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TESI DI LAUREA IN EARTH AND CLIMATE DYNAMICS

**Speleogenesis and morphology of Guerra
Cave: Integrated analysis with LiDAR
techniques**

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*To whoever looked at my little stature
and saw something bigger*

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Abstract

Terrestrial laser scanning (TLS) is an increasingly important tool in the study of medium- to small-scale landforms in geomorphology. Two Leica TLS devices were used to create a detailed 3D model of Guerra Cave (Mt Berici, Vicenza, NE Italy). One device was the lightweight, compact, and mobile BLK2GO and the other was the BLK360, which is more precise but requires fixed topographic stations (tripod). Around 70 scans were used to survey the two branches of the 400-metre-long cave, including a vertical shaft of over 30 meters of depth. The 3D model of the cave facilitates the execution of morphometric measurements on the various cave environments. The TLS data enabled us to calculate the cave's volume and distinguish between different generations of cupolas, phreatic conduits, and basalt dykes. These observations enabled us to distinguish between different karstification processes and speleogenetic phases, highlighting the importance of primary hypogenic inception in the cave formation and following condensation-corrosion in modifying the cave volume.

Abstract Italiano

La scansione laser terrestre (TLS) è uno strumento sempre più importante nello studio delle morfologie del terreno su scala medio-piccola in geomorfologia. Sono stati utilizzati due dispositivi TLS Leica per creare un modello 3D dettagliato della Grotta di Guerra (Monti Berici, Vicenza, Italia nord-orientale). Uno dei dispositivi era il BLK2GO, leggero, compatto e portatile, mentre l'altro era il BLK360, più preciso ma che richiede stazioni topografiche fisse (treppiede). Sono state effettuate circa 70 scansioni per rilevare i due rami della grotta, lunga 400 metri, compreso un pozzo verticale profondo oltre 30 metri. Il modello 3D della grotta facilita l'esecuzione di misurazioni morfometriche sui vari ambienti carsici. I dati TLS ci hanno permesso di calcolare il volume della grotta e di distinguere tra diverse generazioni di cupole, condotti freatici e dicchi basaltici. Queste osservazioni ci hanno permesso di distinguere tra i diversi processi di carsificazione e le diverse fasi speleogenetiche, mettendo in evidenza l'importanza della fase primaria di dissoluzione ipogenica e il ruolo successivo della condensazione-corrosione nell'allargamento dei condotti.

1. Introduction

Terrestrial Laser Scanning (TLS) techniques are increasingly used in geomorphological studies, and in the last two decades have also been increasingly used to create high-resolution 3D maps of underground environments such as natural caves (Westerman et al., 2003). With the development of technology, these devices have become lighter and easier to handle allowing them to be more effective in the harsh environments of caves, without compromising accuracy. TLS has been used in deep karstic caves for geological research (Buchroithner and Gaisecker, 2009; Hajri et al., 2009; Canevese et al., 2011; Jaillet et al., 2011; Roncat et al., 2011; Hobléa et al., 2014; Silvestre et al., 2015), ice caves (Gašinec et al., 2012; Berenguer-Sempere et al., 2014), and also caves with extreme conditions of humidity and temperature such as the Crystal Cave in the Naica Mine, Mexico (Canevese et al., 2009). A current frontier is the development of a mobile laser scanner to survey caves to produce detailed maps (Zlot and Bosse, 2014). TLS offers a handful of advantages in respect to traditional cave mapping, including high operational speed, accuracy, abundant measured points, and the construction of realistic 3D models of caves including cave walls with a resolution of millimeters in some cases. Specific software packages also allow sophisticated postprocessing of the acquired data and various analyses such as volume and other geometric calculations and detailed surveys on voids. In contrast, traditional cave surveying with a laser range finder and a compass-inclinometer would be more tedious and provide only lower density data. The absence of light in caves makes photogrammetric surveys also difficult (Fabbri et al., 2017). In this study, we used TLS (a static and a mobile device) to survey two very important caves in the Berici Mountains, North Italy (Fig. 1): the Guerra cave and the Mura cave.

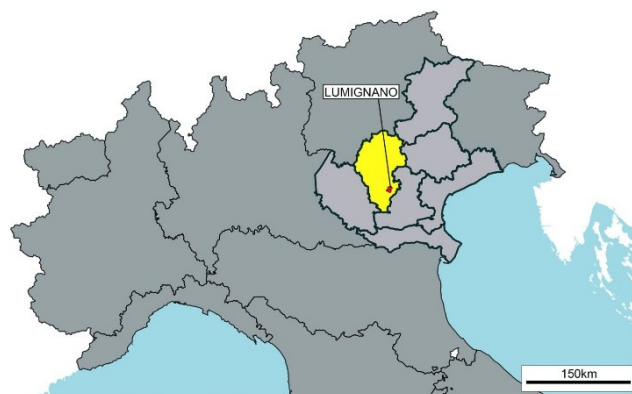


Fig. 1 - Position of Lumignano and Grotta della Guerra in Northern Italy.

The data we obtained have been used for evaluating the cave formation origin and the volume of rock lost during different speleogenetic processes with particular focus on carbonate rock erosion by hypogenic and condensation-corrosion processes. To understand better this survey, we need to address the difference between epigenic and hypogenic caves. Most accessible solution caves are epigenic, produced by the flow of shallow meteoric water. Others, probably 15–20% of the total, are hypogenic, formed by upward flow of deep-seated water or by solutational aggressiveness generated at depths below the surface due to the interaction of groundwaters with magma or sulphur-rich deposits (Palmer, 2011). Human accessibility is used here as the criterion for “cave,” because including smaller openings would make statistical comparisons difficult. Many caves originally thought to be epigenic have been reinterpreted as the product of upward-flowing groundwater (Klimchouk, 2007, Stafford et al., 2009, Audra et al., 2009). The Guerra-Mura Cave System is a mixture of both speleogenetic processes, the main objective of this study is to determine how big was the influence of deep primary processes compared to the secondary ones, measuring the volume of selected sections of the cave (four in particular from the upper branch of Guerra Cave) and confronting them with the volume of different erosional morphologies, i.e. cupolas, bells, mega-cusps and voids created by the weathering of basalt dykes.

2. Geological setting

2.1 The Berici Hills

The Berici Hills is a complex extending for approximately 20 km south of Vicenza. Their morphology is strongly controlled by the lithostratigraphic setting, which comprises mainly a highly erodible calcareous-marly complex, extensively outcropping in the western sector, and a calcareous, locally massive complex, which instead makes up much of the eastern sector. From a tectonic standpoint, the Berici Hills appear as an area characterized by strata with sub-horizontal to gently dipping attitude, involved in very gentle folds whose axes coincide with the direction of maximum elongation of the hill group (SE–NW), and cut by faults oriented normal to the latter (Benvenuti & Norinelli, 1967). The stratigraphic sequence exposed in the Berici Hills consists of sedimentary rocks ranging in age from the Upper Cretaceous to the Miocene. Volcanic rocks of basaltic type are also present, related to the

