



The evolution of the cave's entrance of Bruniquel and consequences for its accessibility by early *Homo neanderthalensis*

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ABSTRACT

The cave of Bruniquel, discovered by cavers in 1990, contains the oldest evidence of deep cave use by early *Homo neanderthalensis*. The discovery and dating of speleothem-based structures and fireplaces demonstrated their ability to investigate the deep subterranean environment in a structured way (Jaubert et al., 2016). The cave has been closed by a succession of rockfalls, flowstone layers and scree cone deposits, which led to the preservation of multiple traces of human and animal activity inside the cave. We studied the cave entrance evolution through a multidisciplinary integrated geomorphological approach, combining 3D surveys inside and outside the cave system, high-resolution geomorphological mapping, Electrical Resistivity Tomography (ERT), and U-series dating. The combination of stratigraphic surveys and U-series dating allowed us to date the closure of the cave to before 142.9 ± 1.3 ka, before the Last Interglacial, thus independently confirming the age of the speleothem structures and of the other traces observed on the cave floor. The proposed virtual 3D reconstruction of the palaeo-cave entrance at the beginning of MIS 6, suggests an entrance less than 2 m high, implying that the space behind the entrance was rapidly dark. This work highlights the central importance of understanding the evolution of cave entrances for constraining the timing and the modalities of use of cave systems and provides a new palaeogeographic framework for future studies of the cave's occupation by early *Homo neanderthalensis*.

1. Introduction

Since its discovery in 1990, the cave of Bruniquel has called into question our understanding of the past use of the cave, and its modalities (Rouzaud et al., 1995; Rouzaud, 1997). Recent work performed on the

chronology of the construction of speleothem-based structures (speleofacts, i.e. “arranged structures composed of whole and broken stalagmites”, Jaubert et al., 2016) revealed their Neanderthal origin (Jaubert et al., 2016). Inside Bruniquel, the roughly circular structures are composed of more than 400 speleothems and have been found more than 336 m

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underground. They also yield evidence of the use of fire and still show burnt areas on the cave soils and inside the speleothem-made structures, thus also making it the oldest evidence of fire structures ever discovered in a cave context (Jaubert et al., 2016). The structures were dated by the U-series method to 176.5 ± 2.1 ka (Jaubert et al., 2016; Verheyden et al., 2017), demonstrating the capacity of early *Homo neanderthalensis* for structuration, organisation, and mental projection into this very particular space (Fig. 1). This discovery bears witness to Neanderthal investment in the deep subterranean environment and raises new research questions regarding the relationship between the Middle-Palaeolithic culture of early *Homo neanderthalensis* (e.g. Moustérian) and their environment, particularly underground.

The structures are now locally covered by different generations of

flowstone that sealed and protected some parts of the archaeological evidence, and were used to constrain the age of the structures (Jaubert et al., 2016). Since 176 ka, sedimentary processes inside and outside the cave progressively transformed the shape of the underground landscape. The former cave entrance was closed by natural sedimentary processes until its discovery by cavers in 1990. Endokarstic processes and biological activity have progressively hidden and covered other potential traces of human activity at the surface of the cave floor. To understand and reconstruct the underground space at the time of its use, it is crucial to correctly identify the succession of processes and traces, in order to investigate the appropriation and past use of Bruniquel by early *Homo neanderthalensis*.

In this contribution, we discuss the landscape evolution of the cave

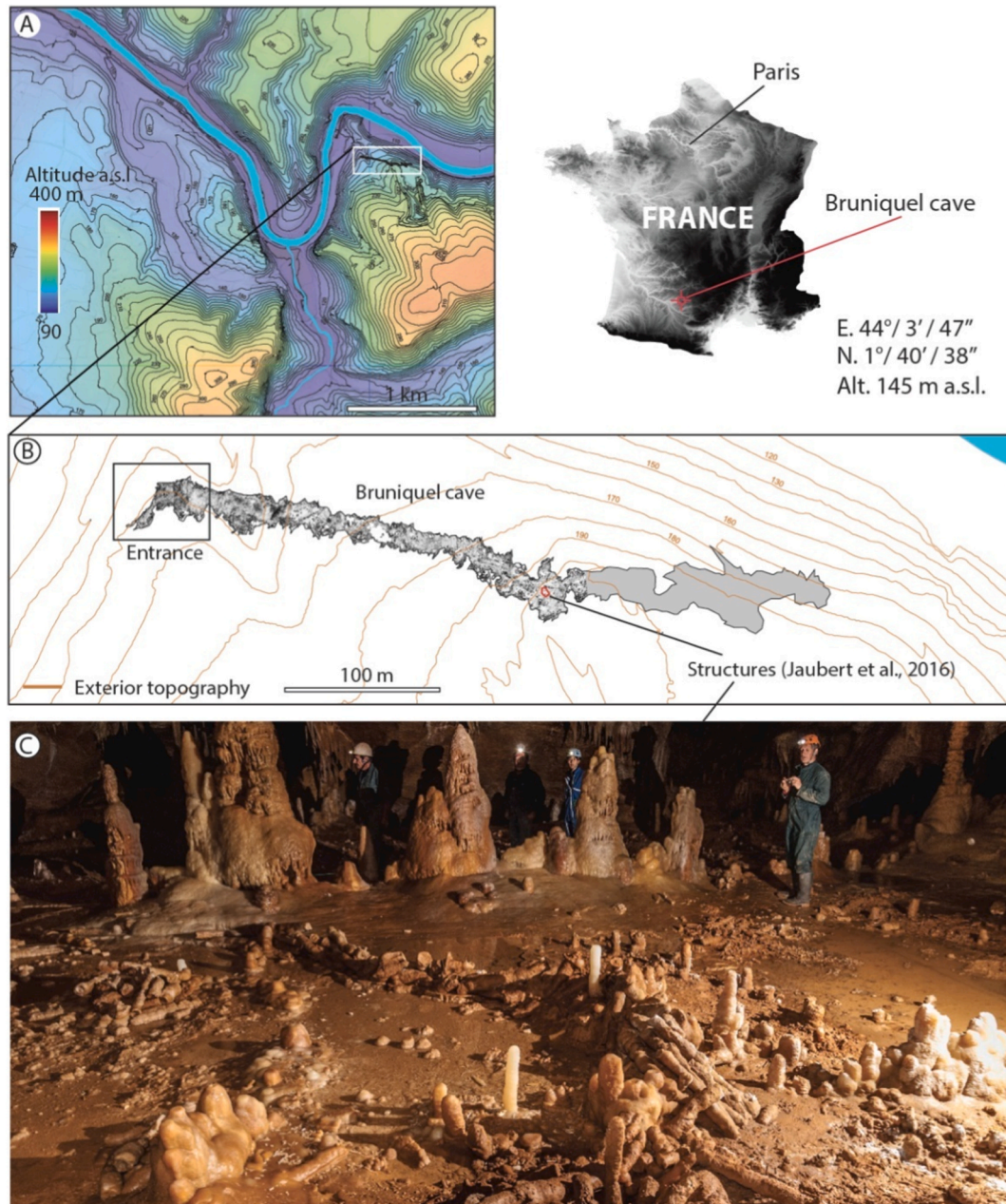


Fig. 1. Location map of the cave of Bruniquel. A. Location of the cave compared to the fluvial system of the Aveyron canyon; B. Closeup to the cave. The first part of the cave (shaded gray) is based on the elevation model of the soils, issues from the 3D laserscan point cloud performed in 2022. The topography of the limits of the last part of the cave (gray area) is based on the acquisitions by Camus et al. (2015); and Camus and Muth (2016); C. The anthropic neanderthal-made structures inside the cave. Those constructions are made of broken speleothems (« speleofacts », i.e. Jaubert et al., 2016; photograph from: L-H. Fage). Cave topography is based on the laserscan acquisitions of AGP + EDYTEM + this work.

system as a key factor for understanding the modalities of investment of underground space and the accessibility of the cave. We focus on the current entrance of the cave and the geomorphological history of this area. It is difficult to picture the evolution of the cave as the entire system cannot be observed at once, and the potential neanderthal entrance is not visible in the current underground and external landscape of the cave. What did it look like around 176 ka? Was it a large entrance such as Chauvet cave (Delannoy et al., 2010; Sadier et al., 2012; Sadier, 2013) or El Castillo (Spain; Bayarri et al., 2021)? Or a more discreet one such as Cussac cave (Jaubert et al., 2017)? Was it visible in the landscape? Did the geometric configuration of the entrance make the access to the cave as difficult as it is today?

Our work aims to provide new insights into the past morphologies of the entrance to better constrain the modalities of the occupation of cave occupation and accessibility. To overcome limitations inherent to cave studies (few open sediment sections, difficult access to some areas), we combine 3D-integrated geomorphological mapping of surfaces inside and outside the cave entrance with local cross sections, ERT geophysical surveys and 3D reconstructions. We also review a series of U-Th datings performed on speleothems and flowstone deposits at the surface of the cave system (Verheyden et al., 2017). Studies of past landscape

morphologies surrounding archaeological caves have proven useful for assessing past human occupation (Sadier et al., 2012), but remain limited to a few sites in Europe (Chauvet cave, Delannoy et al., 2010; Sadier, 2013; Genuite et al., 2021a; Roc-aux-Sorciers, Genuite et al., 2023; Santimamiñe cave, Intxaurbe et al., 2023; La Roche Cotard, Marquet et al., 2023), in Australia (Nawarla Gabarnman, Delannoy et al., 2017; Borolaga rockshelters, Genuite et al., 2021b; Cloggs cave, Delannoy et al., 2020); and in some South African sites such as Sterkfontein (Bruxelles et al., 2014, 2019); Blombos (Jacobs et al., 2020; Haaland et al., 2021) and Wonderwerk (Matmon et al., 2012). Our work provides a first reconstruction attempt of past morphologies and presents a clear methodological workflow for reconstructing them using a 3D geomorphological approach.

2. Site description

2.1. Location and context of the site

The cave of Bruniquel ($44^{\circ} 4' N$, $1^{\circ} 41' E$) is located in France, in the southern part of the Quercy plateau, at the end of the Aveyron canyon, in the last entrenched meander before the confluence with the Vère river

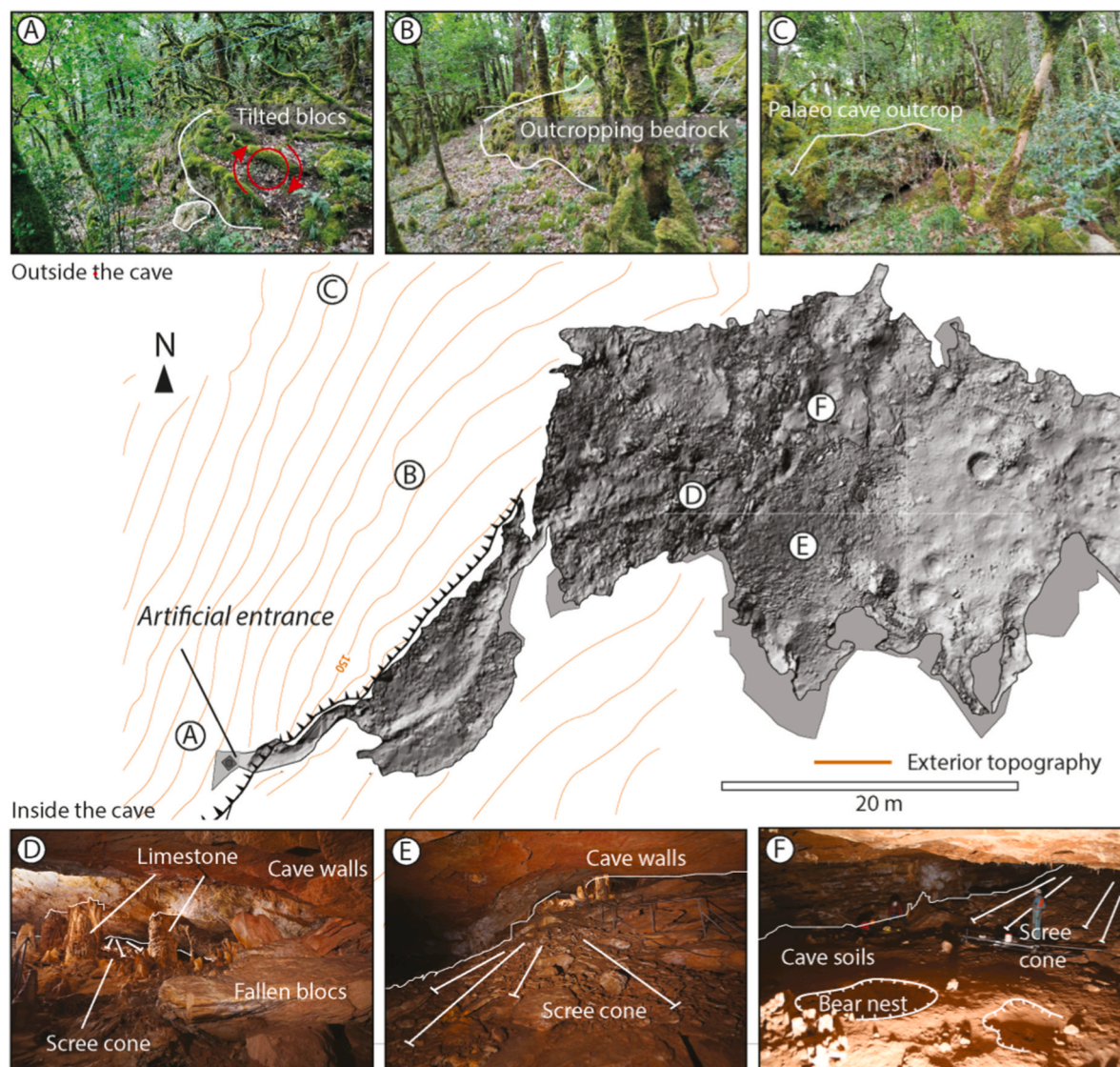


Fig. 2. Photographs of the outside of the cave and of the scree and other deposits in the cave entrance. A, B, C: credits: K. Genuite. D, E, F: credits: E. Fabre. Hillshade map: courtesy of S. Jaillet.

