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Counter-intuitive links between cave genesis and subaerial stream dynamics in the Têt Valley–Lachambre network, eastern Pyrenees, France

Stéphane Jaillet ^{1,*}, Gabriel Hez ¹, Marc Calvet ², Magali Delmas ²,
Edwige Pons-Branchu ³, and Yanni Gunnell ⁴

¹EDYTEM, UMR 5204 CNRS, Université Savoie Mont Blanc, Pôle Montagne, 73390 Le Bourget du Lac, France

²Université de Perpignan, Via Domitia, CNRS UMR 7194 Histoire Naturelle de l'Homme Préhistorique, 52 avenue Paul Alduy, F-66 860 Perpignan, France

³Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay, 91191 Gif-sur-Yvette, France

⁴Université Lumière Lyon 2, CNRS, UMR 5600 EVS, F-69635 Bron, France

Abstract:

The Lachambre cave network (Eastern Pyrenees, France) is well suited to studying the interaction between vertical successions of low-gradient cave passages in the limestone and chronosequences of fluvial terraces in the adjacent valley. Investigations here focus on cave passages striking parallel to the Têt River, and on their topographic, geomorphological, sedimentological and geochronological relationship with the two youngest generations of Pleistocene fluvial terrace, T2 and T1. Results reveal that the longitudinal profiles of the terraces and modern thalweg (1.5–3%) are ten times steeper than the profiles of the subterranean passages (0.1–0.3%), which display typical characteristics of water table caves. The respective cave and fluvial terrace profiles consequently diverge scissor-like on either side of a point of intersection, with the elevation of cave levels upstream occurring below the elevation of comparatively younger terrace treads, and even below the modern thalweg. U/Th ages obtained from speleothems and previously published ²⁶Al/¹⁰Be burial ages of quartz-rich sediment indicate that the downstream segment of the cave passage (i) formed during Marine Isotope Stage 6, (ii) was invaded soon after by a subterranean debris cone (at times of fluvial aggradation in the Têt catchment, cones of river bedload entered the caves through valley-side sinkholes), (iii) was partially filled by an influx of gravel from upstream during MIS 4, (iv) experienced speleothem growth during MIS 3, and (v) underwent further geomorphic changes during MIS 2. Such complicated interactions between subaerial and subterranean dynamics emphasize the necessity for caution when using caves as tools for quantifying valley incision by rivers – particularly when using them as substitutes for fluvial terraces in widespread situations where none are available. Cave altimetry, speleogen inventories, cross-cutting relations in cave sediment stratigraphy and age-bracketing of fluvial deposits and speleothems all contribute to elaborating a more accurate understanding of how cave development interrelates with Quaternary alluvial cycles.

Keywords:

Fluvial terrace, cave genesis, river–karst interaction, speleothem chronology, Lachambre network

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INTRODUCTION

Reliance on vertical successions of low-gradient cave passages in limestone karst for tracking valley incision by rivers is now an established paradigm (e.g., Calvet et al., 2024). Given that the elevations of active cave passages adjust to the local base levels defined by the rivers with which the cave passages join up (Palmer, 1987, 2007; Harmand et al., 2017), stacks of cave passages are thus assumed to be subterranean

substitutes for staircases of subaerial fluvial terraces because the two sets of features are presumed to co-evolve in synchrony. Using a range of available radiometric methods (Rixhon, 2023; Calvet et al., 2024), burial dating of the quartz-rich alluvial deposits that the caves may contain generates further opportunities for comparing the respective ages of cave and terrace deposits in addition to correlating the elevations of the cave floors and terrace treads. Constraints on the age of cave gravel deposits may also be obtained by U/Th-

*stephane.jaillet@univ-smb.fr

dating of flowstone interlayers and calcitic caprock units (Sorriaux et al., 2016; Jaillet et al., 2023).

In many high-energy environment (e.g., in the European Alps: Häuselmann et al., 2007, 2020; Plan et al., 2009; Hobléa et al., 2011; Sauro et al., 2021), sediment-filled cave passages are the only landforms suitable for tracking the history of valley incision because intense mass-movement processes on steep threshold slopes have stripped away the older generations of fluvial terraces (De Waele et al., 2012; Häuselmann et al., 2015; Jaillet et al., 2022). Despite its intuitive appeal, however, the assumption that cave levels are direct and accurate palaeoaltimetric substitutes for terrace treads or river thalwegs has not been widely tested by detailed investigations in settings where fluvial terraces and cave networks still coexist side by side.

Based on work in the Pyrenees (Calvet et al., 2015, 2021; Hez et al., 2015), Calvet et al. (2024) have emphasized the importance of producing independent corroborating evidence alongside unilateral inferences made from

cave levels about base-level change. In favourable circumstances, alluvial deposits in valleys can achieve this goal. This paper focuses on the eastern Pyrenees (France) and presents a detailed analysis of the link between fluvial terraces of the Têt River and the cave passages of the Lachambre network – an extensive speleological complex on the southern flank of the Têt Valley (Fig. 1). This area is well suited to this type of study because the Têt valley displays several generations of preserved fluvial terraces. The karst has also been a focus of intense speleological, topographic and geomorphological research (Hez, 2013; Collectif Conflent Subterrani, 2014; Calvet et al., 2015, 2019; Hez et al., 2015). Among the lower elevations of the valley topography, (i) the well preserved Mid- to Late Pleistocene fluvial terraces T2 and T1 and (ii) the extensive cave networks of En Gorner (20 km), Fuilla-Canalettes (26 km), and Lachambre (26 km) provide a rare opportunity for investigating the functional and chronological links between cave speleogenesis and subaerial channel dynamics (Fig. 1).

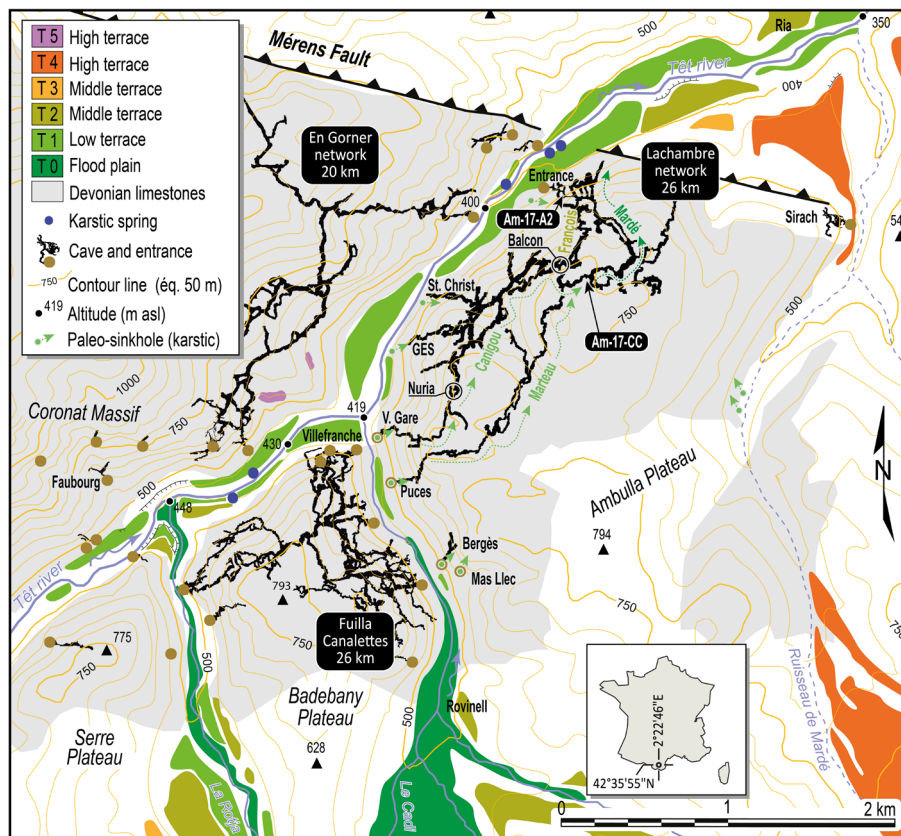


Fig. 1. The subterranean karst around Villefranche-de-Conflent, eastern Pyrenees. This area displays a sequence of cave levels distributed over an elevation range of more than 1,000 meters through the outcrop of Devonian limestone. The lowest cave networks extend continuously for several kilometres and strike roughly parallel to the Têt River valley. The Lachambre network in the Ambulla Massif, east of the trunk river, is the main focus of this study.

THE LACHAMBRE NETWORK AND ITS ASSOCIATED FLUVIAL TERRACES

With over 26 km of mapped topography, the Lachambre network is the largest cave system of Spanish and French Catalonia. Initially known for the quality of its aesthetic concretions in the ‘white canyons’ sector (Cabrol & Mangin, 2000), the cave network displays above all very extensive low-gradient passages that indicate a steady base level during an extended period of glacial or interglacial time. Based on the reconnaissance work provided by the Collectif Conflent Subterrani (2014), which provides detailed

planimetric maps but delivers limited altimetric data, and augmented by personal explorations and observations, here we describe key features of the local river valley terraces and the cave network.

The fluvial chronosequence of the Têt River

The Têt (length: 120 km, catchment area: 1,400 km²) flows eastward from the higher eastern ranges of the Pyrenees (~2,800 m a.s.l.) to the Mediterranean. Repeated valley incision and subsequent deposition has produced a record of Quaternary strath terraces and alluvial sequences extending discontinuously from the Pleistocene frontal moraines of the high

range to the sedimentary depocentres offshore (Delmas et al., 2018). The mid valley section cuts through a syncline in Devonian limestone forming the northern boundary of the Conflent Basin – a Neogene graben filled with clastic deposits which partly buried some of the limestone outcrops. The current position of the Têt River is a result of lateral migration across the basin floor as its channel was pushed northward during the late Miocene by a prograding system of high-discharge alluvial fans descended from the actively uplifting Canigou Massif to the south. During the last 6 to 10 million years, the Têt and its local tributaries – the Cadi and Rotja – cut a gorge through part of the Neogene fill sequence into the underlying limestone, exhuming the bedrock in response to post-orogenic regional uplift of the Pyrenees and generating the conditions for subterranean karst development (Calvet et al., 2015, 2019, 2021, 2022). The deepest gorge section occurs around Villefranche-de-Conflent.

