Digital Twin Technology in Archaeology: Laser Scanning the Underground Mine Galleries at Agios Sostis, Sifnos

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ABSTRACT

This study presents the comprehensive three-dimensional documentation of two underground mine galleries of different periods at Agios Sostis, on the island of Sifnos, Western Cyclades (Greece): an ancient vertical access shaft and a horizontal mine gallery that remained in use into the early 20th century. Sifnos has long been a significant centre of mining activity, with evidence dating back to the late 3th millennium BC and continuing into the modern era. Its basement rocks are rich in mineral deposits, including argentiferous lead, as well as copper, and iron- bearing mineralization, the exploitation of which shaped the island's economic and cultural development across multiple periods. Data acquisition was performed using high-resolution terrestrial laser scanning from multiple fixed positions within each mine gallery, complemented by handheld laser scanning, where it was necessary to capture narrow and irregular sections. Topographic control was ensured through the establishment of a large number of Ground Control Points (GCPs), enabling high spatial accuracy. The surface topography above the galleries was documented using photogrammetric processing of imagery collected via Unmanned Aerial Systems (UAS), producing orthoimages with high ground sampling distances, which were combined with the subsurface scanning data, leading to the construction of static Digital Twins for both galleries. This Digital Twin approach underscores the potential of advanced geospatial techniques for the documentation and protection of vulnerable archaeological heritage, whilst it offers a transferable and scalable framework for similar fragile environments.

Keywords: mine galleries, photogrammetry, UAS mapping, 3D point clouds, terrestrial LiDAR

INTRODUCTION

Underground archaeological features, particularly ancient and historical mine galleries, represent some of the most fragile and least accessible components of cultural heritage. Their preservation is challenged by natural weathering, geotechnical instability, human intervention, and limited opportunities for direct inspection. In this context, non-invasive geospatial documentation methods have become essential tools for both scientific analysis and heritage management (Chiabrando et al., 2017).

Two underground mine galleries at Agios Sostis, Sifnos, were selected for high-resolution three-dimensional documentation using close-range remote sensing techniques. The galleries represent different periods of mining activity on the island, ranging from antiquity to the modern era (Wagner and Weisgerber 1985). In this paper, the term "gallery" is used broadly to refer to underground mine openings, including both horizontal galleries and vertical access shafts. Recent advances in geospatial technologies, particularly terrestrial laser scanning, mobile mapping systems, and photogrammetry, have enabled the creation of high-resolution three-dimensional representations of complex environments such as archaeological sites and cultural heritage landscapes with high spatial and temporal resolution (Themistocleous, 2020). These developments help overcome the challenges associated with accessing harsh or hazardous environments by enabling the integration of data derived from multiple sources (Bartoš et al., 2023). When these datasets are integrated into a coherent, georeferenced framework, they form what is commonly referred to as a static Digital Twin: a digital replica of a physical asset that supports analysis, monitoring, and decision-making (Zhang et al., 2024). This paper presents the application of a Digital Twin approach to the documentation of two mine galleries at Agios Sostis (Figure 1), emphasizing geospatial methodology and its relevance to heritage preservation.

The study was focused on two galleries, representing different phases of mine activity on Sifnos, distinguished by their contrasting morphologies: one following a horizontal tunnelling geometry and the other formed as a vertical access shaft. The area belongs to the North Cyclades Unit (Papanikolaou, 1987; Skarpelis, 2002) and is dominated by blueschist phase metamorphic rocks, mainly schists and gneisses, with intercalated marble horizons. These lithologies exhibit well-developed foliation and structural anisotropy related to high-pressure/low-temperature metamorphism and subsequent tectonic deformation. The Agios Sostis area hosts significant argentiferous lead mineralization, which is structurally controlled and primarily developed within schistose units. Mining activity at Agios Sostis focused primarily on argentiferous lead ores, which were exploited for silver from the Early Bronze Age onward. In later phases, iron ores were also extracted, while minor occurrences of gold, copper, and zinc are reported as part of the broader polymetallic mineralization of the area. The alternation of competent marble layers and more fractured schists results in pronounced lithological and mechanical heterogeneity, which has strongly influenced both the spatial distribution of the ore bodies and the development of the historic mining galleries.

