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A Digital Workflow for the Diachronic Reconstruction and Virtual Re-contextualization of Fresco Palimpsests in the Santa Maria in Via Lata Hypogeum

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Abstract

This study presents a digital workflow for the diachronic reconstruction and virtual re-contextualization of fresco palimpsests in the Santa Maria in Via Lata hypogeum, Rome. By integrating TLS and photogrammetric data, historical documentation, stratigraphic interpretation and the Extended Matrix protocol, the workflow reconstructs the 6th-century architectural setting as a spatial framework for the decorative phases between the 6th and 11th centuries. It formalizes the links between surviving masonry, detached fresco fragments and virtual stratigraphic units, making explicit the evidential chain from measured data to reconstruction hypotheses. The result is a transparent methodology for fragmented, displaced and stratigraphically superimposed heritage evidence.

Keywords

Diachronic reconstruction, Extended Matrix (EM), Virtual restoration, Virtual re-contextualization, 3D Survey, Fresco palimpsests

1. *Introduction*

Located in the historic center of Rome, the complex of Santa Maria in Via Lata represents a highly stratified archaeological and architectural context, where Roman, early medieval and later phases coexist within a limited subterranean space. Early modern sources associated the hypogeum with the memory of St. Paul's house arrest and described it as the "Primo Trofeo della S.ma Croce", contributing to the long-standing sacred significance of the site. Over time, successive functional, liturgical and architectural transformations produced a complex palimpsest of masonry structures, wall paintings and later interventions (Fig. 1).

Archaeological and historical studies have shown a complex diachronic evolution of the site, from a Roman portico and commercial structure to an early medieval *diaconia* and, later, to the upper church. The transformation into a diaconal space was accompanied by successive decorative campaigns between the 6th and the 11th centuries. These phases are particularly challenging to interpret because the surviving wall paintings are fragmentary, stratigraphically superimposed and, in many cases, physically separated from their original architectural context.

The stratigraphic studies carried out by Bordi provided a fundamental chronological and interpretative framework for the wall-painting palimpsests of the hypogeum, clarifying the relationship between masonry supports and pictorial layers. However, the spatial re-contextualization of detached fragments remains problematic. Previous digital reconstructions, often based on schematic or two-dimensional documentation, could not fully account for the geometric irregularities, non-orthogonal walls and structural deformations of the subterranean environment.

Fig. 1: View of the facade of Santa Maria in Via Lata. Source: ACAS3D Soluzioni Digitali Srl (2010)

As a result, the original position of many fragments has remained a plausible interpretative hypothesis rather than a metrically constrained reconstruction.

In this context, digital reconstruction techniques, particularly when implemented through Virtual Reality (VR) and immersive environments, can support archaeological analysis by enabling the spatial visualization and critical examination of lost, transformed or degraded contexts (Bruno et al., 2010; Guidi & Russo, 2011; Sciuto et al., 2023). Nevertheless, such visualizations must not be understood as neutral or self-evident representations. Their scientific reliability depends on the explicit distinction between measured evidence, documented information and interpretative hypotheses, in accordance with the principles of intellectual transparency promoted by the London Charter (Denard, 2009). The Extended Matrix (EM) framework addresses this requirement by extending archaeological stratigraphic logic to virtual environments, linking reconstructed elements to their sources, reliability levels and underlying assumptions (Demetrescu, 2015; Demetrescu et al., 2016; Demetrescu & Fanini, 2017; Demetrescu & Ferdani, 2021).

By implementing the Extended Matrix protocol within a survey-based digital workflow, this study aims to bridge the gap between museum-preserved fresco fragments and their original architectural setting. TLS and photogrammetric data provide a metrically controlled spatial framework in which archaeological traces, archival documentation and stratigraphic interpretations can be compared and tested. The proposed approach does not simply produce a visual model; rather, it establishes a verifiable and traceable workflow in which each reconstructed element is linked to its evidential basis, metric constraints and degree of reliability. Through the EM structure, the different historical and decorative phases can be catalogued, queried, verified and, when necessary, updated without losing the information associated with previous interpretations. Thus, the reconstruction becomes a dynamic and transparent research archive, documenting the passage from measured data to virtual hypothesis while preserving the full chain of evidence and interpretation.

2. *Research context and state of knowledge*

The modern archaeological documentation of Santa Maria in Via Lata began with the systematic investigations conducted by Luigi Cavazzi between 1904 and 1914. His work is particularly relevant for the present study because it recorded the physical relationship between the frescoes and the earlier architectural structures before many later interventions further altered the hypogeum. Cavazzi's observations therefore provide an essential documentary baseline for reconnecting displaced pictorial fragments with their original architectural context.

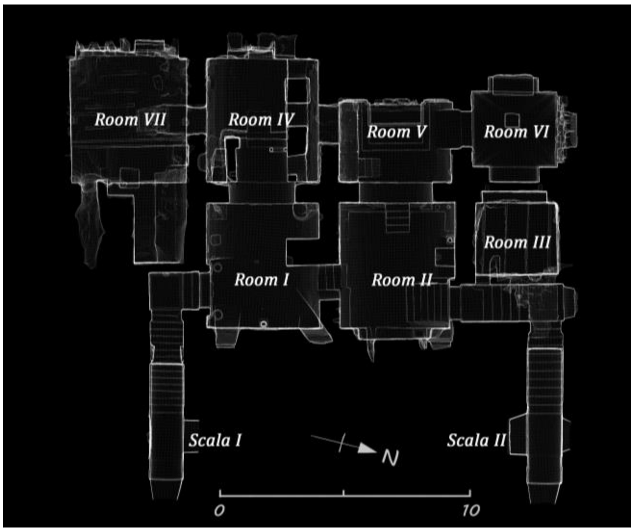

Fig. 2: Orthographic top-view of the hypogeum generated from TLS data (X-ray mode) (elaboration by ZS).

Bordi (2015) emphasized the importance of the "*Κοσμάς*" inscription in the west window of Room IV, interpreting it as material evidence for the early medieval function of the area as part of a diaconal complex (Fig. 2). This evidence is significant because it links the architectural space, the pictorial decoration and the liturgical use of the hypogeum. It also confirms the need to interpret the painted surfaces not as isolated artworks, but as components of a broader architectural and functional transformation.

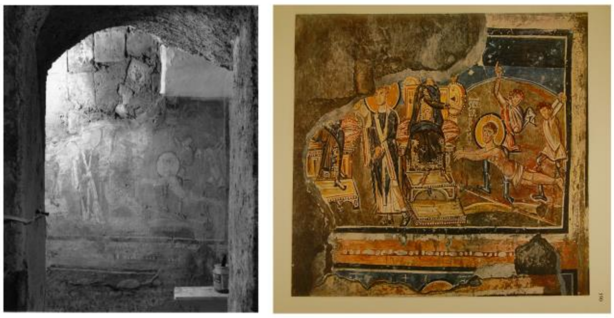

Fig. 3: (Left) Image of the paintings before their dismantling. Source: Istituto Centrale per il Restauro (1959-1961); (Right) Joseph Wilpert's watercolor elaborations. Source: Wilpert 1916, p.698-700.

A decisive break in the physical continuity between the mural paintings and their architectural setting occurred during the large-scale fresco detachment campaign (*stacco*) carried out in the 1960s by the Istituto Centrale per il Restauro (ICR). Following this intervention, many wall-painting fragments were removed from the hypogeum and transferred for conservation; they are now preserved and displayed at the Museo Nazionale Romano, Crypta Balbi (Meneghini & Messineo, 2001). Although this operation displaced the fragments from their original in situ context, the associated technical archives document the original boundaries and contours of the paintings before their removal and include numerous black-and-white photographs. These archives constitute a crucial source for their digital re-contextualization. The comparison between the historical photographic record and Wilpert's watercolor elaborations is shown in Fig. 3.

