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Digitisation and virtual restitution applied to the heritage of displaced mural painting: the case of the medieval mural painting of the church of Saints Julián and Basilisa of Bagüés (Spain)

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Abstract

This study presents an exploration of the digitisation of medieval mural paintings from the church of Saints Julián and Basilisa in Bagüés (Zaragoza, Spain), an *Asset of Cultural Interest*. These murals were removed in 1966, resulting in a disconnection between the artworks and their original architectural context. This removal raised concerns regarding decontextualisation and potential loss of heritage significance. To address these challenges, advanced digital techniques, such as laser scanning and photogrammetry, were employed to create highly accurate 3D models of both the church and the museum where the murals are now housed. These models facilitate a detailed geometric analysis, allowing a direct comparison of the two environments and an exploration of the spatial relationships that were lost over time. The digital data collected through these techniques play a vital role in the preservation, study, and dissemination of heritage, providing new possibilities for the virtual reintegration of the murals into their original context. Additionally, these 3D models offer an innovative tool for virtual restoration, allowing researchers, conservators, and the public to engage with the murals as they might have appeared within the church. This study demonstrates the potential of digital technologies in mitigating the effects of heritage displacement while offering new approaches to the interpretation and virtual presentation of relocated artworks. The research also suggests future applications in heritage conservation, including the development of interactive museum experiences and the integration of these models into virtual and augmented reality platforms, enhancing the public's understanding and appreciation of displaced cultural heritage.

Keywords Romanesque mural painting, Heritage digitisation, Displaced heritage, 3D laser scanning, Documentation, Bagüés

1 Introduction

The concept of displaced heritage refers to cultural assets that have been removed from their original context and relocated to new settings, whether for purposes of conservation, spoliation, or the art trade. In the field of Romanesque art, this phenomenon is particularly significant in the case of mural paintings, whose fragility and susceptibility to deterioration have often justified their removal using the *strappo* technique. This method

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Fig. 1 Removal process of a medieval mural painting. Church of Santa María de Taüll (1921) (Source: Arxiu Mas Fundació Institut Amatller dArt dHispànic)

enables the separation of the pictorial layer from the wall, allowing it to be transferred onto a canvas for subsequent conservation (Fig. 1).

Although wall paintings are considered an integral part of monuments and sites of heritage value and must be preserved in situ (ICOMOS 2003), Spain has numerous examples of displaced Romanesque mural paintings. Many such paintings have been removed from small rural churches and relocated to national and international museums. While the physical substrate of these paintings is preserved in museums, their essence and the imprint and soul of the murals remain in the churches, alongside the local communities that have lived with them for centuries (Sadía 2020, 98). One of the most representative examples of this phenomenon is the mural ensemble from the Church of Saints Julián and Basilisa in Bagüés, which was removed in 1966 by Ramón Gudiol's team and is now conserved and exhibited in the Diocesan Museum of Jaca (MDJ).

1.1 Church of Saints Julián and Basilisa of Bagüés

This small church in the municipality of Bagüés (Fig. 2), located in the Cinco Villas region (Zaragoza), is an outstanding example of early pre-Pyrenean Romanesque architecture among those preserved in Spain. Built in the 11th century, it features a simple ashlar construction with a single nave and an apsidal chancel. A side nave and a tower were later added in the 16th century. In 2010, the church was designated a *Bien de Interés Cultural* (Asset of Cultural Interest) under *Decreto 95/2010* (Gobierno de Aragón 2010).

Bagüés is currently the least populated town in the Aragón region (INE 2024). Some of its 17 remaining inhabitants still recall how the church's mural paintings were taken far away, as many of their neighbours once were.

1.2 Diocesan Museum of Jaca

The MDJ is one of Spain's principal centres for Romanesque art, housing one of the best collections of medieval mural paintings. In 1970, it was inaugurated inside the cathedral of Jaca. The museum brings together a collection of works from different churches in the Aragonese Pyrenees (Lacarra Ducay 1993).

One of its most emblematic spaces is the *Bagüés room*, which houses mural paintings from the church of Saints Julián and Basilisa, the largest preserved Romanesque mural cycle in Spain (Gudiol 1971). The removal of these paintings has ensured their preservation in the face of deterioration and abandonment. However, it has also sparked debate regarding the decontextualisation of artworks and the loss of their intrinsic relationship with their original architectural setting. In response, museums have often sought to reconstruct the original spatial context of these murals by designing exhibition displays that evoke their original layout and guarantee environmental stability and the appropriate temperature (18–22 °C) and relative humidity (45–60%) recommended by organisations such as the International Council of Museums (ICOM 2008), as seen in the Bagüés Room at the MDJ. Nevertheless, the physical separation between artworks and their architectural surroundings presents challenges for interpretation and appreciation. New technologies, particularly digitisation, offer promising solutions to bridge this gap.

1.3 Specific objectives of the work

This study aims to explore the potential of heritage digitisation for the analysis, conservation and virtual restitution of displaced heritage ensembles. It applies this heritage digitisation to the case study of the Romanesque ensemble described in points 1.1 and 1.2 and sets out the following specific objectives:

- Analyse and document the current state of the medieval mural painting ensemble of the church of Saints Julián and Basilisa in Bagüés, both in its original location and in its current museum installation in the MDJ.
- Digitise both the architectural space of the church and the installation of the paintings in the museum with high precision, using laser scanning and photogrammetry techniques.
- Generate comparative three-dimensional models to study and contrast the geometry and layout of the architectural and pictorial ensembles, making it pos-

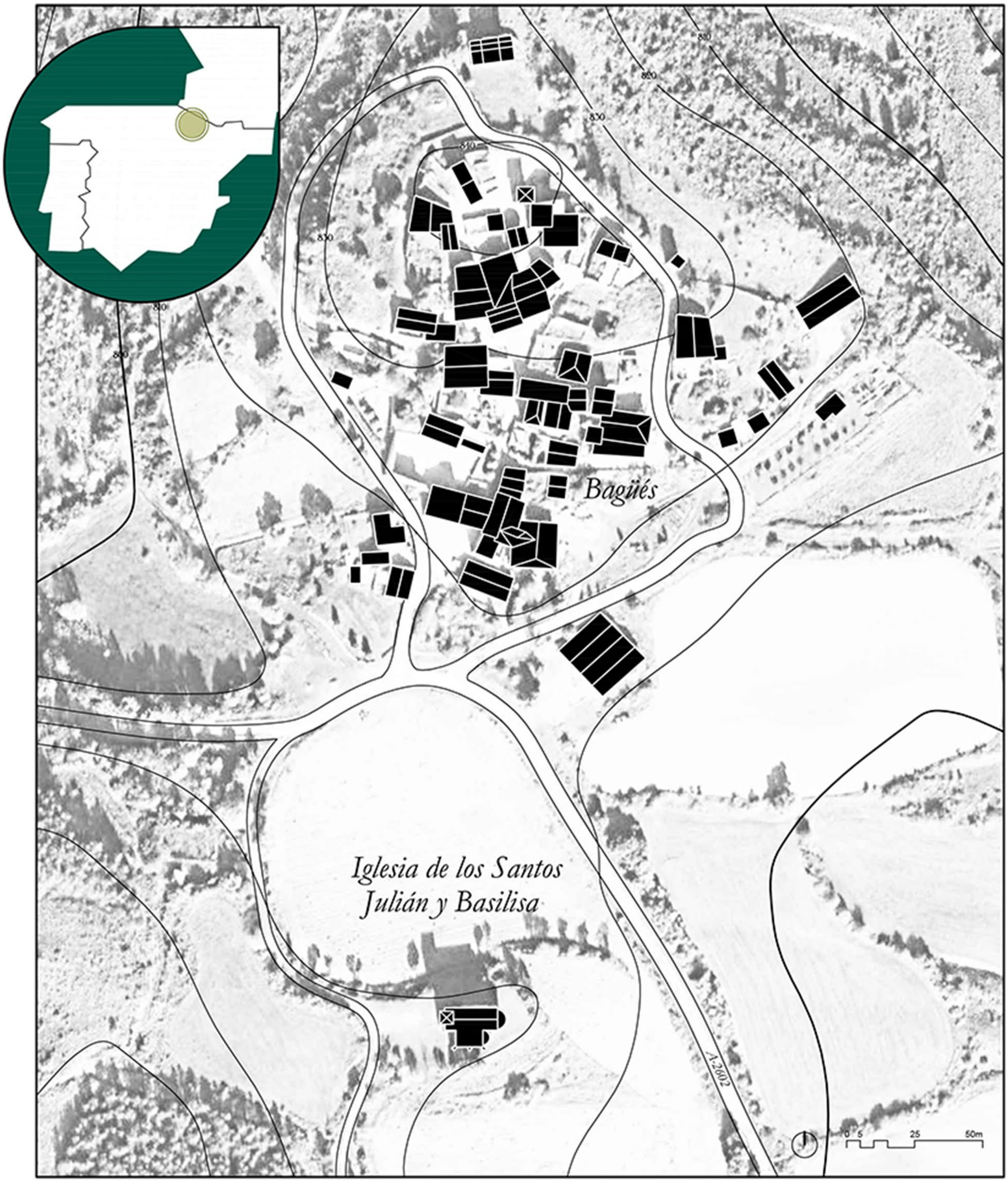

Fig. 2 Site plan of Bagüés and the church of Saints Julián and Basilisa (Source: Instituto Geográfico Nacional, 2018; Google Maps, 2025)

sible to identify hidden or nonremoved pictorial fragments.

