Speleogenesis in Quaternary clastic sequences along the active front of South-Eastern Alps, a case study from Castel Sotterra Cave (Veneto, Italy)

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Abstract

The Castel Sotterra Cave, extending ~ 7 km in length and ~ 125 m in depth, is the longest cave in the Montello Hill and the fourth longest conglomerate cave in the world. The Montello hill is an isolated low plateau composed of conglomerate beds alternating with sandstone and siltstone layers, bordered by a fault system belonging to the most advanced deformation front of the Venetian Pre-Alps. The landscape is shaped by the erosive power of the Piave River and by extensive karst processes characterized by sinkholes, karst valleys, underground cave systems and springs. Speleogenesis within Castel Sotterra is dictated by variability in lithology, which is influenced by the contrasting mechanical properties of the conglomerate matrix and clasts, and fracture networks. As a result of the rapid tectonic uplift, at least three main lithologically controlled cave levels were formed. Castel Sotterra Cave is an example of a remarkably rapid landscape evolution, where Pleistocene fluvial deposits have undergone diagenesis, uplift and karstification within a short geological time frame, and the interplay between fluvial incision and tectonic uplift by the active thrust system has significantly influenced groundwater flow and karst development.

1. Introduction

The karst potential of conglomerate outcrops is poorly explored, yet conglomerates are found on every continent due to erosion of active margins and orogenic belts. Few studies investigate "non-traditional" conglomerate caves around the world and their speleogenesis (Lapaire et al., 2007; Finch and Pistole, 2011; Lipar and Ferk, 2011; Dunkley et al., 2017), reflecting an interplay between dissolution and mechanical erosion, often controlled by inception horizons in well-defined carbonate-bearing portions of the terrigenous bedrock. The Montello Hill is considered a "classic karst" of conglomerate (Ferrarese and Sauro, 2005), due to the presence of the state of the art of sinkholes, karst valleys, karst springs and hundreds of caves in such a small area.

The Montello Hill is a low-elevation WSW-ENE elongated plateau, ~ 13 km long and ~ 5 km wide, which belongs to the subalpine hills, a series of ridges emerging from the Venetian fluvial plain by tectonic scarps due to thrusting by the most advanced fault system in the region (Figure 1A) (Zanferrari et al., 1982; Ferrarese et al., 1998). The Montello hill represents an emerging tectonic pop-up, bounded on the SE escarpment by the main branch of the Montello thrust system and on the NW slope by the Piave river, which cuts the hill on the NE side, creating the Nervesa water gap (Figure 1B). The SW side is characterized by an abandoned dry valley, where the Piave River flowed until ~ 27 Kyr (Mozzi et al., 2015), and a series of seven-order erosional fluvial terraces (Figure 1B). At the top of the hill, two planation plateaus occurred at different elevations (Figure 1B).

The substrate of the subalpine hills is represented by molasse-type terrigenous sequences that show a gradual filling of the Alpine foreland since the Late Oligocene (Massari et al., 1986). The substrate of the outer hills, such as the Montello Hill, consists of two conglomerate formations: (1) the Montello Conglomerate, dated as Late Miocene (Dal Piaz, 1941; Martinis, 1955), and (2) the Conegliano Unit, dated as Pliocene-Middle Pleistocene (see Avigliano et al., 2008; Caputo et al., 2010). Since previous work on the Montello karst system (Ferrarese et al., 1998) and tectonic studies (Benedetti et al., 2000; Picotti et al., 2022), it has been assumed that the Montello Hill is composed entirely of Montello conglomerate, but there is no clear evidence and the borehole stratigraphy (see Mancin et al., 2007) across the hill contradicts the current interpretation.

Therefore, new speleological investigations in the largest cave of Montello, the Castel Sotterra Cave, aim at proposing a renewed stratigraphic model in which the shallower unit is represented by the upper part of the Conegliano Unit. An attempt to determine the age of the substrate can lead to the discovery of the true nature of tectonically modulated karst processes, which represent the main driving factor in the evolution of the Montello landscape. In this work we present a speleogenetic model for conglomerate karst, integrated with a model of hydrostructural evolution in accordance with the tectono-stratigraphic setting of the Montello Hill.

