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8000-6000 year-old anthropically broken stalagmite structures up to 2km deep in the cave of Saint-Marcel, France: Traversing and using underground caves during the Early Holocene.

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Abstract

The cave of Saint-Marcel is known for its extensive network (64 km of galleries) and its history of human occupation (Middle Paleolithic and Neolithic) in the entrance area. Close observation of the main network reveals areas with high concentrations of broken speleothems, which are usually attributed to the first tourist visits of the 19th century. However, archaeo-geomorphological mapping of the broken speleothems, many of which are lying on the floor and sealed by stalagmite regrowth or crust, indicates intentional organisation of the underground space into speleothem supply zones and zones in which the speleothems were used to build structures. Age estimates of the stalagmite seals on these human-made structures suggest that the structures were a result of human activity that occurred between the end of the Upper Palaeolithic and the European Mesolithic. These age estimates radically change the way we look at the broken speleothems in the cave of Saint-Marcel and the structures associated with them. They bring to light the engagement of past human communities with the deep underground environment, at more than 1.5 km from the cave entrance, which can only be accessed by crossing obstacles (pits) that are considered to be difficult to cross today. Our findings as well as ongoing research highlight the unequivocal archaeological significance of the cave.

1. Introduction

Over the past twenty years, research on the modifications of natural cave systems by early human communities has received much attention. The identification of anthropic structures dating back to the Upper and Middle Palaeolithic in the caves of La Garma (Spain), Aldène, Les Trois Frères, Chauvet-Pont d'Arc, and Bruniquel (France) and the profound transformations made by the past communities that occupied archaeological sites in Australia (Nawarla Gabarnmang, Borolaga) has substantially changed the way we look at the engagement of human communities with spaces that have been considered as remote or not very conducive to use or visit (Ontañon, 2003; Bégouën et al., 2007, 2009; Delannoy et al., 2012, 2013; Rossoni-Notter et al., 2016; Jaubert et al., 2016; Verheyden et al., 2017; Arias and Ontañon, 2020; Urwin et al., 2022).

Evidence of human activity in cave areas that are far from the entrance brings to light past communities' incursions into underground spaces, sometimes beyond obstacles that are difficult to get around (narrow or vertical sections, lakes), and people's desires to mark these spaces. These actions, sometimes minimal (moving a block, a speleothem, or a skull), sometimes significant (building structures made of blocks or speleothems, removing material, gutting out of rimstones or gours) are unequivocal evidence of past societies' appropriation of underground spaces. Alongside cave art, these transformations of underground environments, which are sometimes far from the entrance, provide new insights into how past societies engaged with these extraordinary spaces that were on the fringe of their usual territory. Within this context, anthropic structures that have been recently identified in the deep networks of the cave of Saint-Marcel have become a research focus. Results of archaeological research in the entrance and first gallery of the cave indicate Middle and Upper Palaeolithic occupation at the entrance and terminus of the first gallery section (foot of the pit) and Neolithic occupation in the spaces immediately

after the entrance (Gilles, 1986; Moncel, 1998; Szmidt et al., 2010; Lateur et al., 2023). Ongoing work as part of the *Archéologie du réseau de Saint-Marcel d'Ardèche* program (under the direction of D. Dupuy) has revealed evidence of animal and human visits beyond the first pit and into the part of the cave containing infrastructure for contemporary tourists (Fig. 1). There are substantial breakages of stalagmite edifices and numerous speleothems lying on the floor in several sections of the main gallery after the tourist area and up to the terminus of de Joly's excavations. While accounts of vandalism and presence of broken speleothems strewn across the cave floor soon emerged after the rediscovery of the cave in 1838 (de Valgorge, 1846; d'Albigny, 1879; Martel, 1888) and the breaking and looting of crystals from gours continued until the second half of the 20th century, the speleothems in the main gallery appear to have been broken off at a much earlier time. We found evidence of stalagmite regrowth on stumps where stalagmites have broken off; various human-made speleothem structures (steps, alignments, clusters) are sealed by recent stalagmite deposits that are thick in some places (Fig. 2). These observations suggest human activity that predates that of the last two centuries and are the motivation of the research presented in this article.

Research carried out on anthropic structures in the Chauvet-Pont d'Arc cave (Delannoy et al., 2012 a, b) and the Bruniquel cave (Jaubert et al., 2016) has drawn attention to assemblages of broken speleothems. As a result, research began in 2018 in the cave of Saint-Marcel, focusing on the sectors containing organised structures of speleofacts, which are speleothems that have been manipulated by humans (Fig. 3). In order to avoid bias in research analyses and observations, no *a priori* assumption was made with respect to the ages of the features found in the cave. The goal was to, first, examine the organisation of the speleofact structures, relationships between the structures and the broken stalagmites, and the chronology of the structures within the context of the evolution of the cave (Bannay, 2019; Burnet, 2022). High-resolution spatial mapping provided indications of the ages of the structures and was used to develop a robust relative chronology of the major events that marked the underground landscape. Timing of events was determined using Uranium/Thorium (U/Th) dating of broken stalagmites that are on the floor (or recumbent stalagmites) and stalagmite regrowths. Results form the basis for our discussion of the relationship between the spatial organisation and human use of the cave in (pre)history.

The research was focused on three key areas of the cave: the Colonnnes, Colonnades, and Massacre des Colonnnes sectors (Fig. 3). These sectors were selected because they contain (i) large numbers of stumps, which are remnants of standing stalagmites, (ii) different generations of broken stalagmites and regrowths, and (iii) anthropic structures comprising large numbers of broken stalagmites (Bannay, 2019; Burnet, 2022). In addition, there are traces of human intervention (e.g., displaced blocks, clay extraction, and gutted out gours) in these and neighbouring sectors. Lastly, to reach these sectors, which are relatively far (over 1.5 km) from the natural cave entrance, people would have to get over several obstacles that are difficult to negotiate without tools or modifications of the landscape (e.g., ladders or carved steps). This article focuses more specifically on the Colonnnes sector, where all the features mentioned above are concentrated, and where our understanding of the broken stalagmites, their distribution and absolute chronology is the most advanced.

2. Geography of broken stalagmites and associated anthropic structures

From the outset, the study of stalagmite breakage and speleofact structures in the cave of Saint-Marcel has been anchored in the spatial understanding of the features that can be seen in the cave. Our study includes identifying the relationships between the stalagmites that have been broken and those that have been integrated into the human-made structures, studying the organisation of the structures, and understanding the relationship between the components of the structures and the relative chronology of various human activities and natural processes (natural breakage, calcite deposition). This entire set of information was then used to identify the sectors for absolute dating (see Section 3).

For our study of the geography of the observed cave features, we created a high-resolution map using two different methods: laser scanning was used for entire study sectors and photogrammetry was used for the anthropic structures. In the three study sectors, surveys were carried out using a phase-shift terrestrial scanner (Faro Focus 3D). Several hundred scenes, each with 7 million points (quality of x3), were acquired. They were consolidated using the sphere method and the point clouds were cleaned using *3DReshaper*. The floor was separated from the vaults and ceilings and rasterised using *CloudCompare* (grid size of 1 cm). The raster images were produced from the Digital Terrain Model (DTM) and shaded or slope maps (Jaillet et al., 2017) were generated using QGIS 3.16. In the Colonnnes sector, a complementary series of photogrammetric data were collected after the removal of a thick coating of clay. The 231 photos acquired with a Nikon D810 APN were processed in Photoscan to produce a three-dimensional model with 162 million points. This very high-resolution model (sub-millimetre) was used to conduct a detailed analysis of this key sector, where over 90 speleofacts are arranged on the floor. The analysis was conducted after the speleofacts have been cleaned meticulously; the speleofacts were covered by a thick layer of clay that has been deposited by visitor and speleologist traffic due to the presence of clay soils on both sides of the study sectors. The clean-up uncovered broken stalagmites that were hidden beneath the clay; it enabled us to clearly identify connections between broken stalagmites and the relationship between broken stalagmites and the underlying soil.

We used the DTM for archaeo-geomorphological mapping and identified the various natural processes and human activities that were responsible for the current architecture of the Colonnnes area. While this mapping exercise is based on the principle and experience of geomorphological mapping that have been acquired during the mapping of the floors of Chauvet and Garma caves (Delannoy and Geneste, 2020; Arias and Ontañon, 2020) it has been enriched with new cartographic terms (e.g., superposition, interlocking, presence of wedges, sealing by stalagmite deposits) to facilitate detailed descriptions of the relationships between various structural elements and those between the elements and the evolution of the cave (Fig. 4). Our aim is to track all the natural processes and human activities that were responsible for the creation of the landscape that is currently visible in the Colonnnes area and to highlight (in)coherences in morphologies (Fig. 5).

We mapped all the visible objects that are on the floor, associated each object with a specific process, examined the various links between mapped objects, and established a relative chronology (i.e., object A is older than object B and younger than object C). As a result, a status was conferred to even the minutest element, including stalagmite regrowth at the centimetre scale and micro-impacts from strikes. This cartographic absolutism required us to consider all elements involved in the creation of the landscape and, above all, examine the presence or absence of specific objects, their status, and their history. This approach enabled us to identify the following elements (Fig. 6):

1- In the northern sector of the Salle des Colonnes, there is a major structure consisting of an alignment of 69 broken stalagmites and 23 limestone blocks on the ground. The broken stalagmites that make up this structure are relatively large in size and diameter (the largest ones are 60-100 cm in length and 18-38 cm in diameter) (Fig. 7). Regrowth that is several centimetres thick was found on several recumbent stalagmites. Similar regrowth can be seen on various stalagmite stumps in the vicinity of the structure. Stumps that are blackened by a thick, hardened soot deposit can also be seen in the same area.

2- At the southern end of this first structure, recumbent stalagmites were found on the outer rim of a gour that predates the structure. In addition, a piece of broken column (160 cm long with average diameter of 34 cm) lies on the same outer rim of the gour (generation 3); it is wedged in by smaller broken stalagmites and slightly sealed by a calcite crust (generation 5). This first piece of the column lies perpendicularly to a second piece of the same column (170 cm long with average diameter of 39 cm); the second piece rests against the inner rim of the gour and shows no traces of impact that could be associated with the fall of the column. The end of the column that is on the top of the gour is partially sealed by a calcite deposit that overlays the gour rim (generation 4). (This feature is hereafter referred to as Feature A.)

3- Continuing along the direction of the first structure into the central area of the room, which is rich in speleothems (median sector, Fig. 6), there are numerous recumbent stalagmites (136); they are sealed by a flowstone pavement that is fed by active stalagmites and flowstones (generation 4). In the same central area, there are many smaller broken speleothems (30) at the bottom of the immersed gour; they probably came from the numerous broken stalagmites that are in this area, as well as from more recent extractions of calcite crystals. Numerous stalagmite stumps (on the ground or on the edges of stalagmite edifices) are sealed by recent regrowth (generation 4).

4- At the edge of the central gour, two paths go around the towering stalagmite column; along both paths, there are stalagmite stumps and recumbent stalagmites sealed by calcite crust. The path on the right (west) features an arrangement that forms a "staircase" that crosses the inner rim of the gour. On the outer rim, there is a similar arrangement of recumbent stalagmites.

5- Below this central space, numerous recumbent stalagmites can be seen along the outer rim of the gour and below the central stalagmite edifice (southern margin, Fig. 6). Approximately 80 speleofacts are thus arranged along the left wall of the passage that leads southwards to the main gallery beyond the central

stalagmite edifice. These speleofacts are partially sealed by a thick deposit of moonmilk that is present at the bottom of the gours that flow from north to south through the gallery.

Over the entire mapped area, more than 350 recumbent stalagmites were identified (Table 1). This number only takes into account visible elements; elements that are covered by moonmilk and with size and morphology that resemble broken speleothems were not taken into account. Over 172 stalagmite stumps were found in the same geographical area, including 68 with calcite regrowth. It is interesting to note that the diameters of the stumps near the first speleofact structure (northern sector) are generally well below the diameters of the speleofacts that are integrated into the structure. In the same sector, the number of stumps is also far below that of the speleofacts in the structure.

Mapping data reveal a difference between ancient and recent stalagmite breakages on the eastern margin of the Salle des Colonnes. Ancient breakages are always located at a certain height from the ground (5-10 cm), whereas more recent ones are systematically flush with the ground. The presence or absence of regrowths and patinas are also used in the differentiation between ancient and recent breakages. This difference in breakage type is even more striking in the Colonnades sector and suggests that different actions were taken to achieve different goals. In this section of the gallery, people have also extracted crystals by breaking off the edges of gours and flowstones; debris from this looting can be seen at the bottom of the gours and in the hollows dug into the flowstone.