– Explore new forms of virtual reintegration of displaced wall paintings, using advanced digital technologies to mitigate heritage decontextualisation and offer digital tools that facilitate the conservation, study and dissemination of heritage as well as the virtual restitution of murals.

2 Materials and methods

Heritage digitisation technologies, such as laser scanning and photogrammetry, are widely employed for the documentation of artistic and architectural heritage sites. These high-precision digital surveys generate models that accurately capture the current state of heritage ensembles while also enabling their virtual reconstruction. Such reconstructions facilitate analysis, interpretation, and hypothesis development in a manner that respects the integrity of the original works.

In this study, we use laser scanning to digitise the architectural space of the church of Saints Julián and Basilisa in Bagüés as well as both laser scanning and photogrammetry to digitise the displaced mural paintings housed in the MDJ. Photogrammetry and laser scanning remain central to digital heritage research, as they are mentioned in approximately half of the publications analysed (Münster et al. 2021). Additionally, point cloud generation and comparison software are employed to analyse, contrast, and generate simulations of these two elements, which originally formed a unified artistic and architectural complex.

2.1 Premises for digitisation and surveying of the heritage ensemble

The current architectural ensemble of the church of Saints Julián and Basilisa in Bagüés is the result of several interventions and constructions added over the centuries. The 16th century extensions altered the northern wall (the *Epistle wall*), creating two arches that still connect to the new nave. The upper section of the tower may also have modified the western wall, and according to Abbad Ríos, another modification occurred on the southern wall (the *Gospel wall*), with the addition of a sacristy that has since disappeared, although traces of it remain on the exterior of the church. A bricked-up access point near the apse is also visible (Almería et al. 1998). This project focuses on studying the interior of the 11th-century main nave. However, given the architectural significance, data capture also extends to the entire architectural ensemble, including the tower, side nave, and exterior of the church. These data contribute to creating accurate graphic documentation of the current state of the entire complex, enabling comparison with existing materials, including plans, elevations, and sections produced by the Fundación Santa María la Real and available in its online encyclopaedia (Románico Digital 2025). The comprehensive model of the ensemble will provide information for potential future studies.

The mural paintings of the main nave constitute a fundamental part of the Romanesque ensemble of the Church of Saints Julián and Basilisa. This is one of the few examples in Hispanic Romanesque art that preserves almost its entire iconographic program, making it one of the most significant pictorial ensembles in European Romanesque and the most important in Spain (Sureda 1985). Although there is no precise chronological dating, the paintings are believed to be contemporaneous with the original 11th-century construction of the nave, as architecture and mural decoration were closely linked during this period. The paintings were discovered beneath a layer of lime in the mid-20th century, and in 1966, they were detached from the original walls by Gudiol. In 1968, they were transferred to Barcelona for restoration and reattachment to a new portable support panel, after which they were exhibited at the former Hospital de Santa Cruz. Eventually, the ensemble was relocated to Jaca, just 41 km from its original site, where it has been preserved and displayed at the MDJ since its inauguration in 1970.

The digitisation and surveying of the Bagüés mural ensemble align with current efforts in heritage conservation to document, analyse, and disseminate cultural assets through advanced digital techniques. The detachment and relocation of the frescoes altered their spatial context, making it essential to establish a precise and comprehensive digital record of both their original placement and their current setting at the MDJ. As noted by Cinquepalmi and Tiburcio (2023), the preservation of cultural heritage requires a holistic and multifaceted approach involving coordinated actions developed by national and local authorities, stakeholders, and users. This study embraces that perspective by integrating laser scanning, high-resolution photogrammetry, and comparative analysis to ensure an accurate representation of the mural ensemble. The resulting dataset will facilitate future research, conservation planning, and public dissemination, reinforcing the importance of digital tools in the sustainable management of medieval art.

2.2 Fieldwork

The fieldwork was conducted over four digitisation sessions between August and October 2024, involving onsite data collection in the towns of Bagüés and Jaca. The equipment used for laser scanning in both the church of Saints Julián and Basilisa in Bagüés and the MDJ was a FARO Focus M70 scanner capable of capturing high dynamic range (HDR) 360-degree images. For the photogrammetric documentation of the mural paintings at the MDJ, a Nikon D5600 camera with an AF-P Nikkor 18-55mm 1:3.5–5.6G lens was employed, which was mounted on a *HAGUE Sportsmast Elite Highshot Camera Mast*, an extendable carbon fibre pole reaching up to 8 m in height. For colour calibration, the CALIBRITE ColorChecker Passport Photo2 colour chart was used, allowing

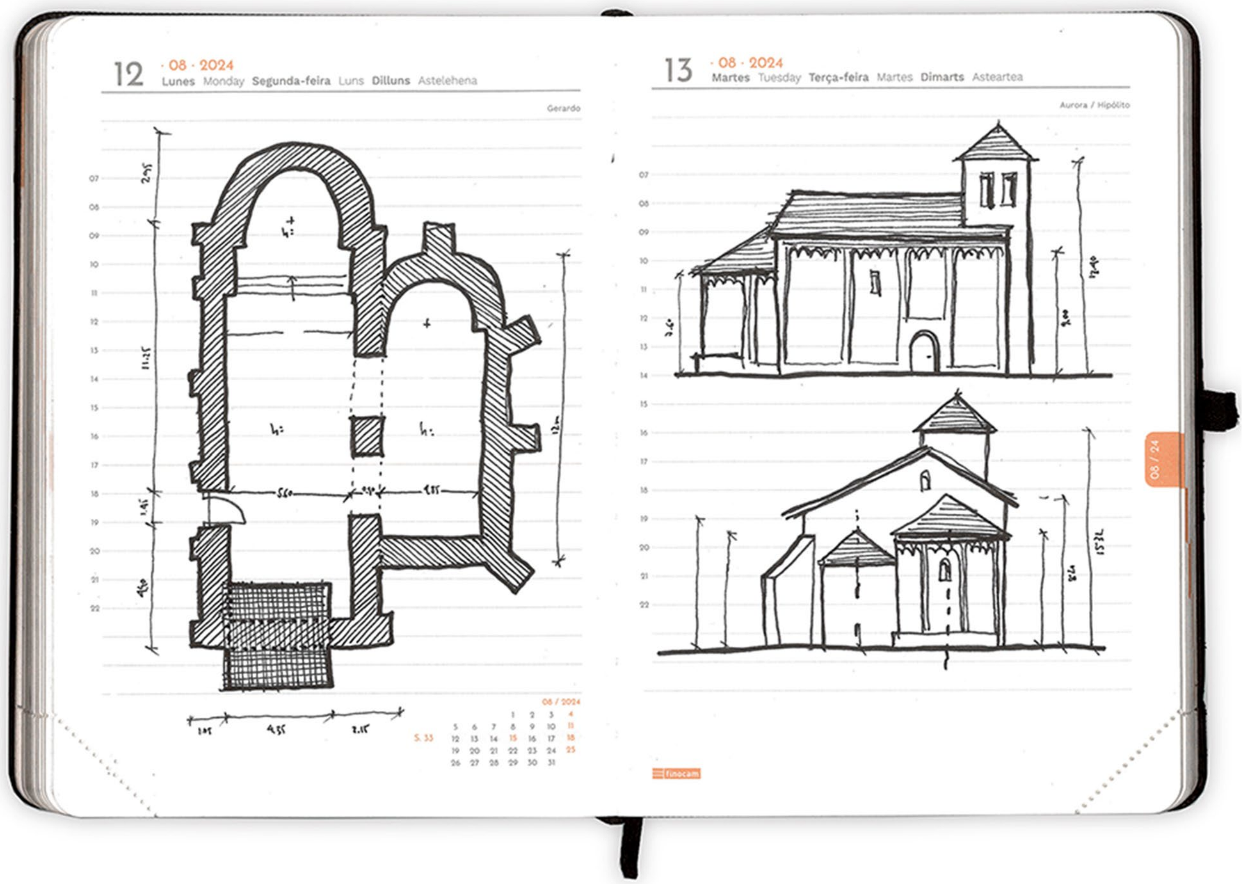

Fig. 3 Manual data collection in the field. Sketches and measurements of the church of Saints Julián and Basilisa. Bagüés, 2024 (Source: the authors)