The work of Joseph Wilpert (1916) represents another important level of visual documentation. His method combined large-format black-and-white photographs with watercolor additions produced in the presence of the original murals. This hybrid technique ensured that the visual recording benefited from the geometric rigor of photography, capturing the chromatic nuances of the frescoes before their deterioration in the 20th century (Fig. 3). Bordi (2016) points out that Wilpert's method of documentation was primarily oriented towards iconographic identification: he treated frescoes as isolated flat artworks rather than as architectural components with stratigraphic properties; he focused mainly on image identification while ignoring the boundaries of the underlying plaster (*arriccio*), the physical joints (*pontate*) and the overlapping logic between the different painting layers (Fig. 4). This led to deviations in the chronological dating and spatial positioning of some scenes in particular.

Fig. 4: Overlapping stratigraphic murals from S. Maria in Via Lata: (Left) Room V fragment (at Crypta Balbi) with three distinct layers; (Right) Room II apse, showing two distinct layers. Source: Bordi 2015, p.203-216.

Building on these documentary and visual sources, Bordi (2015) established a reference stratigraphic framework for the site's palimpsest walls (*pareti palinsesto*). Her analysis moved beyond a primarily iconographic reading of the frescoes by focusing on the material and stratigraphic relationship between pictorial layers and architectural supports. Through the study of superimpositions, wall imprints, plaster boundaries and detachment archives, she defined the chronological sequence of the decorative cycles from the 6th to the 11th centuries and clarified their connection with the architectural and liturgical transformations of the hypogeum. Her work therefore provides the main historical and interpretative basis for the present study. However, since this reconstruction necessarily relied on analogue documentation, archival records and schematic spatial supports, the geometric re-contextualization of the fragments remained only partially addressed. In particular, the complex underground space was represented through simplified geometric surfaces that could not fully account for structural deformations, irregular masonry and non-orthogonal wall geometries. The present contribution seeks to complement Bordi's stratigraphic framework by integrating it within a metrically controlled 3D environment.

The stratigraphic overlapping of fresco layers is a widespread phenomenon within Roman underground sites. Beyond Santa Maria in Via Lata, the subject of this study, similar "visual palimpsest" phenomena have been extensively documented in sites such as Santa Maria Antiqua (Bordi, 2021) and San Clemente (Osborne, 1984). These precedents underscore the necessity of employing stratigraphic analysis when addressing the decorative programs of such sites, as the complex layering reflects continuous historical interventions and functional transformations.

In terms of spatial scale, the studies of Pollio (2020) and Valenti (2011) provide an important reference for the original depth of the site, indicating a datum of approximately -5.0 m. This theoretical value, based on stratigraphic logic and in situ observations, defines the original spatial depth of the hypogeum at a macro level. However, the definition of a general depth datum does not in itself resolve the problem of reconstructing the precise spatial boundaries of the decorated surfaces. A major challenge remains the accurate re-contextualization of detached fresco fragments within a metrically controlled 3D environment (see Section 3.2 and Fig. 9). This issue is addressed in the methodological workflow presented in Fig. 5 and further developed in the survey-based comparisons between TLS data and historical plans shown in Fig. 6.

The data mismatch between such digital hypotheses and physical reality is the main academic bottleneck for restoration to move from schematic to evidence-based. The methodological contribution of this study lies in the integration of high-density 3D survey data and the Extended Matrix protocol within a single interpretative workflow (Demetrescu, 2015; Demetrescu et al., 2016; Demetrescu & Fanini, 2017; Demetrescu & Ferdani, 2021). Rather than relying exclusively on idealized geometric assumptions, the proposed method anchors stratigraphic hypotheses to measurable spatial evidence, while explicitly documenting the degree of reliability of each reconstructed element. This approach reduces the risk of misalignment between detached fragments and architectural surfaces and provides a traceable framework for the digital reconstruction of complex multi-layered heritage contexts.

3. Methodology

This research uses a mixed methods approach combining quantitative metric data with qualitative archaeological inference. The

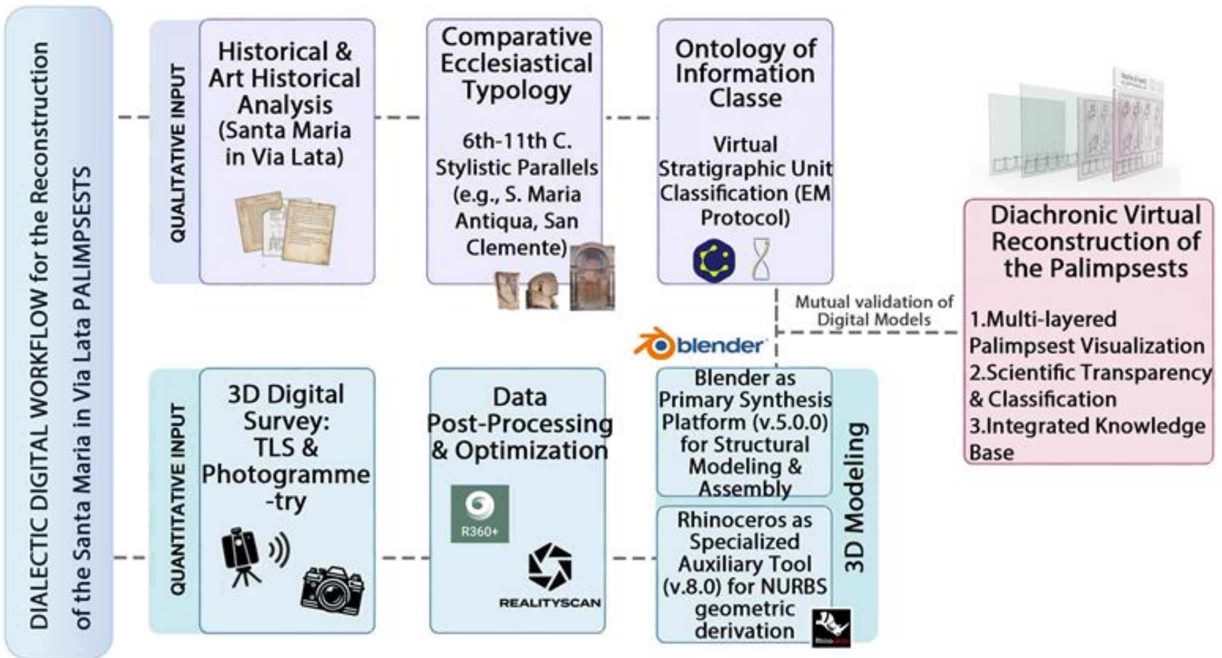

Fig. 5: Methodological workflow: from 3D scanning and stratigraphic analysis to diachronic virtual reconstruction (elaboration by ZS).

methodology is structured as a multi-layered workflow in which 3D survey data, archival documentation, stratigraphic analysis and reconstruction hypotheses are progressively integrated within a controlled digital environment. The aim is not only to generate a virtual model, but to make explicit the evidential chain that connects measured data, historical sources, interpretative reasoning and reconstructed elements (Fig. 5).

The workflow begins with the construction of a metric spatial framework through TLS and close-range photogrammetry. This framework provides the geometric basis for documenting the current state of the hypogeum, including wall irregularities, traces of detachment, plaster remains and structural deformations. Historical archives, previous surveys, iconographic comparisons and stratigraphic studies are then used to interpret the missing or displaced elements. These sources are not treated as interchangeable evidence, but are evaluated according to their nature, reliability and relationship with the measured 3D data.

The transition from hypothesis to virtual model is centralized in Blender (v. 4.3.2), the primary platform for structural modeling, stratigraphic reasoning, and assembly. Within this workflow, Rhinoceros 8.0 is a specialized auxiliary tool used only for NURBS based geometric derivation of specific complex curves where mathematical validation is needed. These geometries are then integrated back into Blender to complete the digital restoration. Finally, the integration is governed by the EM protocol. Using the EMtools (v.1.4.3) plugin, the methodology links each 3D component to its qualitative or quantitative provenance. In this way, each 3D element could be associated with its source data, interpretative status and level of reliability.