Nine levels of low-gradient cave passages striking roughly parallel to the trunk valley have been identified. They are distributed over an elevation range of almost 1 km, between 420 m and 1,365 m. The caves show evidence of evolution under vadose and periodic flooding conditions, with canyon-like passages, but also near-cylindrical phreatic or epiphreatic cross-sections (Calvet et al., 2019). The more elevated cave levels contain quartz-rich allogenic fluvial sediments from which $^{26}\text{Al}/^{10}\text{Be}$ burial ages have been produced (Calvet et al., 2015, 2024; Sartégou et al., 2018). Only one cave level (Grotte du Faubourg) in the vicinity of Villefranche shares matching elevations with an existing fluvial terrace, which lies currently at +125 m above the modern stream channel. The alluvial deposit yielded two electron spin resonance (ESR) ages of $1,133 \pm 159$ and $1,099 \pm 179$ ka, thereby providing a minimum age for the Faubourg Cave passage (Delmas et al., 2018). This early Pleistocene terrace is labeled T5 and is the most elevated in the fluvial chronosequence of the Têt catchment (Delmas et al., 2018). The lowermost cave levels (Lachambre network: +20 to +30 m) are the main focus of this study because of their rich array of speleogens, and because chronological and geometric relationships can be established with terrace levels T1 and T2 in the adjacent valleys.

Published age constraints on T1 and T2 are scarce. ESR ages obtained by Delmas et al. (2018) were 174 ± 44 ka and 259 ± 90 ka (two ages for T2), and 153 ± 30 ka (single age for T1), respectively. The age for T1, nominally compatible with marine isotope stage 6 (MIS 6), was rejected as anomalous because T1 is the youngest fluvial terrace in the landscape above the active floodplain. Validating it as a Middle Pleistocene deposit would leave no room for a Late Pleistocene fluvial terrace in the Têt Valley – when all other documented rivers in the Pyrenees otherwise display T1 analogues with ages usually compatible with MIS 2 or MIS 4. The ages for T2 – indeterminate: MIS 8, or MIS 6 – remained moot until now, but as indirect evidence from this study will show, the Lachambre cave network confirms that the MIS 6 age (174 ± 44 ka) is the more accurate option, and that T1 is a Late Pleistocene deposit. This preliminary chronological

reference frame sets the stage for the forthcoming analysis of the Lachambre cave system.

The Lachambre network

The Lachambre network extends between the Cadi and Têt valleys and is no longer hydrologically active. Furthermore, no ongoing speleogen development has been observed in its active part. The water table has been detected at approximately –35 m below the cave entrance (depth verified at the Bruno shaft and four others, and consistent with the elevation of the Lachambre emergence at 380 m a.s.l.). The cave system is organised around two large passages striking SW–NE, each parallel to the Têt Valley between the towns of Villefranche and Ria: the Galerie du Canigou and the Galerie du Marteau, the latter offset by 250 to 400 m to the SE (Fig. 1). Given their location and strike direction, these sizeable subterranean arteries (Fig. 2) have collected channel inflow from both the Têt and its right-bank tributary, the Cadi, situated further upstream. Downstream, the Galerie du Canigou strikes SE, intersecting the Galerie du Marteau and subsequently bending back to the NW, where its name changes to Galerie de Mardé (Fig. 1). This sudden incurvation is controlled by the rising north limb of a limestone syncline plunging to the WNW, forcing the outlet to be positioned at the contact between the carbonate outcrop and the Mérens Fault, which forms here a sharp boundary between the soluble Devonian limestone and the other non-carbonate Cambrian outcrops – mostly schist – of the region (Fig. 1). The entrance currently used as the access point to the network involves a complex series of sinuous passages (Galerie Pagès, Galerie Paul, Galerie des Desmans, etc.) (Fig. 3). The corresponding aperture may have functioned as a cave outlet, but it also functioned as a sinkhole for the Têt. Several cave passages branch off to the NE and SE along the curve connecting the Canigou with Mardé. Among these, passages striking SE (Galerie du Canyon terminal, Galerie de Cirac-Sirach, Galerie Sophie) reach within ~700 m of the tributary valley formed by the Ruisseau de Mardé (Figs 1 and 3), where sinkholes (as yet unexplored) are also likely to occur at elevations between 520 and 450 m along the segment where that valley intersects the Devonian limestone – i.e., higher than the floor of the main Lachambre arteries. A passage striking NE (Galerie St. Céré) approaches (but does not intersect) the Têt Valley side above Ria railway station. It appears to rise slightly (+18 m above the entrance to the network, i.e., at 432 m a.s.l.), and could also have functioned as a former karstic outlet (Figs 1 and 3). Other hanging cave passages (Nespola, Lise, Grand Canyon) collectively define a geomorphic level situated 6–8 m above the Mardé segment (Fig. 3).

Three other cave passages located further upstream are either believed or proven to be connected to the Lachambre network (Fig. 1): Grotte St. Christophe, near the Têt dam, is an established former sinkhole of the Têt; Grotte GES (Fig. 3), which intersects the valley side near the railway bridge, also probably functioned as a sinkhole for the Têt; and Grotte de

la Vieille Gare, above the easternmost traffic circle at Villefranche, likewise functioned as a sinkhole for the Cadi and possibly also for the Têt. Supporting evidence is based on its location 140 m to the south of the current Cadi–Têt stream junction, and on the fact that it connects to the Galerie du Canigou at a horizontal distance of 350 m to the east. The Puces Cave (Figs 1 and 3) previously functioned as a sinkhole to the Cadi, but speleological connections with the Marteau passage have yet to be confirmed. Lastly, the Mas

Llec Caves, which occur on three levels between 465 and 510 m a.s.l., are situated 670 m south of Galerie du Marteau (Fig. 1). Although currently unmapped (with one exception: the uppermost Bergès Cave), the lowest levels are plugged by ancient alluvial deposits of the Cadi. The longest cave has been explored over a distance of just 30 m (Salvayre, 1977). There is no reason why those caves should not be connected to the Lachambre network given that the limestone mass extends uniformly across the area of interest.



Fig. 2. A segment of the Lachambre network. At over 26 km in length, this is the largest cave network in the eastern Pyrenees. It features low-gradient cave passages displaying the characteristics of water table caves (WTC). Here, in the Galerie du Canigou, a remarkable sidewall notch (1) coincides with the top of an alluvial deposit of small, well sorted pebbles (2), itself surmounted by a clay-rich flood sequence (3). Units (2) and (3) form a depositional terrace. Sand deposits cross-cutting the terrace (4) provide evidence of a more recent phase of incision of the pebble sequence. Photo: S. Jaillet.

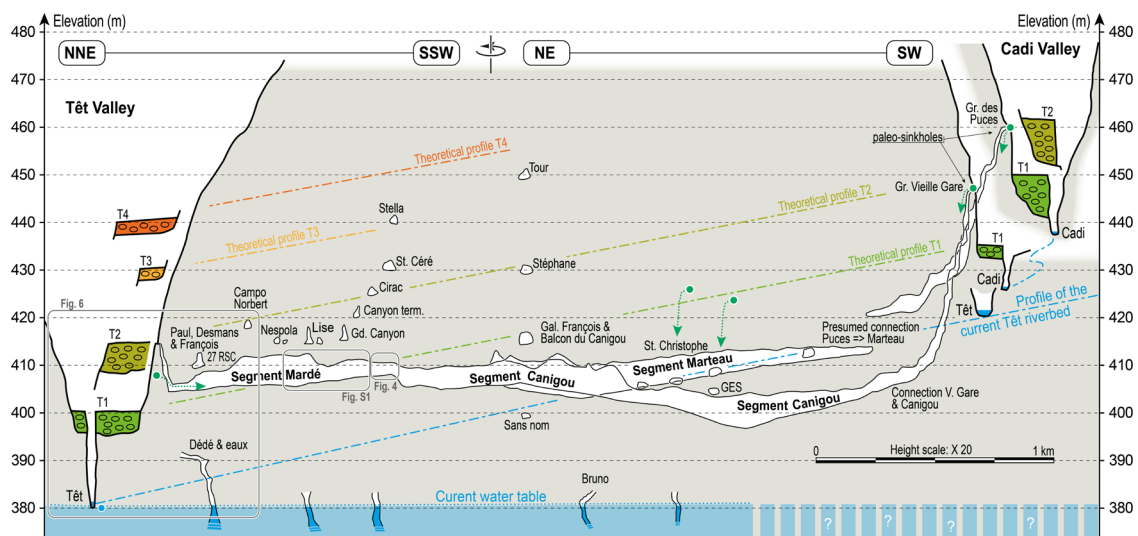


Fig. 3. Longitudinal profile of the Lachambre system between the Cadi (upstream tributary) and Têt (downstream trunk) valleys. The positions of the former sinkholes (Puces, Vieille Gare) and outlets to the T2 and T1 alluvial terraces. The subterranean passages display very low gradients (0.1–0.3%) in a downstream direction, and a reverse gradient in the mid portion of the Canigou segment. The longitudinal profile of the subaerial trunk rivers (Têt) is ~10 times steeper. Note that horizontal distances in this sketch are not systematically accurate. The schematic cross-section is projected on two planes.

