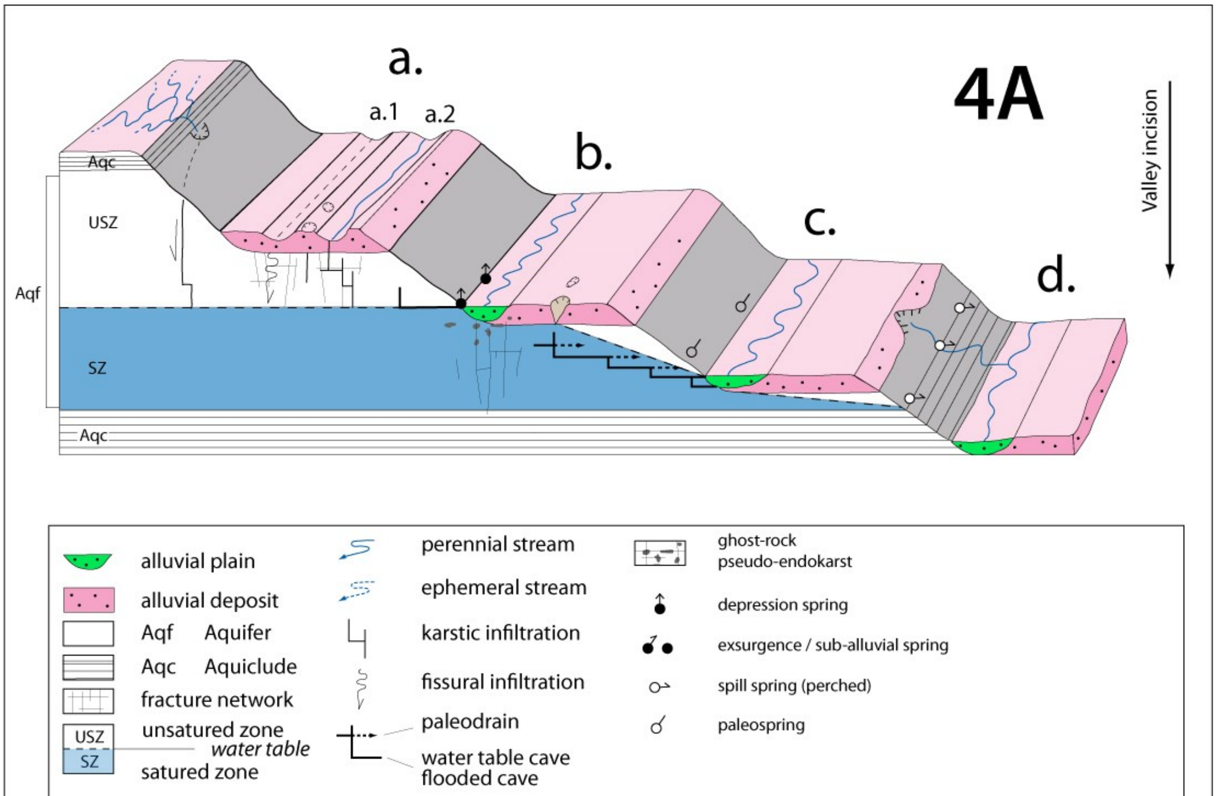

gives information about
Valley incision plays on karst
indirectly
directly
evacuating ghosts
based on piezometric level
can be
as base level
as leakage zone
forced by tectonic
forced by lithology
Type of karst / speleogenesis
pseudo-endokarst
hypogenic
epigenic
dammed
downdip
downstream
per descensum
per ascensum
lateral
subfluvial
partly linked to another base level
Characteristic pattern
3D network and perched
3D network
vauclusian
perched and deltaic
deltaic
leveled
overdeepened
vauclusian (rising drains and "chimney-shaft")
labyrinthine
Example
Mt Bisbino (Tognini, 1999)
Adaouste (Audra et al., 2009)
Champdamoy (Habib, 2015)
Choranche (Delannoy et al., 1999)
Caumont (Rodet, 1992)
Tilff (Ek, 1961)
Rupt du Puits (Jaillet, 2000)
Saint-Marcel (Mocochain et al., 2006)
Nou Maulin (Quinif, 1989)
Pierre-la-Treiche (Losson, 2003)
gives information about
Karst plays on valley incision
by favoring seepage
by using weathered zones (ghost-rocks corridors)
by disrupting hillsides or the valley as a whole
Hanging valley of pays de Caux (Rodet, 2013)
Sorgue (Quinif, 2010)
Gállego River (Benito et al., 1998, 2010)
Key of the sketches :
Carbonated rocks
Impermeable rocks
River and valley deposit
Karst network (active and non active)
Underground flow
Emergence

