

## Article

# Survey and Analysis of Hieroglyphic Inscriptions in the Postern of Yerkapı–Ḫattuša

Leopoldo Repola <sup>1,\*</sup>, Giovanni Varriale <sup>1,\*</sup>, Massimiliano Marazzi <sup>2</sup>, Vincenzo Morra <sup>1</sup> and Andreas Schachner <sup>3</sup>

<sup>1</sup> Department of Earth Sciences, Environment and Resources, University of Naples Federico II, 80126 Napoli, Italy; vimorra@unina.it

<sup>2</sup> Department of Humanities, Suor Orsola Benincasa University, 80135 Napoli, Italy; massimiliano.marazzi@unisob.na.it

<sup>3</sup> Deutsches Archäologisches Institut, 34437 Istanbul, Turkey; andreas.schachner@dainst.de

\* Correspondence: leopoldo.repola@unina.it (L.R.); giovanni.varriale@unina.it (G.V.)

## Abstract

Yerkapı, a prominent structure within Ḫattuša, the capital of the Hittite Empire (17th–12th century BC), exemplifies the sophisticated architectural and cultural practices of this ancient civilisation. The monument, encompassing a Sphinx Gate and an underground tunnel (postern) featuring 249 hieroglyphic inscriptions, is hypothesised to have served ceremonial rather than defensive purposes. This study employs a multidisciplinary approach to document, analyse, and interpret the inscriptions and their architectural context through advanced methodologies. High-resolution 3D digitisation was conducted using drones, terrestrial laser scanning, and photogrammetric techniques, enabling the creation of detailed models of the site. Specific focus was given to the postern, with comprehensive surveys delineating the geometries of the inscriptions and their spatial relationships to the Sphinx Gate. Diagnostic pigment analysis provided insights into the mineralogical and chemical composition of the red figures, further informing the interpretation of the hieroglyphs. The integration of 3D models and petrographic data allowed for the identification of previously unobservable details and facilitated a sequential reading of the inscriptions within their architectural framework. The findings emphasise Yerkapı's function as a site of symbolic and ritual importance, thereby advancing our comprehension of Hittite ceremonial practices and establishing a methodological paradigm for the integration of digital archaeology with the study of geo-materials in the investigation of complex ancient monuments.

**Keywords:** 3D digitisation; geoarchaeology; hieroglyphs; modelling; data visualisation; data analysis

Academic Editor: Francesco Fassi

Received: 16 June 2025

Revised: 23 July 2025

Accepted: 06 August 2025

Published: 11 August 2025

**Citation:** Repola, L.; Varriale, G.; Marazzi, M.; Morra, V.; Schachner, A. Survey and Analysis of Hieroglyphic Inscriptions in the Postern of Yerkapı–Ḫattuša. *Heritage* **2025**, *8*, 321. <https://doi.org/10.3390/heritage8080321>

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Situated ca. 200 km east of Ankara, the archaeological site of Ḫattuša (the Hittite Capital—UNESCO World Heritage Site, inscribed in 1986) represents one of the most significant sites in the entire ancient Near East. Systematic excavations started in 1906 and are still ongoing today, under the supervision of the German Archaeological Institute of Istanbul, in cooperation with the Turkish Ministry of Culture and Tourism, and with the participation of numerous international scientific organisations. The archaeological mission at Ḫattuša, to which the Department of Earth Sciences, Environment and Resources

(DiSTAR) of the University of Naples Federico II is contributing, is funded by the Ministry of Foreign Affairs and International Cooperation of Italy (MAECI).

The integration of the complex topography into which the urban design of the city is integrated is a feature that distinguishes Hattuša as a key site for the study of urban development in the second millennium BC. This approach allowed the Hittites not only to functionally organise the city along natural boundaries—further reinforced by artificial constructions—but also to seamlessly incorporate the landscape into the urban fabric, making it an essential component of both the practical use and symbolic significance of individual structures [1] (p. 32), [2]. The site of Hattuša clearly illustrates the deliberate efforts of the Hittites to redefine the character of the surrounding landscape. This ambition was realised in some cases through the creation of transitional architectural features that linked the symbolic spaces of the city to the perceived natural environment, as exemplified by Yerkapı, a 250 m long, up to 80 m wide, and ca. 40 m high artificial rampart piled up on top of the highest point of the site [3].

In August 2022, during a visit to the Yerkapı postern, B. Genç and the DAI team discovered painted hieroglyphic inscriptions on the stones forming the inner walls of the postern [4]. Following this discovery, two three-dimensional digitisation campaigns were carried out in August and September 2022 and 2023, focusing on Yerkapı and its postern's walls, with the aim of digitally documenting the entire monument. In addition, a specialised diagnostic campaign—conducted in collaboration with the Department of Science and Technology of the University of Sannio—was carried out to analyse the composition of the red pigments used for the hieroglyphs in the Yerkapı postern [5].

This study presents the results of this collaborative research with the DAI, focusing on the painted hieroglyphic inscriptions discovered in the Yerkapı postern. It highlights the contributions of 3D digitisation to the study of Yerkapı and discusses the results of diagnostic analyses of the chemical and mineralogical properties of the pigments used to create the hieroglyphs.

### The Hieroglyphic Inscriptions

Hieroglyphic inscriptions created using either the so-called “puntzen” technique for ephemeral writings or signs worked in high relief are well attested for the Hittite Empire period, especially the late 13th century BC [6]. A third way to use Anatolian hieroglyphic script was to write on wax inlaid into wood frames.

The inscriptions written using the “puntzen” technique are often referred to as “extemporaneous” graffiti. Unlike public monumental inscriptions in high relief, they were personal and entirely non-public in nature. The places where these inscriptions were found are of particular importance, since they were mainly placed in areas of frequent passage, such as on the outside walls of buildings, on thresholds, and along roads. Although not intended as public proclamations, their positioning in transit spaces suggests a connection to the daily activities of the scribes who created them. M. Marazzi [6] has compiled a comprehensive catalogue of these inscriptions, revealing a pattern of distribution that highlights the informal use of public spaces in Hattuša.

The discovery of a so far limited number of examples in the Upper City of Hattuša, known as the *Oberstadt*, lends further support to these hypotheses [7]. In this exclusively ceremonial and public part of the city, graffiti inscriptions suggest that the use of hieroglyphic script had become a “widespread” form of writing, at least among the administrative and religious elites of the capital.

A landmark discovery in 2015 at the site of Kayalıpınar, located near the Kayalıpınar village in the Yıldızeli township of Sivas province, forced scholars to rethink their understanding of Anatolian hieroglyphics even further. During the excavation of Building A, which dates from the late 16th to mid-15th century BC, two groups of painted hieroglyphic signs were found on adjacent blocks at the base of the southern wall in Room 11.

These inscriptions were analysed by A. Müller-Karpe, who identified them as recording a personal name and a title or profession associated with construction work [8]. Müller-Karpe further noted that these inscriptions were not official construction markings, but rather personal graffiti. The theory is that a master builder, proud of his contribution to the structure, inscribed his name on the building before the work was completed.