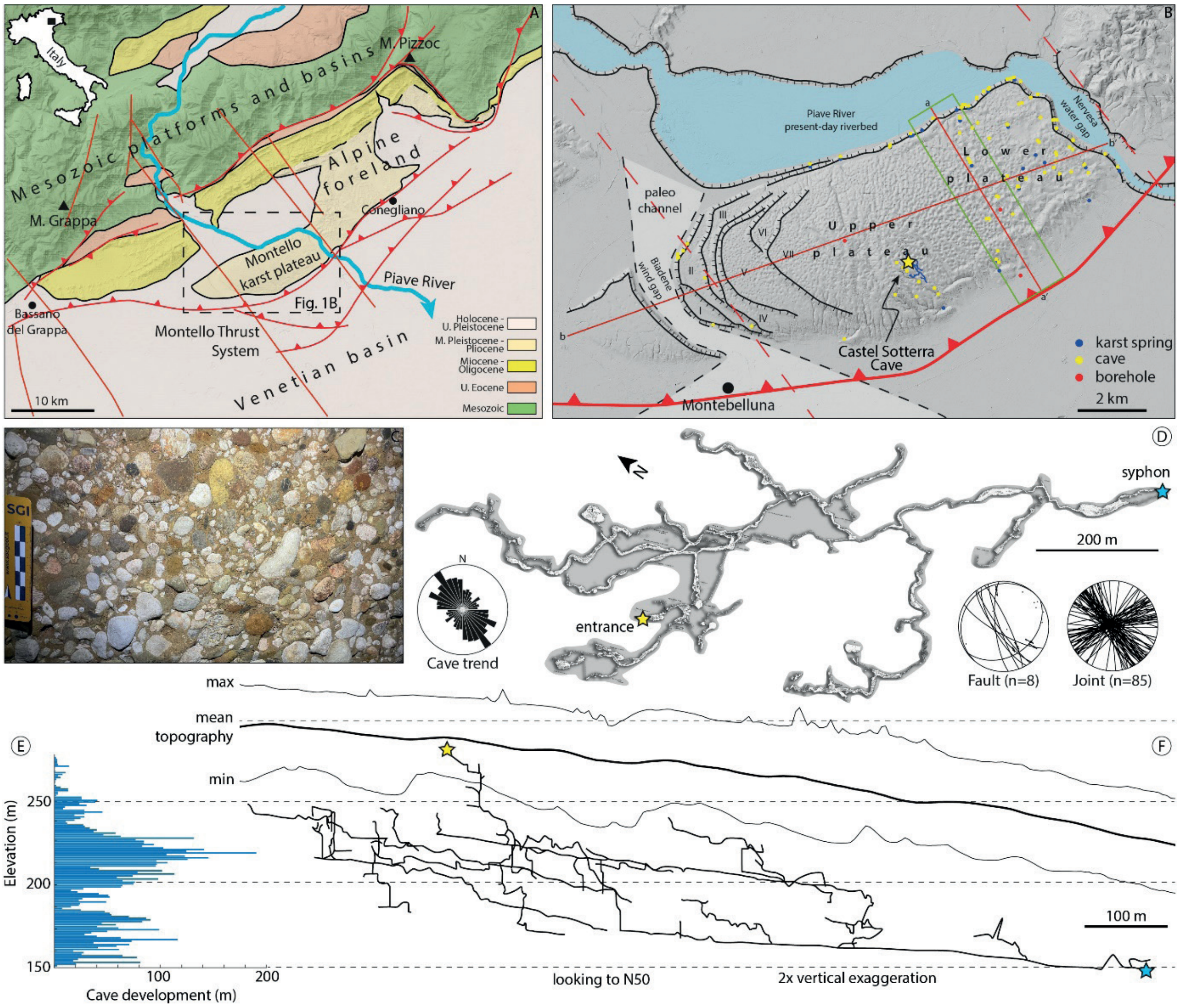

Figure 1: *(a) Simplified geological map of the southeastern Alpine foreland system showing the position of Mount Montello. (b) Main geomorphologic features of the Montello Hill, such as the location of caves and karst springs, and seven orders of fluvial terraces carved by the paleo-Piave river, a-a' and b-b' profile traces refer to Figure 3. (c) The typical conglomerate facies as seen from inside the Castel Sotterra cave. (d) Map of Castel Sotterra; directions of tectonic and morphologic structures are shown in stereonets. (e) Spatial distribution of karst channels on the vertical axis. (f) Cross section of Castel Sotterra cave, topography is represented in a range of elevations averaged over the surface area above the cave.*

2. Materials and methods

This work was done by combining traditional cave mapping and geological field surveys. The first comprehensive map of the cave was drawn in the 90's and the polygonal lines have recently been computerized on C-Survey software, allowing a three-dimensional observation of the cave in Loch software extension. In the last two years a new mapping project has been conceived to add newly explored passages and correct known errors present in the old map. The new map is the result of speleological surveys carried out with a modified Leica Disto-X laser telemeter and the Topodroid mobile application. The topographic analysis of the Montello hill is done in GIS environments with a 2m resolution LiDAR-based digital elevation model (provided by the Veneto Region online repository). Borehole stratigraphies are available on Videpi website and the ISPRA national borehole repository.

