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TESI DI LAUREA IN EARTH AND CLIMATE DYNAMICS

**Structural and lithological control
on speleogenesis in the Peroloch Abyss,
Asiago, Veneto**

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Quello che i miei occhi possono aver visto, non è quello che possono vedere i vostri

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Abstract

The Peroloch Abyss is a karst cave on the Asiago Plateau. The first speleological exploration of the cave took place in the 1980s. At the time, the cave was only known to extend 200 metres underground. Recently, speleological investigations have resumed, enabling the discovery of a narrow fissure which has doubled the size of the cave and expanded its planimetric development. These new findings have raised questions regarding speleogenesis, tectonics, stratigraphy and groundwater flow through the cave system.

This thesis presents the outcomes of a brief field campaign which used CARG survey maps, GIS, 3D cave survey models and photogrammetric imaging, as well as an in-situ survey of the main structural and lithological features which control the speleogenesis of the abyss.

The investigation focused on the geomorphological study of a 5 km² area around the cave entrance, with the aim of improving our understanding of karst phenomena and the relationship between surface features such as regional and local faults and folds, and cave shafts, horizontal passages and chambers.

The results demonstrate that the development of the cave is strictly controlled by the main geological structures and stratigraphic units within a specific area in the proximity of the ramp anticline of Monte Zebio.

Riassunto

L'Abisso Peroloch è una grotta carsica situata nell'altopiano di Asiago. La sua prima esplorazione speleologica risale agli anni Ottanta; all'epoca, la grotta sembrava proseguire fino a 200 metri sotto il suolo.

Recentemente, il prosieguo dell'esplorazione dell'abisso ha permesso la scoperta e il superamento di uno stretto passaggio che ha raddoppiato il suo sviluppo verticale, espandendo maggiormente il suo andamento e la sua estensione planimetrica.

Queste nuove scoperte hanno sollevato questioni riguardo la speleogenesi, tettonica, stratigrafia e flusso idrico sotterraneo del complesso carsico.

Questa Tesi presenta i risultati di una breve campagna esplorativa avvenuta mediante l'impiego di mappe di indagine CARG, GIS, analisi di modelli 3D e fotogrammetria di complessi carsici come allo stesso tempo di un rilievo in situ dei principali attributi strutturali e litologici che controllano la speleogenesi dell'abisso.

L'analisi svolta si è focalizzata sullo studio geomorfologico di un'area di 5 km² attorno all'entrata del Peroloch, con l'obiettivo di rendere più chiara e intelligibile la comprensione dei fenomeni carsici e la relazione tra caratteristiche superficiali come faglie e pieghe regionali e locali, e morfologie ipogee quali pozzi, meandri, camere e saloni.

I risultati dimostrano che lo sviluppo della grotta è strettamente controllato dalle principali strutture geologiche e unità stratigrafiche entro una specifica area in prossimità della rampa anticlinale del Monte Zebio.

1. Introduction

1.1 Caves as geomorphological and tectonic proxy

Karst landscapes account for nearly 20% of Earth's ice-free land surface (Palmer, 2007). Their scientific importance derives not only from the geomorphological information they preserve, but also from the access they provide to cave systems, which constitute valuable archives of geological, hydrological and environmental processes. Subsurface cave networks can also provide important evidence for reconstructing stratigraphic relationships and tectonic structures that are difficult to recognise from surface observations alone.

Karstification processes cannot be fully understood from surface data alone. Despite advances in geophysical and remote-sensing techniques, no technology currently provides a comprehensive means of detecting cavities and water-table-controlled conduits without direct speleological exploration. Surface rock exposures and geological maps are often insufficient because outcrops may be discontinuous and difficult to correlate over large areas. Moreover, the geological structure observed and mapped at a particular stratigraphic or lithological contact is not necessarily representative of the structural conditions occurring elsewhere, either above or below that level. Cave systems therefore provide a unique opportunity to investigate the three-dimensional organisation of geological structures and their role in groundwater flow and speleogenesis.

(Palmer, 2007) also emphasised the fundamental role of fractures—including faults and joints—and bedding-plane partings in controlling the development of karst conduit networks. These discontinuities commonly represent the initial pathways along which groundwater circulates and chemical dissolution begins. Thus, joints and bedding-plane partings can play an equivalent and complementary role in the earliest stages of cave development, depending on their orientation, continuity, hydraulic connectivity and relationship with the regional geological structure.

This concept is supported by several recent studies of cave systems and karst processes, including investigations in the Venetian Prealps and the Trento Plateau, as well as in other tectonically active carbonate settings.

The study of **Spluga della Preta** (Sauro et al., 2011) demonstrated how the stratigraphic organisation of this deep cave system reflects the importance of the regional tectonic framework in controlling erosional and speleogenetic processes. Cave development was also influenced by the lithological, compositional and geomechanical characteristics of the intersected rock formations, as well as by the palaeogeographic evolution of the area. The

cave therefore provides an example of how the present-day morphology of a karst system results from the interaction between stratigraphy, structural discontinuities and the long-term evolution of the surrounding landscape.

A similar relationship between tectonic structure and cave development was documented in the **Tatra Mountains** (University of Silesia & Szczygiel, 2015). Investigations of the pathways of a multilevel cave system within an uplifting fold-and-thrust belt in Poland showed that, although gravity-driven deformation and regional stress fields contributed to the opening of the initial fissures, chemical dissolution was the primary process responsible for subsequent enlargement of the cave passages. Vadose canyons and palaeophreatic conduits developed preferentially along steeply dipping bedding planes and tectonic discontinuities, demonstrating the importance of pre-existing structural anisotropies in guiding groundwater flow and speleogenesis.

In the **Piani Eterni** karst system of the Venetian Prealps, (Sauro, 2011) described the development of caves within Mesozoic limestones and other calcareous formations in relation to different types of inception surfaces. Inception surfaces are geological discontinuities or horizons that are particularly susceptible to the initiation of karstification and can subsequently guide the development of cave passages. Three main types can be distinguished:

- **Stratigraphic Inception horizons**, defined as zones that are particularly prone to karstification because of physical, lithological or chemical deviations from the surrounding carbonate facies (Lowe, 1992). Such horizons may differ from the host rock in terms of mineralogy, permeability, porosity or mechanical properties, favouring the concentration of groundwater flow and the initiation of dissolution.
- **Tectonic inception horizons** in which cave development occurs along bedding planes that have been modified or opened by tectonic deformation (Sauro et al., 2013). These include bedding-plane fractures and discontinuities produced by flexural slip, which can transform originally stratigraphic surfaces into preferential pathways for groundwater circulation and subsequent cave development.
- **Tectonic discontinuities**, such as faults, fractures and associated zones of enhanced void space. These structures can concentrate groundwater flow and therefore act as preferential pathways for speleogenesis. Where fractures remain poorly filled or free of mineral

precipitation, their increased hydraulic conductivity may facilitate the progressive enlargement of the initial voids (Faulkner, 2006; Filipponi, 2009).

These examples illustrate that cave networks cannot be interpreted solely as the products of dissolution acting on homogeneous carbonate rocks. Rather, speleogenesis is strongly conditioned by the pre-existing structural and stratigraphic architecture of the host rock. Joints, faults, bedding planes and lithological contrasts determine the initial distribution of groundwater flow, while subsequent dissolution progressively modifies these pathways and may amplify their original structural controls. Cave systems therefore provide a three-dimensional record of the interaction between lithology, stratigraphy, tectonics, hydrology and landscape evolution that is often inaccessible from surface observations alone.

1.2 Research objectives: the Peroloch Abyss

The **Peroloch (Fig. 1)**, a Cimbrian term meaning "Bear's Den", is a karst sinkhole located at an elevation of 1518 m a.s.l. on the eastern slope of Mount Zebio, in the municipality of Asiago (Vicenza, northern Italy).

During the 1980s, the *Gruppo Grotte Sette Comuni* carried out the first topographic survey of the cave. Exploration was initially halted at a depth of approximately -50 m by a landslide that blocked the passage. The obstruction was subsequently removed in the 1990s by the *Gruppo Speleologi Malo* (GSM), which continued the exploration and extended the known planimetric development of the cave. Exploration eventually reached an apparent terminal point at -212 m, known as the *Vecchio Fondo* ("Old Bottom").



