

Article

Geomaterials and GPR Characterisation of the Castellina Fortress (Norcia, Umbria, Italy): Construction and Reconstruction from the 1500s to the Present

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Abstract

An integrated petrographic–geophysical workflow is applied to the Castellina Fortress (16th century AD) to investigate: the masonry texture, construction techniques and lithological provenance. The field activities focused on several architectural structures of the Castellina, including the main façade that was embedded inside the fortress out of a previous building, named Podestà Palace (13th century AD). The petrographic analyses document the use of lithoid limestones from the Maiolica, Scaglia Bianca and Scaglia Rossa Formations (Umbria–Marche Stratigraphic Succession) in the Podestà Palace, while limestone breccias can be mainly found in the cloister columns. The Ground-Penetrating Radar (GPR) data, supported by advanced numerical modelling, show a heterogeneous internal texture in the Castellina Fortress related to the use of both lithoid materials and earthquake-derived debris for the columns. The provenance analysis points out that the limestones were quarried from Monte di Colle, Monte Belvedere and Monte Poggio Vallaccone (southeast of Norcia), whereas the breccias largely derived from debris cones composed of breccia, gravel, and conglomerate deposits that still crop out today in the mountainous area surrounding the plains of Norcia and Santa Scolastica. This study demonstrates the potential of combining two different geoscience disciplines to reconstruct material supply zones and building characteristics in the field of cultural heritage.

Keywords: geomaterials; Umbria–Marche Stratigraphic Succession; GPR; numerical modelling



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1. Introduction

The history of the Norcia urban complex (Umbria Region, Central Italy) is very complex due to the long series of seismic events and multiple reconstructions. As recently reported in [1], the first seismic event in Norcia occurred in the year 1328, on 4 December, when the shocks almost led to the destruction of the inhabited part of the town, including the buildings of religious worship and part of the surrounding city walls. Starting from this event, eight additional VIII-Intensity earthquakes greatly damaged the city of Norcia [2], affecting the structural integrity of several public buildings, including the Castellina. As a

matter of fact, after the 1703 seismic sequence (with a reconstructed $M_w = 6.92$), damage was recorded for the 1730, 1859, 1979 earthquakes [3].

The Castellina building (Figures 1 and 2), constructed in 1554 based on a design by Jacopo Barozzi da Vignola at the behest of Pope Julius III, was conceived as a fortified residence for the apostolic governors and was used from the outset to control the peripheral territories of the Papal States. When the so-called Mountain Prefecture was established in 1569 in Norcia, the Castellina became its natural seat. Restored in the 18th century following frequent earthquakes (1703 and 1730 events), it became the seat of the municipal offices first (1860–1967), and then the seat of the Castellina Museum.



Figure 1. The Castellina Fortress (1554–1570).

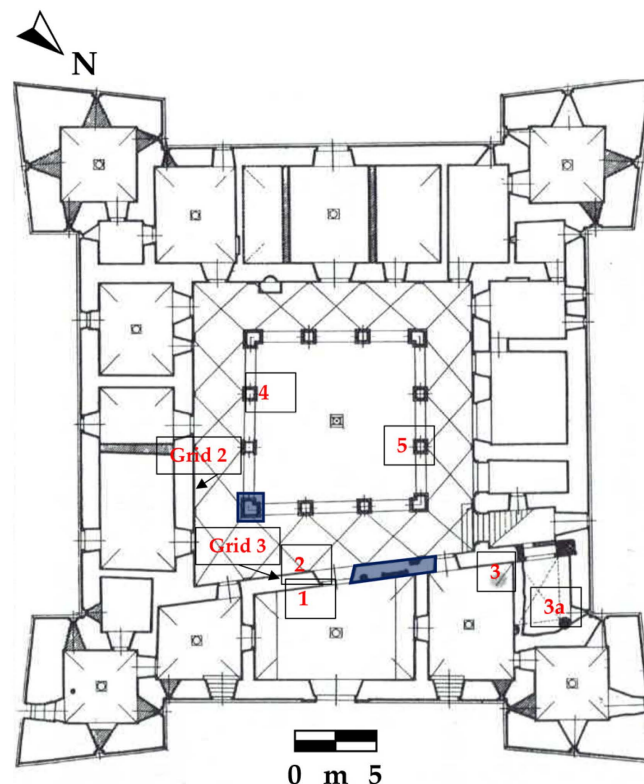


Figure 2. Plan of Castellina with sample locations and GPR targets in blue (modified after [4]).

The possibility of approaching the built environment with the aim of characterising the geomaterials used and identifying their origins, both local and/or external to the Nursine territory, has allowed us to expand the existing historical and archival knowledge [3,4].

From a general view, the contribution provided by geology and stratigraphy, through the analysis of lithofacies, biofacies, and microfacies, represents an indispensable investigative tool in research aimed at the characterisation of lithic materials (blocks, slabs, etc.). Historical sources provide indications about the use of local stones that, already from the 1300s, had common names, such as: *Croigno* or *Corgna* stone, *Crespo* (*Crispo*), *Belvedere* red stone, *Biselli* stone, and *Scagliola* [3–7]. The main source of supply of the geomaterials was confined to the Nursine area and affected the slopes of the mountains surrounding the Piano di Santa Scolastica, with particular attention to Monte Belvedere, Monte di Legogne, Monte di Biselli, and Poggio Valaccone (Figure 3). In some cases, it has also been possible to identify Corniola Formation (Fm), as the white-grey-to-hazelnut calcareous lithoid from Monte Vettore [5] and of *Crispo* and *Croigno* from the Ancarani and Campi villages, several tens of kilometres from Norcia (Figure 3). It is important to remember that many of the lithoid materials, both the building blocks and the rubble, were taken from the debris of constructions that earthquakes had destroyed. Many lithoid materials were therefore reused, and it is not always possible to determine where they were first used.

As a complementary tool, a well-known high-resolution geophysical technique named Ground Penetrating Radar (GPR) was used to characterise the electromagnetic response of such building materials and investigate the internal portion of the Castellina masonry walls (e.g., [8,9] and reference therein) and columns [10,11]. The multidisciplinary approach allows for obtaining information on the condition of the geomaterials of cultural heritage to assess their degradation and to better plan conservation and restoration interventions.

