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GPR investigations at San Nicolò Church: a case-study from the 1669 eruption in the old settlement of Misterbianco (Etna, Sicily)

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ABSTRACT

Misterbianco, located on the southern slope of Mt. Etna (eastern Sicily), was destroyed in the past by two catastrophic events that raised the old town to the ground. The first was the great eruption of 1669, whose lava front buried dozens of villages encountered along its path, entirely destroying the architectural heritage of Etna's southern flank. The second event was the disastrous 1693 Val di Noto earthquake, which caused major destruction throughout south-eastern Sicily, also damaging the few still standing buildings in the town. The GPR survey performed at this site, 350 years after the eruption, allowed a first attempt of planimetric reconstruction of the San Nicolò Church. Starting from the site history, we present the results of an integrated approach that involves history, volcanology and geophysics aimed at addressing future archaeological excavations for the protection of archaeological and monumental assets in a difficult setting as this volcanic environment.

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GPR; SfM; cultural heritage; old Misterbianco; Etna; 1669 eruption

Introduction

Misterbianco is a historically important town located on the southern flank of Mt. Etna (Figure 1). Its favoured position in front of the Simeto river valley dominating the Catania plain earned the town a certain prominence in the local territorial framework (e.g. Amico 1757; Calabrò 2019). In the seventeenth century, the old settlement of Misterbianco, also known as *Monasterium Album* (for its characteristic white colour), was heavily damaged by two natural catastrophes: the 1669 Etna eruption and the 1693 Val di Noto earthquake (e.g. Branca et al. 2015) that severely conditioned the history of Eastern Sicily. The first was classified as the largest flank eruption ever to occur in historical times at Mt. Etna. Lava flows buried tens of villages and settlements, and reached the city of Catania after a path of 17 km, finally entering into the sea. After the eruption, the landscape was transformed into a wasteland and most of the architectural heritage was entirely buried by lava. The second event, which occurred after two decades, caused widespread destruction in south-eastern Sicily, including Catania, Misterbianco and many other localities on the southern slope of Etna (e.g. Boschi and Guidoboni 2001).

While the discipline that identifies the effects of ancient earthquakes on monumental and architectural buildings is known as archaeoseismology (e.g. Stiros and Jones 1996), the branch aimed at the preservation of archaeological and historical remains in volcanic environment is known as archaeological volcanology and it has a very long tradition. The most famous cases in the Mediterranean are the historical eruptions of Akrotiri (Thera- Santorini) in 1652 BCE, whose remnants were preserved by tephra layers, and that of Mt. Vesuvius in 79 CE that caused the destruction of Herculaneum, Pompeii, Stabiae, and Oplontis (e.g. Harris 2015; Elson and Ort 2018).

Although the recovery of the architectural heritage damaged by seismic events in the early modern age is a difficult operation, the investigations into the few surviving remnants after the eruptions represent examples of heritage conservation that is not adequately exploited and still an open issue (Figure 1(a)).

An example is represented by the Sanctuary of Mompilieri, located a few hundred metres south of the 1669 eruption's main vent, which is the most outstanding evidence of this architectural heritage (e.g. Azzaro and Castelli 2013). The Mompilieri site was discovered in the early 1700s (e.g. Santi 2016) and later excavated: the church was completely buried beneath a 15 m thick lava. In the old site of Misterbianco instead, the situation was completely different: here the steep morphology underlying the lava flow led to the formation of zones with limited thickness.

At Misterbianco, the excavation works enabled unearthing the remains of the Mother Church through an accurate restoration plan, which reinforced the structure and recovered the remains of the chapel's

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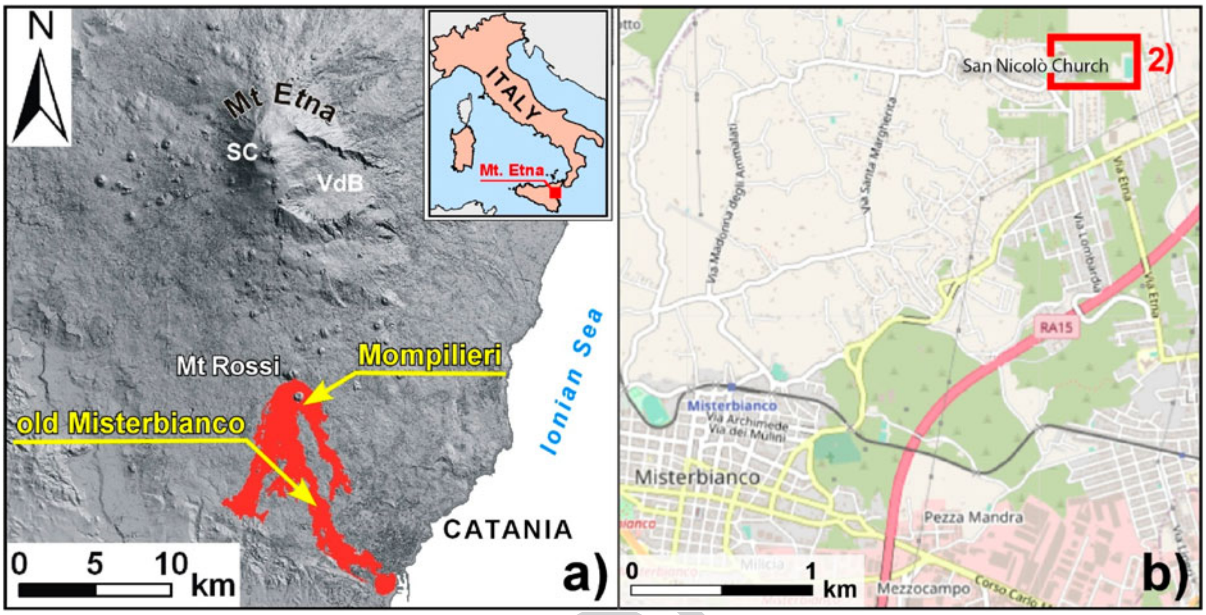

