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3D digital analysis for geo-structural monitoring and virtual documentation of the saint Michael cave in Minervino Murge, Bari (Italy)

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A B S T R A C T

The presence of caves and, in general, of subterranean landforms produced by karst processes is among the most typical geological features of the territory of Apulia, southern Italy. Several examples can be counted throughout the region, especially in the Murge area. The need to perform geo-structural analysis aimed at evaluating the stability conditions is especially significant for those caves open to the public. In the Murge area, the cave of Saint Michael at Minervino Murge is among the most famous. Beside the religious and historical interests, the whole cave needed a detailed analysis of the rock mass stability, both for protection of its architectural and archaeological values, and for safeguard of the visitors. At these aims, we performed various digital surveys by means of laser scanners and drones equipped with high-resolution cameras, in order to understand the geological setting of the entire cave and to identify unstable blocks.

1. Introduction

Caves, and in general the underground environment, belong to the natural heritage as they possess geological and morphological characteristics that are an integral part of our landscapes. At the same time, as sites frequented in the past by human beings, they are also sites of high historical, cultural and archaeological significance. Caves have great potential for scientific studies and can also be used as outdoor disciplinary environments, enhancing the understanding and awareness of both students and general public. The underground environments are fundamental, among other things, for understanding surface processes, local hydrogeology, and the cave evolution over time, even with reference to modifications induced by anthropogenic actions or by climate changes; moreover, many caves, including that object of the present study, should be preserved for their beauty and as sites of religious and social importance. Studying the geology, the geo-mechanical features and, in general, the rock mass conditions are therefore crucial to properly evaluate the possible dangers in these delicate environments.

In order to solve the problems related to traditional, expensive and logistically difficult, geo-mechanical analyses, in the last two decades the implementation of new computational methods, such as close- and long-range remote sensing techniques, has become essential to quantitatively describe the structural setting of rock masses, as well as for the acquisition of high-resolution three-dimensional models (Abellan et al., 2014; Barnobi et al., 2009; Jaboyedoff et al., 2012; Oppikofer et al., 2009; Tomás et al., 2020; Viero et al., 2010). Outcomes from the surveys can be used for diagnostic purposes, to highlight conservation and management problems for restoration, and also for dissemination and advertising purposes, or could be integrated into educational programs, as well as represent a documentation of the state of preservation of the monumental or natural asset at the time of the acquisition. In recent years, as regards geo-structural analysis, many researches have focused mostly on the implementation of new algorithms and methods taking into account the needs related to geology and, in general, the recognition of geometric shapes starting from 3D data (Abellan et al., 2016; Loiotine et al., 2021a, 2021b; Pagano et al., 2020; Riquelme et al., 2014, 2017). At this goal, new techniques have been developed to standardize the processes of recognition, evaluation and, finally, extraction of primitive geometries, such as planes and volumetric shapes representing rock blocks bounded by discontinuities (Hammah and Curran, 1998; Jaboyedoff et al., 2007; Li et al., 2019; Lombardi et al., 2011; Roncella and Forlani, 2005; Schnabel et al., 2007; Tran et al., 2015; Xia et al., 2020). These detailed analyses are very important in cave environments, where the study of the geometrical relations among

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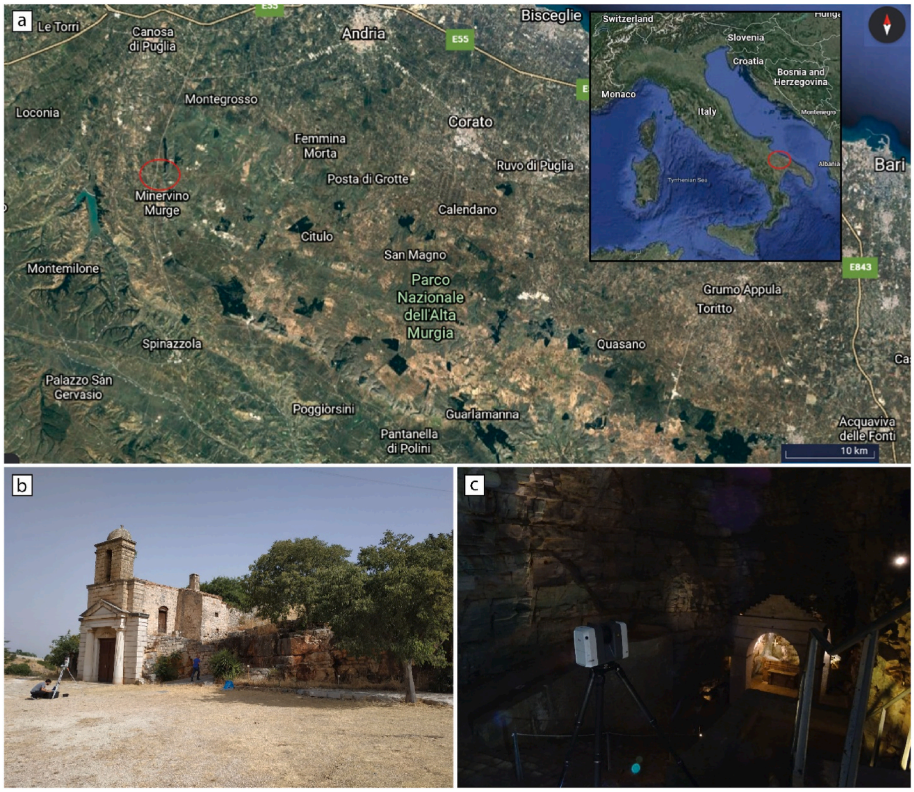

Fig. 1. (a) Geographical location of the cave. (b–c) Photos of, respectively, the monumental entrance of the cave, and of its interior.

joints, faults and fractures represent a necessary step for the protection and the management of the underground assets.