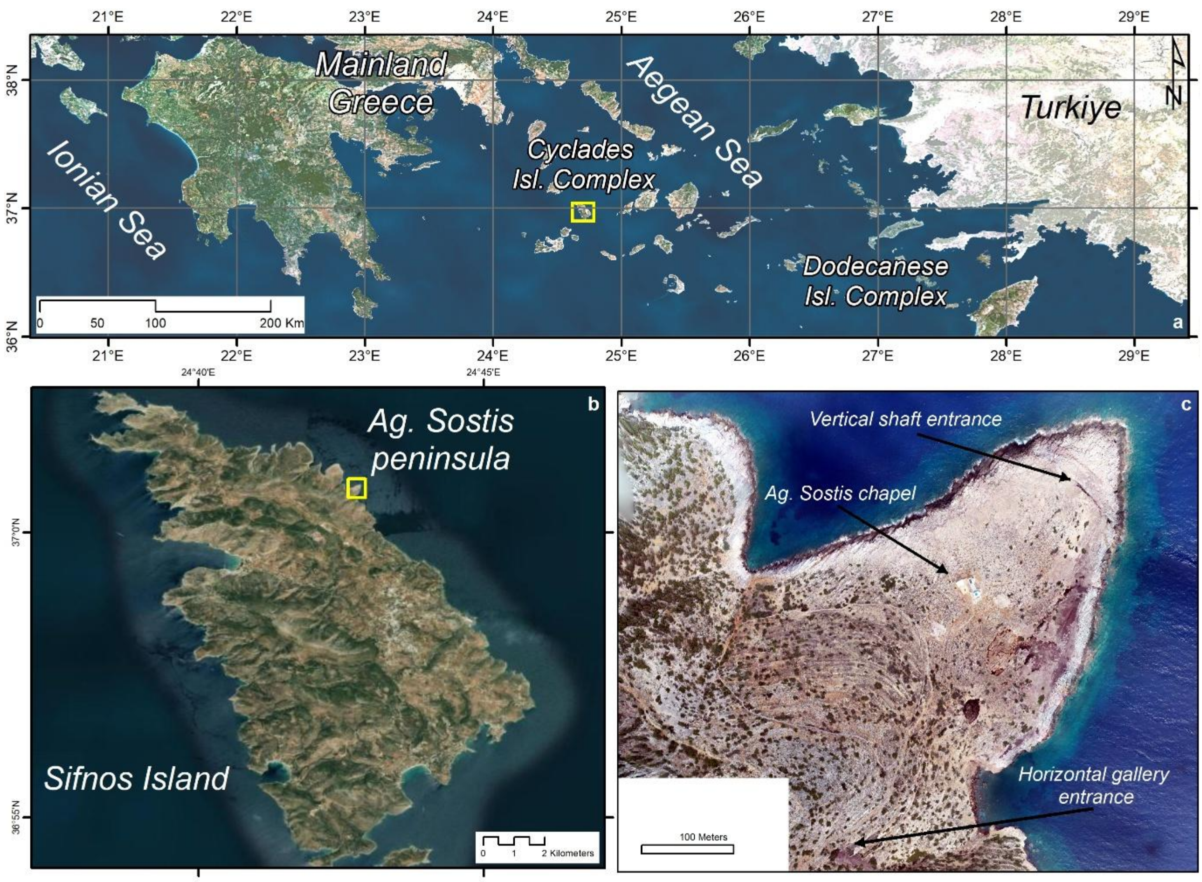

Figure 1. *Index map of the study area, showing the location of Sifnos Island within the Cyclades complex (a), the location of Ag. Sostis peninsula (b) and the entrances of the studied mine galleries (c).*