Figure 1. (a) Sketch map of the 1669 lava flow with the sites of the "buried" churches of Mompilieri and old Misterbianco; (b) The old settlement (red box) is today located in a highly urbanised area, a few kilometres from the new Misterbianco and the northern outskirts of Catania (base map from OpenStreetMap®).

ornaments in the 2000s (e.g. Garozzo, Lo Turco, and Santagati 2019; Longo 2019). Although the Mother Church (Figure 2) was completely excavated, very little attention was paid to the ruins of the San Nicolò Church 300 m away to the south-east. Here, only a boring was performed by the Soprintendenza per i Beni Culturali e Ambientali (Dept. of Catania), thus confirming the presence of the ancient building beneath a dozen- meter-thick layer of lava (e.g. Calabrò 2019).

Notwithstanding the importance of the 1669 eruption in the social context of the territory, from geological and geophysical standpoints little attention was paid to the archeological evidence of the old Misterbianco site. A first diagnostic multidisciplinary study was recently performed in the Mother Church whose results have been published by Bottari et al. (2022), whereas in the San Nicolò church no investigation had been performed so far.

In this paper, we present a first GPR study focusing specifically on the San Nicolò church, aimed at identifying the perimeter walls of the edifice (Figure 2). To this end, we firstly performed a drone survey to map in detail the investigated area in order to acquire a high-resolution aerial view of the 1669 lava field.

The 1669 Eruption

Among the historical eruptions of Etna mentioned in the catalog, the largest flank eruption documented in the last 2500 years is the 1669 event (Figure 3), which caused damage to cultivated areas and settlements throughout the Etna region (e.g. Tanguy 1981; Guidoboni et al. 2014; Branca et al. 2015; Branca and Abate 2019). During this eruption, lasting four months from 11 March to 11 July, a widespread lava field covering an area of 40 km^2 was produced on the southern slope of the volcano (Figure 3(a), for details see Branca, De Beni, and Proietti 2013). The development of a complex lava tube network promoted lava field lengthening as far as the coastline, destroying several villages and partially damaging the western part of the city of Catania (for details see Branca, De Beni, and Proietti 2013; Guidoboni et al. 2014). As frequently occurs in flank eruptions at Etna, also the 1669 event was accompanied by an intense seismic swarm that struck the southern sector of the volcano (e.g. Branca et al. 2015).

In brief, the eruption originated from an eruptive fissure system, trending NNW-SSE, located near the Mts. Rossi cone to the west of the village of Nicolosi, at an altitude between 950 and 700 m a.s.l. The main eruptive vent formed at 850–775 m a.s.l. and was preceded by several earthquakes that caused heavy damage in Nicolosi and its surroundings. The prolonged explosive activity generated the large scoria cone of Mts. Rossi, and it was also accompanied by intense seismic activity, forcing people to leave their homes. After two weeks (11–25 March), the lava field covered much of the total area ($\sim$ 70%) and almost half of the total volume of lava had been emitted at this stage of the eruption. At that time, the three branches of the lava field were formed, thus destroying many other villages and large areas of cultivated land, reaching a maximum length of 10 km. In the last days of March, the central branch reached the Carcarazza district, about 1 km north-west of the old site of Misterbianco, and finally invaded the town on 30 March, at a distance of 8.6 km from the eruptive vent.