the establishment of an accurate colour base and maintaining exceptionally good colour control under all lighting conditions.

The fieldwork was structured as follows:

- Session 1 [12.08.2024]: Laser scanning of the interior of the church of Saints Julián and Basilisa in Bagüés. A total of 17 scan positions were established, covering both the 11th-century nave and the 16th-century extension. Prior to scanning, the intervention area was cleared and manually surveyed (Fig. 3).
- Session 2 [16.08.2024]: Laser scanning of the church's exterior, with 35 scan positions established.
- Session 3 [19.08.2024]: Laser scanning of the Bagüés Room at the MDJ, with 10 scan positions.
- Session 4 [28.10.2024]: Photogrammetric capture of the Bagüés Room at the MDJ, yielding a total of 297 photographs. Colour capture and calibration (Fig. 4). Owing to the height of the mural paintings on the upper sections of the walls, the apse, and the triumphal arch, an extendable pole was required to bring the camera closer to the pictorial surface (Fig. 5).

Fig. 4 Capture of the real colour of the paintings in the *Bagüés Room* of the MDJ for subsequent photographic calibration with ColorChecker Passport, 2024 (Source: the authors)

Fig. 5 High-Resolution photogrammetry digitisation using an extendable mast in the *Bagüés Room* of the MDJ, 2024 (Source: the authors)

The laser scanning fieldwork resulted in a total of 62 effective scans (Fig. 6), generating 62 FLS files containing (X,Y,Z) coordinates for each point, along with colour information (R,G,B) and laser intensity. Additionally, 360° panoramic images in JPG format were obtained, which were used to assign realistic textures to the point clouds. In their processing, the 52 interior and exterior scans of Bagüés Church yielded a maximum point error of 1.1 mm; the average point error was 0.9 mm; and the minimum overlap was 35.9%, generating a cloud of 535.660.498 point passes. The scanner settings were higher resolution for the 10 scans of the Bagüés room of the MDJ; the maximum point error was 1.1 mm; the average point error was 0.9 mm; and the minimum overlap was 78.1%, generating a final cloud of 709.872.211 point passes.

Moreover, the photogrammetric capture of the *Bagüés Room* produced a total of 262 valid photographs in RAW and JPG formats, including RGB colour information and camera metadata (EXIF). The 262 aligned images of 6000 × 4000 resolution generated a cloud of 177.850 point passes and 931.291 projections; the reprojection error was 0.551 pixels. These datasets were further supplemented with hand-drawn sketches, onsite measurements of both sites, and a collection of general and detailed photographs and videos.

2.3 Lighting control and colour correction

The combination of photogrammetry and 3D laser scanning allows very accurate and detailed 3D digital models to be obtained, with six data points of the coordinates of the position (X,Y,Z) and data colour (R,G,B). Laser scanning provides high geometric accuracy (X,Y,Z), whereas photogrammetry provides realistic textures and colours (R,G,B). In this study, both technologies have been optimally combined.

Through laser scanning, precise geometric positions have been obtained with millimetric accuracy of both the church of Saints Julián and Basilisa of Bagües and the pictorial ensemble of the MDJ. The configuration of the laser scans varies depending on the elements digitised. For the Bagüés room of the MDJ, owing to the great detail of the mural paintings, an interior HDR scan with a high-resolution colour image was configured, which involved a scanning time of approximately 14 min per position, generating a very high-resolution point cloud. For the interior of the church of Saints Julián and Basilisa in Bagüés, the configuration was similar but with lower colour image resolution, involving a scanning time of approximately 9 min. For the exterior of the church, an HDR scan was configured for exteriors up to 70 m, with medium/high colour image resolution, which involved a scanning time of approximately 16 min per position.

The comparison between laser scanning and terrestrial photogrammetry has been widely addressed in the literature, and it is well known that although increasingly accurate, the positional fidelity of the (X,Y,Z) points of the cloud generated through photogrammetry is inferior to that obtained in the point cloud through laser scanning (Salazar et al. 2015). However, the colorimetric quality (R,G,B) is much higher than that obtained with the laser scanner, reaching nearly true colours.

To ensure colour fidelity in photogrammetry, Calibrite LLC's ColorChecker Passport Photo2 chart, which has been considered a standard since 1976, was used. This chart contains 24 colour patches that represent natural tones using pure solids, allowing accurate reproduction of the original object colours. In addition to the colour patches, the chart incorporates a spectrally neutral 12% grey reference, which is useful for setting a custom white balance in both RAW and JPG files. This makes it easier to compensate for variations in ambient light, resulting in a more accurate representation of wall paintings. In situations with complex or dim lighting, such as the Bagüés Room, the use of the grey balance chart (18% grey) was

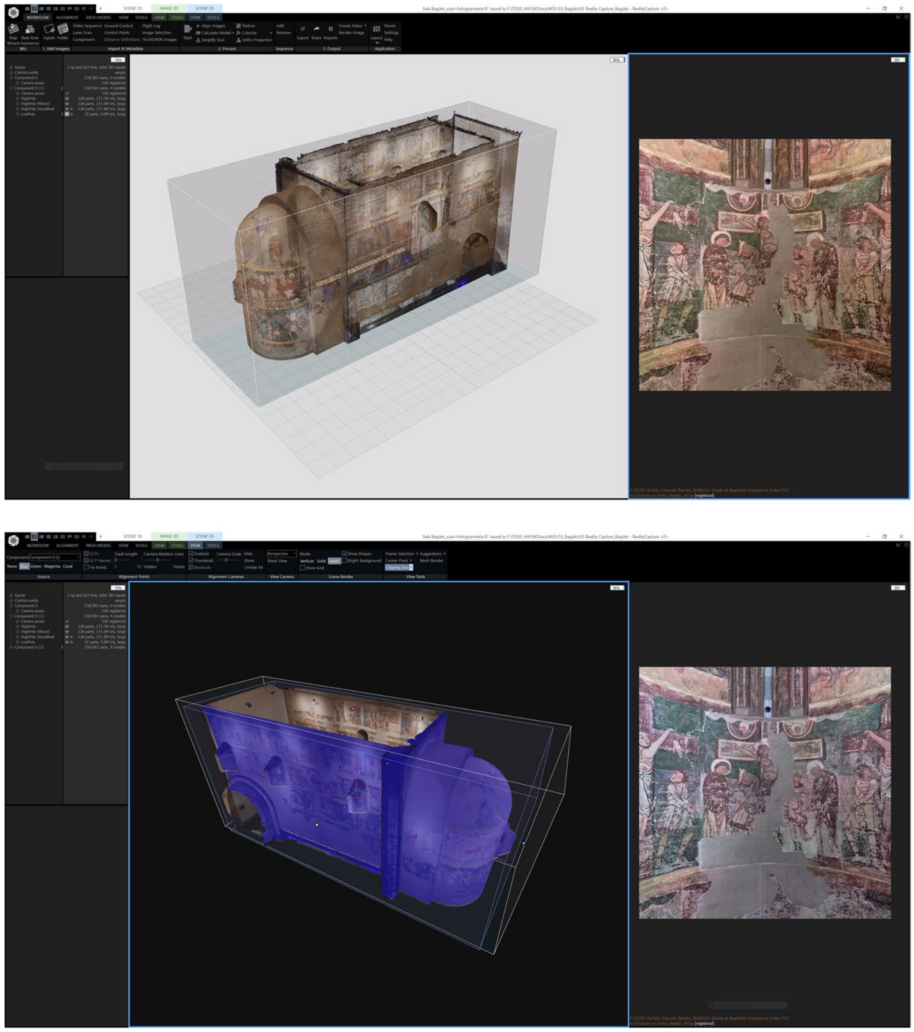

Fig. 6 Base scanning points: **a**) *Bagüés Room* at the MDJ; **b**) church of Saints Julián and Basilisa in Bagüés (Source: the authors)

necessary, as it provides a particularly valuable neutral reference in low light conditions like those in the MDJ.