Taken together, these observations provide a clear indication of the anthropic origin of the structures of broken stalagmites. The structures are characterised by speleofacts that were aligned with each other and sometimes wedged in place with smaller elements. An aerial view of the study sector indicates an arrangement that extends over the entire length of the mapped area. In the southern margin and the northern and median sectors, structures are sealed by stalagmite regrowth or crust, flowstone, or moonmilk; this indicates that the structures are linked to a history of past human occupation. The appearance of the speleothems and the actions that led to their breakage differ from those associated with more recent breakage and looting. This difference can also be seen in the numbers of stalagmite stumps and recumbent stalagmites that are visible (Table 1). In the case of recent breakages, there are hardly any stalagmite tips on the ground, indicating people's desires to take the speleothems with them as trophies. In the case of ancient breakages, almost 40% of the stalagmite tips are visible, on the ground, and integrated into the structures. There is certainly a difference in the intentions behind recent and ancient breakages. The question of the origin of the broken stalagmites still remains: did the stalagmites break naturally or were they broken by humans? Given the large number of broken speleothems in the cave, the possibility of breakages caused by seismicity immediately comes to mind. However, the diversity in the diameter of the broken stalagmites and location of the breakages (top, bottom, or outgrowths of flowstones or large stalagmite edifices) does not correspond to seismic breakage, even if such a hypothesis cannot be totally ruled out for certain breakages, given the proximity of Saint-Marcel cave to active faults with recent activity (Teil earthquake, 11 November, 2019) (Gilli, 2000, Lacave et al., 1999, 2004, 2011; Pons-Branchu et al., 2004). Extraction of the clay substratum could have also caused the stalagmites to break. Several examples can be seen in the cave (in Galerie du Lac and Trou de l'Enfer

in the main gallery); however, the breakage mechanism in these sectors is different (e.g., tilting, stress cracks distributed throughout the columns) from that observed in the study sectors, where the bedrock is relatively close. Finally, we note that as soon as we cross the former terminus of the main gallery (beyond the chatière De Joly that was widened in 1947), the number of broken speleothems is much lower. Stalactites that have fallen from the ceiling could be related to earthquakes. Broken stalagmites and columns are generally associated with clay extraction or recent breakage. Without totally ruling out natural causes, careful examination of old stalagmite stumps indicates that the stalagmites have been broken by intentional strikes, although interpretation is often delicate where there is stalagmite regrowth or patina. In the case of the most “recent” breakages, strike impacts are particularly visible.

Regardless of the cause of breakage, broken stalagmites have been moved, transported, and arranged on the ground by humans to build structures. It is interesting to note that in the Colannes sector, particularly for the speleofact structure in the northern sector, a large number of the speleofacts did not originate from the immediate surrounding area. The number of stumps (20) in the vicinity of the structure (92 elements including 20 stalagmite tips) is small, and the diameters of the stumps are well below those of the recumbent speleofacts. Stump diameters range from 6 to 15 cm, with 60% around 10-12 cm; speleofact diameters are between 25 and 12 cm, with 48% over 20 cm. By matching the diameters of speleothems across the study sector, we found that most of the speleofacts in the structure in the northern sector originated from the central area of the room, and perhaps from edifices that are further north.

All the data from the mapping and field surveys highlight deliberate human modification of the underground space. Large numbers of broken speleothems have been used to build structures and the time at which these activities took place remains to be determined. The breakages of the pieces that form these structures differ from “more recent” ones associated with looting. While close observation of the structures enables us to identify a relative chronology between human activity and natural processes (calcite deposition), only absolute dating can place these events within the history of the cave and human use.

3. Dating the speleofact structures in the Salle des Colannes

Using archaeo-geomorphological mapping, we identified various morphogenetic dynamics and placed them into a robust relative chronology. At this stage of the study, the following sequence can be proposed for the Colannes sector:

-1- There was an intense period of speleothem formation, which resulted in the central stalagmite edifice and its associated columns and stalagmites. The flows feeding these speleothems contributed to the formation of the central gour, which has a depth of 0.7 m. Water overflowing from the gour fed the northern and western peripheral zones and created a system of secondary gours that face the downstream direction of the gallery. A gour with a height of 1.2 m forms the southern limit of the study area (a metal footbridge now crosses it).

-2- Calcite continued to be deposited on the edges of the stalagmite edifice and on the outer rim of the central gour and gave rise to numerous smaller stalagmites. The presence of small stalagmites on the outer rim of the central gour indicates that the activity of the gour had reduced, at least on the western flank.

-3- It is after these phases of speleothem formation that the stalagmite breakages occurred: the stalagmite stumps in the central part of the gallery, the breakage of the speleothems on the outer rim of the central gour, and the breakage of the stalagmites at 15-30 cm above ground in the low-lying area are all related to this episode.

-4- After the speleothems were broken, structures were built by the juxtaposition of broken speleothems over several meters (8 m). The major alignment comprises 92 elements that have been calibrated lengthwise and on which strike marks are visible. Without a reference point in time, we are unable to estimate the length of time between episodes 3 and 4. The two episodes may be part of the same task sequence, or may have occurred during different times of occupation.

-5- The presence of regrowth on both the stumps and the recumbent stalagmites suggests a new phase of calcite deposition similar to the one that created the gours in the northern and western low-lying areas. The gours were fed mainly by the stalagmite edifices to the north of the Salle des Colonnes. There is a thick deposit of moonmilk in the gour pools. Temporary flooding of gours resulted in a slight overflow, which is responsible for the off-white deposit on the stumps and recumbent stalagmites.

-6- Recent events in the room include recent breakage of stalagmites at their bases flush with the ground, looting of crystals in the gours, and covering of the floor and structures by a thick clay mass as a result of visitor traffic.

In order to calibrate this sequence of events and determine when the structures were built, samples were collected for U/Th dating by micro-coring (Fig. 8). They were obtained from two types of target features: stalagmite tips that are part of the anthropic structures and regrowths on both stumps and recumbent stalagmites. Targeting these two types of features provides constraints for age estimates of the speleofact structures. Samples were also taken from the top and the outer rim of the central gour in the direction of the main structure to provide more information on Feature A, which consists of two elements of the same column resting on the top and on the outer rim of the gour that are sealed together by a calcite crust (see Section 2). We used micro-cores with outer diameters of 12 mm to limit visual impact and ensure conservation of the site. The micro-cores provided sufficient sample material for stalagmite dating. To have sufficient material to analyse the dark-coloured materials trapped in the calcite of the rim of the central gour, we obtained a second sample of a larger diameter (32 mm) on one occasion. Particular attention was paid to facies change in all the cores in order to differentiate between the calcite of stalagmite regrowth and that of the broken stalagmites.

A diamond microsaw was used to remove samples for dating. For the cores of regrowths, the bottom part of the core, which is the oldest part, was sampled. For the cores of the tips of recumbent stalagmites

without regrowth, the top part, which is the youngest part, was sampled. In the case of stalagmite tips with regrowth, detailed examination of the facies, particularly along the direction of layering, enabled us to distinguish the phases and sample accordingly (Fig. 9). Samples of between 50 and 200 mg were dissolved in dilute hydrochloric acid, and the Uranium and Thorium fractions were purified on a U-TEVA® ion exchange resin. An MC-ICPMS Neptune plus™ mass spectrometer was used to determine the isotopic composition. For more information on the protocols and procedures that were used, please refer to Pons-Branchu et al. (2014). Age estimates were calculated from isotopic ratios and were corrected for the detrital fraction; $^{230}\text{Th}/^{232}\text{Th}$ activity ratio of the detrital fraction was assumed to be 1.5 ± 0.75 (Table 2).

4. Discussion: Evidence of anthropic structures from the late Upper Palaeolithic to the European Mesolithic

The results of the U/Th dating of the speleothem samples enabled us to determine the absolute chronology of the cave on the basis of the relative chronology that was established from the field surveys. First of all, the general features of the Salle des Colonnes were formed before the first half of the Quaternary, as indicated by the age of the upper part of the central gour. Samples C31 and C32, which were at a distance of 3 cm from the upper lip of the gour, were dated to around 270,000 years before present; this is consistent with the age of the samples that were at a depth of 2 cm from the outer rim of the same gour (250,000 years old). Given that the gour is 0.7 m high, the creation of the gour and the central edifice that feeds it dates back to earlier times.

Stalagmite growth developed during isotopic stage 5, as indicated by the large numbers of speleothems that are between 125,000 and 70,000 years old; speleothems that are around 50,000 years old are also present. The speleothems are mainly in the central area of the room, sealing the western rim of the central gour; in the rest of the room, they are present on the bases of the gours or on raised parts of the floor, notably on blocks that have fallen from the ceiling. These dates are only for the broken stalagmites (speleofacts) that are part of the human-made structures. The youngest broken stalagmite tips are around 10,000 years old, i.e., in the early stages of isotopic stage 1 (Holocene). The youngest stalagmite tip that is part of a speleofact structure is 8,210 years old (core C18; Fig. 10).

Age estimates of stalagmite regrowths show very strong spatial coherence. In the median sector (the centre and rims of the central gour), regrowths on stumps and aligned speleofacts are mostly between 8,209 and 6,060 years old. Many of them are around 7,500 years old. The youngest regrowths are 4,581-3,661 years old. For the major structure of 69 aligned speleofacts (northern sector), regrowth age ranges from 5,850 to 3,100 years old. Samples from the southern edge of the stalagmite edifice in the median sector also have ages of the same order; they were obtained from the regrowths on the recumbent stalagmites (speleofacts) that have been arranged as steps on the flank of the flowstone. Of the 49 age estimates, the youngest ones are between 3,000 and 1,970 years old, which are from the samples obtained from the surface of the lip of the central gour; this is the recent deposit that seals the two column elements resting on the edge and the outer rim of the gour (Feature A).

Ages of the stalagmite tips in the speleofact structures and of the regrowths indicate that the structures were put in place in the central zone between 10,000 and 8,200 years ago. One of the speleofacts (C18) belonging to one of these structures was still standing around 8,000 years ago. After this time, it was broken off and placed on the ground with other broken stalagmites, including C37 and C38; the top parts of C37 and C38 are around 10,000 years old.

The ages of the regrowths in the main alignment structure of the northern sector indicate that the structure was built over 6,000 years ago.

These dating results indicate that the alignment structures of broken stalagmites were built during the final period of the Upper Paleolithic and European Mesolithic (Figs. 11 and 12).

These findings radically alter the way we look at the broken stalagmites in cave of Saint-Marcel and the associated structures. While some of the broken stalagmites can be traced back to the successive visits following the rediscovery of the cave in the early 19th century and the subsequent development of the cave into a tourist attraction, age estimates of the samples from the Colannes sector call into question the age and status of many of the structures, which are sealed by stalagmite regrowth (Figs. 3 and 13). Ongoing work in the cave will enable us to assess the significance of these ancient structures in the prehistoric use of deep cave networks.

The age estimates of the speleofact structures in the Salle des Colannes bring to light a route through the main gallery, which runs for around 1.5 km from the current entrance and contains two difficult passages: the first pit, which is several tens of metres high, and the wall closing off the Salle du Cirque in the upstream direction (Cascade de Gours then Galerie des Maçons). Given the number of speleofacts in the alignment structures in the Salle des Colannes (388), we hypothesise that there was recurrent human occupation in this sector. The age of sample C14, which was taken from the tip of a recumbent stalagmite (Figs. 10 and 12), indicates that the stalagmites were broken over time and highlights repeated use of the deepest parts of the cave by prehistoric human communities.

The age of the stalagmite regrowth on the speleofact structures in the median sector differs from that in the other sectors of the Salle des Colannes; this raises a question: does this difference indicate that the structures were built during two phases that occurred at different times, or is it linked to differences in the stalagmite record, which are caused by differences in speleofact height above the floor? The aligned speleofacts in the median sector are perched above the gallery floor; this is not the case for the alignments in the other sectors, including the major structure in the northern sector. The alignments outside the median sector are at the bottoms of gours and may have been flooded regularly; this would have limited stalagmite regrowth on the speleofacts that were on the floor, at least until around 6,000 years ago when regrowth began in the low-lying areas. Ongoing work on gour water levels based on marks on the walls and recumbent stalagmites aims to provide further evidence for this second working hypothesis.