The study cave is located at the toe of the north-western margin of the Murge area of Apulia (Fig. 1).

2. Research aim

In this work we propose a geo-structural analysis, starting from the recognition of the major sets of discontinuities in the rock mass, performed in the Saint Michael cave at Minervino Murge by using the virtual 3D point cloud of a cave, acquired by means of laser- and photo-scanning. The analysis, then, takes benefit of techniques relying on the use of customized algorithms and graphical representations typically utilized for geo-structural investigations. In the present case study, our aim is to emphasize the importance of such an approach in relation to the protection and the management of such peculiar environments. These outcomes provide valuable information for the detection of possible dangers, but can also be used to conduct further analyses on instability of individual blocks and to predict their possible kinematics. Furthermore, this paper aims to highlight the importance of having high-resolution 3D data of monumental and natural assets of historical and geological relevance, in an era when these products can provide several advantages for the proper exploitation of the cultural heritage.

3. Historical notes

The complex figure of the archangel Michael and his mythical attributes are deeply rooted in the collective memory of European people, so much as to generate a strong typification of the places of worship dedicated to him, and of the traditions and legends connected to the saint as well. The places of worship, in addition to being connected to the pilgrimage network, have the peculiarity of being often nestled in the nature, to underline the need to meet the archangel in places that are difficult to access, anthropogenically uncontaminated, or that simply lead their way underground. Furthermore, the connections of the michaelic places of worship, especially in Apulia, with the periods and places of transhumance inevitably lead to rural contexts that strengthen the bond with an archaic religious spirituality linked to nature (Bronzini et al., 1985; Paone, 2007; Renna, 2007a). The environment where the sanctuary of St. Michael in Minervino Murge is located responds exactly to these conditions.

The frequentation of the place seems to go very far back in time. Recent researches carried out on the material found in the cavity, revealed an archaic frequentation of the underground environment, until not long ago considered not earlier than the 10th century AD (D'Aloja, 1977). In the deepest sector of the cave, abundant presence of fragmentary ceramic material was documented. Along the rock walls fragments of turned ceramic were found, ascribable to very small clay vessels, some of which have layers of glossy black paint that would probably date back to the 4th - 2nd century BC; furthermore, the presence of small quantities of unadorned pottery remains could lead the dating of the first attendance even back to the late Bronze Age, i.e. around the second or first millennium BC (Lorusso and Larocca, 2002). As reported by De Palma (2006), a writing dated December 1, 1923, written by the archdeacon-parish priest Ignazio Bevilacqua, mentions a legend of the foundation of the sanctuary, which, in pagan times was meant to be sacred to the goddess Minerva, who also gave the name to the town of Minervino Murge. According to this report, existence of the sanctuary is therefore strictly connected to the progressive anthropization of the territory.

The legend of its foundation at Minervino shows some analogies with the narration of the origins of the more famous.

Monte Sant'Angelo sanctuary in Gargano, a UNESCO World Heritage Site since 2011. This sanctuary was built on a cave where, according to the legend, the Arcangel Michael appeared many times, but always seem on the occasion of strong earthquakes; as proof of this, the sanctuary is located along a segment of the well-known Mattinata fault, and inside it, the “Footprins Altar” show important tectonic structures, which due to their shape are interpreted and venerated as the footprints that the Archangel Michael imposed to defeat the devil who produced tremors and strong roars; namely, earthquakes (Piccardi, 2005).

Although there is no mention of a revelation of the archangel, nor of one of his appearances, the michaelic sanctuary of Minervino would have risen at the time of the evangelization of the local population, where a pagan place of worship was already present. The new dedication had, therefore, de-consecrated the previous sacred space, but at the same time inserted a Christian cult reserved for the archangel. According to several other testimonies (Berend, 2007; Cathasaigh, 1982; Nolan and Nolan, 1989), the grafting of a Christian cult on localities and previous pagan sanctuaries is quite widespread around Europe, including southern Italy (Gandolfo, 1989). This happened in fact at the cave of Monte Sant'Angelo, the Gargano sanctuary, where around the 5th century AD the local Bishop of Larino is witnessed to linger on the dedication of the cave to the archangel due to the pre-existence of the cult of Mithras (Carletti and Otranto, 1980), or at *San Michele alle Grottelle* (Padula), where the cult of Attis pre-existed (Carletti and Otranto, 1994), and in other cases of transformation of the cult of the Italic Hercules or of divinities such as Calcante or Podalirio (Bouet et al., 2007).

Other testimonies, such as Carbone (1836), mention different dynamics linked to the rediscovery of the cave in more recent times, in quite casual ways. In fact, the author quotes a story dating back to the late middle age, referring to the fall of a farm animal into a "narrow ditch", while it was grazing on the hill just above the cave. The farmer, forced to go down into the cavity to retrieve the animal, would have come across, among other things, a soft stone statue that was believed to represent St. Michael the Archangel, but which would later be more rightly attributed by archaeologists to the goddess Minerva. According to this testimony, therefore, the cave was abandoned and its attendance interrupted for a long time before it was rediscovered and dedicated to the saint.