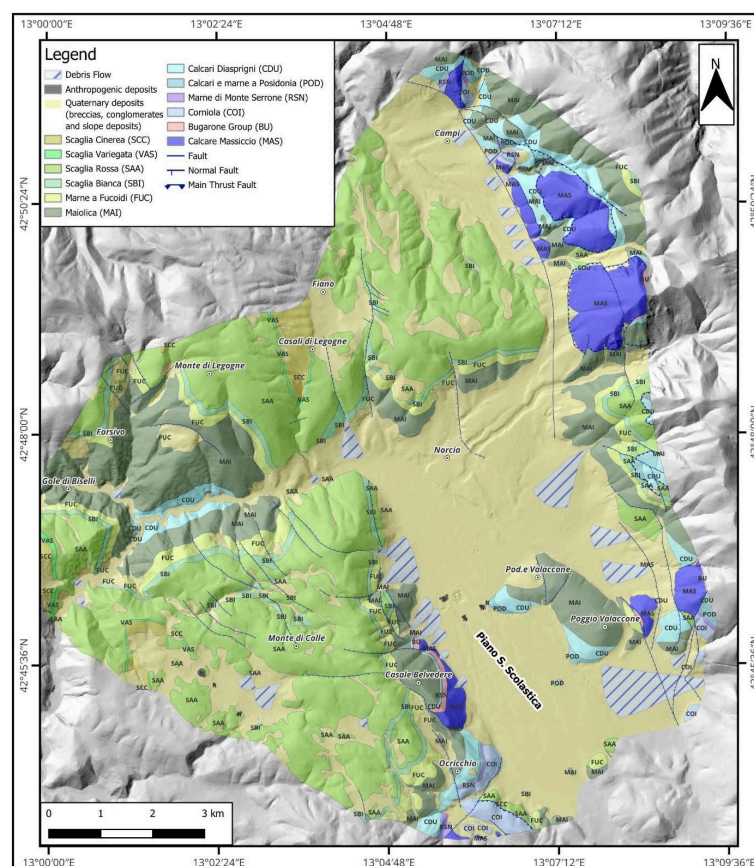


Figure 3. Geologic map (made in QGIS [12], EPSG:4326) detailing the formations outcropping over the Norcia area and surrounding mountains, potential sources for geomaterials used at the Castellina.

Even though, as testified by the lack of combined study in the scientific literature, Archaeometry and Geophysics are often treated as two disjointed sectors of geoscience, they can still be used as complementary techniques to provide a double characterisation of any given medium by combining direct-but-punctual information from samples analysis with indirect-but-planar (and/or volumetric) information supplied by geophysical methods. In this work, an integrated approach is proposed to define the geological properties of several portions of Museo della Castellina by providing not only a detailed examination of exploited materials and their extractive areas, but also associating such results, if available, with the respective electromagnetic (EM) response of studied materials by means of GPR.

2. Geology of the Norcia Area

The mountains surrounding Norcia and the Santa Scolastica alluvial plain are composed of Mesozoic carbonate rocks (Figure 3), pertaining to the Umbria–Marche sedimentary succession, deposited into the Umbrian–Marchean basin. The basin originated in the lower Jurassic through the action of extensional tectonics that fragmented a pre-existing Triassic carbonate platform [13,14]. From the platform margin, detrital materials, predominantly of biogenic origin, were discharged into the basin, intercalating with pelagic sedimentation [15]. Detrital supplies were found frequently in the Corniola (Lower Jurassic), Calcari e Marne a Posidonia (Middle Jurassic), Scaglia Rossa and Cinerea (Late Cretaceous to Oligocene) Formations. The Scaglia Rossa Formation is the one that received the greatest thickness of detrital material. These are present in the upper portion (Late Cretaceous–Paleocene) with considerable thicknesses (10 to 20 m) and are easily recognisable because of their white colour compared to the red limestone of the Scaglia [16,17]. The Scaglia Rossa contains several metres of a particular lithotype named Pebbly mudstone [17], represented by a red matrix with dispersed clasts of white calcarenites largely employed from the medieval age to now.

Italian seismicity, among the highest in the Mediterranean, is largely aligned along the axis of the Apennines. The most destructive earthquakes are generated by large extensional faults oriented parallel to the chain and generally outcropping at the eastern edge of the intramontane continental basins [18,19]. Such faults developed during the Quaternary in the downthrown block of the faults themselves. This is the specific case in the Norcia fault system, composed of several segments that have individually released modest or moderate-magnitude earthquakes over time, but that sometimes have been activated in groups (e.g., in 1328, 1599, 1730, 1859, 1979; $6 < M_w < 6.5$) or even all together, as happened on 14 January 1703, when one of the most destructive events in Italian seismic history (M_w 6.9, Io XI MCS) levelled dozens of settlements in the Norcia area [20,21].

The Norcia basin, located in the Sibillini Mountains National Park, is a vast intermontane basin of rectangular shape (formed during the Early Pleistocene), about 10 km long and about 4 km wide ([22,23] and reference therein). It is divided into two sectors by the mountainous spur of Poggio Valaccone (905 m above sea level), which extends from the eastern side in a NW–SE direction. At the foot of the eastern slopes of the basin there are debris cones and numerous alluvial and torrent fans. On the terminal portion (formed during the last glacial maximum, LGM) of one of these, namely the Patino cone, the city of Norcia rises [20].

In the northwestern sector, downstream of the historic centre of Norcia, the alluvial plain of Santa Scolastica ends with an extensive marshy area (the Marcite), into which the waters from the Patino Valley, the springs of the Salicone, the Capregna Valley, and the Torbidone Stream flow, the latter being characterised by a markedly intermittent regime, historically documented and connected to the seismicity of the area [24,25].

3. Materials and Methods

Non-destructive sampling of the masonry was carried out by collecting small fragments of blocks from the grids previously excavated on the walls for previous sonic analysis (Figure 2) [26,27]. The samples were used to make thin sections to be analysed under a polarising light microscope (PLM), to provide litho-micro-biofacies information and then evaluate their provenances. The investigation aimed to identify the source area, the quarries of surface extraction rock slabs, involved a field survey of the area surrounding the city of Norcia, from the Santa Scolastica plain to the Apennine mountains. Following the information indicated by Patrizi-Forti and Cordella [4,5] and the geological research of Colacicchi and Baldanza [16,17] during the '80s in the past century, an attempt was made to trace ancient routes for the supply of lithic materials.

In order to obtain additional information regarding the internal state of the medium as well, indirect survey techniques can be employed to overcome the non-invasiveness limitation for such applications. In particular, GPR was used to investigate the inner features of the bottom left-hand corner column in the cloister area (Figure 4), after conducting a wide validation phase which took into account both the experimental and synthetic data. GPR profiles were collected using a 1.5 GHz impulsive radar system by *Radsys Inc.* (Riga, Latvia), with a trace spacing of 0.01 m and a time window of 50 ns, consisting of 1024 samples. The data were processed in ReflexW [28] using a conventional workflow as follows: trace editing, dewow to remove the “wow effect” caused by electrostatic and inductive fields [29], bandpass frequency to remove unwanted frequency ranges, background removal to evaluate the shallowest useful signal covered by direct arrivals, averaging filter to smooth the data after background removal and gain to compensate for energy decay affecting later arrivals (see Table 1 for numerical parameters).