Figure 1: Peroloch entrance seen from above

The cave was considered closed to further exploration in 2000, and investigations were subsequently abandoned. Nearly two decades later, in June 2020, a group of young speleologists detected a weak but persistent airflow in a passage located above the apparent

terminal point. This observation led to the reopening of the cave and to the discovery of a previously unexplored continuation.

Beyond the constricted passage, the cave system was found to continue through a network of shafts, leading to new meanders and chambers. During the following two years of exploration, the known depth of the abyss was progressively increased to -392 m. At the current deepest point, the cave bifurcates into two meandering passages, both associated with persistent air circulation. These features indicate that the system may continue beyond the currently explored extent and provide a clear target for future exploration.

The primary aim of this study is to investigate the geological and geomorphological controls on the development of the Peroloch karst system, with particular emphasis on the processes responsible for the morphology and evolution of the abyss. The study also provides a framework for assessing the potential for further exploration of the cave.

Previous explorations lacked a comprehensive geomorphological interpretation. Several aspects of the cave system therefore remained poorly constrained, particularly the relationship between its morphology and the surrounding geological structure and the mechanisms governing groundwater circulation.

The results presented here aim to improve the understanding of both the local and regional controls on cave development and to place the Peroloch system within the broader speleogenetic framework of the caves of the Asiago Plateau. Particular attention is given to the relationship between cave morphology, stratigraphy and tectonic structures, and to the extent to which local geological conditions reflect the larger-scale structural setting of the plateau and the nearby Zebio Anticline.

The longitudinal and cross-sectional geometry of the Peroloch system provides an important reference framework for interpreting both the cave and the surrounding surface morphology. The cave survey was therefore integrated with investigations of the adjacent surface area to assess how the local geological setting influenced the development and morphology of the abyss.

A particular objective was to correlate the stratigraphic and tectonic structures observed within the cave with those recognised at the surface and at the regional scale. This approach was used to investigate the relationship between cave development and the structural architecture of the area, including the influence of the nearby Zebio Anticline.

Field investigations were supported by **single-rope techniques (SRT)**, which allowed systematic access to the vertical sectors of the abyss. The integration of speleological

surveying and GIS provided a broader framework for analysing the three-dimensional relationships between the cave system, geological structures and surface morphology.

Post-acquisition analysis included the interpolation of cave-survey and the construction of three-dimensional models of the cave system. Structural-orientation data were analysed using rose diagrams to identify the correlation between tectonic features and cave passage orientations. These datasets, combined with geomorphological observations and rock sample analyses, were used to evaluate competing interpretations of the origin and evolution of the abyss.

Overall, the integrated approach adopted in this study provides a basis for interpreting the Peroloch not simply as an isolated cave system, but as a component of the broader karst and structural evolution of the Asiago Plateau.

2. Geographical and Geological setting

2.1 Asiago Plateau and its macro-regional relevance

The Asiago Plateau is the largest mountain plateau in Italy and one of the most extensive upland areas in the European Alps. Located in the Vicentine Prealps at an average elevation of approximately 1000 m a.s.l., it covers an area of more than 466 km². The plateau is characterised by a combination of extensive forested areas, open highland surfaces, karst depressions and deeply incised valleys, and represents one of the most important karst areas of the southern Alps. The geological evolution of the plateau is closely related to the development of the Trento Platform (or Adige Platform), a shallow-water carbonate domain that formed along the southern margin of the Alpine Tethys. During the Jurassic and Early Cretaceous, the area was characterised by predominantly shallow-marine carbonate environments in a tropical to subtropical palaeogeographic setting. These environments supported highly diverse carbonate-producing ecosystems, and the resulting successions contain abundant fossils and bioclasts, including foraminifera, bivalves, gastropods, algae and other carbonate-producing organisms. The subsequent convergence between the European and Adriatic–African plates and the development of the Alpine orogenic belt progressively deformed and uplifted the former carbonate platform. Within this regional palaeogeographic framework, the Asiago Plateau occupied a position towards the southeastern sector of the Trento Platform. Variations in depositional environments through the Jurassic and Early Cretaceous produced significant lateral and vertical changes in lithology, facies and rock properties. These variations, together with the structural

discontinuities generated during the Alpine deformation, exerted a strong influence on the subsequent development of karst systems.

Karstification is particularly well developed across the plateau. More than 2500 karst sinkholes have been mapped, together with an extensive network of caves and underground drainage systems. Among the best-known examples is the Oliero cave system, which represents an important resurgence system draining a substantial portion of the groundwater infiltrating through the karstified carbonate rocks of the plateau.

For descriptive purposes, the most significant cave systems can broadly be grouped into two sectors. The northern sector is characterised by a more rugged morphology, extensive rocky surfaces and higher elevations. This area hosts some of the deepest cave systems of the plateau, including Abisso di Malga Fossetta (7,210 m of surveyed passage and 1,011 m depth), Abisso del Corno (3,313 m and 863 m depth), Blade Runner (around 1900m of cave development and 760 m depth), and Però prometteva bene (approximately 2200m and 870 m of depth).

In contrast, the central and southern sectors are generally characterised by more subdued relief, broad karst depressions, rolling hills and locally flattened upland surfaces. Nevertheless, these areas also contain several important deep cave systems, including Giacominerloch (3,568 m of development and 508 m depth) and Obelix (4,396 m and 800 m depth), in addition to the Peroloch Abyss.

The distribution and morphology of these cave systems provide an important framework for understanding the relationship between karst development and the geological and geomorphological evolution of the Asiago Plateau. The occurrence of deep caves in different sectors of the plateau suggests that speleogenesis is controlled by the interaction of several factors, including lithological and stratigraphic architecture, structural discontinuities, topographic gradients and the evolution of the regional drainage network. Within this framework, the Peroloch Abyss (Fig. 2) represents a



Figure 2: Caver descending through the cave entrance

particularly valuable case study because its morphology, depth and structural setting provide an opportunity to investigate the controls exerted by the local geology within the broader tectonic and geomorphological framework of the plateau.

2.2 Mount Zebio: geological settings

Mount Zebio (1,717 m a.s.l.) is located in the eastern-central part of the Asiago Plateau.

The study area is bounded to the north by Mount Colombara and Mount Zingarella, to the west by the Galmarana Valley, and to the south by the town of Asiago (Fig. 3). To the east, the study area borders the municipality of Gallio and extends towards the Melette region, from which it is separated by Mount Ongara and the Nos Valley.

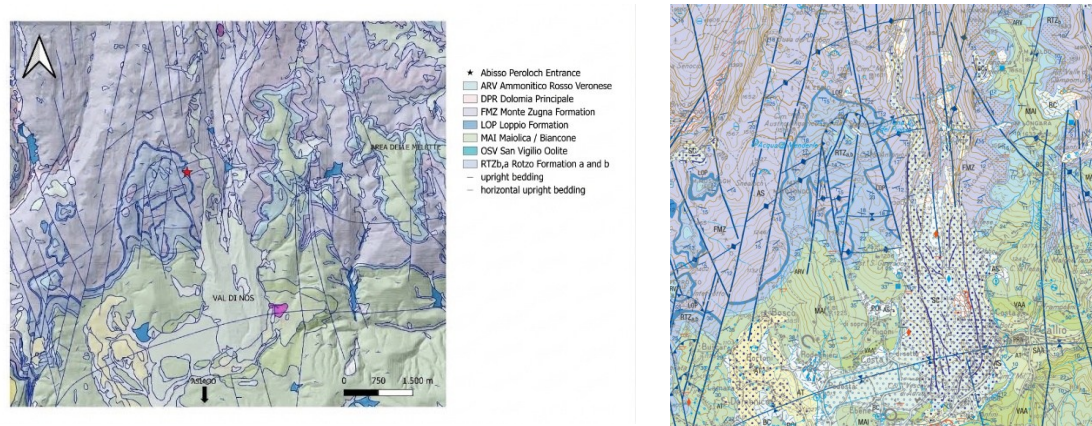


Figure 3: Geological detail of the Mount Zebio area. Geological map adapted from the CARG Project, 'Foglio 082 Asiago'.