Of a similar opinion is the more recent Renna (2007b), who, as already mentioned, in his investigation focuses on the cults present in Minervino Murge, and connected to transhumance. Some useful information for the history of the sacred cave of Minervino can be deduced from the author's analysis. A crucial fact is related to chronology, since there is news of the naming of the cave to the archangel Michael only in the late 17th century. The source certifying its dedication is the "*Perizia Tango*", a document drawn up in 1667 for the sale of the feud of Minervino. A second information concerns the cave morphology, which made it a sanctuary in the image and likeness of the Gargano cavern. A whole series of natural features make the Minervino cave an imitation of the Gargano model, which, as mentioned above, represents the meeting of the saint's culture with the rural one, in which the caves were considered spiritual and/or cultural sites, especially where, as often occurs in the karst environment of Apulia, there was the presence of springs (Parise and Sammarco, 2015)). As Renna states, the michaelic cult was imported from the east, and settled in Gargano during the 5th century, then spread all around Italy and beyond, by exporting from Apulia, at the beginning of the 7th century, the features of the rocky sanctuary and the therapeutic properties of its waters. It is of common opinion (D'Angela, 1998; Sensi, 2001) that the peculiar typology for the several michaelic sanctuaries was adopted where the morphology of the territory allowed to imitate the Gargano cavern, or where there was presence of springs, or of waters dripping from the rock walls in karst caves, as documented in many other caves in Apulia (Parise and Liso, 2023).

The cave of St. Michael, together with the churches of *Madonna della Croce* and the *Incoronata* (*olim* St. Marc), and the sanctuary of *Madonna del Sabato*, represents a mesh of the fabric of extra-urban settlements that gave shape to the apparatus prepared by the local church for religious services intended mainly for shepherds, along one of the most important areas of transhumance north of Bari.

Other news about the religious history of the town comes from De Palma (2008): according to his sources, Minervino was not recognized as a *civitas* before the 11th century, and there was no established diocese; thus, a real consecration of a sanctuary dedicated to an important saint before that time is unlikely. Nevertheless, it is not to be completely excluded, as for example D'Aloja (1977) first pointed out, that thanks to the spread of the michaelic cult since the 5th century, during the following centuries and, especially during the 10th and 11th (time of establishment of the diocese at Minervino), the sanctuary was already known and dedicated to the saint, and constituted a point of passage in the medieval Apulia, a region known at the time for an intense pilgrimage of devotees. The pilgrims would have then continued their journey towards the Holy Land, following the old paths of Via Appia, Via Traiana and their branches, along which many other sanctuaries, monasteries, churches, chapels, oratories, hospices and hospitals for pilgrims were scattered (Fonseca, 1980; Dell'Aquila and Messina, 1998; Bianchi, 2010). Traces of these important roads and trails are still partially visible and, in some cases, practicable today.

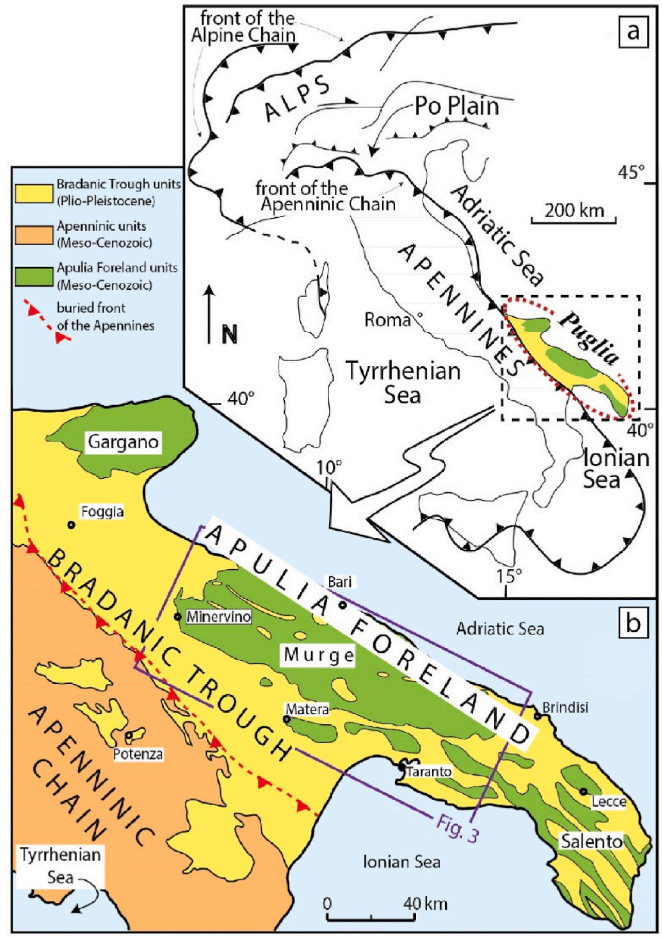

Fig. 2. (a) Simplified structural scheme of Italy (modified after Doglioni, 1994). Apulia represents both the foreland and the foredeep of the Apenninic chain in southern Italy. (b) Schematic geological map of southern Italy showing the three orogenic domains (modified after Sabato et al., 2019): chain (Apenninic Chain), foredeep (Bradanic Trough), foreland (Apulia Foreland).