(Fig. 1). The main level of the cave system is located at around 130 m a.s.l, more than 33–35 m above the current level of the Aveyron River. The cave is more than 460 m long and ranges between 8 and 44 m in width. The cave is therefore one of the largest caves of the Aveyron canyon, along with the Pyramide cave. Bruniquel occupies a particular position as it almost intersects both sides of the central part of a meander of the Aveyron river. The eastern part of the cave is only 100 m from the outside (Fig. 2). The cave is developed within the middle Jurassic Bajocian series of the Autoire formation (Pélissié, 1982; Lézin, 2000). Most of the cave is developed in grainstone-rich limestone, while the entrance area is also hosted in recrystallised red-orange limestone and microcrystalline dolomitic rocks. The orientation of the main gallery intersects a fault with weak rejection (150°). This direction, associated with $20^\circ/30^\circ$ fracturing, is frequently observed in the morphology of the gallery walls, which locally evolve into karstic conduits that are variably filled or emptied of clay infill. Although it may be tempting to interpret this gallery as an underground meander cutoff, the observed morphologies do not display classic epiphreatic markers indicative of river flow through the cave (e.g. rounded pebbles or scallops), despite its location suggesting a bypass of the penultimate meander of the Aveyron canyon (Fig. 2). Areas of rock alteration remain visible on the cave walls, and seem to be comparable with the ghost rock weathering of limestone observed along the margins of the Quercy plateau, a process affecting many karstified rocks, in southwestern France (Dandurand, 2011; Pellegriin and Maire, 2012; Dubois et al., 2014; Dandurand et al., 2017).

2.2. The entrance of the cave of bruniquel

The cave was discovered in 1990. Sediments and rock were removed to open a passage for cavers and researchers. The current entrance is directly connected to the outside (western part of the cave) through a narrow artificial passage excavated within clastic sediments and host rock at the upper part of the entrance scree (Figs. 1 and 2). Outside the cave, a 20 m long cliff line reaching up to 4 m of vertical height is visible. In this area, several plurimetric blocs crop out along the slope (Fig. 2). Approximately 15 m to the north-east, the topography becomes less pronounced and is characterized by a relatively regular slope of about 40%. Indicators of a possible palaeo-entrance are very scarce on this surface, and dense vegetation hides the underlying morphologies (Fig. 2). In 1990, cavers created an artificial passage through the sedimentary infill corresponding to the collapse of the former cave entrance (Rouzaud et al., 1995).

A first narrow passage, approximately 8 m long, follows the limestone roof. This straight section crosses a small chamber filled with clasts and decimetric blocs sealed by flowstone (Fig. 2). The chamber ends in a narrow passage filled with blocks and clast that are locally cemented by calcite (breccia). This narrow passage corresponds to the upper part of the cave entrance and is located at the top of a 13 m high scree cone descending into a wide passage, around 10–15 m in width. This scree cone represents the internal slope of the sedimentary infill that seals the entrance area (Fig. 2) and is masked externally by slope deposits and, above all, dense vegetation.

3. Methods

To overcome the limitations imposed by the karstic environment, dense vegetation, and buried morphologies, a 3D-based geomorphological approach was adopted. Detailed geomorphological mapping, cross-sections and ERT geophysical surveys were supported by high-resolution 3D surveys conducted both inside and outside the cave system. The combined use of these methods enables the integration of internal and external processes within a common framework for interpreting past landscape evolution (Genuite et al., 2021a, 2022), and provides a basis for reconstructing past or buried cave morphologies.

3.1. 3D survey and mapping of the cave

The acquisition of topographic data aimed to reconstruct the geometry of the present-day landscape. 3D mapping was performed inside and outside the cave system. We used a Terrestrial Laser Scanning (TLS) approach to capture the cave environment. Several acquisitions were performed for different objectives (mostly related to heritage and conservation issues) in various areas of the cave. At the scale of the external landscape, the LiDAR HD French national data (<https://geoservices.ign.fr/lidarhd>) was used to represent the valley hosting Bruniquel. For the area immediately surrounding the former cave entrance, both the inside and the outside were surveyed using a short-range, phase-shift terrestrial 360° LiDAR. These acquisitions provided a subcentimetric survey inside the cave system (AGP society). Outside the cave, dense vegetation resulted in a lower and more variable point density at the local scale (EDYTEM laboratory). All the scan scenes were registered within the Faro SCENE software using spherical targets (Jaillet et al., 2017; Genuite, 2019; Genuite et al., 2021b).

Because of differences in acquisition dates, locations and point density, a consolidation step was applied to the entire dataset. Point clouds were merged into a common referential using CloudCompare software (Girardeau, 2018) through a best-fit alignment method (Besl and McKay, 1992), constrained by a previously acquired polygonal topographic acquisition (S.O.M. section S1; Figs. S1 and S2). Topographic data at the scale of the Aveyron valley was extracted from the LiDAR HD dataset, and the ground surface was automatically classified (<https://geoservices.ign.fr/lidarhd>). Vegetation (outside) and people or infrastructure (inside) were removed using automatic filtering methods (CloudCompare, CSF Filter, Zhang et al., 2016). Additional manual cleaning was also performed inside the cave through the use of clipping planes (Genuite et al., 2021b) because the low quality of the 3D scans (AGP, Table 1) prevented fully automated classification. The cave floor and roof were classified separately to generate 2D elevation models. The surfaces of the cave were then meshed in two steps. First, a preliminary mesh was obtained in CloudCompare with the screened Poisson surface reconstruction algorithm (quadric calculation every 10 cm). Then, a more refined mesh was obtained by Delaunay 3D triangulation (Delaunay, 1934; Gomes et al., 2009; Maur, 2002; Verhoeven, 2017) with the Cyclone 3DR software/3DReshaper software (Remondino, 2003; Genuite et al., 2021b). All 3D objects were georeferenced considering the polygonal calculations performed in RGF 93/Lambert 93 CC44 (S.O.M. section S1).

3.2. Geomorphological mapping inside and outside of the cave entrance

Geomorphological mapping and cross sections were produced for the entire entrance area following the workflow presented in Fig. 3. Mapping was conducted in the area surrounding the cave entrance (120×80 m) and over a 50×30 m area corresponding to the cave entrance floor. The map of the cave soil is supported for a high-resolution elevation raster map of 2×2 cm that was generated with CloudCompare. Slope calculation was later performed using QGIS 3.34. After initial field sketches, cross sections were directly extracted from the 3D point cloud to ensure accurate geometries. Final maps and cross-sections were digitised using drawing software (Adobe Illustrator). A common figurative legend was developed for all maps. The legend is directly inspired from the Chauvet cave geomorphological map (Delannoy and Geneste, 2020), which currently serves as a reference for geomorphological mapping in cave systems (Fig. 3). A similar, but more simplified, legend was applied to the external landscape (see Fig. 4).

3.3. ERT geophysical survey inside and outside of the cave

Six Electrical Resistivity Tomography (ERT) profiles were acquired in the entrance area. Four profiles were conducted outside using a 2 m electrode spacing (ERT1, ERT2, ERT3, ERT4), while two profiles were

Table 1

Specifications of the 3D data acquired and used for the study.

Studied area	Survey method	Number of stations	Registration uncertainty	Point cloud accuracy	Point cloud density	Mesh triangles size
Landscape setting	Airborn LiDAR	1	3 cm	12 cm	1 pt/m ²	10-15 m
Outside the cave	TLS LiDAR	43	0.7 mm	2 mm at 10 m	0.5-5 cm/m ²	20-30 cm
Inside the cave	TLS LiDAR	>400	3-4 mm	2 mm at 10 m	0.1-0.8 cm	

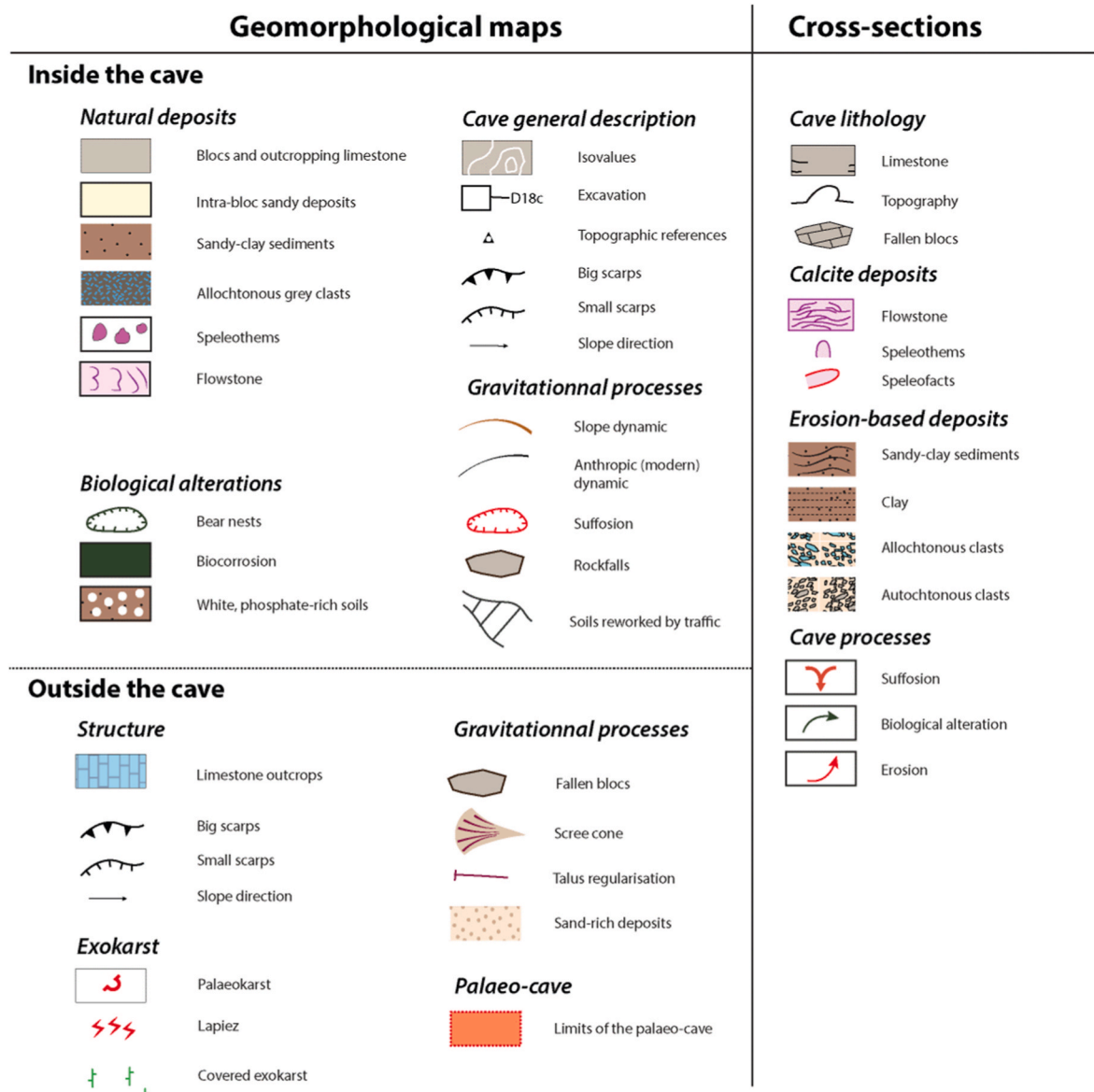


Fig. 3. Legend of the cave geomorphological maps and associated cross-sections, inside and outside the cave. Cross sections were drawn at a more detailed scale than the planar geomorphological map.

acquired inside the cave: one starting from the entrance (ERT5, metal electrodes, 2 m spacing), and one on the internal scree cone (ERT6, silicone electrodes, 50 cm spacing). Measurements were carried out using an ABEM LS2 terrameter multi-electrode system. The Wenner-Schlumberger 64 protocol (Loke and Barker, 1996) was selected due to its suitability for karst environments (Carrière et al., 2013; Torrese et al., 2014; Prins et al., 2019a, 2019b). Electrode positions were recorded using a handheld Global Positioning System (GPS), while key electrodes (E1, E16, E32, E33, E48, E64), were surveyed with differential GPS, providing positional accuracy better than 5 cm. Z values of the electrodes were extracted from the 3D model. When necessary,

especially inside the cave, electrode positions were manually adjusted using photogrammetric surveys acquired during the ERT acquisitions (Fig. 4).