3.1 Integrated 3D Survey and High-Resolution Texturing

To overcome the limitations of previous schematic reconstructions, the study established a metrically controlled spatial basis through the integration of Terrestrial Laser Scanning (TLS) and close-range digital photogrammetry. This multi-source survey strategy was designed to document both the geometric configuration of the hypogeum and the visual characteristics of its stratified surfaces, providing a reliable reference for the subsequent reconstruction and re-contextualization processes.

By digitally aligning the historic survey plans of Cavazzi (1908) and Krautheimer et al. (1971) with our newly derived 3D survey plans (Fig. 6c, d), this approach explicitly illustrates the spatial relationship between legacy documentation and current site conditions, highlighting historical geometric discrepancies while verifying the layout continuity.

The integrated 3D documentation campaign, encompassing both TLS and photogrammetry, was executed in technical collaboration with Acas3D Soluzioni Digitali Srl. The TLS survey was performed using a Leica RTC360 and a Faro Focus S150 laser scanner. The survey plan aimed to achieve full coverage of the target object, keeping shadow zones below 5% of the total volume. A total of 64 scan stations were acquired at a scanning density of 3 mm at 10 m, and cloud-to-cloud algorithms were used for data registration (Fig. 6a). During data acquisition, the scanner maintained a distance of approximately 150 cm from the subject. Due to the complex spatial layout, the stations were densely positioned with an average baseline of approximately 200 cm. The instrument height was varied via the tripod during acquisition to detect low-visibility points. Individual scans were performed with high overlap to minimize cloud-to-cloud errors, producing a complete point cloud dataset of 818.4 million points. Point-cloud analysis in CloudCompare indicated a mean point spacing of approximately 1.25 mm on the main archaeological surfaces. This value refers to the local sampling density of the registered point cloud and should not be confused with the nominal instrumental resolution or with the overall survey accuracy. This level of point density allowed the documentation of non-orthogonal walls, surface irregularities and structural deformations that are often simplified or lost in two-dimensional representations.

Subsequently, a high-resolution photogrammetric survey was conducted to generate a metric 3D model and orthophoto bases for art-historical analysis.

The target pixel size for the orthophotos was set to 1 mm. Image acquisition utilized a full-frame Nikon D850 (45.7 megapixels) equipped with 35 mm and 50 mm fixed focal lenses.

The primary survey was completed using the 50 mm lens; the 35 mm lens was deployed exclusively for complex geometries such as tunnels and restricted interiors. All images were shot handheld

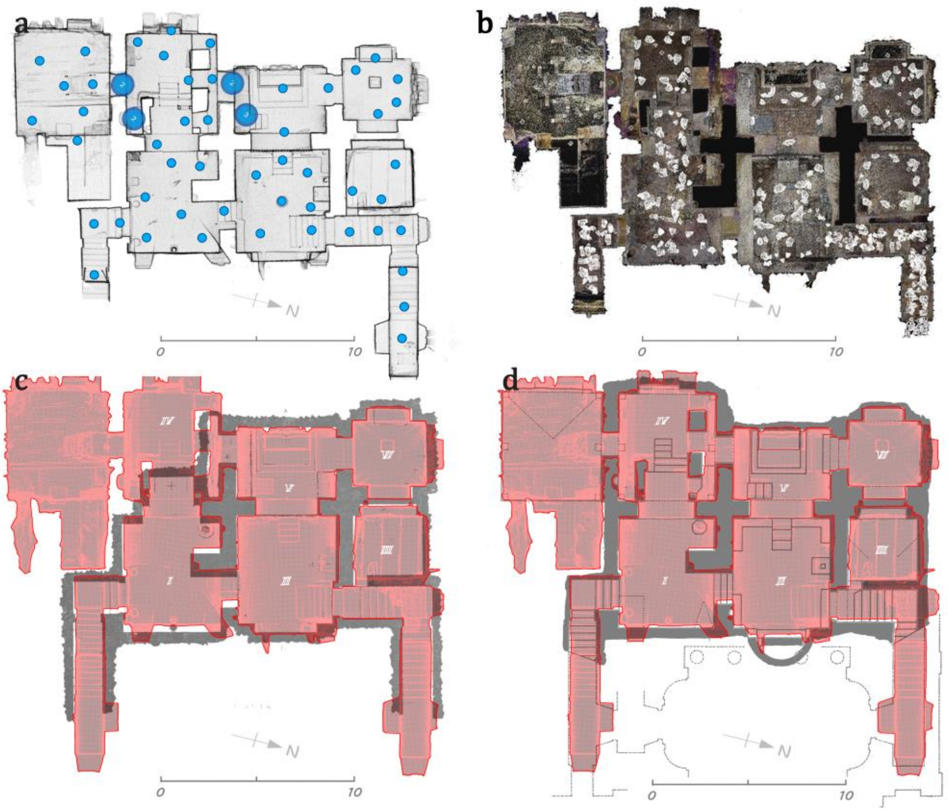

Fig. 6: 3D digital documentation of the Crypt of Santa Maria in Via Lata. Top: (a) TLS scanner positions; (b) Photogrammetric acquisition paths. Bottom: Digital overlay of TLS survey with hand-drawn survey plans by: (c) Cavazzi (1908) and (d) Krautheimer et al. (1971) (elaboration by ZS)

without a tripod at a fixed shutter speed of 1/250 s, with the aperture maintained between f/10 and f/14, utilizing a camera-mounted Godox AR400 ring flash and Lupo 5600K LED panels. The average shooting distance was maintained at 150 cm. For close-up or distant shots, the flash intensity was adjusted to achieve colorimetric uniformity. An X-Rite ColorChecker target was photographed whenever ambient lighting shifted significantly. Through this strategy, the average Ground Sample Distance (GSD) achieved was 0.2 mm. A total of 5,796 RAW (.NEF) images were captured, ensuring the required accuracy for the subsequent orthophoto generation (Fig. 6b).

The active TLS point clouds and close-range photogrammetric datasets were jointly processed within RealityScan (formerly RealityCapture) to generate a combined, high poly triangular mesh mapping the complex geometries.

The uncompressed baseline reconstruction yielded an ultra-high-poly master mesh comprising 481 million polygons. To ensure geometric and metric control while facilitating real time visualization and multi-disciplinary cross platform editing (such as in Unity 3D), a multi-stage decimation and retopology workflow was executed. The 481M master mesh was initially downsampled to a 100 million polygon intermediate model texturized with 98 high-fidelity 16K resolution texture maps.

This model was subsequently retopologized to produce a final low poly proxy of 1 million polygons equipped with ten 8K resolution texture maps. This 1M configuration optimized the physical file size to approximately 300 MB, guaranteeing computational efficiency for secondary software comparison and geometric measurements without deviating from the metric accuracy and positional tolerance of the original 481M high poly baseline. While the point spacing and GSD describe the dataset sampling density rather than the absolute instrumental accuracy, the resulting 3D model provides a metrically controlled spatial framework to constrain and verify reconstruction hypotheses. Within the EM-based workflow, these digitized in situ elements were classified as primary physical evidence and represented in red, forming the basis for subsequent reconstruction hypotheses.