According to historical sources (e.g. Guidoboni et al. 2014), the town was almost totally covered by two lava flows, the first causing the destruction of the main

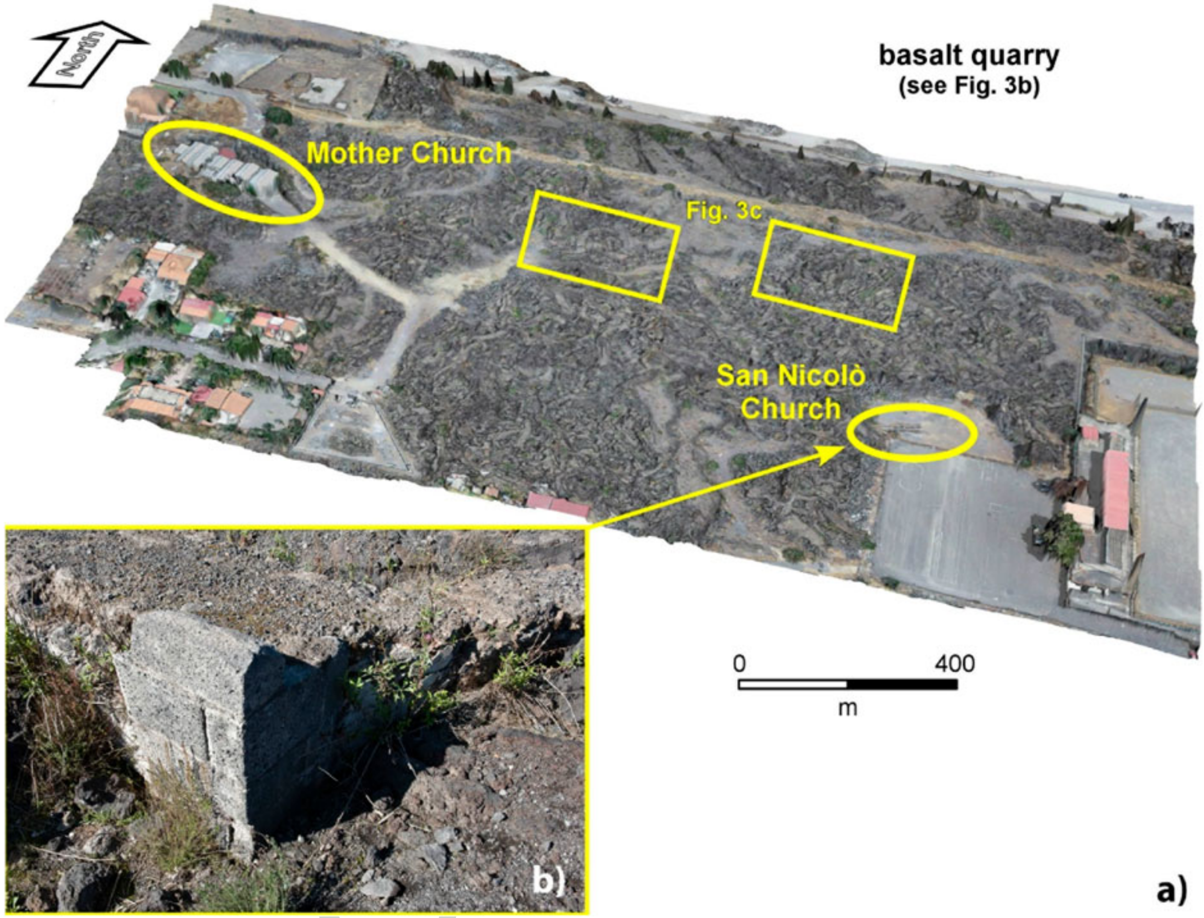

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Figure 2. View of the studied area. (a) Orthophoto-mosaic overlapped on the digital surface model (DSM) of the investigated site, showing the position of the San Nicolò Church and the Mother Church; (b) the remains of the San Nicolò Church southern wall emerging from lava (photo taken in 2012 by Azzaro). Yellow rectangles indicate the position of typical features of lava morphology (see Figure 3(c) for details).

square area while the second passed around the Mother Church area, channelled onto steep terrains and finally reached the church of San Nicolò, at the southeastern tip of the settlement. No damage was caused by the seismic activity in Misterbianco, although earthquakes were felt by the inhabitants. In April, this branch went on to reach Catania.

During those months, the ephemeral vents fed by the numerous lava tubes led to the formation of new lava flows in the Misterbianco territory, producing a thickening of the lava field up to 21 m in a quarry located near the study area (i.e. about 300 m to the northeast) consisting of a basal unit characterised by a minimum thickness of 14 m (Figure 3(b)) that is superimposed by several flow units with thickness ranging from 1.5 to 4 m. The lava field morphology consists mostly of toothpaste lavas, often fractured and tilted (e.g. Rowald and Walker 1987), with the presence of many ephemeral vents and small tumuli (Figure 3(c)).