The procedure consisted of photographing the chart together with the wall paintings at the beginning of the photogrammetry session. The images were subsequently colour calibrated using the ColorChecker camera calibration software and the Adobe Lightroom plug-in, which automatically detects the chart and adjusts the camera profiles. Once calibrated, the images could be processed via software such as Metashape and Reality Capture, reproducing the precise colour for the photogrammetric reconstruction of the mural paintings. (Fig. 7).

2.4 Digital processing

After the onsite digitisation process, the collected data were processed and integrated to generate a complete model of the heritage ensemble. The laser scan data were processed using SCENE 2023.0.1.10677 (11.0.1.10677) software by FARO Technologies, Inc. The point cloud was generated to achieve maximum precision without prioritising colorimetric or sharpness issues. To ensure the best connection between the different clouds, the associated photographs were taken via HDR to avoid overexposure or underexposure of the photographs. Moreover, the photogrammetric model of the *Bagüés Room* was generated with AGISOFT Metashape Professional, Version 2.0.2 build 16,334 (64-bit) by AGISOFT LLC. Invoice n° 7897/2019/AS-1305-ES. Although using autofocus modified the optical conditions of the image, this setting maximises the sharpness of the photographed image, since the Metashape software compensates for optical differences without the need for prior calibration. This photogrammetric cloud is intended to achieve maximum colorimetric quality and sharpness. Both software solutions ensure full control over calculation parameters, as

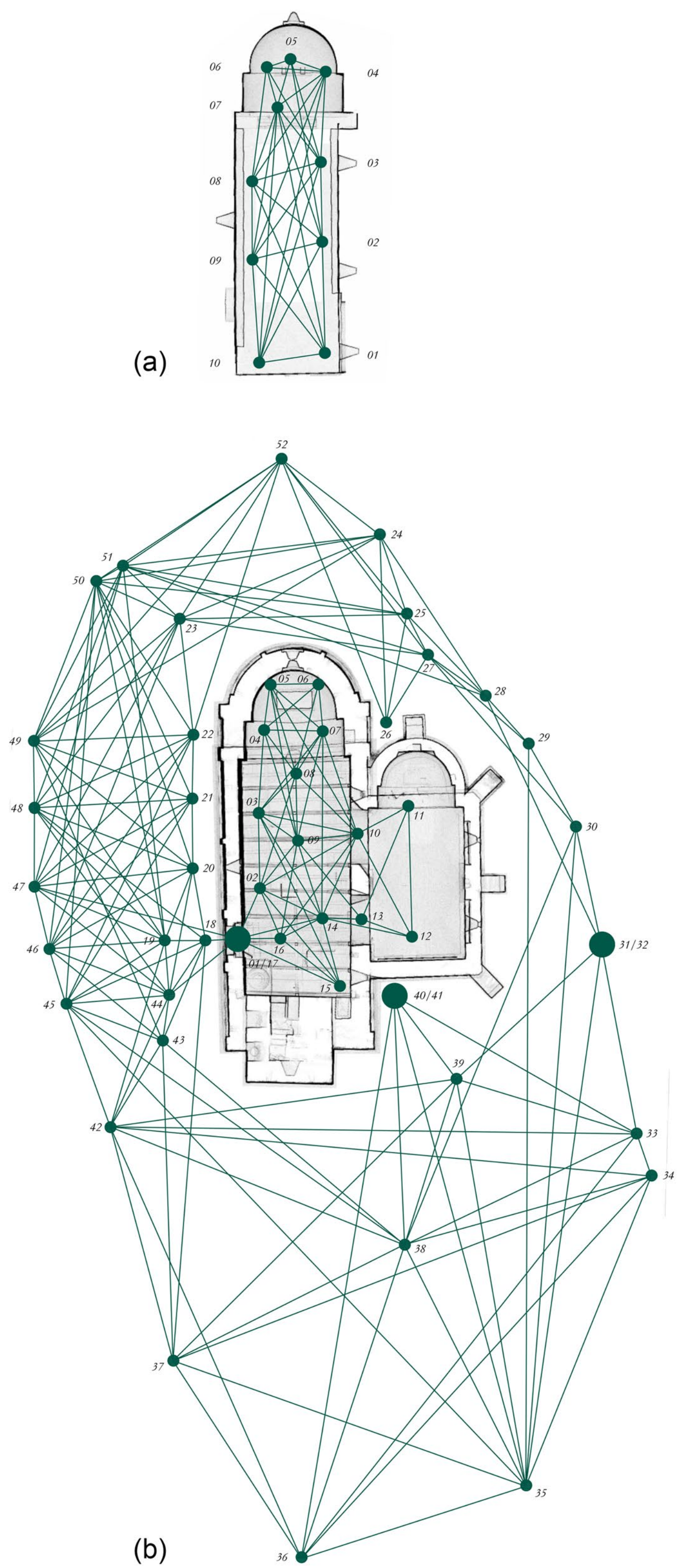

Fig. 7 Comparison of the models and texture maps generated in the photogrammetry process without colorimetric image calibration (**a**) and after calibration with ColorChecker (**b**) (Source: the authors)

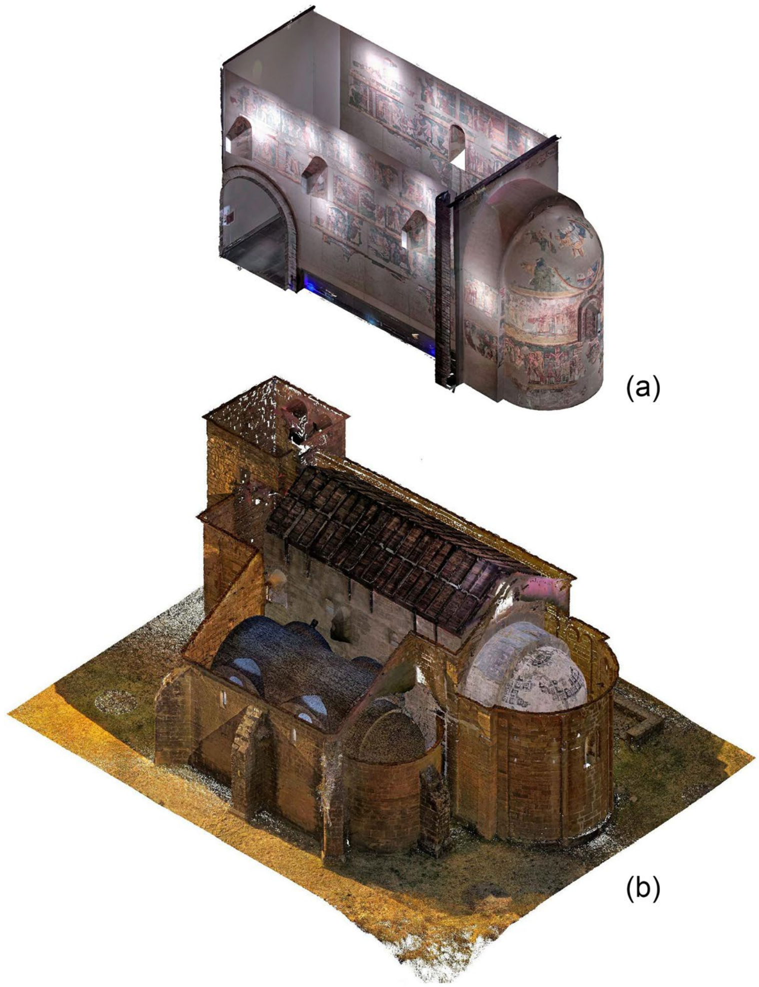

Fig. 8 **a**) Point cloud of the MDJ pictorial ensemble; **b**) Point cloud of the church generated through laser scanning (Source: the authors)

well as the management and verification of the resulting 3D models.