4. Geological setting

The study cave is located at the toe of the north-western margin of the Murge that, together with Gargano and Salento, corresponds to one of the uplifted regional structural highs belonging to the Apulia Foreland, i.e. to the southern Apennines foreland (D'Argenio et al., 1973; Ricchetti et al., 1988) (Fig. 2). In this setting, the Murge area corresponds to an articulated NW-SE elongated karst region mainly made up

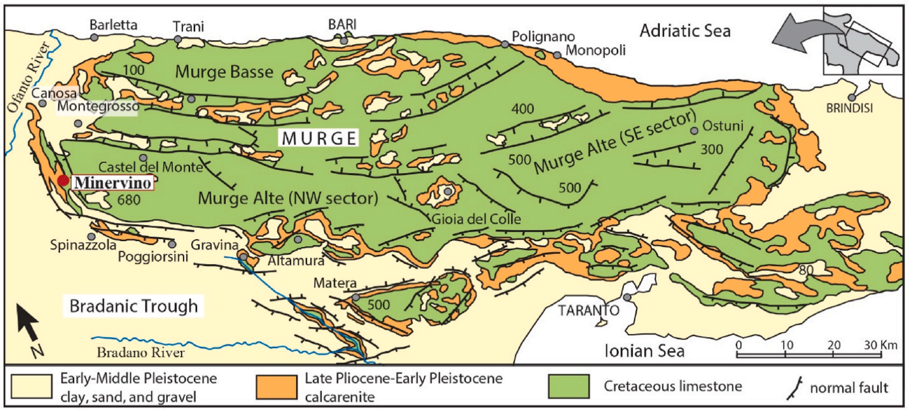

Fig. 3. Structural sketch of the Murge (modified after Pieri et al., 1997; see the inset and Fig. 1b for location). The red dot indicates the location of the cave, at Minervino Murge.

of well-stratified Cretaceous limestones of the Apulia Carbonate Platform (Pieri, 1980; Sauro, 1991; Parise, 2011) (Fig. 3). Due to the presence of a regional discontinuity of Turonian age, the outcropping Cretaceous succession was regionally subdivided into the units of the Calcare di Bari Fm (Valanginian to Senonian), overlain by the Calcare di Altamura Fm (Coniacian to Maastrichtian) (Valduga, 1965; Azzaroli and Valduga, 1967).

From a geomorphological standpoint, the highest part of Murge, corresponding to the "Murge Alte", is a NW-SE trending plateau about 15–20 km by 60–80 km in size, and about 500–600 m a.s.l. in elevation (Pieri et al., 1997). The location of the study cave corresponds to the north-western corner of the north-western sector of the Murge Alte plateau (Fig. 3). The south-western and north-eastern flanks of the plateau are stepped faulted blocks, respectively representing the bedrock of the Apennines foredeep (i.e. of the Bradanic Trough), filled by a transgressive-regressive first-order sedimentary cycle, and a staircase of plateau dipping towards and below the Adriatic Sea (the "Murge Basse" plateaux) (Ricchetti et al., 1988) (Fig. 3). This configuration is mainly related to Pliocene-Quaternary tectonics, with the north-western corner of the Murge area being a segment of a steep scarp, corresponding to erosionally receded highest normal-fault (Martinis, 1961; Iannone and Pieri, 1982) locally cutting part of the Cenomanian succession belonging to the Calcare di Bari Fm (Iannone and Laviano, 1980). The activity of this fault is the most recent in the area and occurred at least up to the end of the Early Pleistocene (Iannone and Pieri, 1982; Tropeano et al., 1997). Older tectonic phases affected the outcropping succession before Quaternary, the oldest of which, Cretaceous in age, was recognized both: i) regionally, through the aforementioned mild angular Turonian unconformity bounding the two Cretaceous formations cropping out in the Murge area and marked by bauxites, green clays and/or marly sands (Crescenti and Vighi, 1964) suturing normal faults affecting Cenomanian strata and interpreted to be induced by a lithospheric bulge (D'Argenio and Mindszenty, 1995; Agosta et al., 2021); and ii) locally, close to the study area, in a quarry located in the surroundings of the town of Minervino Murge, where a syn-depositional normal fault in the Cenomanian succession appears to be subsequently reactivated as reverse fault during Tertiary (Festa, 2003). This relatively younger tectonics, as well as gentle folds, were interpreted either as due to intraplate deformations related to Eocene-Oligocene Alpine compressional phases (Ricchetti et al., 1988) or as foreland deformations related to the Neogene compressional tectonic regime responsible for the building of the adjacent Apennines chain (Pieri 1980; Festa 2003). The Plio-Quaternary extensional tectonics is the last deformative phase in the Murge area and basically is responsible of the morpho-stuctural features characterizing the landscape, such as two main grabens cutting from NW to SE the whole Murge or the aforementioned main scarp bounding the Murge area toward the Bradanic Trough (Iannone and Pieri, 1982; Pieri et al., 1997; Tropeano et al., 1997, 2023). Two main distinct evolutionary stages occurred in the area during this deformative phase. During the Pliocene and the beginning of the Early Pleistocene the area underwent subsidence while from the upper part of the Early Pleistocene it underwent uplift (Ciaranfi et al., 1988; Pieri et al., 1997). On the flanks of the Alta Murgia Plateau, subsidence was accompanied by the syn-tectonic sedimentation of the Calcarenite di Gravina Formation, diffusely showing growth structures due to tensional and *trans*-tensional faults (Pieri et al., 1997). During uplift, many of these structures enhanced their displacement, and older ones were reactivated (Festa, 2003). Because of this uplift, the Murge area records the deepening of the drainage network with some deep gorges incised in the Cretaceous bedrock.