Both galleries at Agios Sostis are carved into schist bedrock and exhibit complex morphologies, characterized by variable cross-sections, sharp bends, and locally unstable ceilings, creating a geo-environment very similar to karstic caves, several of which have been investigated using

comparable methods (Idrees and Pradhan, 2016; De Waele et al., 2018; Giordan et al., 2021; Konsolaki et al., 2022; Konsolaki et al., 2026). From a geotechnical perspective, such underground galleries are commonly affected by fractures, weathering, and localized collapses, underscoring the need for precise, non-invasive, geometric documentation (Cardia et al., 2024). Detailed geometric documentation is still lacking for many of the island's mine galleries, which remain insufficiently documented.
The static Digital Twin method seems to be a convenient and efficient way for producing high-fidelity, georeferenced models that support both archaeological interpretation and long-term heritage management (Tanduo et al., 2023).

MATERIALS AND METHODS

A multi-sensor survey strategy was designed to ensure complete spatial coverage of both underground and surface features. Data acquisition was performed in several phases, which included using a high-end portable terrestrial laser scanner (TLS) from multiple fixed positions within each mine gallery (Figure 2a,b). The latter was complemented by a handheld laser scanner (HLS) to ensure the detailed capture of geometrically complex, constricted, and otherwise inaccessible sections within the mine galleries (Figure 2c). Topographic control was achieved by establishing numerous Ground Control Points (GCPs) both within and around the galleries, measured with GNSS receivers and Total Station instrumentation to ensure high spatial accuracy. Additionally, patterned markers were distributed at gallery entrances, interior junctions, and corridors, to ensure the low values of bundle-error during the data co-registration procedure, which were also used for aligning ground-based photographs, which were acquired with a DSLR camera to improve the texture quality of the final products. The surface topography above the mine galleries was documented using photogrammetric processing of imagery acquired via Unmanned Aerial Systems (UAS), resulting in ultra high-resolution orthoimages (Figure 2d,e).
The interior survey campaigns were conducted using a Leica BLK360 TLS, positioned at multiple fixed base stations along each mine gallery. A total of 20 stations were required to cover the 75-m-long horizontal mine gallery, while 8 stations were used for the 9-m-deep vertical shaft, whose geometry was considerably more complex. High-density scans were acquired to capture wall morphology, ceilings, and floor surfaces. To address areas with limited accessibility, a Leica BLK2GO HLS was employed, enabling continuous data acquisition along narrow or irregular passages (Huang, 2021). This approach proved particularly effective in the vertical shaft gallery, where HLS data were collected while operators were secured by safety ropes.
All datasets were processed using specialized geospatial and 3D-modelling software (Cyclone, 2025) to generate dense, accurately georeferenced point clouds. The interior laser-scanning datasets, comprising more than 500 million 3D points, followed a structured processing workflow that included initial scan preprocessing, noise reduction, and target-based and cloud-to-cloud registration. Registration processing was performed in several stages, including: (1) intra-station alignment, in which individual scan positions were co-registered using patterned markers and planar features; (2) bundle adjustment, minimizing residual alignment errors across all stations; and (3) georeferencing, achieved by tying the registered point clouds to GCPs measured with GNSS and Total Station instrumentation. Quality control involved evaluating registration residuals, verifying the consistency of overlap zones, and ensuring sub-centimetre registration accuracy throughout the mine galleries.
Once the interior point clouds were fully registered and georeferenced, they were optimized through filtering, decimation, and meshing procedures. This enabled the generation of high-resolution digital terrain models, detailed surface reconstructions, and textured meshes suitable for quantitative analysis.
Open surface documentation was performed using a DJI Phantom 4 RTK UAS, capturing high-overlap imagery of the terrain above the mine galleries and adjacent gangue-rich waste rock. For the UAS imagery, photogrammetric processing was performed in Agisoft Metashape Professional (2025), following a workflow that included camera-parameter optimization, image alignment, dense-cloud generation, Digital Surface Modelling (DSM) creation, and orthoimage production with spatial resolutions of 4.18 cm (for the horizontal gallery) and 1.62 cm (for the vertical shaft). Ground Control Points collected during the field campaigns were incorporated during the georeferencing phase to ensure consistent spatial alignment with the TLS/HLS datasets (Vassilakis and Konsolaki, 2022).
The interior models were then spatially integrated with surface terrain models derived from UAS-based photogrammetry, using common control points and iterative closest point (ICP) refinement to ensure seamless alignment. Interior and exterior models were merged into a unified static Digital Twin, from which high-resolution meshes and digital terrain models were derived. Spatial analyses included overburden thickness calculations and volumetric estimation of gangue-rich waste rock deposits.
In the final step of the methodology, the datasets were cleaned and subsampled into new point clouds decimated for more effective handling. Point cloud decimation primarily influences the level of geometric