Regardless of the cause of this age difference, there is an overall coherence in the organisation of the speleofact structures within the geography of the Salle des Colonnes. This impression is based on the following points:

(i) there is a spatial relationship between the median sector where the speleofacts were “produced” and adjacent sectors. In fact, a large number of the speleofacts in the alignments of the northern sector and the southern margin originate from the median sector. Some of the largest speleofacts that were brought into the northern sector weigh between 100 and 315 kg, which means that they had to have been transported and laid out on the ground by several people. These data suggest a social organisation of space into speleofact production zones and zones where structures were built;

(ii) the alignment structures of recumbent stalagmites in the northern and median sectors are continuous, disrupted only at the crossings of the outer and inner rims of the central gour (Fig. 6); the two elements of the same massive column on and spanning the rim of this gour (wedge) (Feature A) have been undoubtedly put there by humans at least more than 3,000 years ago, as indicated by the ages of their respective stalagmite seals; the arrangement of these two elements in the room creates a connection, at least visually, between the alignments in the northern and median sectors;

(iii) this spatial continuation appears to extend beyond the median sector (Fig. 6). At the southern end of the central alignment, a “staircase” comprising 23 speleofacts crosses over the rim of the central gour into the southern margin (Fig. 14). Below this structure, there are numerous recumbent stalagmites, which are laid out side by side for almost 6 m. They follow the western edge of the towering stalagmite column and continue all the way to the gour at the top, which marks the boundary of this area.

All the field and dating data confirm that people visited the deep networks of the cave of Saint-Marcel from the end of the Upper Palaeolithic and during the Mesolithic and that the cave was the site of significant intentional organisation of space. In the Salle des Colonnes, no fewer than 460 speleothems have been broken, moved, and arranged on the floor. Although the functions of these structures are still unknown, they nevertheless indicate that past communities were highly committed to reach these spaces, which are far from the natural entrance, and above all, to build speleofact structures that are sometimes of considerable size. The study of the Salle des Colonnes enables us to better understand the other deep areas of the cave system (Salle des Colonnades and Massacre des Colonnes), where there are also arrangements of broken speleothems on the floor, and to better distinguish recent acts of breakage (looting of calcite crystals and stalagmites) from more ancient actions that have been sealed by stalagmite regrowth (Burnet, 2022). Work that is in progress in these areas will enable us to improve our estimates of the absolute chronology of speleothem breakages and associated structures and to consider the geography of human visits to Saint-Marcel cave over time (from the late Upper Palaeolithic to the 19th century).

5. Conclusions

Research conducted on broken speleothems and their arrangement on the ground (e.g., into steps and alignments) in Saint-Marcel cave reveals the presence of human activity that is much older than that which is usually mentioned (tourism-related developments from the second half of the 19th century and the looting of speleothems). The evidence for prehistoric human activity in the cave of Saint-Marcel is conclusive; detailed studies are needed in order to better identify the traces left behind by this prehistoric activity on the underground landscape, particularly around the areas that are more difficult to cross (e.g., pits and underwater passages). Similarly, there is no doubt that the cave has been looted for its speleothems and crystals during the 20th century, as indicated by the fresh breakages and debris. In addition to this historical evidence, geomorphological research in various deep areas of the cave (upstream of the contemporary tourist area) has been underway since 2018 and it has revealed that (i) stalagmite stumps and recumbent stalagmites are sealed by calcite regrowth and (ii) the speleofact structures are results of intentional efforts to organise the underground space. High-resolution geomorphological mapping based on laser scanning and photogrammetry has made it possible to identify zones of speleofact “production” and construction of predesigned and organised structures. Even if the distance between these zones is not large, the weight of certain pieces (for example, the two elements of the column that are on the rim of the central gour in the Salle des Colonnes; Feature A) means that speleofact transportation and arrangement required the collaboration of several people; this raises the question of the engagement of past communities with the underground environment and the transformation of this landscape following codes that we still have yet to identify. The archaeo-geomorphological approach that was developed for the Chauvet Cave, Points Cave (Ardèche and Gard), La Garma cave complex (Spain), and Cloggs Cave (Australia) facilitates differentiation between the morphogenetic and the anthropogenic processes responsible for the creation of underground landscapes and lays the foundations for the development of a precise relative chronology comprising the different events that marked the study sectors (Monney and Jaillet, 2019; Delannoy et al., 2020; David et al. 2021).

The application of this approach to the Colonnes, Colonnades, and Massacre des Colonnes sectors revealed (i) a geography of the human organisation of space and (ii) different traces of prehistoric and recent human activities, which needed to be confirmed with objective data from U/Th dating of the human-made structures. Dating results indicate that the structures were built in prehistoric times. The structures in the Salle des Colonnes date from the end of the Upper Palaeolithic to the European Mesolithic. Archaeological work had revealed a strong Neolithic presence in the current entrance area (Gilles, 1986; Moncel, 1998) and incursions as far as the base of the first pit in the Middle Paleolithic (Szmids et al., 2010; Lateur et al., 2023). Our results reveal hitherto unexpected incursions into the cave’s deep network (over 1.5 km from the entrance), and raise the question of how past communities overcame obstacles that are considered to be difficult to cross today. For the Salle des Colonnes, dating results also indicate that most of the current landscape was already in place during these ancient incursions: past communities would have walked through a cave that was very similar to the present one in terms of volume and speleothem setting; most of the large stalagmite edifices and associated gours were already present. The only unknown is whether water was in the gours and depressions at the time of their visits (work in progress). The presence or absence of water has implications for the understanding of the

geography of the speleofact structures: in the various study sectors, there is a recurring presence of broken speleothems at the bottoms of gours, sometimes in very large quantities (e.g., the central gour of the Salle des Colonnnes). Our study results are changing the way we look at the Saint-Marcel cave network, giving them a cultural dimension linked to prehistoric use. Although examples of human occupation of deep caves in the Mesolithic already exist (Aldène cave in France; Ambert et al., 2004), the results from Saint-Marcel cave invite us to take a new look at these societies, their use of caves, which has hitherto been considered to be limited to the entrance areas, their engagement with deep underground landscapes, and the associated symbolic dimensions.

Declarations

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Competing Interests

Partial financial support was received from Savoie-Mont Blanc University (Edytem laboratory). The authors have no competing interests to declare that are relevant to the content of this article.

Data Availability

Data sets generated during the current study are available from the corresponding author on reasonable request.

Authors' contributions

All the authors participated in conducting the research presented in this article and in the writing of the article. **J.-J.D., J.K. and S.J.** wrote the body of the article (Sections 1, 2, 4 and 5) and designed Figures 1-8

and 11-14. **E.P.-B., A.D.** and **S.V.** carried out the U/Th processing and analysis, wrote the second part of the results section (dating) and produced Figures 9 and 10 as well as Table 2. **D.D.** helped with the research at the Saint Marcel cave site. **All the authors read and contributed to the final draft of the article.**

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References

1. **Ambert P., Simone S., Colomer A., & Galant Ph.** (2004) Cesseras –Grotte d'Aldène; Note of archaeological project. *ADLFI. Archéologie de la France*. <http://journals.openedition.org/adlfi/11626>
2. **Arias P. & Ontañón R.** (2020) La Garma: un sitio excepcional, una metodología diferente. *Actualidad de la investigación arqueológica en España (2018-2019): Conferencias Impartidas en el Museo Arqueológico Nacional*, n°1, pp. 45-64.
3. **Bannay J.** (2019) *Les spéléothèmes cassés et fragmentés de la grotte de Saint-Marcel-d'Ardèche: hypothèses et clés de lecture*. Mémoire Master, Université Savoie Mont Blanc. 63 p.
4. **Bégouën R., Fritz C., Tosello G., Clottes J., Faist F., Pastoors A., Lacombe S., & Fosse P.** (2007) Les Magdaléniens modelaient aussi l'argile. *Les Dossiers d'Archéologie*, n°324, pp. 30-37.
5. **Bégouën R., Fritz C., Tosello G., Clottes J., Pastoors A., & Faist F.** (2009) *Le sanctuaire secret des bisons : il y a 14 000 ans, l'art et la vie des Magdaléniens dans la caverne du Tuc d'Audoubert*. Somology, Paris. 416 p.
6. **Burnet H.** (2022) *Étude anthropo-géomorphologique du secteur des Colonnes – Grotte de Saint-Marcel-d'Ardèche*. Mémoire Master 2, Université Savoie Mont Blanc. 82 p.
7. **Cheng H., Lawrence Edwards R., Shen C.-C., Polyak V.J., Asmerom Y., Woodhead J.D., Hellstrom J., Wang Y., Kong X., Spötl C., Wang X., & Calvin Alexander E.** (2013) Improvements in 230Th dating, 230Th and 234U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth and Planetary Science Letters*, vol. 371-372, pp. 82–91.
8. **d'Aligny P.** (1879) La vallée de l'Ardèche de Vallon à Saint-Martin- d'Ardèche. *Annuaire du CAF*, 6^{ème} année, pp. 370-391.
9. **David B., Delannoy J.-J., Urwin C., Fresløv J., & Mullett R.** (2021) Engaging and designing place: furnishings and the architecture of archaeological sites in aboriginal Australia. In I.J. McNiven & B. David (Eds.), *The Oxford Handbook of the Archaeology of Indigenous Australia and New Guinea*. Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190095611.013.16>
10. **de Valgorge O.** (1946) *Souvenirs de l'Ardèche*. Tome second, Paulin Editions, Paris, pp. 27-37.
11. **Delannoy J.-J., Geneste J.-M., Jaillet S., Boche E., & Sadier B.** (2012) Les aménagements et structures anthropiques de la grotte Chauvet-Pont-d'Arc: apport d'une approche intégrative géomorpo-

- archéologique. *Collection EDYTEM, Cahiers de géographie, n°13, Karsts, Paysages et Préhistoire*, pp. 43-62. <https://doi.org/10.3406/edyte.2012.1204>
12. **Delannoy J.-J., David B., Geneste J.-M., Katherine M., Barker B., Whear R.-L., & Gunn R.-G.** (2013) The social construction of caves and rockshelters: Chauvet cave (France) and Nawarla Gabarnmang (Australia). *Antiquity*, n°87, pp. 12-29. <https://doi.org/10.1017/S0003598X00048596>
 13. **Delannoy J.-J. & Geneste J.-M. (dir)** (2020) *Monographie de la grotte Chauvet-Pont-d'Arc, Volume 1: Atlas*. Collection: Documents d'archéologie française, Edition de la Maison des Sciences de l'Homme, Paris. 384 p. <https://doi.org/10.4000/books.editionsmsmsh.49690>
 14. **Delannoy J.-J., David B., Fresløv J., Mullett R., Gunaikurnai Land and Waters Aboriginal Corporation, Green H., Berthet J., Petchey F., Arnold L.-J., Wood R., McDowell M., Crouch J., Mialanes J., Ash J., & Wong V.-N.-L.** (2020) Geomorphological context and formation history of Cloggs Cave: what was the cave like when people inhabited it? *Journal of Archaeological Science: Reports*, n°33, 34 p. <https://doi.org/10.1016/j.jasrep.2020.102461>
 15. **Gilles R.** (1986) La grotte de Saint Marcel. *Ardèche Archéologie*, n°3, pp. 1-5.
 16. **Gilli E. & Delange P.** (2000) Utilisation des spéléothèmes comme indicateurs de néotectonique ou de paléosismicité. *Revue d'Analyse spatiale*, N° spécial 2001, Université de Nice, pp.1-10.
 17. **Jaillet S., Delannoy J.-J., Monney J., & Sadier B.** (2017) 3D Modelling in Rock Art Research Terrestrial Laser Scanning, Photogrammetry, and the Time Factor. In B. David & I.J. McNiven (Eds.), *The Oxford Handbook of the Archaeology and Anthropology of Rock Art*, Oxford Handbook.
 18. **Jaubert J., Verheyden S., Genty D., Soulier M., Cheng H., Blamart D., Burlet C., Camus H., Delaby S., Deldicque D., Edwards R.-L., Ferrier C., Lacrampe-Cuyaubère F., Lévêque F., Maksud F., Mora P., Muth X., Régnier E., Rouzaud J.-N., & Santos F.** (2016) Early Neanderthal constructions deep in Bruniquel cave in southwestern France. *Nature*, n°534, pp. 111-114. <https://doi.org/10.1038/nature18291>
 19. **Lacave C., Koller M., & Levret, A.** (1999) Measurement of natural frequencies and damping of speleothems. *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 18p.
 20. **Lacave C., Koller M. G., & Egozcue J.J.** (2004). What can be concluded about seismic history from broken and unbroken speleothems? *Journal of Earthquake Engineering*, Vol. 8, No. 3, pp. 431-455.
 21. **Lacave C., Sadier B., Delannoy J.-J., & Egozcue J.J.** (2011) Contribution à la caractérisation de l'aléa sismique du Liban par l'étude des spéléothèmes. *8^{ème} colloque national AFPS 2011*, École des Ponts, ParisTech.
 22. **Lateur N., Moncel M.-H., Mocochain L., & Fernandes P.** (2023) Fréquentations des réseaux karstiques profonds par Néanderthal. Nouveaux exemples à la grotte de Saint-Marcel (Ardèche, France). *Comptes rendus PALEVOL*, n° 22, pp. 265-277 <https://doi.org/10.5852/cr-palevol2023v22a15>
 23. **Martel E.A.** (1888) *Les Cévennes et la région des Causses (Lozère, Aveyron, Hérault, Gard, Ardèche)*. 8e édition, Edition Ch. Delagrave, Paris, 408 p.
 24. **Moncel M.-H.** (1998) Les niveaux moustériens de la grotte de Saint-Marcel d'Ardèche (Ardèche, France). Fouilles René Gilles. Reconnaissance de niveaux à débitage discoïde dans la vallée du

Rhône. *Bulletin de la Société préhistorique française*, 95 (2), pp. 141-171.