Low-gradient water table cave passages

An important highlight of the Lachambre cave network is the frequent and extensive occurrence of low-gradient passages (Fig. 2). The most conspicuous among these (Canigou, Marté) also present a succession of sinuosities, each flanked on both cave walls by solutional notches generated by a former subterranean river. These outstanding notches are continuous, occur on the convex and concave sides

of the cave meanders (Fig. 2), and are plugged at many places by residual accumulations of medium to coarse sand, gravel, and well sorted (long axis: 1–3 cm on average) and mostly well rounded quartz and schist pebbles, with rare occurrences of granite and gneiss. These are observed along the entire length of Marté passage. The residual deposits lodged inside the notch cavities are vestiges of perhaps the last river bedload sequence to have entered the karst. This

pebble deposit is also at places capped by a clay-rich, laminated silt deposit that suggests contemporary or later flooding events in the gallery prior to definitive base-level fall. The silts occasionally reach the cave ceiling, particularly in the Mardé segment and in the north part of Galerie François. Subsequent channel scour, however, depleted these finer-textured cave sediments without further eroding the limestone (Fig. 2).

The combination of speleogen features and sediment deposits described above is typical of water table cave (WTC) passages, i.e., karstic systems where inflow rates through sinkholes are fairly constant and the cave passages do not experience major variations in water depths during their growth into cylindrical cavities (Audra & Palmer, 2011, 2013, 2015; Gabrovšek et al., 2014). No underground features typical of antigravitative speleogenesis (Farrant & Smart, 2011) were observed that might suggest paragenetic processes in the development of the cave passage. There is likewise no external environmental evidence to support the hypothesis of antigravitative cave development during the Late Pleistocene. Paragenesis occurs by upward solution of the limestone, which implies a rising base level over an extended period. The Têt Valley, however, was not glaciated, never dammed by a lake or backfilled by large thicknesses of aggrading sediment, and no Pleistocene marine transgressions likely to have raised water tables in the Têt valley to the point of generating antigravitative limestone solution and sedimentation are recorded. Base-level changes have, instead, been quite steady, as testified both (i) by the external sequence of alluvial terraces, which are all thinly covered strath terraces rather than thick fill terraces (Delmas et al., 2018); and (ii) by the extremely regular diagnostic notch in the Lachambre Cave, which indicates very steady flow rates over an extended period (this study).

At certain locations in the network, particularly those closest to the Têt valley side, accumulations of coarse fluvial debris displaying steep depositional gradients have nonetheless also entered the cave system. These discrete spreads of cobble-sized bedload, which result from episodic fluvial intrusions entering the WTC environment through sinkholes (not unlike sand falling through the neck of an hourglass), are defined here as subterranean debris cones. The cobbles and boulders, ranging between 10 and 40 cm in diameter, consist mainly of gneiss and granite. The cobble-rich deposit partly filling the entrance area to the Lachambre network (Galerie Pagès, Galerie du Canal, Galerie Paul) is further examined in section “U/Th age results”.

After cave passage abandonment, speleothem growth took hold – with calcite concretions developing on exposed bedrock as well as over the various bedload lag deposits. Speleothems of this nature indicate environmental conditions usually typical of interglacial periods (Pons-Branchu & Quinif, 2018; De Waele & Guttiérrez, 2022). However, significant postdepositional corrosion of the speleothems was also observed, with for example a large recumbent stalagmite (Am-17-CC, Fig. 1) which has been conspicuously gouged by a series of erosional scallops.

Given its geomorphological and speleological features, the Lachambre network is ideally suited to addressing links between the subaerial dynamics of alluvial rivers and the dynamics of underground cave passages. The aim here is to understand the chronology of events affecting the cave passages – speleogenesis, cavity filling, emptying and refilling, abandonment – in relation to stream aggradation and channel incision cycles occurring in the valley. In this area, the Têt valley hosts two generations of alluvial terraces (Figs 1 and 3): T2 at +30–35 m (415 m a.s.l. near the official entrance of the Lachambre network), and T1 at +15–20 m (400 m a.s.l.). The elevations given are those of the terrace tread. Alluvial thicknesses are highly irregular, ranging between 5 and 10 m, even locally 12 m down to the underlying strath in the case of T2. At an intermediate elevation between those two terrace levels, the Mardé passage boasts a rich sequence of solutional forms (notches) and deposits (fluvial sediments and speleothems). This environment therefore provides an ideal showcase for analyzing the links between subterranean and subaerial geomorphic features. Key information required to achieve this was obtained by collecting a series of geodetic geomorphological, geochronological data.

METHODS

Topographic leveling and geomorphological analysis

In addition to the existing map of fluvial terraces in the valley section of the Villefranche limestone (Fig. 1, after Calvet, 1996 and Delmas et al., 2018), a differential GNSS survey using a Trimble GEO7x was conducted to control the elevations of the terrace treads. Measurements were post-processed by calibrating them against the RGP–IGN reference station network (permanent GNSS network maintained by France’s Institut National de l’Information Géographique et Forestière), thereby securing vertical inaccuracies of less than 10 cm. Several cave entrances were also surveyed, including the main public entrance to the Lachambre network and the former sinkholes at Vieille Gare and Puces on the Cadi side. Below ground, we relied on the topographic maps produced by the Conflent Subterrani Collective (2014), which are essentially very high-quality 2-D surveys. No elevations are provided, but the surveys offer several simplified and horizontally compressed vertical profiles for the Mardé, Blanchés, François, Canigou and Marteau passages using as a benchmark the elevation of the public entrance to the Lachambre network. The documents also include a few local cross-sections. Although it remains difficult to picture the 3-D organization of the network, particularly the number of cave levels, it was nonetheless possible to compile the existing data, produce a synthetic longitudinal section, and provide an operational overview of the cave patterns between the sinkholes of the Cadi Valley upstream at 450–460 m and the karstic emergence point in the Têt Valley at 380 m (Fig. 3). Additional topographic surveys were conducted

in the Canigou, Marteau and Mardé passages to refine this longitudinal profile and to determine the exact elevation of the water table. In this study we mainly focus on the downstream section of the Mardé, on the central section of the Canigou, and on the Marteau segments.

In order to refine our understanding of cave passage topography, a levelling survey was also carried out along the sidewall notch in the Mardé segment. More than 30 notch points were surveyed over a distance of 350 m using an optical level and a grade rod (Supplementary Fig. S1), thereby guaranteeing millimeter precision. Given, however, the volume of the notch cavity (height: <1 m), it was impossible to select a consistent position in the crook of the notch at each successive measurement. As a result, we postulated instead a conservative uncertainty value of ± 0.1 m for each measurement point.

U/Th dating of speleothems

Constraints on the ages of the various sedimentary deposits – particularly the Am-17-CC recumbent stalagmite – were obtained from a series of samples considered suitable for U/Th dating. Micro-coring techniques (Supplementary Fig. S2), which limit the visual impact and physical damage of sampling to a hole 10 to 12 mm in diameter (Spötl & Matthey, 2012; Monvoisin et al., 2022), were prioritized. Five such cores were extracted from Am-17-CC: two from the base, one from the broken top, one from the flank, and another from a secondary stalagmitic flowstone unit (Fig. 4). Despite the limited number of cores, two to three age results were obtained from each sample – some of them replicates from a single level and others internal to the core stratigraphy. An additional sample (Am-17-A2-1) from a flowstone deposit capping the previously mentioned debris cone in the Lachambre entrance cave was also collected (Fig. 1).

The samples were analyzed at the Laboratoire des Sciences du Climat et de l'Environnement at Gif-sur-Yvette, France. Dissolution in beakers containing known quantities of ^{229}Th – ^{233}U and ^{236}U spikes was followed by co-precipitation with $\text{Fe}(\text{OH})_3$. U and Th purification was performed using U-TEVA[®] resin. The U and Th fractions obtained were measured with a Thermo Scientific[™] Neptune Plus multi-collector inductively coupled plasma mass spectrometer fitted with a jet pump interface and an Aridus[™] II desolvating system. The full procedure is described in Pons-Branchu et al. (2022). After blank and mass fractionation corrections, ages were calculated from measured atomic ratios through iterative age estimation (Ludwig & Titterton, 1994). The ages were corrected for inherited ^{230}Th , under the assumption of a ($^{230}\text{Th}/^{232}\text{Th}$) ratio in the detrital fraction of 1.5 ± 0.75 .

RESULTS

Fluvial terrace altimetry, cave network geometry, and sinkhole connectivity

The geodetic surveys of the fluvial terraces were compared with the altimetric results obtained from

the cave surveys, thereby allowing an accurate appreciation of possible dynamic connections between the various surface and subterranean landforms. In this section, cave elevations and topographic gradients are presented and compared with the elevations and gradients of terraces T2 and T1, and the modern bedrock channel of the Têt. Three cave segments are successively presented: Mardé, Canigou, and Marteau. Elevations for each are given either as + or – altitudes relative to the Lachambre network entrance, or as values relative to sea level – in which case they are noted as above sea level.