The latter preserves an important record of Quaternary landscape evolution. Its Quaternary deposits include glacial and moraine sediments associated with the Last Glacial Maximum (LGM), as well as younger colluvial deposits accumulated during the Late Glacial and Holocene (Figures 4 and 5). These deposits provide evidence of the progressive transition from glacial to post-glacial environmental conditions and contribute to the reconstruction of the recent geomorphological evolution of the area.

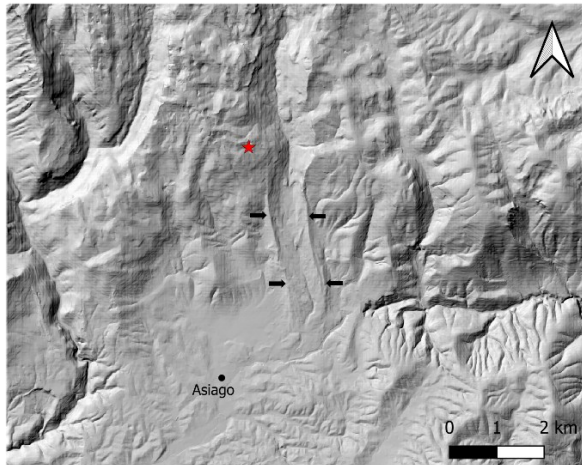


Figure 4: detail of Nos Valley from Digital Terrain Model, black arrows points morenic and quaternary deposits, red star represents Peroloch's entrance

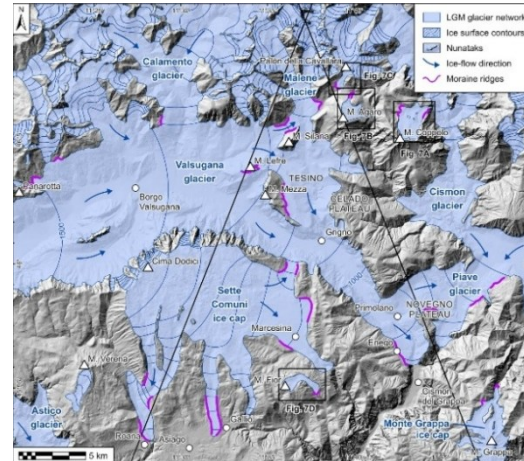


Figure 5: Topographic configuration of Asiago plateau during the Last Glacial Maximum. Lowermost glacial tongue corresponds topographically to Nos Valley contoured by morein ridges in purple colour

The study area represents a local expression of the broader Alpine compressional regime responsible for the structural evolution and uplift of the Asiago Plateau. The area is underlain mainly by Jurassic and Cretaceous marine carbonate rocks deposited within the shallow-marine Trento Platform.

A major structural feature of the area is the ramp anticline extending from Mount Zebio towards the Gallio–Melette sector, which forms part of the regional fold-and-thrust architecture of the Asiago Plateau. The Peroloch Abyss opens to the north of this major tectonic structure. Mesozoic normal faults and associated fractures were subsequently reactivated or overprinted during Alpine compression. Regional deformation produced folding, thrusting and strike-slip faulting, together with extensive secondary fracture networks. Bending and deformation of the carbonate succession also generated semi-vertical joints and fissures, locally showing preferential N–S apertures and E–W orientations. These structures are particularly relevant to karst development because they can provide preferential pathways for groundwater circulation and cave initiation.

The lithological succession around Mount Zebio shows a broad spatial differentiation. The northern and western sectors are dominated by the Monte Zugna and Rotzo formations, with more limited exposures of the Rosso Ammonitico Veronese and Loppio Oolite formations. The southern and eastern sectors are mainly characterised by the Maiolica Formation and, locally, by Quaternary deposits including glacial and ablation tills. The interaction between this lithological variability and the structural framework provides the geological context for the development of the Peroloch Abyss.

2.3 Lithostratigraphic sequence of the study site

The lithological succession exposed in the study area comprises three carbonate units belonging to the Calcarei Grigi Group: the Monte Zugna Formation (FMZ), Loppio Oolite

(LOP) and Rotzo Formation (RTZ) (Geyer et al., 1993). These formations record predominantly shallow-marine carbonate sedimentation during the Early Jurassic.

Rotzo Formation (RTZ) – Late Sinemurian to Late Pliensbachian

The Rotzo Formation represents the uppermost unit of the succession exposed in the study area and can be subdivided into two main lithofacies, RTZa and RTZb. RTZa consists of calcareous-marly deposits characterised by thinly bedded calcilutites, marls and dark-grey marly limestones, with abundant bivalves and plant-derived debris. Its thickness ranges from 0 to approximately 35 m.

RTZb consists mainly of oolitic-bioclastic calcarenites and thick-bedded to massive lithitic limestones, reaching a maximum thickness of approximately 175 m. The upward transition from the marly-calcareous deposits of RTZa to the more carbonate-rich and bioclastic facies of RTZb records a progressive shallowing of the depositional environment.

Loppio Oolite (LOP) – Sinemurian

The Loppio Oolite underlies the Rotzo Formation and consists predominantly of oolitic limestones occurring in thick beds and banks. Ooids commonly display poorly differentiated cortical envelopes, while cross-lamination is locally preserved. The formation reaches a maximum thickness of approximately 30 m and has a discontinuous distribution, particularly along the northeastern margin of the Asiago Plateau.

Monte Zugna Formation (FMZ) – Hettangian to partly Sinemurian

The Monte Zugna Formation constitutes the lowermost unit of the Calcarei Grigi Group exposed in the study area. It comprises predominantly marly calcilutites, grey pseudonodular limestones, stromatolitic limestones and bioclastic calcarenites. *Gervillia buchi* is relatively abundant, particularly in the upper part of the formation.

The predominantly micritic succession consists of hazel-grey to whitish limestone beds organised into metre-scale shallowing-upward cycles. Ooids and molluscan fragments become progressively more abundant towards the tops of individual cycles, which are locally characterised by thin greenish clayey to clayey-dolomitic horizons. These horizons may represent palaeoexposure surfaces or periods of reduced carbonate production and are potentially relevant to the development of stratigraphically controlled discontinuities.

Underlying the Calcarei Grigi Group is the *Dolomia Principale (DPR)*, of Late Carnian–Rhaetian age. It consists predominantly of light-grey, well-stratified dolostones with an average thickness of approximately 500–600 m. The succession is characterised by repeated cycles of bioturbated subtidal deposits alternating with intertidal to supratidal layers containing stromatolitic laminites. The lower part of the formation locally contains breccias occurring in metre-thick beds, together with discontinuous conglomeratic lenses. The

Dolomia Principale therefore represents the deeper stratigraphic substrate beneath the carbonate succession hosting the Peroloch karst system.

2.4 Tectonic features in the surroundings of Peroloch Abyss

The Asiago Plateau reflects the regional structural framework produced by Alpine Orogenesis and subsequent post-compressional deformation. The main tectonic features include the Spitz–Campolongo Anticline, Monte Zebio Anticline and Melette Anticline, together with the regional Schio–Bassano knee fold and the Gallio Syncline, whose axis extends across much of the plateau, passing through the municipalities of Rotzo, Roana, Asiago, Gallio and Foza.

The regional fault network includes normal and transverse faults, with two main preferential orientations around N350° and N020°, respectively. These structures accommodated deformation during the Alpine tectonic evolution and locally exerted a strong control on the geometry of the carbonate succession and associated fracture networks.

Within this regional framework, Mount Zebio is structurally associated with a secondary thrust zone, whose approximately rounded fold axis occurs at an elevation of around 1600 m a.s.l. Two nearly parallel strike-slip faults, oriented approximately N345°, occur in the vicinity of the massif. The easternmost fault passes within approximately 200 m of the Peroloch entrance, making it a potentially important structural control on the local fracture network and cave development.

Two secondary folds occur close to the Peroloch Abyss. North of the cave, a synclinal axis follows the flank of Mount Zebio and the adjacent valley, whereas to the south a secondary anticline intersects the cave system approximately after the first third of its development. The spatial relationship between these structures and the cave passages provides an important framework for assessing the structural controls on speleogenesis.