3.2 Structural Reconstruction: From Traces to Inference

The virtual reconstruction of the 6th-century architectural configuration was based on the cross-referencing of multiple categories of evidence: 3D survey data, historical documentation, in situ masonry remains and displaced fresco fragments preserved in museum collections. This comparative approach was adopted to ensure that reconstructed elements were not derived from a single source, but from the convergence of metric, archaeological and documentary evidence. Taking Room II as an example, the core challenge of the reconstruction lies in restoring its vanished apse structure. According to historical records, this apse was completely backfilled and blocked with masonry in the 17th century to support the porch of the upper church, leaving its spatial form concealed for centuries. It was not until 1961, with the support of Richard Krautheimer, that Carlo Bertelli rediscovered this lost structure through stratigraphic trial trenches (*saggi*) excavated into the masonry of the east wall (Krautheimer et al., 1971). To scientifically determine the scale and morphology of the apse, this study utilized digital tools to perform a geometric validation of this archaeological discovery. First, through meticulous observation of the 3D point cloud model, we precisely identified four existing cavity traces on the current blocking wall. Although the 1961 records mention that Bertelli conducted three trial trenches (Fig. 7), scanning reveals a more complex field condition: in addition to the three primary deep trenches, an associated shallow trace exists (S4). This phenomenon may stem from local structural adjustments during the 1961 exploration or represent a negative feature left over from the 17th-century modifications.

Fig. 7: 3D scanning model of the East Wall in Room II of the crypt of Santa Maria in Via Lata. Highlighted, the four cavity traces identified S1, S2, S3 e S4 (elaboration by ZS).

By analyzing the spatial distribution of these cavities, they were determined to be vestigial nodes of the original apse arch or support structures, providing critical physical anchor points for the reconstruction.

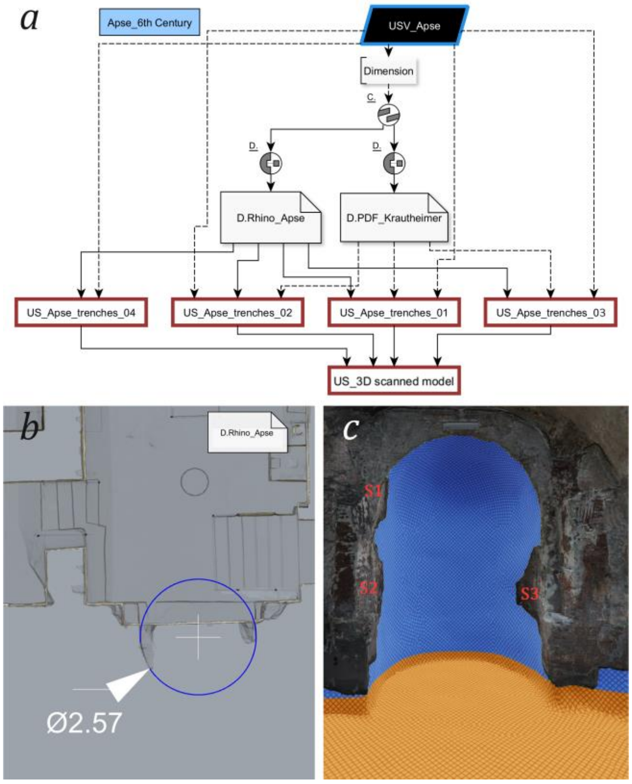

Fig. 8: Multi step virtual reconstruction process of the concealed Apse. (a) EM evidence mapping defining the archaeological logic;(b) The diameter of the Apse is determined through a three-point circle fitting on the TLS-scanned trenches in Rhino; (c) Virtual reconstruction model with thematic color-coding based on the EM protocol (elaboration by ZS).

Building upon this, and leveraging the non-contact advantages of 3D scanning, a horizontal section analysis of the point cloud was performed on the east wall area from a top-view orthogonal projection. Even with the wall being heavily blocked and modified, the scan data captured a distinct curvilinear trend in the surviving wall footings and structural edges. To reconstruct the spatial logic of the original architecture, the study focused on deriving the primary geometric parameters of the apse. The survey dataset was imported into the Rhinoceros 8.0 software environment to perform a NURBS-based geometric analysis. By identifying the specific coordinates of the wall footings within the orthographic top view, a three-point circle fitting algorithm was applied to determine the diameter and center point. This finding replaces the vague conjectures regarding the apse's proportions found in previous schematic drawings, anchoring the 6th-century architectural reconstruction to a measured baseline (Fig. 8).

This process provides a metrically controlled geometric basis for the virtual reconstruction of the architectural space and establishes a 1:1 spatial reference for the subsequent line-drawing reconstruction (Fig. 9) and the re-positioning of documented fresco fragments. Within the Extended Matrix framework, these structurally inferred elements are coded in blue as virtual stratigraphic units (USV/s), distinguishing them from directly preserved remains and making explicit their interpretative status within the reconstruction process.

Regarding the 6th-century floor levels, this study calibrated elevations by synthesizing historical evolution logic with on-site measured data. Multiple archaeological records establish the original depth datum for this area: according to Pollio's (2020) interpretation of Corbett's survey, the original elevation of the Via Flaminia is situated at approximately -5.3 m (Fig. 10). Valenti (2011), through an in-situ investigation of an ancient well (*Pozzo*) within the site, confirmed that its bottom reached the original Roman period aquifer, physically validating this depth datum at approximately -5.0 m. Furthermore, beam holes preserved on the original stone columns confirm the existence of a Roman period timber mezzanine. Historical documents verify that these structures were dismantled during the site's 6th-century transformation into a *diaconia*, implying that the interior clear height at that time should

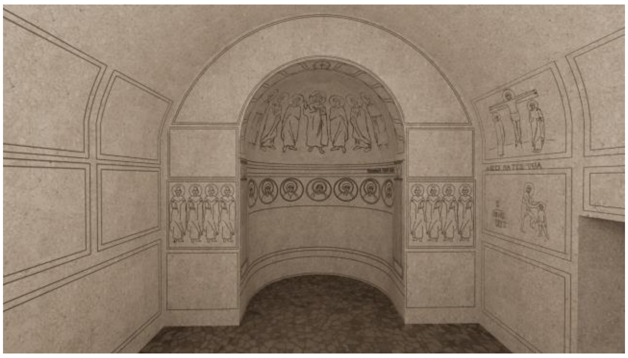

Fig. 9: Final reconstruction rendering of the Apse, synthesized by the authors in Blender. The decorative scheme is based on a CAD restoration, derived from the author's 3D metric data and typological analysis.

have approximated the building's original structural height.

Addressing the current inconsistent floor heights across the subterranean rooms, this study argues that these discrepancies reflect a divergence between overall urban evolution and localized human intervention. To analyze this, S. Corbett's historical elevation drawing (Pollio, 2020) was digitally superimposed onto our 3D TLS dataset (Fig. 10). Corbett's data explain that due to alluvial flooding, the average urban ground level in the 11th century rose by about 1.0 m compared to the Roman period, and the site interior underwent intentional backfilling. However, as demonstrated by the cross-sectional alignment in Figure 10, 3D scanning shows that the current interior clear height of Room II and Room IV remains around 4.6 m. when accounting for the overhead structural thickness, this value aligns almost with the original -5 m datum, proving that these key interior areas