Lessini–Berici–Euganean eruptive cycle of Palaeogene age (Piccoli, 1966). The oldest rocks documented in the Berici Hills are red or pinkish bedded limestones, locally containing beds of light or red chert, belonging to the "Scaglia Rossa" Formation of Upper Cretaceous age, which records a relatively uniform pelagic marine environment. A general stratigraphic hiatus encompasses the entire Palaeocene (Massari, Medizza & Sedeà, 1976); subsequently, effusive volcanic activity began, with the emission of basaltic products (Barbieri et al., 1981). The depositional environment was a relatively shallow sea strongly influenced by terrigenous and volcanoclastic input and the progressive decrease in terrigenous influx subsequently allowed the deposition of a rock unit highly characteristic of the Middle Eocene, the "Nummulitic Limestones". Interbedded with the nummulitic limestones are levels and lenses of volcanoclastic rocks, at times highly fossiliferous. During the Upper Eocene—which takes the name Priabonian from its type locality of Priabona near Monte di Malo—the sea progressively re-occupied the emerged land and a complex of predominantly marly strata, called the "Priabona Formation", began to be deposited; in the eastern Berici this unit directly overlies the uppermost nummulitic limestones. The Priabona Formation is therefore widespread throughout the Berici Hills, where it may reach a thickness of nearly 200 m. This environment was a shallow, muddy sea, extremely rich in organisms that are found today as fossils in the rocks of Berici, among which colonies of scleractinian corals, hydrozoans and calcareous algae, at times fossilised in life position, are readily recognisable. Important outcrops of this palaeolandscape occur at Lumignano, where high rock walls, formed of massive limestone sculpted by innumerable cavities including the Grotta della Guerra, display a geological cross-section of the Berici. The Venetian Oligocene is represented in the Berici by a coral reef (Frost, 1981), formed of discontinuous massive bodies and readily observable along the Lumignano valley on the slope of Monte della Croce. In the area behind the Berici reef (back-reef) and at the tidal channels, i.e. in high-energy environments, another characteristic coarse deposit is found: a whitish nullipore calcarenite composed of fragments of calcareous algae, known as "Pietra di Vicenza" (Vicenza Stone). In the lagoonal environment, by contrast, low-energy conditions were occasionally disturbed by moderate explosive volcanic activity, which gave rise to highly localized volcanic structures, the necks: circular or elliptical conduits (diatremes) filled with basaltic breccias containing both lava blocks and clasts of sedimentary rock torn from the conduit walls during the explosion. There are a great many necks in the Berici Hills; among the most significant is that of Lumignano, consisting of a highly compact breccia which, with a diameter of almost 400 m, is one of the largest in Berici. The largest is indeed the Brendola neck, with a diameter

exceeding one kilometer, largely composed of compact basalts, locally displaying columnar jointing. At the end of the Oligocene the entire lagoon became emergent; this relatively rapid event was accompanied by a local resumption of effusive volcanic activity. This activity was responsible for the cross-cutting of the sedimentary sequence by basalt dykes, with ages probably as documented in the Lessini mountains for the Upper Oligocene (Zorzin et al., 2026): sheets of basaltic rock that formed from the filling of pre-existing fractures by magmatic fluids. The fractures in question are very probably conjugate to the main faults of the area: the Schio–Vicenza Fault, trending NW–SE, and the Riviera dei Berici Line, trending NE–SW (Fig. 2).

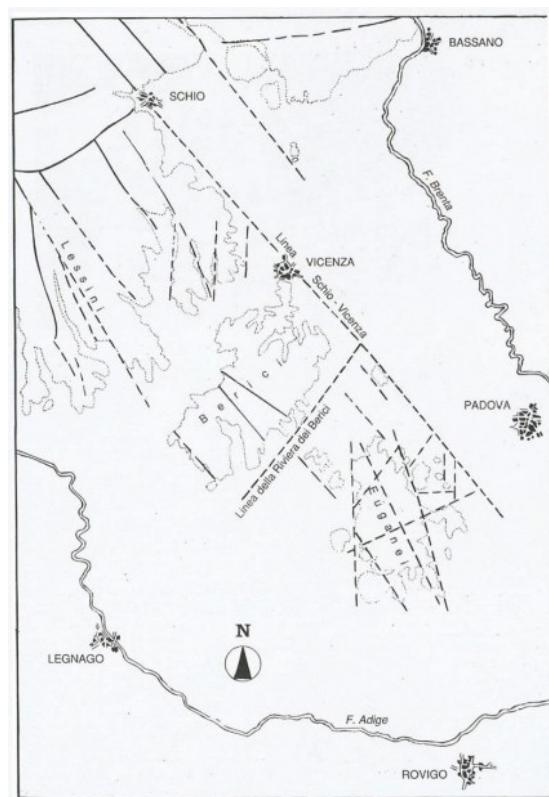


Fig. 2 – Map of main faults and fractures around Berici Hills.

The onset of the new Miocene transgressive cycle displays sedimentary structures typical of a coastal environment evolving towards shallow-marine conditions. These rocks belong to the "Arenarie di S. Urbano" (S. Urbano Sandstones) Formation and constitute the youngest rock unit among those preserved in the Berici Hills. Already by the end of the Miocene, the entire Berici block had been brought, under the drive of Alpine uplift, into definitive emergence from the sea (Albertini, 1952), leading to the development of karst processes in

the region. In the present-day morphology of the Berici it is possible to recognize several erosional phases superimposed over time; examination of karst landforms—among which the caves and, above all, their infills—allows one to recognize, to some extent, different stages of deepening, evidently linked to the climatic conditions, at times markedly different, that characterized the Early Quaternary in particular. The oldest evidence of karstification—more correctly termed palaeokarst—affecting the Berici Hills consists of doline-like depressions carved into the Oligocene calcarenites. Palaeokarst would have developed further during the subsequent Pliocene, bringing the Berici, in the Early Quaternary, i.e. the Pleistocene, to a physiognomy similar to the present one and elaborating the karst systems of the Berici, some of which are still active and explorable. A large number of cavities of varying size, scattered throughout the Berici area, are filled with typical karst-related deposits, namely calcite speleothems or residual clays such as "terra rossa", at times associated with calcareous breccias. Today more than 400 cavities are recorded in the Berici Hills; this number of caves represents the end result of phenomena that began at least in the Early Quaternary and were characterized by repeatedly superimposed phases of erosion and infilling. Much of the Berici karst is therefore a predominantly fossil karst, from which a few reactivated subterranean systems branch off, often feeding the few springs located at the foot of the Berici relief or at the contact between permeable rocks and the overlying limestones, through which surface waters are absorbed by karst processes (Mietto P., 1988).

2.2 Grotta della Guerra – Grotta della Mura

On Monte Castellaro, at Lumignano, in the municipality of Longare, two tall triangular openings stand out, belonging to the Grotta della Mura – Grotta della Guerra complex. Both caves are well known for their high archaeological interest (Lioy, 1895; Da Schio et al., 1947; Leonardi, 1958) and, especially the second cavity, for the extremely rich hypogean fauna it hosts, of the greatest value from a biospeleological standpoint (Boscolo, 1968). The Grotta della Mura consists of the phantom of an original tall basalt dyke, emptied out over several tens of meters, gently ascending and articulated into small chambers and lateral spherical passages; this type of cave pattern is termed sponge-work (Klimchouk, 2009). An artificial tunnel, excavated out of the need to adapt the caves as shelters during the war, connects it to the nearby but distinct Grotta della Guerra. Beyond its wide entrance, a gallery with a

muddy floor incised by a trickle of water immediately branches off to the right until, after a few tens of meters, it is barred by a colossal reddish flowstone. The ceiling remains high, sculpted into large cupolas produced by mixing corrosion, which frequently host colonies of thousands of bats. Beyond the flowstone the cave continues for a few tens of meters before finally being lost in extremely narrow fissures from which the stream seeps. From the vestibule, to the left, the gallery continues to a shaft over 30 m high, partly filled by an enormous speleothem column leaning against the wall. Almost at the top of the shaft the cave continues and its upper branch begins, developing for hundreds of meters, always with voids of large dimensions, between galleries and two big chambers characterized by transversal basalt dykes. The cavity progressively narrows and tends to take on an ascending trend until it terminates in vertical fissures choked with soil and debris (Mietto P., 1988). We have reasons to believe that the Guerra Cave upper branch develops along a pre-existing fracture parallel to the Riviera dei Berici line and the basalt dykes intercepting it are all parallel to the Schio-Vicenza fault possibly meaning that the magmatic fluids used conjugates of said fault to reach the cave (Fig. 3-4).