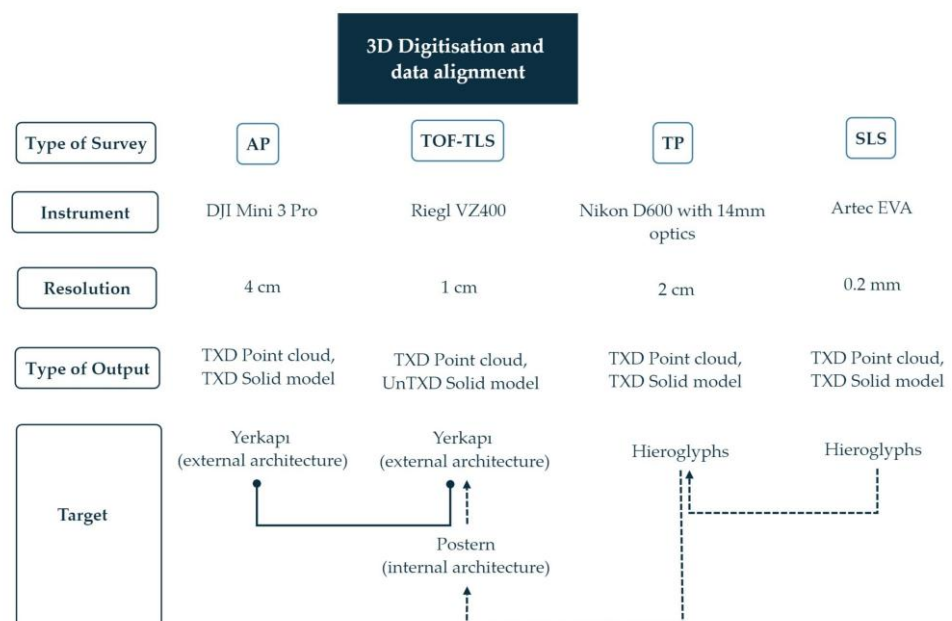
This discovery is significant not only for its informal nature but also for its context. The inscriptions were only visible during the construction phase of the building, suggesting that they had no public function and were intended as a personal marker. This finding first challenged the prevailing view that hieroglyphic writing in Anatolia was confined to formal, public contexts. Instead, it suggests that this script may have been more integrated into everyday life than previously thought.

A few years after the discoveries at Kayalıpınar [4], the accidental discovery of a total of 249 painted hieroglyphs within the postern of Yerkapı prompted the implementation of a detailed digitisation plan to record their geometries, their colours, and the surfaces they occupy. This effort has significantly improved our understanding of the spatial organisation of these inscriptions within the architectural framework.

## 2. Materials and Methods

### 2.1. Three-Dimensional Digitisation Activities: A Comprehensive Survey and Post-Processing of the Yerkapı Rampart and Postern

The 3D digitisation activities focused on a comprehensive survey of the Yerkapı monument, located in the southern part of the Hattuša site. The workflow involved multi-resolution data collection using a combination of techniques, followed by post-processing to generate denoised point clouds and polygonal models for analysis. Advanced technologies were employed to conduct a thorough survey of Yerkapı and sections of the surrounding city walls, as shown in Figure 1.



**Figure 1.** Survey techniques and data integration applied in this study. The diagram shows relationships between acquisition methods—AP (aerial photogrammetry), TOF-TLS (time-of-flight terrestrial laser scanning), TP (terrestrial photogrammetry), and SLS (structured-light scanning)—and their respective targets (architectural elements and hieroglyphic inscriptions). The solid arrow indicates alignment based on ground control points (GCPs); dashed arrows represent manual registrations.

Aerial photogrammetric data were collected using a DJI Mini 3Pro drone operated by three qualified UAV professionals in Turkey. The collected data were processed using Agisoft Metashape software version 1.8.4 following standard procedures. To align the model with the local topographic coordinate system, ground control points—consisting of 50 cm scale bars and 5–10 cm cylindrical markers—were assigned coordinates measured with a total station at topographic points 100 and 110 of the DAI reference system.

Higher-resolution 3D models of the site were obtained using a Riegl VZ 400 time-of-flight (TOF) laser scanner. The primary objectives were to study the fortifications surrounding the Yerkapı rampart and to understand the interaction between the topography of the hill and the wall structures. Precise alignment of the 3D models to the DAI's local coordinate system was achieved using previous total station measurements. The TOF laser scanner allowed the digitisation of Yerkapı's architectural features with extensive coverage, including intermediate passageways between different architectural levels, the two staircases on the eastern and western sides of the rampart, the Sphinx Gate, and the southern and northern gates leading to the postern. The data were acquired at a resolution of 7 mm at a distance of 10 m to capture fine architectural details. The point clouds were textured with images captured using a Nikon D600 with 14 mm optics integrated into the scanning system. The same acquisition parameters were applied to the TOF laser scanner survey conducted within the postern, aiming to digitise the entire tunnel's architectural structure.

The post-processing of the TOF laser scanner datasets was carried out using Riscan Pro software version 2.9. The 89-point clouds related to Yerkapı and the 49 scans from the postern were merged into two different point clouds and then segmented into eastern and western parts.

The Yerkapı point cloud was further divided into macro blocks—GATE, EAST, and WEST—which were then subdivided into sub-layers (e.g., GATE\_Hill, GATE\_Architecture, EAST\_Hill, EAST\_Architecture, WEST\_Hill, WEST\_Architecture). Each sub-layer was processed individually, including manual noise removal, Octree 10 mm filtering, and export to text format. For high-resolution mesh generation, the eastern and western parts of the rampart were divided into primary levels: LEVEL 0, LEVEL 1, LEVEL 2, EXTERNAL WALLS, and WALLS. The Sphinx Gate (called GATE SECTIONS) was processed separately to match the postern to the external architecture. Filters were applied to minimise noise and reduce outliers.

For the postern, the 49-point clouds were first automatically registered, followed by multi-station adjustment and verification using the Global Registration algorithm. The final merged point cloud was filtered with an Octree 10 mm filter to remove redundant reflections and exported in text format. The postern walls were segmented into EAST and WEST sections and aligned with corresponding sections of the Sphinx Gate point cloud.

## *2.2. Detailed Three-Dimensional Digitisation of the Hieroglyphs*

Each inscription was systematically numbered according to its location, ensuring complete coverage of both the eastern and western walls [4,5,9]. The survey began with the scanning of the hieroglyphs using an Artec EVA structured-light scanner. Photogrammetric surveys were then carried out with a Canon EOS camera, progressively defining the areas of the postern using 50 cm aluminium scale bars. The photographs were processed using Agisoft Metashape software version 1.8.4, and the resulting 3D photogrammetric models were manually registered with the laser scanner data related to the postern's internal architecture.

The ARTEC 3D models were produced using ARTEC Studio 17 software. Texture editing procedures were also applied to enhance the chromatic distinction between the

hieroglyphs and the stone surfaces of the postern. Subsequently, the structured-light 3D models were aligned with the photogrammetric data.

All manual alignment procedures were carried out using CloudCompare software version 2.13.1 through the systematic identification of homologous points on the tunnel wall stones for each pair of 3D models. This software proved particularly effective for managing alignment tasks of this kind and can be reliably applied to other case studies adopting similar methodologies.

Finally, the subsequent vectorisation of the hieroglyphs was performed using Rhinoceros software version 7.