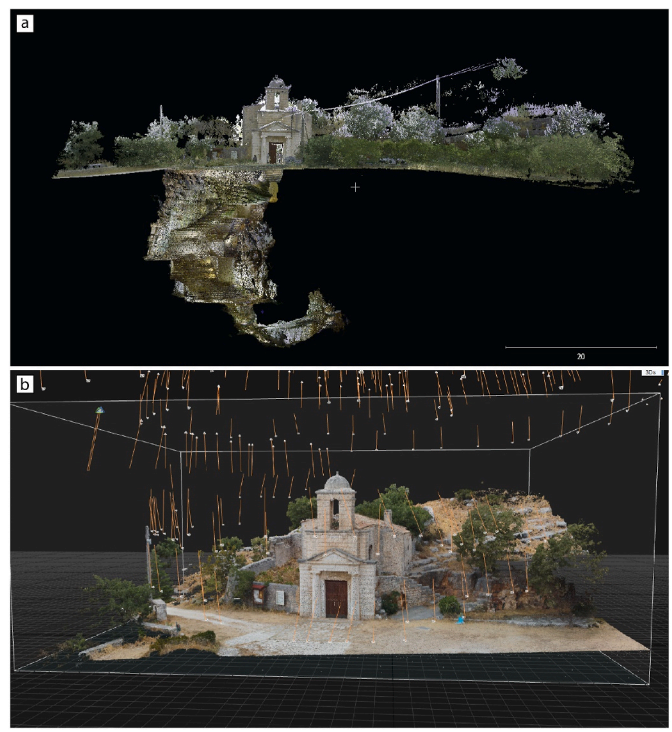

Fig. 4. (a) 3D point cloud of the cave and its surroundings, acquired through laser scanner; the scale of the software is in meters. (b) 3D point cloud of the entrance, acquired through drone photogrammetry; the smallest mesh on the grid measures 1 m.

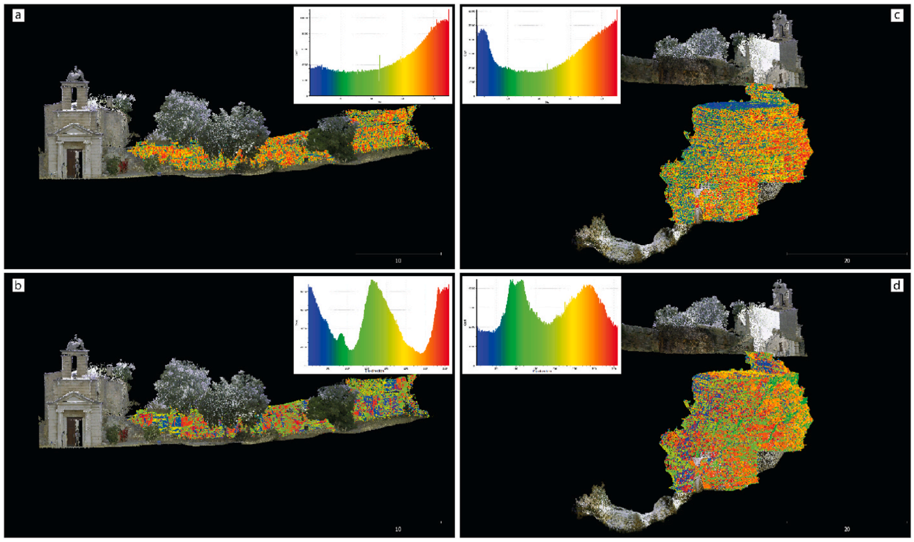

Fig. 5. 3D point cloud of the cave: every investigated point is colored according to its geological orientation, and shown on the related plot. (a) Rock walls outside the cave - dip. (b) Inside of the cave - dip. (c) Rock walls outside the cave - dip direction. (d) Inside of the cave - dip direction.

5. Methodology

The proposed method relies upon the acquisition of a high-resolution 3D point cloud (Fig. 4), necessary primarily to identify and locate the structural discontinuities of the rock mass and, secondly, to obtain a model representing a thorough documentation of the state of preservation of the whole underground site. Further, such a model can be used as a basis to realize digital contents in order to virtually promote the valorization of the cultural asset. The analysis is carried out using a series of combined and customized algorithms for the detection of geometrical features on a 3D dataset, previously implemented on other underground environments (Cardia et al., 2021a-b). Starting from the calculation of the normal orientation for each point of the 3D data – frame, dip and dip direction values are then extracted. Based on the user experience at the site, among those available, the most useful algorithm is chosen to identify different sets of discontinuities on the rock mass, and to then highlight the most significant by means of clustering techniques. All digital outputs are then compared to the observations made *in situ*, evaluating the results to validate them and to reach a better understanding of the geological setting. Knowing the major discontinuity sets in the rock mass, both inside and outside the cave, allows to estimate the most susceptible areas to rock instability. This outcome is of crucial importance for a correct understanding of the cave evolution, and could provide meaningful information to monitor the cave over time, or to directly predict the kinematic behavior of individual blocks.

5.1. Materials

The surveys were performed using a RIEGL VZ400i and a Leica RTC360 laser scanners, later integrated with a photogrammetric survey from RPAS, performed with the aircraft DJI Mavic Mini. The RIEGL scanner has a range of detection greater than 500 m, is equipped with a high-definition digital camera (8 MP) and an integrated inclinometer, lead laser, GPS system and compass. It performs high-velocity acquisition, precisely more than 120.000 pt/s with a 3 mm resolution. The Leica scanner is a more suitable device for scanning indoor environments, having a smaller range (about 30 m). It has anyway a measuring rate of up to 2 million pts/sec and an advanced HDR imaging system, an automated targetless field registration based on VIS technology, GPS system and compass. Analysis of the acquired data was then conducted on different machines, all of them operating on Windows 10 OS. For the visualization of the point clouds, the internal softwares of the RIEGL and Leica scanner RiSCAN PRO 2.0 and Cyclone REGISTER 360 were first used; then, to process the data for the geo-mechanical analysis, a series of Python 3 scripts were utilized. The results of the method were finally visualized by means of the open GPL software CloudCompare 2.12.