The surface morphology of the area is characterised by karren fields, colluvial deposits and exposed bedrock. Bedding generally ranges from horizontal to sub-horizontal, locally reaching dips of approximately 35°, with an average inclination of about 15° towards the NNW.

3. Methodologies

3.1 Field survey

The research methodology comprises two main components: in situ field investigations and cave surveying, followed by post-fieldwork data organisation, topographic analysis and structural–geomorphological interpretation.

Field investigations were conducted during three short campaigns covering the approximately 5 km² study area, together with five cave-exploration trips carried out from May 2026 onwards. Progressive exploration over a four-month period documented the

development of the cave at depths of approximately -50 , -150 and -240 m, reaching a final depth of about -260 m by the end of August.

Existing geological data from the CARG project, collected during the 2000–2003 geological survey by G. Barbieri and P. Grandesso (ISPRA - Servizio Geologico d'Italia, 2007), were integrated with new structural measurements collected throughout the study area. Strike and dip were measured at numerous locations using a geological compass and a digital clinometer application, providing a more detailed spatial coverage of the orientation of bedding and structural discontinuities.

Cave exploration provided an opportunity to combine geomorphological observations, structural measurements and rock sampling. Bedding and fault orientations were measured at selected sites within the cave, while geomorphological features and secondary mineral deposits were documented along the main passages. Single-rope techniques (SRT) enabled access to vertical shafts, meanders and traverses and supported the progressive exploration and survey of the abyss.

The resulting field and survey datasets were subsequently integrated within a GIS environment and used for structural analysis, including the evaluation of fracture and bedding orientations, as well as for the three-dimensional interpretation of the cave morphology and its relationship with the surrounding geological framework.

3.2 Post campaign and topographic survey data analysis

Topographic survey data were analysed using GIS and cave-survey software, including QGIS and CompassCave, to integrate cave-survey data with geomorphological layers and develop a spatial and three-dimensional representation of the cave system.

Historical survey data collected since 1995 using measuring tapes and electronic distance meters were digitised and processed using professional computer-aided design (CAD) software. For each survey shot, the available measurements of horizontal distance (α), zenith angle (β) and azimuth (γ) were converted into digital coordinates to reconstruct the three-dimensional geometry of the cave (Fig. 6).

Figure 6: Peroloch survey lines showing superimposed passages

ferential orientations and frequency of bedding planes, joints, and faults.

Laboratory analyses were carried out to characterise the chemical composition and mineralogy of representative rock samples collected from different parts of Peroloch Abyss, providing additional information on the lithology encountered along the cave profile.

Four samples were analysed by X-ray fluorescence (XRF) and X-ray diffraction (XRD). The samples were ground to a homogeneous grain size of approximately 500 μm prior to analysis. Their location within the cave are shown in Figure 7.

The four samples were collected at key points along the abyss. Sample PLA was collected from a ledge at the bottom of the first shaft, at approximately -18 m , where the lithology was unclear. Sample PLB was collected from a lithology apparently belonging to the Monte Zugna Formation. Sample PLC, collected at approximately -180 m , showed a similar lithology but was characterised by a distinctive boxwork-

like pattern. Sample PLD was collected at approximately -190 m and consisted of a greenish, muddy-looking material occurring locally as thin layers.

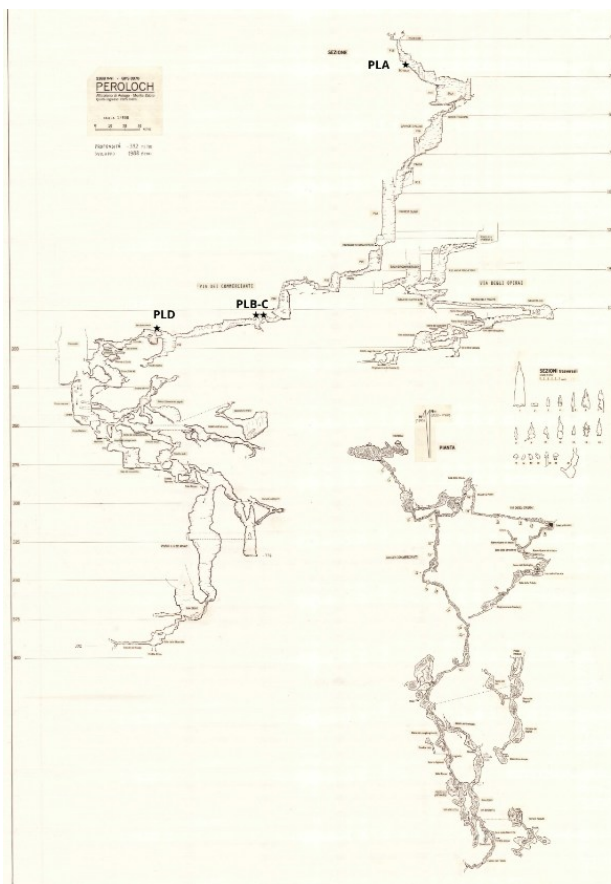


Figure 7: Vertical profile of the abyss, showing sampling sites marked by black star symbols.

XRF analyses were performed using a PANalytical Zetium wavelength-dispersive spectrometer. Loss on ignition (LOI) was determined by heating the samples in a muffle furnace at $860\text{ }^{\circ}\text{C}$ for 20 min followed by $980\text{ }^{\circ}\text{C}$ for 2 h. Fused beads were then prepared using lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) flux at a 1:10 sample-to-flux ratio in a Claisse Eagon 2 fluxer at approximately $1150\text{ }^{\circ}\text{C}$.

The BB-Co analytical protocol was adopted for XRF measurements. This configuration, combining broad-band excitation with a cobalt target/filter, is optimised for the geochemical characterisation of carbonate-rich samples. It reduces spectral background and matrix-related interferences associated with the high Ca content of carbonate rocks, thereby improving the detection and quantification of trace elements.

Major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K and P) were determined as oxides and reported as percentages, whereas trace elements (Sc, V, Cr, Ni, Cu, Zn, Rb and Sr) were reported in ppm. The analytical time was approximately 1.5 h per sample.

Calibration was performed using natural geological reference standards (Govindaraju, 1994). Instrumental precision, evaluated through replicate measurements, was better than 0.6% relative for major elements and 3% relative for trace elements.

For XRD analysis, powdered samples were prepared using the back-loading technique to minimise errors associated with preferential orientation. Mineral phases and their relative abundances were determined using both the Reference Intensity Ratio (RIR) method and Rietveld refinement.

The agreement between RIR-based and Rietveld-derived phase abundances was used as an internal consistency check of the quantitative XRD results. Comparison between the XRD-derived mineralogical assemblages and the XRF-derived bulk chemical compositions provided an additional independent assessment of their consistency.

As shown in Fig. 14 (paragraph 4.2), the analyses produced well-defined diffraction patterns and LOI values, allowing the mineralogical and chemical composition of each sample to be characterised in detail.

4. Results

4.1 Geomorphological aspects of Peroloch Abyss

Field surveys and cave observations allowed for the characterization of the main geomorphological features of the abyss. As shown in Fig. (8), the entrance opens within a sinkhole developed in Calcarei Grigi beds dipping at 25°–35°.

Flexural slip and a normal fault control the uppermost section of the cave system; the development of the Main Chamber and Grande Diaclasi along tectonic discontinuities is associated with block-breakdown deposits and fault displacement (Fig. 9).



Figure 8: Dipping limestone strata exposed near Peroloch entrance



Figure 9: Main Chamber view of Normal fault and dipping beds. Floor composed of block-breakdown and younger deposits. (southward view)

Pozzo Forrest Gump (-100 m) marks the boundary between the vertical and sub-horizontal sections; here, limestone sidewalls partly dolomitized and friable along with boxworks and clay-rich interlayers control the pathway of the meanders down to Pozzo Medusa. Beyond a depth of 200 m, the cave conduits resume a vertical development, with a distinct flexural slip occurring at the top of Pozzo Medusa. As shown in Figure 10, this trend in cave development is further supported by three-dimensional models generated from survey line data using the CompassCave software suite (Viewer32 and CaveXO).