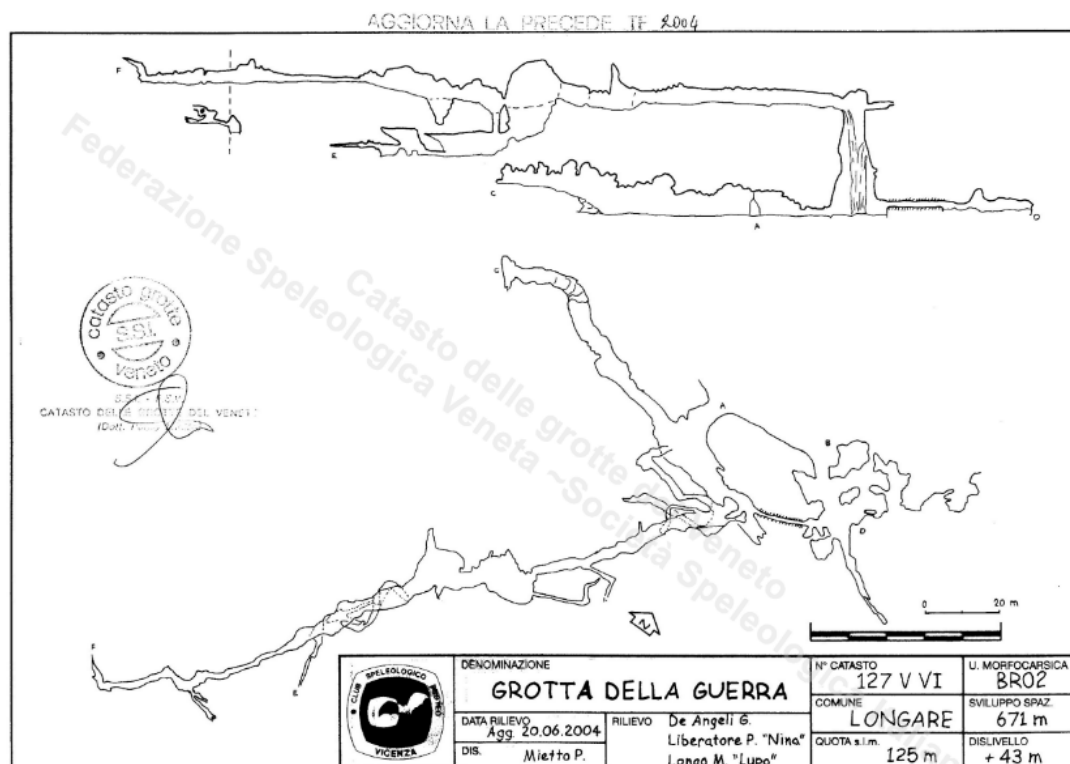


Fig. 3 – The most recent (2004) speleological map of Guerra-Mura Cave



Fig. 4 – A) a complex chamber with domes, cupolas, mega-cusps in Guerra Cave, B) bell-hole near basalt dike phantom, C) coral fossil on the wall of Guerra Cave, D) entrance of Mura Cave.

The Guerra Cave has more than 600 m of linear extension and it is an example of cave system developed starting from hypogenic networks with magmatic intrusions and secondary sediments. Some authors have proposed that the first speleogenetical stages of these caves were probably determined by the circulation of hydrothermal waters during or after the

emplacement of the volcanic dykes (Sauro, 2001). The same author proposed the hypothesis that caves voids predate volcanic activity and were subsequently infilled by the basalt intrusion. The solutions circulating at the interface between the basalts and the limestones caused both the weathering of the magmatic fillings and the solution of the carbonates; the solution has been certainly aided by the ions released by the not karstifiable rocks. It is particularly interesting that Cave A in Veja exhibits morphological features that are entirely similar to those observed in the Guerra Cave in the Berici Mountains (Dal Molin et alii, 2000). In fact, both caves feature numerous domes, karst dissolution features on the walls, some of which resemble mega-scallops or mega-cusps, and basalt intrusions (often oxidized and eroded) of varying sizes that partially overlie the pre-existing karst features. (Gonzato et al., 2018). Nonetheless, the work of Fabbri et al. (2017), showed that in the case of Ponte di Veja the dykes were filling only an enlarged fracture, with signs of mega-cusps and dissolution superimposed by the intrusion, while most of the volume of cavity is related to subsequent epigenic stream karstification and aerial condensation-corrosion processes on the roof. Grotta della Guerra is characterized by four typical morphologies that will be defined shortly: basalt dykes corridors, wall mega-cusps, large condensation-corrosion cupolas and smaller elongated bat bell-holes. After the infilling of fractures and its solidification, basalt was exposed to water and air and, since it is easily alterable, it was progressively chemically weathered. Subaerial weathering of the basalt dike on the roof has contributed to the formation of the cave void and the removal of the weathering products, mainly clays, must have happened when water in the cave conduits was still flowing. Basalt dykes corridors were formed only after the weathered material has been evacuated (Fig.5). An evident result of the interaction of basalt with a water table is the great enlargement of the cave void just near the two parallel dykes. The thermal contrast can be created in caves close enough to the surface and influenced by seasonal temperature changes or be maintained over long periods by thermal rising waters, or by the presence of guano deposits that decay through an exothermal reaction providing moisture and CO₂ to the cave atmosphere and the wall/roof (especially in the Guerra Cave given the abundance of guano deposits present). Warm and moist air masses are frequent in coastal or lacustrine environments, so condensation–corrosion is often seen in coastal caves close to the entrances. Condensation can also occur at the interface between a cool and dense (cave) air body and the moving warm and moist air above. When this condensation-corrosion process occurs at a certain height interval we have the formation of cusps. In some cases, they can develop up to meters in size and become mega-cusps (Fig. 6a,b).

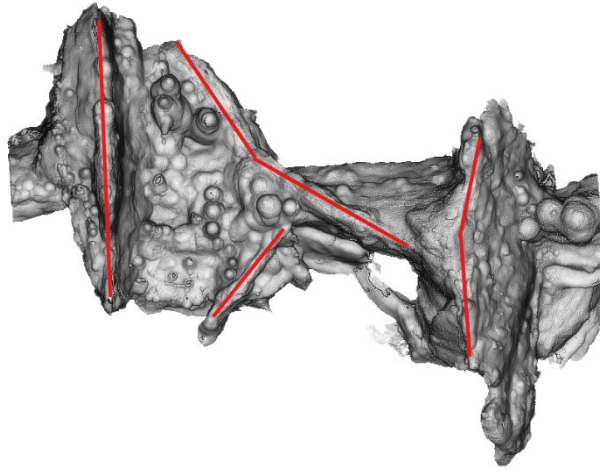


Fig. 5 – Basalt dyke corridor (left) and basalt dykes from above of 3D model (right).



Fig. 6a – Mega-cusps in the second half of the upper branch of Guerra Cave.