### 2.3. Diagnostic Analysis of the Postern Hieroglyphs

A specific diagnostic campaign, conducted in collaboration with the Department of Science and Technology of the University of Sannio during the 2023 investigations, aimed to analyse the composition of the red hieroglyphs found in the Yerkapı postern. This analysis focused on four inscriptions—designated GERO 1, GERO 2, GERO 3, and GERO 4—corresponding to hieroglyphs L60, L69, R62, and R73 respectively, as identified in the nomenclature provided by Marazzi [5,9] (L = left = eastern wall; R = right = western wall; see Marazzi, 2023 for further details).

Given the importance of the discovery and the logistical challenges involved, non-invasive techniques were used to study the textural, mineralogical, and chemical properties of the red figures. The analytical protocol included multispectral surface analysis using digital microscopy, as well as pXRF and Raman spectroscopy, all of which are widely recognised for their effectiveness in pigment analysis [10–15].

Within the Yerkapı postern, four hieroglyphs (GERO 1, GERO 2, GERO 3, GERO 4) were analysed [5] using the following techniques:

#### -Digital Microscopy (DM):

The surface details of the hieroglyphs were examined using a Dino-Lite digital microscope with a magnification range of 20–220×, built-in coaxial illumination, and flexible LED control (FLC). The microscope had a 5.0-megapixel colour CMOS sensor, and images were captured using Dino-Capture 2.0 software.

#### -Portable X-ray Fluorescence Spectroscopy (pXRF):

The chemical composition of the pigments was determined using a Bruker Tracer 5G X-ray fluorescence spectrometer. Key parameters included a 30 kV/10 μA power supply, rhodium (Rh) transmission target, 10 s acquisition time, and 8 mm spot size. XRF spectra were processed using Bruker ARTAX Spectra 8.0 software.

#### -Raman Spectroscopy (RS):

The mineralogical composition of the pigments was analysed using a BRUKER BRAVO handheld Raman spectrometer using Duo Laser excitation and the Sequentially Shifted Excitation technique (SSETM, patent number US8570507B1) for fluorescence mitigation. The system featured a charge-coupled device (CCD) detector, and variable acquisition times were used to avoid saturation. Raman spectra were recorded within the spectral range of 3200 to 178 cm<sup>-1</sup>, with acquisition and processing (including baseline correction and smoothing) performed using Bruker Opus 7.2 software.

#### -Multispectral Imaging:

Multispectral imaging involved capturing two-dimensional images at different wavelengths within a defined spectral range using different light sources. Modes included the following:

- Visible Reflected Imaging (VIS): Captured in the visible spectrum using standard photographic equipment and visible light irradiation. These images represent surfaces as seen by the human eye.

- Infrared Reflected Imaging (IRR): Captured in the 700–1100 nm spectrum using infrared illumination and three filters (750, 850, and 950 nm). Infrared radiation penetrates protective agents, consolidants, and pigments, revealing elements hidden by them. In some cases, materials absorb IR radiation and appear darker.
- Reflected Ultraviolet (UVR) Imaging: Captures the reflected ultraviolet spectrum (220–400 nm) from a UV radiation source. These images highlight surface-level materials, such as paints and transparent coatings, providing insights into the uppermost layers of the inscriptions.

### 3. Results

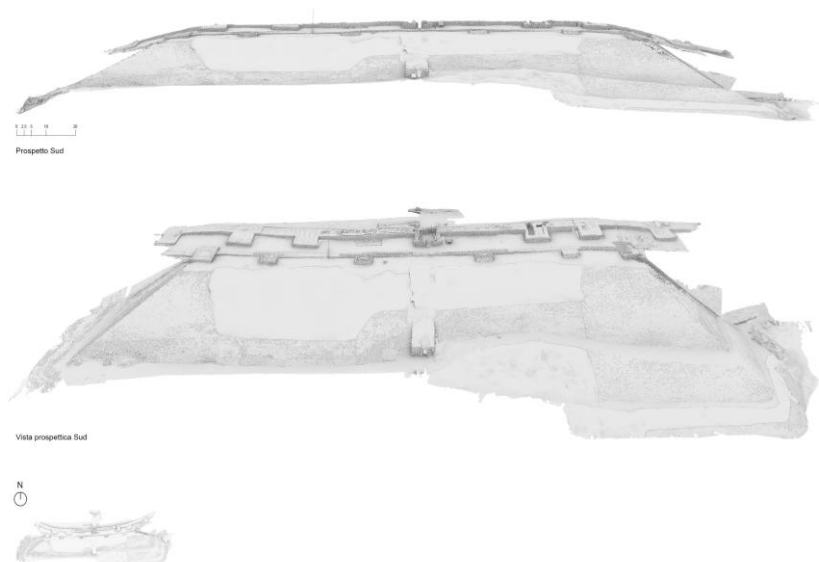
#### 3.1. Three-Dimensional Digitisation of Yerkapı Rampart and Postern

From the photogrammetric survey, a dense point cloud of 39 million points was obtained, from which a polygonal model of 34 million triangles was generated after vegetation removal and noise filtering. Orthophotos, including zenithal, frontal, and perspective views, were derived from the photogrammetric model.

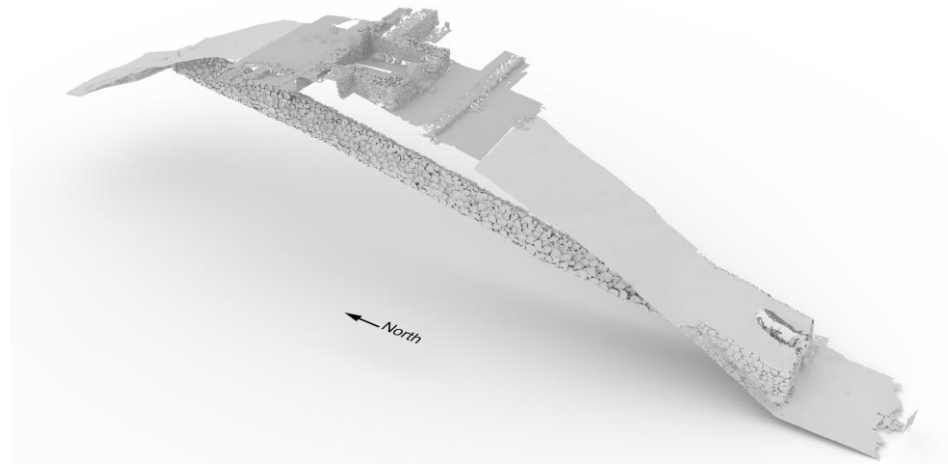
The TOF laser scanner allowed the digitisation of Yerkapı's architectural features with extensive coverage, including intermediate passageways between different architectural levels, the two staircases on the eastern and western sides of the rampart, the Sphinx Gate, and the southern and northern gates leading to the postern.

The alignment of postern data with the Sphinx Gate point cloud achieved an average accuracy of 1 cm, allowing efficient mesh generation for both structures.

The 3D polygonal models (Figures 2 and 3) were then imported into a CAD environment (Rhinoceros 7 software) to produce detailed drawings to aid the analysis and study of the monument.