detail that can be represented, even though it does not alter the inherent measurement accuracy of the original laser-scanning acquisition.

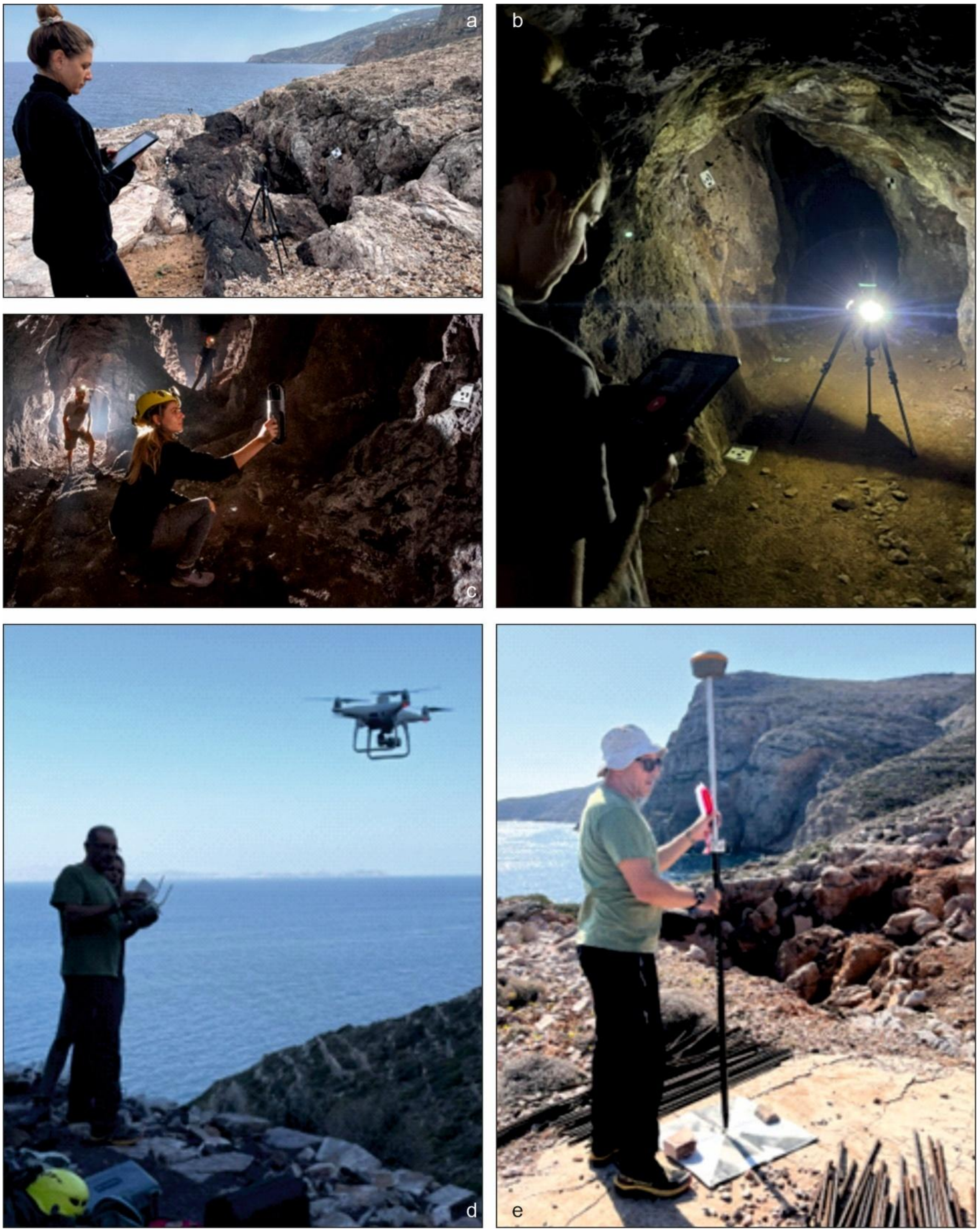

Figure 2. *Photo gallery of the equipment used during fieldwork. Terrestrial Laser Scanning (TLS) was applied to document the exterior parts of the galleries (a) and was also employed for interior mapping (b). The interior was additionally captured using a handheld laser scanner for capturing the complex parts of the gallery morphology (c), while aerial images of the open area above the site were acquired with an Unmanned Aerial System (UAS) (d). All datasets were georeferenced using Ground Control Points (GCPs) measured with RTK-GNSS receivers.*

By increasing the average point spacing, the sampling density of the surface is reduced, which has several implications for the representation of fine-scale features. Decimation algorithms are designed to remove redundant points while maintaining the overall shape, dimensions, and structural characteristics of the scanned surface. Thus, the reduced dataset continues to provide an accurate large-scale representation suitable for most analytical or visualization tasks, with the primary trade-off being a decrease in local surface resolution rather than a loss of measurement accuracy.

RESULTS

The structured registration workflow, including target-based alignment, cloud-to-cloud refinement, and georeferencing with GNSS and Total Station observations, ensured sub-centimetre accuracy and the creation of coherent, georeferenced point clouds.
The initial interior laser-scanning dataset of the vertical access shaft comprised more than 140 million georeferenced 3D points, forming a unified dense point cloud with an average point spacing of 5 mm. For easier management, the dataset was cleaned for removing unnecessary points (noise) and subsampled, producing a new point cloud of approximately 35 million points. This decimation increased the average point spacing to about 1cm, while still preserving the essential geometric characteristics of the shaft (Figure 3a). The resulting static Digital Twin provides a unified and geometrically faithful representation of the underground galleries, enabling direct interpretation of their spatial configuration without schematic abstraction. Furthermore, the processed point clouds were converted into high-resolution digital terrain models and textured 3D mesh (Figure 3b,c). These products enabled virtual navigation through internal cavities, providing a realistic visualization of the underground spaces and offering valuable insights into the challenges associated with mining activities.