The ancient settlement of Misterbianco and the San Nicolò Church: historical background

Some authors (e.g. Bruno Licciardello 1867; Garozzo 2017–2018) documented the historical evolution of the ancient settlement of Misterbianco before its destruction in 1669. Briefly, the old settlement was located on the southern slope of Mt. Etna at about 213 m a.s.l., 7 km far from Catania (Figure 2(a)), of which it represented one of the nine hamlets (*casali*). Its favoured position at the periphery of the volcano earned the village a certain prominence in the local territorial framework until the mid-seventeenth century (e.g. Amico 1757). It included 11 churches, counting the Mother Church and the San Nicolò as the main ones, as well as noble palaces, and had a population of about 3.600 inhabitants (e.g. Santonocito 1995; Calabrò 2019). After the 1669 eruption, the new settlement of Misterbianco was rebuilt 3 km away from the old site, in a safer place in order to safeguard it against future eruptions of Mt. Etna.

San Nicolò Church, located at the southern tip of the old settlement, dates back to the sixteenth century CE as documented by Calabrò (2019); however, we do not know any other information on this building, neither on its area or layout development. We tried to get more information through pastoral visits which are the reports of the bishop where the status of observed churches was illustrated through the description of some architectural elements (e.g. ASD 1666). The report

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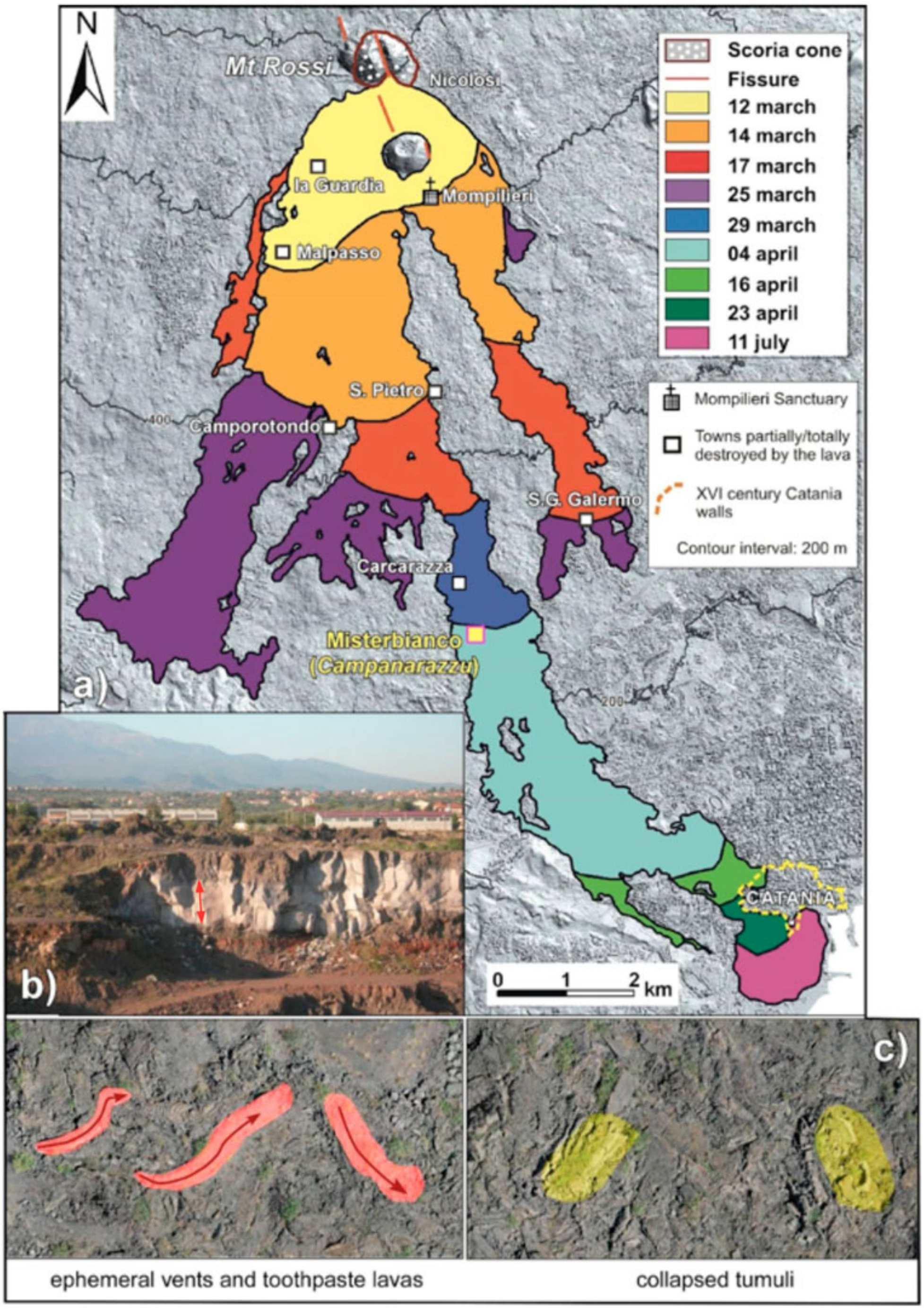

Figure 3. (a) Temporal progression of the 1669 lava flow field and location of the main settlements overrun by the lava; (b) view of the basalt quarry 300 m north of the San Nicolò Church showing the basal flow unit, 14 m thick (red double arrow), of the 1669 lava field, that rests on a thin reddish paleosoil; (c) detail of the drone photogrammetry showing the typical features of lava morphology in the investigated area (their location is shown in Figure 2(a)).

dated October 24th, 1666 documented the presence of four altars, the major one dedicated to San Nicolò probably located in the presbytery area, and the other three placed along the central nave. It also had a baptismal font near the entrance door.