Figure 4



a) perched rivers situated above the saturated zone, a1: local rivers with low flow produce diffuse and fissural, infiltration into the karst, a2: allochthonous rivers with moderate to high flow produce a stronger karstification through suffosion and the transport of water and sediments through karstic conduits in the vadose zone; b) river in contact with the saturated zone, where the lack of hydraulic gradient induces a ghost rock process; c) a river strongly entrenched into the limestone substratum drains the flooded karst zone; d) a river entrenched into the clayed aquiclude is disconnected from the perched karst.

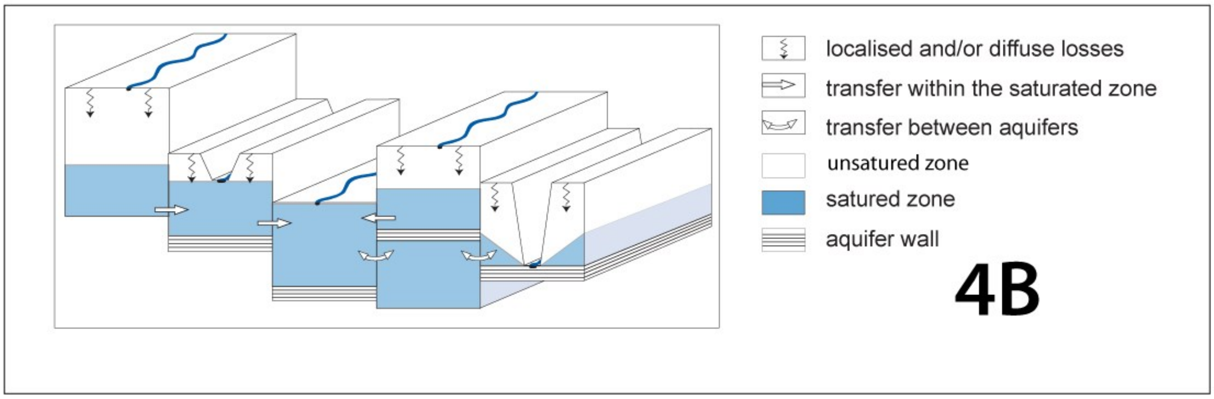
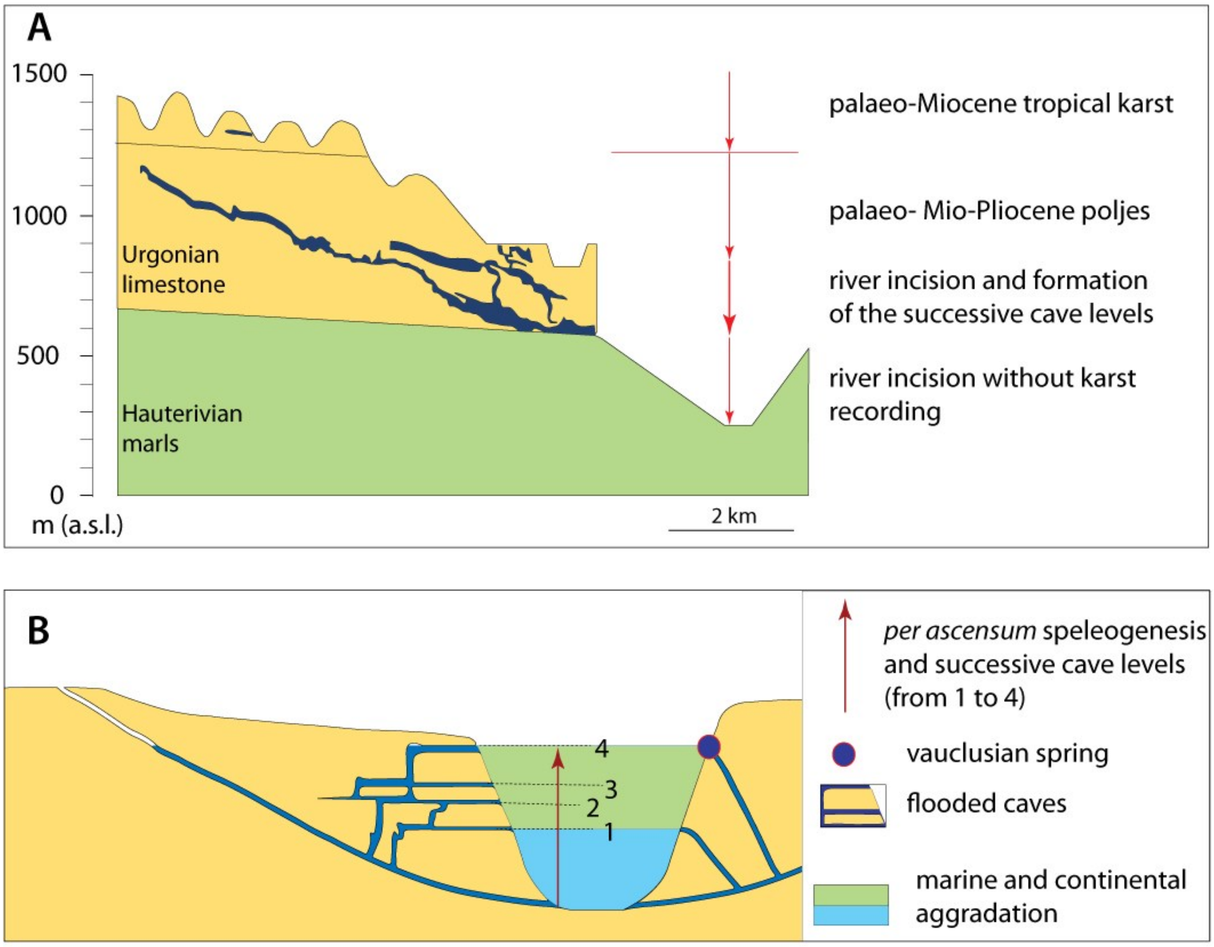