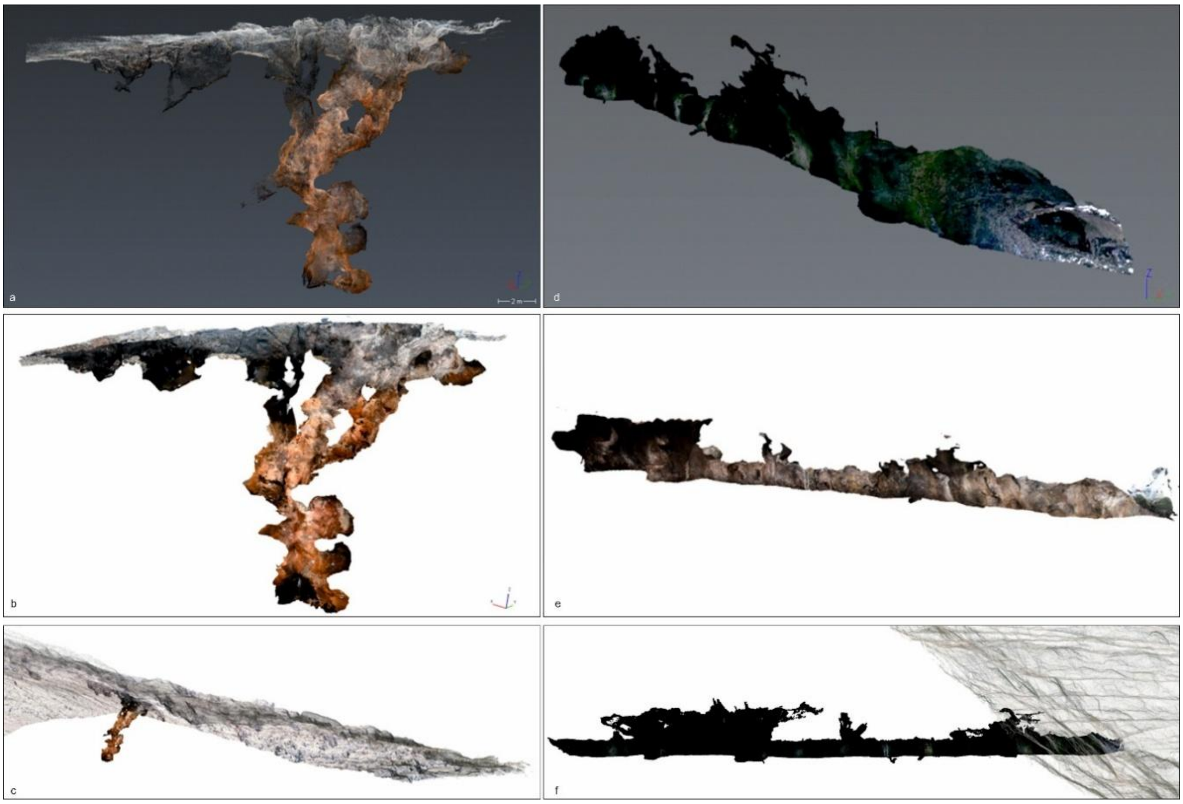

Figure 3. *Static Digital Twin representations of the underground structures at Agios Sostis generated from 3D survey data. Point clouds (a, d) and corresponding static 3D Digital Twin models (b, e) illustrate the geometry of the vertical shaft (left) and the horizontal gallery (right). Panels (c, f) present the integrated, georeferenced Digital Twin dataset combining underground point clouds with surface data reconstructed using photogrammetric techniques.*

A similar outcome was obtained from the processing of the laser-scanning datasets acquired within the horizontal gallery. The unified dense point cloud contained approximately 220 million georeferenced 3D points, representing the interior geometry of the gallery with an average spacing of 10 mm (Figure 3d). This dataset was subsequently cleaned and subsampled into a refined point cloud of 50 million points,