3.4. Reconstruction of the palaeo-geometries

Reconstruction of the palaeo-geometries was based on the combination of geomorphological mapping, cross-sections and the 3D model, inside and outside the cave system. The workflow follows the protocols described in Genuite et al. (2021a; 2023) and Kemper et al. (2023) and highlighted in Fig. 5. Scree cone morphologies were reconstructed by

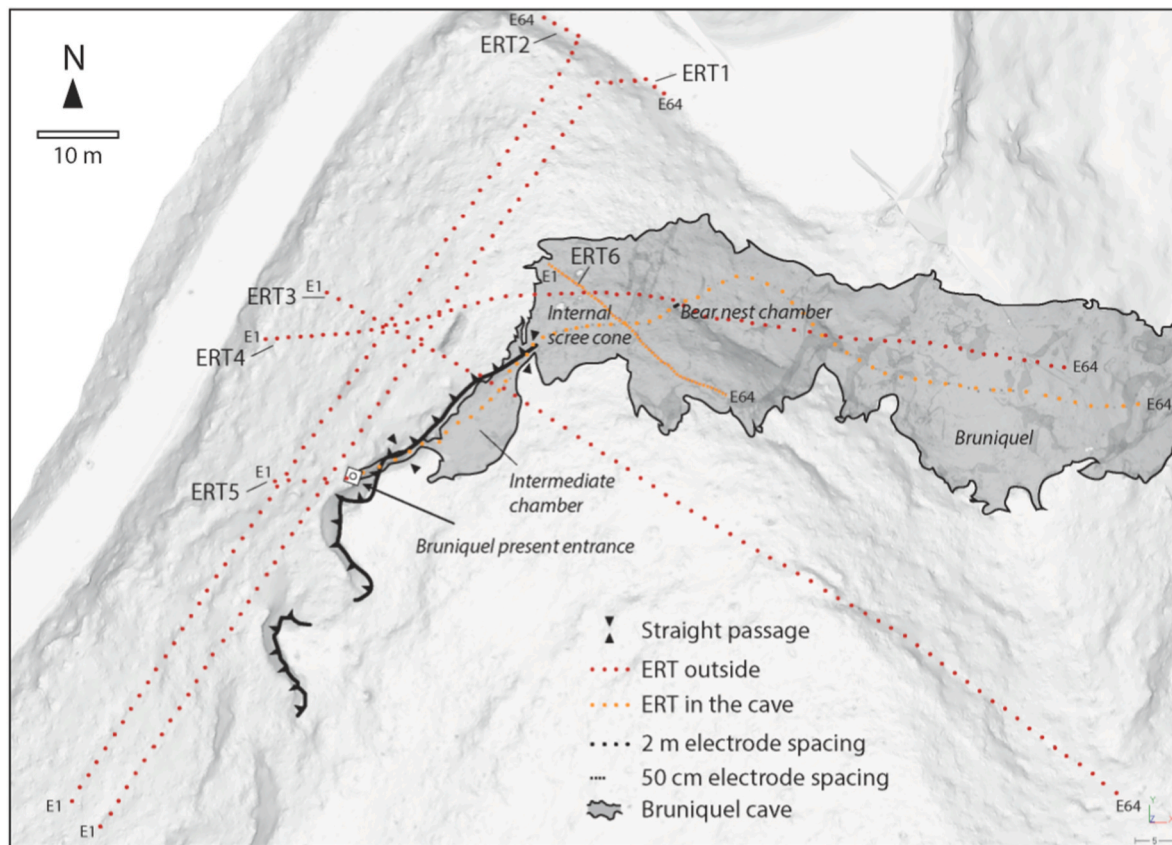


Fig. 4. Location of the 6 ERT profiles performed in the entrance area of the cave. Points acquired with differential GPS.

projecting cross-sections onto the 3D model using the monoplottting technique (Wiesmann et al., 2012) in order to extract colour or geometric information, and to recreate the geometry of surfaces that have now disappeared (Berthet, 2016; Génuit et al., 2018; Kemper et al., 2023). Scree cone geometries that show the outward forms of scree were automatically extracted from the areas identified as palaeo-morphologies on the geomorphological map (Fig. 5). To reconstruct the archaeological palaeo-topography, surface interpolation was performed using the extent of archaeological levels inside the cave and the projection of the palaeo-scree conical morphologies outside. The entire area comprising the fill from the two scree generations and the Eemian were removed from the 3D model, leaving only archaeological surfaces, projected slopes, cliffs, and rock shelters. Interpolation outside investigated areas should be considered with caution because of steep altitudinal gradient, the lack of stratigraphic observations and geophysical prospection on the outside. This area is given with caution and less confidence. Virtual control points were generated at the junctions between archaeological surfaces and structural elements to guide interpolation. Final surface meshing was performed using 3D Delaunay triangulation in 3DReshaper (Génuit et al., 2021a; Kemper et al., 2023, Fig. 6).

3.5. U-series dating and bayesian hierarchical modelling of the events

Numerous U-series ages were obtained from speleothems and flowstone layers growing inside the cave entrance. Those are well distributed spatially and most of them were published in Verheyden et al. (2017). Unlike tufa and travertines, the calcite that grows inside cave systems, in the dark, leads to the development of flowstone layers and vertical shaped-structures called speleothems (Hill and Forti, 1997). The dating of the base and the summit of the speleothems and flowstone layers by

U-series can provide chronological constraints for other processes occurring before or after calcite deposition. The entrance of Bruniquel is sealed by multiple generations of *in situ* flowstone and speleothems that locally cement stones and clastic sedimentary deposits coming from the outside of the cave. These chronological constraints guided the selection of areas used for palaeo-entrance reconstruction. The high number of available U-series ages ($n = 30$) allowed the construction of a detailed chronology of the geomorphic events that transformed the cave entrance. To address potential issues related to unreliable age estimates (detrital thorium contamination, open geochemical system of some speleothems), U-series ages were modelled using a Bayesian Hierarchical approach based on the stratigraphy of the events. Two models were constructed: a first one with all the ages (Model A, see S.O.M. section S4), and a second one without the ages affected by possible contamination and geochemical problems (Model B, see S.O.M. section S4). We use the “Event model” implemented in Chronomodel 2.0.18 (Lanos and Philippe, 2018) to propose a global integrated chronology, and combine individual dates (t_i), associated uncertainties and stratigraphical data into events (θ). The discrepancy between (θ) and (t_i) was modelled by an individual variance (σ_i^2) allowing the model to be robust to outliers without requiring their removal from the original data set (for other examples, see Génuit et al., 2022, 2023). Each U-series measurement was modelled independently and was entered following the distribution of the calibrated date (Lanos and Philippe, 2018). Four Markov chain Monte-Carlo (MCMC) were run with the following parameters: burn-in: 1000; batch iterations: 500; acquisition iterations: 10000.

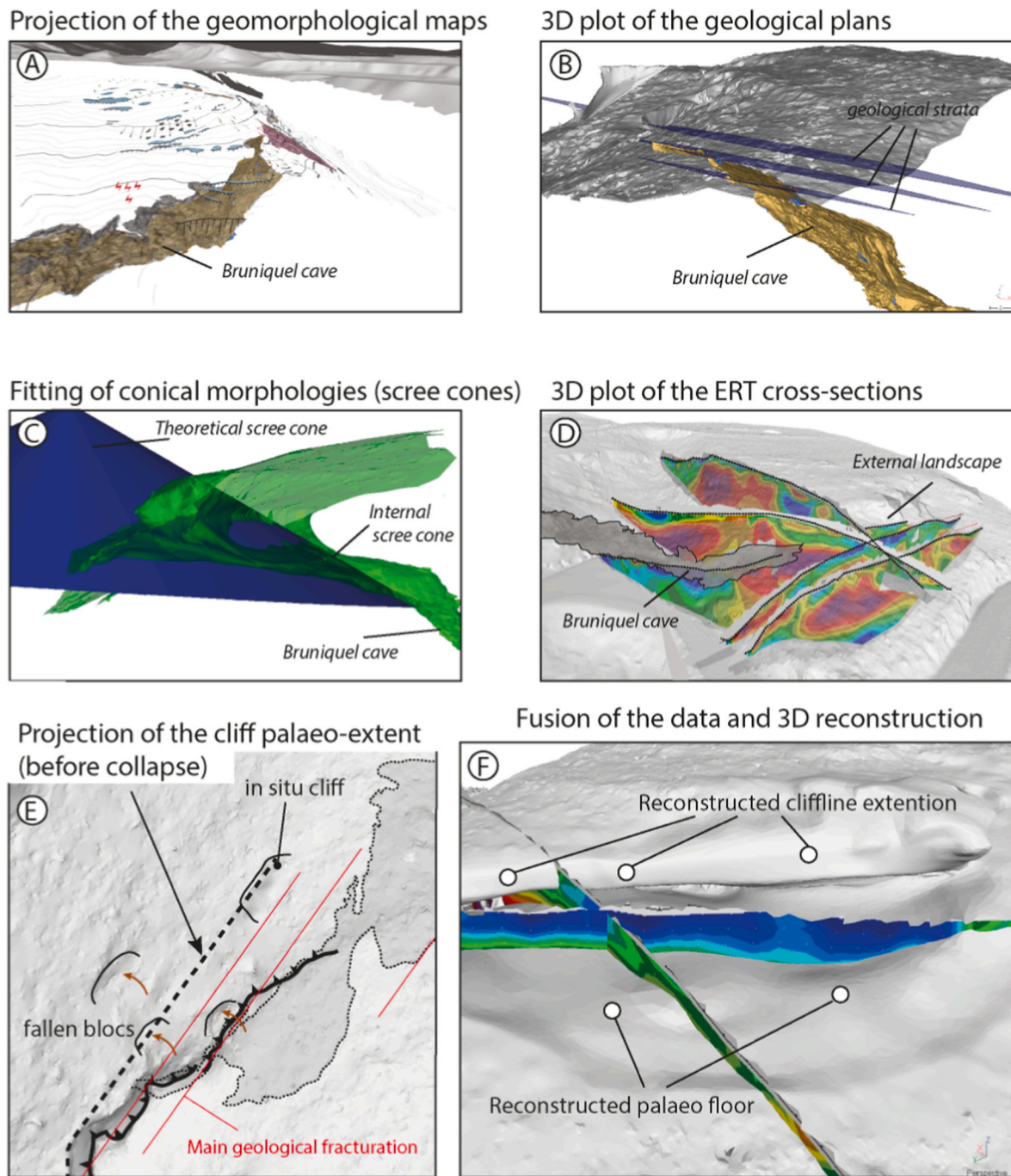


Fig. 5. 3D geomorphology reconstruction method (based on Genuite et al., 2023).

4. Results

4.1. Geological and geomorphological mapping of the cave entrance

4.1.1. The outside of the cave

In the geomorphological map of Fig. 5, the slope facing NW corresponds to the side of the Aveyron valley and the slope facing NE corresponds to the left bank of the valley (Figs. 1 and 5). The slope where the cave opens is currently covered by dense vegetation mainly growing during the spring and summer seasons, and by a thick layer of moss that hides the limestone outcrops. The moss also covers a soil that is made up of a sandy-clay matrix, and large plurimetric blocs. Near the surface of the plateau, the limestone substratum regularly crops out between sandy deposits, favouring vegetation. Nearby the cliff line overhanging the

entrance to the cave and the NW slope, we can note that the cliff line is prolonged by a lone outcrop, and, further to the East, by a plateau-filled scree cone (Fig. 5). On top of the cave, a collapsed zone is observed on the geomorphological map. This area is characterised by a small steep step in the upper part of the slope, but located significantly below the scarp formed by the plateau. This scarp corresponds to the direction of the palaeo-entrance, part of which collapsed downslope to form a talus slope of plurimetric blocs and large tilted slabs. Those rock slabs are partially masked by more recent slope deposits. Some outcrops of limestone that are located downslope cap plurimetric rock slabs. Several holes are visible between these slabs, showing signs of significant voids. The material expelled by burrowing animals is soft, which differs from the topsoil and the forest floor. The base of this destabilised zone is not visible in the underlying excavation from the road. Several cave

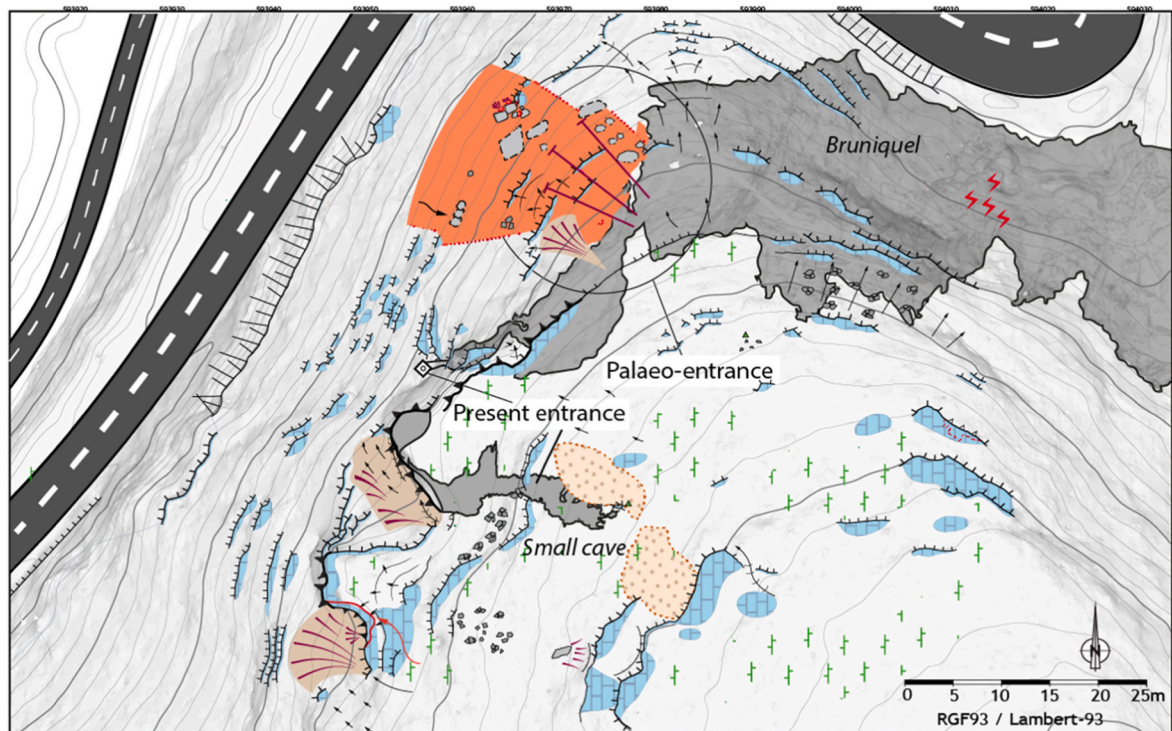


Fig. 6. Geomorphological map of the cave exterior morphologies. The map is georeferenced in RGF93/CC44. A. Original map by Camus and Jaillet, modified.

components are visible around this area. Numerous balms are visible under the main cliffline. These balms that currently constitute some rock shelters, are almost systematically associated with karstic conduits, areas of alteration or palaeokarst features. These karstic conduits may indicate potential cave continuities. On the geomorphological map (Fig. 6) some palaeokarst elements were observed in the external landscape. Finally, some broken speleothems were discovered in the area delineated in orange (Fig. 6), indicating reworking of former cave components. Most of these morphological markers are nowadays largely eroded because of the surface evolution of the Aveyron riverbanks.