The network is described below in successive segments from downstream in an upstream direction, justified here by the primary purpose of examining connections between caves and fluvial terraces in the vicinity of the former stream resurgence. At 404 m a.s.l. in its downstream section, the floor of the Mardé segment lies ~3 m above the nearest tread of T1 (401 m a.s.l.; Figs 1 and 3), and therefore lower than the tread of T2 (415 m a.s.l.). In the upstream direction, the Mardé passage rises by 4 m over a distance of 1,200 m (mean gradient: 0.3%). Over a 350 m subsection of that cave passage, levelling measurements of the sidewall notch obtained an even more gentle gradient of 0.1% (Supplementary Fig. S1). By extrapolation, a steady gradient would also be expected in the upper part of the network (i.e., Marteau and Canigou passages). However, available topographic data indicate some counter-intuitive slope angles and directions (Fig. 3). In its lower section, for example, the Canigou Passage slopes very gently upward (0.14%) in an upstream direction over a distance of ~700 m. In its middle section, however, i.e., between the Balcon du Canigou and the junction with the Nuria passage, the Canigou floor reverses and begins to slope downward in an upstream direction (Fig. 3). It reaches –14 m (i.e., 400.5 m a.s.l.) at the junction with the St Christophe Passage, which is a former Têt sinkhole (its valley-side aperture occurs at 425 m a.s.l., see Fig. 3), and a minimum of –18 m (i.e., 396.5 m a.s.l.) at the intersection with the Nuria passage, which is the lowest point of the Canigou segment (Fig. 3). Because of the backsloping character of the Canigou floor in its middle section, existing cavewall notches (Fig. 2) extend below the elevation of the surveyed Mardé notch situated further downstream (Supplementary Fig. S1). Although these two cavewall notches cannot, as a result, be correlated from strict altimetric criteria, the lower elevation of the Canigou notch suggests nonetheless that it is more recent than its Mardé counterpart. Several more elevated notches have been observed in the Canigou ‘canyon’ segment at around +3–4 m and +7–8 m – not yet studied in detail but suggesting a relative chronology still remaining to be elucidated in finer detail. Beyond the Canigou low point at 396.5 m, the cave slope reverses and rises again upstream, ending at around –11 to –12 m (i.e., 402.5 m a.s.l.) near the underground junction with the steep Vieille Gare sinkhole (Fig. 3).

In map view, the Marteau segment aligns with the upstream extension of the Galerie François via a short (150 m) N–S segment of the Canigou passage

(Fig. 1). The Balcon du Canigou can therefore be interpreted as a former underground stream junction between the Canigou and Marteau passages. Marteau shares the same gradient anomaly as the Canigou, i.e., a significantly lower position than the upstream termination of Mardé (−9 m at its junction with the Canigou; see Fig. 3). However, while Marteau descends in an upstream direction over a distance of 450 m, its lowest point is only −12 m, i.e., 402.5 m a.s.l. (instead of −18 m for Canigou), after which it rises very steadily for 1.3 km to −2 m in the upstream direction (i.e., 412.5 m a.s.l.). The sidewall notches observed at mid distance along the Marteau segment (Salle de l'Union, 406 m a.s.l.) are cut very low above the passage floor and are unlikely to be cogenetic with the Mardé notches at 404 m a.s.l., which occur more than 1.5 km downstream of this point.

Several other generations of cave levels were explored for this study. They are plotted on the longitudinal section in Figure 3. An older cave floor occurs at ~+5 m above the Mardé segment (i.e., 409 m a.s.l.). Known as Galerie François, its likely extensions to the north are the Paul and 27 RSC caves. The elevations of Galerie François and the tread of terrace T2 in the adjacent valley are almost identical. Another very clearly defined level extends above the Galerie François in the form of Galerie Lise, Grand Canyon, Galerie Nespola and Galerie Norbert (Fig. 3). They all extend roughly parallel to the Mardé, lie ~8 m above it, and host a separate (and presumably older) bundle of coarse sand and gravel deposits. Rising further into the cave sequence, Canyon Terminal and Galerie Cirac occur between +13 and +17 m above Mardé, followed by Galerie St Céré at +24 m, and a horizontal segment of Galerie Stella around +34 m (440 m a.s.l., similar to Galerie Tour). The most elevated is Galerie Tour, at 449 m a.s.l. All those levels, except perhaps the Lise–Grand Canyon–Nespola–Norbert bundle which is nominally compatible with T2 based on elevation criteria, extend above the elevation of terrace T2 and are therefore most likely older – perhaps correlating with periods of fluvial incision between alluvial accumulation phases T4 and T3 given that they occur below the tread of T4 at Sirach (450–455 m a.s.l., see Figs 1 and 3).

Several near-vertical shafts under the Mardé segment and some of its neighbors are known to reach the top of the modern water table at −35 m below the Lachambre entrance cave (Galerie Dédé, Galerie Bruno), i.e., at an elevation of 380 m a.s.l. The space between this drowned system and the main Mardé and Canigou passages above it appears devoid of cave passages other than the small Galerie Dédé and other steep counterparts (Fig. 3), all of phreatic origin based on their morphology. The Dédé and others at that elevation are the only occurrences likely to be associated with the valley incision stage between T2 and T1. They could, however, also be coeval with the modern Têt channel. In each case the connection remains tentative.

The topographic overview provided above gains from also examining network connections with the abandoned sinkholes situated upstream. At least

three former sinkholes have been identified along the Têt and Cadi rivers: St Christophe (425 m a.s.l.), GES (417.5 m a.s.l.) and Vieille Gare (445 m a.s.l.). The Puces Cave (~460–465 m a.s.l.) is also a former sinkhole of the Cadi River, which today flows 21 to 26 m below the sinkhole aperture. However, floor elevations along the upstream part of Galerie des Puces oscillate between 443 and 448 m a.s.l., indicating that they extend more than 17 m below the Puces entrance and therefore +4.5 m to +9.5 m above the modern Cadi Valley floor. The Galerie des Puces pinches out downstream between 420 and 425 m (i.e., 40 m below the sinkhole aperture), and therefore −26.5 to −21.5 m below the Cadi channel.

Multiple generations of fluvial terraces also occur in the Cadi Valley, the nearest upstream tributary to the Têt (Fig. 1). At Rovinell, the tread of T2 occurs at 502 m a.s.l. (i.e., +26 m), and displays an alluvial thickness of 12 to 14 m. T1 occurs at 488 m a.s.l. (i.e., +12 m), with the Cadi flowing at 476 m a.s.l. When projected onto a longitudinal profile between Rovinell and Ria, the data confirm the narrow correlation between the elevations of the terrace treads in the lower Têt and the elevations of the abandoned sinkholes situated further upstream: both sinkholes (i.e., Puces: 462 m a.s.l., and Vieille Gare: 450 m a.s.l.) extend below the tread of terrace T2 and above the tread of T1. These correlations are highlighted in Figure 3.

In addition to the more outstanding features described above, particularly the gentle gradients of the cave floors and continuity of sidewall notches extending over kilometer length scales, a few ceiling collapses in the passages have generated secondary side loops cut directly in the bedrock (e.g., Salle de la Réunion). Thus, while being an upstream continuation of the low-gradient Mardé segment, the low-gradient Canigou segment is separated from it by a rockfall area. In altimetric terms, a 2–3 m vertical offset occurs with the Mardé segment as a result: whereas Mardé appears to terminate at −6.5 m, the Canigou Passage thus begins upstream at −9 m. Four rockfall areas occur likewise in the Mardé passage, and the Marteau segment comprises ten collapse zones, making a systematic continuity analysis of speleogen altimetry a delicate task (not attempted here). Three additional ceiling collapse areas in the middle section of the Canigou segment, i.e., where elevations drop from −400.5 to −396.5 m in the upstream direction (see above and Fig. 3), further rule out hopes of correlating sidewall notch features which occur at three to four slightly contrasting elevations along the length of that passage continuously and consistently between the uppermost and lowermost reaches of the cave system.

U/Th age results

The five cores from the Am-17-CC stalagmite produced thirteen stratigraphically consistent U/Th ages (Fig. 4 and Supplementary Table S1). The two cores from the base yielded the following four dates: 43.9 ± 1.7 ka, 44.3 ± 1.8 ka, 46.1 ± 0.6 ka and 45.4 ± 0.6 ka. At the top of the stalagmite, a sample from the core of the speleothem yielded three results close in age

to the previous ones: 49.7 ± 6.0 ka, 52.2 ± 3.2 ka, and 43.4 ± 3.6 ka. The side core produced two results: 31.2 ± 0.2 ka and 31.0 ± 0.5 ka. The fifth core, taken from a younger

flowstone layer (see Fig. 4), provided age duplicates of 10.1 ± 1.2 ka and 11.3 ± 0.2 ka for the base, and 4.5 ± 4.5 ka and 6.1 ± 4.6 ka for the top.

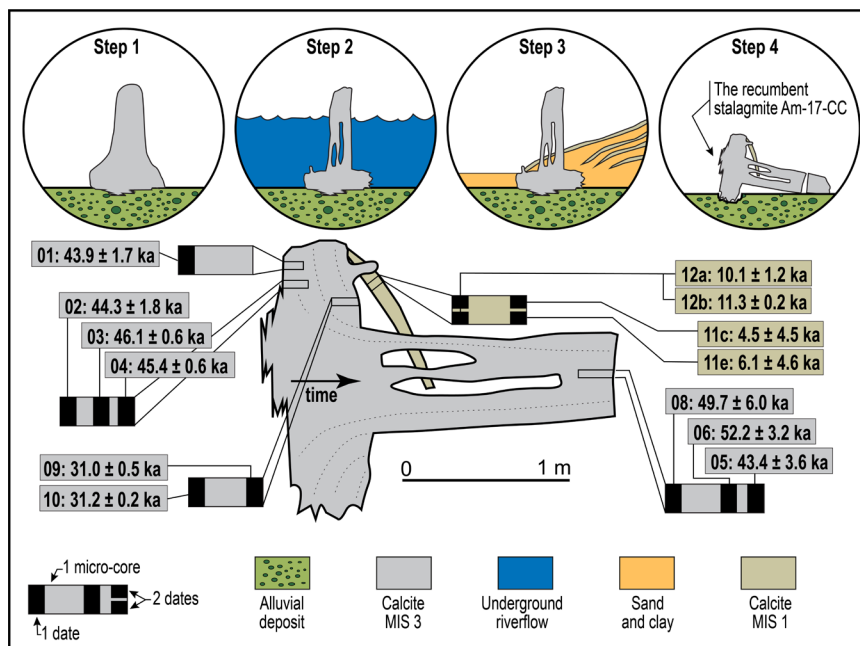


Fig. 4. Sequence and chronology of geomorphic events. The recumbent stalagmite initially grew vertically on an alluvial deposit but was toppled at a later date by high-energy flow through the cave. Nine U/Th ages obtained from the base and summit of the concretion, supplemented by four additional ages from another flowstone unit capping a sequence of younger deposits, provide a full event chronology for this composite speleothem.