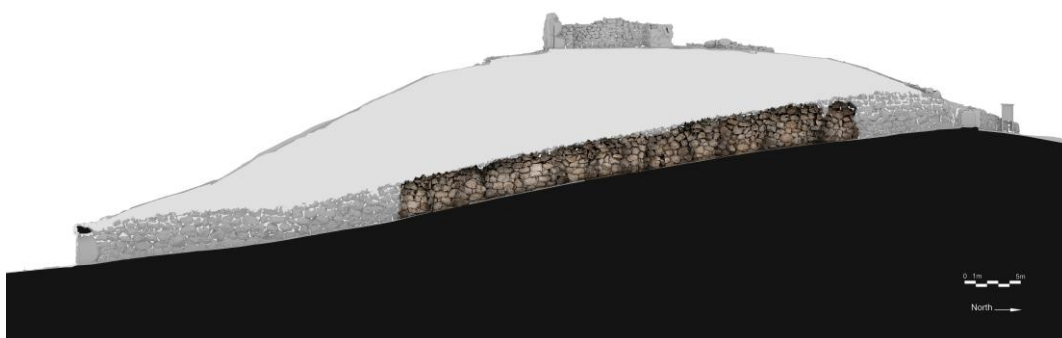
**Figure 2.** Boğazköy-Ḫattuša, Yerkapı. Technical representations of Yerkapı 3D model with subcentimetric resolution. © Leopoldo Repola, Giovanni Varriale [5] (p. 113).



**Figure 3.** Three-dimensional models of the eastern and western walls of the postern, aligned with the external architectural elements (Yerkapı Gate section layers). © Leopoldo Repola, Giovanni Varriale [5] (p. 70).

### 3.2. Post-Processing and Visualisation of Three-Dimensional Models Derived from Hieroglyph Scanning

The alignment of the photogrammetric models with the laser scanner data enabled accurate mapping of the hieroglyphs in relation to the postern walls and the overall architectural structure of Yerkapı (Figure 4). The objective of this survey was also to accurately trace the progression of the inscriptions on orthophotos [9]. This outcome was achieved through the combined use of different survey techniques (Figure 1), which allowed for the generation of interoperable 3D models at varying levels of resolution. This approach proved to be a key factor during the manual data registration phases. The textured photogrammetric models, which preserve both the geometric features of the wall stones and the epigraphic details, served as a crucial link between the architecture of the tunnel—captured through laser scanning—and the hieroglyphs depicted on the wall stones, surveyed with the Artec EVA system.

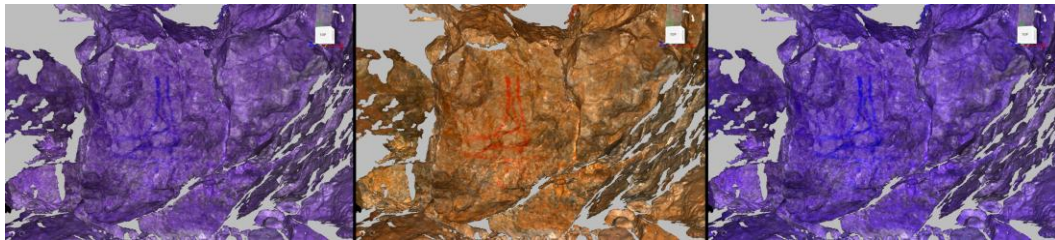


**Figure 4.** Three-dimensional photogrammetric models aligned with subcentimetric accuracy to the walls of the postern (western section view) and the Sphinx Gate. © Leopoldo Repola, Giovanni Varriale.

The margin of error in the localisation of the inscriptions is directly related to the resolution of the models used during the alignment phase and is, therefore, strictly dependent on the technology adopted. In the manual registration of the photogrammetric

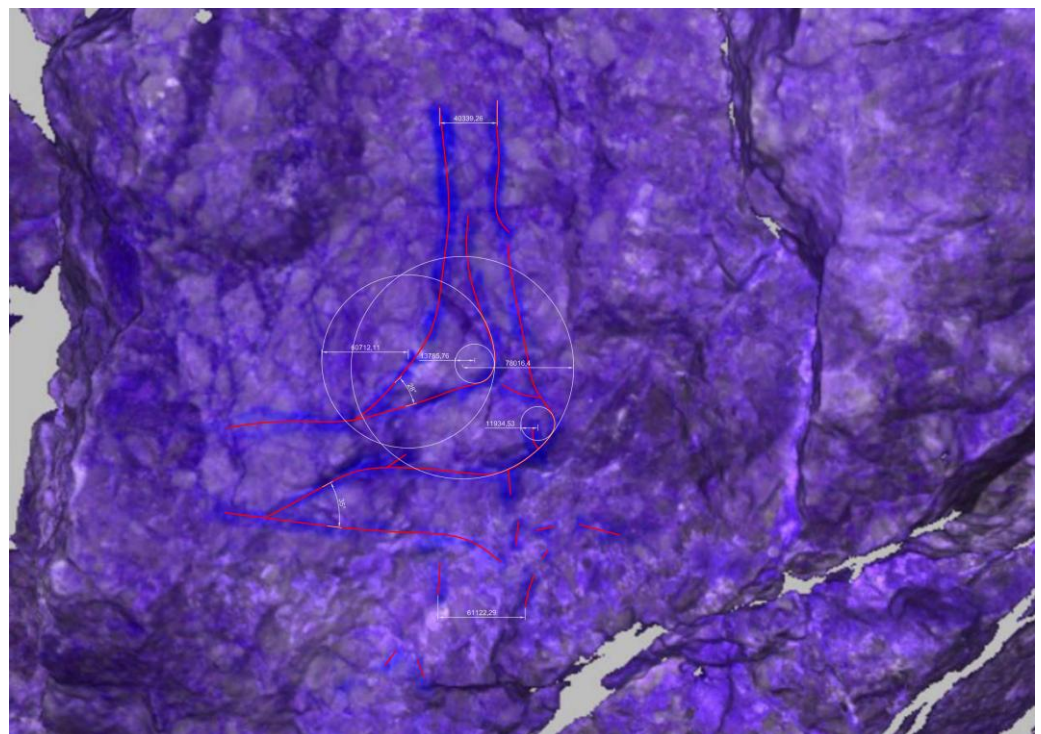
models of the postern with the internal architecture—surveyed through TOF laser scanning—an average distance of approximately 2.5 cm was achieved, while the structured-light models were aligned with the photogrammetric models with a precision of 0.2 mm.

ArtecEVA 3D model alignment with the photogrammetry, achieving submillimetre accuracy, further enhanced the detail captured in the characterisation of the hieroglyphs. Texture editing procedures were applied to the Artec 3D models, adjusting parameters such as brightness, saturation, hue, contrast, and gamma correction (Figure 5). These modifications, combined with the use of false-colour visualisations, provided a more accurate representation of the geometries of the hieroglyphs.



**Figure 5.** False-colour 3D models of hieroglyphs produced through the post-processing of data acquired with the Artec EVA structured-light scanner. © Leopoldo Repola [5] (p. 112).