All these elements must be considered when characterising the extension of the initial porch and the geometry of the sedimentary plug following its collapse (Fig. 5).

4.1.2. The inside of the cave

The intersection of the cave with the external talus caused the cave entrance to be blocked off by the progradation of sediments. The geomorphological map (Fig. 7) is described by the following sectors.

- In the excavated area, before entering the larger volumes of the cave, we cross a first room that was not buried under the sediments (*intermediate chamber*, Fig. 7). The floor of this first area is composed of clastic limestone deposits. An internal stratification is visible in some sections of the clasts and shows a general dynamic of scree cone formation originating from the outside of the cave (see Fig. 7, cross section C17). The upper part of this scree formation is composed of large blocs that seem to originate from the cave roof. Some large blocs are also partially covered by the clastic scree cone dynamic, which reveals a well stratified sedimentation process. (Fig. 7, cross section C18). Some speleothems are also visible in this area. The C18a cross section is located at the distal part of the top of the scree cone area (Fig. 7). It shows some speleothems and flowstone growing on top of the last generation of scree cone, and on some fallen blocs.

The C17 cross-section (Fig. 7) represents a more proximal area of the scree cone, visible in the *intermediate chamber* (intermediate chamber,

Fig. 7). This part of the scree cone provides the closest view of the top of the clastic sediments. Some speleothems grew on top of this scree cone (BR-STM2; BR-STM3) (Fig. 7; Table 2). The scree underlying these speleothems can thus be considered contemporaneous with or older than them. The slope of the scree is different from that observed in the lower part of the *intermediate chamber* C18a cross section), accounting for later sediment inputs or local reworking of the scree cone.

Entering the larger areas of the cave, the same scree cone (*upper scree cone*) remains visible and stratigraphically connected. Similar stratigraphic information is observed at the top of the *scree cone chamber* (Fig. 8). The top of this area is largely covered by clastic forming the continuation of the scree cone. Larger blocs are also visible at the contact between the allochthonous sediments and the cave roof and constitute the final sealing of the *scree cone chamber*. The granulometric variability is well expressed: larger blocs generally overlie smaller ones and reflect more local processes (desquamation of the cave roof), whereas the finer clastic components of the scree reflect slope processes related to external slope evolution. This scree cone partially covers five calcite pillars (i.e. joined stalagmites and stalactites) with metric diameters. Their base are currently buried beneath the scree, whereas the tops of the pillars reach the ceiling (Fig. 7, cross section C2). The northern pillar shows some corrosion process that may be related to airflow circulation or bat guano influence. Some of the southern pillars are also affected by fractures, and reflect a general suffosion process affecting the deposits (Fig. 7, cross section C2).

The *upper scree cone* can be divided into three main members: the first one covers the entire area from the southern to the northern cave wall. Most of the scree cone sedimentation consists of cryoclastic deposits that are poorly sorted and embedded in a sandy matrix. A small cone composed of larger blocs is visible at the centre of the cone, just behind the northern pillar. This cone may have been generated by a late influx of yellow sediments entering the cave. The speleothem found in secondary position at the top of this cone (BR-STM4) yielded unreliable U-Th results (Figs. 7 and 8; Table 2). The southern part of the scree cone is sealed by flowstone deposits (Fig. 7). A final member of the scree cone is represented by black lines in Fig. 7 and corresponds to recent scree

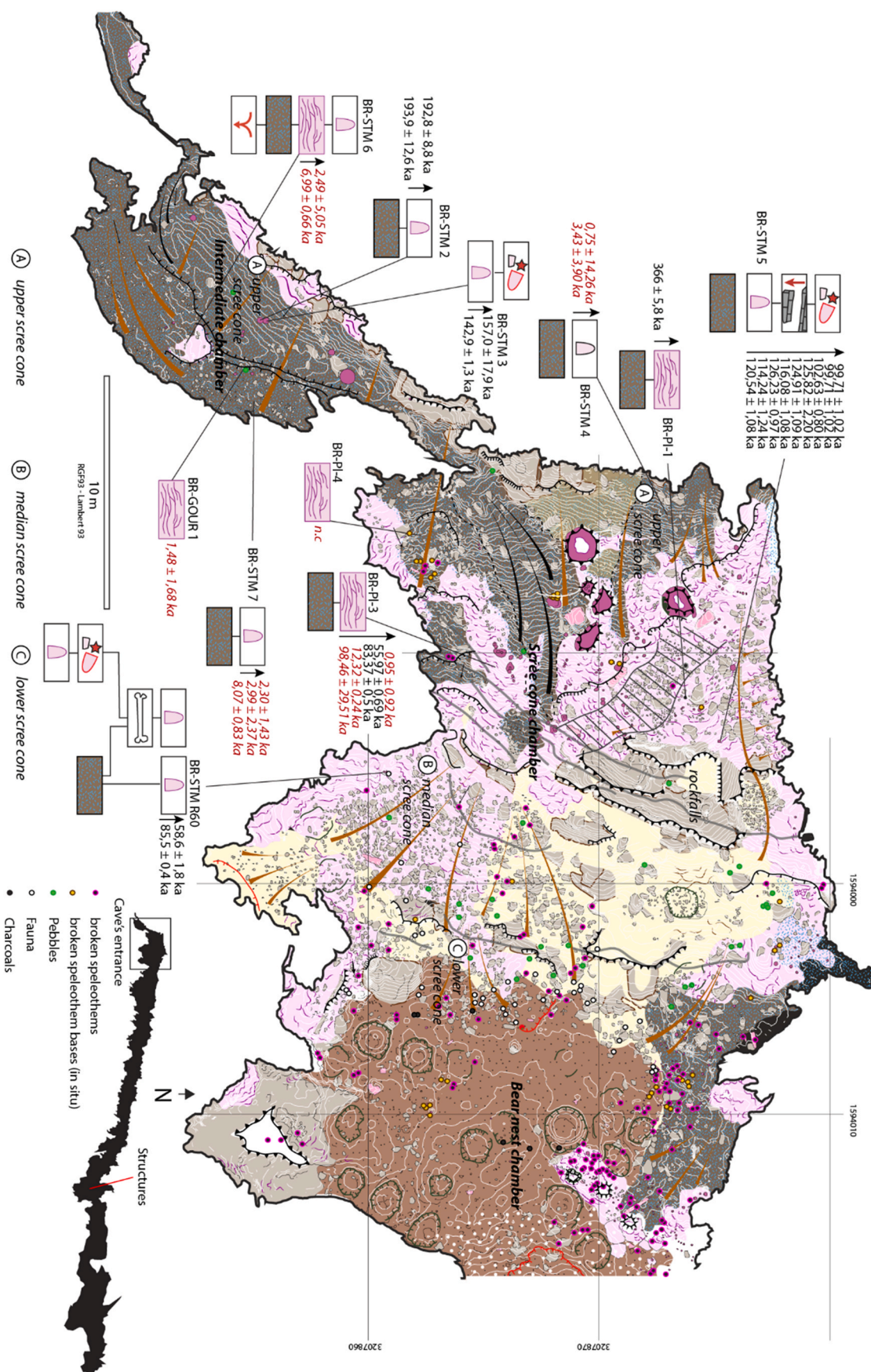


Fig. 7. Geomorphological map of the entrance of the cave of Bruniquel, and location of the dated speleothems (Verheyden et al., 2017). The chronological values highlighted in red are considered less reliable. The map extension is georeferenced in RGF Lambert 93 CC 44. For the legend, the reader is referred to Fig. 3.

Table 2

U-series obtained on speleothems of the cave's entrance. Most of the ages were published in [Verheyden et al. \(2017\)](#), except for the BR-PL-1-base 2 sample. *The values highlighted in italics and preceded by an asterisk represent unreliable values which may be caused by opening of the calcite system, generating uranium losses or ^{232}Th contamination. U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013). ** $d^{234}\text{U} = ([^{234}\text{U}/^{238}\text{U}]_{\text{activity}} - 1) \times 1000$. *** $d^{234}\text{U}_{\text{initial}}$ was calculated based on ^{230}Th age (T), i.e., $d^{234}\text{U}_{\text{initial}} = d^{234}\text{U}_{\text{measured}} \times e^{\lambda_{230}T}$. Corrected ^{230}Th ages assume the initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values for a material at secular equilibrium, with the bulk earth $^{232}\text{Th}/^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%. ****B.P. stands for "Before Present" where the "Present" is defined as the year 1950 C.E.