Figure 5



A: Per descensum speleogenesis incision in connection with uplift and valley incision (model of the Vercors subalpin chain, after Delannoy et al., 2009); B: Per ascensum speleogenesis : model of the Lower Ardèche river (after Audra & Palmer, 2011)

Figure 6

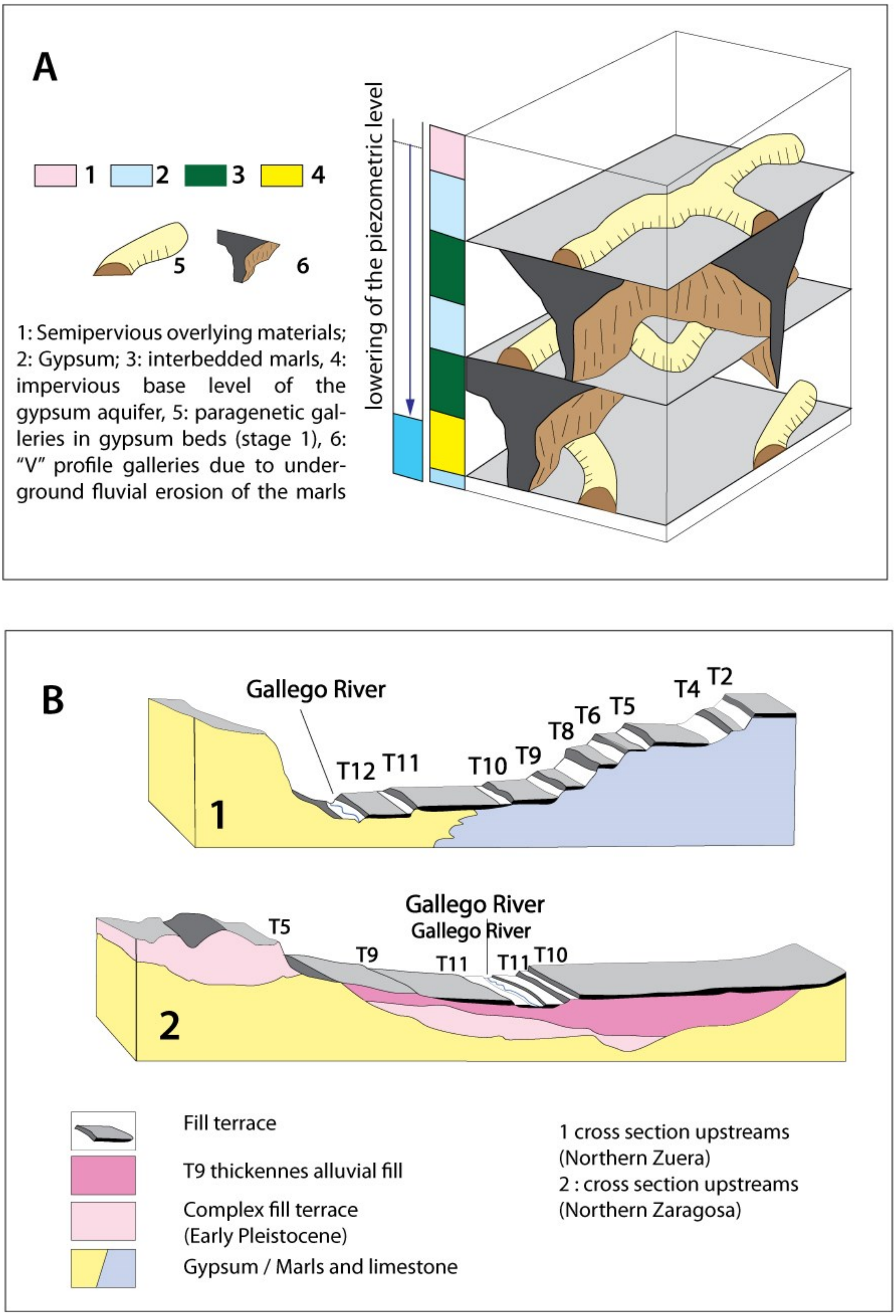

A
1
2
3
4
5
6
lowering of the piezometric level
1: Semipervious overlying materials; 2: Gypsum; 3: interbedded marls, 4: impervious base level of the gypsum aquifer, 5: paragenetic galleries in gypsum beds (stage 1), 6: "V" profile galleries due to underground fluvial erosion of the marls
B
Gallego River
T12 T11
T10 T9
T8 T6 T5
T4 T2
1
Gallego River
Gallego River
T5
T9
T11
T11 T10
2
Fill terrace
T9 thickennes alluvial fill
Complex fill terrace (Early Pleistocene)
Gypsum / Marls and limestone
1 cross section upstreams (Northern Zuera)
2 : cross section upstreams (Northern Zaragosa)