<https://doi.org/10.3406/bspf.1998.10765>

25. **Monney J., Jaillet S.** (2019) Phases de fréquentations humaines, ornementation pariétale et processus naturels: mise en place d'un cadre chronologique. *Karstologia*, n° 77, pp. 49-62. <https://hal.science/hal-01957634>
26. **Ontañón R.** (2003) Sols et structures d'habitat au Paléolithique supérieur, nouvelles données depuis les Cantabres: la Galerie Inférieure de La Garma (Cantabrie, Espagne). *L'Anthropologie*, n°107, pp. 333-363. [https://doi.org/10.1016/S0003-5521\(03\)00037-2](https://doi.org/10.1016/S0003-5521(03)00037-2)
27. **Pons-Branchu E., Hamelin B., Brulhet J., & Bruxelles L.** (2004) Speleothem rupture in karst: tectonic or climatic origin? U-Th dating of rupture events in Salamandre Cave (Gard, South-Eastern France). *Bulletin de la Société Géologique de France*, 175 (5), pp. 473-479.
28. **Pons-Branchu E., Douville E., Roy-Barman M., Dumont E., Branchu E., Thil F., Frank N., Bordier L., & Borst W.** (2014). A geochemical perspective on Parisian urban history based on U-Th dating, laminae counting and yttrium and REE concentrations of recent carbonates in underground aqueducts. *Quaternary Geochronology*, 24, pp. 44-53.
29. **Rossoni-Notter E., Notter O., Simone S., & Simon P.** (2016) Acheulean technical behaviors in Aldène cave (Cesseras, Hérault, France). *Quaternary International*, n°409, pp. 149-173. <https://doi.org/10.1016/j.quaint.2015.11.016>
30. **Szmidt C., Moncel M.H., & Daujeard C.** (2010) New data on the Late Mousterian in Mediterranean France: First radiocarbon (AMS) dates at Saint-Marcel Cave (Ardèche). *Comptes Rendu Palevol*, 9, pp. 185-199.
31. **Urwin C., David B., Delannoy J.-J., Bell J.-A., & Geneste J.-M.** (2022) Aboriginal monumental stone-working in Northern Australia during the Pleistocene. In L. Laporte & J.M. Large (Eds.), *Megaliths from the World – Part III: Megaliths from Easter Island to Indonesia*, Archaeopress, pp. 241-255.
32. **Verheyden S., Jaubert J., Genty D., Soulier M.** (2017) Grotte de Bruniquel (Tarn-et-Garonne): éléments de datation complémentaires. *Karstologia*, N°70, pp. 1-14.

Tables

Table 1 Number of broken stalagmite stumps and recumbent stalagmites in the Colongnes, Colonnades, and Massacre des Colongnes sectors. For Massacre des Colongnes, only numbers in the central zone are reported.

Sector	Sub-sector	Number of stalagmite stumps			Number of recumbent stalagmites				Recent breakages	
		Total	without regrowth	with regrowth	Total	Stalagmite tips	Broken stalagmites without tips	Limestone blocks	Number of stumps	Number of elements on the ground
Colongnes	Northern sector (NS)	67	34	33	121	29	55	37	14	0
	Aligned structure in NS				92	20	49	23		
	Median sector	60	45	15	136	40	96	0	39	0
	Southern margin	45	25	20	122	29	93	0	24	2
Total		172	104	68	388	118	293	60	77	2
Colonnades		154	30	124	?	85	?	8	124	?
Massacre des Colongnes		280	180	100	409	54	355			

Table 2 Uranium/Thorium data (concentrations, isotope ratios, and ages) from Salle des Colonnes core samples. Ages are in thousands of years (ky) before present. For the detrital correction, $^{230}\text{Th}/^{232}\text{Th}$ activity ratio was assumed to be $1.5 \pm 50\%$; $\delta^{234}\text{U} = \left(\frac{^{234}\text{U}/^{238}\text{U}}{\text{measured}} / \frac{^{234}\text{U}/^{238}\text{U}}{\text{equilibrium}} - 1\right) \times 1000$ where $^{234}\text{U}/^{238}\text{U}_{\text{equilibrium}} = 54.89 \times 10^{-6}$ (molar ratio, following Cheng et al., 2013); $\delta^{234}\text{U}_0$ is initial $\delta^{234}\text{U}$. In the sample description column, colours correspond to those indicating sample types in Figure 8. A white background in the sample description column indicates a recumbent stalagmite; the corresponding numbers in the age and corrected age columns refer to the age of the speleothem before breakage and integration into a structure.

Sample	Sample description	[²³⁸ U] ppm	[²³² Th] ppb	$\delta^{234}\text{U}_M$ (‰)	(²³⁰ Th/ ²³⁸ U)	(²³⁰ Th/ ²³² Th)	Age (ky before measurement)	$\delta^{234}\text{U}_T$ (‰)	Corrected age (ky before measurement minus the year 2022/3)
C1	SMC1-1	0,201 ±0.002	1,642 ±0.013	-250,6 ±0,8	0,02313 ±0,000	8,67 ±0,16	3,429 ±0,069	-252,7 ±0,8	3,060 ±0,263
	SMC1-2	0,197 ±0.002	4,484 ±0.036	-230,6 ±1,2	0,03087 ±0,000	4,14 ±0,06	4,481 ±0,078	-232,8 ±1,3	3,480 ±0,600
C2	SMC2-1	0,197 ±0.002	3,913 ±0.031	-252,0 ±0,8	0,07425 ±0,001	11,40 ±0,09	11,482 ±0,113	-259,6 ±0,9	10,575 ±0,587
	SMC2-1	0,197 ±0.002	3,916 ±0.032	-250,3 ±1,1	0,07464 ±0,001	11,58 ±0,12	11,519 ±0,148	-257,6 ±1,3	10,110 ±0,845
	SMC2-b	0,182 ±0.001	0,506 ±0.004	-276,0 ±0,6	0,01704 ±0,000	18,72 ±0,39	2,605 ±0,057	-277,9 ±0,6	2,475 ±0,126
C4	SMC2-d	0,117 ±0.001	0,524 ±0.004	-235,5 ±1,0	0,03140 ±0,001	21,32 ±0,48	4,589 ±0,111	-238,4 ±1,1	4,389 ±0,216
	C4-1	0,318 ±0.003	2,433 ±0.020	-225,5 ±1,1	0,06383 ±0,000	25,26 ±0,16	9,431 ±0,079	-231,3 ±1,2	9,091 ±0,257
C5	SMC4-2	0,235 ±0.002	1,799 ±0.018	-115,1 ±1,1	0,53606 ±0,006	231,17 ±2,62	104,760 ±2,309	-154,6 ±1,9	104,481 ±2,452
	SMC5-d	0,149 ±0.001	0,208 ±0.002	-266,8 ±0,8	0,03851 ±0,001	84,05 ±1,12	5,910 ±0,087	-271,2 ±0,8	5,845 ±0,122
C6	C6-1	0,270 ±0.002	0,741 ±0.006	-160,8 ±1,8	0,30364 ±0,001	334,67 ±1,43	49,869 ±0,416	-185,1 ±2,0	49,755 ±0,477
C7	SMC7-1	0,160 ±0.001	4,755 ±0.038	-220,4 ±0,8	0,04821 ±0,000	4,95 ±0,05	6,991 ±0,075	-224,0 ±0,9	5,699 ±0,751
C9	SMC9-1	0,210 ±0.002	0,613 ±0.005	-126,3 ±0,7	0,03306 ±0,000	34,24 ±0,36	4,216 ±0,049	-127,7 ±0,7	4,101 ±0,109
	SMC9-2	0,135 ±0.001	0,280 ±0.002	-91,0 ±1,1	0,43844 ±0,001	640,18 ±1,48	72,915 ±0,383	-111,8 ±1,4	72,836 ±0,425
	SMC9-A	0,329 ±0.003	0,772 ±0.006	-155,4 ±0,7	0,15126 ±0,001	195,90 ±1,15	21,683 ±0,162	-165,1 ±0,8	21,533 ±0,237
	SMC9-B	0,192 ±0.002	0,179 ±0.001	-166,0 ±1,2	0,28556 ±0,003	934,69 ±8,25	46,510 ±0,611	-189,3 ±1,4	46,449 ±0,642
C10	SM1:C9-C	0,142 ±0.001	0,584 ±0.005	-99,2 ±1,1	0,40407 ±0,003	300,06 ±1,86	65,888 ±0,695	-119,5 ±1,4	65,640 ±0,819
	SM C10-1	0,143 ±0.001	7,682 ±0.062	-162,3 ±1,2	0,43223 ±0,002	24,23 ±0,09	81,781 ±0,639	-203,2 ±1,8	79,498 ±1,818
	SM C10-2	0,118 ±0.001	0,631 ±0.005	-145,2 ±1,1	0,49100 ±0,002	276,78 ±1,30	96,587 ±0,986	-190,7 ±1,6	96,445 ±1,032
	SM C10-3	0,143 ±0.001	1,114 ±0.009	-163,4 ±1,0	0,47634 ±0,002	185,22 ±0,86	95,712 ±0,950	-214,0 ±1,4	95,500 ±1,019
C11	SM C11-1	0,211 ±0.024	0,098 ±0.004	-127,6 ±57,1	0,01248 ±0,000	81,22 ±2,69	1,585 ±0,157	-128,2 ±57,3	1,567 ±0,165
C12	SM C12-1	0,186 ±0.001	2,060 ±0.017	-133,2 ±1,0	0,03094 ±0,001	8,46 ±0,17	3,973 ±0,085	-134,6 ±0,9	3,698 ±0,177
	SM C12-2	0,197 ±0.002	0,961 ±0.008	-128,7 ±0,9	0,05310 ±0,001	32,90 ±0,55	6,877 ±0,124	-131,2 ±1,0	6,756 ±0,165
	SM C12-3	0,244 ±0.002	1,102 ±0.009	-167,7 ±1,0	0,15991 ±0,001	107,34 ±0,67	23,473 ±0,195	-179,2 ±1,0	23,354 ±0,234
	SM C12-4	0,233 ±0.002	0,760 ±0.006	-101,6 ±0,9	0,46984 ±0,001	436,35 ±0,95	82,345 ±0,416	-128,2 ±1,2	82,264 ±0,442
	SM1:C12-5	0,345 ±0.003	1,578 ±0.013	-46,0 ±0,9	0,76714 ±0,001	511,23 ±0,82	182,983 ±1,365	-77,1 ±1,6	182,719 ±1,494
	SM1:C12-6	0,190 ±0.002	1,170 ±0.009	-21,9 ±0,9	0,86529 ±0,001	427,99 ±0,62	241,183 ±2,353	-43,3 ±1,8	240,842 ±2,518
C13	SM C13-1	0,137 ±0.001	0,234 ±0.002	-142,6 ±0,9	0,05525 ±0,000	97,44 ±0,84	7,287 ±0,072	-145,6 ±0,9	7,218 ±0,108
	SM C13-A	0,404 ±0.003	4,696 ±0.038	-87,8 ±1,2	0,61342 ±0,001	159,44 ±0,33	125,461 ±0,878	-125,0 ±1,8	125,175 ±0,971
	SM C13-2	0,250 ±0.002	4,357 ±0.035	-67,0 ±0,9	0,69903 ±0,001	121,11 ±0,23	155,728 ±1,111	-103,8 ±1,5	155,067 ±1,453
C14	SM C14-1	0,149 ±0.001	2,287 ±0.018	-115,2 ±1,1	0,04729 ±0,001	9,34 ±0,11	6,006 ±0,084	-117,0 ±1,2	5,414 ±0,394
C15	SM C15-1	0,136 ±0.001	0,614 ±0.005	-119,1 ±0,7	0,04883 ±0,000	32,93 ±0,32	6,236 ±0,067	-121,1 ±0,8	6,061 ±0,160
	SM C15-2	0,154 ±0.001	0,860 ±0.007	-124,3 ±0,7	0,06175 ±0,000	34,35 ±0,23	7,998 ±0,063	-127,0 ±0,7	7,662 ±0,231
C16	SM C16-1	0,174 ±0.001	1,237 ±0.010	-136,3 ±0,9	0,33109 ±0,001	144,64 ±0,29	53,590 ±0,221	-158,4 ±1,0	53,147 ±0,441
C18	SM C18-1	0,116 ±0.001	0,175 ±0.001	-138,9 ±0,5	0,06291 ±0,001	128,64 ±1,48	8,302 ±0,106	-142,2 ±0,5	8,209 ±0,153
C19	SM C19-1	0,167 ±0.001	0,510 ±0.004	-117,6 ±0,9	0,04940 ±0,000	50,12 ±0,50	6,299 ±0,072	-119,6 ±0,9	6,116 ±0,163
	C19-3	0,132 ±0.001	0,312 ±0.002	-114,3 ±1,0	0,06136 ±0,001	65,08 ±0,84	7,853 ±0,095	-116,9 ±1,0	7,743 ±0,153
C20	C20-1	0,252 ±0.002	0,227 ±0.002	-120,7 ±0,5	0,02923 ±0,000	98,95 ±0,82	3,696 ±0,034	-122,0 ±0,6	3,661 ±0,052
C31	C31-A	0,195 ±0.002	2,092 ±0.017	-134,0 ±1,2	0,02062 ±0,001	5,85 ±0,23	2,634 ±0,109	-134,7 ±1,2	1,970 ±0,440
	C31-D	0,086 ±0.001	0,186 ±0.002	-6,8 ±1,6	0,90686 ±0,004	1272,16 ±5,12	269,313 ±7,224	-14,5 ±3,4	269,199 ±7,275
C33	C33-B	0,242 ±0.002	0,403 ±0.003	-201,0 ±1,5	0,05301 ±0,001	96,20 ±2,18	7,518 ±0,190	-205,2 ±1,5	7,405 ±0,246
	C33-C	0,117 ±0.001	0,323 ±0.003	-92,9 ±1,4	0,60674 ±0,002	660,38 ±2,49	124,423 ±1,339	-131,9 ±2,1	124,252 ±1,423
C35	C35-A	0,136 ±0.001	0,092 ±0.001	-165,9 ±0,8	0,03454 ±0,001	153,13 ±5,14	4,626 ±0,162	-168,0 ±0,8	4,581 ±0,183
C36	C36-A	0,131 ±0.001	0,377 ±0.003	-187,0 ±1,4	0,05781 ±0,001	60,47 ±1,43	8,077 ±0,211	-191,3 ±1,5	7,884 ±0,306
C37	C37-A	0,117 ±0.001	1,032 ±0.008	-179,5 ±1,8	0,07786 ±0,002	26,25 ±0,77	10,928 ±0,354	-184,9 ±1,8	10,336 ±0,647
C38	C38-A	0,175 ±0.001	44,680 ±0,361	-132,8 ±1,0	0,18025 ±0,001	2,14 ±0,02	25,603 ±0,269	-137,0 ±3,0	10,897 ±7,197
C32	SM_C32_A2	0,218 ±0.002	1,449 ±0.012	-132,8 ±0,5	0,02600 ±0,001	12,18 ±0,27	3,327 ±0,079	-134,0 ±0,6	2,925 ±0,280
	C32-B1	0,306 ±0.002	1,662 ±0.013	-53,8 ±0,8	0,65494 ±0,002	375,33 ±1,01	131,031 ±0,978	-77,8 ±1,2	130,724 ±1,130
	C32-D2	0,266 ±0.002	0,814 ±0.007	-19,3 ±1,2	0,86013 ±0,005	874,71 ±4,52	233,200 ±5,572	-37,3 ±2,3	233,038 ±5,647
	C32-E	0,214 ±0.002	0,153 ±0.001	-8,2 ±1,6	0,89921 ±0,002	3905,26 ±8,98	261,630 ±4,899	-17,2 ±3,4	261,593 ±4,917