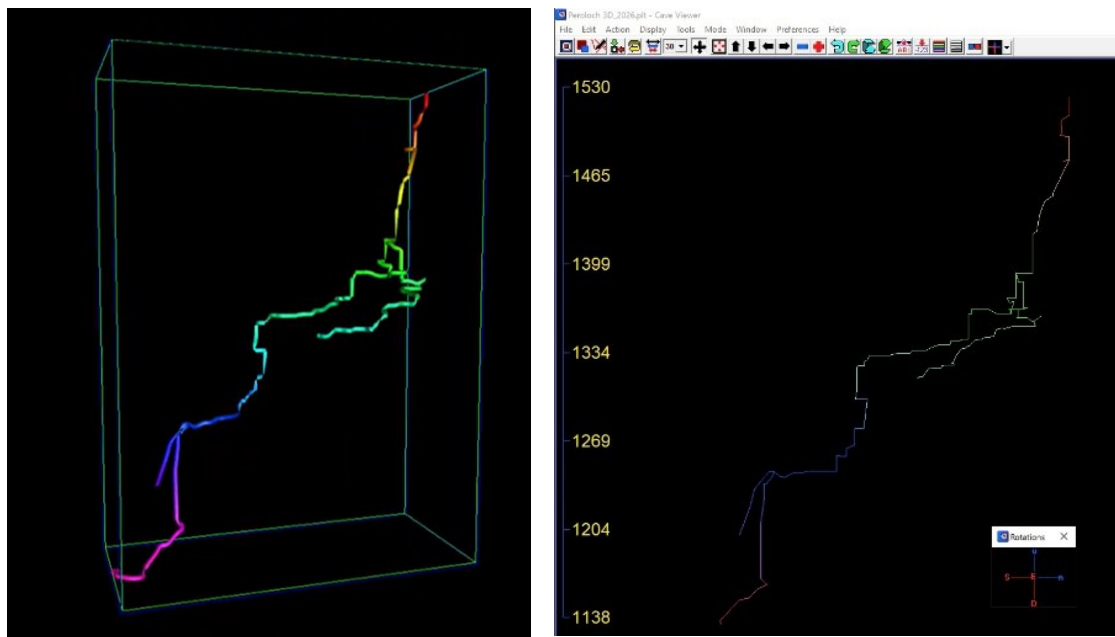


Figure 10: Left: Elevation profile rendered in Cave Viewer software, right: 3D model perspective of the Peroloch cave system.

4.2 Lithological variability

The results of the rock sample analyses (Fig. 11), combined with the structural observations, provide further evidence for the lithological variability of the Peroloch Abyss and support the initial interpretation of its lithological distribution.

PLA. XRD and XRF analyses indicate a mineralogical composition dominated by calcite (99% CaCO_3), with minor silica (1.45% SiO_2) and MgO (1.08%), and a Sr concentration of 263 ppm. This mineralogical and geochemical signature is consistent with an almost pure micritic limestone, potentially corresponding to the Loppio Oolite Formation or to the uppermost part of the Monte Zugna Formation. The $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratio is relatively high (0.91, compared with approximately 0.4 for schist), which may indicate the presence of secondary Fe-bearing oxides or hydroxides.

PLB. The sample contains approximately 76% calcite and 23% dolomite, together with 3.07% SiO_2 and 7.51% MgO . The low Sr concentration (29 ppm) is notable compared with typical values reported for marine limestones (approximately 100–400 ppm). This strong Sr depletion is consistent

%Ox	PLA	PLB	PLC	PLD
SiO_2	1,45	3,07	2,81	19,75
TiO_2	0,04	0,08	0,07	0,76
Al_2O_3	0,65	1,30	1,20	9,77
Fe_2O_3	0,59	0,79	0,69	2,93
MnO	0,01	0,03	0,02	0,02
MgO	1,08	7,51	6,01	2,86
CaO	96,03	86,83	88,85	61,29
Na_2O	0,04	0,03	0,02	0,11
K_2O	0,01	0,13	0,08	2,35
P_2O_5	0,02	0,16	0,17	0,04
Tot	99,92	99,93	99,92	99,88
L.O.I.	43,43	43,71	43,30	35,36

ppm	PLA	PLB	PLC	PLD
S	289,00	280,00	212,00	54,00
Sc	169,00	154,00	159,00	112,00
V	11,00	23,00	19,00	94,00
Cr	22,00	20,00	21,00	66,00
Ni	8,00	7,00	10,00	52,00
Cu	33,00	33,00	40,00	45,00
Zn	35,00	156,00	34,00	99,00
Rb	4,00	11,00	10,00	91,00
Sr	263,00	29,00	25,00	53,00

Figure 11: X-ray fluorescence (XRF) data for the samples analyzed

with fluid-mediated recrystallisation and partial dolomitisation, during which Sr may be expelled from the carbonate crystal lattice. Importantly, the low Sr content is not restricted to the dolomitised fraction but characterises the bulk rock, suggesting that fluid circulation affected and re-equilibrated the carbonate mass more extensively than indicated by the proportion of dolomite alone. The sample is therefore interpreted as a partially dolomitised Monte Zugna Formation limestone rather than as dolomite. Its depth is also consistent with the elevation of outcropping rocks in the Nos Valley, where the CARG project ‘Asiago

Foglio 082' identified late-stage dolomitised or recrystallised facies (ISPRA - Servizio Geologico d'Italia, 2007).

PLC. Similar to PLB, PLC is dominated by CaCO_3 (85%), with 2.81% SiO_2 , 6.01% MgO and only 25 ppm Sr. The strong Sr depletion, together with the XRD and XRF results, supports the interpretation of a Monte Zugna Formation limestone affected by dolomitisation and fluid circulation.

The boxwork-like structures observed in this sample (Fig. 12) provide an additional indication of fluid migration and associated diagenetic alteration.

The sample also shows poorer surface refinement than PLB. This may be related to the coarse crystallinity of the carbonate material: the presence of large calcite crystals or blades produces poorer grain statistics during surface analysis. This observation is consistent with the coarse crystalline texture expected for the calcite blades forming the boxwork structures.



Figure 12: Calcitic boxwork structure within Monte Zugna Formation strata (Sample C).

PLD. The sample (Fig. 13) contains approximately 72% CaCO_3 , 19.75% SiO_2 and 2.86% MgO , with 53 ppm Sr. XRD analysis also identified approximately 20% illite, confirming the presence of clay minerals. The relatively high silica content and the mineralogical composition are consistent with the thin greenish interlayers locally observed within the Monte Zugna Formation.

The green colour of these clay-rich layers may be associated with Fe-bearing clay minerals such as chamosite, reflecting reducing conditions during mineral formation or alteration. The absence of detectable kaolinite may indicate

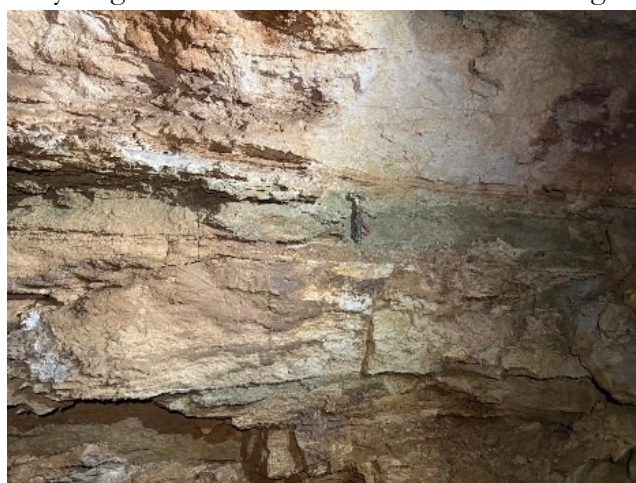


Figure 13: Green clay-rich interlayers of Monte Zugna Formation (Sample D).

either that the original marine signature has been largely overprinted or that subsequent burial-related illitisation removed or transformed primary clay minerals. These results are therefore consistent with a marine carbonate succession subsequently affected by diagenetic and burial processes.