which was used to construct a high-quality 3D model for the quantification of several geometric parameters (Figure 3e).
The most significant was the overburden thickness along the horizontal gallery, which was quantified by integrating the 3D geometry of the underground passage, derived from the subsampled TLS dataset, with the high-resolution surface topography generated from the UAS survey. After both datasets were transformed into the same geodetic reference frame, the roof surface of the gallery was extracted from the TLS 3D model and spatially aligned with the photogrammetric DTM (Figure 3f).
The vertical distance between the roof surface of the gallery and the projected ground surface above it was then computed continuously along the entire length of the passage. This was performed by calculating the elevation difference between the TLS-derived roof model and the high-resolution photogrammetric DTM at matching planimetric positions, enabling a detailed, fine-scale estimation of overburden thickness. The resulting values represent the thickness of bedrock overlying the gallery at each point along its length. This method provided a continuous and highly precise estimation of overburden thickness, which varied from 5.2 m (near the entrance) to 66.8 m (at the end of the gallery), revealing how the mining infrastructure was positioned relative to the morphology and geological structure of the overlying terrain.
Additionally, the unified, multilayered 3D framework derived from the integration of TLS and UAV datasets provided a robust basis for structural interpretation and for assessing the spatial relationship between the underground workings, surface morphology, and associated mining features. This integrated model enabled not only the detailed visualization of the subsurface–surface system but also the volumetric quantification of modern-era mine spoil (waste-rock; gangue-rich material) accumulated near the gallery entrances. The calculated volume of these mine-spoil (waste-rock; gangue-rich) accumulations was approximately 4,914 m^3, representing substantial material removal and disposal associated with modern-era extraction. This quantitative estimate provides a useful proxy for the scale of recent mining operations at the site and supports assessment of the spatial relationship between underground openings, surface deposits, and local geomorphology. These results highlight the value of integrated subsurface–surface 3D modelling for interpreting mining landscapes and for informing documentation and management of vulnerable underground heritage.

CONCLUSIONS

This study demonstrates the effectiveness of a multi-sensor geospatial workflow for the comprehensive three-dimensional documentation of underground mining features on Sifnos Island. By integrating terrestrial and handheld laser scanning with UAS-based photogrammetry, it was possible to capture both the internal morphology of the underground workings and the external topography with high spatial accuracy. The combined TLS–HLS acquisition strategy proved particularly valuable in areas of restricted accessibility, allowing detailed documentation of narrow, irregular, and vertically oriented passages that would otherwise remain insufficiently surveyed.
This Digital Twin generation approach underscores the potential of advanced geospatial techniques for the documentation and protection of vulnerable cultural heritage. It offers a transferable and scalable framework for similar fragile environments. The Agios Sostis digital twins presented in this study provide an example of robust analytical frameworks for the investigation of subterranean environments, with significant applicability in geoheritage research and related scientific domains (Stek, 2016; Cucchiaro et al., 2020). The resulting static Digital Twin offers a high-fidelity representation of the mining site, supporting both archaeological interpretation and geological assessment. Beyond documentation, the dataset enables volumetric analyses, structural evaluations, and long-term monitoring of stability and preservation conditions. Overall, this approach demonstrates a transferable and scalable methodology for recording fragile underground environments and contributes to the broader protection and study of underground cultural heritage across the Aegean and similar regions. The resulting models highlight the value of advanced geospatial methodologies in preserving fragile underground heritage sites and provide a transferable framework for similar sites worldwide.
Within the context of geotechnical engineering, the generation of static Digital Twins emerge as a powerful technique for documentation, analysis, and long-term preservation planning of fragile underground heritage features, in particular. The methodology described here aligns closely with the objectives of geotechnical engineering for heritage preservation, supporting informed decision-making and risk mitigation. High-resolution 3D models allow the identification of unstable ceilings, zones of deformation, and structurally sensitive areas, supporting proactive risk assessment and targeted conservation interventions. Although no localized collapse or instability features were identified, the overall geometry of the excavations, as observed through the Digital Twin datasets, reflects the influence of lithological contrasts and structural anisotropy within the host rock mass. During the virtual movement

in both the galleries, it became very clear that variations in surface roughness and cross-sectional shape are consistent with excavation along foliated schist units and more competent horizons, rather than with geotechnically driven failure. As a result, correlations with rock mass characteristics remain qualitative and constrained by the absence of discrete instability indicators.

The Digital Twin also establishes a permanent baseline against which future deformation, collapse, or environmental change can be monitored through repeat surveys. Moreover, the digital archive ensures that the geometry and condition of these vulnerable features are preserved even if future physical degradation occurs. By providing accurate, shareable visualizations, the approach also facilitates interdisciplinary collaboration and public engagement, strengthening the broader framework of cultural heritage protection.

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