Figures

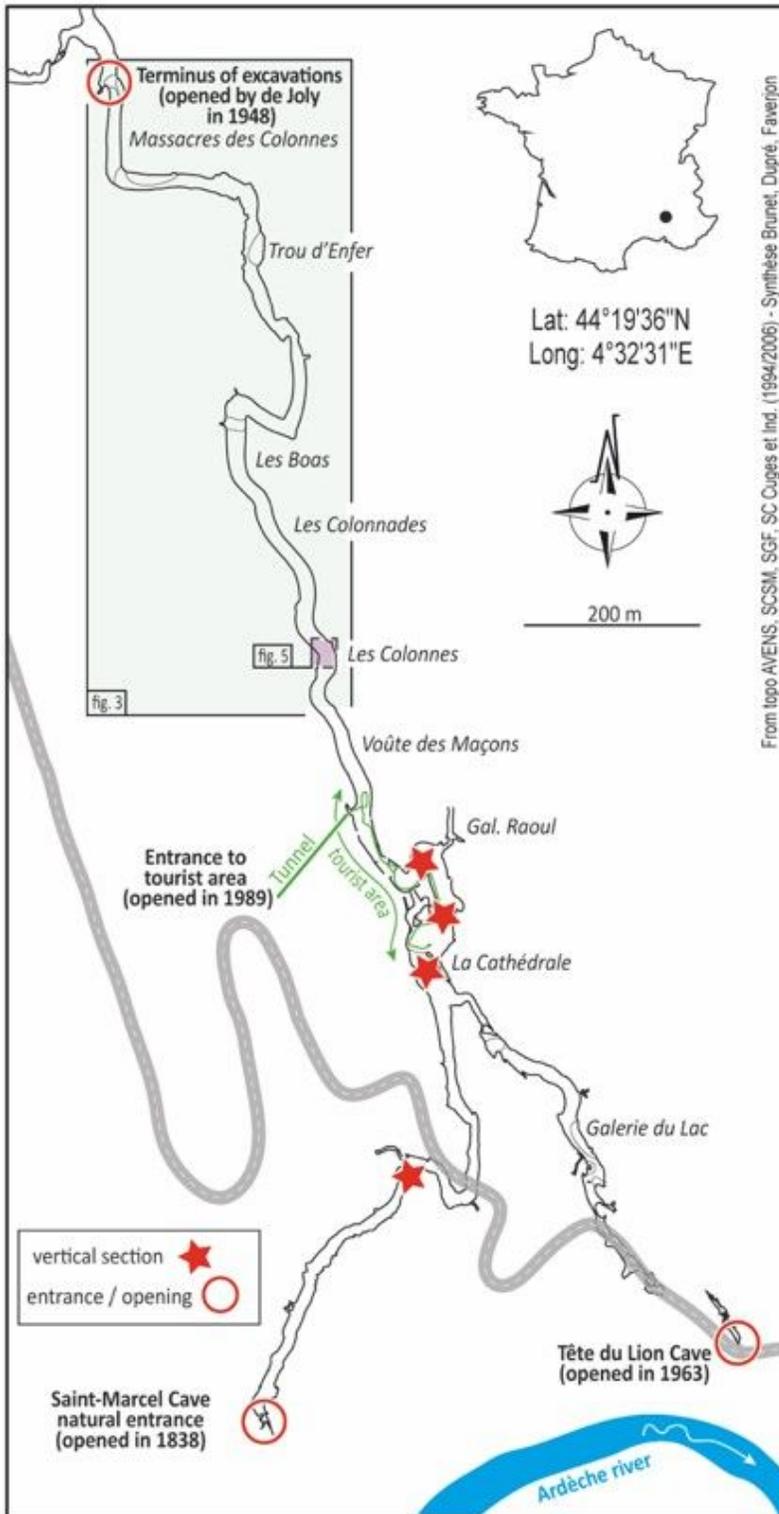


Figure 1

Map of the cave of Saint-Marcel (France), the sectors that are the focus of this study, and the topography of the main gallery.



Figure 2

Speleofact structure in the Salle des Colonnes. *This structure comprises 69 broken stalagmites and stumps aligned on the floor. Photo: S. Jaillet*

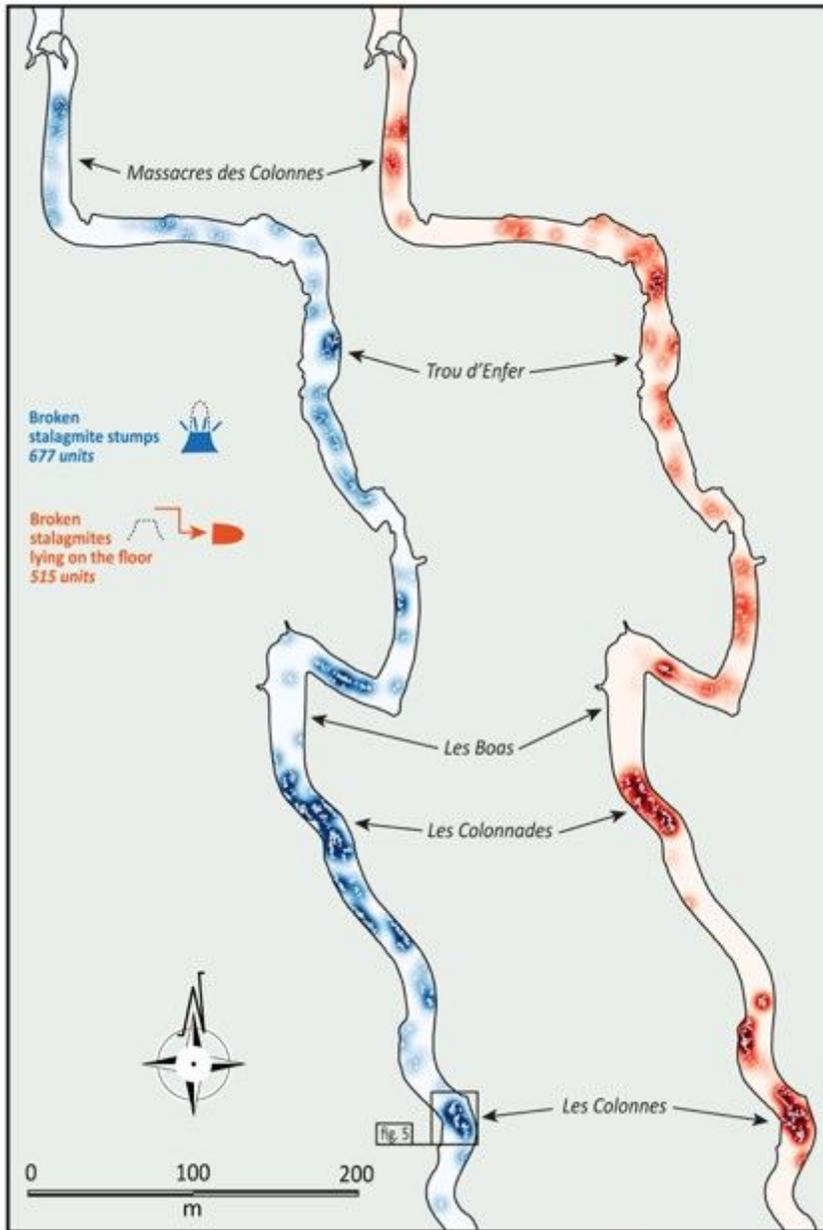


Figure 3

Density and distribution of broken stalagmites that are on the floor in the second part of the main gallery in Saint-Marcel cave. *Each stump, which is a remnant of a standing stalagmite (left) and each broken stalagmite lying on the floor (right) were overlaid on to the topographic map of the underground network. The Heatmap algorithm in QGIS 3.16 (radius 2.4, value 16) was used to create this map, which shows the spatial distribution and density of broken stalagmites.*