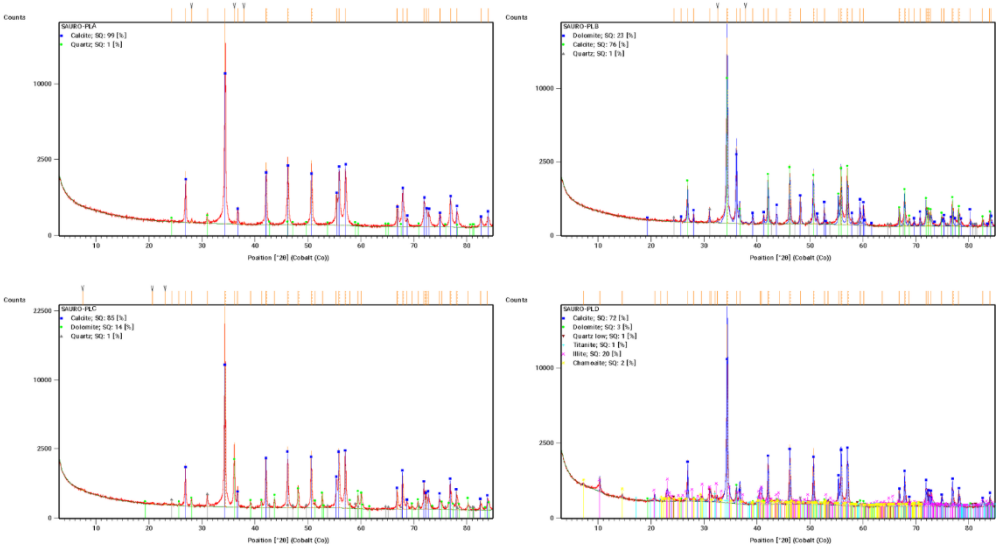


Figure 14: Representative XRD diffractograms of the analyzed rock samples (PLA–PLD from top right to bottom left).

4.3 Structural controls in the genesis of the abyss

As shown in Fig. 15, the histograms illustrate the horizontal development of the abyss as a function of depth. The distribution shows three distinct peaks corresponding to intervals of partially dolomitised limestone and clay-rich interlayers, which are characterised by lower permeability and reduced susceptibility to dissolution compared with the surrounding limestone.

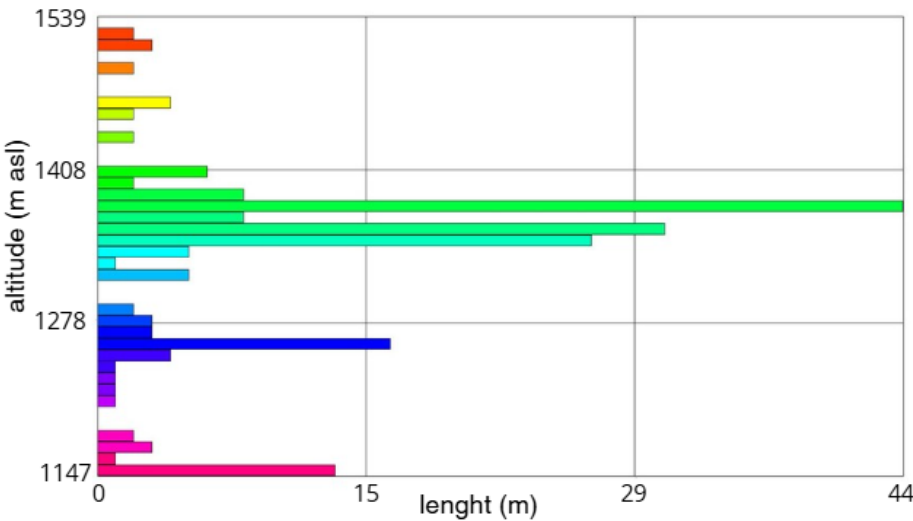


Figure 15: horizontal extent of Peroloch cave system relative to depth

This stratigraphic control suggests that the development of Peroloch Abyss is strongly influenced by variations in lithology, particularly by differences in carbonate solubility and permeability. Less permeable and less soluble layers may locally limit downward water infiltration and favour lateral development along more permeable or structurally favourable horizons.

At an elevation of approximately 1368 m a.s.l. (−150 m), the cave maintains its predominantly horizontal trend down to approximately 1338 m a.s.l. (−180 m). A further sub-horizontal level occurs at approximately 1250 m a.s.l., while another horizontal development appears close to the present cave terminus at approximately −392 m. Overall, Peroloch shows a recurrent pattern of sub-horizontal development following major vertical shafts.

A prominent example begins at the bottom of the Pozzo Forrest Gump (Fig. 16), continues towards the former terminal section and develops again beyond the Pozzo Medusa.

At the current terminus, the passage at the bottom of the Pozzo De Marzi appears to mark the beginning of a further sub-horizontal continuation.

Rose diagrams were used to compare the orientations of cave survey lines with the measured orientations of faults and bedding planes. The main regional faults and thrust axes identified from the CARG geological mapping were also plotted to assess the relationship between cave development and the regional structural framework.

The lower part of Fig. 17 shows the relationship between cave development and bedding dip. The distribution indicates that cave passages preferentially develop where bedding planes intersect major faults and conjugate fracture systems, highlighting the combined control exerted by lithological anisotropy and structural discontinuities.



Figure 16: Bottom-up view of Pozzo Forrest Gump

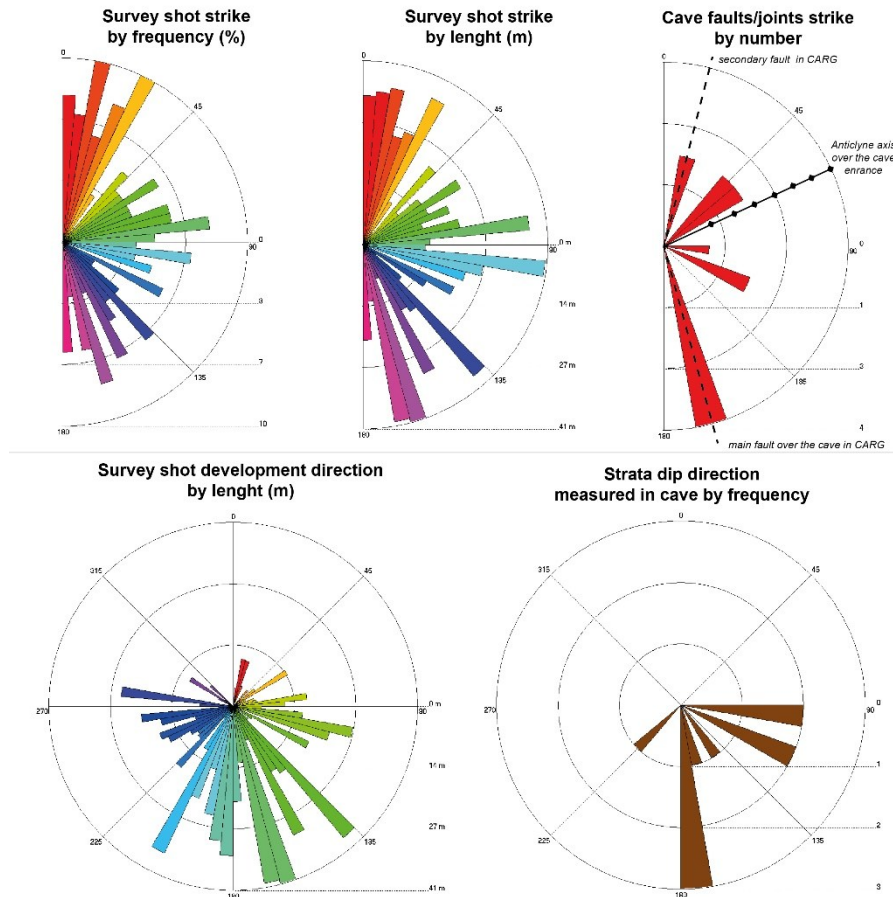


Figure 17: Structural and cave survey orientation data. Top: survey shot strikes and fault/joint orientations. Bottom: survey shot development direction (frequency and length)

As shown in the figure, the first two polar area charts show the frequency and cumulative length of survey-shot orientations, respectively. In terms of passage length, the main direction of cave development is towards the SSE. The right-hand chart shows the measured fault strikes within the cave in red, while the dashed black lines represent the orientations of tectonic structures mapped in the CARG geological survey.