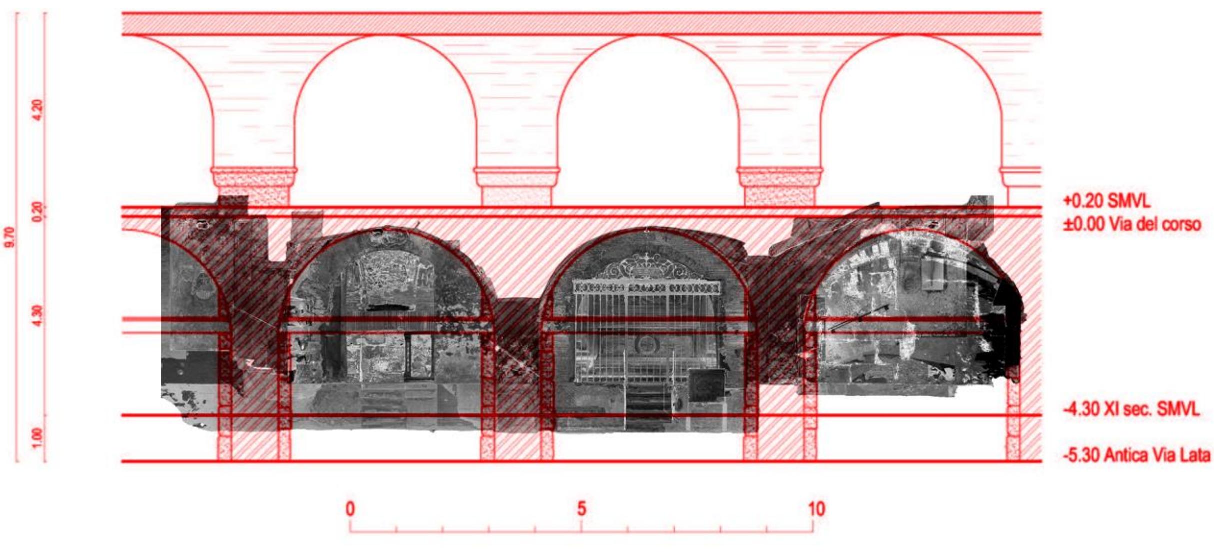

Fig. 10: 3D scan data superimposed on S. Corbett's elevation drawing, showing the difference between urban stratification and interior heights (Graphic re-elaboration by ZS, based on Bellini 2017 and Corbett 1973).

Fig. 11: a) Current state of Room V. Source: ACAS3D Soluzioni Digitali Srl; (b) Image of the paintings before their dismantling. Source: ICR, 1959-1961; (c) Virtual repositioning of museum frescoes below the current floor level, integrated with conjectural line drawing restoration (elaboration by ZS).

did not rise synchronously with the external urban strata. Nevertheless, these data only constrain the 6th to 11th century floor level within a margin around -5 m. To resolve this and perform a quantitative calculation, critical archaeological evidence from the fragments of the Procession of Saints (Teoria di Santi, late 8th century), originally located on the north wall of Room V and now preserved in the Museo Nazionale Crypta Balbi. These fragments were excavated from below the current floor level of the north wall in Room V, where detachment scars from the fresco's removal remain visible. Records indicate that the excavation depth for these frescoes extended from the current floor of Room V to 1.0 m underground. Considering the measured 1.1 m floor level difference between the current Room V and Room II (which contains the apse), this study performed a geometric restoration of the five incomplete sets of decorative drapery (*Velario*) at the base of the frescoes. Based on the proportional characteristics and stylistic conventions of frescoes from that period, the reconstructed patterns indicate that the interior clear height at the time should have been approximately 4.8 m (Fig. 11). Consequently, this study adopts an analogous reconstruction method for architectural elements that have disappeared or changed fundamentally, aiming to restore the functional and aesthetic continuity of the 6th-century *diaconia*. Historical records show that the underground space underwent a total renovation in the 17th century; the current spaces, especially Room V and VI, are not in their original state, having undergone artistic pruning to match the reconstruction of the upper church and the Oratorio di San Paolo. Returning to the example of the Procession of Saints, although the fragments only preserve the lower limbs and clothing folds, they are sufficient to infer that this area was a solid, continuous wall during the medieval period. Considering these spaces were originally designed in the Roman period as regular horizontal warehouse units (*horrea*) sharing a universal vault support system, they must have possessed structural unity. Based on this spatial symmetry and modular logic, the virtual reconstruction of the 6th-century phase assumes that Room V shared similar geometric features with the well preserved Room II and IV.

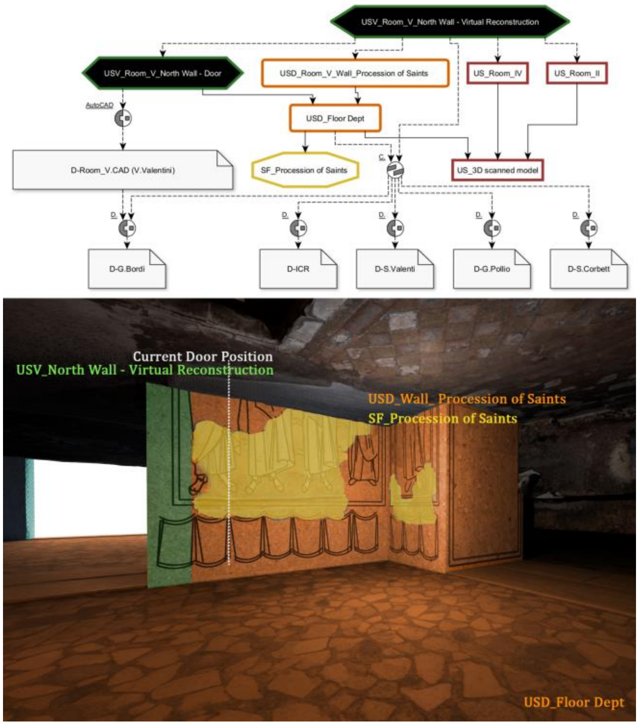

Fig. 12: Correlation between the EM logic and the virtual reconstruction of the North Wall (Room V). (Top) EM evidence mapping defining the archaeological logic and stratigraphic relationships; (Bottom) Virtual reconstruction model with thematic color coding based on the EM protocol (elaboration by ZS).

In summary, this study translates the aforementioned inferences into standardized expressions within the 3D Extended Matrix (EM) model. The elevation datum, determined by synthesizing the stratigraphic evidence of excavated frescoes with archival records, is represented in orange. This setting scientifically

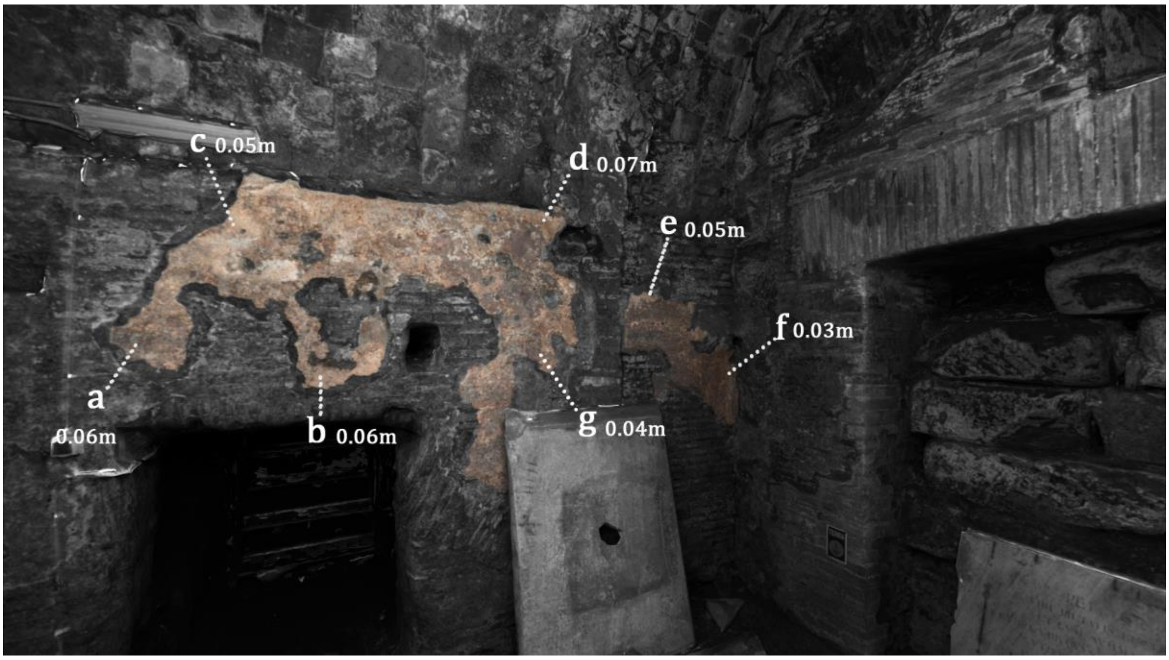

Fig. 13: Diagram of the extant plaster residues on the masonry. The vertical distances from the points on the intonaco to the masonry wall are used as a reference to create a continuous, idealized plane (elaboration by ZS).

utilizes the physical evidence while validating the archaeological archives, authentically restoring the spatial proportions of the early 6th-century *diaconia*. Conversely, structural parts based on architectural modules and spatial logic rather than direct physical evidence (such as the proportions of Room V) are classified as green, ensuring the scientific rigor and traceability of the virtual reconstruction (Fig. 12).