Remote sensing survey

Remote sensing methods do not define a subsurface geological model depicting the actual ground features, starting from a detailed topographic survey of the area, which is covered by the 1669 lava flow, and together with the well-known techniques of surface prospections (i.e. GPR) used in the archaeological field to investigate buried structures (e.g. Gaffney 2008; Deiana, Leucci, and Martorana 2018). In general, the integration of different methods allows defining the geometry of walls and detecting voids inside the structures (Martorana and Capizzi 2020). The efficiency of the geophysical Q4 methods depends on the contrast between the physical properties of the material characterising the searched bodies and those of the host material: the greater the

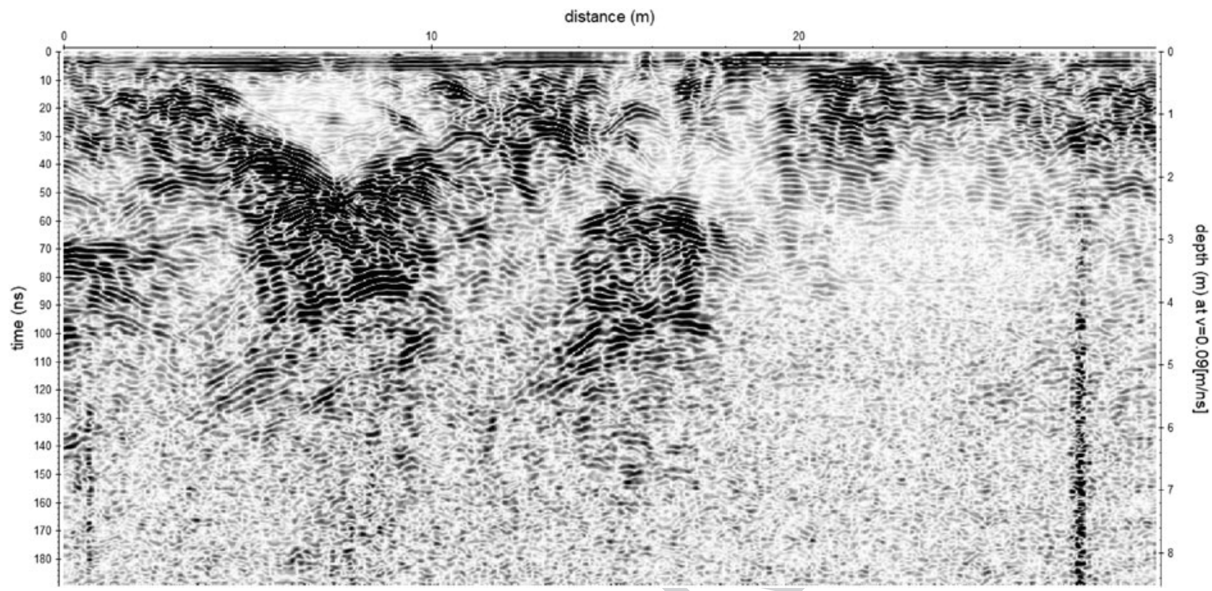

Figure 4. The processed GPR profile, carried out at $x = 17.5$ m, shows evidence of reflection surfaces, whose shape is best delineated by 3D modelling.

contrast, the more effective the result. For this study, we applied the following two different methods: (i) aerial photogrammetry by drone to obtain a high-resolution mapping of the studied site within the 1669 lava flow; (ii) ground-penetrating radar (GPR) to detect the boundary walls of the buried San Nicolò church. The acquisition was carried out on the external portion of the roof that is actually walkable (Figure 4); here, some remains of the southern wall building can still be seen.

Structure-from-Motion aerial photogrammetry

The use of drones for aerial surveys provides new opportunities for topographical mapping, given the rapidity, low cost, and ultra-high resolution achievable (e.g. Nex and Remondino 2014). Among the possible applications, photogrammetry is a very effective and useful tool in all research fields, including archaeological and volcanological investigations (e.g. Fernandez-Hernandez Q5 Q6 et al. 2016; Campana et al. 2017).

The aerial photographic survey of the Misterbianco site produced a high-resolution digital surface model (DSM) and an orthophotomosaic by using the Structure-from-Motion technique (SfM). About 540 aerial images were acquired using a DJI Phantom 4 ProV 2.0, equipped with a 1″ CMOS 20 MP sensor and a 24 mm (35 mm equivalent) focal length lens with a double grid flight path and nadir to off-nadir camera angles. A constant flight altitude of about 50 m above ground level was maintained and images were acquired via a dual grid flight plan with 75% front and 75% side overlap. The flight altitude was fixed to obtain a ground sampling distance (GSD) of 1.5 cm / pixel.