5.2. Procedure

The major scanning stage carried out with the laser scanners consisted of 3 scan positions outside the cave with the VZ400i, and of approximately 50 scan positions inside the cave with the RTC360. The drone flight was carried out for the benefit of the texturization of the area outside the cave, taking approximately 300 photos around the entrance and above the cave opening. This texturized model was mainly acquired in order to have a clear 3D documentation of the state of preservation of the historical asset and, moreover, to realize a virtual tour of the cave (Cardia et al., 2023a). The laser scanner survey rather has been carefully designed with the aim to acquire most of the discontinuity planes in the area in order to have a reliable and full data population.

Before starting the digital geo-structural analysis, it is necessary to pre-process the point cloud, through the steps of alignment of the various point clouds acquired, the merging of point clouds deriving from the different instruments, georeferencing the final output, and, eventually, cleaning the noise and redundant points. As regards the laser scanning, each single scan position indicates a sufficient number (minimum of 4) of georeferenced targets (control points). The registration error between different scans varies from 2 to maximum 4 mm. The control points are georeferenced by survey celerimeter with total station and GPS. The survey is carried out through a polygonal survey line starting from the outside to within the cave. The output model from the drone photogrammetry is georeferenced and scaled through the information contained in each photo as a metadata, having these registered the right coordinates through the internal GPS of the drone itself. The noise cleaning is then done by manually removing from the 3D point cloud all spurious elements without geological meaning (e.g. vegetation, floor points) as these areas are misleading for discontinuity identification and could lead to unnecessary computation. A sub-sampling of the points is also carried out in order to reduce the large density of points in excess for small areas, and to lighten the cloud, not to incur in long and not necessary computation times, usually not leading to benefits for the recognition of rock mass discontinuities. Then, the geometrical normal of each point is calculated. At this aim, we adopted a PCA (Principal

Table 1
Outside the cave: numerical values of the clustering.

Gaussian Mixture clustering			K-means clustering			Manual clustering		
SET	Dip	Dip dir.	SET	Dip	Dip dir.	SET	Dip	Dip dir.
K1	79.7	146.9	K1	68.8	150.0	S1	10.6	187.9
None	45.1	186.7	None	55.6	334.2	K1	78.4	152.2
None	46.4	17.7	None	46.0	16.4	K2	81.8	45.7
S1	10.7	184.0	K2[a]	63.6	227.5	K1[a]	82.3	332.1
None	31.7	348.9	None	64.7	65.5	K3	82.5	78.2
K1[a]	74.9	332.6	S1	17.6	184.2	K2[a]	83.1	227.3

[a] Set complementary values.

Component Analysis) that randomly starts to picking points on the cloud and performs the evaluation based on a prefixed number of neighborhoods. The result of this process is that every point, rather than having just a position (XYZ) in the 3D virtual space and a color (RGB), has subsequently also an orientation, again based on a three-column matrix (N_x, N_y, N_z). It is then possible to convert the normal values of each point in an orientation with geological meaning, which is a two-column matrix with dip and dip direction (Fig. 5). Knowledge of these values allows to evaluate the discontinuity orientations in the rock mass, that can be represented as peaks of density on a graph, highlighting one of the most significant geological features of the rock surface. Then, starting from these outputs, it was performed a KDE (Kernel Density Estimation) to visualize the data onto stereoplots and, subsequently, two different types of automated clustering (Gaussian Mixture and K-Means) were launched. The developed Python script gives however the possibility of reading values while hoovering the mouse onto the graph, and to perform a point-picking directly on this, to have as output a sort of manual clustering. All these results were later compared, taking also into account the observation made *in situ* before extracting from the point cloud the sets of rock discontinuities. This last step was done through a specific algorithm previously developed and tested (Cardia et al., 2021a), the SSE (Supervised Sets Extraction), which performs an extraction of clusters of discontinuities on the basis of an input gave by the user, who, in this way, keeps the complete control of the operation. The final outputs are then “chunks” of the original point cloud, each of which is basically a set of planar structures representing one cluster of rock discontinuities. The implementation of this combination of new scripts and customized algorithms is widely described and discussed in a recent work (Cardia et al., 2023b).

Through this analysis, it is finally possible to determine the main discontinuity sets and their points of intersections, and, knowing the orientation of the rock walls, the possible block kinematics and the most likely danger areas, with possibility of rock detachment, can be estimated.

6. Results

We first evaluated the visible rock walls outside the cave. The outcropping succession is made up of Cretaceous limestone beds, several tens of centimeters thick, gently dipping toward S-SW and mainly showing a mudstone/wackestone texture. Bedding planes are well defined diastemas and correspond to one (S1) of the four major sets of recognized discontinuities. In addition to bedding planes (S1), three about vertical sets of discontinuities (K1, K2, K3), one of which (K2) showing relatively scarce density at the site were observed. The cave

Table 2
Outside the cave: numerical values of the extracted sets.