3.3 Diachronic Re-contextualization of Mural Decorations

The reconstruction of the plaster layer (*intonaco*) follows the principle of evidence based anchoring and logical completion. Through 3D scanning, the surviving intonaco remains within the site were recorded, to establish the geometric baseline for the digital restoration. Based on the integrity of Early Medieval decorative programs, where mural decorations typically covered the entire interior space as a unified architectural language, these fragmented remains provide crucial spatial clues. The method of this study is to perform point to point geometric correlation and coordinate extraction of the existing intonaco surfaces distributed at different positions on the same wall (Fig. 13). By analyzing these measured points, the workflow fits the spatial coordinates and offset distances of the plaster surface in its ideal state relative to the irregular masonry substrate. This geometric abstraction effectively eliminates the interferences and structural deformations of the walls, filtering out the "visual noise" of modern decay to provide a unified coordinate carrier for the subsequent repositioning of mural fragments.

After establishing the virtual reference plane for the plaster, the repositioning of mural fragments achieved a return from museum artifacts to the original physical space through multi source data comparison. Since the existing mural fragments were moved to the museum for preservation using the *stacco* (detachment) method, the core work of this study lies in using 3D scan data to capture the existing detachment traces on the walls. By combining these with the original mural textures and wall features (such as brick joints and holes) recorded in ICR photographs, the spatial coordinates of the museum fragments were confirmed within the 3D environment. Through this correspondence, digital fragment images with 1:1 scale dimensions were anchored in the 3D space. These detachment traces appear in the 3D model as specific edge contours and exposed masonry areas, forming a direct physical index for fragment repositioning. This method uses the dual constraints of artifact dimensions and on-site traces to minimize the errors inherent in visual estimation, ensuring that the spatial reconstruction of mural fragments is derived directly from the observed physical remains of the site (Fig.14).

Fig. 14: Virtual repositioning of the museum frescoes to the North Wall (Room IV). (Top) Traces of the mural detachment; (Bottom) Virtual restoration of the original fresco position (elaboration by ZS).

In addition to the digital repositioning of museum artifacts, this study also performed a spatial logical reconstruction of the decorative evolution during different phases from the 6th to the 11th centuries. For the plaster remains currently on the walls, trace amounts of non-detached mural remains, and *sinopie*, this study performed spatial coordinate labeling within the 3D model (Fig. 13). These fragmented visual clues found in situ, combined with the original stratigraphic layers of the detached murals in the museum, provide critical physical positioning evidence for determining the extent of decorative coverage in different historical phases.

To fully present the dynamic process of the artistic narrative evolution in the underground chambers, this study collaborated with Professor Valeria Valentini (University of Tuscia) and Professor Giulia Bordi (Roma Tre University). To provide a metric basis for iconographic reconstruction, the 3D survey data was used to generate 1:1 scale orthophotos of each wall within the RealityScan environment. These orthophotos, maintaining a consistent resolution of 1 mm/pixel, were aligned with the previously established elevation datum and the virtual architectural reconstruction. On this basis, the professors used CAD software to draw proportional virtual restoration line drawings using these 1:1 scale images as templates, incorporating existing damage details and the synthesis of long term archaeological research. Since these templates maintain a direct coordinate alignment with the 3D workspace, the resulting line drawings were mapped back onto the model without spatial distortion. This process validates the archaeological hypotheses by demonstrating that the proposed iconographic layouts conform to the physical constraints of the site, including specific masonry contours and vault curvatures recorded in the 3D survey (Fig. 15).

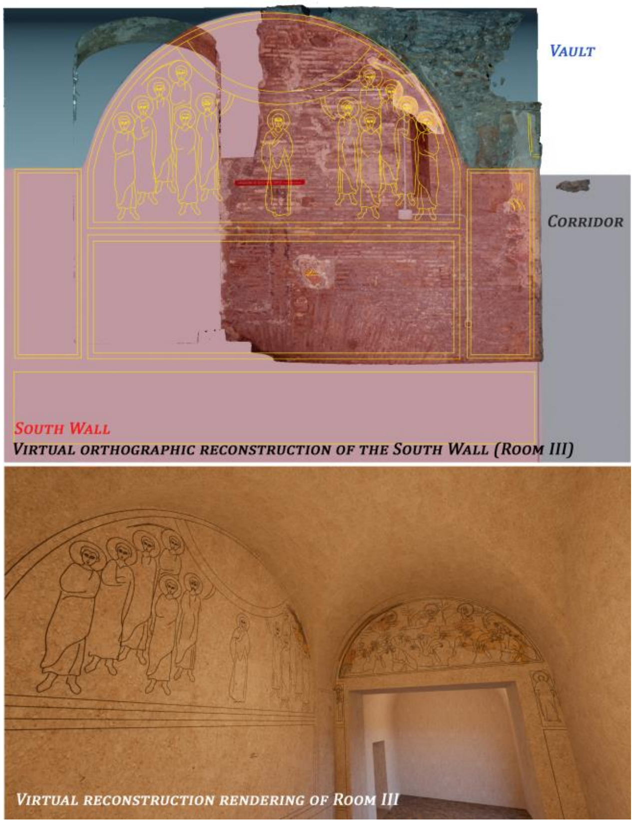

Fig. 15: Virtual restoration of the Room III. (Top) Orthographic drawing of the South Wall, featuring the CAD based restoration of the mural fragments (by Valeria Valentini); (Bottom) 3D mapping and rendering of the integrated scene performed in Blender (elaboration by ZS).

By re-mapping 2D academic line drawings into 3D space, this study achieved a digital transformation from planar archaeological drafting to 3D spatio temporal evolution. This integration not only finds an original spatial home for museum fragments but also provides an intuitive and transparent digital research foundation. Through the superimposition of multi-dimensional data, this foundation allows for the

Fig. 16: Chronological evolution of the mural decorations in Room IV. Phase I illustrates the West Wall, while Phases II - IV focus on the decorative transitions of the North Wall (elaboration by ZS).

analysis of five centuries of visual evolution within the underground space, ensuring that the reconstruction remains consistently anchored to the measured physical remains of the site (Fig. 16).

3.4 Reliability Management Based on the Extended Matrix (EM)

The virtual reconstruction in this study is not limited to the modelling of geometric forms, but is organized according the five-step logic of the Extended Matrix (EM) to construct an expert system with stratigraphic topological relationships (Demetrescu & Ferdani, 2021). The EM is a methodological protocol designed to bridge the gap between archaeological data and 3D virtual environments. It is an evolution of the traditional Harris Matrix (Harris, 1989), which is the standard tool for representing the temporal sequence of archaeological layers. By using the EM, researchers can integrate virtual reconstructions into a unified logical graph through Virtual Stratigraphic Units (USV). This framework combines discrete fragments, elevation derivations, and collaborative line drawings into a complete and traceable chain of evidence. To ensure intellectual transparency, every USV is linked to its specific data provenance, such as 3D scan traces, historical watercolors, or stratigraphic reports. Furthermore, the use of standardized color encodings within the EM protocol serves as a critical visual warning against over-interpreting speculative areas. This ensures that the digital restoration remains a scientific synthesis grounded in a structured and verifiable logical chain (Fig. 17).