Speleothem	Sample	Descr.	^{238}U	^{232}Th	$^{230}\text{Th}/^{232}\text{Th}$	$d^{234}\text{U}^{**}$	$^{230}\text{Th}/^{238}\text{U}$	^{230}Th Age (ky)	^{230}Th Age (ky)	$d^{234}\text{U}_{\text{initial}}^{***}$	^{230}Th Age (ky BP)****
			(ppb)	(ppt)	(atomic $\times 10^{-6}$)	(measured)	(activity)	(uncorrected)	(corrected)	(corrected)	(corrected)
Stalagmites on the collapsed rocks in the entrance zone.											
BR-stm-3	31	Base	41,8 $\pm 0,1$	2780 ± 56	226 ± 5	203,2 $\pm 1,5$	0,9104 $\pm 0,0020$	144,5 $\pm 0,8$	143,0 $\pm 1,3$	304 ± 3	142,9 $\pm 1,3$
BR-stm-3	32	Top	15,7 $\pm 0,1$	14278 ± 286	17* ± 1	139,1 $\pm 3,7$	0,9476 $\pm 0,0080$	181,2 $\pm 4,1$	157,1 $\pm 17,9$	217 ± 12	157,0* $\pm 17,9$
BR-stm-2	21	base	32,5 $\pm 0,1$	21647 ± 434	25* ± 1	131,7 $\pm 2,8$	0,9959 $\pm 0,0050$	211,0 $\pm 3,6$	194,0 $\pm 12,6$	228 ± 9	193,9* $\pm 12,6$
BR-stm-2	22	top	28,1 $\pm 0,1$	13737 ± 275	34* ± 1	143,0 $\pm 2,6$	0,9975 $\pm 0,0035$	204,9 $\pm 2,5$	192,9 $\pm 8,9$	246 ± 8	192,8* $\pm 8,9$
Other speleothems in between the small passages – entrance zone – upper scree cone											
BR-STM-6	sup		30,7 $\pm 0,1$	8338 ± 167	6* ± 0	146,5 $\pm 2,8$	0,0974 $\pm 0,0023$	9,7 $\pm 0,2$	2,6 $\pm 5,1$	148 ± 3	2,5* $\pm 5,1$
BR-STM-6	inf		14,0 $\pm 0,0$	445 ± 9	44* ± 2	232,5 $\pm 2,9$	0,0853 $\pm 0,0043$	7,8 $\pm 0,4$	7,1 $\pm 0,7$	237 ± 3	7,0* $\pm 0,7$
BR-GOUR-1			43,4 $\pm 0,1$	4008 ± 80	7* ± 0	144,7 $\pm 1,9$	0,0406 $\pm 0,0014$	3,9 $\pm 0,1$	1,6 $\pm 1,7$	145 ± 2	1,5* $\pm 1,7$
BR-STM-7	3-top		20,2 $\pm 0,0$	1630 ± 33	10* ± 1	183,8 $\pm 3,1$	0,0465 $\pm 0,0029$	4,4 $\pm 0,3$	2,4 $\pm 1,4$	185 ± 3	2,3* $\pm 1,4$
BR-STM-7	2-middle		18,3 $\pm 0,0$	2406 ± 48	8* ± 1	179,0 $\pm 2,9$	0,0668 $\pm 0,0044$	6,4 $\pm 0,4$	3,1 $\pm 2,4$	181 ± 3	3,0* $\pm 2,4$
BR-STM-7	1-base		10,6 $\pm 0,0$	469 ± 9	36* ± 2	204,6 $\pm 3,6$	0,0978 $\pm 0,0035$	9,2 $\pm 0,3$	8,1 $\pm 0,8$	209 ± 4	8,1* $\pm 0,8$
Entrance collapse – south – upper scree cone											
BR-PL-3	1-base		55,1 $\pm 0,1$	10605 ± 213	70 ± 1	305,7 $\pm 2,5$	0,8210 $\pm 0,0030$	102,6 $\pm 0,7$	98,5 $\pm 3,0$	404 ± 5	98,5 $\pm 3,0$
BR-PL-3	2		196,0* $\pm 2,4$	623 ± 15	576 ± 14	24,8 $\pm 11,3$	0,1109 $\pm 0,0015$	12,5 $\pm 0,2$	12,4 $\pm 0,2$	26 ± 12	12,3* $\pm 0,2$
BR-PL-3	3		69,0 $\pm 0,1$	175 ± 4	4395 ± 93	236,0 $\pm 1,8$	0,6752 $\pm 0,0025$	83,5 $\pm 0,5$	83,4 $\pm 0,5$	299 ± 2	83,4 $\pm 0,5$
BR-PL-3	4		22,8 $\pm 0,0$	572 ± 12	324 ± 7	210,2 $\pm 3,3$	0,4923 $\pm 0,0045$	56,0 $\pm 0,7$	55,4 $\pm 0,8$	246 ± 4	55,3 $\pm 0,8$
BR-PL-3	5-top		32,0 $\pm 0,1$	1576 ± 32	8* ± 1	145,4 $\pm 2,8$	0,0237 $\pm 0,0026$	2,3 $\pm 0,3$	1,0 $\pm 0,9$	146 ± 3	1,0* $\pm 0,9$
BR-PL-4	SV249		18,6 $\pm 0,3$	31811 ± 663	5* ± 0	383,2 $\pm 21,1$	0,4660 $\pm 0,0089$	43,9 $\pm 1,3$	1,2 $\pm 33,1$	385 ± 41	1,2* $\pm 33,1$
Entrance collapse – north – upper scree cone											
BR-STM-4	sup		11,1 $\pm 0,0$	8592 ± 172	5* ± 0	239,1 $\pm 3,9$	0,2143 $\pm 0,0067$	20,6 $\pm 0,7$	0,8 $\pm 14,3$	240 ± 10	0,8* $\pm 14,3$
BR-STM-4	inf		11,5 $\pm 0,0$	2510 ± 50	7* ± 0	188,3 $\pm 3,6$	0,0938 $\pm 0,0060$	9,0 $\pm 0,6$	3,5 $\pm 3,9$	190 ± 4	3,4* $\pm 3,9$
BR-STM-5 (core)	8-top		31,5 $\pm 0,1$	89 ± 2	4824 ± 115	336,2 $\pm 3,5$	0,8277 $\pm 0,0049$	99,8 $\pm 1,0$	99,8 $\pm 1,0$	446 ± 5	99,7 $\pm 1,0$
BR-STM-5	7		51,8 $\pm 0,1$	65 ± 2	10846 ± 278	321,3 $\pm 2,6$	0,8325 $\pm 0,0037$	102,7 $\pm 0,8$	102,7 $\pm 0,8$	429 ± 4	102,6 $\pm 0,8$
BR-STM-5	6		42,4 $\pm 0,1$	5758 ± 115	114 ± 2	304,8 $\pm 2,2$	0,9385 $\pm 0,0037$	128,7 $\pm 1,0$	125,9 $\pm 2,2$	435 ± 4	125,8 $\pm 2,2$
BR-STM-5	5		46,2 $\pm 0,1$	115 ± 2	6062 ± 133	299,1 $\pm 2,4$	0,9185 $\pm 0,0042$	124,9 $\pm 1,1$	124,9 $\pm 1,1$	425 ± 4	124,8 $\pm 1,1$
BR-STM-5	4		39,4 $\pm 0,1$	1283 ± 26	440 ± 9	281,0 $\pm 2,6$	0,8701 $\pm 0,0038$	116,8 $\pm 1,0$	116,2 $\pm 1,1$	390 ± 4	116,1 $\pm 1,1$
BR-STM-5	3		43,9 $\pm 0,1$	387 ± 8	1736 ± 35	304,9 $\pm 2,4$	0,9296 $\pm 0,0035$	126,5 $\pm 1,0$	126,3 $\pm 1,0$	435 ± 4	126,2 $\pm 1,0$
BR-STM-5	2		48,0 $\pm 0,1$	159 ± 3	4398 ± 96	310,6 $\pm 3,3$	0,8813 $\pm 0,0046$	114,4 $\pm 1,1$	114,3 $\pm 1,1$	429 ± 5	114,2 $\pm 1,1$
BR-STM-5	1-base		40,5 $\pm 0,1$	283 ± 6	2141 ± 45	308,5 $\pm 2,4$	0,9081 $\pm 0,0043$	120,7 $\pm 1,1$	120,6 $\pm 1,1$	434 ± 4	120,5 $\pm 1,1$
BR-PL-1	1-base		68,5 $\pm 0,1$	4066 ± 81	316 ± 6	132,9 $\pm 1,4$	1,1389 $\pm 0,0017$	367,4 $\pm 5,8$	366,1 $\pm 5,8$	373 ± 7	366,0 $\pm 5,8$
BR-PL-1-base 2	SV 170	above 1-base	64,3 $\pm 0,1$	11887 ± 239	105 ± 2	164,6 $\pm 1,6$	1,1815 $\pm 0,0023$	370,2 $\pm 6,9$	366,5 $\pm 7,1$	463 ± 10	366,4 $\pm 7,1$
Entrance collapse – east (cores) – median scree cone											
BR-stm-R60	SV177	base	45,3 $\pm 0,0$	933 ± 19	724 ± 15	591,0 $\pm 1,8$	0,9044 $\pm 0,0020$	86,0 $\pm 0,3$	85,6 $\pm 0,4$	752 ± 2	85,5 $\pm 0,4$
BR-stm-R60	SV178	top	57,6 $\pm 0,0$	5052 ± 101	82 ± 2	18,6 $\pm 1,1$	0,4383 $\pm 0,0023$	61,2 $\pm 0,4$	58,7 $\pm 1,8$	22 ± 1	58,6 $\pm 1,8$

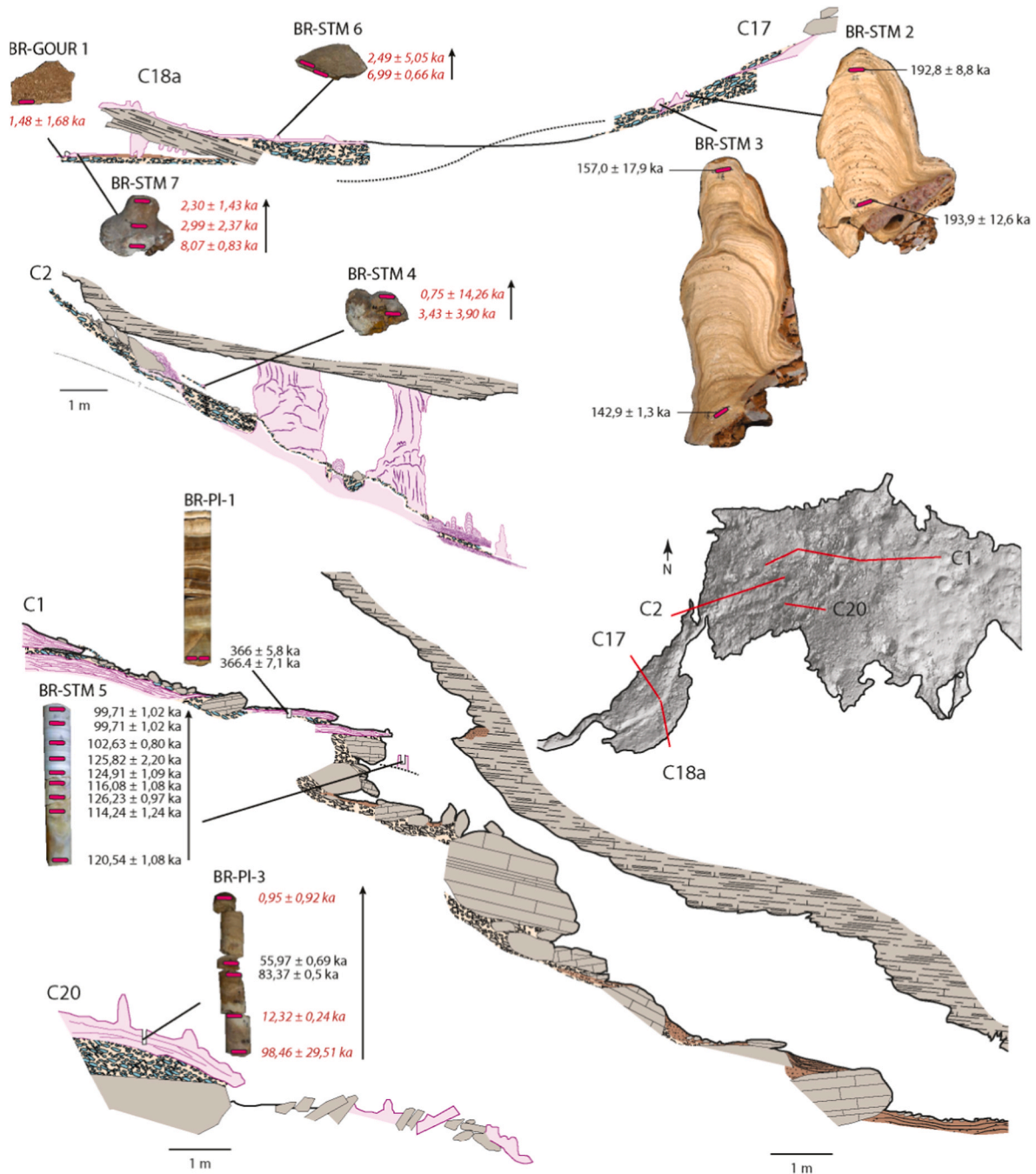


Fig. 8. Cross sections of the lower part of the scree and the associated dated speleothems by the U-series method. Values highlighted in *italics red* are considered less reliable. For more details, the reader is referred to [Table 2](#).

movements linked with to scientific and speleological activity since the discovery of the cave in 1990.

Below the distal part of the scree cone, in the middle of the general slope of the *scree cone chamber*, some plurimetric blocs are visible. They lie beneath the scree cone and the stalagmitic pillars and reflect the general rockfall dynamics of the cave roof. The consequences of this generalised plurimetric rockfall are visible on the soils along a 18.5×3.5 m band, and in the cave roof geometry, which still bears scars of these events ([Fig. 7](#), cross section C1). These large blocs are sealed at their tops by a 10 cm thick flowstone layer. Other speleothems and flowstone deposits (BR-STM5, [Table 2](#)) are visible in the northern part of the *Grand éboulis* chamber and also seal large blocs ([Figs. 7 and 8](#), cross section C1). These speleothems do not appear to have been impacted by

biocorrosion processes, contrary to the large pillars.

At the bottom of the *scree cone chamber*, beneath the area dominated by the plurimetric blocs (cross section C1, S.O.M section S2), another scree cone (*median scree cone*) is visible in the southern part of the chamber ([Fig. 6](#)). The distal part of the scree cone ends in the clay-rich surface of the *bear nest chamber* (bear nests chamber, [Fig. 6](#)), which represents the internal part of the karstic system. This scree cone partially covers some of the large blocs, and is strictly separated from the upper scree cone by some of these blocs (S.O.M section S2). The main supply of the scree cone appears to be driven by the fall of clastic deposits coming from the roof, and caused by desquamation processes. This desquamation process affects the entire limestone layer, and is also observed in the northern part of the *scree cone chamber*. However,

clasts in this area do not form a conical morphology and are probably more related to the consequence of cold airflow circulations in this part of the cave. The **median scree cone** is locally sealed by multiple flowstone deposits (S.O.M section S2). Its distal part lies on top of the clay-rich sediments of the **bear nest chamber** and shows slight reworkings by local water flows, some of which originate directly from the median scree cone and form flowstone deposits that partially cover the surface of the **bear nest chamber** (S.O.M section S2).

Nearly sixty bone (including antler) and dental remains have been collected from the **scree cone chamber** and the surface of the **bear nest chamber** (S.O.M Table S3). These remains belong to brown bear (*Ursus arctos*), deer (*Cervus elaphus*) and reindeer (*Rangifer tarandus*). Wolf (*Canis lupus*) and a medium-sized ungulate (cf. Caprinae) are also present. They are dispersed across the base of the scree cone, with no discernible concentration or anatomical connection. It is noteworthy that the remains are remarkably complete and in an excellent state of preservation, although frequently calcified. In addition, a few remains of small vertebrates, including passerine-sized birds, reptiles, rodents and foxes, were recovered. Importantly, no chiropteran remains were found on the surface of the sedimentary fill. The taphonomic history of the small vertebrates appears to differ from that of the large fauna, as evidenced by the lesser degree of alteration observed on their bone surfaces and the identification of anatomical connections.

In the remaining part of the **bear nest chamber**, beyond the slope deposits, the clay-rich soils are heavily disturbed by numerous bear nests (Fig. 7). Ten metres after the end of the slope deposit, the clay-rich nature of the soils changes and becomes more sandy, and shift in colour from brown-red to brown-yellow. This change may result from the altered facies of the bedrock in this area. The cave roof indeed shows very altered morphologies that may have been enlarged by condensation-corrosion processes (Dreybrodt et al., 2005). Nevertheless, some biological bell holes (caused by bat activity, Barriquand et al., 2021) remain visible (S.O.M section S2). In this area, the lighter soil colour may also be caused by the transformation of bat guano into phosphate-rich layers, as observed in other cave systems (Giurgiu and Tămaş, 2013; Audra et al., 2021). In this area, several fallen blocs are visible and partially buried within the clay-rich sediments of the soils (Fig. 5). Some speleothems seal those blocs, forming three slender pillars (Fig. 5). Their morphology is strongly impacted by the bat-induced biocorrosion (S.O.M section S2).