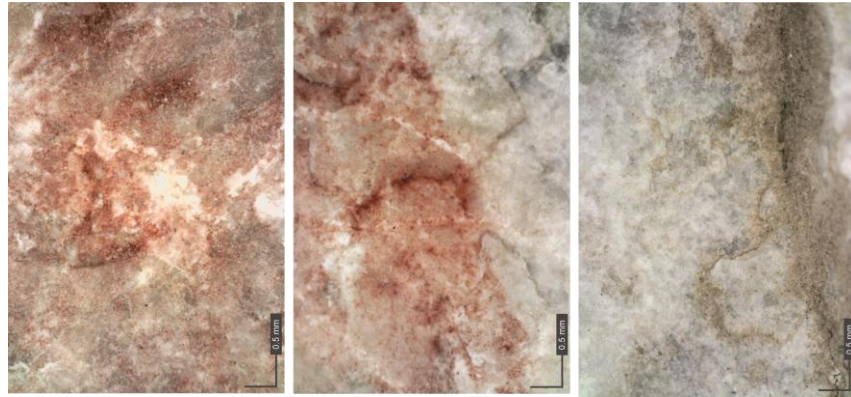
The vectorisation of the hieroglyphs, performed using Rhinoceros software version 7, allowed a comprehensive comparative analysis of their curvature patterns (Figure 6). This workflow not only improved the visualisation of the painted figures but also facilitated a deeper understanding of the stylistic and technical characteristics of the inscriptions, contributing valuable insights to the study of Hittite hieroglyphic writing.



**Figure 6.** Geometric curvature analysis of the hieroglyphs. © Leopoldo Repola [5] (p. 112).

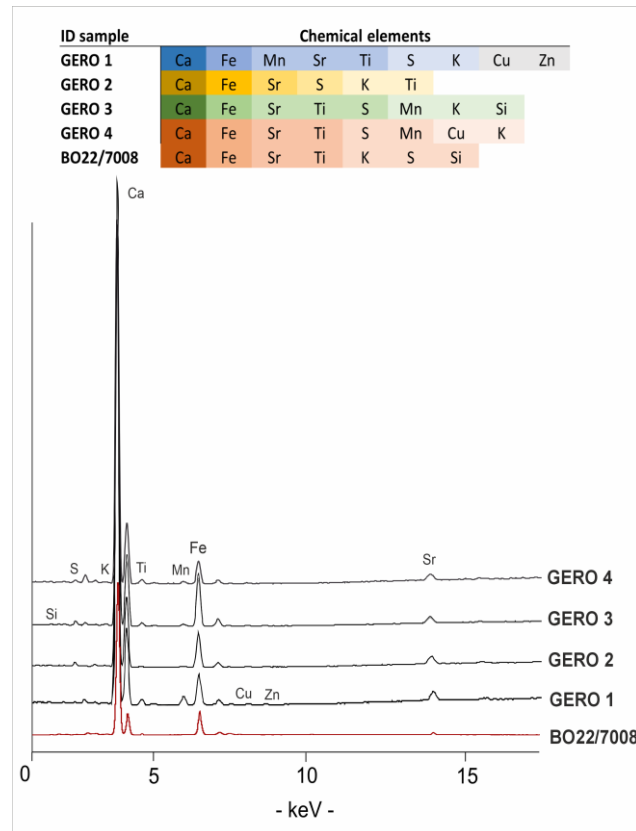
### 3.3. Diagnostic Campaign

The red figures were painted on roughly cut conchoidal limestone surfaces. DM images revealed that red particles, probably applied with a cloth, were embedded in the irregular surface of the stone (Figure 7). The pigments were evenly distributed to form the symbols, although variations in technique resulted in differences in the intensity and compactness of the figures. No evidence of dripping was observed, but some areas showed pigment loss and occasional white efflorescence.



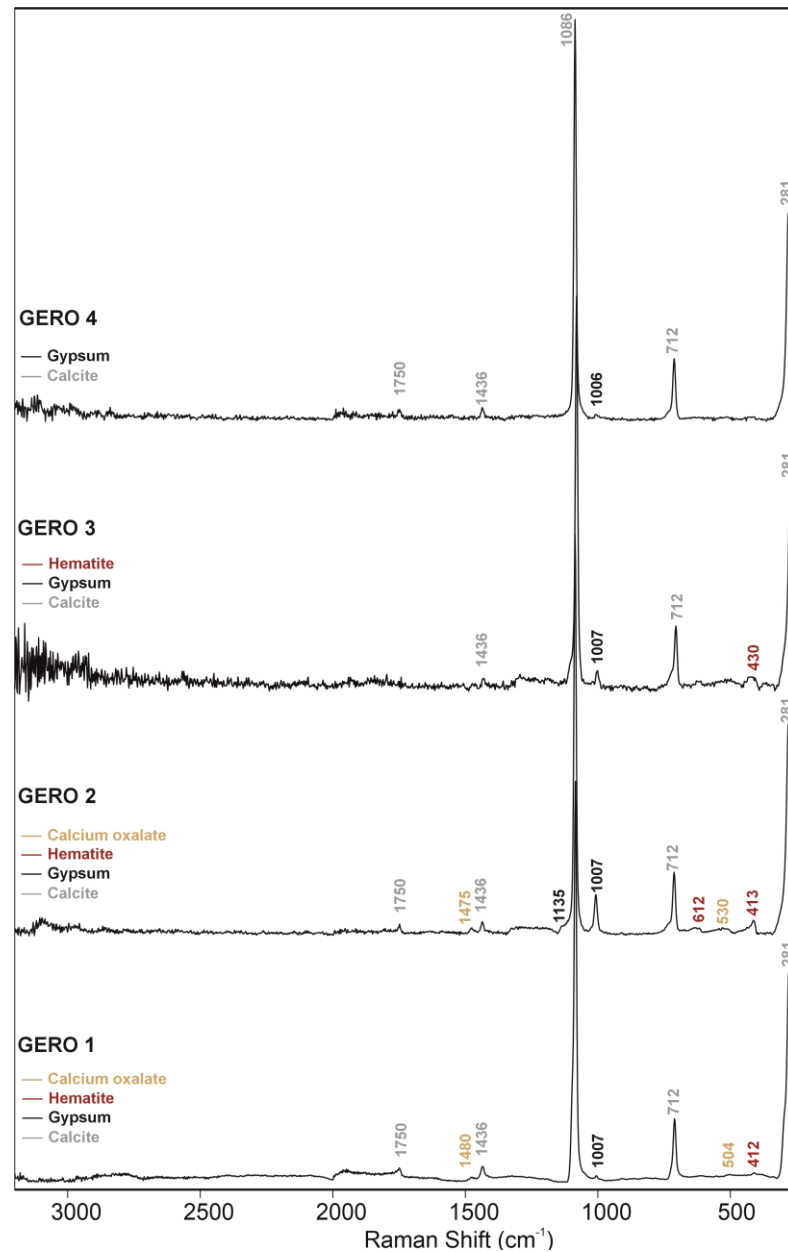
**Figure 7.** Boğazköy-Hattuša, Yerkapi. Digital microscopy (DM) images of the GERO 1 area. © Vincenzo Morra, Celestino Grifa [5] (p. 115).

Chemical analysis using pXRF identified calcium, iron, strontium, and manganese as major elements, with titanium, sulphur, potassium, silicon, copper, and zinc as minor components (Figure 8). Iron, titanium, manganese, and silicon were associated with the red pigment, while calcium, strontium, and sulphur were derived from the limestone substrate and its alteration products. Minor elements (K, Cu, and Zn) indicated impurities within the pigment. These results are consistent with analyses of other artefacts, such as BO22-0-7008 [9] (pp. 133–135), [5] (p. 114).