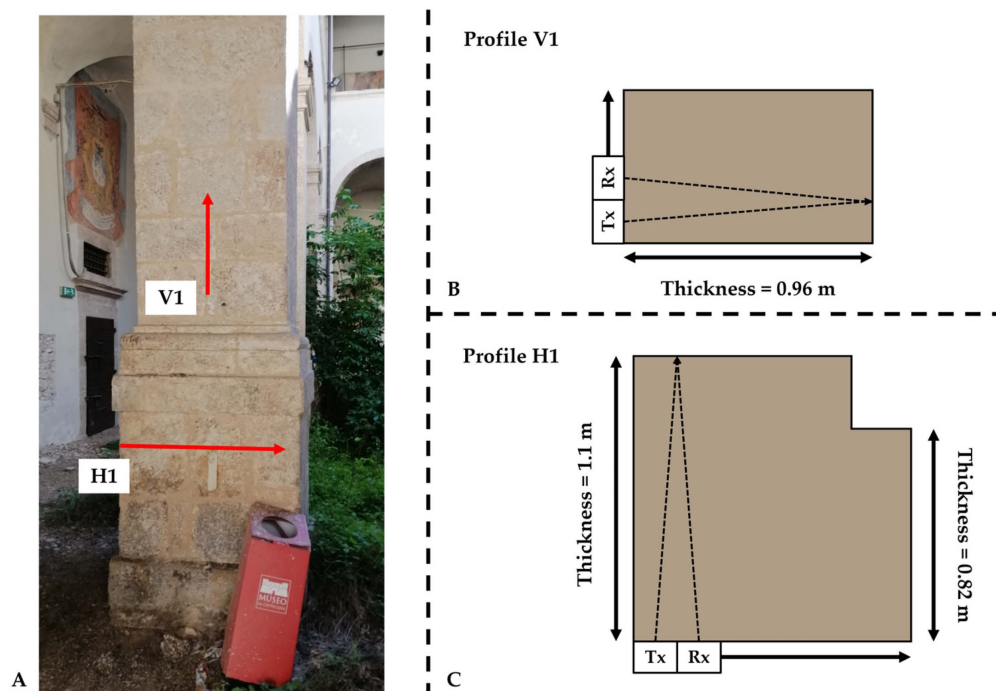


Figure 4. In (A), GPR profiles (red arrow with the tip indicating profile orientation) surveyed over the bottom left-hand cloister column. In (B,C), graphical sketch representing surveyed 2D plane of the column for V1 and H1 profiles, respectively. The main difference between the surveyed portions of the column is the thickness variation across the pedestal, while it remains constant in the case of shaft. Column location can be found in Figure 2.

Table 1. GPR Processing.

Processing Step	Numerical Parameters
Move start time (ns)	−3.43
Time cut (ns)	Removed window: 25–50
Dewow (ns)	0.87
Bandpass frequency (MHz)	200–400–1200–1500
Background removal (ns)	Time window: 0–3
Average xy filter	Samples: 3
	Traces: 3
	a: 0.2
Gain $g(t)$	b: 0.4
$g(t) = (1 + at)e^{bt}$	Maximum value: 1000
	Time window: 3–25 ns

4. Results

4.1. Geomaterials Results

The analytic data about the geomaterials allow us to identify: (1) the blocks utilised for external fortified walls and (2) the different lithotypes utilised in the masonry interne wall constructions for the Castellina Fortress. The preliminary data are reported in [26].

Other results concern the autoptic identification of very particular geomaterials, locally named *Crispo* or *Crespo* and *Crogho* or *Corgna*, utilised as large blocks for external walls of Castellina and also easily recognisable in ancient religious buildings (i.e., San Benedetto Church and Santa Maria Argentea Cathedral) and in even earlier constructions from the 5th to 6th centuries AD (e.g., house of San Benedetto and Santa Scolastica, patrons of Norcia).

4.2. Geomaterials Used for External Walls of Castellina Fortress

The external walls were mainly built with large blocks of variable sizes (Figure 5A–D), composed of lithotypes classifiable as carbonate breccias. The breccias are composed of sharp-edged fragments of white and pink limestones and red flint. The matrix and calcitic cement may exhibit various colours: red, white, and light yellow (Figure 5A–E). The white clasts are made of limestone with microfossils (foraminifers and radiolarians) and come from the Scaglia Bianca and Maiolica Formations, while the red clasts with foraminifers come from the Scaglia Rossa Formation. The breccias, depending on the typology of clasts, can be classified as monogenic (all same type) or polygenic (from different types) and, in both cases, the matrix can be white, red, or yellow (Figure 5).

4.3. Geomaterials Used for Internal Walls of Castellina Fortress

The wall with the large portal of Palazzo del Podestà was incorporated within the Castellina as a load-bearing wall [26], and was built with large blocks of *Crispo* (monogenic breccia) and limestones of Scaglia Rossa and Scaglia Bianca Formations (Table 2).

The samples taken from the grids (Grids 2 and 3) opened in the walls to carry out the sonic tests (Figure 6), pertaining to the internal side of old wall of Palazzo del Podestà (built in 1300) and to the original wall of the Fortress (Figure 2), highlighted the prevalence of very heterogeneous sizes of blocks of white and pink limestones and a subordinate number of breccia blocks (Table 2).

4.4. Geomaterials Used for Cloister Columns of Castellina Fortress

The history of squared columns (pilasters) is very complex; during the earthquake of 1703 they were destroyed, causing the collapse of the first-floor balcony [5]. The columns were rebuilt after the earthquake of 1703 and underwent further restorations after the seismic swarm of 1730. The latter restoration and cleaning of the dark patina highlights

particular workmanship. They were assembled with mortar of multiple slabs for the outer wall and the internal quadrilateral space was filled with a large amount of recycled material (multi-leaf structure). The slabs are of *Crispo* lithology (Polygenic breccia) (Figure 7), with frequent fragments of red chert and red matrix, which were further investigated thanks to the PLM microscope (Figure 8). In addition to the laboratory activities, the *Crispo* characterisation also involved fieldwork aimed at defining the outcrops used as the constructive materials supply zone nearby Norcia (Figure 9).



Figure 5. Breccia lithotypes from external walls (Figure 2) of Castellina (A–D): (A) Breccia ashlar of different dimensions; note the grey patina of alteration. Basement of towers with *scarpa* walls. (B) Polygenic breccia with red matrix. (C) Monogenic breccia with red matrix. (D) Three types of polygenic breccias with a red matrix and heterometric clasts; in (B–D), the surface of ashlar are free of grey patina, removed during the recent restoration. (E) Column of old Podestà Palace (1300 A.D.) worked in polygenic breccia with red matrix. (F) Detail of the internal staircase of the Castellina, composed of a particular lithotype with clasts belonging to the detrital levels (packstone) of the Corniola Fm.

Table 2. Lithotypes used for building the old Podestà Palace and the Castellina Fortress and their attribution to local stratigraphic formations.

Main Buildings	Structural Position (See Figure 2)	Lithotypes	Formations
Palazzo del Podestà (about 1300 A.D.)	External wall (1)	Light-pink limestone with foraminifers (FI 01)	<i>Scaglia Rossa</i>
	Internal wall (2)	Light-grey–hazelnut limestone (FI 02)	<i>Calcari e Marne a Fucoidi</i>
		White and red limestone clasts with red matrix; red-to-pink limestones (S3-1 in Grid 3)	<i>Breccia</i>
	Internal wall (3)	Light-pink limestone with foraminifers	<i>Scaglia Rossa</i>
	Column (3a)	White limestone clasts with red matrix	<i>Breccia</i>
Castellina Fortress (old wall of Podestà Palace)	Grid 3	Light-pink limestone with foraminifers	<i>Scaglia Rossa</i>
		White limestone with radiolarian	<i>Maiolica</i>
	Grid 3	Light-grey–hazelnut limestone	<i>Calcari e Marne a Fucoidi</i>
		White limestone clasts with red matrix	<i>Breccia</i>
Castellina Fortress (1556–1574)	Grid 2	Light-pink-to-red limestones with foraminifers	<i>Scaglia Rossa</i>
		White limestone with foraminifers	<i>Scaglia Bianca</i>
		White and red limestone clasts with red matrix	<i>Breccia</i>
Castellina Fortress (after 1703–1730 earthquakes)	Cloister columns (4, 5)	White limestone clasts with red matrix	<i>Monogenic Breccia</i>
		White and red clasts; red cherts with red matrix	<i>Polygenic Breccia</i>

4.5. GPR Experimental Results

The external wall of Castellina is characterised by different types of blocks made from local limestone formations and carbonate breccias, while the structure of cloister columns is more heterogeneous due to rebuilding. For this reason, the first step was focused on understanding the electromagnetic response of carbonate breccias used as blocks for the external wall, thus providing an initial validation before the later focus on columns. Therefore, GPR profiles were collected to provide a helpful ground-truthing for the columns' interpretation. Figure 10 shows the most representative GPR profile that was extracted from the dataset for the purpose of this work.