4.1.3. Uranium-series dating (U/Th)

In total, 30 U/Th ages were obtained from 11 speleothems covering the entrance scree. Some U/Th ratios are affected by detrital Th contamination, resulting in large analytical uncertainties (Table 2). Samples with Th ratios lower than 50, indicating a high proportion of detrital Th, were discarded. Sample BR-PL3-2 was also discarded due to its abnormally high uranium content, which suggests an open geochemical system. In total, only 16 ages were retained, justifying the use of the Bayesian chronology of “Model B” (S.O.M., Section S4). Fig. 8 summarizes the ages obtained from speleothems covering the scree and their locations on the cross sections.

Overall, calcite ages from the scree range from 360 ka to 0.8 ka. On the upper part of the scree cone, despite the high detrital Th content of samples BR-STM6, BR-STM7, and BR-Gour-1—which led to the rejection of these ages due to large uncertainties—their macroscopic appearance and the coherent clustering of the rejected ages within younger periods suggest a Holocene age (Table 2). Two stalagmites covering the upper western part of the scree cone (BR-STM2 and BR-STM3) yielded four ages ranging from 193.9 ± 12.6 ka to 142.3 ± 1.3 ka. Among these, the age of 142.3 ± 1.3 ka is considered the only reliable one, given the high detrital Th content of the other three samples (Fig. 7; Table 2).

Sampling of flowstone deposits covering the intermediate and upper parts of the scree cone (BR-PL-3; Fig. 7, cross section C20) yielded multiple U/Th ages, including two reliable ages ranging from MIS 5a (83.4 ± 0.5 ka) to MIS 3 (56.0 ± 0.7 ka). Other speleothems sampled

from the intermediate part of the scree cone (BR-STM5) yielded ages spanning MIS 5e to MIS 5c, ranging from 120.54 ± 1.08 ka to 99.71 ± 1.02 ka (Table 2).

Finally, samples collected from the base of the ~10 cm-thick flowstone capping a large portion of the northeastern scree (BR-PL-1) yielded two ages of 366.0 ± 5.8 ka and 366.4 ± 7.1 ka (Figs. 6 and 7, cross section C1; Table 2). The U-Th ages of the calcite covering the scree provide a minimum age constraint for the scree deposits. These results demonstrate that the northeastern part of the scree is at least as old as MIS 10, the upper northwestern part at least MIS 6, the middle western and lower southern parts at least MIS 5e–5a, and the uppermost northern “lip” at least MIS 1.

4.2. Electrical Resistivity Tomography

The six ERT profiles delivered convergent results (Fig. 9, S.O.M section S3). All the profiles acquired in the external part of the cave show good convergence results after the third iteration (RMSE lower than or close to 5 %). The ERT5 and ERT6 profiles that were acquired inside the cave system with conductive rubber pads (non-invasive method) and show comparable resistivity values, but the inversion process yields higher RMSE values for the third iteration (Fig. 9). This is probably because some pads had to be placed on top of high-resistivity calcite blocks in the scree cone, inducing high electrode-ground contact resistance (up to 200000 Ω m). Nevertheless, resistivity values remain coherent with the outcropping topography and geology of the scree cone. The ERT1 profile that passes right in front of the cave entrance (Fig. 3). It shows a layer of more conductive values (500- Ω m) that locally reaches a depth of 4 m. This area of conductive values highly contrasts with the general resistivity values of the bedrock (around 3000 Ω m, Fig. 9). This area of conductivity is successively imaged by the ERT2 profile (centre of the profile), the ERT3 profile (beginning on the left side), and the ERT4 profile (beginning on the left side). When projected onto the 3D model, this area is clearly visible and is interpreted as the infilling of the sediments that obturate the former cave entrance. This could be directly checked thanks to the cross-referencing of the 2D ET sections, the subsurface-underground 3D model of the cave, and the observation of the sediments and cave walls. The bedrock limits also appear quite well on ERT4 and ERT5 profiles, and can be correlated with layers that are still visible at the surface (Fig. 5). On almost every profile, the influence of the air-filled voids of the cave system is visible, and yields high resistivity values (>4000 Ω m, extreme values reaching more than 20000 Ω m). On the ERT5 and ERT6 profiles, the impact of flowstone deposits also generates high resistivity values. Those two profiles highlight the areas inside the internal scree cone that are filled with calcite. It is noteworthy that on the ERT5 profile, the high resistivity values that penetrate deeply into the cone only start after 34 m (at the end of the **intermediate chamber**, Figs. 6 and 9). The ERT6 profile allows for a better visualisation of the subsurface levels of the scree cone because of its higher spatial resolution (50 cm electrode spacing, Figs. 3 and 9). It allows the visualisation of one of the plurimetric blocs (4 × 2 m, Fig. 9). On the ERT6 profile, the 3D mapping and the visualisation of a small interbedding between high resistivity values and lower ones also led to the interpretation of the calcite pillar thicknesses which locally reach 65 cm. These are not clearly linked with deeper high-resistivity areas, which may represent other large blocs or earlier calcite deposits (Fig. 9).

The ERT5 profile that continues inside the **Bear nest chamber** also reveals the thickness of local flowstone deposits on the cave floor (up to 1 m) as well as horizontal reflectors at 3.5 m depth (Fig. 9). This reflector may constitute the base of the clay infill.

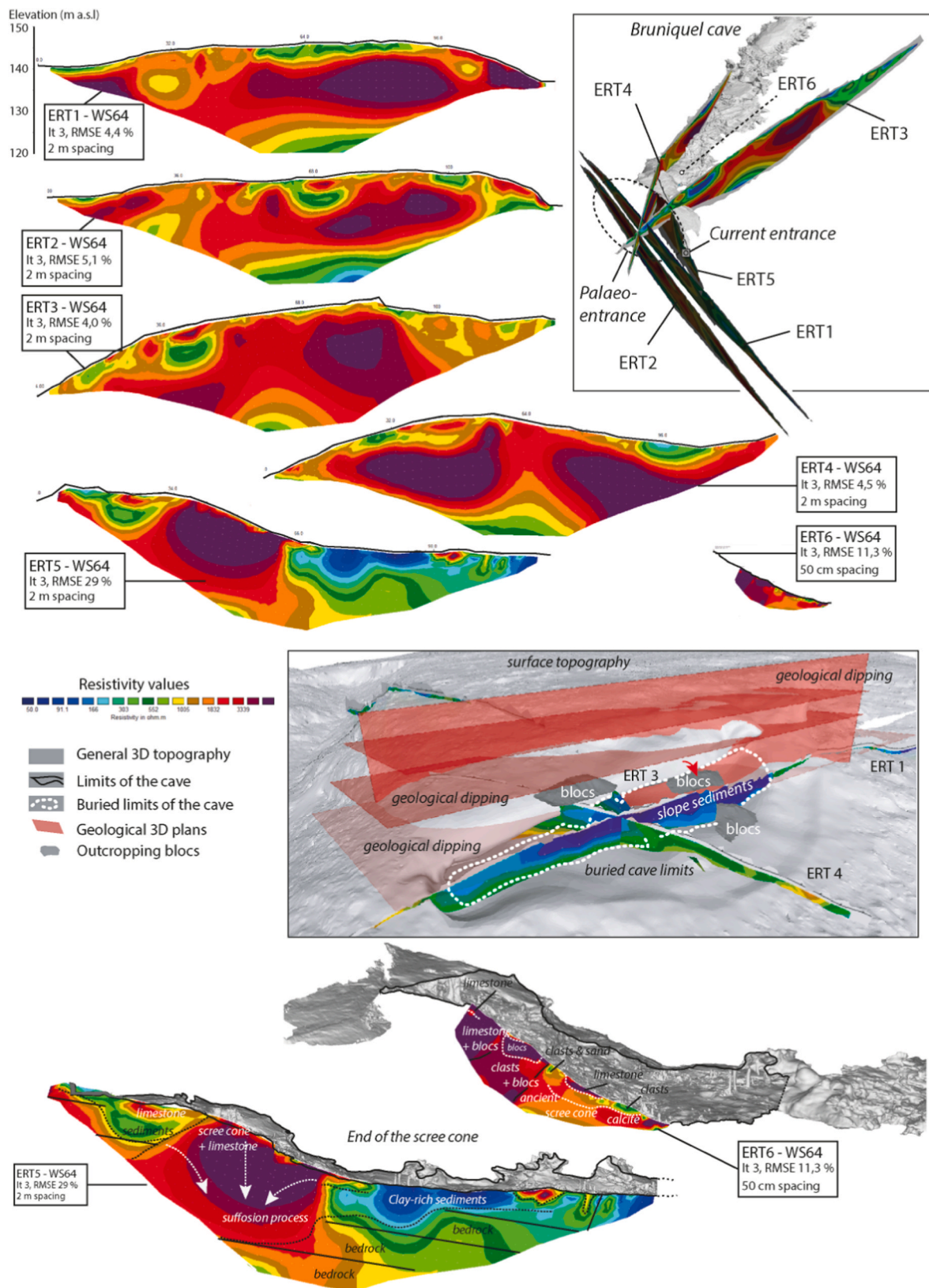


Fig. 9. Electrical Resistivity Tomography 2D inversion results. It: Iteration of the inversion process. The third iteration was chosen for all the profiles because the convergence was good for most of them. The RMSE error of ERT5 and ERT6 profiles is more important because of the acquisition method that was used within the cave (conductive rubber electrodes instead of metallic ones). RMSE: Root Mean Squared Error of the inversion process. The same inversion protocol was performed for all the profiles with RES2DINV 3.54.44 software (Combined inversion method, least-square inversion).

5. Discussion

5.1. Dating the closure of the cave's entrance

The geomorphological maps and the chronological information derived from the U-series results show that the entrance scree developed in relation to the proximity of the cave entrance. It started with rockfall events. Some limestone bench outcrops located downslope correspond

to rock slabs that tumbled out when the porch collapsed and tilted. The consequence of these rockfalls and the general evolution of this area are also visible in the most distal and buried parts of the scree cone, which are imaged in the middle of the ERT5 profile (Fig. 9). These plurimetric blocs were then sealed by a flowstone deposit that started growing at ~366 ka. After these events, a generation of stalagmitic pillars started to grow until it reached the cave roof. The bases of the stalagmitic pillars were later partially covered by clastic inputs coming from the outside of

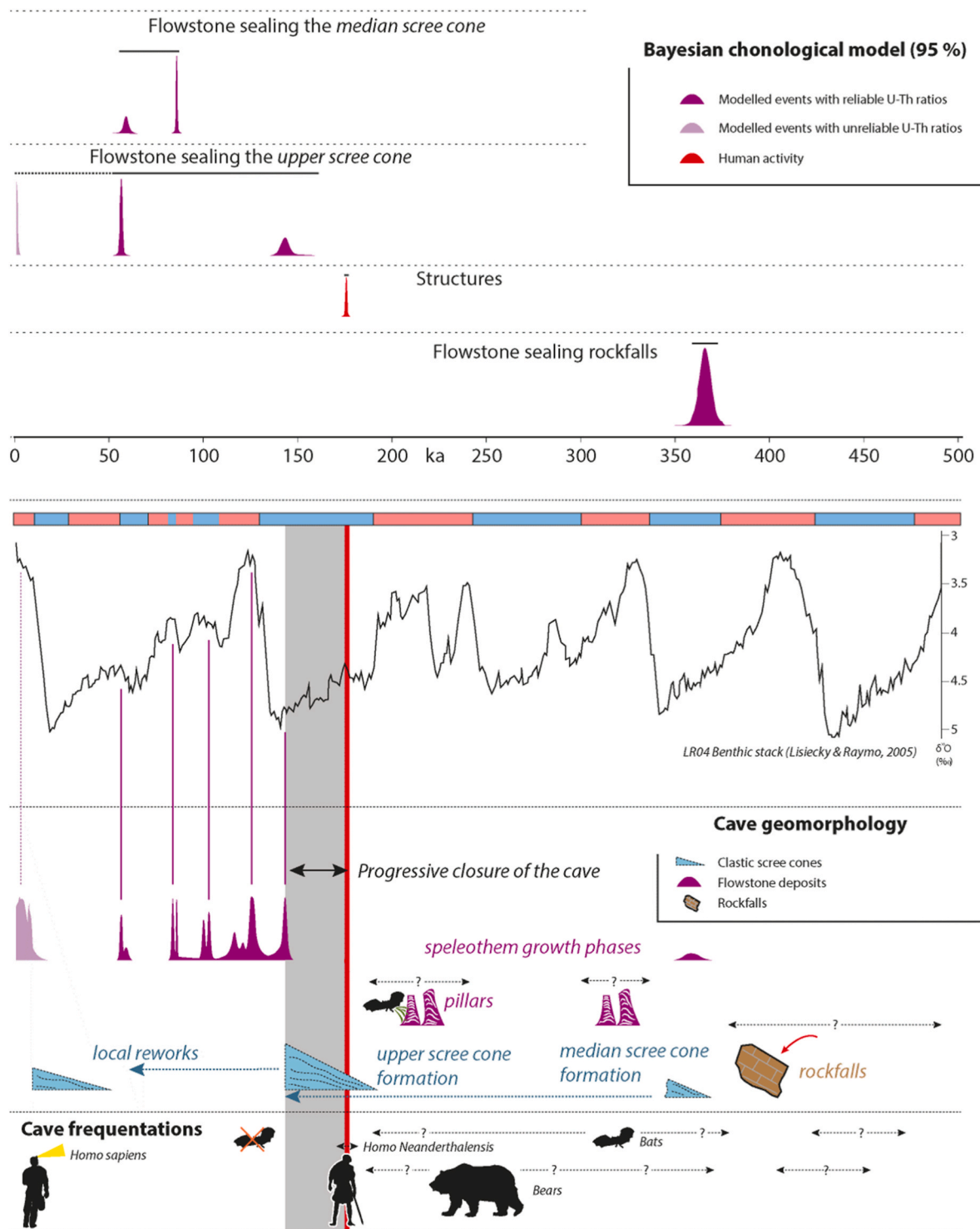


Fig. 10. Timing of the cave phases of activity and chronological view of the events. Bayesian hierarchical model was computed with Chronomodel 2.0.18. Results are presented at 95 % confidence (see S.O.M. section S4). The modelled events are presented on top of Fig. 10. The density distribution of the speleothem growth was obtained through the tempo plot function of chronomodel 2.0.18 (Lanos and Philippe, 2018).

the cave, generating a large scree cone that reached the cave roof. Subsequent flowstone deposits sealed parts of this scree cone until it reached its present configuration.