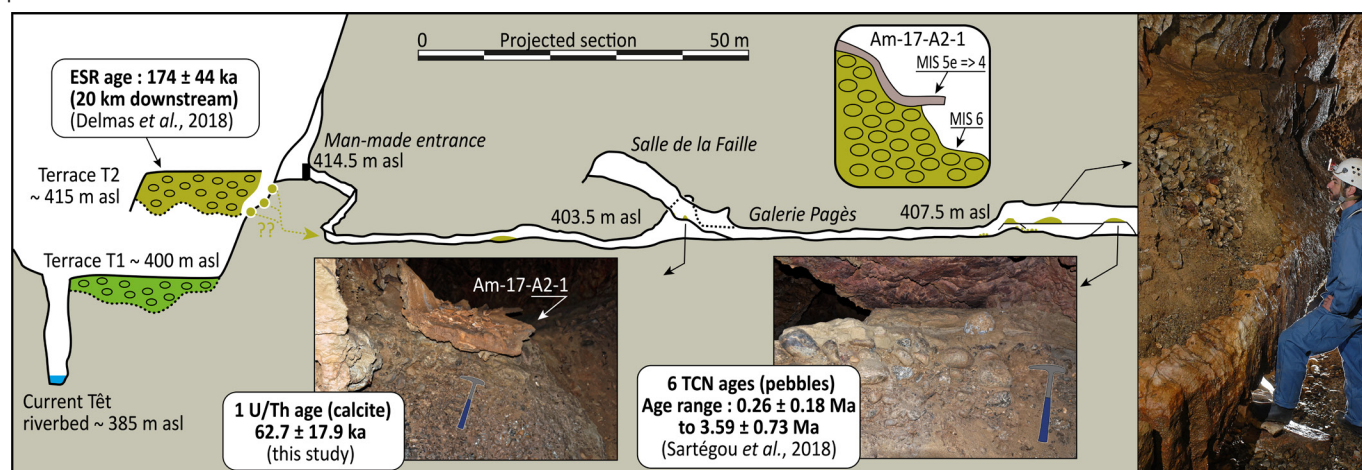


Fig. 5. Detail of the Lachambre entrance area, where an intrusion of channel bedload into the cave has occurred through a lateral sinkhole previously connected to the Têt. The spread of weathered pebbles and cobbles extends a few hundred metres into the Mardé segment studied here. Terrestrial cosmogenic nuclide burial dating has yielded a wide range of depositional ages, only the youngest of which is credible (see Calvet et al., 2024). Aggradation of terrace T2 during MIS 6, i.e., aftergenesis of the Mardé segment, is compatible with this pebble mass and with the age of the Am-17-A2-1 speleothem capping it.

A sample from another speleothem was collected from the entrance zone of the Lachambre network (Am-17-A2-1, ~415 m a.s.l., Fig. 5). The flowstone is draped over the previously described debris cone in which median cobble size (tens of centimetres) and steep depositional slope indicate high-energy local inputs of bedload through a sinkhole (Fig. 5). The deposit would have poured into the cave and spread out by a few hundred metres at most. The flowstone yielded a U/Th date of 62.7 ± 18.9 ka. Given the large age uncertainty, ascribable to the presence of detrital material in the sample ($^{232}\text{Th} = 88$ ppb and $^{230}\text{Th}/^{232}\text{Th} = 1.83$), this flowstone would have developed at some time between the end of MIS 5 and the beginning of MIS 3 (age corrections are explained in Supplementary Table S1). The age of the speleothem is nonetheless consistent

with $^{26}\text{Al}/^{10}\text{Be}$ burial ages obtained by Sartégou et al. (2018) from the underlying cobble deposit itself. The burial age results ranged between 260 ± 180 ka and 3.59 ± 0.73 Ma. Considering that this debris accumulation was introduced into the cave system through a sinkhole in the flank of the valley, it seems reasonable to retain as most valid only the youngest age – i.e., 260 ± 180 ka – based on Lyell's stratigraphic Law of included fragments (see detailed discussion in Calvet et al., 2024). Despite the large uncertainty around the burial age of the deposit (potential range: MIS 10 to MIS 5), positioning the emplacement of the cobble unit somewhere within the MIS 6 time window would make it consistent with the depositional age of terrace T2 (174 ± 44 ka).

DISCUSSION

Summary of key findings

A stack of cave passages has been identified in the Lachambre network, some of which can be superficially correlated with fluvial terraces T2 and perhaps T3 based on approximate elevation criteria. With values of ~0.1%, the topographic gradient of the main subterranean passages is very gentle. These very low-gradient passages cut through the fractured and intensely folded limestone mass. They are never associated with impervious bedrock. This is fully consistent with the water table cave model, where widespread sidewall notches cut by the corresponding underground rivers are recognizable as markers of WTC-related processes. The notches could not be mapped continuously throughout the entire network because of cave ceiling collapses, but the survey documents counter-intuitive occurrences of notch distribution, with notches occurring at elevations lower in the upstream than in the downstream portions of the Canigou–Mardé cave passages.

Results also reveal a clear mismatch between the gentle gradients of the Lachambre WTCs and the longitudinal gradients of subaerial terraces T1 and T2 and of the modern Têt channel. Here, former sinkholes in the upstream area join the low-gradient cave passages via very steep conduits, some of them nearly vertical (Fig. 3). Such configurations document transient states during which the subaerial river flows at a higher elevation than the underground river, feeding it with water and sediment through the sinkholes. The large contrasts (10 to 1 ratio) in hydraulic gradient between the subaerial and subterranean rivers suggest highly contrasting transport capacities. This explains the predominance of sand and gravel and the small size of the pebbles (average: 1–3 cm).

The U/Th ages obtained from the speleothems have also provided clear constraints on successive episodes of cave growth, cave speleothems chronology, and cave sediment residence times. The age sequence outlines a robust four-stage stalagmite growth and destruction history (Fig. 4). The large, postdepositional stalagmite established itself over the gravel bed between 50 and 30 ka – therefore spanning part of MIS 3, a period of relative warming during the Late Pleistocene ice age. Climatic conditions at the time thus allowed stalagmite growth to take place in a cave passage devoid of high-energy flows likely to disrupt speleothem development. Subsequent cave reflooding during MIS 2 promoted a major erosional episode during which the stalagmite underwent severe corrosion by solutional processes – hence the deep scallops on its flanks. At the same time, substantial masses of gravel were removed under suitably powerful shear stress conditions. The stalagmite did not, however, break or topple under this regime. Suspension load aggradation during flood recession stages explains the clay-rich silt accumulations also present. These finer deposits are themselves capped by another stalagmitic floor of early Holocene age that also post-

dates the scallops. A final interval of high-energy flow resulted in scouring away the fine sediments, toppling the stalagmite, ploughing into the underlying gravel fill deposit, and thereby clearing much of the cave passage of its pre-Holocene sediment fill (Fig. 4). In the vicinity of the toppled stalagmite, more recent speleothems are nonetheless intact (see new generation of stalagmites in Supplementary Fig. S2), indicating that the Holocene remobilizations belong to the geological past.

Considered together, these results provide tentative answers to three scientific questions relevant to cave science: (i) the speleogenesis of the Lachambre network, (ii) topographic and chronological links between sequences of fluvial terraces and subterranean cave passages, and (iii) the functional interaction between a trunk river and its limestone host rock in an epigenetic karst environment.

Process-related implications for cave science

In its downstream section, the cave network displays clear connections with some of the subaerial fluvial terraces of the Têt. Based on the topographic criteria obtained in this study (see Calvet et al., 2024 for additional petrographic and geochronological criteria), it seems reasonable to connect the pebble- and boulder-filled Mardé deposits (elevation: ~405 m a.s.l.) with the aggradational sequence of terrace T2. The Mardé passage hosting them, therefore, is clearly older. The deep and continuous sidewall notch in Galerie Mardé provides a robust speleological indication of past base-level stability – itself implying that inlet and outlet flows through the cave were occurring through suitably calibrated sinkholes and resurgences, respectively, to allow the typical WTC morphology to develop.

Further upstream, several notches displaying similar dimensions to their Mardé counterparts were also identified. As described in section “Fluvial terrace altimetry, cave network geometry, and sinkhole connectivity”, they all occur at lower elevations than at Mardé. Based on the numerous rockfall deposits obstructing the cave passages and the notion that they could have been earthquake-induced, the hypothesis of tectonic offsets in the cave floors is a *prima facie* possibility. However, more extensive research on Quaternary neotectonics in the eastern Pyrenees has until now only documented evidence of scarce, low magnitude and low frequency seismic activity (Calvet et al., 2021). Whereas tectonic offsets of about 1 m in cave passages were previously reported from the Grotte du Faubourg above Villefranche, on the north side of the Têt valley (Hez et al., 2015), they occur at an elevation compatible with a vestige of terrace T5 (see earlier section “The fluvial chronosequence of the Têt River”) rather than with younger fluvial landforms of T1 or T2 vintage. It would thus appear more consistent to explain the decline in cave notch elevation in an upstream direction by a series of underground stream captures and autocaptures which have entailed local cave-passage grading anomalies and driven sinkhole migration incrementally upstream. Underground drainage capture scenarios of this nature have

previously been recognized in drainage systems driven by headward stream erosion, including in stable intraplate settings, undisturbed by neotectonics, such as the Champagne and Lorraine regions of NE France (Jaillet, 2001). Likewise, the lower reaches of the upstream section of the network (Canigou segment) are thus plausibly younger than its downstream section (Mardé segment).