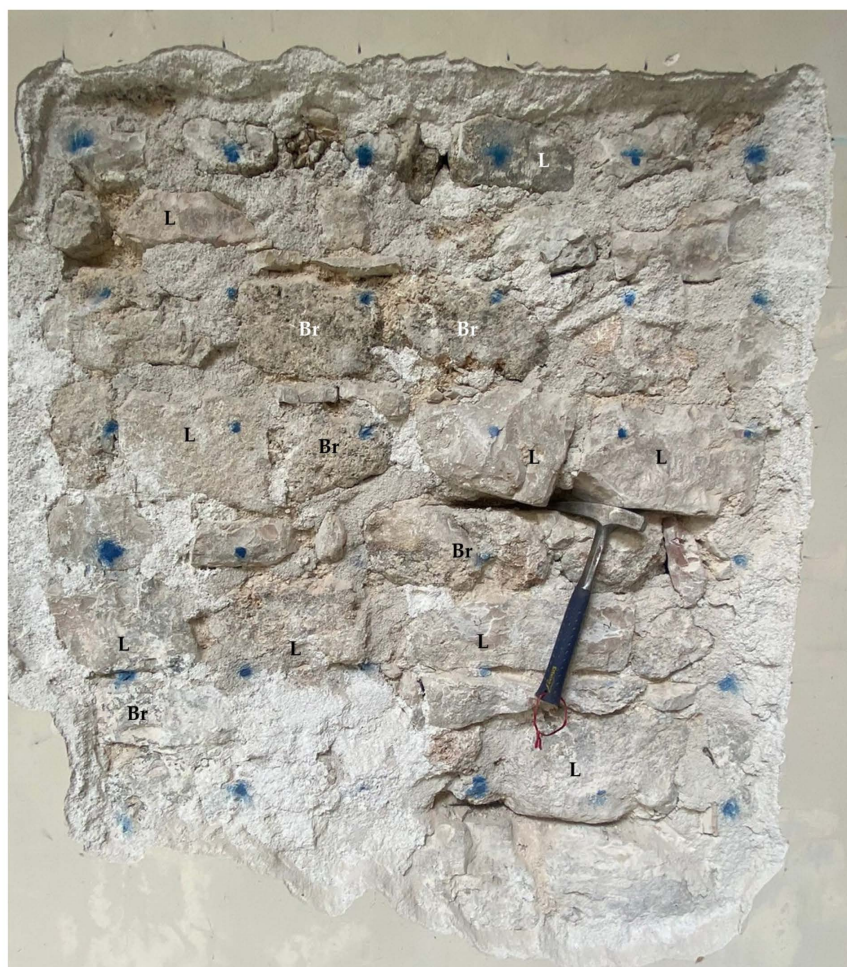


Figure 6. Grid 3, details of lithotypes utilised (1300 A.D.): Br—breccias; L—red and white limestones.



Figure 7. Breccias of cloister pilasters: (A) Two different types of breccia slabs. (B) Details of heterometric and polygenic clasts with red matrix. (C) Surface of breccia with traces of plastering (red line).

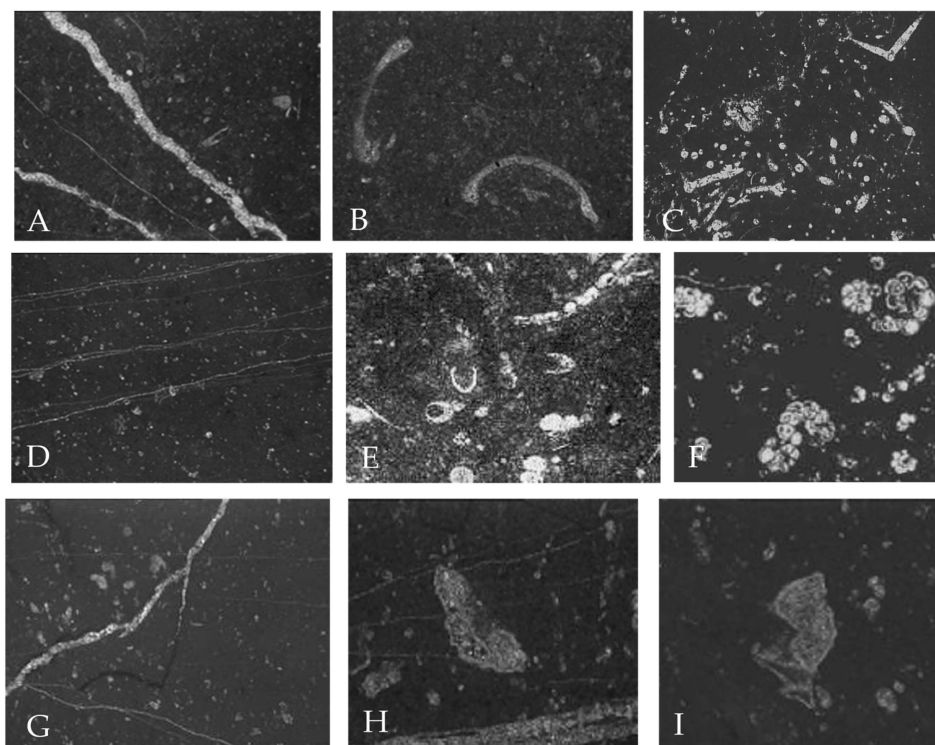


Figure 8. Microfacies of breccia clasts. (A–C) Corniola Fm. mudstone and wackestone with bivalve shells and sponge picules; (D,E) Maiolica Fm. wackestone with Calpionellids and Radiolaria; (F) Scaglia Bianca wackestone with Hedbergellids; (G–I) Scaglia Rossa Fm. wackestone with Globorotalids.

In the first 2.5 ns, approximately, the radargram is mainly characterised by horizontal reflection, lying above another interval of similar reflections showing a gentle apparent dip for an increasing distance down to 6 ns, with a variable lateral continuity. This interval could potentially correspond to two different layers of carbonate breccias arranged in the shape of blocks, whose thickness is around 0.15 m each; the first layer is very regular. Such results were easily validated by analysing the nearby recess visible in Figure 10, which was carved into the wall down to a depth of 0.15 m, allowing for direct observation of the first level of blocks. The remaining part of the radargram (6–18 ns) shows a decrease in the Signal-to-Noise (S/N) ratio, although some strong reflections can still be identified, thus suggesting that similar configurations of carbonate blocks may be present. Even though no direct information regarding this section is available, the EM response may suggest a more heterogeneous inner structure, which could be comparable to what is observable on the adjacent wall, as shown in Grid 3.