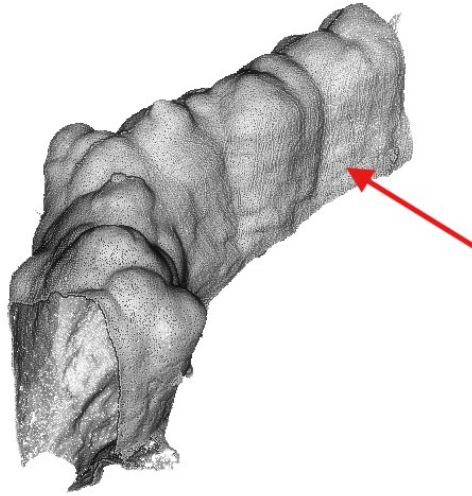


Fig. 6b – Mega-cusps from the 3D model.

Cupolas are generally meter-sized, rounded, dome-shaped solution hollows occurring in the roofs and sometimes along the walls of caves (Osborne, 2004). These morphologies display a wide range of dimensions, with the smaller ones grading into solution pockets, which are less than 1 m wide, and the larger ones reaching several tens of meters in diameter. Cupolas can generate in different ways and in different conditions: in vadose cave passages, they can form by condensation–corrosion induced by convectional air movements in closed thermal caves above the thermal water pools, or by advective air flow between two cave entrances at different altitudes or in large cave entrance areas. To be able to form by condensation–corrosion, the air flow and the thermal gradient between the cave atmosphere and the wall has to remain stable over sufficient time to produce enough condensation water. The aggressive water condensed on the rock surface causes its progressive dissolution, to form large solution features such as cupolas (Fig. 7). Bell holes are cylindrical, cigar-shaped, ceiling pockets with round tops that extend vertically upward. Their depth is generally greater than their diameter, penetrating into the cave roof up to several meters and with widths at their mouths ranging between 25 cm and 1.3 m (Tarhule-Lips & Ford, 1998). Their depth/width ratio is typically greater than 1, which distinguishes them from cupolas and their vertical-upward development in cave roofs differentiates them from normal solution pockets. Bell holes are sometimes occupied by bats (Fig. 8), in which case their mouths are sometimes covered with brownish crusts composed of hydroxylapatite or other material related to

excreta of the bats i.e. guano and urine (De Waele J., 2022). The study of these morphologies can help to understand the primary genetic mechanisms and the subsequent evolution for the cave.

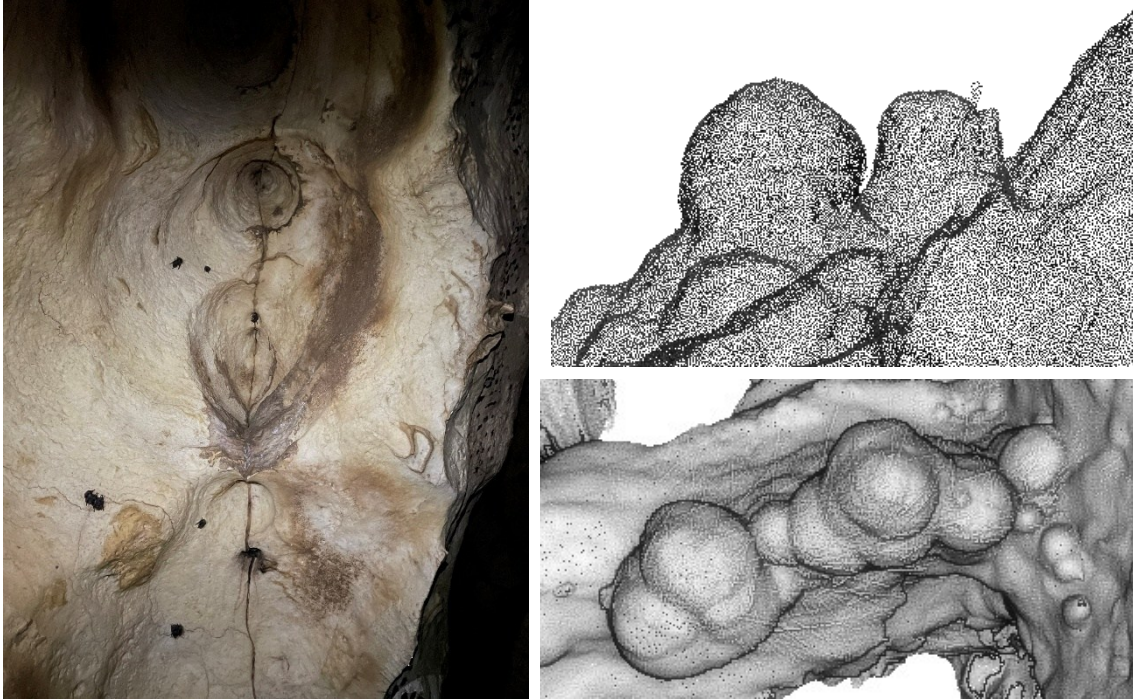


Fig. 7. – Cupolas cut by bell-holes (left) and cupolas shapes visible from 3D model (right).



Fig. 8 – Bats sleeping in a bell-hole (left) and bell-holes from under (right).

3. Methods

3.1 Laser scanning devices

For the cave study two Leica laser scanners were used: the BLK360 and the BLK2GO (Fig. 9). The BLK360 is an advanced precision imaging laser scanner, it is a powerful terrestrial LiDAR scanner and uses laser pulses and time-of-flight enhanced by Waveform Digitizing (WFD) technology to measure distances and rapidly capture precise 3D point clouds of rooms, buildings, and outdoor environments. Its scan distance can range up to 45 meters with a precision of 4 millimeters and with four scan settings it captures data in 7, 13, 30, or 75 seconds at 680,000 points per second, sending laser light in the short infrared field (830 nm). BLK360 operates based on the scanning optics of a vertically rotating mirror on a horizontally rotating base. A rotating optical mirror is used to transmit the laser beam to an object and receive a return beam. With its small dimensions (155 x 80 mm) and light weight (850 g with batteries) it can be carried easily even inside caves. In addition to that it has dust and humidity protection so it can survive better the cave environment. The Leica BLK2GO is a handheld, wireless 3D imaging laser scanner that creates digital twins and colorized point clouds in real time as you walk through indoor or outdoor environments.



Fig. 9 – BLK360 (left) and BLK2GO (right).

It features a lightweight (775g with battery) and compact (279 x 80 mm), single-button design that eliminates the need for traditional tripods. This device is equipped with the so called “GRANDSLAM” (Simultaneous Localization and Mapping) is a combination of high-speed dual axis LiDAR (both axes constantly spin while scanning), multi-camera vision system and an inertial measurement unit that makes the BLK2GO self-navigating, it can also be monitored easily on the phone while it scans with the compatible app Cyclone Field. BLK2GO works similarly to the BLK360 except for a lower frequency of scanning (420,000 points per second) but since it is mobile it can be used in smaller or more difficult passages. Both scanners have incorporated the Visual Inertial System (VIS) technology that automatically pre-registers scans in the field and allow the devices to know where they are comparing the scans and putting together the clouds, making the postprocessing part easier (Leica Geosystems, 2026). The scans of the upper branch of the Guerra cave were made mainly with the BLK360 since it is easily accessible and for the rougher parts of the tunnel the BLK2GO was chosen. Scanning operations with the BLK360 were spaced every 3-5 m and a total of 45 scans were made and with the BLK2GO the rest of the cave system was covered with a total of just 5 scans which is more convenient but also heavier in terms of memory space and it can cause some issues when working with the data. This work was made in one day during the winter season because in spring and summer the cave is inhabited by a large colony of bats. The physical limit of TLS in this environment is constituted by narrowness, because at a distance shorter than 0.6 m from the object (i.e., cave's walls), this device cannot work properly due to an exceeding noise effect on the returning signal. Another strong feature of these scanners is that they do not need additional equipment to reference the scans unlike other machines.