SET	Supervised Set Extraction	Dip direction
	Dip	
S1	15 ± 5	185 ± 5
K1	75 ± 5	149 ± 3
K2	80 ± 2	48 ± 3
K3	82 ± 2	81 ± 4

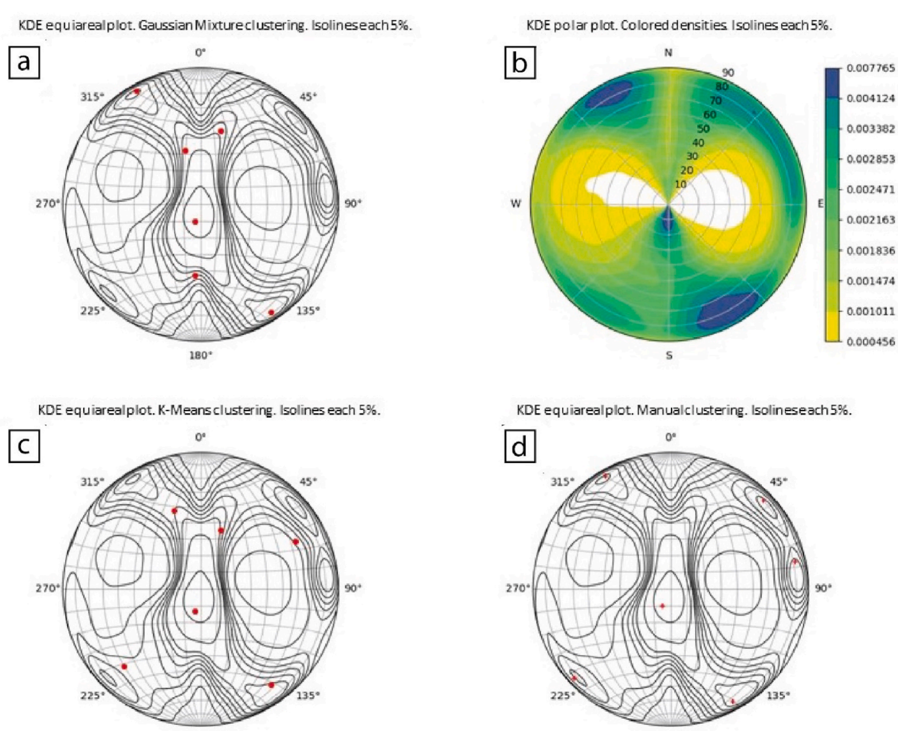

Fig. 6. Stereoplots outside the cave. (a) KDE with Gaussian Mixture on Lambert-Schmidt projection, the red dots are the centroids of the clusters. (b) KDE on polar projection with colors for visualization purpose. (c) KDE with K-Means on Lambert-Schmidt projection, the red dots are the centroids of the clusters. (d) KDE with manual selection on Lambert-Schmidt projection, the red crosses are the selected centers of the clusters.

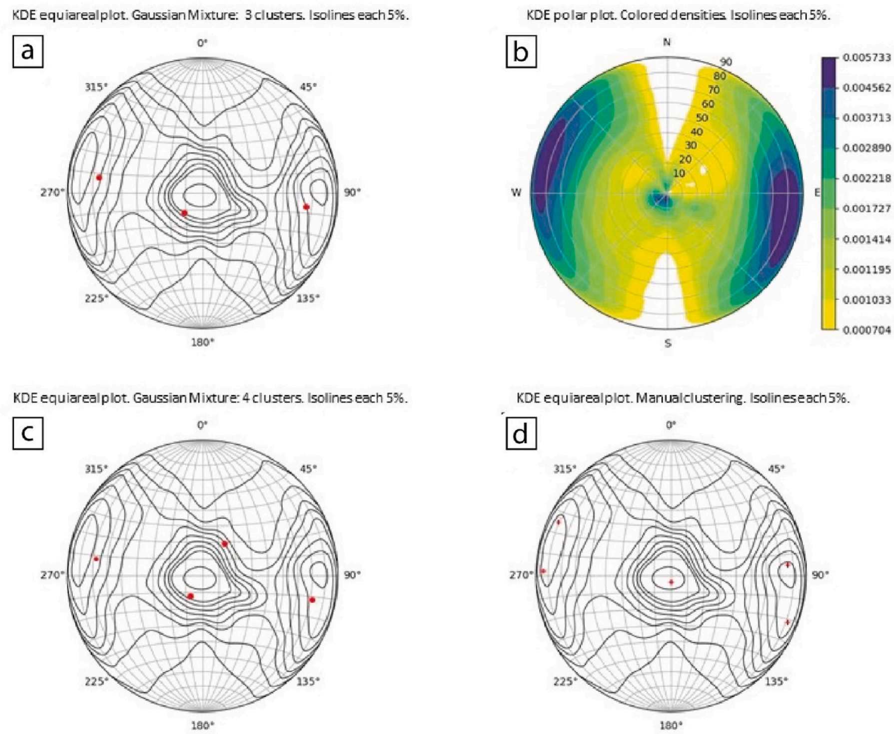

Fig. 7. Stereoplots within the cave. (a) KDE with Gaussian Mixture on Lambert-Schmidt projection, 3-input clusters, the red dots are the centroids of the clusters. (b) KDE on polar projection with colors for visualization purpose. (c) KDE with K-Means on Lambert-Schmidt projection, 4-input clusters, the red dots are the centroids of the clusters. (d) KDE with manual selection on Lambert-Schmidt projection, the red crosses are the selected centers of the clusters.

Table 3
Numerical values of the automated clustering within the cave.

Gaussian Mixture: 3 clusters			Gaussian Mixture: 4 clusters			Gaussian Mixture: 5 clusters		
SET	Dip	Dip dir.	SET	Dip	Dip dir.	SET	Dip	Dip dir.
K1/K2	66.7	97.9	K1/K2	71.1	101.0	K1/K2	70.4	101.8
K1/K2[a]	66.5	279.5	K1/K2[a]	68.6	279.9	None	42.9	325.1
S1	12.1	191.6	None	29.7	21.4	S1	14.4	193.8
			S1	15.7	204.9	None	32.1	23.3
						K1/K2[a]	70.7	279.7

[a] Set complementary values.

Table 4
Numerical values of the manual clustering within the cave.