As mentioned above, the Lachambre Cave passage gradients (0.1–0.3%) are conspicuously more gentle than average river channel gradients in the adjacent valleys (~1.5% for the Têt and 3.06% for the Cadi). As a result, the respective cave and channel profiles diverge progressively downstream and upstream in scissor-like fashion on either side of a point of intersection: thus, whereas the Lachambre Cave network hangs above the modern valley floor in its downstream segment, with a maximum of relative relief where the emergence occurs at ~380 m a.s.l., the cave passages in the upstream segments are situated at or below the elevation of the modern riverbed – i.e., where the ancient stream sinkholes occur (Fig. 3). This configuration can be explained by delays in the way the network operates: whereas, at any given time, the karstic resurgence downstream defines the base level of the subterranean network, each increment of subaerial river incision will also be propagated by

headward erosion through the active cave network. As they progress upstream, these migrating subterranean knickpoints trigger a succession of breakthrough undercaptures. Lengthy WTC passages such as the Mardé–Canigou are thus diachronous, with their younger sections and tributary passages upstream ending up being less elevated than their relatively more mature counterparts downstream because of the successive waves of headward cave solution driven by channel incision along the trunk river. The headward waves of cave solution bypass the lower cave sections (e.g., Mardé) and propagate instead through the middle and upper part of the cave network. Under such a scenario, we would expect some mid- to upstream segments of the Canigou WTC to lie several meters below the Mardé. The linking undercapture cave passage has not yet been discovered (see ‘???’ symbols in Fig. 6), but a study involving a more complete and definitive topographic resolution of the Mardé/François/Marteau/Canigou junctions could allow this question to be resolved. This could offer a more fully coherent interpretation for all the low-gradient cave passages, thereby testing the validity of the diachronous WTC passage hypothesis – its downstream section being synchronous with terrace T2, and its upstream part being instead synchronous with terrace T1.

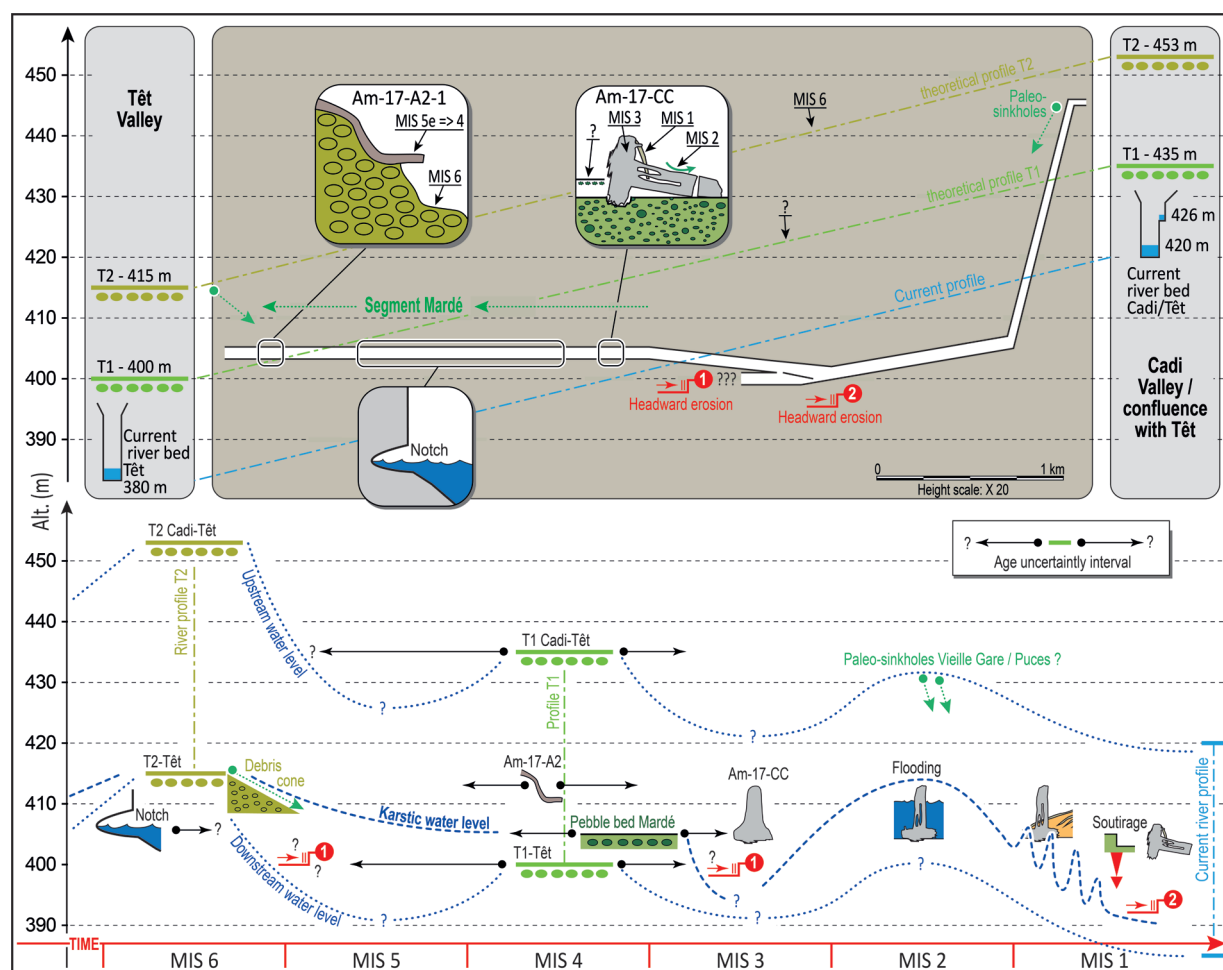


Fig. 6. Model summarizing the co-evolution of terraces T2 and T1, here affiliated to the Têt and Cadi rivers, and the subterranean karstic features documented in the Lachambre network. Each geomorphic feature is positioned on a timeline according to its elevation and age uncertainty. Water levels upstream (Têt–Cadi), downstream (Têt), and within the karst are indicated at each time step. Despite being almost horizontal, the Mardé segment studied here, underwent three major phases of hydrological activity during MIS 6, MIS 4, and MIS 2. Initial formation of the cave passage, successive alluvial influx and flooding events, speleothem growth, and definitive cave abandonment all occurred over a time period spanning the formation of terraces T2 and T1.

Implications for the emplacement of fluvial terraces T2 and T1

Here we articulate the cave stack chronosequence with the fluvial terrace chronosequence (Fig. 6). The model is based on the schematic longitudinal sections shown in Figure 3. The subaerial key components are the elevations of T1 and T2, the current bedrock channel profiles, and the theoretical past and present longitudinal channel profiles. The key subterranean landforms are the Mardé cave notch (Supplementary Fig. S1), the recumbent flowstone concretion (Fig. 4), and the Lachambre entrance debris cone (Fig. 6).

In Figure 6, the chronosequence-defining landforms are plotted on a timeline divided schematically into six marine isotopic stages (MIS). The T2 and T1 terrace profiles and the modern bedrock channel elevations are shown as segments with their upstream and downstream occurrences at different altitudes. Variations in elevation of the Têt River channel are indicated, with some uncertainty regarding the positions of the points of maximum incision of T1 relative to T2. Some of the speleological indicators, which document the history of the large recumbent stalagmite (Figs 4 and 6), plot on the timeline with excellent age precision, whereas others carry greater chronological uncertainty. The Mardé notch, for example, was generated almost certainly during MIS 6, i.e., before the definitive aggradation of T2 was completed (T2 age: 174 ± 44 ka). Given that the Lachambre debris-cone deposit, of suspected MIS 6 age but with a large error bar (see section “U/Th age results”), rises over the sidewall notch, it can be inferred that its debris entered the cave after the notch had fully developed under WTC conditions, and therefore probably during the aggradation of T2.

The gravel unit in the upstream part of the Mardé segment (Fig. 1) was emplaced before MIS 3 given that the deposit is capped by stalagmite Am-17-CC – itself a MIS 3 feature. The Mardé gravel unit would thus be consistent with a MIS 4 minimum age, thereby making it compatible with the aggradation of T1 (see section “The fluvial chronosequence of the Têt River”). The chronology becomes more precise between MIS 3 and the Present. Stalagmite Am-17-CC was severely eroded by high-energy subterranean flow during MIS 2, then buried by fine-textured fluvial deposits and subsequently draped by secondary speleothems at the beginning of MIS 1. An internal reorganisation of epiphreatic flows driven by breakthrough undercapture (‘soutirage’, sensu Häuselmann et al., 2002) destabilized the large stalagmite, causing it to topple over during a later interval of MIS 1.

To summarize the history of the Mardé segment, this cave passage was generated at the latest during MIS 6, and was also invaded through a sinkhole by a population of bedload cobbles and small boulders from the Têt during MIS 6, forming the Lachambre subterranean debris cone. Possibly during MIS 4, the Mardé segment was once again filled by alluvial deposits – this time supplied from upstream rather than locally through the Lachambre sinkhole. The Mardé cave subsequently hosted powerful water discharges during MIS 2, resulting in severe corrosion

of stalagmite Am-17-CC. In conclusion, while it seems reasonable to correlate the Galerie Mardé with fluvial deposit T2, this low-gradient cave passage has effectively recorded the entire T2 alluvial cycle of the Têt: pre-T2 channel incision, T2 alluvial aggradation, T2 floodplain incision, and terrace abandonment. The Mardé segment thus also remained functional during the transitional phase of base-level change leading to incremental valley incision and the aggradation of T1.