3 Results

The development of digital tools used by researchers for data visualisation and management plays a crucial role in shaping methodologies for heritage documentation. The need to handle vast amounts of data efficiently and display it quickly, accurately, and without information loss has led to the development of structured systems that organise data in an accessible and interpretable manner for various users (Quintilla Castán, and Agustín Hernández 2022). This study explores different techniques for the visualisation, interrogation, and interactive navigation of 3D models generated from scans. Once the data have been processed, point cloud models are created for both the architectural and pictorial ensembles (Fig. 8). These three-dimensional, high-precision elements allow for direct comparison, as they capture real-world geometries through automated sensors. Their processing enables the inference of causal processes that shape their unique structures, demonstrating how past human actions transformed natural materials into material evidence with specific visual properties such as size, shape, texture, composition, and location (Barceló and Vicente 2011).

Owing to these digital models, it is now possible to study both the medieval construction and decorative geometry of the church of Saints Julián and Basilisa in Bagüés and the reconfiguration of the mural paintings that were removed from its walls in the 20th century and are now preserved at the MDJ. This technology opens new avenues for understanding the architectural and artistic evolution of the site, providing a comprehensive view of how the building and its decoration have transformed over time. The ability to reconstruct the spatial and artistic relationships between the original church and the relocated murals is invaluable for scholars and conservators alike. While the potential of 3D visualisation technologies is undeniable, it is important to recognise that such tools are best understood as complementary aids that support rather than replace physical conservation strategies (Dieb et al. 2024). To achieve this, we rely on orthoimages generated from the point clouds—bidimensional representations of the scanned ensembles with corrected perspectives and distortions. These orthoimages allow for precise measurements at the true scale, enabling direct comparisons and serving as an accurate foundation for the creation of traditional 2D representations such as plans, elevations, and sections. Moreover, they facilitate a more in-depth analysis of the mural's spatial context, and such help provided for the church and the relocated murals is invaluable for scholars and conservators alike.

While mesh-based models offer smoother navigation and are optimal for interactive exploration, the geometric interpolation process introduces a degree of uncertainty that may lead to errors in certain analyses. In contrast, point cloud models are better suited for geometric characterisation as well as for extracting floor plans, elevations, and sections. The high level of detail in these digital models necessitates a streamlined analysis process, requiring careful decision-making to ensure both efficiency and accuracy in reconstructing the original setting, which is essential for future conservation and educational efforts.

3.1 Geometric analysis of the building

The generation of relevant architectural graphic documentation for the study of point clouds involves converting three-dimensional geometry into precise two-dimensional representations of the building's current state. Initially, the point clouds are cleaned and aligned to remove noise and optimise their metric accuracy. Next, the clouds are segmented, and orthoimages are extracted on the basis of the main architectural planes. Horizontal cuts are made to denote floor plans, and vertical cuts are made to produce elevations and sections. This step not only ensures the highest accuracy but also helps in visualising the building's geometry in a way that is both clear and manageable for further analysis.

The resulting documentation includes the floor plan, roof plan, north elevation, south elevation, east elevation, west elevation, longitudinal section A-A' (showing the interior face of the Epistle wall), longitudinal section B-B' (showing the interior face of the Gospel wall), and transverse section C-C' (providing a front view of the apse and triumphal arch). This information serves as a precise reference for understanding the architectural structure of the church, ensuring that no significant detail is overlooked.

Geometric lines are delineated in CAD software through the manual vectorisation of point clouds. For the floor plans, the point clouds are projected onto horizontal planes, extracting the contours of walls, openings, and structural elements (Fig. 9). For the elevations and sections, the point clouds are projected onto various vertical planes, allowing for the faithful recreation of facade openings, voids, ashlar stones, Lombard arches, ornaments, and other textures and masonry. In this case, the cut plane reveals the spatial stratigraphy of the building, facilitating the morphological analysis of its openings and architectural invariants. This enables a precise comparison with the documentation of the mural painting installation at the MDJ. The geometric detailing also provides invaluable insights into how the architectural elements were constructed and how they relate to the overall artistic expression of the church.

The geometric analysis of architectural layouts requires intensive engagement with the studied reality. While the models, both of the church and the MDJ exhibition setup, are recorded with precision and objectivity, it is important to note that all planimetric restitution involves some subjectivity when interpreting the layouts that form the architectural plans (Sancho Mir et al. 2018). For this reason, the generated documentation includes both orthoimages produced from laser scan data and the plans, elevations, and sections drawn from those records (Fig. 10). These steps ensure that the final representations are as accurate as possible while maintaining the flexibility to explore various interpretations on the basis of the data collected.

The planimetric documentation generated in the research study on the church of Saints Julián and Basilisa was compared with the existing planimetric documentation (plans, elevations, and sections) from *Románico Digital*. The architectural survey and documentation produced is the work of the technical team of the Santa María la Real Foundation, which is made up of architects, historians and heritage specialists. The comparison of the data from our study with the data published in the *Enciclopedia del Románico en Aragón* (Pérez 2010) provides the deviation data and percentages shown in the following table (Table 1):

3.2 Geometric analysis of the apse complex

The following section provides a detailed analysis of the structure of the triumphal arch and apse, which together form a single element in the Bagüés Room of the MDJ. This structure consists of a solid wood and plywood frame that serves as a support for the 22 mural painting panels originating from the original site. In general, both the paintings and the structure are in good, stable condition, with only minor damage, including a slight fracture

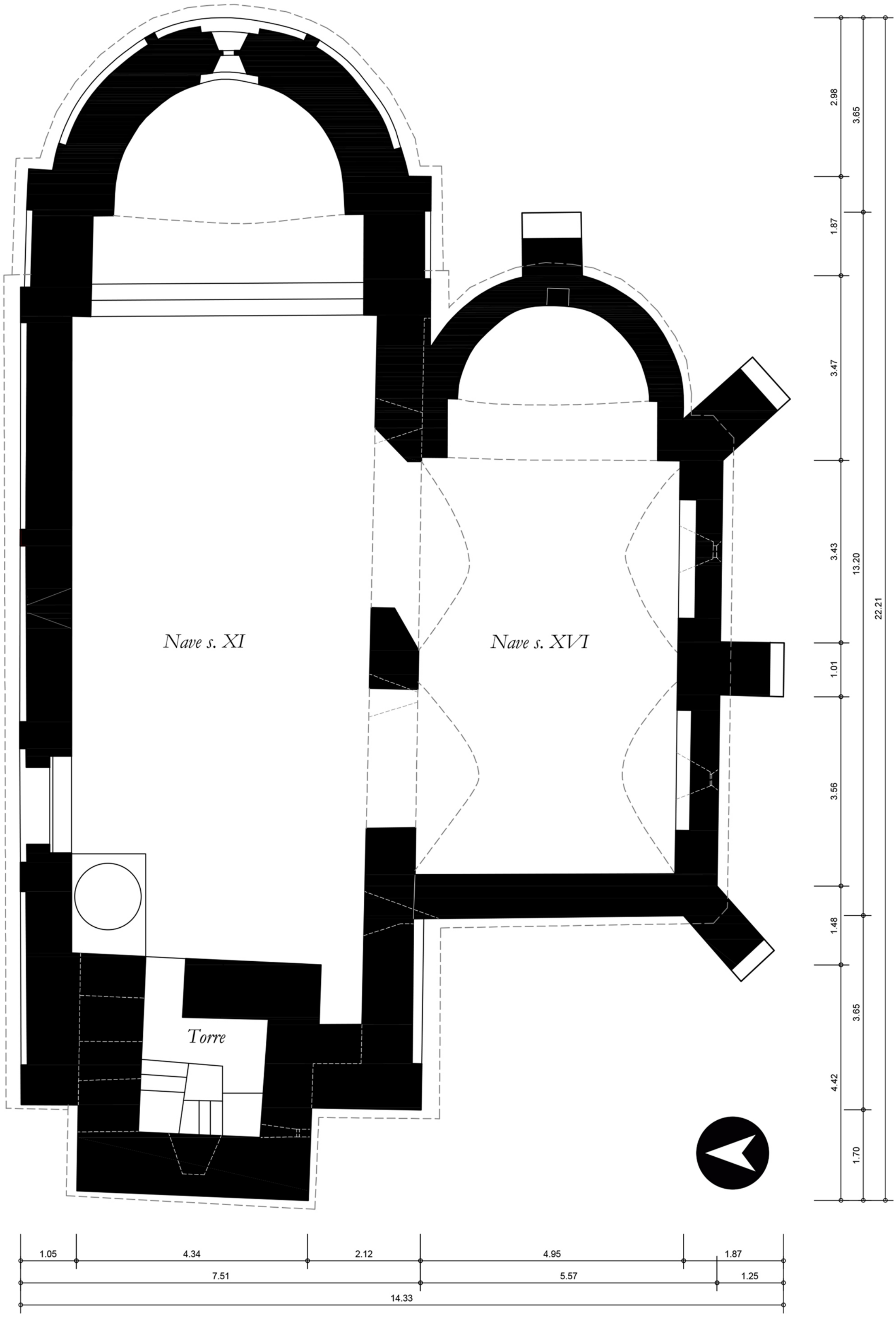

Fig. 9 Floor plan of the current state of the church, drawn from laser scan data (Source: the authors)