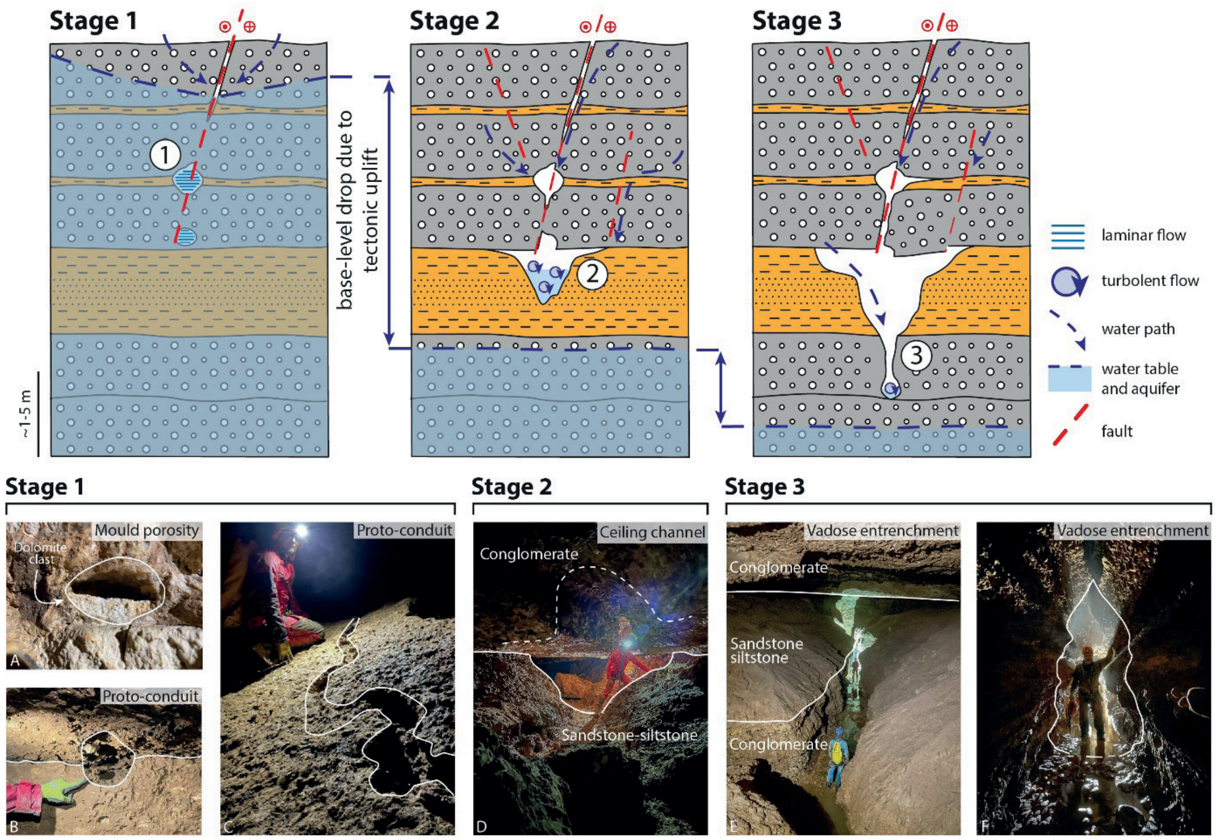

Figure 2: Model of cave evolution in the conglomerate facies of the Montello Hill. The engine of karst evolution is represented by the lowering of the basement due to tectonic uplift, and the morphologies reflect the local stratigraphy.

3. Results

The Castel Sotterra Cave extends for more than ~ 7 km below the upper plateau (Figure 1B), with the entrance at 275 m a.s.l. and the terminal syphon at the end of the active canyon 125 m lower (Figure 1D, F). The cave is mainly formed by several kilometers of vadose passages, such as meandering canyons, phreatic tubes, horizontal fissures following bedrock stratification, breakdown rooms and shafts connecting parts of vadose passages at different elevations.

Bedrock formation is characterized by the alternation of decametric to metric layers of polymictic matrix-dominated carbonatic conglomerates and centimetric to metric unconformable bodies of siltstone and sandstone. Vadose passages carved in fine-grained lenses are usually wider than deeper, because erosion spreads rapidly to the sides due to instability caused by erosion at the base of poorly consolidated silty walls. Canyons in conglomerate are generally narrow and 10 to 30 meters deep. Rooms created by ceiling collapses extend horizontally along weak discontinuities in the substrate, generally represented by centimeter-thick layers of fine-grained sediments. Bedrock stratigraphy exerts strong control over the development of cave passages. The occurrence of fine-grained lenses enhances formation of nearly-horizontal vadose canyons at several levels (Figure 1E-F). Different clusters of elevations characterized by the development of long passages occurred (Figure 1E). Since the first explorations, three main cave levels have been identified and named: (1) "*Superiori*" (upper passages), (2) "*Argilloni*" (mud passages), (3) "*Inferiori*" (lower passages). The other key factor that controls the karst development in this cave is the presence of an extensive network of fractures and faults (Figure 1D). The general azimuthal trend of the passages, striking NW-SE, is almost identical to the orientation of the fractures and strike-slip faults. In addition, conglomerate beds are often offset by vertical planes. Evidence of movement along the planes is represented by fault striae and calcite slickensides, and in rare cases by mud squeezed between blocks. Tectonic structures are also observed to control large gravitational collapses.