Systemic interaction between Earth-surface and subterranean dynamics: a conceptual model

The counter-intuitive findings from the Lachambre network summarized above raise the wider question of (i) whether water table cave levels are reliable palaeoaltimetric substitutes for thalweg levels in the absence of evidence from subaerial alluvial deposits, and (ii) whether the model summarized in Figure 6 only has local validity or could instead have wider relevance among other valleys in limestone karst.

The conditions encountered in this case study are typical of networks displaying extensive WTC passages supplied by river sinkholes, themselves fed by losing rivers descended from upper catchment areas in impervious silicate rocks. In the present case, the cave section occurs in a limestone outcrop intersected by a trunk river mostly conveying non-carbonate bedload (Calvet et al., 2015). Other similar settings are encountered along the northern Pyrenean mountain front, such as the Aude valley and its associated Grotte TM71 (Bigot, 2004; Calvet et al., 2024). The Aude would merit a similar study, but another case in NE France has already provided valuable insight into the crucial function of breakthrough undercapture sinkholes connecting fluvial terraces and subterranean karst.

The karst system at Pierre-la-Treiche, near Toul in Lorraine, displays a well exposed sequence of former sinkholes associated with the Moselle River gorge. Understanding the functional connection between the stack of cave passages – which in this region are stuffed with alluvial gravels – and the fluvial terraces of the feeder stream was made possible by direct observation of valleyside exposures crosscutting undercapture shafts and other cave geometries in small quarries (Jaillet et al., 2002; Losson & Quinif, 2004; Losson et al., 2006). Evidence showed that, despite the low-gradient topography of the cave passages, the connecting zone between terrace deposits and subterranean WTC galleries (specifically Grotte Sainte-Reine) consisted of a multitude of smaller, steep to nearly vertical feeder shafts. It was concluded that the horizontal cave passage receiving the allochthonous sediments developed neither at the elevation of the subaerially aggrading alluvial mass nor just above it, but emphatically a few meters below the bedrock channel floor undergoing subaerial alluvial aggradation.

Like this analogue from the eastern Paris Basin, the low-gradient limestone cave passages of the Lachambre network are polygenetic karstic features. They have diachronously recorded the following event sequence, summarized in Figure 7: (i) a period

of cave growth during an interval of valley incision by the trunk river; (ii) a period of cave sediment accumulation associated with simultaneously ongoing alluvial aggradation in the valley; (iii) a period of incision of these cave sediments driven by a resumption of valley incision, with subterranean headward erosion generating subterranean stream

captures or autocaptures, periodic flooding of the upper passages, and suspended load settling out during flood recession; and finally (iv) a resumption of cave flooding and sediment plugging of the lower segment of the cave passage. Figure 7 also attempts to link climate-driven alluvial cycles (Cordier et al., 2017) with the observed dynamics of the cave system.

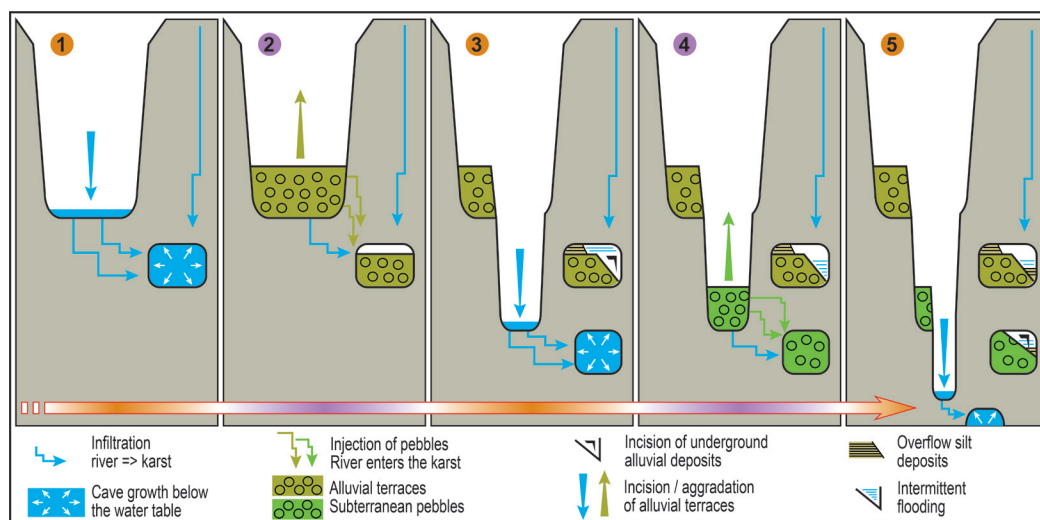


Fig. 7. Simplified theoretical model of the development of cave passages associated with the alluvial cycles of a river recharging the karst. During periods of channel incision (stages 1, 3, and 5, e.g., during an interglacial period for this type of karst), the river contributes to cave recharge. Limestone solution maintains cave growth in a fully drowned environment. During periods of channel aggradation (stages 2 and 4, e.g., during a glacial period), new fluvial bedload enters the karst. Through successive reorganisations, the underground channels also undergo secondary changes involving incision, flooding, etc.

CONCLUSIONS

The extensive Lachambre system in the Têt River valley has proved to be a highly relevant area for investigating the dynamic interaction between diachronous sequences of alluvial terraces and sequences of limestone cave passages. Based on the evidence of fluvial terrace gradients being typically ten times steeper (1–3%) than water table cave gradients (0.1–0.3%), the case study strongly suggests that alluvial terrace aggradation and cave passage growth do not develop in lockstep with one another.

In mid-latitude environments, cave development occurs mainly during interglacials and interstadials, or at the end of the cold-to-warm transition periods that drive valley incision (Maddy et al., 2001). Therefore, and with the exception of paragenesis (a scenario ruled out in the Lachambre setting), speleogenesis and alluvial fills are not synchronous. A low-gradient WTC passage thus documents a phase of riverbed stability, and indicates the approximate level of a strath terrace over which alluvial deposits of the following cold phase will aggrade, thereby also spilling into the neighboring cave passage during that period.

The co-evolution of fluvial terraces and karstic levels thus involves substantial time lags, with the caves also expanding diachronously upstream in response to migrating subterranean knickzones driven by channel incision in the trunk valley. In the absence of independent controls from fluvial terrace ages and geometries, cave passages may thus not be entirely reliable paleoaltimetric proxies for conducting reconstructions of landscape evolution unless specific precautions are taken. In the Lachambre example, the

downstream and upstream sections of the continuous low-gradient cave passage record different intervals – i.e., slightly offset in time – of the alluvial and channel incision cycles occurring in the trunk river.

Discrepancies between cave and stream channel gradients imply that, over length scales no greater than a few kilometers, the respective WTC and thalweg profiles intersect in scissor-like fashion. Upstream of the pivot, the low-gradient cave passages will be encountered accordingly at elevations situated below the elevations of the subaerial terrace treads and their corresponding sinkholes, and potentially even below the modern bedrock floor of the trunk stream – as observed in the case of the mid-Canigou segment in Figure 3. The consequence is that during periods of valley-floor aggradation, the invasion of WTC passages by gravel bedload is facilitated by very steep to subvertical feeder shafts connecting the river channel to the cave system via sinkhole apertures. Such shafts have been observed in the Moselle valley, and likewise occur in the Lachambre system (e.g., Pucés, Vieille Gare and St Christophe in relation to T2 and T1; see Fig. 3). Within the extended time interval of a full alluvial cycle, and even of up to two cycles in low-energy environments where successive increments of channel incision by the trunk river are small, any given cave passage may thus undergo a diachronous sequence of transformations that include passage growth by chemical solution during warmer periods, cavity choking by fluvial bedload influx during colder periods, and one or more subsequent reflooding events involving partial cavity clearance interspersed with episodes of speleothem growth and speleogen development. This scenario was tightly

documented by investigations in the Mardé segment. This low-gradient (0.1%) passage was (i) generated during MIS 7, or at the latest during the beginning of MIS 6; was additionally (ii) invaded through a sinkhole by an accumulation of bedload cobbles during MIS 6; was (iii) partially filled upstream by a gravel deposit, perhaps during MIS 4; (iv) hosted widespread growth of speleothems during MIS 3; and (v) underwent flooding during MIS 2, with evidence of erosional scallops gouging the MIS 3 stalagmites. The event chronology recorded by the Mardé cave segment is associated with the MIS 7–MIS 6 alluvial cycle, which, in the Têt valley, generated fluvial terrace T2. The cave history also documents a number of younger geomorphic episodes, the chronology of which could only be unravelled by detailed analysis and U/Th dating of speleothems.

In conclusion, cave levels in limestone karst are reliable paleoaltimetric proxies, but they provide the paleoelevation of the resurgence area, and only the resurgence area. Thus they provide potentially valuable records of drainage evolution wherever intersecting rivers drive incision of the trunk valley and feed water and allogenic sediment into the cavities. However, approximate altitudinal correlations between cave levels and subaerial alluvial deposits gain from additional speleological analysis, with attention to precise altimetry, cave geomorphology, cross-cutting relations in the cave sediment and speleothem record (Häuselmann, 2007, 2010), all supported whenever possible by multi-method radiometric dating of the clastic deposits and speleothems.