After this first phase, fundamental to learning the EM response of blocks made up of carbonate breccias and obtaining a validation via ground-truthing, two GPR profiles were collected over the bottom left-hand cloister column to look for its internal structure, as well as to verify potential differences due to the thickness variations between the pedestal and the shaft (Figure 11).

As for the V1 profile (Figure 11D), three different layers can be recognised: the first one (0.24/0.25 m ca.; interpreted between 0 and 4 ns) is characterised by high-amplitude reflections whose lateral continuity is more distinct for distances between approximately 0 and 22 cm and 44 and 59 cm. The second one (0.45 m ca.; between 4 and 12.7 ns) appears more irregular for the EM response, in terms of both geometry and amplitude. The third layer (0.25/0.26 m ca.; identified between 12.7 and 17.2 ns) shows a thickness compatible with the first one, but with lower-amplitude reflections.



Figure 9. Outcrops of breccias (*Crispo*) and pebbly mudstone (Scagliola) along the way from Norcia to Legogne: (A,D) polygenic breccia with white and red clasts; (B,C) monogenic breccia with red matrix and white clasts; (E,F) pebbly mudstone of Legogne outcrop.

In the case of H1 profile (Figure 11B), the interpretation is slightly different: while a potential first layer with high-amplitude reflections appears to be present, a distinction between the intermediate level and the final one cannot be drawn. As for the intermediate layer, some reflections can be observed at its edges. These signals occur between 2.5 and 10 ns on the left side and between 2.5 and 12 ns on the right one. On the other hand, in the central part of this layer (for a distance between 0.25 and 0.75 m), the GPR reflected signal is strongly irregular, showing a pseudo-arcuate geometry.

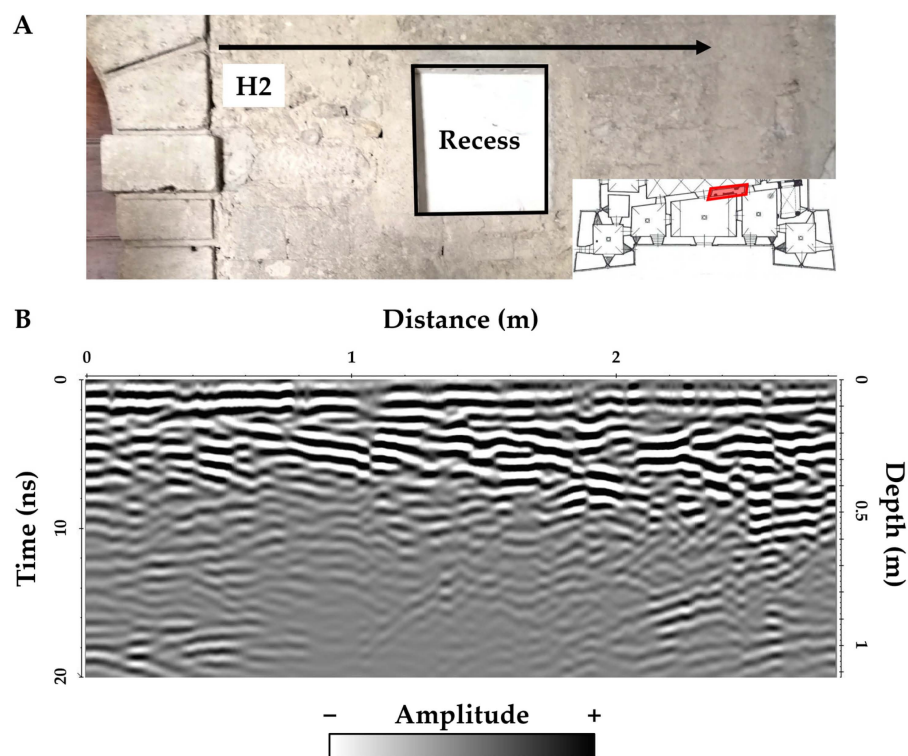


Figure 10. In (A), H2 profiles (black arrow with the tip indicating profile orientation) are surveyed for ground-truthing purposes above the recess (black rectangle) over the external wall, whose position is shown by the red rectangle in the planimetry. In (B), H2 radargram processed using the same workflow described in Section 3. The depth axis is computed considering an EM velocity of 0.112 m/ns, following [9].

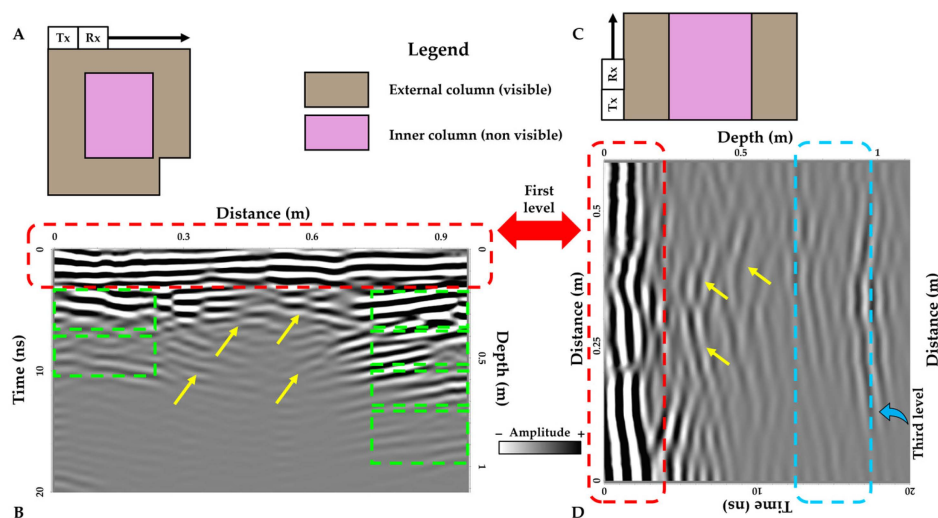


Figure 11. In (A,C), graphical representations of surveyed column for radargrams H1 and V1, respectively. Brown colour indicates the external part of the column that can be directly seen *in situ*, while the pink indicates the inner part that cannot be directly accessed. In (B,D), processed radargrams (H1 and V1, respectively) sharing the same EM response for the first layer of carbonate breccias (red dashed polygon). Yellow arrows point to the examples of irregular signals belonging to the intermediate layer (i.e., inner column). In the case of H1, the green dashed rectangles suggest the possible arrangement of blocks. Instead, in the case of V1, the cyan dashed polygon indicates the deepest recognisable layer (i.e., third level) corresponding to the visible carbonate breccias. Both radargrams are processed using the same workflow described in Section 3. The depth axis is computed considering an EM velocity of 0.112 m/ns. Horizontal exaggeration (for both profiles): $\times 2$.