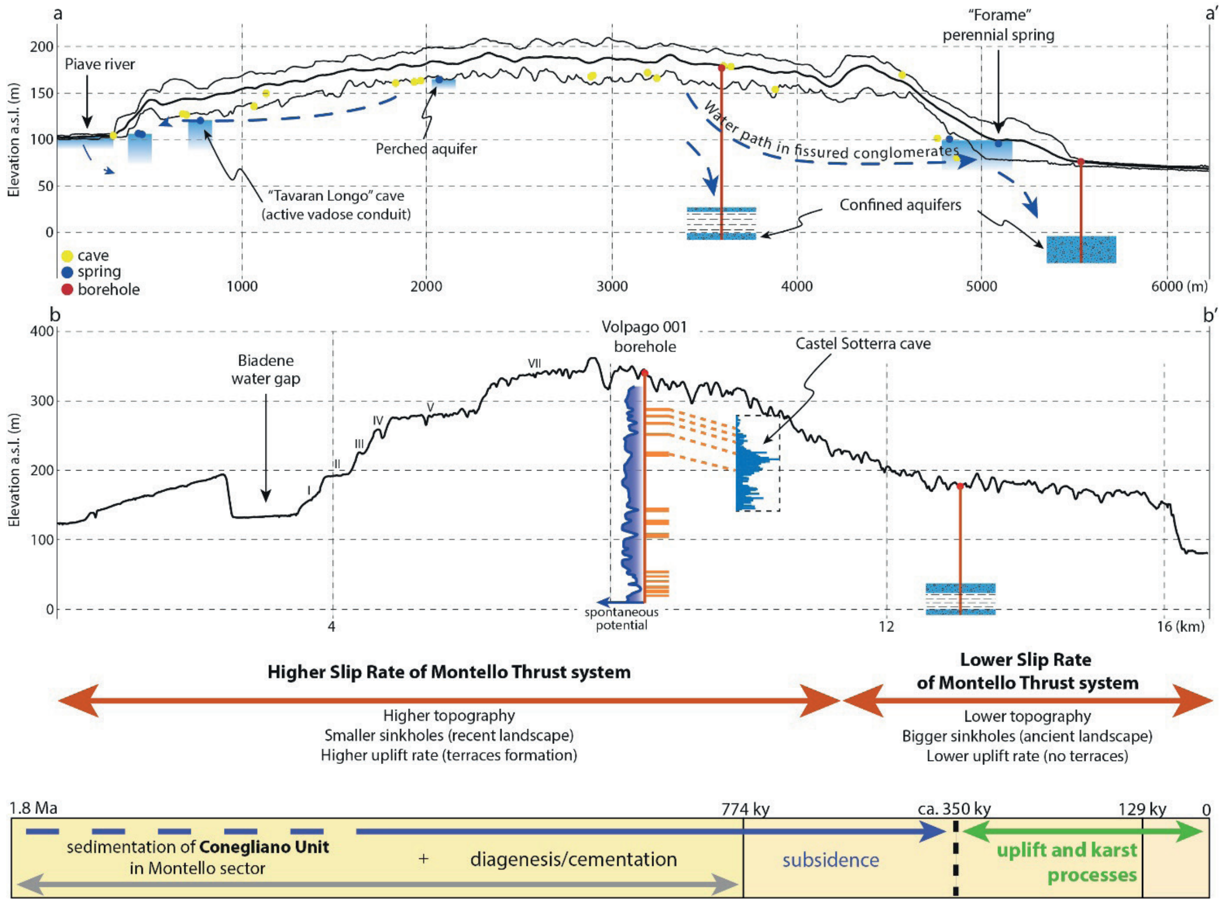

Figure 3: *a-a' swath profile across the lower Montello plateau showing the main hydrostructural features. b-b' topographic profile across the entire length of the Montello Hill, highlighting the fluvial terraces, the elevation difference between the higher and lower plateau, and the stratigraphy of the fine-grained sediment layers detected in the Volpago 001 borehole. the bottom panel shows the inferred geological evolution of the Montello hill since the Early Pleistocene.*