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Authorship statement: SJ, GH and MC designed the study and carried out the observations, measurements and field sampling. EPB carried out the U/Th analyses at the LSCE facility. SJ, GH, MC, MD and YG compared the endokarst results with data concerning the alluvial terraces of the Têt. SJ, GH, MC, MD, YG and EPB contributed to the writing and design of the manuscript.

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Supplementary information for:

Counter-intuitive links between cave genesis and subaerial stream dynamics in the Têt Valley–Lachambre network, eastern Pyrenees, France

Stéphane Jaillet^{1,*}, Gabriel Hez¹, Marc Calvet², Magali Delmas², Edwige Pons-Branchu³, and Yann Gannell⁴

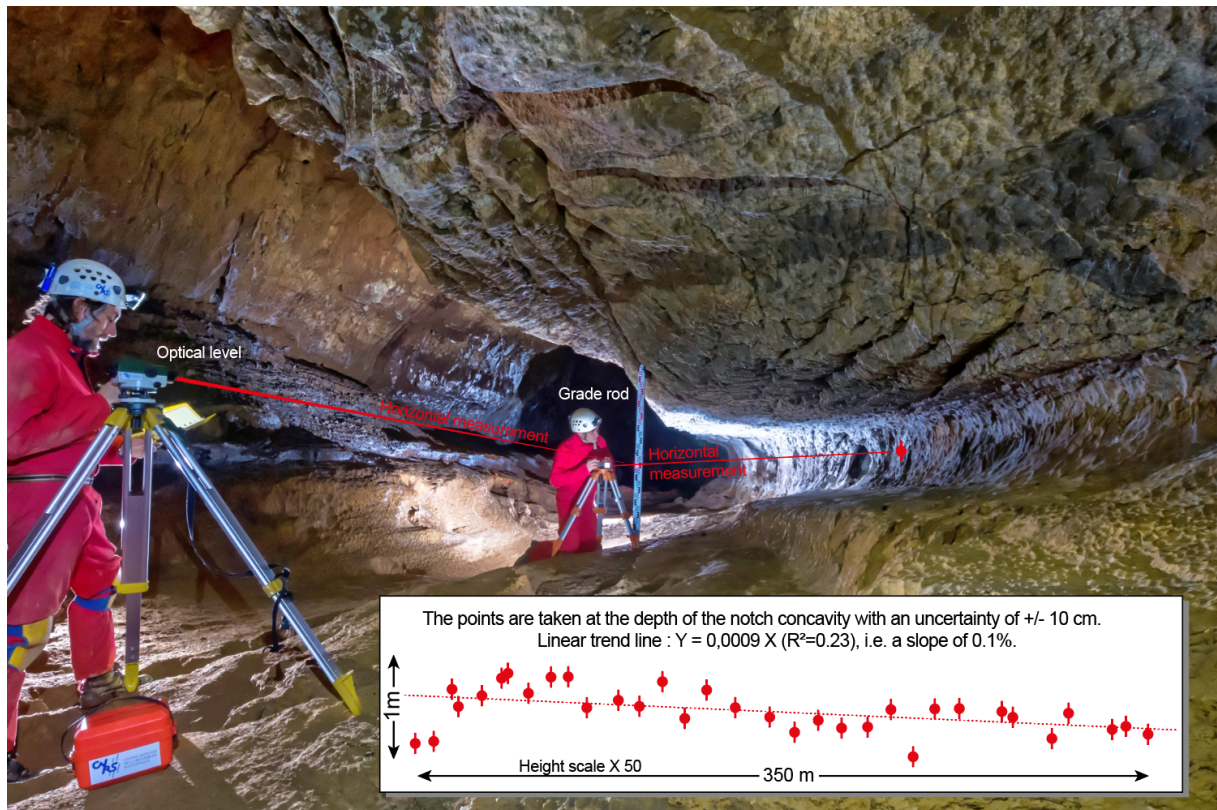
¹EDYTEM, UMR 5204 CNRS, Université Savoie Mont Blanc, Pôle Montagne, 73390 Le Bourget du Lac, France

²Université de Perpignan, Via Domitia, CNRS UMR 7194 Histoire Naturelle de l'Homme Préhistorique, 52 avenue Paul Alduy, F-66 860 Perpignan, France

³Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay, 91191 Gif-sur-Yvette, France

⁴Université Lumière Lyon 2, CNRS, UMR 5600 EVS, F-69635 Bron, France

*Corresponding author: stephane.jaillet@univ-smb.fr



Supplementary Fig. S1. Millimeter-precision leveling of the underground river notch in the Mardé segment. Despite uncertainty in the positioning of measurement points along the length of the notch, the large population of measurements ($n > 30$) confirms the very gentle ($\sim 0.1\%$) gradient of this water table cave. Photo: M. Thomas.



Supplementary Fig. S2. Micro-coring, here into the top of the recumbent stalagmite on the floor of the Mardé segment (location in Figure 1). The intense gouge marks scarring the speleothem testify to the passage of a powerful underground river, interrupting the stalagmite's growth prior to stalagmite toppling at a later date. Ages obtained from the base, summit and secondary regrowth structures provide further age brackets to the cave's geomorphic history (results in Figure 4). Note intact active stalagmites in the background (unsampled, age unknown). Photo: S. Jaillat.

Supplementary Table S1. U/Th ages of speleothem micro-cores in the Lachambre network, eastern Pyrenees.

Sample code name	$[^{238}\text{U}]$		$[^{232}\text{Th}]$		$\delta^{234}\text{U}_M$		$(^{230}\text{Th}/^{238}\text{U})$		$(^{230}\text{Th}/^{232}\text{Th})$		Age before 2018		$\delta^{234}\text{U}_i$		Corr. age before 2018	
	ppm	$\pm 2\sigma$	ppb	$\pm 2\sigma$	‰	$\pm 2\sigma$	$^{230}\text{Th}/^{238}\text{U}$	$\pm 2\sigma$	$^{230}\text{Th}/^{232}\text{Th}$	$\pm 2\sigma$	ka	$\pm 2\sigma$	‰	$\pm 2\sigma$	ka	$\pm 2\sigma$
Am 17-CC-01	0.0640	0.0005	11.82	0.09	2018.6	3.0	1.099	0.0040	18.14	0.07	46.89	0.26	2285.4	11.6	43.92	1.72
Am 17-CC-02	0.5829	0.0047	113.31	0.91	2004.4	2.7	1.1042	0.0036	17.24	0.06	47.42	0.23	2271.6	11.8	44.28	1.78
Am 17-CC-03	0.0550	0.0004	2.37	0.02	2081.4	3.0	1.1195	0.0036	78.81	0.25	46.75	0.23	2370.7	5.2	46.06	0.57
Am 17-CC-04	0.0537	0.0004	2.44	0.02	1979.9	3.2	1.0704	0.0040	71.95	0.27	46.16	0.27	2251.0	5.5	45.41	0.64
Am 17-CC-05	0.1599	0.0013	54.63	0.44	1314.4	1.7	0.8890	0.0020	7.96	0.02	50.40	0.19	1485.8	15.3	43.37	3.62
Am 17-CC-06	0.1210	0.0010	39.33	0.35	1720.9	2.3	1.1742	0.0053	10.97	0.05	57.83	0.39	1994.4	18.0	52.19	3.15
Am 17-CC-08	0.1304	0.0010	91.70	0.75	1666.1	1.8	1.2100	0.0024	5.24	0.01	61.64	0.21	1917.1	32.5	49.65	5.99
Am 17-CC-09	0.1055	0.0008	5.00	0.04	2120.0	3.9	0.8110	0.0021	51.77	0.14	31.76	0.14	2314.1	5.5	30.99	0.52
Am 17-CC-10	0.0784	0.0006	0.64	0.01	2136.1	2.3	0.8044	0.0020	299.85	0.74	31.29	0.11	2332.7	2.7	31.16	0.18
Am 17-CC-11 c	0.0645	0.0005	41.53	0.34	2070.7	2.8	0.3810	0.0019	1.80	0.01	14.26	0.09	2097.0	26.7	4.47	4.47
Am 17-CC-11 e	0.0700	0.0006	39.57	0.32	2060.9	1.7	0.4074	0.0029	2.19	0.02	15.36	0.12	2096.7	27.5	6.11	4.63
Am 17-CC-12 a	0.0664	0.0005	8.86	0.07	2200.6	3.2	0.3431	0.0023	7.83	0.05	12.23	0.10	2264.1	8.2	10.06	1.17
Am 17-CC-12 b	0.0975	0.0008	2.08	0.02	2204.1	2.1	0.3275	0.0016	46.71	0.23	11.64	0.07	2275.5	2.6	11.29	0.24
Am 17-A2-1	0.0627	0.0005	87.70	0.71	319.0	1.6	0.8408	0.0028	1.83	0.01	104.81	0.78	380.8	20.5	62.69	18.93

Note on U and Th content, isotopic ratios and ages. $\delta^{234}\text{U}_i$ is the initial $\delta^{234}\text{U}$ calculated using measured value and calculated age. Ages were corrected (corr. ages) for inherited ^{230}Th assuming a $(^{230}\text{Th}/^{232}\text{Th})$ of the detrital fraction of 1.5 ± 0.75 . In this study, $\delta^{234}\text{U} = (^{234}\text{U}/^{238}\text{U})_{\text{measured}} / (^{234}\text{U}/^{238}\text{U})_{\text{equilibrium}} - 1) \times 1000$, with $^{234}\text{U}/^{238}\text{U}_{\text{equilibrium}} = 54.89 \times 10^{-6}$ (molar ratio after Cheng et al., 2013). Thirteen age results (Am17-CC-01 => Am17-CC-12) concern the toppled stalagmite and the younger, post-topple, flowstone units. One additional result (Am 17-A2-1) documents the age of a speleothem capping a debris cone in the Lachambre Cave entrance.