These observations indicate that most of the lower part of the scree already acquired its present shape before 366 ka. Some of the bear nests of the **scree cone chamber** are formed in the clay-rich sediments of the **bear nest chamber**, on top of the rockfall formation (Fig. 7). They cover the most distal parts of the scree cones formation, which are buried at depths of 1–2 m (Figs. 9 and 10). Those evidence also show that part of the cave use by bears occurred after the establishment of the lower part of the scree cone, hence, during or after 366 ka.

The presence of a relatively diverse vertebrate fauna on the surface of the **scree cone chamber** and the **bear nest chamber** raises questions about the origin of this accumulation and, by extension, about the configuration of the cave entrance. The anatomical connections observed among the small vertebrates and the low degree of bone fracturing suggest that some individuals died *in situ*, without predator intervention. However, the origin of the large mammal remains is more complex. Brown bears clearly frequented the cave, as evidenced by numerous direct traces (grooves, footprints, scratches, Lafon, 1996). Evidence for other carnivores and ungulates is more ambiguous, and the bone remains do not provide conclusive evidence of whether these animals entered the cave alive (Lafon, 1996; S.O.M.). While the circulation of Caprinae and carnivores has been documented in cave environments (Blant et al., 2012; Packard, 2003), this is, to our knowledge, not the case for Cervidae. The cave entrance undoubtedly allowed the passage of large species before and during MIS 6 (Boudadi-Maligne et al., 2023), yet it is not possible to determine, on the sole basis of biomarkers, the exact chronology of the cave's closure.

The stalagmitic pillars have not been directly dated, but they could have only started to grow during or after 366 ka, as they seal the plurimetric blocs. This geomorphological configuration is visible on cross sections C1 and C2 (Fig. 8) and on the ERT6 profile (Fig. 9). The surfaces of the pillars are impacted by alteration processes such as bat-induced biocorrosion, similarly to other speleothems inside the cave, including the three pillars of the **bear nest chamber**, or other flowstone deposits deeper in the cave system. This configuration accounts for a generalised phase of bat occupation that affected several calcite formations within the cave.

The sedimentary deposits that later seal the calcite pillars (upper part of the scree cone) is also considered as an event posterior to 366 ka. This scree cone overlaps the stalagmitic pillars, and fills the cave up to the roof. This sedimentary infill is sealed by speleothems and flowstone, most of which are Holocene in age but the BR-STM-02 speleothem provides an age of 142.9 ± 1.3 ka, indicating that this upper part of the scree cone is set in place before the end of MIS 6. This suggests that scree cone formation most likely occurred during the MIS 6 cold stage. The decision not to consider the 3 ages around 190 ka, due to possible Thorium contamination, is consistent with the well dated activity of Neanderthal at 176.5 ± 2.1 ka (Jaubert et al., 2016; Verheyden et al., 2017; Bayesian « Model B », S.O.M. section S4). Otherwise, the entrance would have been closed before the construction of the structure (see differences between « Model A » and « Model B », S.O.M. section S4). This interpretation is also consistent with the western part of the scree cone being sealed by MIS 5 speleothems (Fig. 10, Verheyden et al., 2017), and with the sealing of the southern part of the median scree cone during MIS 3 (Fig. 7). Few reworks seem to happen on the median scree cone, which sedimentation seems to have been mostly dominated by in-situ clastic falls. The essential part of the cone morphology is then acquired since 85.5 ± 0.4 ka (Fig. 7). The upper scree cone progradation is probably set during MIS 6 and ends before 142.9 ± 1.3 ka. Because the calcite pillars that are located on top of the **scree cone chamber** are impacted by biocorrosion processes, contrary to the proximal flowstone deposits dated to the MIS 5 interglacial period, it implies that bats did not enter again inside the cave during MIS 5, hence a cave closure in agreement with the speleothem growth at 142.9 ± 1.3 ka, at the end of

MIS 6. The early *Homo Neandertalensis* activity in Bruniquel was dated back to 176.5 ± 2.1 ka (Jaubert et al., 2016; Verheyden et al., 2017), which implies an open cave at this period. The sedimentation processes of cryoclastic deposits in poorly sorted sandy matrix are generally related to cold stages (Bertran et al., 2009). The final clastic infilling of the cave probably occurred between 176.5 ± 2.1 ka and 142.9 ± 1.3 ka, which means a time-window of less than 34 ka. This closure probably prevented animals and humans to occupy the cave system until its discovery by cavers in 1990 (Rouzaud et al., 1995). The closure dynamic is then mostly related to external processes such as slope colluvial sedimentation. Such sedimentation dynamics on the slopes are typical of cold phases in Europe (Bertran et al., 2009) and may explain the tilted blocs and the talus regularisation that are visible in the external landscape (Fig. 6). The dating of the cave's closure before 142.9 ± 1.3 ka indicating that the human activity and the faunal remains discovered inside the cave may be more ancient, unless another entrance existed at the other side of the tunnel-like cave. To our current knowledge, no evidence of other entrance has been found yet. The currently known limits of the cave ends (Fig. 1) are between 55 m (vertical distance) and 110 m (lateral distance) from the exterior (Fig. 1). Other traces of activity are visible in the deep part of the cave such as bear tracks (Lafon, 1996), that can suggest other entrances. Other entrances could have been possible in more extended time periods, however, the bat-induced biocorrosion processes does not affect the MIS5 flowstone, even at the central part of the cave, which pledges for a complete cave closure before MIS 5.

5.2. Reconstruction of the palaeo-entrance

The 3D geomorphological reconstruction performed on the entrance of the cave proposes a situation before the MIS 6 scree cone progradation, which means a morphological situation that may be close to the topography during the early Neanderthal activities inside Bruniquel (Fig. 11). Considering the size of the outcropping blocs (Fig. 6), and the results of the ERT geophysical survey (Fig. 9), the palaeo-extension of the cliff line before the cave closure could be reconstructed. The cliff line retreated back by at least 2 m since the situation before the cave closure (Fig. 11). The reconstruction of the palaeo-floor morphology based on the interpolation of the geophysical survey results, the internal scree cone limits, and the conical projection of the scree cone outside the cave system, allows the proposal of a palaeo-entrance that was progressively sealed by a scree cone that mostly sedimented in the middle of the cave entrance. As a result, the cave was progressively divided into two parts, the southern part, through which we still enter today and that was progressively disconnected from the cave network, (Fig. 11), and the northern part, which was the main palaeo-entrance of the cave (Fig. 11). The palaeo-entrance at the beginning of MIS 6 was probably different from the bedrock cave limits. This may be caused by the fact that at 176.5 ± 0.5 ka, the site may have been partially filled with scree cone sediments, hence a relatively small entrance compared to the cave bedrock borders (Fig. 11). The size of the northern palaeo-entrance reached around 10 m in width, and around 2 m in height. The reconstruction shows that the entrance geometry is heavily guided by the geological strata constraints (Fig. 11). The flowstone pillars were then already set and may have visually structured the palaeo-entrance after 8 m inside the palaeo-cave entrance. Their relatively good state of preservation inside the cave also argues for a relatively small entrance, hence fewer air exchanges with the outside than for larger cave entrances such as Chauvet (Sadier et al., 2012).

At the time of the currently known early Neanderthal activities (Jaubert et al., 2016), the two sides of the scree cone may have already sedimented enough to split the cave into two areas, and to make the current cave entrance (**intermediate chamber**, see Fig. 7), a separate cave, that was accessible from the outside but not connected with Bruniquel. This may explain why some faunal remains were found in this part of the cave system (Rouzaud, 1997), whereas the cavers still had to

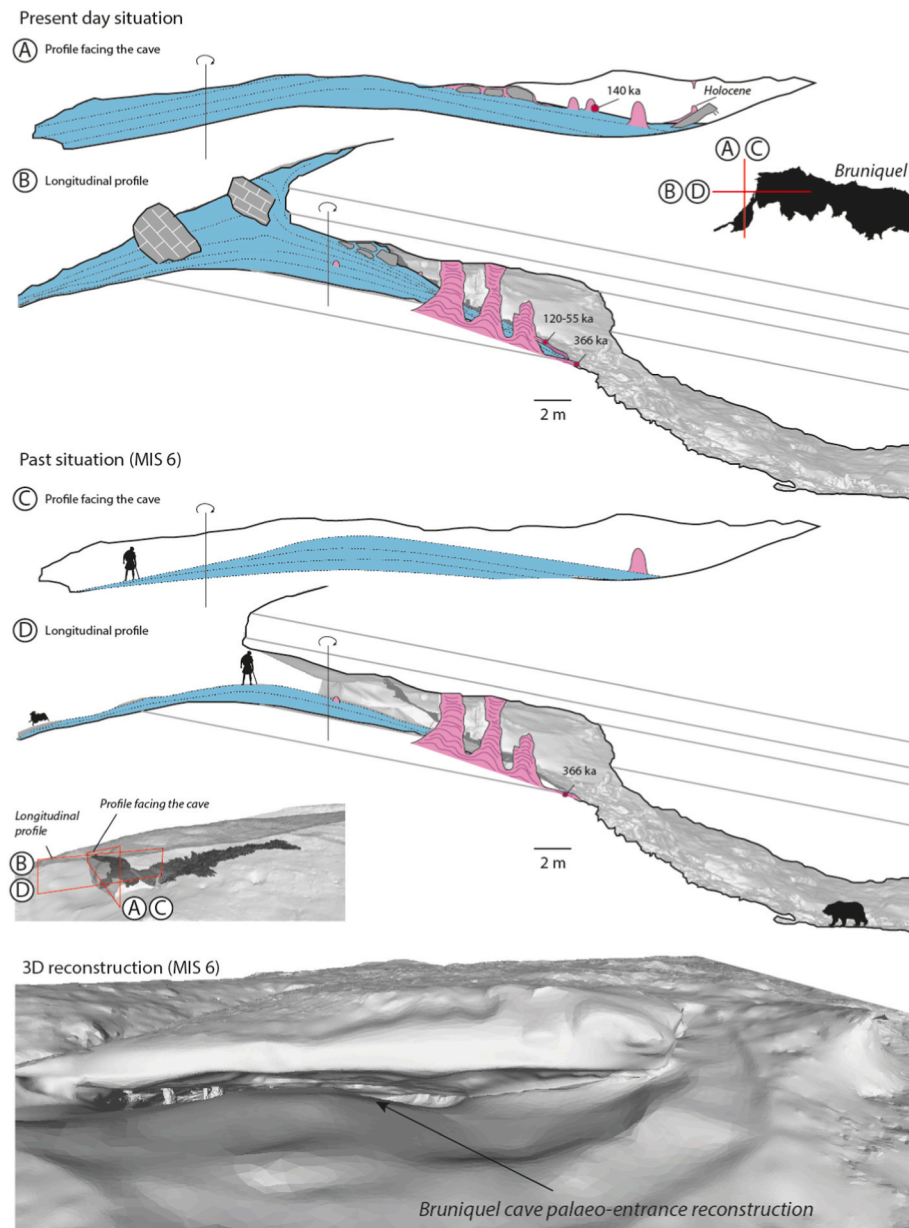


Fig. 11. 3D geomorphological reconstruction of the cave palaeo-topography at the time of the early Neanderthal activities.

dig inside the scree cone to enter Bruniquel, in 1990 (Rouzaud et al., 1995). The beginning of the current cave entrance is also filled with some soil-rich sediments that show the continuity of the scree sedimentation process, which is typical of cave entrance and rock-shelter scree cones in a periglacial context (Guendon et al., 2004; Bertran, 2004; Bertran et al., 2009; Lenoble and Agsous, 2012; Kemper et al., 2022). The valley slope probably continued to evolve with cryoclastic sedimentation during the last glacial period (Obanawa et al., 2009; Wilson, 2017), as it is generally the case in other north-western European periglacial valleys such as the Seine (Lécolle, 1984), the Ardèche (Genuite et al., 2022), or the Somme (Antoine et al., 2007). The long amount of time since the cave closure (around 140 ka) may explain why so few indices of karstification were found in the landscape morphologies outside the cave system (Fig. 6), as those features are sensitive to fast chemical weathering and meteoric weathering in similar locations of north-western Europe (Sadier et al., 2012; Curry and Morris, 2004), and are rapidly buried due to colluvial slope evolutions in periglacial contexts (García-Ruiz et al., 2001; Bertran, 2004; Bertran et al., 2009).

Bruniquel provides an example of long-term, multi-process evolution

of its entrance. The succession of rockfalls and scree cone sedimentation is a typical example of sedimentary processes in cave entrances and shows that those processes can be slow (Bertran et al., 2009), yielding more than 360 ka of slope, rockfall and scree cone evolution, and continuous (dominance of scree cone sedimentation instead of rockfalls, Figs. 7 and 11).