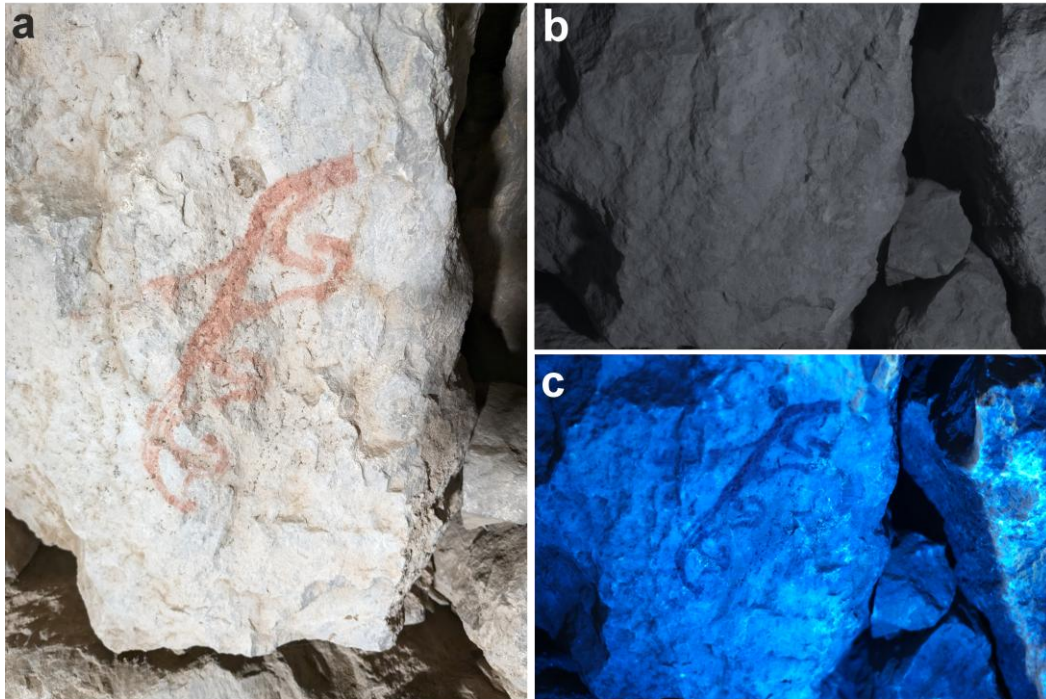
**Figure 8.** Boğazköy-Ḫattuša, Yerkapı, pXRF spectra of each area (GERO 1–4) and evaluation of intensities of chemical elements (from dark to light colour). The pXRF spectrum acquired on artefact BO22–0–7008 is also reported for comparison. © Celestino Grifa, Chiara Germinario, Vincenzo Morra [5] (p. 115).

Raman spectroscopy (Figure 9) confirmed haematite as the primary red pigment, with calcite from the limestone as a secondary component. In contrast, GERO 4 lacked haematite and instead showed gypsum—probably an alteration product—along with calcium oxalates.



**Figure 9.** Boğazköy-Ħattuša, Yerkapı. Raman spectra of the investigated areas. . © Celestino Grifa, Chiara Germinario, Vincenzo Morra [5] (p. 116).

Based on the chemical and mineralogical analyses, the VIS-IR-UVR images (Figure 10) demonstrated a red colour behaviour characteristic of an iron-based pigment. The red figures observed in the VIS image (Figure 10a) fully absorb IR radiation, appearing black (Figure 10b), while UVR radiation penetrates them entirely (Figure 10c).



**Figure 10.** Boğazköy-Ḫattuša, Yerkapı. VIS (a), IR (b), and UVR (c) images of the investigated areas. © Celestino Grifa, Chiara Germinario, Vincenzo Morra [5] (p. 116).

#### 4. Discussion

The integration of advanced three-dimensional digitisation technologies enabled the creation of high-resolution models of the entire structure of Yerkapı to support various geoarchaeological targets. A comprehensive model of the entire architectural complex of Yerkapı, oriented in local coordinates using a total station, was produced using time-of-flight (TOF) laser scanner data and drone-based photogrammetry. Manual alignment of the laser scanner data from the postern with corresponding photogrammetric and structured-light scanner models allowed precise mapping of the hieroglyphs over the entire monument. Post-processing of the textures of the 3D structured-light models further enhanced the detailed representation of the hieroglyphs, aiding the epigraphists in the analysis and characterisation of the inscriptions.

The photogrammetric survey produced a series of orthophotos, with 12 orthophotos produced for each wall of the postern, ensuring georeferenced documentation of all the inscriptions. A total of 122 inscriptions were identified on the east wall and 127 on the west wall, resulting in a meticulously detailed digital archive of each inscription [4,5,9].

Marazzi and his team's analysis identified six different types of inscriptions (labelled A to F) from the orthophotos. These inscriptions, consisting of personal names, occupations, and toponyms, typically appear as one inscription per stone. Their distribution is concentrated in the central sections of the postern walls, with a noticeable decrease in the number of inscriptions towards the northern and southern portals, where they eventually disappear.

All the inscriptions are oriented towards the northern portal, with a consistent reading direction from north to south. One of the most striking aspects of this discovery is the structured arrangement of the inscriptions on the walls. The east wall contains only types A and D, while types B, C, E, and F are restricted to the west wall. This distribution follows a deliberate pattern, with each type occupying specific segments of the walls. In addition, vertical orientation patterns were observed: types A and D are aligned on the east wall, while types B and E are vertically grouped on the west wall [9]. This organisational system

reflects other examples of Anatolian hieroglyphic inscriptions, such as the painted inscriptions from Kayalıpınar [8].

A stone fragment found as part of the restoration filling of the Hittite city wall running over the Yerkağı rampart accidentally found in 2022 (Sample BO-22-0-7008) appears to match the design of Inscription D with respect to the geochemical composition of the paint. According to Marazzi [5,9], the design of the sign may symbolise a chisel, representing the craft of stonemasonry. It reinforces the hypothesis that these painted hieroglyphs are not an isolated phenomenon at Yerkağı. An additional trace of painted signs identified on a stone at the King's Gate further reinforces the hypothesis of a widespread use of hieroglyphic writing as a means of public communication.

A multi-analytical, non-invasive study of the rock surfaces of the Yerkağı postern provided significant insights into the composition of the red pigments used to create the hieroglyphs. The analysis consistently revealed the use of haematite-based pigments. Digital microscopy (DM) images showed red particles embedded in the irregular limestone surface, with textural and compositional features—such as the detection of calcium (Ca) and strontium (Sr) associated with calcite—consistent with the underlying rock. Portable X-ray fluorescence (pXRF) analysis identified iron (Fe), titanium (Ti), and manganese (Mn) as the primary elements in the pigment, confirming its iron-rich composition typical of natural red ochre. Red ochre, a pigment widely used since prehistoric times, can be sourced from iron-rich deposits in the continental crust or produced by heating yellow ochre to form anhydrous iron (III) oxide [16,17]. Minor elements such as potassium (K), copper (Cu), and zinc (Zn) detected in pXRF spectra are likely to represent impurities in the raw pigment, originating from primary minerals in igneous deposits that have been altered by weathering processes that generate iron-rich deposits [18,19]. Similar deposits have been documented in Central Anatolia [20].

The analysis also identified weathering products affecting the rock surfaces. Sulphur (S) signals detected in the pXRF spectra are indicative of gypsum formation, suggesting sulphation processes affecting the limestone [21]. This finding is supported by the presence of white efflorescence on the rock surfaces. In addition, Raman spectroscopy has detected calcium oxalates, indicating surface alteration caused by (micro)biological activity such as lichens, algae, or fungi [22,23].