The lower part of the chart presents 360° rose diagrams comparing the orientation of cave survey shots with the dip direction of bedding planes measured in the cave, shown in brown. Although most passages are structurally controlled by faults, their predominant southward trend appears to reflect the southward dip of the strata. The cave therefore preferentially develops along the intersection between fault zones and south-dipping bedding planes. An exception is represented by the flexures in the E–SE sector, between N90° and N120°, which locally exert an additional control on passage orientation. Speleogenesis in this setting can be interpreted in terms of tectonic inception and inception horizons, with evidence that both mechanisms operated concurrently. Tectonic inception occurs where faults with localised displacement or enhanced aperture—particularly in

flexural zones—provide preferential pathways for groundwater circulation and subsequent dissolution. Inception horizons, in contrast, develop along lithological or structural interfaces that favour preferential water flow and dissolution.

The upper part of the cave, down to approximately 125 m below the entrance, including the Pozzo Forrest Gump shaft (P33), appears to be primarily controlled by the interaction between the main fault and a flexural zone. As shown in the Main Chamber (Fig. 18), an abrupt change in bedding dip produces a pronounced flexure.



Figure 18: Left: Flexural slip of strata observed from above the landslide. Right: Bottom-up perspective of the main chamber.

Here, the mechanical contrast between competent limestone beds limits plastic deformation and favours bed-parallel slip and fracturing, creating pathways for groundwater circulation and subsequent dissolution.

A clear example of this structural relationship is visible at the bottom of the Grande Diaclasi shaft, at approximately -75 m (Fig. 19).

A sub-vertical normal fault produces a marked displacement of the strata, connecting the nearly horizontal beds on the left with the SSE-dipping flexural zone. Below the Pozzo Forrest Gump, cave development is also strongly influenced by inception horizons, more

specifically lithological inception horizons Type 1 as defined by (Filipponi, 2009). Clay-rich interlayers and locally dolomitised horizons within the

Monte Zugna Formation display contrasting permeability and dissolution susceptibility. These lithological variations influence groundwater circulation and appear to guide the development of sub-horizontal passages, as illustrated by the depth-distribution histograms in Fig. 15.

Overall, the passage network does not simply follow the bedding dip. Rather, its geometry results from the interaction between fault zones, bedding planes and lithological contrasts (Fig.

20). The combined influence of these structural and lithological controls explains the alternation between vertically oriented shafts and sub-horizontal passages that characterises the Peroloch cave system.



Figure 19: Grande Diaclasi, quasi-horizontal layers (left) and SSE-dipping flexural zone are displaced by a normal fault (right)

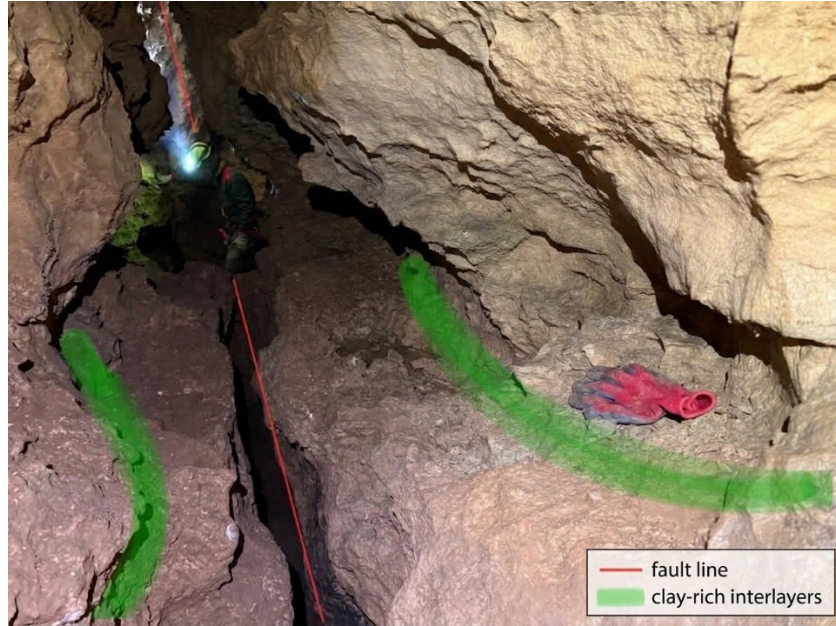


Figure 20: muddy interlayers interaction with fault zone (PLB, -180m)

5. Discussion and conclusions

5.1 Genetic controls on the cave development

It should first be noted that the present investigation covered approximately 260 m of the total 392 m depth of Peroloch Abyss, corresponding to less than 70% of the currently known development. Moreover, the longitudinal profile and plan view had not been updated for approximately three years. The interpretation presented here should therefore be regarded as a preliminary reconstruction, to be refined as exploration and surveying progress. The inferred geological profile shown in Figure 21 highlights the close relationship between lithological and structural controls on the development of Peroloch Abyss.

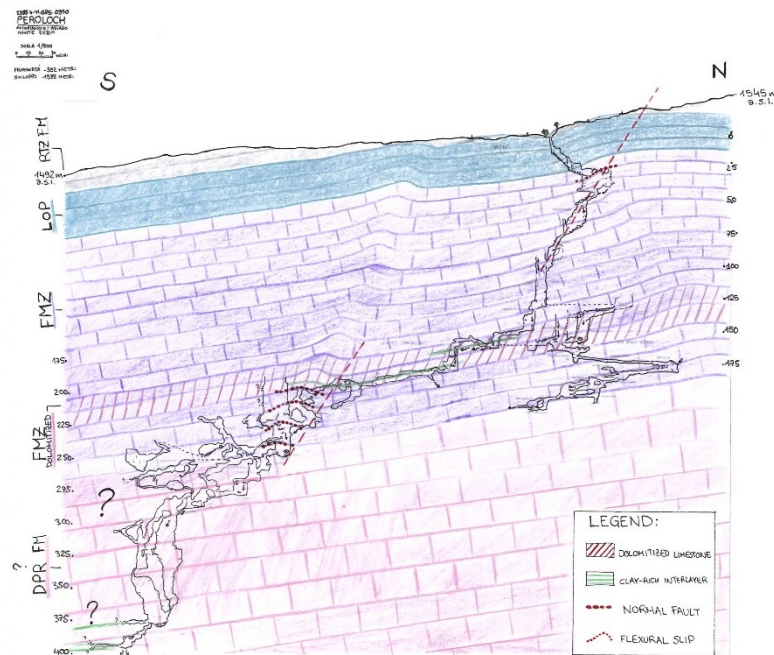


Figure 21: Geological cross-section of the Peroloch Abyss. Question marks denote uncertain interpretations and deductions



Figure 22: Another view of the main chamber from a wider perspective.

The results presented above indicate that cave morphology is controlled by the combined effects of bedding orientation, faulting, flexural deformation (Fig.22) and lithological contrasts.

The most labyrinthine sections, particularly between approximately -175 and -300 m, may reflect local variations in the susceptibility of the host rock to dissolution and in the permeability of the stratigraphic succession. Where groundwater encounters clay-rich interlayers and partially dolomitised limestone, downward percolation may be locally inhibited. This could favour lateral flow and the development of sub-horizontal and locally labyrinthine, locally phreatic, passages above or along less permeable horizons. In this sense, the observed geometry may reflect the development of perched or semi-perched groundwater pathways rather than a simple vertical progression towards the regional water table.

On the basis of the available evidence, the following evolutionary scenario can be proposed for the development of the Peroloch karst system:

- Mesozoic carbonate-platform development. Carbonate sediments accumulated in shallow-marine environments on the Trento Platform during the Mesozoic.
- Synsedimentary tectonic deformation. Jurassic rifting generated normal faults and associated fracture systems that subsequently became important structural discontinuities within the carbonate succession.