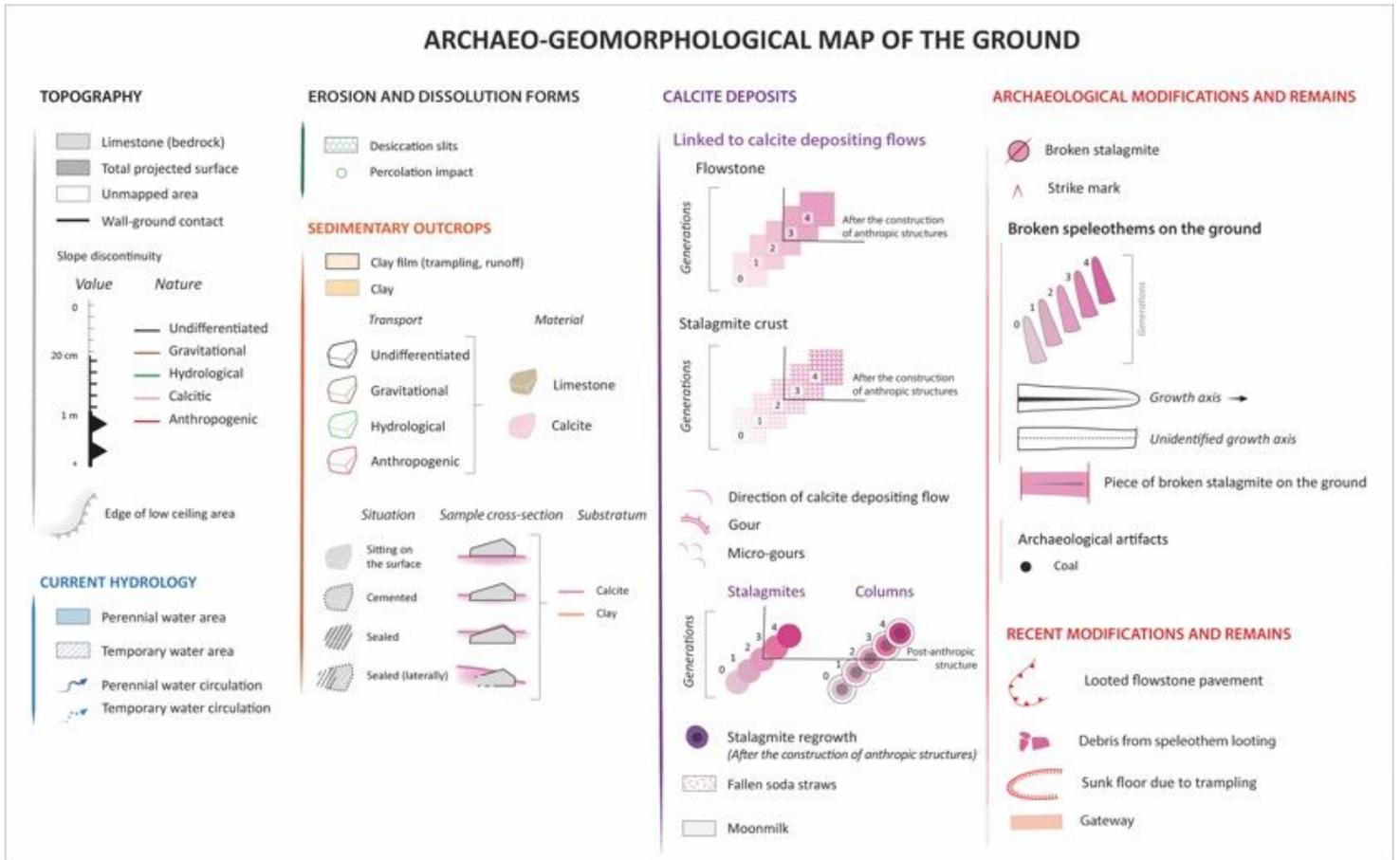


Figure 4

Legend for the archaeo-morphological map of the Salle des Colonnes (cave of Saint-Marcel, France). *The legend is based on the cartographic principles that were developed for the study of Chauvet cave (Delannoy and Geneste, 2020) and La Garma cave. It has been adapted for the study of the Salle des Colonnes and Massacre des Colonnes (Burnet, 2022). Stalagmite generations are based on a relative chronology of nesting and superposition. Early human occupation predates Holocene generations 3 and 4. Stalagmite generations are defined on the basis of observations of the surface of the mapped object. While the object may have formed over a long period of time, only the visible generation is represented on the map.*

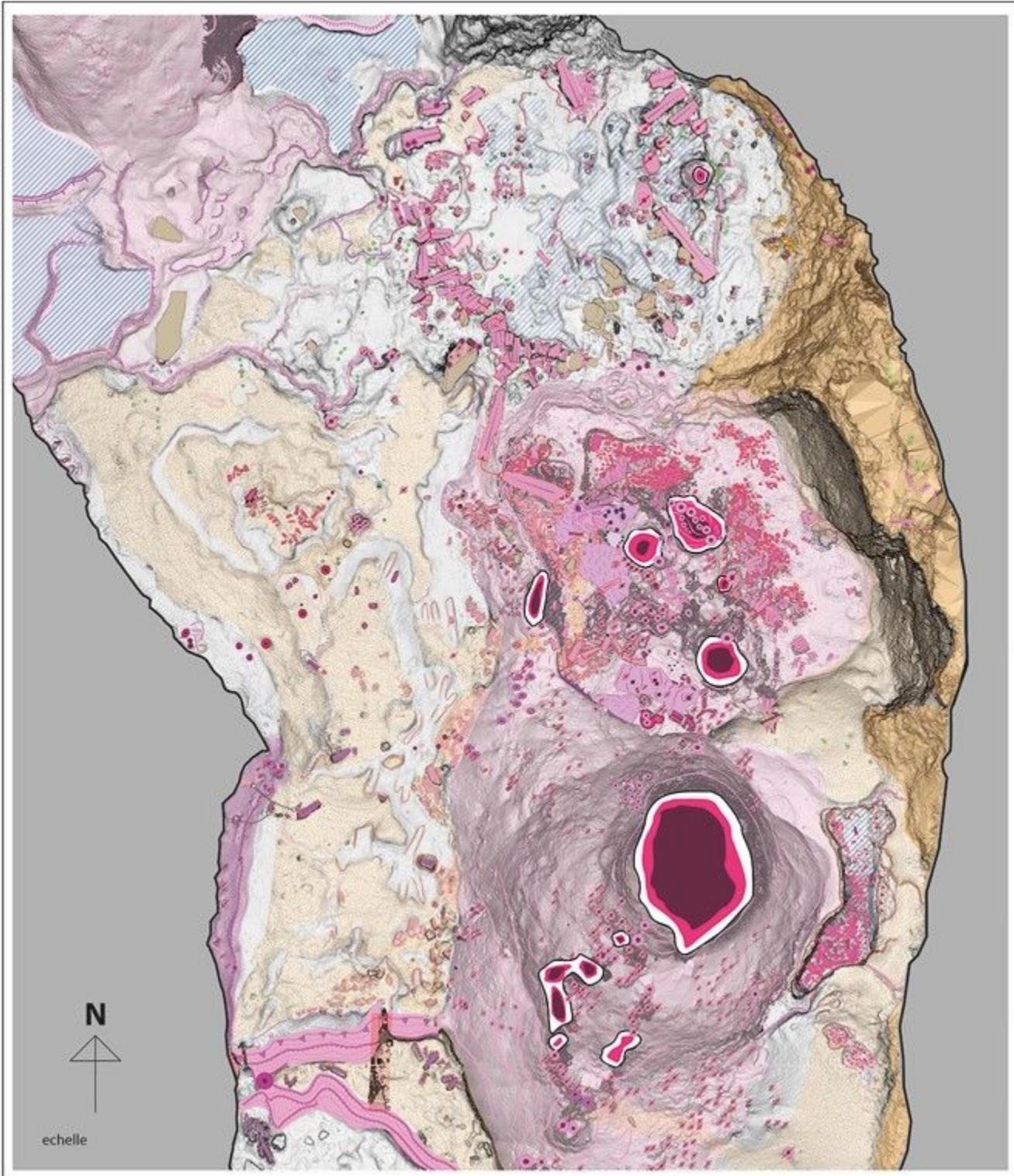


Figure 5

Archaeo-geomorphological map of the Salle des Colonnes (cave of Saint-Marcel). *Base DTM: S. Jaillet and J. Kemper; Field survey and mapping: J.J. Delannoy and J. Kemper*

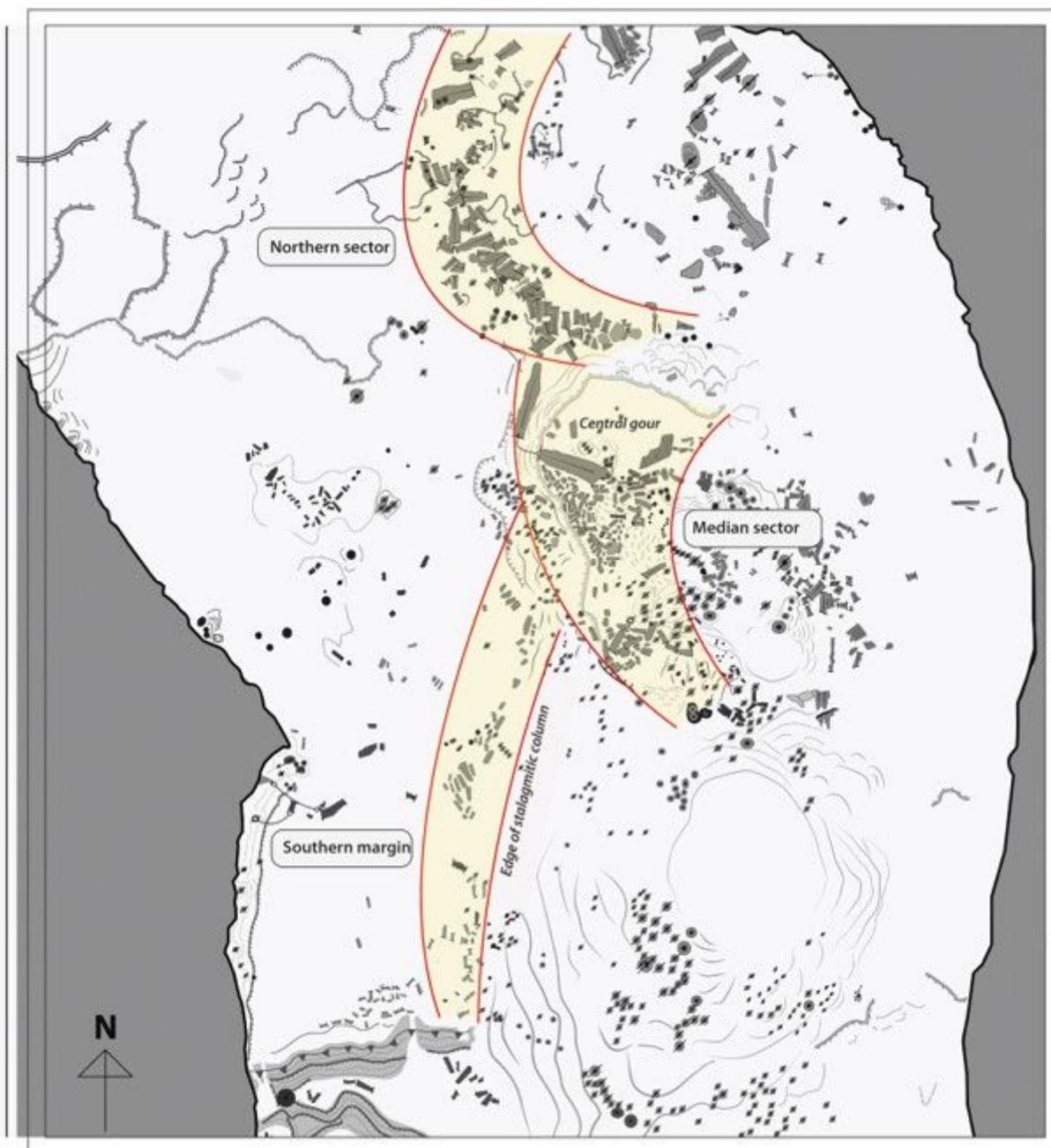


Figure 6

Map of anthropic structures made up of stalagmite stumps and recumbent stalagmites in various sectors of the Salle des Colonnes.