The analyses conducted on the chromatic characteristics and the chemical composition of the accidentally recovered BO-22-0-7008 stone confirm its correspondence with the hieroglyphs on the postern [5] (§ 175, pp. 185–194). Although its original placement cannot be determined with certainty, the evidence clearly suggests that painted inscriptions on architectural elements were likely widespread throughout the Upper City, extending beyond the confines of the Yerkağı postern. This finding provides significant support for the hypothesis that Anatolian hieroglyphic writing was employed in public spaces earlier and far more extensively than previously assumed. The widespread use of painted hieroglyphs on architectural elements in the city of Hattuša finds no parallels at other archaeological sites, with the sole exception of Kayalıpınar. However, the discovery of the fragment BO-22-0-7008, which was not part of the architectural masonry but rather an element likely intended as a decorative piece, represents a unique example within the broader context of Hittite Anatolia. Unlike the painted hieroglyphs preserved in situ on the postern wall stones, this fragment likely attests to a different application of hieroglyphic decoration, further enriching our understanding of the visual and communicative strategies employed within the urban fabric of Hattusa.

Moreover, on the basis of ongoing palaeographic studies on the signs that characterise the inscriptions (reference is made to the detailed analysis included in the forthcoming edition of the inscriptions by M. Marazzi, scheduled for publication in the 2025 issue of *News from the Lands of the Hittites*), it has been possible to identify a variant of the sign

depicting a donkey's head. The graphic features of this variant appear to have been in use exclusively between the 16th century and the first half of the 15th century BC. This internal dating within the epigraphic corpus is fully consistent with the recently revised chronological framework for the development of the so-called Oberstadt of Hattusa, as outlined by A. Schachner [24].

The present research constitutes a multidisciplinary study focused on the use of advanced technologies for the documentation and characterisation of historical, geoarchaeological, and architectural features. Although these technologies—such as time-of-flight laser scanning, aerial and terrestrial photogrammetry, structured-light scanning, and non-invasive diagnostic techniques, including pXRF and Raman spectroscopy—have been widely applied in the fields of cultural heritage and landscape survey, they have never been systematically and integrally employed at Hattuša. Recent studies have demonstrated that the integrated use of different technologies offers clear benefits for research, documentation, and the preservation of cultural heritage. A. Crisan et al. [25] emphasise the importance of combining 3D digitisation technologies to produce interoperable models across various resolutions, even within the BIM environment. In doing so, they reference the AIR guidelines by Historic England [26], which state that, in historical and archaeological contexts, extremely high data accuracy during scanning is not always necessary, especially for larger structures [25] (p. 1426). This contrasts with the approach adopted in the present study, which focuses on the digital documentation of Yerkaḫ. Here, we believe that the application of centimetre-resolution laser scanning technology, combined with aerial photogrammetry, has enabled us to produce outputs that better support the digital graphic representation required in geoarchaeological research. Moreover, our research methodology does not require the development of simplified BIM models for the analysis and management of monuments. Instead, all procedures are conducted directly on high-resolution polygonal models, allowing for the identification of traces of workmanship and use on the stone surfaces. This approach is specifically aimed at understanding construction phases and the spatial and volumetric development of ancient structures.

With regard to the acquisition activities carried out using Artec structured-light scanners, surveys are typically performed on small or medium-sized objects, such as cuneiform tablets [27]. In this case, however, due to the extensive areas of the postern walls bearing sequences of hieroglyphs, it was necessary to apply structured-light scanning to large surfaces. Despite the size of the surveyed areas, it was possible to preserve both a high resolution of the models (0.2 mm) and the quality of the textures.

Within such an archaeological framework, the application of non-destructive diagnostic technologies has also proven essential for characterising the pigments used in the painting of the hieroglyphs [28].

This research clearly demonstrates the potential of integrating these complementary methodologies within a single, coherent workflow specifically tailored to complex geoarchaeological contexts. The combination of remote sensing technologies providing high-resolution 3D survey data and in situ material analyses has proven particularly effective in delivering both qualitative and quantitative outputs to support ongoing archaeological investigations.

Finally, in order to enhance data accessibility and support the dissemination of the results within the scientific community, the implementation of an online visualisation platform is planned. This platform will enable users to explore the 3D models at a resolution specifically calibrated to ensure the accurate visualisation of the hieroglyphs, following methodologies recently adopted in similar studies [29].

Moreover, comparative analyses with alternative technologies are foreseen in the framework of future geoarchaeological fieldwork, during which new datasets will be

acquired using a phase-shift laser scanner, specifically the “Z + F 5016A” model. This technology is expected to substantially increase the resolution of the outputs, thereby reducing the margin of error during manual alignment procedures and achieving millimetric accuracy. On the basis of these higher-resolution datasets, a further objective will be the development of imaging detection algorithms aimed at facilitating the recognition of hieroglyphic signs through comparison with a standardised sign catalogue.

**Author Contributions:** Methodology, L.R. and M.M.; investigation, G.V. and V.M.; supervision, A.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Ministry of Foreign Affairs and International Cooperation of Italy (MAECI) - Prot. N. 0079296-P/180.

**Data Availability Statement:** Data is not freely available. Please contact the corresponding authors for further information.

**Acknowledgments:** We would like to express our sincere gratitude to Celestino Grifa for his invaluable support in collecting and processing the diagnostic data of the postern hieroglyphs (Boğazköy/Ḫattuša), which included DM, pXRF, Raman, and multispectral survey. We also wish to acknowledge his colleague, Chiara Germinario, for her indispensable assistance in processing the complete dataset at DST—Unisannio.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## Abbreviations

The following abbreviations are used in this manuscript:

UAV	Unmanned Aerial Vehicle
TOF	Time of flight
TOF-TLS	Time-of-flight terrestrial laser scanning
AP	Aerial photogrammetry
TP	Terrestrial photogrammetry
SLS	Structured-light scanning
TXD	Textured
UnTXD	Untextured
Z + F	Zoller + Fröhlich

## References

- Schachner, A. The Historical Development of the Urban Geography of Hattuša, the Hittite Capital City, and Beyond. In *Places and Spaces in Hittite Anatolia: Proceedings of an International Workshop on Hittite Historical Geography in Istanbul, 25th–26th October 2013*; Alparslan, M., Ed.; Türk Eskiçağ Bilimleri Enstitüsü: Istanbul, Turkey, 2017; pp. 29–51, ISBN 978-605-9680-48-6.
- Schachner, A. 9 Building for King and Country: Architecture as a Symbol of the Hittite Empire. In *Handbook of Hittite Empire*; De Martino, S., Ed.; De Gruyter: Berlin, Germany, 2022; pp. 421–466, ISBN 978-3-11-066178-1.
- Neve, P. *Ḫattuša-Stadt der Götter und Tempel: Neue Ausgrabungen in der Hauptstadt der Hethiter*; Zaberns Bildbände zur Archäologie; 2., erw. Aufl.; von Zabern: Mainz am Rhein, 1996; ISBN 978-3-8053-1478-7.
- Schachner, A.; Alparslan, M.; Bolatti Guzzo, N.; Becker, J.; James, B.; Doğan-Alparslan, M.; Genç, B.; Gruber, M.; Krüger, D.; Marazzi, M.; et al.; Die Ausgrabungen in Boğazköy-Ḫattuša 2022. *Archäologischer Anz.* **2023**, 1–210 (S). <https://doi.org/10.34780/E12D-4AC2>.
- Schachner, A.; Alparslan, M.; Baskın, S.; Becker, J.; Bolatti Guzzo, N.; Gruber, M.; Kibaroglu, M.; Krüger, D.; Marazzi, M.; Mielke, D.; et al. Die Ausgrabungen in Boğazköy-Ḫattuša 2023. *Archäologischer Anz.* **2024**, *1*, 1–238 (S). <https://doi.org/10.34780/FA2T-66DA>.