5.3. Consequences for the early neanderthal activities

The reconstructed palaeo-entrance shows a relatively small space. Consequently, it may not have been highly visible in the Aveyron canyon landscape (Fig. 12), contrary to other sites with highly visible entrances such as Shanidar (Pomeroy et al., 2020), Chauvet (Sadier et al., 2012), or El Castillo (Valdés, 1984). For example, the position of the cave's entrance was not visible from the Aveyron River. However, the palaeo-geography of the river systems in southern France was probably different during the MIS6 glacial period (see Delmas et al., 2018; Genuite et al., 2022), and may have led to better visibility of the cave entrance from the river (Fig. 12). Furthermore, the orientation of the

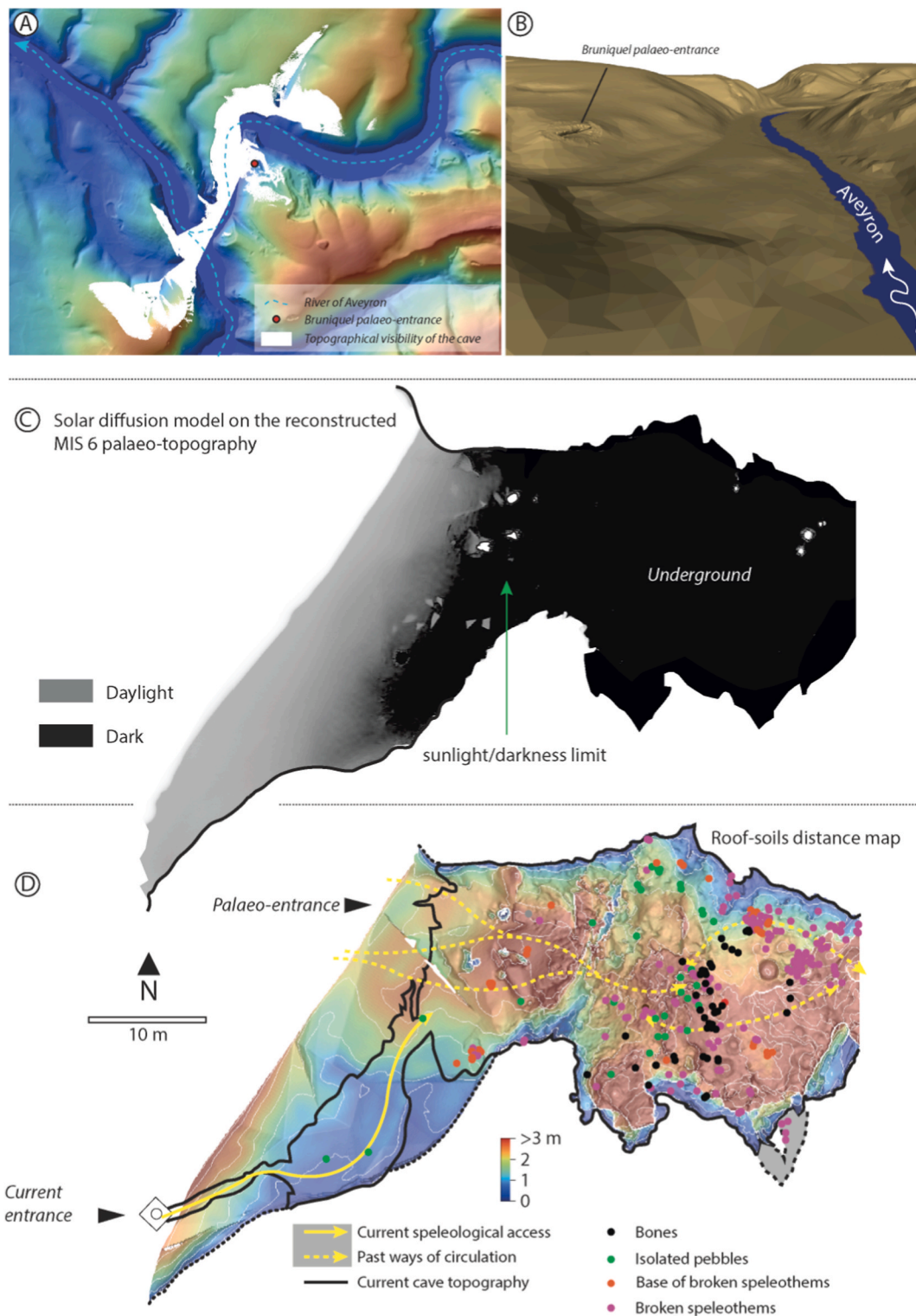


Fig. 12. Palaeo-entrance 3D reconstruction and palaeo-speleological circulation modalities. A. Visibility map of the cave entrance in the vicinity of the Aveyron canyon, B. reconstruction of the cave palaeo-entrance in the current topography of the Aveyron canyon, C. Daylight diffusion model performed on the 3D reconstructed palaeo-topography of Bruniquel. The modelling of daylight repartition was performed with Blender stochastic light engine (S.O.M. section S5), D. Map of the distance between the reconstructed soil and the reconstructed roof of the cave's entrance. The difference map was calculated from SAGA GIS (Conrad et al., 2015), with the raster difference calculation tool.

cave entrance (west-facing), during glacial periods (MIS 6), and the observed amount of cryoclastic inputs, argue for a sparse vegetation cover around the cave system at this time, hence a potential visibility of the cave entrance in the landscape for animals and humans, even if the opening may have been relatively small (Figs. 11 and 12). The small

height of the cave's palaeo-entrance can also be discussed as a potential constraint regarding the accessibility of the cave, as discussed in other more recent Palaeolithic cave contexts (Vialou, 2004; Pastoors and Weniger, 2011; Kemper et al., 2023). The cave yields traces of early Neanderthal activity (Rouzaud, 1997; Jaubert et al., 2016), bears and

other animals (Rouzaud, 1997). Considering the small size of the entrance reconstruction (2×10 m), the occurrence of those traces of activity directly questions the modalities of activities inside the cave by animals and past human groups.

The reconstruction of the cave palaeo-entrance provides new insights into the cave space. Floor-roof distance maps could be obtained from the 3D morphological reconstruction (Fig. 12). The impact of cave entrance evolution on the modalities of activities inside the cave system has already been discussed in a few, more recent cases, such as the scree cone progradation at the entrance of the Pech Merle cave that divides the cave network into two main areas (Lorblanchet, 1981; Duday and Garcia, 1983), but is not well known, even for the Upper Palaeolithic activities (Vialou, 1986). The soil-roof map (Fig. 12) shows a preferential passage on the north side of the cave. This passage yields height values between 2 and 3 m. To the south of the entrance, the height does not exceed 1 m, which does not make it a preferential passage for past human groups. The proposed passage passes through and next to the calcite pillars of the **scree cone chamber** (Figs. 7 and 12). This area shows some clasts that seem to have been reworked and spread over a few metres on a subhorizontal area, and later sealed at their base by flowstone formation (Fig. 12). This observation might be the consequence of past passages in this area, as observed in other cave systems (Delannoy and Geneste, 2020; Kemper et al., 2023). Consequences of human and animal passages in cave systems on scree cones and clay-rich floors are frequently observed in the present day (scree cones of the Caumont cave entrance, see (Ballesteros et al., 2022; Rabelle et al., 2021), and also for past periods (Clay-rich floors of the Cussac cave (Jaubert et al., 2017), the Aldène cave (Guendon et al., 2004). On scree cones, circulation of people and animals tends to create small pathways that generate compression in the centre (Ontañón, 2003; Kemper et al., 2023), while some clasts are evacuated on the sides, generating small topographical elevations at the borders of the pathway. Those morphologies are visible in other cave networks such as Chauvet cave (Delannoy and Geneste, 2020) or La Garma cave (Ontañón, 2003; Kemper et al., 2023). These morphologies can partially be observed below the stalagmitic pillars, hence a potential marker of passages inside the cave (Fig. 12). Other past traces of activity, such as pebbles that are visible on the scree cone, could also be related to past presence and activities in this area (Rouzaud, 1997). The high amount of broken speleothems visible on the **scree cone chamber** and the **bear nest chamber** contrasts with the low amount of broken speleothem bases (Figs. 7 and 12). Those objects could be related to past human or animal circulations inside the cave, or to specific uses, as it can be seen deeper inside the cave with the structures (Jaubert et al., 2016).

Downslope from the main rockfall of the **scree cone chamber**, the general shape of the cave and the lowering of the roof morphology prevent most of the incoming daylight from reaching the cave after the main rockfalls (Figs. 7, 8 and 11), which reduces the possibilities of natural visibility in the **bear nest chamber**. The daylight simulations performed on the reconstructed 3D model show the same pattern in the light distribution: the influence of daylight decreases rapidly inside the cave and seems to be not significant at the beginning of the **bear nest chamber** (Fig. 12; S.O.M section S5). These results then question the modalities of all the traces of activity generated by animal and human passages in this area (Lafon, 1996; Rouzaud, 1997). The poor influence of daylight and the predominance of darkness at the very beginning of the cave's entrance then question the modalities of fire usage in this area by early *Homo neanderthalensis*, similarly as what was observed in the deeper parts of the cave (Rouzaud, 1997; Jaubert et al., 2016).

This study confirms that the possibility that Middle Palaeolithic populations and certain medium-sized mammals (e.g., cervids, ursids) used this entrance is plausible. This remains the case, even if a second entrance at the other end is also possible. The size of the fossil cave entrance/'palaeo-entrance', completely hidden today by collapses and sediment clogging, and even invisible in today's landscape, was clearly suited to the gallery's possible use, by both humans and animals. It is

worth remembering that there was no archaeological survey on the slope to uncover such a site, which only skilled speleologists could hope to find. However, it does not appear to be a monumental site such as Bédeilhac (Arège), El Castillo (Cantabria), or Mas d'Azil (France). The reconstructed entrance presents a configuration that may look like Pech-Merle, Lascaux, Santimamiñe or Cussac: a modest opening onto a slope that does not have any exceptional geomorphological features. This result contrasts with other Middle Palaeolithic sites of this period whose functionality seems to have been driven by the external biogeographical contexts such as knapping sites or animal exploitation sites (kill sites, butchery sites like Coudoulous (Brugal and Jaubert, 1991). To our current knowledge, we do not yet have enough data to discuss a specific function (such as human settlements or base camps, Binford and Binford, 1966; Hole and Flannery, 1968) of the cave's entrance. However, the modest configuration of the cave's entrance leads us to propose a cave usage that may have been motivated by specific objectives. It is worth noticing that the traces of activity occur during a full glacial period (176.5 ka; MIS6; Jaubert et al., 2016; Verheyden et al., 2017), with a dominance of cold climatic conditions. This context should be considered in the investigation of the modalities of activity inside a deep cave, as the cave entrance may not have offered sufficient protection against the cold, hence a deeper penetration into the underground parts of the karst network to avoid difficult conditions (see the influence of cold on the clastic sedimentation in Fig. 7). The modest configuration of the cave entrance and the originality of the remains in Bruniquel (constructions with 'speleofacts', Jaubert et al., 2016), which represents, to our knowledge, the first evidence of deep penetration of Neanderthals in cave systems, reinforce the interpretation of a very specific kind of activity inside this cave. The hypothesis of a site with specific or limited activities (limited-activity locations: Wilmsen, 1973) is then all the more justified.

6. Conclusions

Bruniquel hosts the earliest evidence of organised and structured activities inside deep caves by early *Homo neanderthalensis* genus (Jaubert et al., 2016). The study of the cave's entrance evolution highlights more than 366 ka of landscape evolution of the first part of the cave. The slow evolution of the cave entrance through the alternation of rockfalls, scree cones and flowstone deposits led to a good preservation of the different morphologies of rockfalls and scree cones. The closure of the cave before 142.9 ± 1.3 ka by the progressive infilling of a scree cone confirms the antiquity of the speleothem-made structures built in the middle of the cave (Jaubert et al., 2016), as well as the antiquity of the animal traces of passage that are still visible and preserved on the floors of the cave.

The 3D integrated geomorphological approach presented in this work demonstrates that it is possible to recover the past morphologies of cave entrances to an extended time of more than two Quaternary glacial cycles. To our knowledge, few comparable sites of this age (e.g. Le Lazaret, Vaufray cave) have been studied in this integrated way, regardless of their status. The proposed 3D reconstruction shows a relatively small north-west facing entrance, which constrained the human and animal palaeo-traffic to the north side of the cave entrance, in a space that received very little daylight, hence the necessity of artificial light since the beginning of the cave. The results provide a physical support for interpreting the other traces of activity inside Bruniquel. The study and reconstruction of the landscape evolution of the cave's entrance sheds new light on the potential of combining geomorphological and archaeological approaches, and highlight the importance of better studying the dynamics affecting the entrance areas of cave and rockshelter entrances to address archaeological questions.

Author contribution

K.G., S.V., and J-J. designed research; K.G., S.V., J.J., M.B-M., L.B.,

Ch. B., H.C., D.C., S.D., E.F., C.F., L.L., P.M., X.M., D.S., and M.S performed research; K.G., S.V., J.J., M.B-M., L.B., Ch. B., H.C., D.C., S.D., E. F., C.F., L.L., P.M., X.M., D.S., and M.S analyzed data; K.G., S.V., J.J., M. B-M., L.B., Ch. B., H.C., D.C., S.D., E.F., C.F., L.L., P.M., X.M., D.S., and M.S wrote the paper. All authors reviewed the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2026.109866>.

Data availability

Supplementary data are provided in Supplementary Online Information files, and at request.

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