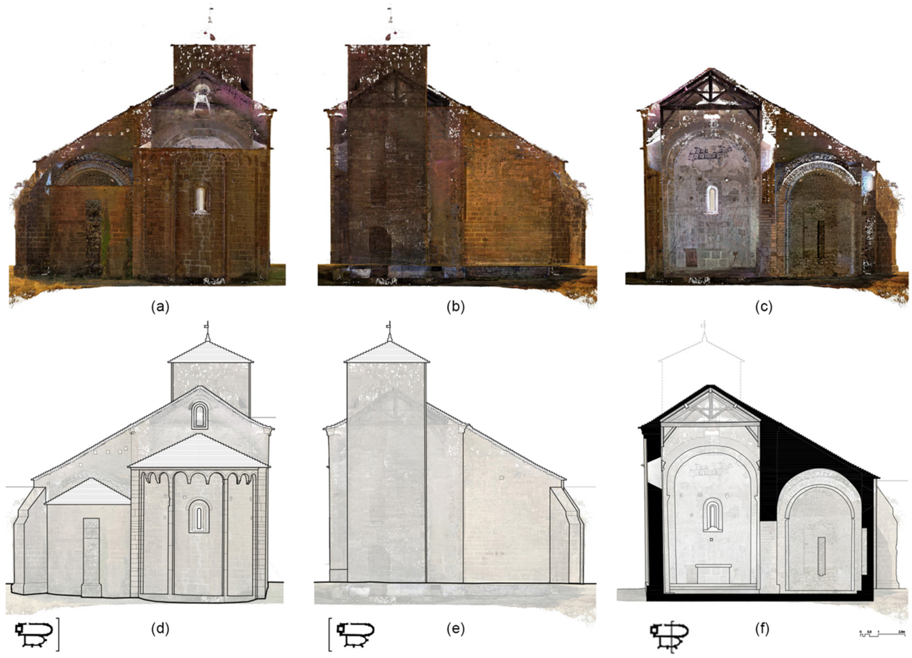

Fig. 10 Laser scan orthoimages: **a**) West elevation; **b**) East elevation; **c**) Transverse section. Elevation plans drawn from laser scan data: **d**) West elevation; **e**) East elevation; **f**) Transverse section (Source: the authors)

and a small burned area in the lower section, as noted in a conservation study of the mural paintings (Buil Martínez 2019). Seven of these panels correspond to the triumphal arch (Fig. 11); however, the front face contains only a small portion of the geometric decoration, which is composed of friezes and bird motifs. The intrados of the arch integrate the narrative cycle of Christ's Ascension from Earth to Heaven, which is depicted on the cylindrical body of the apse. The lower section of the cylinder preserves remnants of the painted imitation of textiles and drapery that originally adorned the entire space. In the five panels of the second register of the cylinder, scenes of the Crucifixion are displayed. The upper register contains a splayed central window and four panels depicting the eleven apostles and the Virgin Mary, flanked on the left and right by Saint John the Baptist and Saint John the Evangelist, respectively.

The most complex part of the ensemble, which forms the quarter sphere of the apse, consists of only three lunette-shaped pictorial panels. These panels depict two prophets introducing the Christ in Ascension, accompanied by two angels in the upper section (Rubio 2018).

The laser scan measurements conducted in both the church and the exhibition hall of the MDJ allow for a precise comparative analysis of the geometries, the remnants of the pictorial layer, and the relocated mural paintings. The measurement margin of error does not exceed 3 mm. This study compares the volume and geometry of the apse complex, designed as a support for detached paintings, with the original volume of the apse in the church of Bagüés.

Key architectural elements such as sinopias, mouldings, openings, niches, beam holes, the central window, and the lipsanotheca (a reliquary cavity clearly visible in the stone masonry of the apse) serve as essential reference points for positioning the detached paintings. In addition to the most evident references, such as the splayed window and the partial sinopias of the mandorla, eight additional openings have been identified, correlating with reserved areas or losses in the mural decoration. The opening corresponding to the lipsanotheca is also a valuable reference, as it was typically aligned with the halo or head of Christ.

The geometric comparison of both structures from the orthographic images generated by the laser scanner measurement is shown in the following table of results:

4 Discussion

4.1 Planimetric documentation

A precise comparison between the existing documentation of the church of Saints Julián and Basilisa of Bagüés, produced by the Santa María la Real Foundation, and the plans generated in the present study using laser scanning reveals an average deviation of ± 3.77%. Given the limitations of traditional architectural surveying methods, this margin of error is considered acceptable. Although the

Table 1 Dimensional comparison of relevant architectural elements (generated and existing planimetric documentation)

	Generated planimetry	Románico Digital planimetry	Deviation (%)
Surfaces:			
Usable area	139.82 m²	130.92 m²	−6.37%
Built area	222.86 m²	212.23 m²	−4.77%
Elevation N:			
Height	8.97 m	8.63 m	−3.79%
Length	22.21 m	21.10 m	−5.00%
Elevation S:			
Height	6.23 m	7.07 m	+ 13.48%
Length	17.52 m	17.06 m	−2.63%
Elevation E:			
Height	8.91 m	8.69 m	−2.47%
Length	14.33 m	13.89 m	−3.07%
Elevation W:			
Height	7.62 m	7.16 m	−6.04%
Length	7.55 m	7.28 m	−3.58%
Epistle wall:			
Height	9.50 m	9.08 m	−4.42%
Length	13.33 m	12.85 m	−3.60%
Gospel wall:			
Height	9.46 m	9.08 m	−4.02%
Length	11.96 m	11.87 m	−0.75%
Apse			
Height	7.43 m	7.39 m	−0.54%
Length	4.18 m	4.21 m	+ 0.72%
Depth	2.55 m	2.41 m	−5.49%
Triumphal arch:			
Height	8.39 m	8.15 m	−2.86%
Width	4.92 m	4.82 m	−2.03%
Side nave:			
Height	6.49 m	6.77 m	+ 4.31%
Length	10.68 m	10.38 m	−2.81%
Width	4.67 m	4.87 m	+ 4.28%
Tower:			
Height	12.68 m	12.14 m	−4.26%
Length	4.44 m	4.35 m	−2.03%
Width	4.34 m	4.30 m	−0.92%

exact date of the previously recorded plans is unknown, they appear to predate the church's most recent renovation, during which repairs were made to the roof, and the brick transverse arches of the main nave were removed.

Owing to the high precision of the measurement techniques used, the planimetric documentation produced in this study more accurately reflects the current state of the church as of 2024. The study updates the floor plan, cross-section, and north and east elevations. Additionally, it provides new documentation, including a roof plan, south and west elevations, and three longitudinal and transverse sections that had not been previously recorded with precision.

The digitisation of the Bagüés mural ensemble not only enables its detailed documentation but also facilitates its reintegration into its original architectural context through virtual reconstructions. In this context, as Llopis Verdú et al. (2024) noted, 'virtual reconstruction offers us an accessible means to recover the original image of these disappeared buildings, which were part of the history and landscape of urban environments, in order to disseminate their appearance and relevance.'