3.2 Data Processing

LS data processing needs high computing power and expensive softwares, although open-source software is also available. Data from the scanners was downloaded with the program BLK Data Manager, a free software utility by Leica Geosystems used to download, manage, and archive raw scan data from the BLK sensor series. The 45 BLK360 scans and the 5 BLK2GO scans were put together both automatically and manually with the licensed Leica

program Cyclone REGISTER 360 PLUS to create a single point cloud of the whole cave system (Fig. 10).

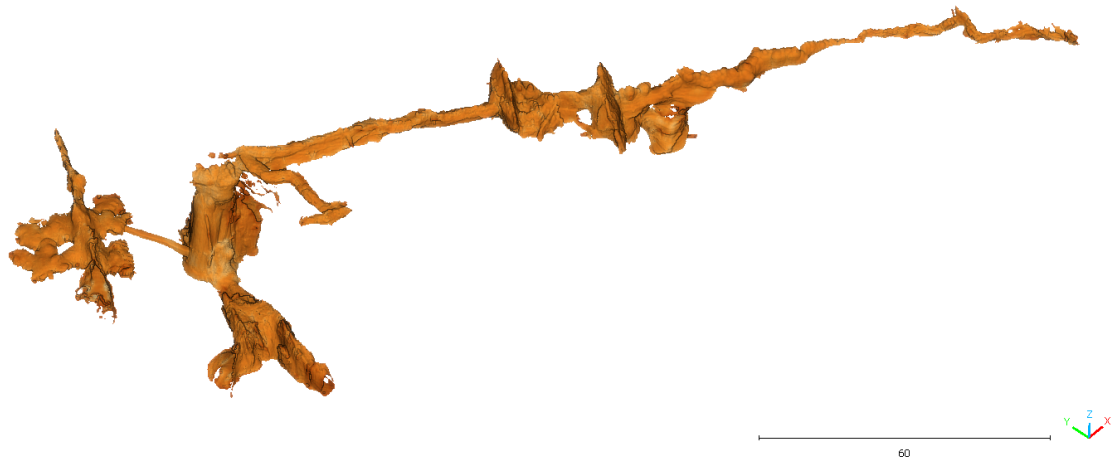


Fig. 10 – 3D model of the entire cave system.

It must be mentioned that not all the scans come out perfect or are easy to work with and sometimes we had to redo some parts of the cave that were incomplete or we had to give up on surveying some difficult zones. The final project then was resized (points were spaced 5 cm at first and then 1 cm and 2 cm to have more accuracy in the post-processing) and exported due to the fact that it was heavy and it needed to be lighter in order to work with it, subsequently the noise and the outliers in the scans was cleaned both automatically and manually with Leica Cyclone 3DR and then 6 sections were cut for practicality. The selected sections used to carry out the analysis were taken from the upper branch of Guerra Cave and referred to as: Beginning (1), Dykes (2), Mega-cusps (3), End (4) (Fig. 11a,b,c,d). The clean and resized data was processed on CloudCompare, a free, open-source 3D point cloud and triangular mesh processing software which can do different volumetric calculations that were essential for the survey. In the end, the point cloud object was also transformed into a mesh surface, constructed from triangular units. This procedure was necessary because sometimes it is not possible to carry out volume calculations based only on point clouds (a surface is needed).

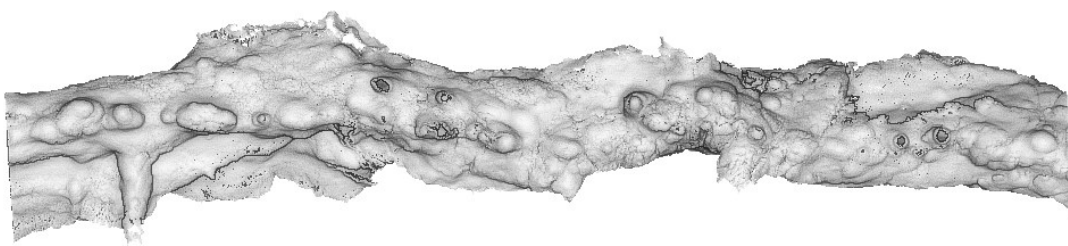


Fig. 11a – Section 1 (above).

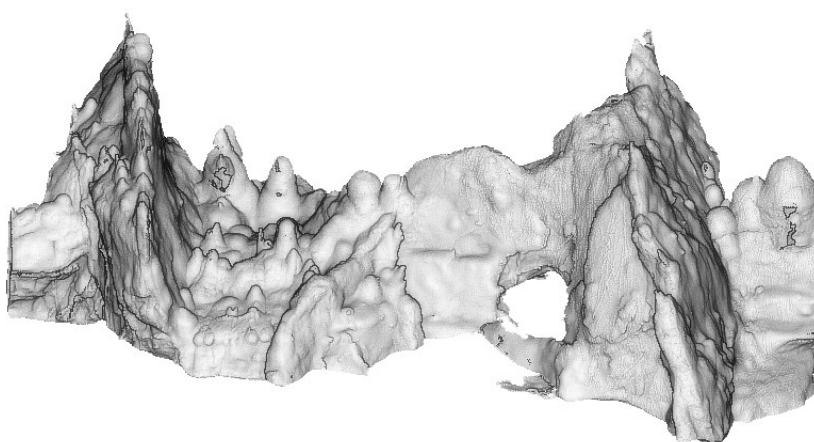


Fig. 11b – Section 2.

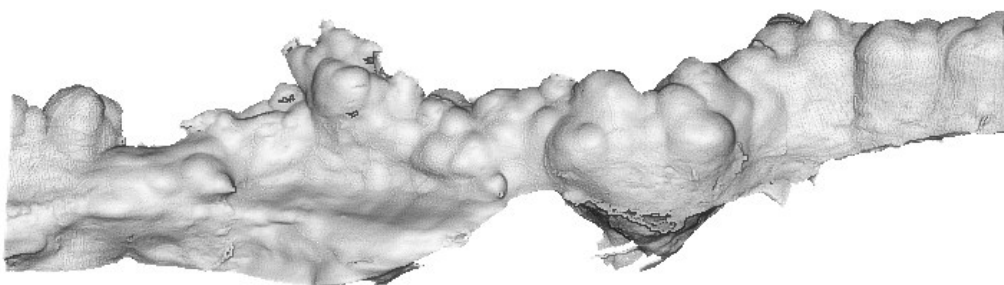


Fig. 11c – Section 3.

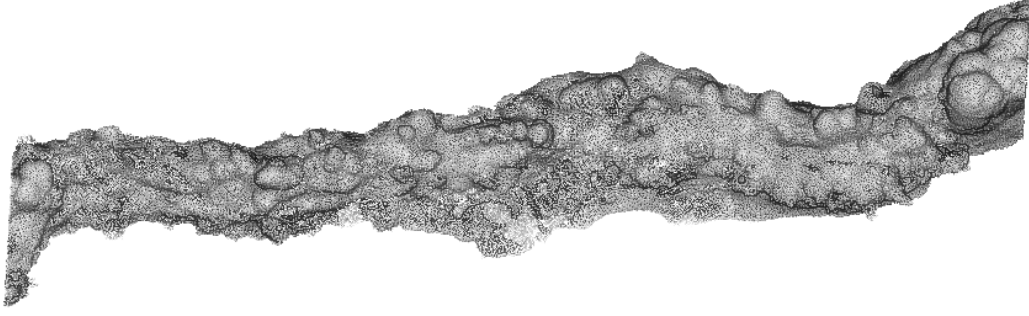


Fig. 11d – Section 4 (above).