- Alpine deformation and uplift. Alpine convergence produced folding, thrusting and strike-slip deformation, reactivating or overprinting pre-existing structures and generating additional fracture networks.
- Development of preferential groundwater pathways. The fractured carbonate succession provided pathways for meteoric water infiltration. More competent and fractured units, including the Maiolica Formation where exposed in the regional succession, may have facilitated relatively efficient vertical water circulation. However, the actual hydraulic behaviour of these units requires further investigation.
- Structural focusing of groundwater. In the deeper carbonate succession, groundwater circulation was locally concentrated along pre-existing Jurassic faults and conjugate fractures, subsequently modified by Alpine shear and thrust structures. These discontinuities provided preferential pathways for dissolution and may have contributed to the development of the main shafts.
- Development of inception horizons (Fig. 23). Where downward flow encountered less permeable clay-rich interlayers or partially dolomitised limestone, infiltration was locally impeded. Groundwater was consequently redirected along stratigraphic interfaces, promoting lateral passage development. At structural discontinuities, particularly faults and flexural zones, flow could again be focused downwards, producing the alternation between sub-horizontal passages and vertical shafts observed in Peroloch.

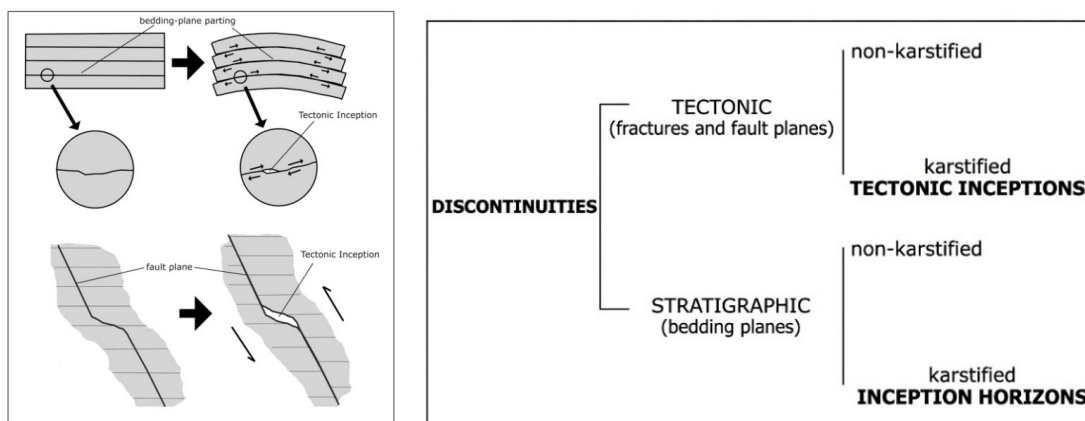


Figure 23: Left: Schematic diagram showing the formation of a tectonic inception along a curved fault plane (bottom) and a Type 3 inception horizon associated with flexural slip. Right: Chart representing different types of geological discontinuities. (Piani Eterni, Sauro, 2011)

The subsequent evolution of the cave was likely influenced by Quaternary glacial and periglacial processes. During the Last Glacial Maximum, the Asiago Plateau was covered by the Sette Comuni ice cap, while a major glacial tongue occupied the Nos Valley. Glacial

deposits and landforms preserved in the surrounding area document this phase of landscape evolution (Figs. 4 and 5). Although the direct influence of glaciation on the development of the deeper parts of Peroloch cannot currently be demonstrated, deglaciation and the associated increase in meltwater infiltration may have substantially modified the hydrological regime of the karst system.

An additional clue to the evolution of the upper part of the cave is provided by a breccia-like deposit observed on a ledge near the bottom of the entrance shaft, immediately before the descent towards the initial chamber (Fig. 24). The deposit contains fragments of rock apparently derived from stratigraphically higher levels, enclosed within a calcite-rich matrix.



Figure 24: Breccia-like deposits with clear evidence of heterogeneous lithology

The occurrence of these fragments, which were also encountered at greater depths, may indicate gravitational or collapse-related reworking during the early development of the cavity. Alternatively, some material may have been introduced by glacial or periglacial

processes and subsequently incorporated into the cave deposit. The presence of lithologies potentially corresponding to Maiolica, Rosso Ammonitico Veronese or Scaglia Rossa within this deposit would require confirmation through petrographic and mineralogical analyses.

If confirmed, their occurrence could indicate either mechanical transport from higher stratigraphic levels during cave development or the incorporation of reworked surficial or glacial material. Subsequent calcite precipitation may have cemented the deposit, producing the observed breccia-like texture.

This interpretation may also provide a possible explanation for the anomalously high $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ ratio measured in sample PLA, collected only a few decimeters from the breccia-like material. The ratio of 0.91 may indicate a contribution from Fe-rich phases not associated with the primary carbonate matrix, potentially including iron oxides or hydroxides such as hematite, goethite or related phases. However, the available XRF data alone does not allow the specific mineral phase or its origin to be established. The Fe enrichment could therefore reflect either secondary weathering processes affecting the cave wall or the incorporation of oxidised material derived from reworked sediments or lithologies exposed at higher stratigraphic levels.

Glacial and post-glacial conditions may also have enhanced karstification. Increased infiltration associated with snow and ice melt could have supplied large volumes of cold water to the karst system, potentially accelerating carbonate dissolution. Such processes have been described in the context of glacial and periglacial karstification and may have contributed to the post-glacial modification of the Peroloch system (Ford & Williams, 2007; Palmer, 2007; Williams, 1983). Nevertheless, the relative contribution of glacial meltwater to the present morphology remains difficult to quantify.

The most recent phase of cave evolution is represented by gravitational breakdown and collapse, together with secondary mineral precipitation. Speleothem growth, moonmilk (Fig. 25) formation and the development of clay-rich secondary deposits, including vermiculite, indicate prolonged interaction between the cave atmosphere, groundwater and host rock. Recent studies of carbonate moonmilk have also demonstrated the potential role of microbial communities in its formation and preservation (Ghezzi et al., 2024). These processes represent the latest stage of an evolution in which the present morphology of Peroloch results from the superposition of lithological, structural, hydrological, glacial and secondary mineralisation processes.



Figure 25: Moonmilk formation on the walls of Sala Bianca (left) and bottom of Pozzo Medusa (right)

5.2 Scientific perspectives and future research

Scientific research on Peroloch Abyss is still at an early stage, and several aspects of its hydrology and speleogenesis remain poorly constrained. Further exploration and targeted investigations could substantially improve the understanding of the cave system.

Even during dry periods, a persistent stream from Pozzo Forrest Gump provides water, but no perennial underground stream or clear connection with local water tables has been identified. Constraining groundwater pathways and identifying possible hydrological connections could be achieved by conducting dye-tracing experiments from sinkholes or other recharge points at higher elevations.

The existing three-dimensional model could be improved through additional measurements and high-resolution LiDAR scanning, providing a more accurate representation of passage morphology and its relationship with geological structures. Continued exploration towards the current terminus is particularly important for identifying new passages and testing the proposed speleogenetic model. The suspected Dolomia Principale sample collected in the last cave exploration should also be analysed to clarify whether lithological changes

contribute to the marked variation in passage morphology and width below Pozzo 112 De Marzi.

Further structural and lithological investigations could improve the understanding of how faulting, fracturing, bedding and lithological contrasts interact to control passage development. This knowledge may also help identify unexplored conduits and guide future exploration.

Overall, Peroloch represents an important natural laboratory for investigating the interaction between geological structure, lithological variability and groundwater circulation in the development of deep Alpine karst systems.

6 Acknowledgments

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I wish to extend my heartfelt thanks to Nicola Bellinaso for photographically documenting every cave exploration throughout the campaign, as well as for his forthcoming photographic project that will give voice to this abyss and its peculiar characteristics.

Finally, I would like to thank my family and friends who supported me throughout this journey, and in particular the professors who conveyed their passion and deep interest in their subjects.

Declaration of Generative AI and AI-assisted Technologies:

During the preparation of this thesis, Generative AI tools (e.g., Gemini, ChatGPT) were used for early-stage literature searching and outline structuring, as well as for language editing and proofreading to improve text clarity. All literature sources were manually verified against original scientific publications, and the author reviewed, edited, and approved all linguistic suggestions, retaining full responsibility for the content, scientific accuracy, and integrity of this work.

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