Furthermore, the application of digital technologies has revolutionised the documentation and preservation of cultural heritage, enabling greater accuracy and accessibility in scholarly studies (Başarır, and Demir 2024). Likewise, this digitisation process not only supports conservation efforts but also paves the way for a reinterpretation of the original context through virtual reconstructions, as highlighted by Moráis Morán (2019). Additionally, the development of high-resolution 3D models provides considerable advantages over traditional documentation techniques.

4.2 Apse complex geometry

The dimensional comparison of key geometric elements between the apse complex of the church of Bagüés and the shell structure designed for the mural painting installation at the MDJ (presented in Table 2 of this study) reveals an average geometric deviation of ± 7.31% in the new shell relative to the current apse of the church. The greatest discrepancies are found in the lateral sections of the triumphal arch and in the height measurements of both the arch and the apse dome.

The geometric documentation of the 3D models generated in this study allows for an accurate visual assessment of the deformations in both structures (Fig. 12). A comparative analysis clearly shows that the upper portion of the church's apse complex is deformed. The width of the triumphal arch at its base is 4.92 m, widening to 5.10 m at the top. This 18 cm expansion is also reflected in the apse dome. Such deformations are typical in structures of this type and may be attributed to the compressive settling of the apse over time. Additionally, the apse dome is not a perfect quarter sphere, as it appears flattened in its vertical dimension. This deformation may have resulted from both the original construction technique and subsequent structural settling, which could have caused lateral thrust and outwards displacement of the upper sections of the sidewalls.

Moreover, the significant variation in the geometry of the apse's quarter sphere between the church and the

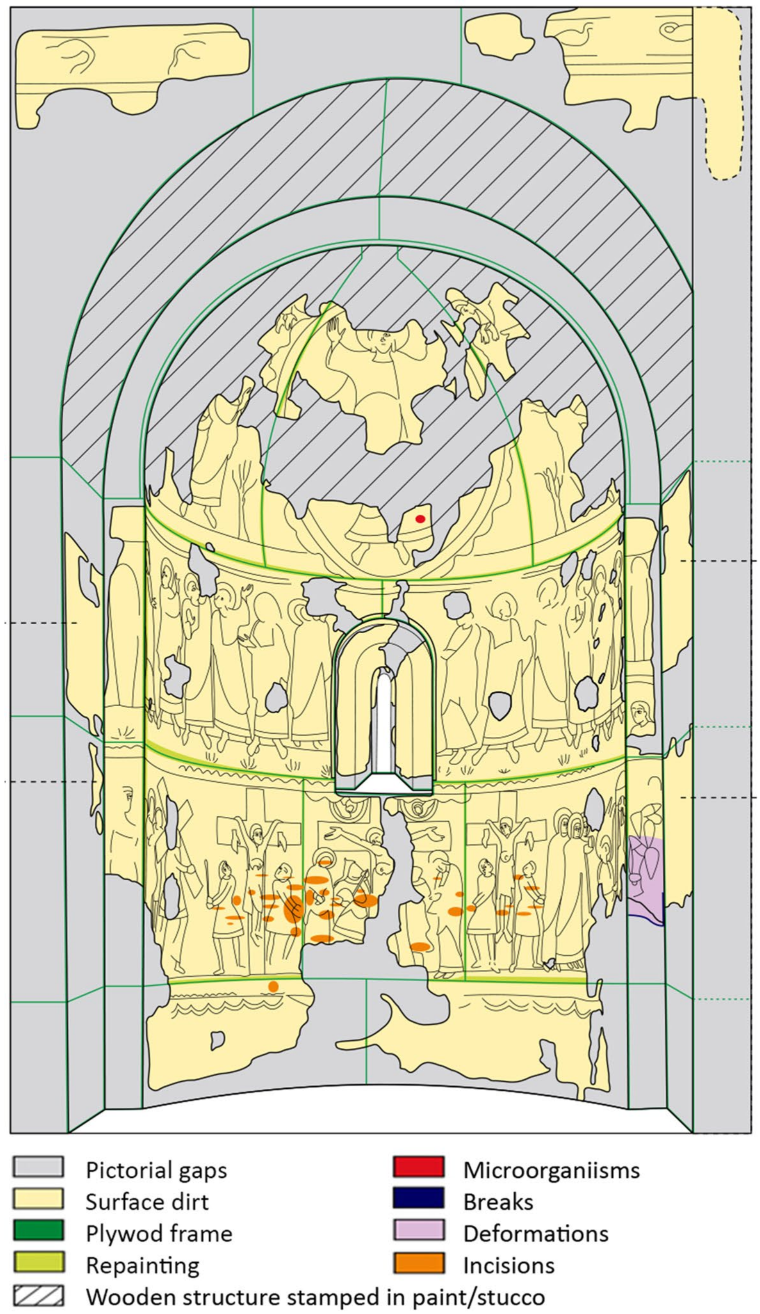

Fig. 11 Analysis of the panels of the apse complex, study and proposal for intervention on the mural paintings of the MDJ (Source: Adela Buil Martínez)

MDJ underscores the challenges inherent in transferring a mural ensemble from its original architectural setting to a museum environment. This difference not only affects the spatial perception of the artwork but also introduces new variables in its musealisation.

The wooden framework supporting the mural paintings at the MDJ partially replicates the deformations of the original structure. The triumphal arch accommodates the upper widening, showing an 11 cm deformation that is also transferred to the apse dome. However, the framework does not account for the flattening of the dome, as it was constructed as an almost perfect quarter sphere. This geometric correction or simplification results in the total height of the MDJ's apse complex being 8.48

Table 2 Dimensional comparison of relevant geometrical elements (apse of the church and the MDJ apse)

	Apse of the Bagüés church	*Apse of the MDJ Bagüés room*	*Deviation (%)*
Triumphal arch:			
Height	7.83 m	8.48 m	+8.30%
Left side A	0.44 m	0.41 m	−6.82%
Left side B	0.40 m	0.33 m	−17.50%
Right side A	0.36 m	0.31 m	−13.89%
Right side B	0.35 m	0.27 m	−22.86%
Depth A	1.95 m	2.02 m	+3.59%
Depth B	1.90 m	1.95 m	+2.63%
Apse:			
Height	7.44 m	8.03 m	+7.93%
Width A	4.31 m	4.42 m	+2.55%
Width B	4.18 m	4.42 m	+5.74%
Depth A	2.56 m	2.49 m	−2.73%
Depth B	2.55 m	2.45 m	−3.92%
Window:			
Height	1.95 m	1.97 m	+1.03%
Width	1.09 m	1.05 m	−3.67%
Distance base	2.92 m	3.11 m	+6.51%

m, compared the current apse of the Church of Bagüés, which is 7.83 m. This discrepancy, which may stem from the simplification of the framework's construction or an intentional volumetric correction aimed at achieving geometric purity, could lead to confusion when comparing the two 3D models. Therefore, any virtual reconstruction must account for these geometric discrepancies and adapt both models accordingly to ensure coherent restitution. Further research and analysis will be needed to determine whether these structural alterations have any impact on the overall perception and spatial dynamics of the original appearance.

In addition, these findings underline the importance of collaboration among conservators, architects, and local communities to develop musealisation strategies that not only respect the authenticity of the heritage but also address contemporary needs for sustainable tourism and dissemination (Soler Estrela et al. 2024).

5 Conclusions

5.1 Digital material

The materials generated for this study—including high-quality digital scans, models, and planimetric documentation—provide accurate and reliable representations of the current state of the heritage complex under examination. In today's technologically advanced society, it is possible to interpolate all these elements to create fully virtual models that are useful not only for scholars but also for a broader audience (Staropoli et al. 2023).