4.6. GPR Numerical Modelling

Next to the reflections associated with the carbonate breccia blocks, an EM signature characterised by a lower amplitude content and less laterally continuous extension can be recognised in both the V1 and H1 profiles. Such characteristics, together with the documented restorations occurring from the 18th century, might suggest a multi-leaf structure. However, while the presence of carbonate breccias' blocks levels is proven by *in situ* direct inspections, the only possible way to validate the presumed infilling chaotic structure relies on the use of electromagnetic numerical modelling. Therefore, several synthetic models were tested to determine the most probable scenario for both the V1 and H1 profiles. Each simulation was carried out in gprMax [30] using a 900 MHz Ricker wavelet transmitted by a Hertzian dipole, while the antenna offset, traces inter-distance and model cells' dimensions (i.e., dx, dy and dz) were, respectively, 0.1, 0.01 and 0.005 m.

In the case of V1 profile, as shown in the previous section, three different levels were detected. To better investigate such phenomenon from a qualitative viewpoint, the intermediate level was modelled following the two most likely structural models for a column: blocks vs. rubble infilling (Figures 12 and 13).

From the results of synthetic simulations, it is possible to observe how Model A appears overly simplistic to describe the experimental data. Instead, in the case of Model B, some elements do not appropriately match with the experimental data, such as the reflection occurring around 9 ns and the overall weak attenuation of the GPR signal. In the case of Model C, the homogeneous distribution of blocks' physical parameters causes both: a poorly realistic signal pattern in the first 3–4 ns and a too weak attenuation in the imaged rubble portion. In contrast, Model D appears to be the most reliable one for replicating the main EM features that can be seen in the experimental data, for instance: high-amplitude reflections in the first 3–4 ns, a highly heterogeneous signal pattern in the interpreted rubble portion with a lower S/N and, to conclude, a non-perfectly flat rear façade reflection, probably due to local EM velocity variation since the investigated thickness is pretty much constant (details in [9]).

Using an approach similar to the one proposed for Model D, numerical modelling was employed to support the interpretation of H1 profile as well (Figure 14). One difference in this case from V1 is the presence of breccia in the left and right edges of the column too. Nevertheless, the typical EM signature is not always found, as their reflections are lower in amplitude asymmetrically (starting from 6 ns on the left side and from 10 ns on the right one). This condition, along with the most common causes linked to EM energy attenuation, could be explained by a sharp decrease in electrical resistivity. Therefore, the blocks were modelled with different physical parameters to account for this phenomenon.

For V1, the breccia's relative permittivity was computed from the definition of EM velocity, since the thickness was known while the TWT of backside reflection was derived from the radargram. The value, in agreement with the literature values ($4 \leq \epsilon_r \leq 8$, as shown in [29]), was attributed to the clast, while the matrix's ϵ_r was chosen to allow for a small dielectrical contrast. Using the same approach, the rubble's ϵ_r was selected. As for σ , it was chosen after a trial-and-error to calibrate the proper influence of this parameter over the final results. All these values were used in the case of H1 too, with the addition of attenuated breccias that were defined to allow for both a dielectric contrast between materials and strong signal attenuation due to the high electrical conductivity.

Furthermore, another important topic to address is the discrepancy between the experimental antenna central frequency (1500 MHz) and the central frequency used for numerical modelling (900 MHz). This choice was made since frequency spectra of experimental data show a Gaussian-like frequency distribution centred around 900 MHz. Therefore, the selection of 1500 MHz as the central frequency for numerical modelling would have led to

synthetic data with a neat mismatch, in terms of frequency distribution, compared to the surveyed data as shown in Figure 15.

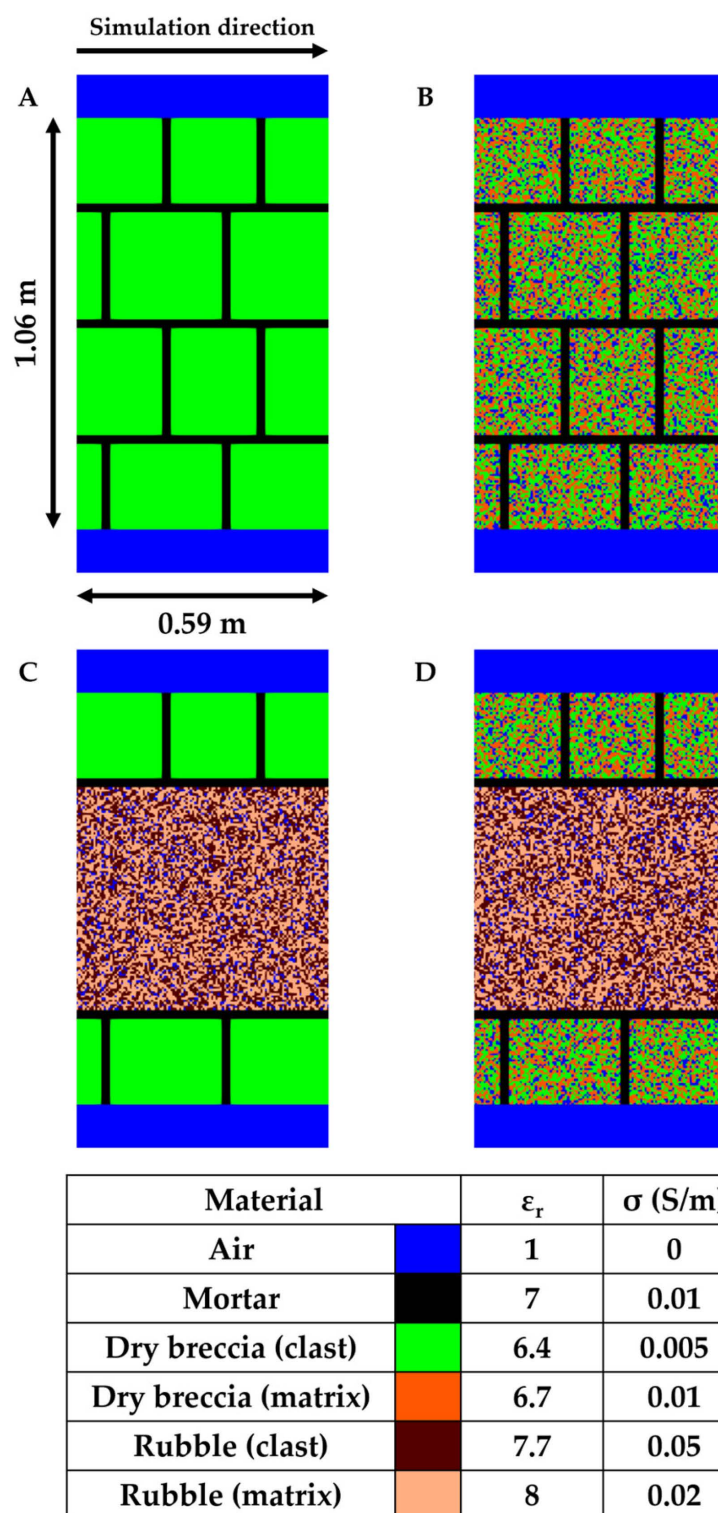


Figure 12. Synthetic models discretised to represent the experimental model (i.e., cloister column). All the models share the same dimensions. In (A), the model is discretised as a set of blocks arranged into levels with homogeneous physical properties (i.e., relative permittivity ϵ_r and electrical conductivity σ). In (B), the same geometry as in A is discretised by assigning random physical parameters to all the blocks. In (C), the model is discretised using two external layers characterised by homogeneous blocks and an inner one made up of rubble infilling. In (D), the same geometry as in C is discretised by assigning random physical parameters to both the rubble (as in (C)) and blocks (as in (B)).