Figure 7

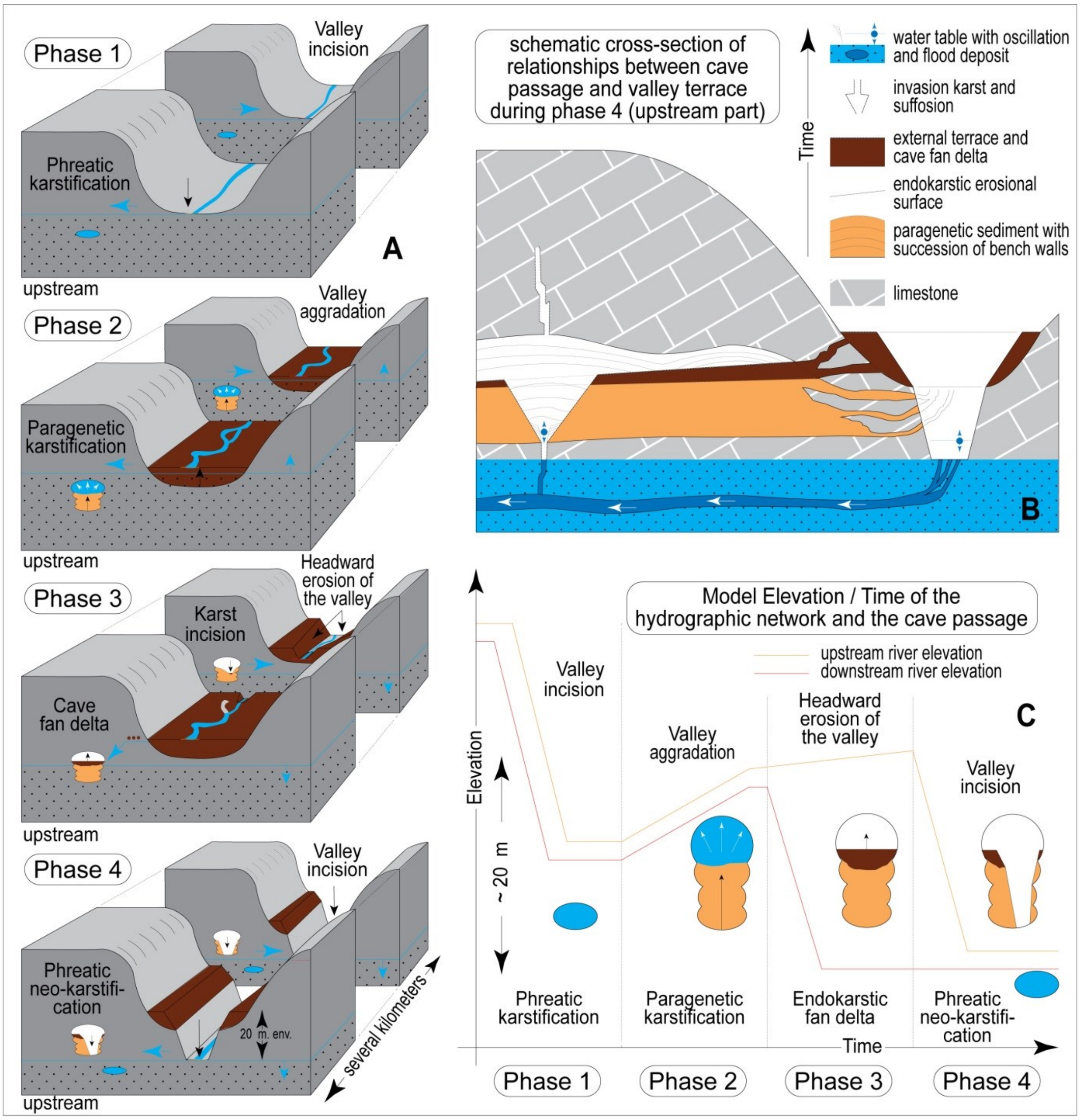