In the specific implementation, this study avoided a direct modeling approach that would permanently alter the original 3D scan data. Instead, Proxy Models were used to simulate stratigraphic stacking in virtual space. A Proxy Model is a simplified, lightweight 3D geometry acting as a digital container for hypothesized structures, positioned over the original scan without merging with it. This method ensures that every reconstruction action maintains clear data provenance and follows a logical timeline within the EM. By linking external academic resources to corresponding USV nodes, this workflow separates the visual geometry from the underlying academic reasoning.

This resulting modular structure allows for iterative updates, ensuring that new archaeological findings or revised hypotheses can be incorporated into specific nodes without altering the 3D physical base or necessitating a complete reconstruction of the digital environment (Fig. 12).

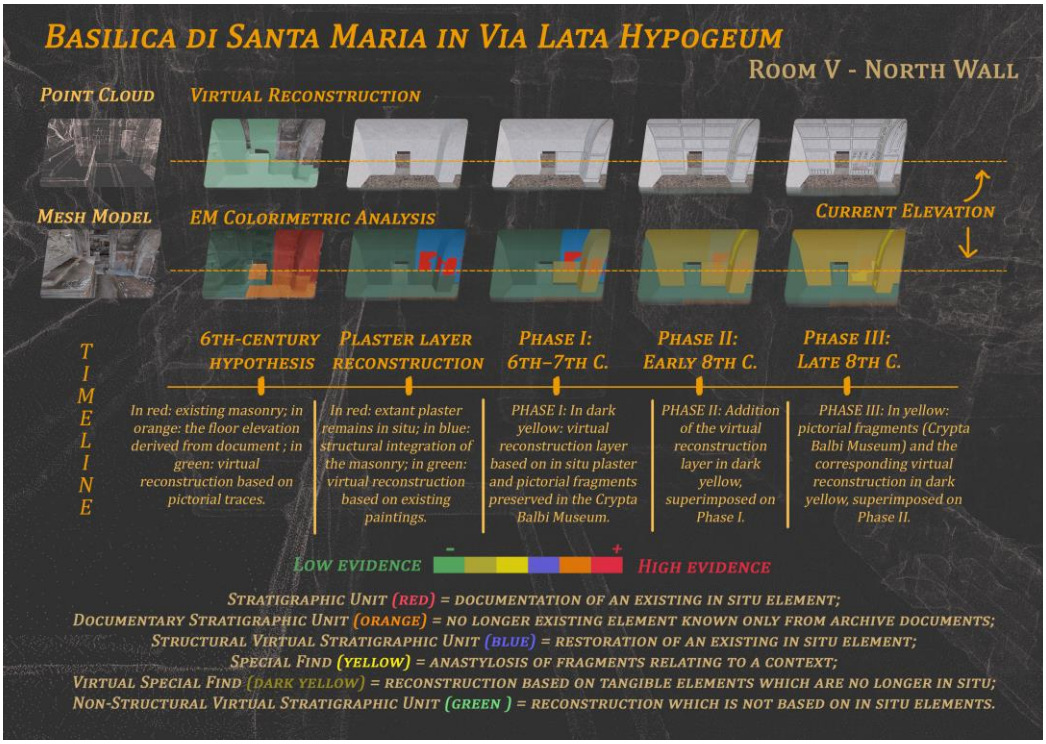

Fig. 17: EM protocol semantic mapping of the Room V North Wall (elaboration by ZS).

Tab. 1: Classification and Evidence of 3D Archaeological Units

Unit ID (US/USV/SF)	Type	colour code	Evidence Source	Relationships
Stratigraphic Unit （US）	In situ	Red #dd2d42	TLS Laser Scanning & Photogrammetry	Supports USV and SF units
Documentary Stratigraphic Unit（USD）	Archival	Orange #dd7509	Historical documents & Restoration reports	Associated with the original phase of US
Structural Virtual Stratigraphic Unit （USV）	Structural Virtual	Blue #605bd1	Geometric extrapolation	Covers or abuts existing US elements
Special Find (SF)	Fragment	Yellow #d9cc0f	preserved in the museum	Originally part of the surface of US
Virtual Special Find (VSF)	Virtual Restoration	Dark Yellow #aba435	based on coeval historical comparisons	Integrates and completes SF
Non-Structural Virtual Stratigraphic Unit (USV)	Interpretative	Green #53a55d	Stylistic analogies	Speculative contextual integration

This EM-based workflow transforms the 3D model from a static image into a dynamic research archive designed to support multidisciplinary collaboration. By maintaining logical transparency and full documentation, the model clearly defines the boundary between established physical evidence and academic hypotheses (Tab. 1). This visibility allows the reconstruction to function as a scholarly tool for independent verification, ensuring that the interpretative reasoning remains open to inspection. On a methodological level, this practice aligns the digital reconstruction of the underground chambers with international standards, specifically the transparency and documentation requirements of The London Charter (2009).

4. Results and Analysis

The first result of the study is the construction of a metrically controlled 3D spatial framework for the Santa Maria in Via Lata hypogeum. The high-density point-cloud dataset acquired through laser scanning documented not only the overall geometry of the subterranean spaces, but also wall irregularities, structural deformations and surface discontinuities resulting from the long-term transformation of the site. This digital framework provides the geometric basis for the subsequent re-contextualization of the mural fragments and for the visualization of the diachronic decorative phases. The 3D survey data also allowed the generation of 1:1 orthophotos of the main wall surfaces, with an image resolution of 1 mm/pixel. These orthophotos supported the identification of fine-scale features of the original *horrea* brickwork, including masonry joints, plaster remains, detachment marks and discontinuities between original structures and later repairs. Together with the point-cloud geometry, they provided primary visual and metric constraints for the subsequent spatial repositioning of the fresco fragments.

On this basis, the main interpretative output of the study is the digital integration of the detached fresco fragments from the Santa Maria in Via Lata underground site. By combining metric survey data, detachment traces, archival photographs and stratigraphic interpretation, the fragments were repositioned as spatially referenced elements rather than treated as isolated museum objects. This process reconnects the pictorial evidence with the architectural surfaces to which it originally belonged, extending Bordi's stratigraphic interpretation into a metrically controlled 3D environment. The resulting renderings make it possible to examine the relationship between supporting walls, plaster layers and pictorial phases, as shown in Fig. 18. Unlike traditional 2D overlays, the 3D environment allowed us to examine the parallax and volumetric relationships between multiple stratigraphic layers, addressing the spatial ambiguities inherent in complex palimpsests. Even though the physical evidence remains scattered, the sense of scale reproduced by the model supports Bordi's academic hypothesis that the 8th-century decorative program possessed a coherent narrative structure and significant visual impact. The virtual re-contextualization makes more legible the relationship between the painted decoration, the architectural configuration of the hypogeum and the liturgical role of the *diaconia* as an important early medieval religious space.

Although the virtual restoration drawings in this study are generated based on the 3D scanned data, their academic mission is to reconstruct the vanished aesthetic visual effects. While this stage involves the significant degree of interpretative reasoning due to the substantial loss of physical remains, the process followed a hierarchy of evidence to constrain the reconstruction through documented and verifiable sources.