SET	Manual clustering	Dip direction
	Dip	
S1	4.1	180.0
K1	77.7	84.4
K2	81.3	112.7
K1[a]	83.3	272.1
K2[a]	81.9	295.4

[a] Set complementary values.

entry is crossed by a gentle fold, probably a fold propagation fault, that can be followed in the cave without a clear interaction with the vertical sets of discontinuities.

Both Gaussian Mixture and K-Means gave as output three out of six reliable clusters (Table 1) (Fig. 6a–c). Coupling these outcomes with the manual clustering (Table 1) (Fig. 6d), we finally extracted four clusters, two of which have complementary values (Table 2).

Table 5
Numerical values of the extracted sets within the cave.

SET	Supervised Set Extraction	Dip direction
	Dip	
S1	9 ± 5	190 ± 10
K1	75 ± 5	89 ± 5
K2	80 ± 5	107 ± 5

As regards the cave, we performed only the Gaussian Mixture method for the automatic clustering, as for this type of situation the K-Means seemed to be less suitable. Relying on the KDE resulting on the stereoplot, we first gave three as input for the number of clusters (Fig. 7a). Then, the analysis was repeated giving input values of four (Fig. 7c) and five, which resulted in the same output, namely three cluster values (Table 3). After that, we manually selected the points considered the most significant geologically (Fig. 7d), dividing each pole visible on the plot in two (Table 4).

The poles extracted were therefore three (S1, K1, K2), two of which with complementary values since they pertain to rock surfaces with almost vertical inclination (Table 5).

Two areas were thus identified where the detachment of some blocks could potentially occur: the sector above the altar (where some works have been already realized), and a relatively small area facing the cave entrance and an ancient baptismal font aside of the staircase.

7. Discussion

As concerns the area outside the cave, no situation of instability has been identified for the rock wall, higher less than 3.5 m. The discontinuity systems found outside both with traditional methods and through the semi-automatic analysis of the point cloud are almost in agreement with those found in the cave, at least for two sets: the bedding plane and a set corresponding to K3 (outside) and to K2 (inside). In the cave, three main systems of discontinuity can be defined, creating critical intersections in two specific sectors: the wall towards the bottom of the cave, and an area behind the monumental altar, where in the past a containment net was installed. In this portion of the interior of the cave, potentially unstable blocks protruding from the wall are also visible; the other area where the three families of discontinuities meet is a small part of the wall facing an ancient baptismal font carved into the rock, immediately near the entrance.

Both automatic clustering methods started on the external portion give controversial results and in the face of six total clusters identified, in both cases only three correspond to the families of discontinuities identified through geo-mechanical analysis, which was probably due to the high density of that referred to the bedding plane, which tends to mask all other poles, especially for a cluster detection system based on distance between points like the K-means.

With an access from the back of the altar, there is eventually a narrow tunnel, ending in the final room of the cave where breakdown deposits point out to evident rock failures. Given the difficulty in moving through these environments, and the lack of frequentation by people, this part of the cave was not object of our survey.

The advantage in conducting such an analysis by combining the results of an expert observation with three-dimensional digital models is evident. It is possible to physically take measurements on the orientation of discontinuities deemed evident and to compare them with the orientations provided by the geo-referenced three-dimensional models, without the need, for example, of involving geologists-rock climbers to take measurements in high and inaccessible parts of the cave, an operation which in itself requires rather long organizational times when compared to the scanning activity. Furthermore, having an entire model referring to the asset guarantees an all-encompassing vision to an expert eye, crucial for the initial considerations on the optimal parameters to be included in the algorithms; at the same time, an analysis conducted in this way guarantees overall lower costs as well as safety of any rock climbing operators possibly involved in the survey.

Finally, the highly detailed and textured results were used to produce polygonal models (mesh) that have been (Cardia et al., 2023a) and can be used in the future in the dissemination phase of the historical asset, as single renderings images, videos and virtual tours or augmented reality navigations, as well as, moreover, for a temporal monitoring of the rock outcrop and for a temporal study of the deterioration of the architectural structures included in the scans.

8. Conclusions

Geo-mechanical analyses of rock masses are important if not indispensable in underground sites of worship and, in general, of historical and naturalistic values, visited by people for both religious functions and tourism. The need to safeguard the asset itself, and the life of visitors, is crucial in order to keep allow frequentation of these sites. In this sense, a periodic geo-mechanical monitoring through multi-temporal studies can represent a future development of this investigation. In addition, the relationships between the potentially unstable blocks and the action of water in the cave should be thoroughly investigated, aimed at numerically predicting the potential failures. So far, two potentially dangerous areas have been identified inside the cave, with the first, more extensive, which was already known and object of stabilizing works, whilst the other is smaller but definitely needs to be monitored. Ultimately this work highlights the importance that high resolution 3D scans have for underground, logistically difficult to access, sites. As a further point, importance in data management of 3D digital geo-mechanical analysis based on user experience with a geo-mechanical knowledge of the site must be emphasized, too. Having something more than an image that portrays the conditions of the asset examined at the time of scanning in an extremely detailed way, proves today to be fundamental for all the underlying implications, such as designing a temporal monitoring, developing new techniques of remote investigation for the preservation of the architectural and historical heritage, and, last but not least, using the results of the scans for realistic 3D reconstructions for museological, advertising and educational purposes.

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CRediT authorship contribution statement

Stefano Cardia: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Francesco Langella:** Investigation, Validation, Visualization. **Marco Pagano:** Investigation, Visualization. **Biagio Palma:** Conceptualization, Resources, Supervision, Validation. **Luisa Sabato:** Validation, Writing – original draft. **Marcello Tropeano:** Validation, Writing – original draft. **Mario Parise:** Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

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

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