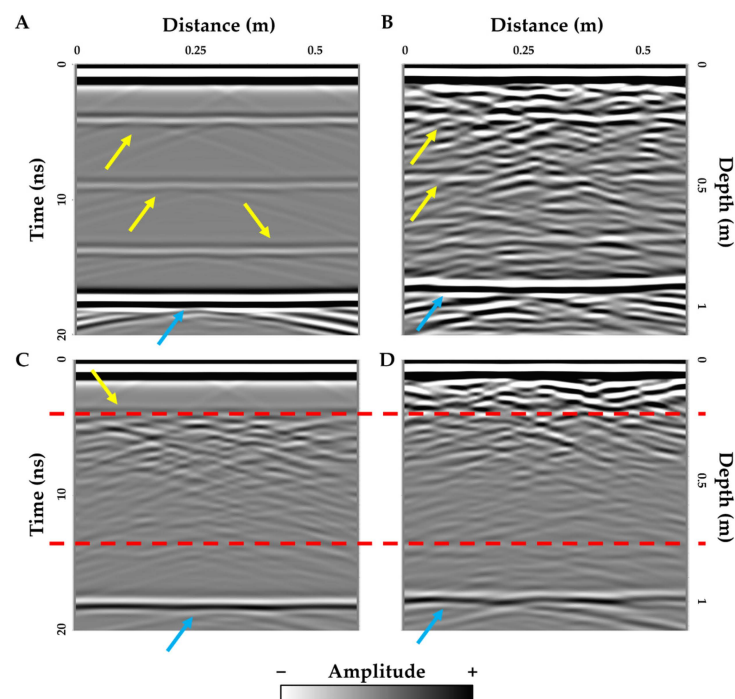


Figure 13. Synthetic simulations with every letter corresponding to the models shown in the previous figure. In (A–C), yellow arrows indicate recognisable intermediate reflections while blue arrows in (A–D) indicate the rear façade reflection (caused by column–bottom air layer interface). In (C,D), red dashed lines mark the upper and lower boundary between the breccias and rubble. Finally, data are processed to cut the time window beyond 20 ns (occurring after rear façade reflection) and to recover amplitudes by application of a suitable recovery function. The depth axis is computed considering an EM velocity of 0.112 m/ns. Horizontal exaggeration (for both profiles): $\times 2$.

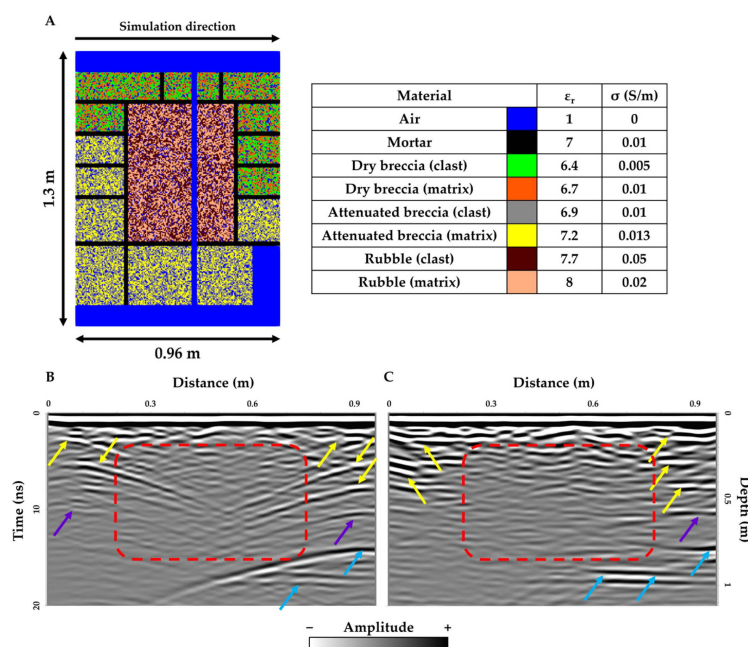


Figure 14. In (A), synthetic models are discretised to represent experimental model (i.e., cloister column). All materials shared between V1 and H1 models have same physical parameters. Data are processed by: cutting time window to 20 ns (B) and applying migration (C) using Stolt algorithm (scaling factor: 1.5; EM velocity: 0.11 m/ns). Yellow arrows indicate diffractions from dry breccias, purple ones diffractions from attenuated breccias, and blue ones rear façade reflection (caused by column–bottom air layer interface). Red dashed polygon encloses rubble portion. Depth axis is computed considering EM velocity of 0.112 m/ns. Horizontal exaggeration (for both profiles): $\times 2$.

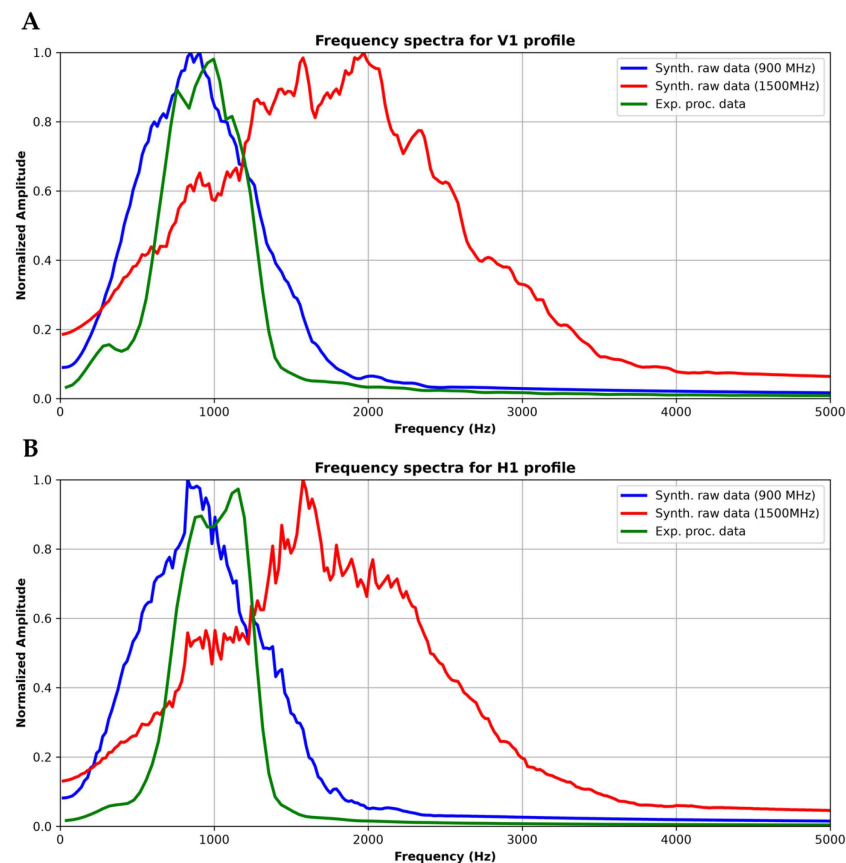


Figure 15. Frequency spectra for experimental-processed V1 and H1 profiles (in green), together with synthetic simulations (central frequencies: 900 MHz in blue and 1500 MHz in red). In (A), V1 synthetic data refer to Model D in Figure 12. In (B), V1 synthetic data refer to Model A in Figure 14.