4. Discussion

We propose a simple speleogenetic model based on direct observations of cave morphology. The conceptual formation and evolution of cave morphologies can be resumed in a three-stage model (Figure 2). Initially, near or below the base of a conglomerate karstic aquifer, widespread dissolution promotes the development of secondary porosity in the silty carbonaceous matrix. In addition, dissolution is concentrated on limestone-dolostone pebbles (Figure 2 - Stage 1). Along inception horizons more prone to karstification and tectonic structures, fluid flow under phreatic conditions is able to form proto-pipes (Figure 2 - Stage 1), which are able to expand by exploiting muddy interlayers commonly found between massive conglomerate beds. As confirmed by fluvial terraces (Benedetti et al., 2000; Ferrarese and Sauro, 2005; Picotti et al., 2022), the entire Montello Hill structure was uplifted in the Quaternary by the Montello thrust system, leading to multiple base level drops. When phreatic conduits are formed in conglomerate beds just above arenaceous-silty beds, it can happen that the expansion of the conduits leads to the encounter of softer sediments, which in a short time form large cave passages, such as horizontally developed fissures or vadose canyons. Non-paragenetic ceiling channels formed by vertical vadose entrenchment are recurrent morphologies in Castel Sotterra (Figure 2 - Stage 2). Mechanical erosion is dominant at this stage, considering the reworking of soft arenite-siltstone beds by particles dispersed during floods. As the base level is continuously lowered, vadose entrenchment continues to the bottom of the stratigraphic sequence, cutting narrow canyons in the conglomerate beds (Figure 2 - Stage 3). Together with lithological variability in the local stratigraphy, a series of large vadose canyons and narrower fractures and tubes alternate vertically in Castel Sotterra. Even small variations in grain size lead to differential and gradual sculpturing of vertically oriented passages (Figure 2 - Stage 3, last image). In addition, gravitational collapse and fault activity are key mechanisms in speleogenesis. Huge sectors of the cave are completely filled by rockfall deposits, and conglomerate beds are often displaced along nearly vertical planes. The true extent of gravitational collapses is certainly underestimated by the low-resolution of traditional cave mapping in imaging three-dimensional spaces. Collapses and tectonic structures facilitate connections between cave levels, enhancing water circulation and dissolution. The concurrent interplay of gravitational and tectonic movement is difficult to distinguish, but fault striae coherent with the local stress field (stereonets in Figure 1D) are found along cave passages.

We believed that the tectonic uplift was not uniform, considering that it is directly related to the activity of the thrust system, as also highlighted by the uplift rates estimated for the terraces (Benedetti et al., 2000). Cave development along three main levels may reflect three phases of local water table stability due to tectonic quiescence or climatic stability of the paleo-Piave fluvial system, ultimately related to the Quaternary glacial cycle.

The present-day base level is poorly constrained by few boreholes (Figure 3, section a-a'). Borehole stratigraphy and aquifer analysis suggest that below the present fluvial plain elevation (~ 75 m on the

SW side of Montello Hill), several local aquifers are confined between low-permeability layers. Water entering Montello Hill through karst passages can follow three pathways (Figure 3) by: (1) reaching deep aquifers confined in highly porous conglomerate beds, (2) remaining near the surface and discharging at springs on the plateau, (3) feeding perennial springs typically found at the base of the Montello Hill escarpment. The stratigraphy of the Volpago 001 borehole confirms the presence of fine-grained beds along its entire length (Figure 3, section b-b'). At the present stage of geological exploration of the Montello structure, a clear correlation between fluvial terraces, fine-grained sediments and cave levels is lacking (Figure 3). Nevertheless, a stratigraphic control of erodibility on bedrock planation processes will certainly be a key point in evaluating the lithological control on landscape evolution, which could even lead to a rethinking of uplift rates. However, looking at the topography of Montello (Figure 3), the SW sector presents a higher relief with respect to the NE sector (Upper vs. Lower plateau in Figure 1B). This observation suggests a structural model where the southern part of Montello Hill is more uplifted than the northern part. Also considering the morphometry of sinkholes (Ferrarese and Sauro, 2005), a more stable and therefore older landscape is expected in the northern plateau, where larger sinkhole diameters and higher coalescence rates are found with respect to the surface at the same elevation in the southern sector.