Figure 7

The major structure of broken stalagmites aligned on the floor of the Salle des Colonnes (northern sector). *The black-and-white picture shows the broken stalagmites (purple) and boulders (orange) that form the structure. Photo: S. Jaillet; Artwork: J.J. Delannoy*

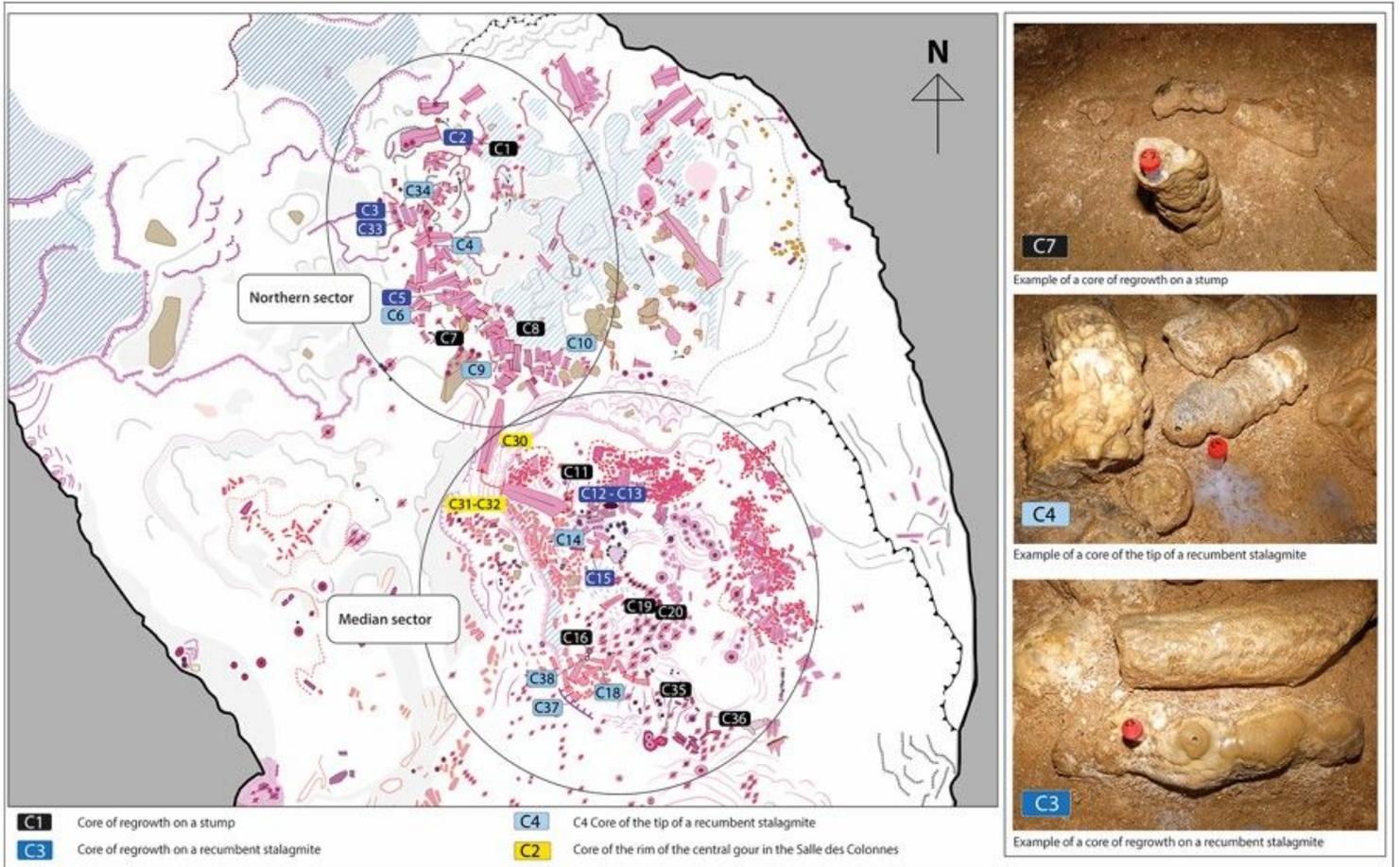


Figure 8

Location map of core samples taken from speleothems in the Salle des Colonnes for U/Th dating. *The elements on this map are based on the legend of the archaeo-geomorphological map (Fig. 5). The colour of the label of each sample indicates the sample type. Sample numbers correspond to those in Table 2 (age estimates).*

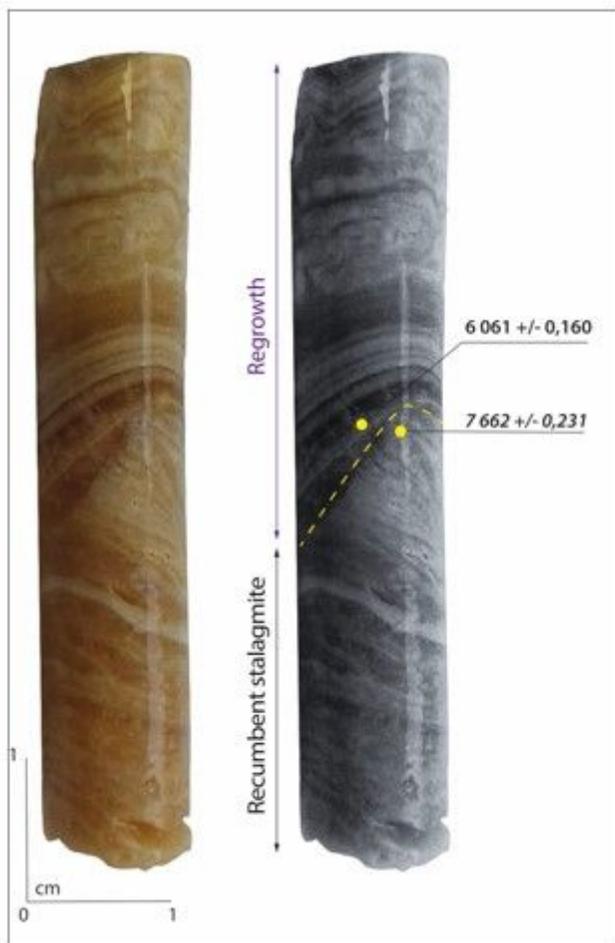


Figure 9

Photograph of core C15 showing a change in the layering direction, marking the contact between the recumbent stalagmite and the regrowth. *Photo: E. Pons-Branchu*

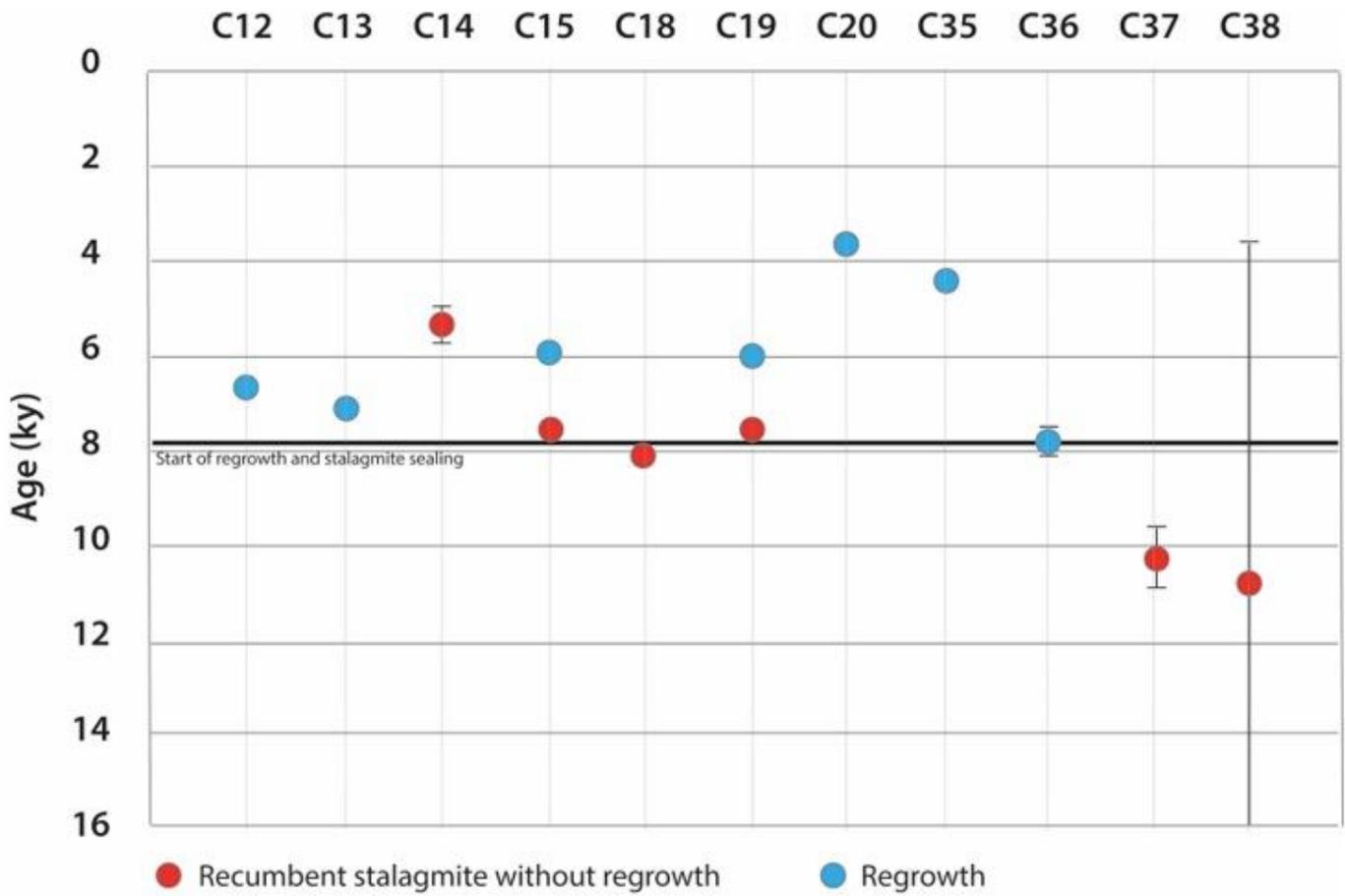


Figure 10

Age of stalagmites before breakage (obtained from the tips of recumbent stalagmites without regrowth) and age of regrowths on speleofacts in the structure of the median sector. Samples C15 and C19 provide the best temporal constraints. *Data: E. Pons-Branchu*

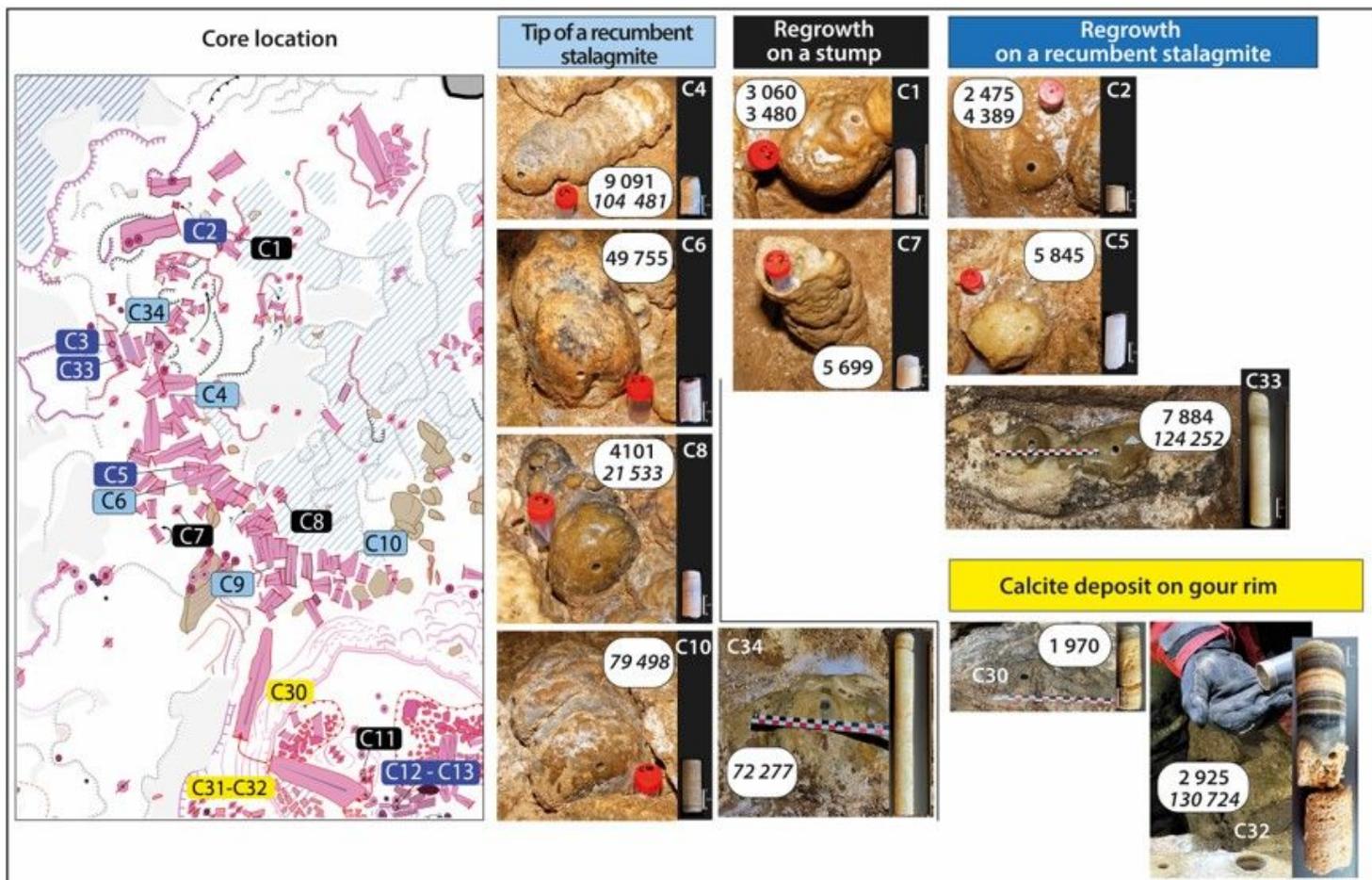


Figure 11

U/Th dating results for the structure in the northern sector of the Salle des Colonnes. *Non-italicised number indicates age of regrowth or tip of recumbent stalagmite. Number in italics indicates age of the part of the recumbent stalagmite that is beneath the stalagmite seal (regrowth or flowstone).*