Aerial images were processed using Agisoft Meta Shape® software (version 1.6.3) based on SfM and multi-view stereo photogrammetry algorithms (SfM-MVS; James et al., 2012). Q7 The photogrammetric acquisition entailed the following steps: (i) identification of key points and image matching followed by scattered point cloud; (ii) filtering of the scattered point cloud, thus deleting incorrect geometry of those points characterised by significant coupling errors; (iii) generation of the dense point cloud; (iv) generation of the digital surface model (DSM) and of the orthophotomosaic.

The coordinates of a set of ground control points were also acquired with a GNSS system in Real-Time Kinematic (RTK) mode, in order to georeference and scale the point cloud obtained with the SfM technique. As a result, the DSM and the orthophotomosaic are characterised by a spatial resolution of 10 and 5 cm/pixel, respectively, for the whole area of about 10 ha (Figure 2(a)).

GPR survey

Ground penetration radar (GPR) technology is the most common technique used in archaeogeophysics (e.g. Conyers and Leckebusch 2010; Capizzi et al. 2012; Dojack 2012; Conyers 2013; Goodman and Piro 2013; Q8 Garrison 2016; Ranieri et al. 2016; Casas et al. 2018), and it allows detecting buried structures and reconstructing 2D maps and 3D models. The use of GPR in archaeogeophysics is recommended because, through a high acquisition speed, it enables obtaining high-resolution images in the areas close to the surface (e.g. Daniels 2005). Furthermore, GPR is a method that can easily be integrated with other non-destructive methods, thus allowing to detect anthropogenic structures in great detail (e.g. Forte and Pipan 2008; Casas et al. 2018; Obrocki et al. 2019; Martorana and Capizzi 2020; Bottari et al. 2022).

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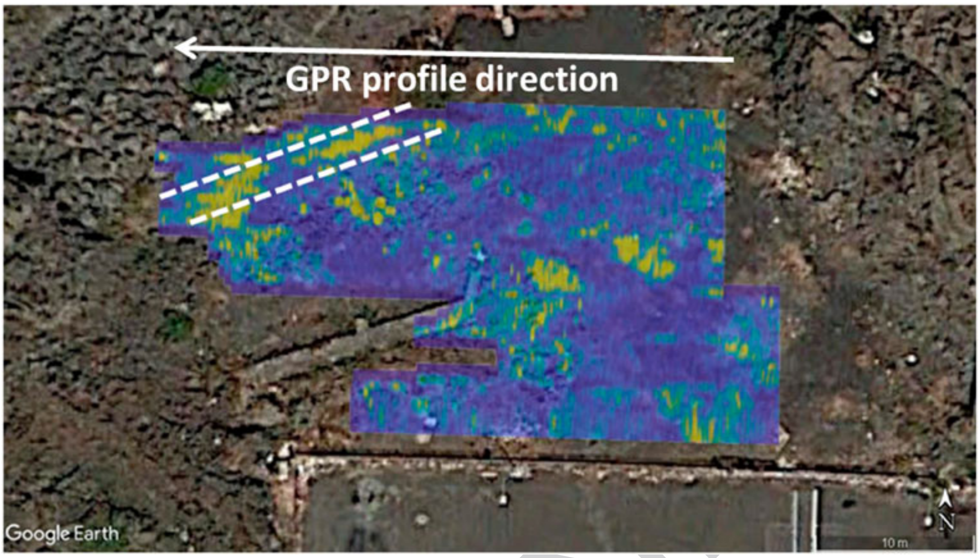

Figure 5. Depthslice referred to the depth of 1.2–1.8 metres superimposed on the satellite image of 2013. The white dotted line indicates the position of the wall identified by the investigations.

GPR has often been applied with good results on the floors of churches and other monuments, in order to detect underground rooms and tombs (e.g. Cozzolino et al. 2020; Bottari et al. 2022) or underground archaeological remains dating back to phases prior to the construction of buildings (e.g. Casas et al. 2018; Capizzi et al. 2021).

The GPR surveys were performed at the top of the church, on the external part of the roof, which is currently a walkable area. The investigated area is around 800 m^2 where the ancient wall remains are still outcropping.

The survey was carried out using a RIS MF HI-MOD system (IDS GeoRadar s.r.l.), equipped with a dual system of 600 MHz to 200 MHz antennas. The antennas were selected according to the resolutions and depth of investigation. A time window of 100 ns was used for the 600 MHz antenna and of 200 ns for the 200 MHz antenna. In particular, 41 parallel profiles were acquired with a spacing of 0.5 m, according to the hypothetical average size of the buried structures. A total of 1127 metres of GPR profiles have been analysed and processed to reconstruct a 3D GPR model of the investigated area.