4. Results

Once all data had been prepared, we computed different geometric features using the tools available in CloudCompare, focusing specifically on roughness and sphericity. Geometric features describe the spatial relationships between neighboring points within a point cloud and are derived through principal component analysis (PCA). For each point and its local neighborhood, PCA identifies three orthogonal unit vectors corresponding to the principal directions of variance. These vectors are equivalent to the eigenvectors of the covariance matrix, while the associated eigenvalues λ_1 , λ_2 , and λ_3 ($\lambda_1 > \lambda_2 > \lambda_3$) quantify the variance along each principal direction (Fig. 12).

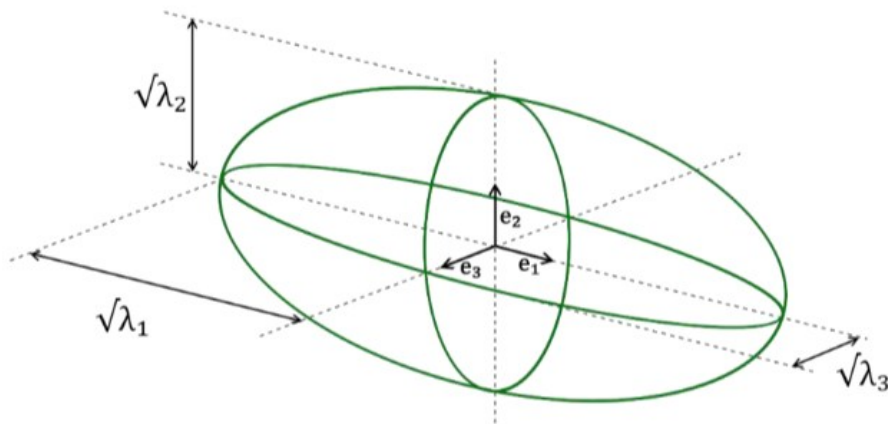


Fig. 12 – Sketch of an ellipsoid with its eigenvectors and eigenvalues

For each point in the cloud, the *roughness* value is defined as the distance between that point and the best-fitting plane calculated from its neighboring points. This feature is particularly effective for highlighting condensation cupolas, as these cavities develop predominantly perpendicular to, and away from, the original cave surface (i.e. the ceiling or walls), producing local deviations from the surrounding surface geometry. Sphericity, on the other hand, describes the degree to which the points in the neighborhood are distributed in all directions ($S = \lambda_3 / \lambda_1$). In our case it shows the coalescence of cupolas (Boušek M. et al., 2026). First, we settled on certain fixed parameters to have consistency in the results between the different sections. Roughness was calculated with a local neighborhood radius of 0.75 to highlight the condensation cupolas and the saturation was set between 0.11 and 0.3 (approximately) to differentiate them from steeper bells formed by the passage of chiroptera. It is evident that the shape of cupolas has different development phases and the resulting values fit best for their classification: values between 0.09-0.19 show the original shape of cupolas while values between 0.19 up to 0.5 indicate more bell holes (Fig. 13). Sphericity was then calculated using the same neighborhood radius, while the saturation range was adjusted to 0.06–0.30/0.35. The resulting distribution highlighted a consistent alignment of cupolas along the conduit ceiling (the results for Section 1 are shown in Fig. 14).

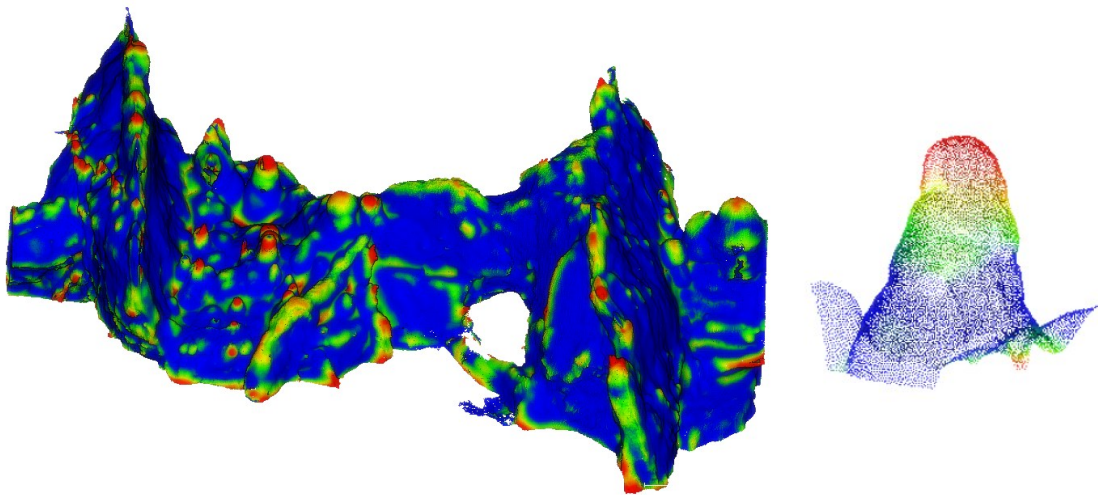


Fig. 13 – Roughness values applied to Section 2 (dykes) point cloud and particular of a bell-hole.

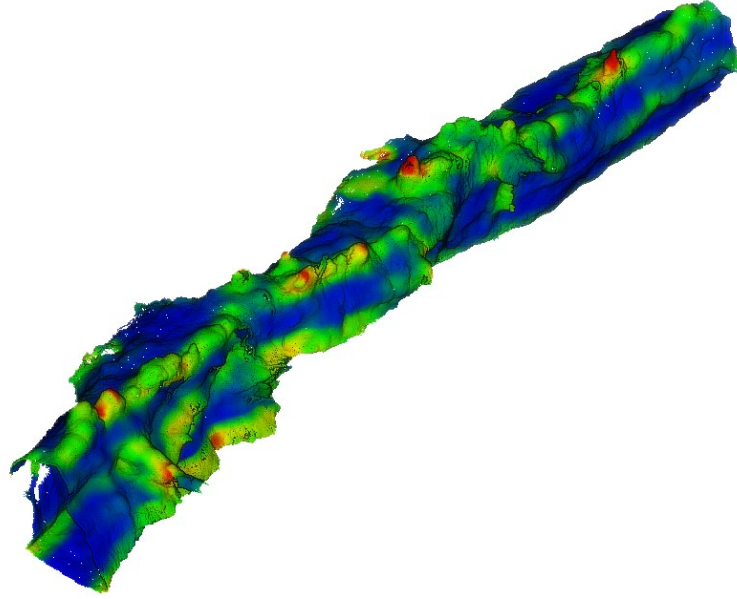


Fig. 14 – Sphericity values applied on Section 1 (beginning) point cloud.