The reconstruction was anchored first in primary in situ remains, then integrated with secondary museum fragments, and finally guided by tertiary iconographic analogies from contemporary sites such as Santa Maria Antiqua. This rigorous inferential process demonstrates

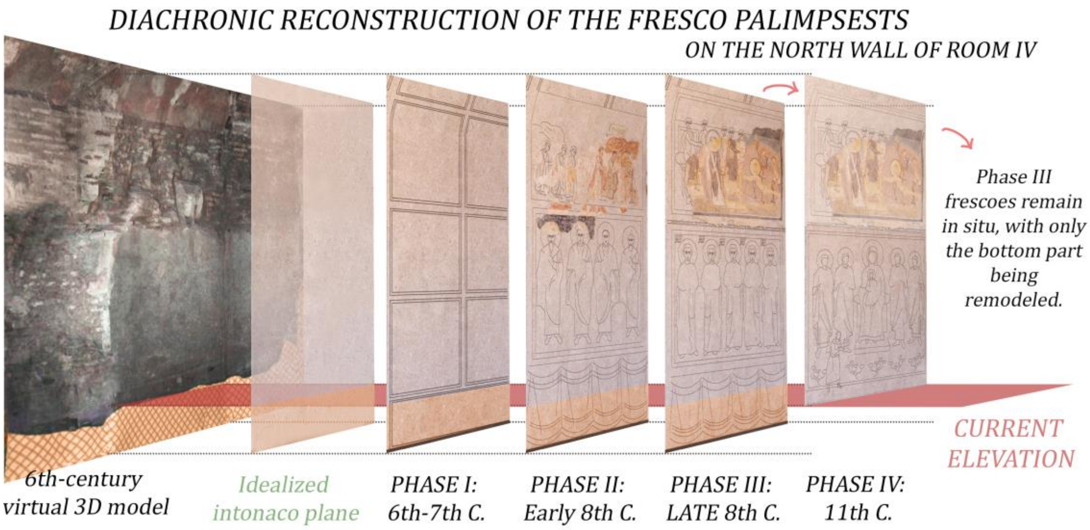

Fig. 18: Diachronic reconstruction of the fresco palimpsests on the North Wall of Room IV (elaboration by ZS).

that the digital restoration is not merely a visual completion, but a scholarly synthesis underpinned by a verifiable logical chain. By extending the brushstrokes, colors, inscriptions, and iconography of the surviving murals, these drawings reweave the broken narrative chains within the 3D space. This ensures that the painting skin (*pelle pittorica*) described by Bordi is no longer a collection of scattered color patches, but a more coherent visual and spatial system grounded in structured logic. This restoration further suggests that the decorative programs of the early Christian *diaconia* were rather than isolated or random additions, but an artistic evolution process highly compatible with the building structure and possessing a diachronic logic. By overlaying virtual drawings from different periods in the 3D model, it is observed that the earliest decorations strictly followed the architectural layout of the Roman *horrea*. This validates that early renovations utilized the original brick structures to support the transition from secular functions to ritual spaces by visually strengthening core areas like the apse. The palimpsest analysis of the mural decorations also suggests a progressive intensification of the decorative program. As the liturgical role of specific spaces increased over time, the frescoes appear to have shifted from simpler geometric or ornamental schemes toward more complex narrative scenes. The superimposition of the reconstructed phases shows how later interventions reused, covered or reinterpreted earlier pictorial and architectural arrangements, producing a long-term dialogue between visual languages from the 6th to the 11th centuries within the limited space of the hypogeum.

This confirms the viewpoint proposed by Bordi (2016) that the wall itself is a dynamically evolving entity. The results of the Via Lata restoration suggests that the evolution of the *diaconia's* decoration was not an isolated artistic act, but the result of the combined forces of architectural functional transformation and the progressive redefinition of the hypogeum as a sacred space.

This study contributes to the Intellectual Transparency advocated by The London Charter (Denard, 2009) through the EM protocol. By classifying the reliability levels of the restoration nodes, we have transformed the restoration results from purely visual outputs into scientific empirical archives, supporting a falsifiable approach of the research. The model clarifies which elements are based on direct physical evidence, which rely on archival or stratigraphic documentation, and which derive from interpretative or iconographic hypotheses. This structure allows future researchers to verify, question or update individual inference nodes without losing the information associated with previous interpretations or rejecting the reconstruction as a whole.

Overall, the results demonstrate the value of integrating 3D survey, stratigraphic interpretation and EM-based reliability management for the study of fresco palimpsests. The workflow enables the spatial re-contextualization of detached fragments and the diachronic visualization of long-term decorative change. At the same time, it preserves the distinction between measured evidence, documentary sources and reconstruction hypotheses, allowing the model to function as a transparent tool for analysis rather than as a definitive visual restitution.

5. Conclusion and Future Development

The workflow developed in this study provides archaeologists, art historians and architects with a verifiable spatial framework for analyzing complex palimpsest contexts. It demonstrates that, in sites characterized by fragmented evidence and stratigraphic superimposition, 3D survey data can support not only metric documentation, but also the spatial testing of archaeological and art-historical hypotheses. By integrating 3D survey, historical documentation, stratigraphic interpretation and the Extended Matrix protocol, the proposed method makes the transition from measured evidence to virtual reconstruction explicit and traceable. By integrating scanning with the EM protocol, this research proposes and supports a falsifiable approach to virtual reconstruction. It utilizes the 3D space to compare hypotheses with the measured geometry of the site, allowing geometrically inconsistent solutions to be identified and revised. The significance of this approach lies in transforming restoration results from static image conclusions into sustainably auditable logical archives, marking the transition of digital heritage research from visual representation toward scientific validation. Beyond the specific findings of this case study, this integrated workflow offers significant methodological reference for other complex archaeological sites. It is particularly applicable to heritage contexts characterized by multi-period stratigraphic overlaps and fragmented mural remains. Despite the transparency of the EM workflow, certain physical limitations remain. Specific areas of the 6th-century masonry are currently concealed behind 17th-century structural reinforcements, limiting direct 3D capture. Future research could integrate non-destructive testing (NDT) methods, such as Ground Penetrating Radar (GPR), to perform subsurface investigations behind these later additions. This new data could be integrated as updated USV nodes into the current model, further refining the accuracy of the spatial evolution.

To address the current situation where restoration models are limited by professional modeling software (Blender), making cross-disciplinary sharing difficult and complicating the intuitive switching between different historical phases, future work will explore integrating 3D models and EM archives into independent interactive applications. This platform aims to lower technical barriers, enabling experts such as historians and conservators to intuitively retrieve evidence nodes, engage in spatial interaction, and conduct collaborative research within the same digital context, thereby achieving true sharing of academic archives. This initiative also aligns with the evolving focus on impact and accessibility frameworks within the GLAM (Galleries, Libraries, Archives, and Museums) sector (Siso-Calvo et al., 2024). Additionally, the study will further investigate the original orientation and size of the windows to explore the influence of natural light and shadow on the narrative logic of the murals through light environment simulation, providing perceptual evidence from the perspective of visual perception in addition to the physical level (Fig. 19).

The present reconstruction mainly focuses on the underground site prior to the 11th century. Future research plans to integrate scan data from the upper Church to construct a holistic digital model in the vertical dimension. By analyzing the structural logic correlations between the upper and lower levels after the 11th century, the study will infer the spatial pattern changes of the site during later urban evolution. This extension aims to examine the Via Lata site as a continuously evolving stratified architectural complex, using digital technology to bridge the spatial fractures caused by ground level rise, thus constructing a complete spatial evolution picture spanning a thousand years from the 6th century to the present.

Fig. 19: Natural lighting simulation of the Room IV murals based on the reconstructed aperture of the only extant infilled window (elaboration by ZS).

Finally, in the research process, it was also found that the current EM protocol has certain limitations when dealing with multi-temporal mural decorations. Since its standardized color coding system was originally designed for the logical expression of architectural structures, it struggles to provide sufficiently granular dimensions of expression when facing complex stratigraphic relationships such as mural palimpsests. This effort aligns with the EM v1.5 protocol currently being refined, which introduces experimental features such as dotted connections between node instances, allowing for the formal representation of diachronic transformations of the same physical element over time. However, future research will attempt to perform customized extensions of the EM protocol, referencing richer color hierarchies or superimposed texture semantics from fresco restoration to adapt to the unique fragmented characteristics of murals, promoting the evolution of the EM protocol toward a more inclusive recording standard for artistic heritage.

6. *Acknowledgments*

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