6. Marazzi, M. Die Sogenannten, eingepunzten' Hieroglypheninschriften von Boğazköy: Status Quaestionis. In *Audias Fabulas Veteres. Anatolian Studies in Honor of Jana Součková-Siegelová*; Velhartická, Š., Ed.; BRILL: Leiden, Netherlands, 2016; pp. 194–209, ISBN 978-90-04-31260-9.
7. Neve, P. Die Oberstadt von Hattuša-die Bauwerke. 2: Die Bastion des Sphinxtores und die Tempelviertel am Königs- und Löwentor. In *Boğazköy-Hattuša/Herausgegeben Von Peter Neve*; Verlag Philipp von Zabern: Mainz am Rhein, Germany, 2001; ISBN 978-3-8053-2706-0.
8. Müller-Karpe, A.; Müller-Karpe, V.; Rieken, E. Untersuchungen in Kayalıpınar 2015. *Mitteilungen Der Dtsch. Orient-Ges.* **2017**, *149*, 59–84.
9. Marazzi, M., The New Painted Hieroglyphic Inscriptions of Hattusa : Overview and Status of Research. *News Land Hittites Sci. J. Anatol. Res.* **2023**, *7*, 119–153.
10. Smith, G.D.; Clark, R.J.H. Raman Microscopy in Archaeological Science. *J. Archaeol. Sci.* **2004**, *31*, 1137–1160. <https://doi.org/10.1016/j.jas.2004.02.008>.
11. Liritzis, I.; Zacharias, N. Portable XRF of Archaeological Artifacts: Current Research, Potentials and Limitations. In *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*; Shackley, M.S., Ed.; Springer: New York, NY, USA, 2011; pp. 109–142, ISBN 978-1-4419-6885-2.
12. Fontana, D.; Alberghina, M.F.; Barraco, R.; Basile, S.; Tranchina, L.; Brai, M.; Gueli, A.; Troja, S.O. Historical Pigments Characterisation by Quantitative X-Ray Fluorescence. *J. Cult. Herit.* **2014**, *15*, 266–274. <https://doi.org/10.1016/j.culher.2013.07.001>.
13. Bersani, D.; Lottici, P.P. Raman Spectroscopy of Minerals and Mineral Pigments in Archaeometry. *J. Raman Spectrosc.* **2016**, *47*, 499–530. <https://doi.org/10.1002/jrs.4914>.
14. Caggiani, M.C.; Cosentino, A.; Mangone, A. Pigments Checker Version 3.0, a Handy Set for Conservation Scientists: A Free Online Raman Spectra Database. *Microchem. J.* **2016**, *129*, 123–132. <https://doi.org/10.1016/j.microc.2016.06.020>.
15. Larsen, R.; Coluzzi, N.; Cosentino, A. Free XRF Spectroscopy Database of Pigments Checker. *Int. J. Conserv. Sci.* **2016**, *7*, 659–668.
16. Barnett, J.R.; Miller, S.; Pearce, E. Colour and Art: A Brief History of Pigments. *Opt. Laser Technol.* **2006**, *38*, 445–453. <https://doi.org/10.1016/j.optlastec.2005.06.005>.
17. Becker, H. Pigment Nomenclature in the Ancient Near East, Greece, and Rome. *Archaeol. Anthropol. Sci.* **2022**, *14*, 20. <https://doi.org/10.1007/s12520-021-01394-1>.
18. Coleman, R.G. *Ophiolites: Ancient Oceanic Lithosphere?* Minerals and Rocks; Springer: Berlin/Heidelberg, Germany, 1977; Volume 12, ISBN 978-3-642-66675-9.
19. Peterson, J.A. *Metallogenic Maps of the Ophiolite Belts of the Western United States*; Miscellaneous Investigations Series; U.S. Geological Survey: Denver, USA, 1984; pp. 1–16.
20. Orhan, A. Mineralogy, Fluid Inclusions and Carbon Isotopes of the Kaman Iron Deposits, Central Anatolia, Turkey: Implication for Ore Genesis and Hydrothermal Evolution. *Ore Geol. Rev.* **2020**, *127*, 103808. <https://doi.org/10.1016/j.oregeorev.2020.103808>.
21. De Gennaro, M.; Calcaterra, D.; Langella, A. *Le Pietre Storiche Della Campania: Dall'oblio Alla Riscoperta*; Luciano: Napoli, Italy, 2013; ISBN 978-88-6026-182-3.
22. Franzini, M.; Gratzu, C.; Wicks, E. Patine ad ossalato di calcio sui monumenti marmorei. *Rend. Della Soc. Ital. Di Mineral. E Petrogr.* **1984**, *39*, 59–70.
23. Zoppi, A.; Lofrumento, C.; Mendes, N.F.C.; Castellucci, E.M. Metal Oxalates in Paints: A Raman Investigation on the Relative Reactivities of Different Pigments to Oxalic Acid Solutions. *Anal. Bioanal. Chem.* **2010**, *397*, 841–849. <https://doi.org/10.1007/s00216-010-3583-1>.
24. Schachner, A. A new look at an ancient city: An outline of the chronological and urban development of the Hittite capital Hattuša. *Anatol. Stud.* **2024**, *74*, 13–46. <https://doi.org/10.1017/S0066154624000012>.
25. Crisan, A.; Pepe, M.; Costantino, D.; Herba, S. From 3D Point Cloud to an Intelligent Model Set for Cultural Heritage Conservation. *Heritage* **2024**, *7*, 1419–1437. <https://doi.org/10.3390/heritage7030068>.
26. Bryan, P.; Joanna, H. BIM for Heritage—Developing the Asset Information Model. 2019. Available online: <https://historicengland.org.uk/advice/technical-advice/recording-heritage/> (accessed on 4 August 2025).
27. Diara, F. Structured-Light Scanning and Metrological Analysis for Archaeology: Quality Assessment of Artec 3D Solutions for Cuneiform Tablets. *Heritage* **2024**, *6*, 6016–6034. <https://doi.org/10.3390/heritage6090317>.

28. Van der Perre, A.; Boschloos, V.; Hameeuw, H.; Braekmans, D. A complementary integrated approach using non-destructive optical and X-ray methodologies for pigment characterisation on an ancient Egyptian coffin. *Eur. Phys. J. Plus* **2025**, *140*, 428. <https://doi.org/10.1140/epjp/s13360-025-06360-7>.
29. Repola, L.; Varriale, G.; Ilacqua, S.; Letizia, M.A. Cumae Archeological Site—Processes and Technologies for the Analysis and Monitoring of Anthropogenic Cavities. *Heritage* **2025**, *8*, 199. <https://doi.org/10.3390/heritage8060199>.

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.