The 2D GPR profiles were firstly processed using ReflexW software (e.g. Sandmeier 2016) to eliminate background noise. For this purpose, static correction, filtering for background removal, Kirchoff migration and Butterworth type frequency filtering, were performed. Figure 4 shows an example of processed GPR profile in which some anomalous reflections are clearly visible.

For each georadar profile, the envelope of the radargrams was calculated by normalising the amplitudes (e.g. Capizzi et al. 2021; Bottari et al. 2022) and data were reorganised in timeslices (e.g. Goodman, Nishimura, and Rogers 1995). In order to obtain a three-dimensional model of the electromagnetic reflectivity of the subsoil (Figure 5), a code implemented in Matlab was used for the construction of the data matrix. In particular, the Matlab code used builds a 3D matrix of the acquired geolocated data and allows the application of mathematical operators to better highlight the recorded reflections. Finally, the Voxler application (Golden Software) was used for the graphic rendering by applying the Inverse Distance Weighting algorithm for the spatial interpolation (e.g. Shepard 1968). The model extends to a depth of about 7 metres. In particular, the first 3 metres were reconstructed with the data acquired with a 600 MHz antenna, while the deeper data were obtained from the 200 MHz antenna. The main refractive hyperbolae made it possible to reconstruct an average speed of about 0.09 m/ns. Using this value depth slices have been constructed.

Furthermore, another Matlab code was used to calculate the depthslice relative to the investigated volume. The depth slice referred to a depth of 1.2–1.8 metres shows an alignment with the same direction as the unearthed wall, as can be seen by superimposing the depthslice on the 2013 satellite image (Figure 5).

The data clearly shows an anomaly elongated and parallel to the wall, at a distance of about 10 metres. It is probably the outer perimeter wall of the church. This anomaly has also been highlighted in the 3D model shown in Figure 6. The 3D model also highlighted other anomalies that can be interpreted with the presence of buried wall structures.

Furthermore, some anomalous dipping surfaces from a depth of two metres up to about 6–7 metres deep have been detected (Figure 7). These are probably due to the presence of the lava front which, once it reached and broke through the perimeter walls of the church, invaded its interior. The shapes of these anomalies are in fact compatible with the presumed direction of the lava flow.

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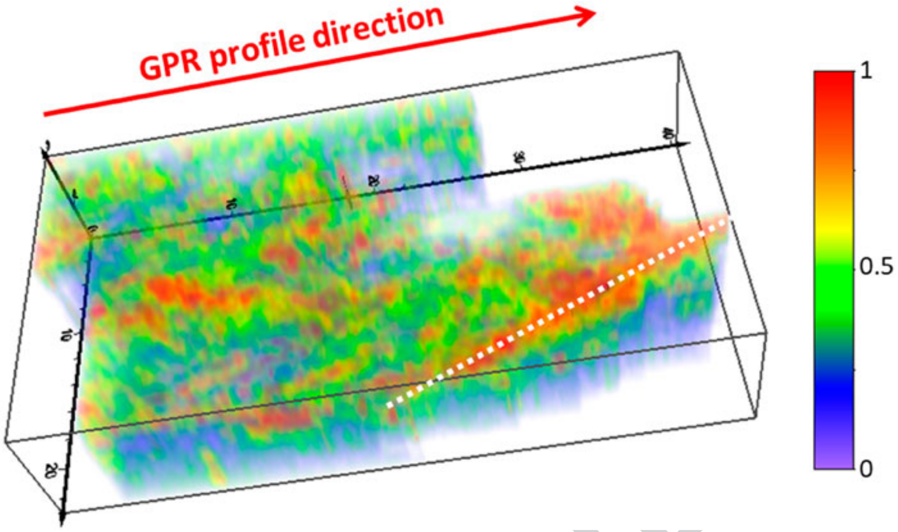

Figure 6. GPR 3D model highlighting an elongated anomaly that can be interpreted as the outer perimeter wall. The white dotted line indicates the position of the wall identified by the investigations.