The next step was to estimate the volume of cupola and bell-hole morphologies using the CloudCompare *2.5D Volume* tool. This tool computes the volume between a 2.5D point cloud and an arbitrary plane of constant height, or between two 2.5D point clouds, through a rasterization and gridding process. The total volume is obtained by summing the contribution of individual grid cells, with each contribution corresponding to the cell area multiplied by the height difference between the ground and ceiling surfaces ($dV = \text{grid step}^2 \times \text{height difference}$). Only cells with valid height values for both the ground and ceiling surfaces contribute to the total volume, whereas empty cells or cells for which only one height value is available are excluded from the calculation (CloudCompare, 2026). Because the point cloud is highly irregular and locally incomplete, this approach has inherent limitations that may affect the accuracy of the resulting volume estimates. The calculation parameters were therefore adjusted for each section to minimize potential errors. A specific height level was selected as the ground surface for each section, based on the spatial referencing of the model, while the corresponding point cloud was used as the ceiling surface. Empty cells were left unfilled, as the available interpolation options generated artificial volumes that could bias the calculations. The grid step was also adjusted for each section according to the characteristics and density of the point cloud (Fig. 15).

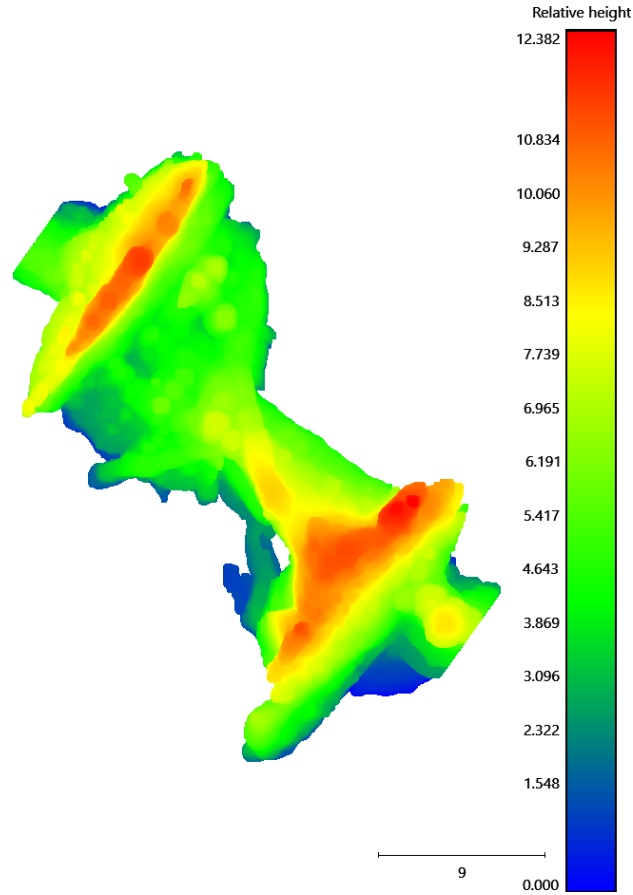


Fig. 15 – Grid with relative height for computation of 2.5D Volume.

To assess the reliability of the resulting estimates, the calculated volumes were cross-checked using an independent, simplified approach. The largest and smallest cupolas within each section were isolated from the point cloud and their volumes measured individually. Their mean volume was then multiplied by the total number of cupolas and bell holes identified within the section. The resulting estimate was comparable to that obtained using the 2.5D Volume tool, providing an independent check on the adopted methodology. The same procedure was subsequently applied to the remaining sections (Table 1).

Table 1. Computed volumes of the four sections

Section	Total Volume	Corrosion volume	Ratio
	m^3	m^3	% (approx.)
1 (Beginning)	115.158	11.333	9.84 (10)
2 (Dykes)	1408.159	108.802	7.73 (8)
3 (Mega-cusps)	391.293	53.587	13.7 (14)
4 (End)	37.305	3.177	8.52 (8)
Total	1951.915	176.899	9.06% (9)

5. Discussion

The 3D cave model, combined with field observations, reveals clear spatial and cross-cutting relationships among the different cave morphologies, allowing their relative chronology to be reconstructed. Basalt dykes occur along regional fractures, which may have already been enlarged by fluid circulation prior to magma injection. Mega-cusps are developed on both cave walls and ceilings, preferentially along specific limestone interlayers or at distinct elevation levels within the cave passages. Cupolas occur mainly on the ceiling but also overprint and develop within pre-existing mega-cusps, indicating a later phase of speleogenetic modification. Finally, bell holes occur within the cupolas, representing a subsequent generation of corrosional features. Based on these spatial and cross-cutting relationships, together with the geological characteristics of Guerra Cave, its evolution can be reconstructed as a succession of four main stages (Fig. 16):

1. **Basalt intrusion and fracture infilling.** Pre-existing fractures, possibly already affected by hypogenic enlargement, were intruded and partly infilled by basalt during the late Oligocene, approximately 32 Ma ago.
2. **Development of the hypogenic phreatic conduit.** A hypogenic phreatic cave system subsequently developed preferentially along limestone interlayers and, locally, along the contacts between limestone and basalt dykes. Speleogenesis was presumably favored by the interaction between ascending hypogenic fluids—

possibly thermal and/or CO₂-rich and H₂S-rich and associated with the basaltic intrusions—and a water table, either represented by a local groundwater body or controlled by sea level.

3. **Basalt weathering and vadose reworking.** Following uplift and the transition towards vadose conditions, weathering of the basaltic infill and removal of the resulting residual clay by flowing water progressively reopened and modified the conduits. Condensation-corrosion processes may also have commenced during this stage.
4. **Entrance opening and enhanced condensation corrosion.** The opening of the cave to the surface profoundly modified its internal atmospheric circulation and promoted more intense condensation-corrosion. An initial phase may have been driven primarily by condensation associated with air circulation and/or gas-rich cave atmospheres, potentially involving elevated CO₂ and H₂S concentrations. Subsequently, bat occupation and thermally driven gradients within the cave atmosphere may have further enhanced condensation and corrosion. The intensity and spatial distribution of these processes probably varied through time in response to intermittent bat occupation and changes in regional climatic conditions.

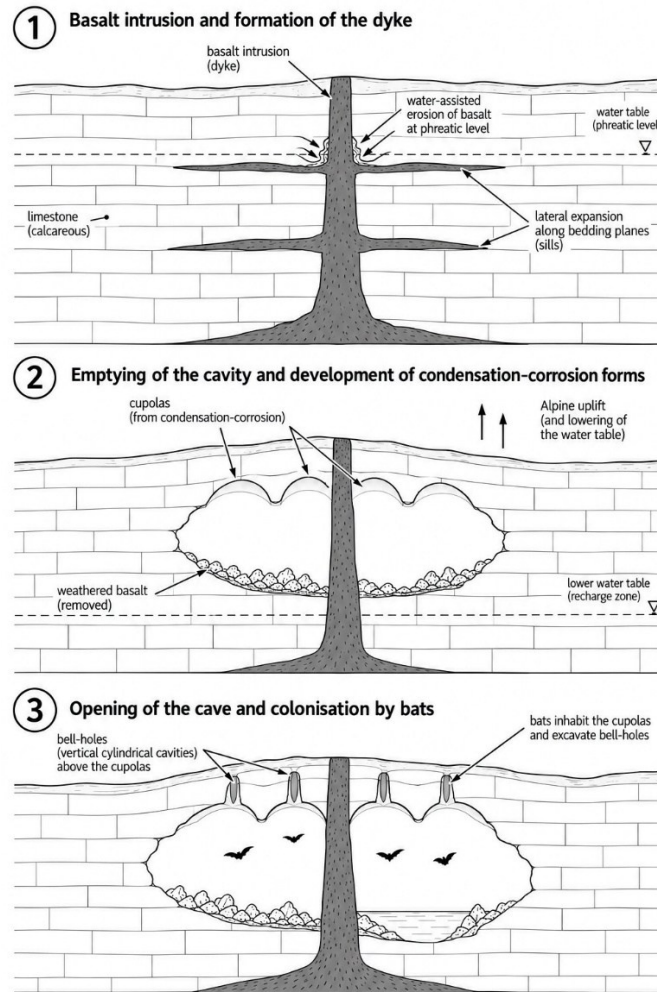


Fig. 16 – Sketch of the main stages.