The landscape evolution interpretation described above is consistent with the increase in modeled uplift rate towards the southern tip of the Montello Thrust (Benedetti et al., 2000) and a change in geometry just south of the Montello Hill (see Figure 1A-B). A contrasting interpretation of the tectono-stratigraphic evolution has shown that the northern plateau has been affected differently by erosion and weathering, as the Conegliano Unit unconformably overlaps the Montello Conglomerate, the latter inferred to outcrop on the upper plateau. Picotti et al. (2022) stated that the northern plateau is formed by less weathered younger conglomerate with respect to the southern plateau. However, considering the uniformity of the conglomerate sequences studied by speleological exploration and the borehole stratigraphy of Mancin et al. (2007), the entire Montello hill structure appears to be composed of the Conegliano Unit at least in the first few hundred meters of depth. The age of the substrate forming the Montello structure, inferred to be Messinian by Dal Piaz (1941) on the basis of gastropod association, must be revised in the light of more recent biostratigraphic correlations, since a single paleontological finding may not be representative of the entire conglomerate facies. These observations may lead to a renewed interest in the rate of uplift and convergence of the southeastern Alpine deformation front.

Assuming that the entire Montello Karst system developed within the Conegliano Unit sequences, whose sedimentation is constrained by the Villafranchian fauna described by Venzo (1977), correlated with the Calabrian stage (1.8-0.77 Ma), and that the onset of uplift is constrained to be ~ 350 Kyr by modeling of thrust activity (Benedetti et al., 2000), karst processes occurred in a very short time (Figure 3, bottom panel). Cave development is accelerated by (1) enhanced mechanical erosion, which is fundamental to the carving of deep vadose passages, (2) abrupt base-level drops due to thrusting, (3) conglomerate collapses, and (4) neotectonics.

5. Conclusion

The Castel Sotterra Cave is a remarkable example of rapid landscape evolution dominated by dissolution processes in a non-traditional conglomerate karst. The transition from the end of the deposition of continental Molasse-like fluvial conglomerates in the Pleistocene to uplift, karst dissolution, weathering and erosion has occurred in a very short time. The incision caused by the Piave river and the uplift caused by the active thrust system have significantly influenced the groundwater flow and the karst development. Geomorphic evolution and neotectonic processes are ongoing within the cave. Speleogenesis is initially dominated by dissolution of conglomerate matrix and carbonate pebbles, followed by mechanical erosion in hydrologically active cave passages and gravitational collapses. Deep entrenchments, structurally-controlled rock collapses and vertical movements induced by faulting are observed. The lowest level of the cave reaches a local water table, but the hydrologic connection to springs remains unresolved. Aquifer levels are documented at perennial springs, on the Montello Hill escarpment, and in boreholes. Elsewhere, rapid tectonic uplift and numerous fine-grained horizons acting as seals suggest a hydrostructural model of multiple confined and perched aquifers.

Acknowledgments

This study is part of the multidisciplinary speleological project “Progetto Castel Sotterra”, supported by the Club Alpino Italiano and the Federazione Speleologica Veneta. We would like to thank the speleologists of Gruppo Grotte Treviso, Gruppo Speleologico Padovano, Gruppo Grotte Solve, Gruppo Naturalistico Montelliano, Club Speleologico Proteo, Gruppo Speleologico San Marco, Unione Speleologica Pordenonese, for the data collected with passion in the last 60 years, without which it would have been impossible to know the hidden details of the underground world.

The digital elevation model is taken from the Veneto repository (https://idt2.regione.veneto.it/idt/downloader/download). Volpago borehole stratigraphy is from the Videpi repository (https://www.videpi.com/videpi/videpi.asp). Water borehole stratigraphy from the ISPRA repository (https://www.isprambiente.gov.it/it/banche-dati/banche-dati-folder/suolo-e-territorio/dati-geognostici-e-geofisici). The software used in this work are: C-Survey (https://csurvey.it/site), TopoDroid (https://sites.google.com/site/speleoapps/home/topodroid), QGIS Desktop 3.34.3, ArcMap 10.8.2, Adobe Illustrator 2023, MATLAB R2022b with the packages Topotoolbox (https://topotoolbox.wordpress.com) and TAK (https://github.com/amforte/Topographic-Analysis-Kit).

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