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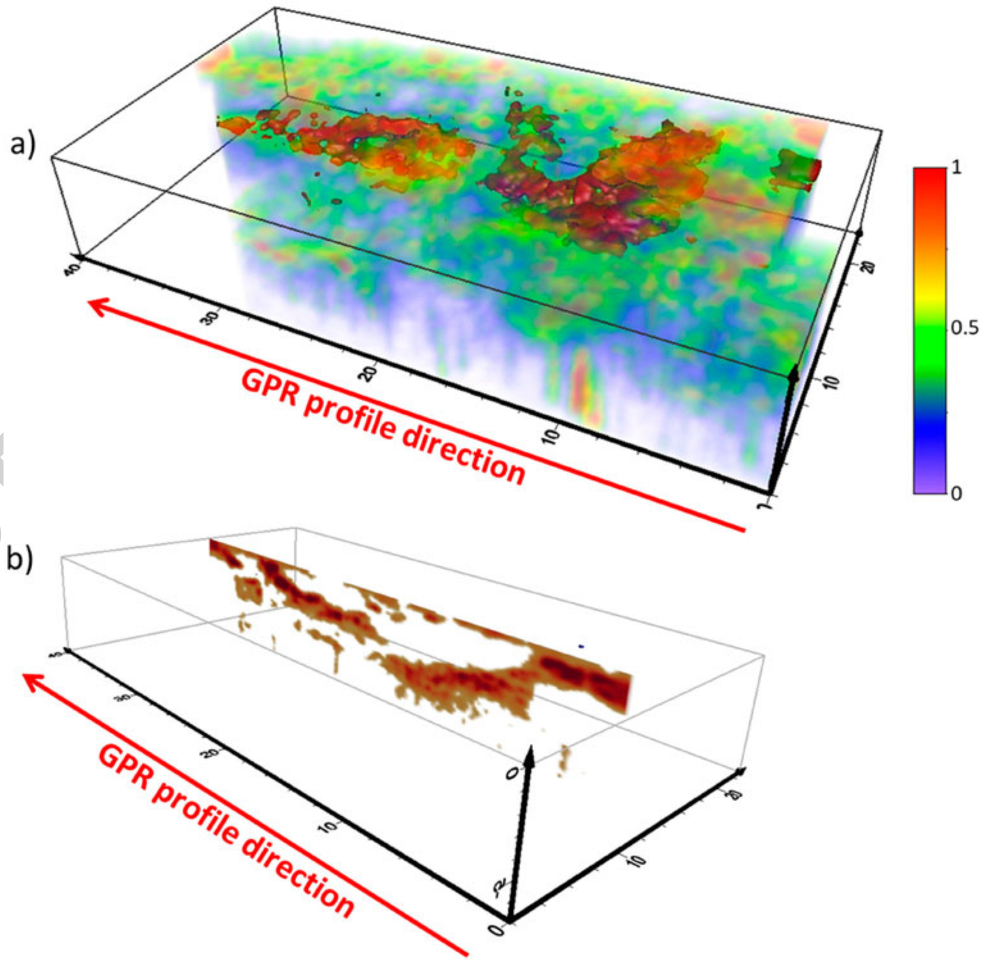

Figure 7. (a) GPR 3D model where the red isosurface highlights the dipping surfaces interpreted as lava fronts; (b) Vertical section of the GPR 3D model in which the dip of the lava flow is evident.

Discussion and conclusive remarks

The integration of historical and volcanological data with the geophysical ones has allowed a first attempt at a planimetric reconstruction of the San Nicolò church, thus enhancing the knowledge on this building before its destruction in 1669. In particular, the GPR survey performed on the external portion of the roof church, which is currently a walkable area, revealed a clear anomaly that can be interpreted as a perimeter wall, parallel to that partially outcropped in the area (Figures 2(b) and 4). Other anomalies are probably due to other buried remaining walls, probably partially destroyed by the lava flow and consequently not clearly aligned. The construction of the complete 3D model has enabled recognising some dipping surfaces that are probably due to the presence of the lava front that only partially filled the inner portion of the church.

By comparing the hypothesis of the lava impact on the Mother Church proposed by Bottari et al. (2022) with the San Nicolò Church, then a similar process of lava burying can be assumed. Indeed, its position at the southern tip of the old settlement in a lower topographical position with respect to the Mother Church of about 10 m at least, has been revealed by the depth of a core drilling performed by the Soprintendenza di Catania in 2002 (e.g. Calabrò 2019). The 1669 eruption had two main phases of lava flow impact: the first one, dated to the end of March, where the basal lava flow initially surrounded the village buildings as well as the Mother Church with a lava front some dozens of metres thick; the second phase, between May and June, is related to the evolution of the lava flow field, with the development of lava tunnels, ephemeral vents and spilling of toothpaste flows (Figure 3(c)) that gradually covered the village. The low effusion rate of the toothpaste flows, a few metres thick, gradually filled the site, destroying it completely. On observing the external part of the church roof through the results of GPR, it was possible to identify some new structures. It can be presumed the church had a central nave, 10 m wide and probably more than 14 m long, as revealed by the GPR investigation. Four altars were located inside, the largest one dedicated to San Nicolò was probably in the presbytery area, whereas the other three were placed along the nave. It is important to point out that the description of the altars found in the 1666 pastoral visit was carried out without any distributive order of the architectonic elements.

The GPR investigations and the following 3D model reconstructions carried out made it possible to formulate a first reliable hypothesis on the church layout and lava burying process, where the integration of historical and volcanological data with the GPR technique is fundamental for a correct interpretation. However, such hypothesis should still be verified through direct investigations and excavations, such as those recently performed in the Mother Church, which presumably could bring to light the old remains of the church thus allowing its restoration.

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Disclosure statement

No potential conflict of interest was reported by the author(s). Q9

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