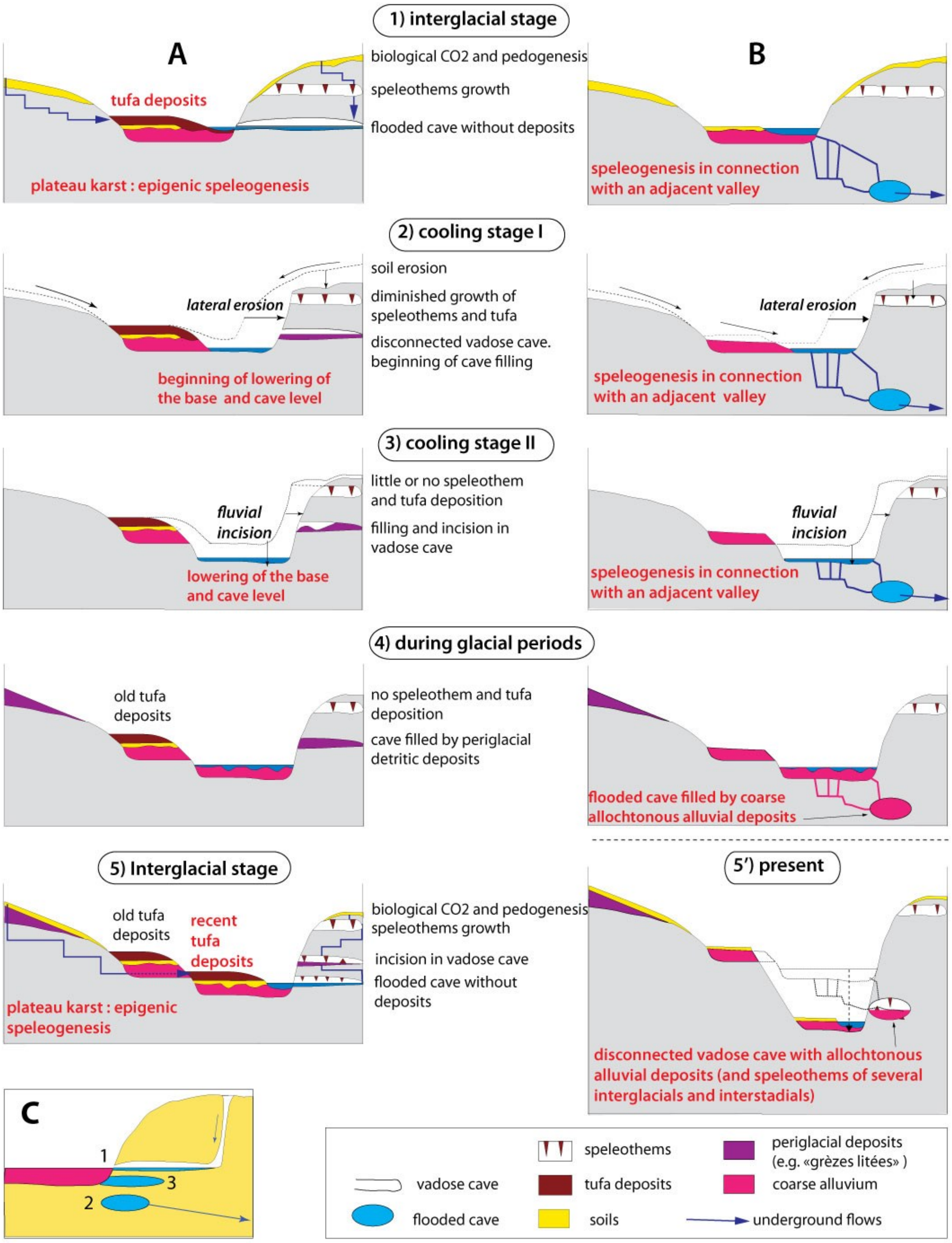