This method has several advantages over traditional methods. These include the objective nature of the graphic basis, ease of updating and symbolising, more accurate area and length measurements, unlimited overlay and display possibilities, ease of manipulation, ease of cross-linking with other data, and relatively simple 3-D simulations. (Murariu and Petrescu 2000). These digital models are particularly valuable in cases of displaced heritage, where certain elements have been removed from their original context. Three-dimensional (3D) and virtual technologies can serve as tools to digitally preserve these sites and raise awareness about the importance of historical properties to the general public, particularly when physical sites are at risk or no longer exist (Forte Alkhatib et al. 2025). The 3D model obtained with the combined geometric information of both sets can serve as a foundation for incorporating information from other technicians involved in the documentation or monitoring process. The recorded information will allow the organisation of heterogeneous information, such as materials, repainting, construction systems or descriptive characteristics of the symbology or artistic and constructive processes. According to the Principles for the Preservation, Conservation and Restoration of Wall Paintings, ratified by the 14th General Assembly of the ICOMOS, the conservation and restoration of wall paintings should be accompanied by a well-defined documentation program that consists of an analytical and critical report, illustrated with drawings, copies, photographs, plans, etc. The condition of the paintings, the technical and formal data relating to their creation process, and the history of each object should be recorded. All stages of the conservation process, the restoration, the materials and the methodology used should also be documented. The report should be deposited in the archives of a public institution and made available to the interested public (ICOMOS 2003). Through the use of 3D graphic information representation systems for heritage assets, accessible via web platforms, it is possible to develop heritage catalogues that help disseminate and exchange information between public administrations and citizens (Germanese et al. 2019). The digital material obtained serves as a foundation for virtual restoration exercises, academic research, dissemination, and experience design.

Owing to adaptable and accessible digital language, the visual results of this study offer a simple yet effective way to reconnect disassociated architectural and pictorial elements. The digital reconstruction of the displaced mural ensemble of Bagüés not only serves as a precise documentation tool but also plays a crucial role in shaping the way we perceive and interpret this medieval artwork

Fig. 12 Geometric comparison: a) Apse of the church section view; **b**) Apse of the church front view; **c**) Apse built for the MDJ painting installation section view; **d**) Apse built for the MDJ painting installation front view (Source: the authors)

in its original context. As Montesinos (2014) states, the representation of space is never neutral; it is always mediated by those who create it, shaping narratives that influence our perception of the territory. This assertion underscores the importance of digital methodologies in heritage studies, as they not only record the physical attributes of an artwork but also actively participate in its reinterpretation. By integrating 3D models and comparative digital analysis, this study seeks to bridge the gap between the mural's current museum setting and its original architectural environment, offering a more immersive and historically contextualised understanding of its artistic and cultural significance.

This approach facilitates the development of tourism revitalisation strategies in depopulated areas while creating a digital bridge between architecture and mural painting. On the one hand, it restores the pictorial ensemble to the architectural framework for which it was originally conceived; on the other hand, it provides a virtual architectural context for the mural installation preserved in the museum.

5.2 Proposals and future lines of research

As a result of the research and analysis process developed, the following strategies and lines of action are proposed for the revitalisation, museumisation and conservation of the studied architectural and pictorial heritage:

- Creation of digital cultural routes. 3D models and virtual reconstructions may be used to design interactive heritage routes that connect the MDJ medieval mural painting collections with the church of Bagüés and other outstanding enclaves of Aragonese Romanesque architecture, such as the ermita of Nuestra Señora del Rosario de Osia (Huesca) and that of San Juan de Ruesta (Zaragoza), both with important installations of medieval mural painting in the MDJ.
- Implementation of immersive tours. The development of augmented reality and virtual reality applications allows visitors to explore both the church and the Bagüés Room of the MDJ, facilitating the visualisation of the virtual restitution of the paintings in their original context and enriching the experience of heritage interpretation.
- Educational and informative material. Educational resources and audiovisual materials are generated based on the obtained digital models and are aimed at schools and tourist platforms, with the objective of promoting knowledge and appreciation of the displaced heritage among different audiences.
- Complementary virtual museography. A virtual room accessible both from the museum and online is created, showing the geometric comparison between the original space and the museographic installation, which allows the visitor to understand the process of displacement and restitution of the mural paintings through interactive resources.
- Interactive panels in the museum. Interactive devices installed in the Bagüés Room allow the public to manipulate digital models, visualise hidden details and access contextual information on the history and conservation of the paintings.
- Conservation and maintenance of the heritage assets. Monitoring systems may be developed through periodic scanning and comparative analysis of 3D models in order to detect alterations and plan preventive interventions on the architecture and mural paintings, thus contributing to the long-term conservation of the heritage ensemble.

These proposals constitute a concrete framework for action aimed at both the social enhancement and scientific preservation of the heritage assets under analysis.

5.3 Sinopias and mural remnants

Finally, this study proposes a hypothesis that opens new avenues for a more comprehensive analysis of the mural paintings under investigation. A geometric comparison of both apse complexes reveals a precise correspondence between the surviving mural fragments on the apse dome and the triumphal arch of the Church of Saints Julian and Basilisa of Bagüés and the gaps present in the *Ascension* composition and the upper lateral sections of the triumphal arch in the MDJ installation (Fig. 13).

The geometric adaptation to the apse of the church of the UV texture map of the original mural paintings of the MDJ was carried out in RealityCapture by combining the software point clouds obtained via laser scanning and the photogrammetry of the Sala Bagüés of the MDJ. A precise UV texture map was obtained, which is the 2D result associated with the precise 3D coordinates of the apse. This was then superimposed on the apse geometry of the church obtained by means of a point cloud generated by laser scanning. Owing to the numerous coinciding control points detected through the geometry and the hollows, it was possible to adapt this texture map of the paintings on their original support, once again linking pictorial film and architecture.

This observation suggests that beneath the existing church paintings, characterised by a coffered geometric pattern likely from a postmedieval decorative phase, there may be remnants of the original medieval mural paintings that were either undiscovered or intentionally

Fig. 13 **a**) Apse of the church, front view and sections; **b**) The MDJ painting installation, front view and sections; **c**) Geometric adaptation of the mural paintings to the original walls and comparison of possible reserves or remains of unremoved medieval paintings, front vies and sections (Source: the authors)

left in situ. To verify this hypothesis in a noninvasive manner, this study proposes the use of stratigraphic imaging techniques to examine the preserved layers of paint on the walls of Bagüés. A targeted analysis employing these advanced imaging technologies could provide critical insights into the extent of the surviving medieval pictorial layers and offer a deeper understanding of the artistic and historical transformations of the site over time.

In summary, this study demonstrates that the integration of advanced digital technologies—such as laser scanning, photogrammetry, and geometric analysis—not only ensures precise and up-to-date documentation of cultural heritage but also enables the virtual reintegration of displaced elements into their original context. The results underscore the potential of these tools to detect subtle deformations and reinterpret the historical and structural evolution of spaces, thereby providing a novel perspective on the conservation and dissemination of medieval heritage. Furthermore, the development of high-resolution 3D models opens promising avenues for future research, notably through the application of stratigraphic imaging techniques to reveal hidden pictorial layers and deepen our understanding of artistic transformation processes over time. This interdisciplinary digital methodology, which links technical preservation with tourism revitalisation and public engagement, lays the foundation for innovative strategies that ensure the continuity and relevance of cultural heritage in the contemporary era.

Abbreviations

BIC	Asset of Cultural Interest (Bien de Interés Cultural)
EXIF	Exchangeable Image File Format
HDR	High Dynamic Range
ICOM	International Council of Museums
ICOMOS	International Council on Monuments and Sites
INE	National Institute of Statistics (Instituto Nacional de Estadística)
MDJ	Diocesan Museum of Jaca (Museo Diocesano de Jaca)

Acknowledgements
The authors express their gratitude to the *GRAPHYC Research Group* for providing the technical resources essential to this research. This study would not have been possible without the generous support of the mayor of Bagüés, Mr. José Alberto Pérez, who kindly granted us access to the village church, as well as the hospitality of the residents of Bagüés during our architectural digitisation work. We also extend our sincere appreciation to the staff of the MDJ, particularly its director, Ms. Belén Luque, for allowing us to digitise the Romanesque mural paintings in their collection and granting us access to the museum archives. Finally, we would like to express our gratitude to Ms. Alba Vera for her support and assistance during the scanning process in Bagüés and to Mr. Nicola Rossi for his invaluable contribution to the photogrammetry work at the MDJ.

Authors' contributions
Domingo-Ballestin: Conceptualisation, Software, Illustrations, Writing - Original Draft, Validation. Agustín-Hernández: Conceptualisation, Methodology, Supervision, Validation. Vallespín-Muniesa: Conceptualisation, Supervision, Validation. All authors read and approved the final manuscript.

Funding
Not applicable.

Data availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 14 May 2025 Revised: 14 August 2025 Accepted: 21 August 2025
Published online: 09 October 2025

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