5. Discussion and Conclusions

5.1. Provenance Area of Geomaterials

In the Norcia area, various types of sedimentary limestone rocks are identified, which were extracted from the surrounding areas, in the valleys connecting Norcia with Preci and with Serravalle, as well as in more distant areas, such as Monte Vettore [6]. Many of the extraction sites have now been erased both by exploitation and by the morphological evolution of the territory, ravaged by a continuous history of earthquakes, and by the anthropisation of the area; however, there remain scars and anomalies in the rock outcrops that suggest a targeted extraction intervention. The Crispo lithology that comprises all different types of breccias is the most utilised in the Norcia buildings. Limestone breccias with clasts of white and pink limestone are found in various locations within the Nursine area, mainly as accumulations of cemented debris at the foot of mountainous and hilly slopes (Figure 9).

The Nursine area is configured as an almost inexhaustible source of lithoid materials, unfortunately subject to strong and intense earthquakes that complicated the lives of the quarrymen with landslides and the burial of the quarries. The quarried material often appears intensely fractured. The layers, even if seemingly in good condition, frequently show veins of calcite that mark points of fragility, ready to open during chiselling work.

We summarise the extractive areas of lithoid materials currently identifiable and indicated (see toponyms) on the geologic map in Figure 3:

- Legogne area and Rodolfano (Fiano): Extraction of white Maiolica and Scaglia Bianca limestones; pink–red limestones of the Scaglia Rossa with levels of pebbly mudstone

(Scagliola) and white detrital levels. Monogenic and polygenic breccias with white and/or red matrix.

- Biselli area: Extraction of red limestones from the Scaglia Rossa and partially cemented slope debris (red breccias).
- Monte Belvedere area: Extraction of red and white limestones of the Scaglia Rossa and Scaglia Bianca.
- Poggio Valaccone area: Extraction of Calcari a Posidonia, Calcari Diasprigni, and Maiolica.
- Monte Vettore area—Fosso Mergani (not included in Figure 3): Possibility of extracting white and hazelnut (Corniola Fm) limestones and grey limestones with soft clasts (pebbly mudstone) interbedded with the Corniola Fm.

For the breccia quarries, it is not easy to identify the exact location, unless there are still outcrops, as in the case of the Legogne area (Figure 9) (Strada Norcia–Legogne).

The main sources of cemented breccias are found at the foot of the mountain slopes overlooking the Piano di Santa Scolastica and along the valley (Figure 3) that connects Campi with Norcia, where they form large debris cones. Their distribution has allowed the Crispo lithotype to be extracted in large quantities, making it the most used lithotype over the centuries. Massenzi [6] indicates that there are only two active stone quarries in the area: the pink limestone (Scaglia Rossa) quarry in the Biselli district (still clearly visible even if inactive) and the other in the Quattro Cascine locality (of which we have found no traces) opposite to Norcia, which could provide good coarse stone, used in the past to build various buildings, including the Castellina. The sites of greatest exploitation are within a radius of no more than 9 km from Norcia; the areas of Preci and the Castoriana Valley can be reached after a journey of approximately 13 km, while the extraction areas of Monte Vettore and the Fosso Mergani (Piano Grande) are much farther and require a tortuous and difficult route along mountain roads.

5.2. GPR Experimental and Synthetic Data

The interpretations that can be provided for the H1 and V1 radargrams are partially different in the light of several factors, which are: the EM observed features, profile orientation, and column thickness variation. As for V1, the first and third layers can be ascribed to carbonate breccia blocks. This finding is certainly reliable thanks to the direct *in situ* inspection, since all columns' faces are accessible. Nevertheless, while in the case of the first layer this information is corroborated by the EM signature (which is comparable to the one observed for profile H2), in the case of the third layer, such an inference cannot be made as the signals show different characteristics, probably influenced by scattering phenomenon causing a decrease in signal strength. On the other hand, the EM response for the intermediate layer (yellow arrows in Figure 11) suggests an actual internal variation, not fitting with regular levels of the carbonate breccia blocks, but more similar to an heterogeneous structure, like a rubble infilling. In the case of H1, on the other hand, the first layer is easily recognisable as a breccia level from both the EM signature and visual inspection. Analogously, lateral blocks (green dashed rectangle in Figure 11) can be identified even though the different levels of signal attenuation between the left and right edges suggest a lateral variation in the electrical resistivity. Unlike V1, in this case the final layer, which can be directly seen in the field (carbonate breccias), cannot be identified, as both rubble–breccias and breccias–air interfaces are not discernible. Once again, the rubble is characterised by the heterogeneous EM response in terms of geometry and amplitude.

In GPR applications for cultural heritage study, the presence of rubble-filled structures between more homogeneous layers has been documented in columns [31], walls [32] and bridges [33]. As demonstrated in [32], different core structures have been found, all of

them having a specific EM signature. In this case study, the filling materials are probably voidless, since no high-amplitude reflections associated with well-known features, such as polarity reversal [34] and hyperbolic diffractions, can be identified. Nevertheless, the rubble and breccias seem to be slightly different in terms of EM parameters, since several interfaces can be recognised. For rubble infilling, a typical observed EM response is represented by scattered signals that can be caused by different sources, such as rough surfaces of inner ashlar [35], increase in water-saturated pores [36], geometrical variations in aggregates [37] and material heterogeneity of infilling [38], with the last two probably being the most reasonable ones for this case study.

Next to scattering, another factor affecting signal attenuation is the electrical resistivity content. As a matter of fact, as pointed out by synthetic simulations, small-to-moderate variations in the electrical conductivity content can strongly decrease the EM signal energy, therefore causing weaker reflections due to energy dissipation [29]. Regarding this specific application, a numerical approach provides a wide support for the interpretation step, with particular focus on the understanding of the internal portions of the studied column. The synthetic results show how, although the geometry of the model is mainly fixed, the choice of fair physical parameters (i.e., relative permittivity and electrical conductivity) can still be insufficient if heterogeneous mediums are modelled as homogeneous. This approach can be valid not only for mediums having supposedly variable (geometrically and/or physically) properties, like in the case of rubble infilling, but also for blocks that are expected to bear a higher degree of both geometrical and physical homogeneity, though in cases like the studied one, this condition is not met.

Even though this work focuses mainly on the response of blocks and rubble, an important role, in terms of EM signature, is played by mortar. In particular, degradational processes occurring to this material may produce opposite outcomes. For example, mortar erosion is often responsible for larger void volume creation that can cause a relevant increase in the reflection strength [39]. On the opposite side, mortar loss, together with capillary fractures, can facilitate moisture spreading, which strongly decreases the electrical resistivity content while the EM attenuation coefficient increases [36,40]. Moreover, mortar can sometimes be made of up clay materials, and so, due to their high electrical conductivity, attenuation can be caused by the mortar itself rather than its degradation [41].

In conclusion, the set of information provided by the petrological analysis is extremely precious not only from a historic-architectural point of view but also from a geophysical perspective. As a matter of fact, next to the achieved results, additional interesting developments could rely on monitoring the degradational state of different materials, after an initial classification (both petrographic and geophysical) is provided, thus testifying to the significance and the enormous potential of multi-methodological integrations in the field of Geosciences.

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