The volumetric analysis focused on the fourth evolutionary stage and, in particular, on the main condensation-corrosion morphologies —cupolas, and bell holes—and their superimposition. By estimating the combined volume of these morphologies and comparing it with the total volume of the analyzed cave sections, we found that they account for approximately 9% of the present-day cave volume. This relatively limited contribution indicates that condensation-corrosion acted primarily as a secondary process, modifying and enlarging pre-existing conduits rather than being responsible for their initial development. The main volume of Guerra Cave must therefore have formed during an earlier speleogenetic stage, most likely under hypogenic phreatic to epiphreatic conditions.

Further support for this interpretation is provided by the adjacent Mura Cave (Fig. 17). Its overall geometry and characteristic morphologies suggest that its conduits developed predominantly through the interaction of magmatic-hydrothermal fluids with the carbonate host rock. In contrast to Guerra Cave, Mura Cave lacks the well-developed condensation

cupolas associated with the later evolutionary stage. Evidence of fluid interaction with specific limestone interlayers is particularly well preserved in Mura Cave, supporting the hypothesis that similar structurally and stratigraphically controlled hypogenic processes were responsible for the initial development of Guerra Cave.

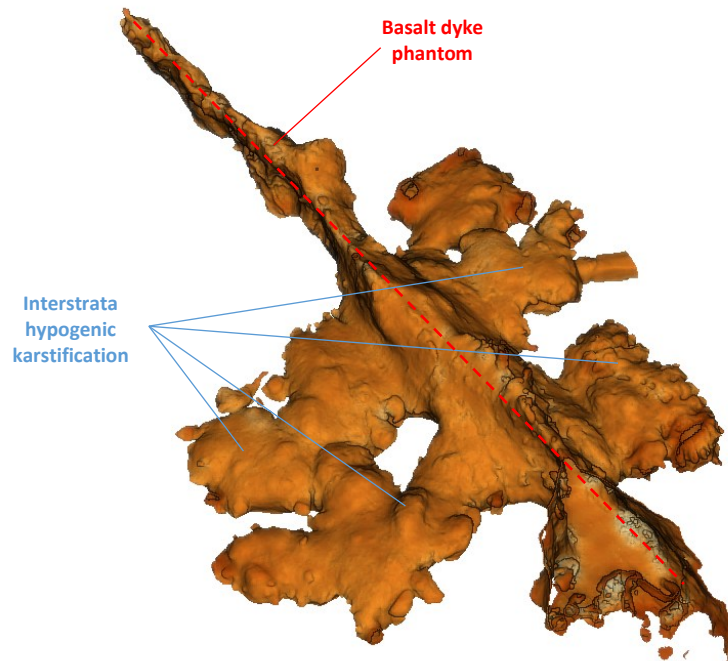


Fig. 17 – 3D model of Mura Cave.

6. Conclusion and future work

In conclusion, both caves of the Guerra–Mura Cave System preserve a diverse assemblage of morphologies formed during successive stages of their evolution. Nevertheless, their overall geometry and morphological characteristics indicate that the principal phase of conduit development occurred under hypogenic phreatic to epiphreatic conditions. The volumetric analysis further supports this interpretation, showing that morphologies associated with later vadose and subaerial condensation-corrosion processes account for only a relatively small proportion of the present-day cave volume. These later processes therefore primarily modified and enlarged pre-existing conduits rather than controlling the overall development of the cave system. On this basis, the Guerra–Mura Cave System can be confidently classified as predominantly hypogenic in origin.

Future investigations should focus on establishing the chronology of the different evolutionary stages. Dating of wall alteration secondary minerals (sulphates), speleothems, and other sedimentary deposits could provide important chronological constraints on the timing of hypogenic speleogenesis, subsequent vadose modification, and the development of condensation-corrosion features. Additional fieldwork would also allow completion of the 3D survey, filling the remaining gaps in the point clouds and improving the accuracy of morphological and volumetric analyses.

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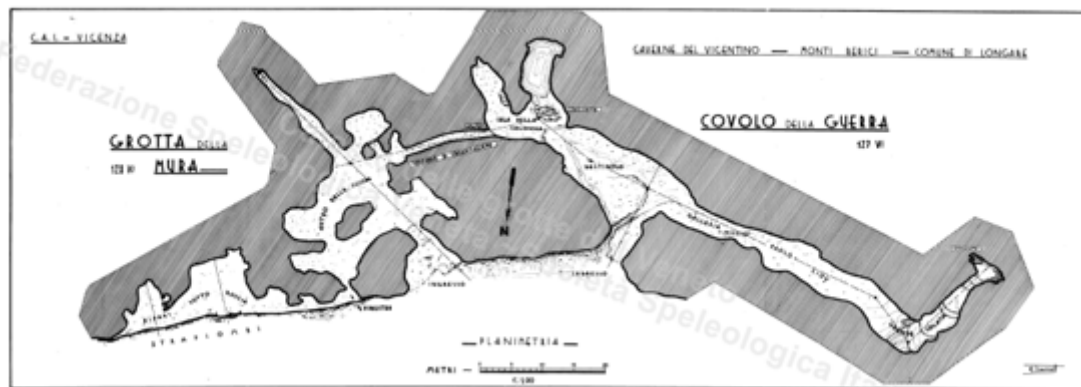
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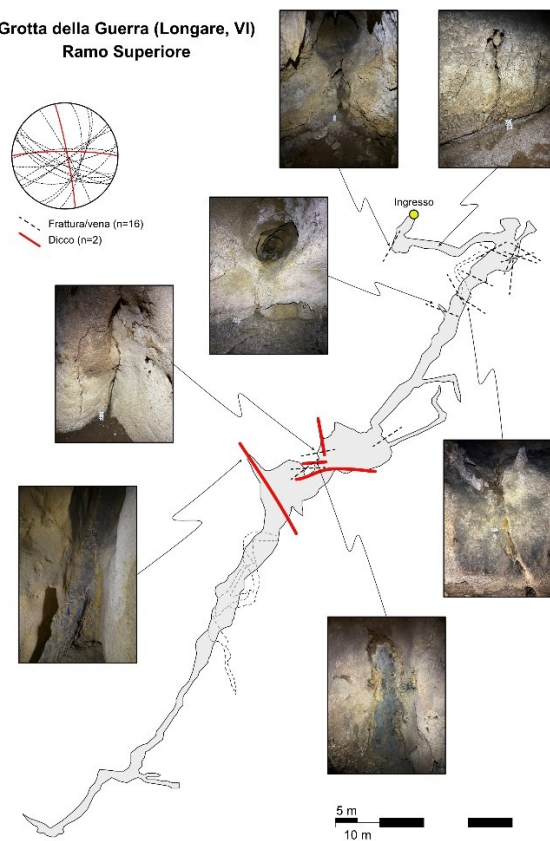
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Generative Artificial Intelligence tools were used in the preparation of this thesis as support for language revision and content organization. All outputs were critically reviewed by the author, who takes full responsibility for the final content of the thesis.

Appendices



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