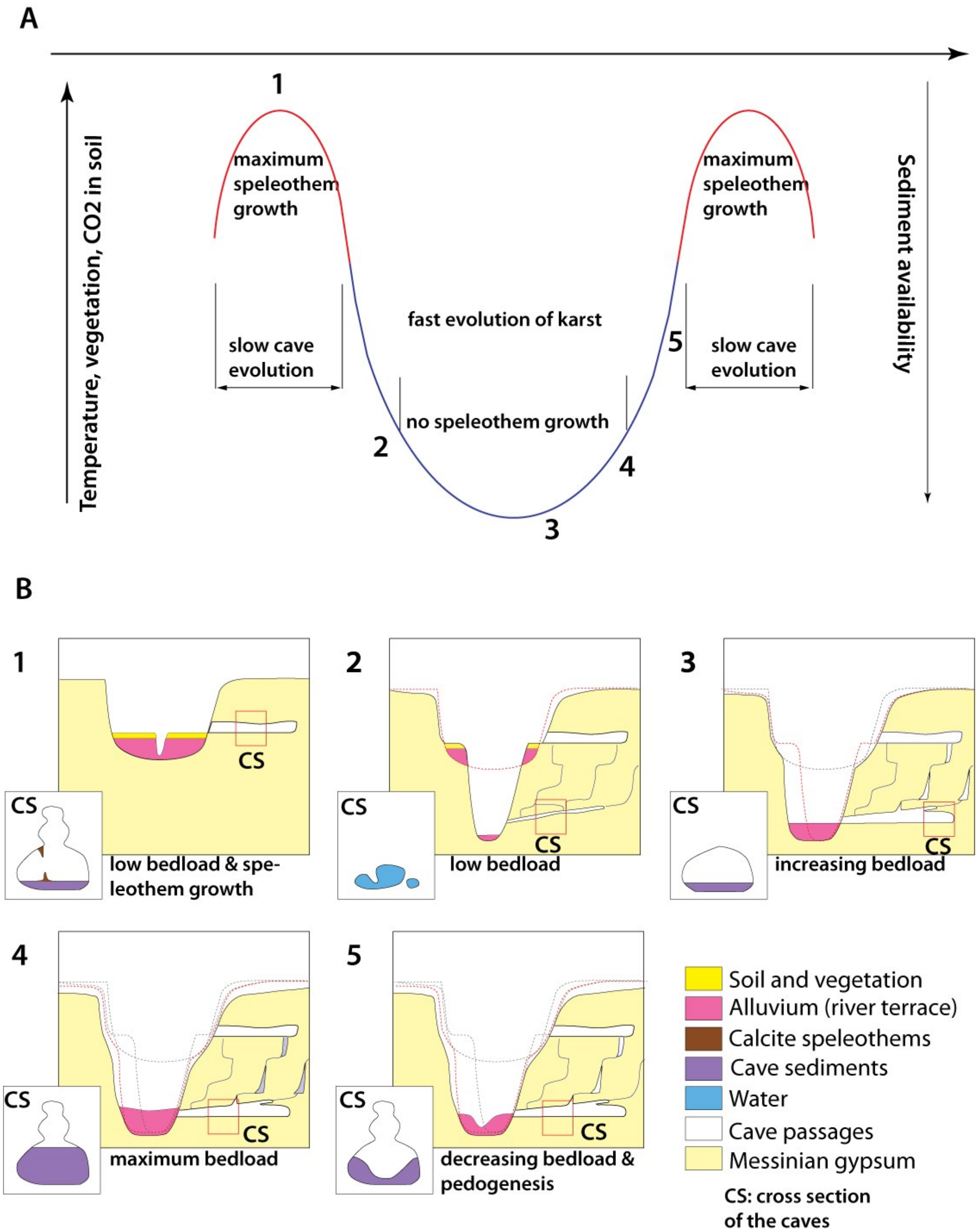
Figure 6

Figure 8:



Figures 8A & 8B are based on the numerous studies on karstic areas (Ford & Williams, 1989), the model of Pleistocene valley evolution of Antoine (1994), and the evolution of a karstic network during a full Quaternary climatic cycle (Quinif, 2006). Figure 8B is also based on the fluvial stepped terraces of the Moselle catchment (Cordier et al., 2006) and the cave filling of Pierre-la-Treiche upstream of Toul (Losson, 2003). Both models are applicable to karst regions elsewhere.
Figure 8C: 1: plateau karst (see fig .8A), 2: speleogenesis in connection with a base level situated downstream in an other valley (see fig. 8B), 3: speleogenesis in connection with a base level situated downstream in the same valley

Figure 9:



A
1
maximum
speleothem
growth
maximum
speleothem
growth
Temperature, vegetation, CO2 in soil
Sediment availability
fast evolution of karst
slow cave
evolution
5
slow cave
evolution
no speleothem growth
2
4
3
B
1
CS
CS
low bedload & spe-
leothem growth
2
CS
CS
low bedload
3
CS
CS
increasing bedload
4
CS
CS
maximum bedload
5
CS
CS
decreasing bedload &
pedogenesis
Soil and vegetation
Alluvium (river terrace)
Calcite speleothems
Cave sediments
Water
Cave passages
Messinian gypsum
CS: cross section
of the caves