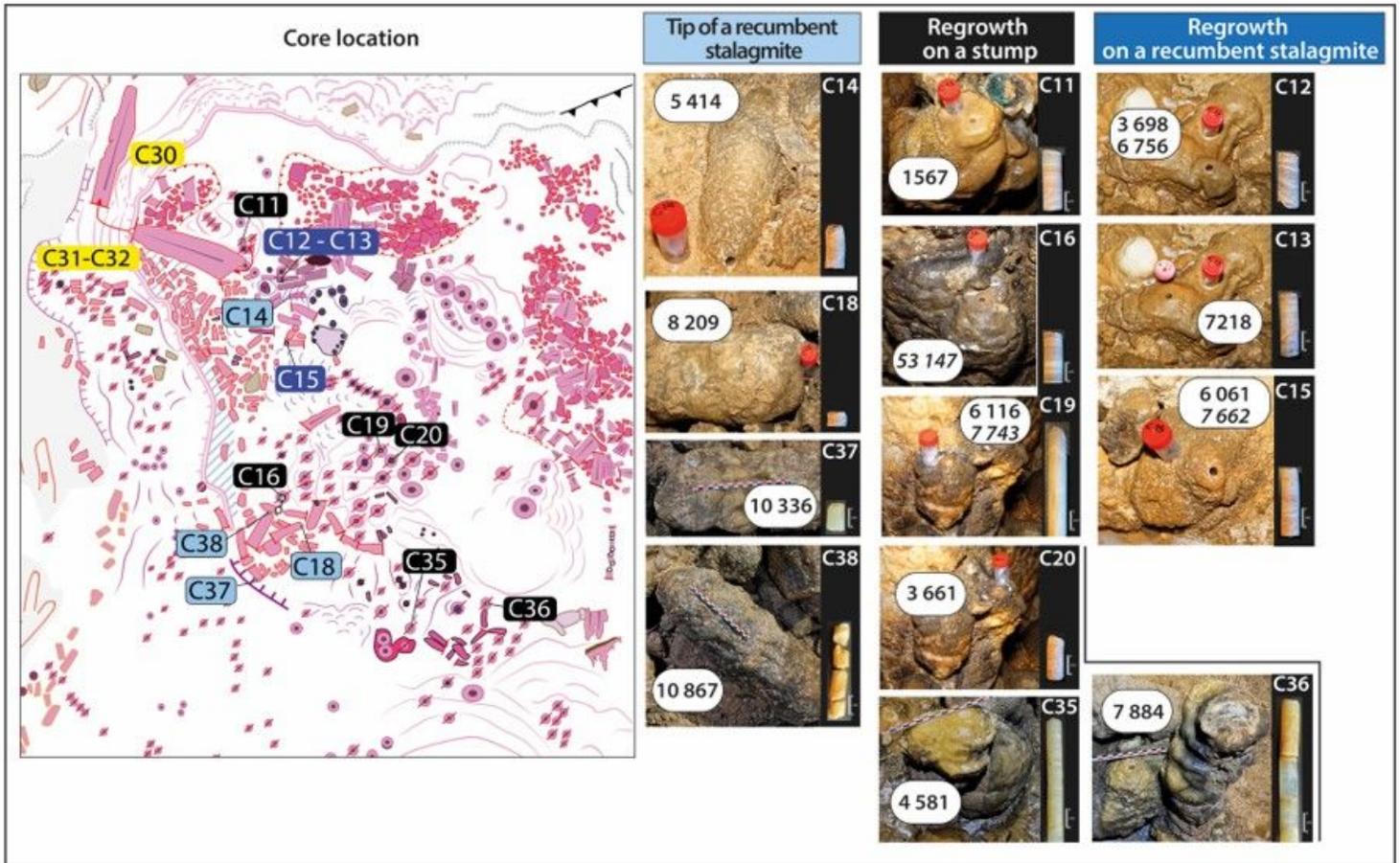


Figure 12

U/Th dating results for the structure in the median sector of the Salle des Colonnes. *Non-italicised number indicates age of regrowth or tip of recumbent stalagmite. Number in italics indicates age of the part of the recumbent stalagmite that is beneath the stalagmite seal.*

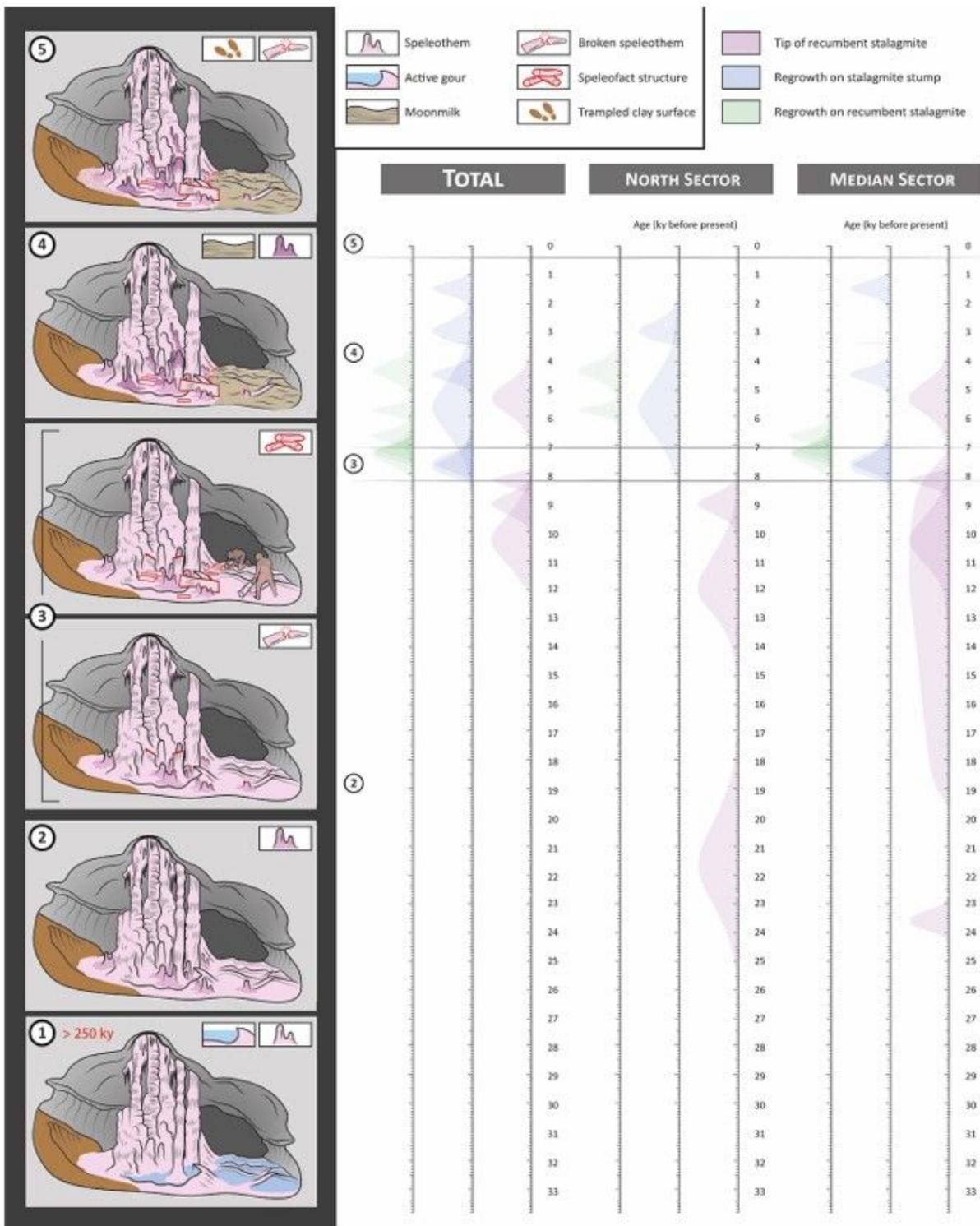


Figure 13

Summary of morphological evolution and anthropic events in the Salle des Colonnes over the last 300,000 years. *U/Th* dates obtained from the Salle des Colonnes were processed using the software *Chronomodel* to create a Bayesian model of relative chronology.

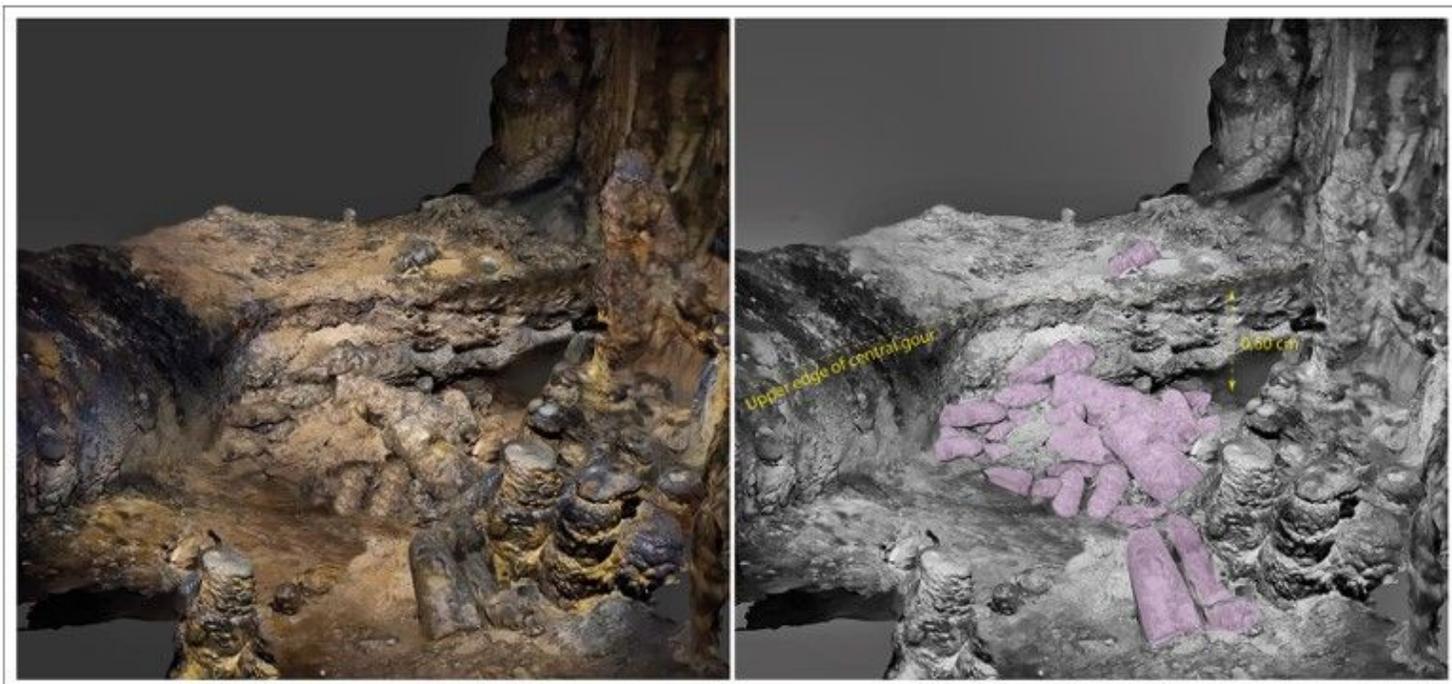


Figure 14

Organised cluster of broken speleothems at the southern end of the speleofact alignment in the median sector of the Salle des Colonnes. *This arrangement is made of 23 visible speleofacts that are superposed on top of each other and wedged together.*