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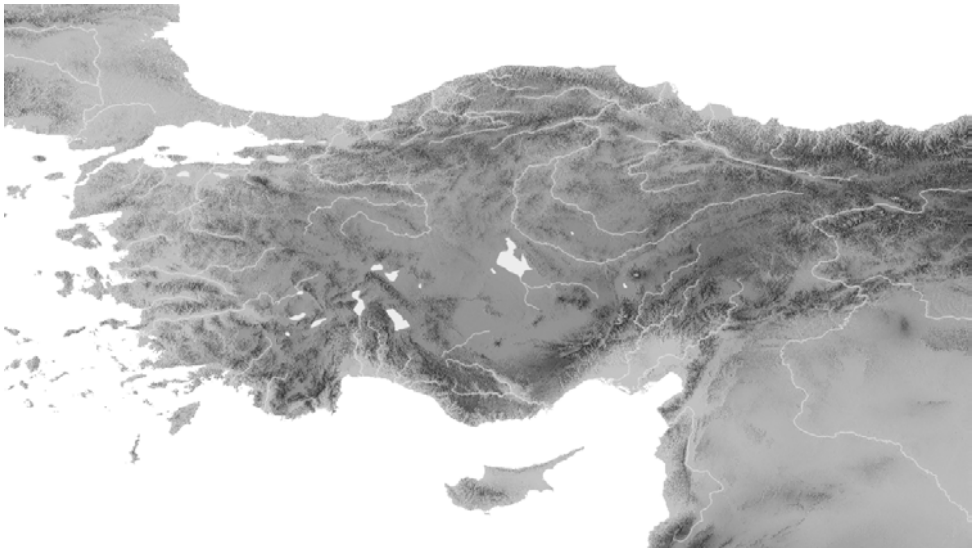

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From numerical models of the pyramid to the geometric analysis of Yerkapı hieroglyphics

Leopoldo Repola
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SURVEY AND STUDY OF THE PORTION OF THE CITY WALLS CORRESPONDING TO THE ARTIFICIAL HILL OF YERKAPI

In August and September of 2022 and 2023, two 3D digitisation campaigns of the entire hill and wall structures of Yerkapı were conducted using a drone (through the support of three UAV-qualified operators in Turkey) (**Fig. 18**) and a Riegl VZ 400 laser scanner. The survey phases involved the localisation of targets within the area in order to align the new models to the local reference system defined by the German Institute, by means of total station surveying. The acquisition procedures concerned the section of fortifications between the east and west limits of the Yerkapı pyramid in order to determine the exact connection between the orography of the artificial hill and the geometry of the double wall structure. Furthermore, the models made it possible to verify the different construction techniques of the *septa* with particular reference to the materials used, an activity which led to the discovery, at the west tower, of a fragment of rock, in the form of an irregular parallelepiped measuring approximately 11x8x4 cm, decorated with an ochre-coloured hieroglyphic, very similar in production to the other signs found in the postern.

SURVEY AND STUDY OF THE ARCHITECTURAL STRUCTURES OF YERKAPI

The survey of the orography of the artificial hill and the walls of the southern sector were supplemented by three-dimensional digitisation procedures of Yerkapı's architectural structures using the Riegl VZ 400 laser scanner (**Fig. 19**). These activities covered all sides of the pyramid, including the intermediate paths at the different levels of the inclined planes, the two staircases located on the east and west elevations of the monument, the Sphinx Gate, and the south and north elevations at the entrances to the postern. A resolution of 7 mm was adopted at a distance of 10 metres and all scanpositions were aligned in the field by marker recognition, with an overall error of less than 3 mm. The clouds were textured with the images acquired with the Nikon D600 with 14 mm optics, which was integrated to the scanner (**Fig. 20**).

The postern was the subject of specific survey procedures; a first acquisition phase involved 13 scanpositions, during which particular attention was paid to the alignment procedures of the data related to the wall structures and the Sphinx Gate, in order to precisely locate the tunnel in relation to them and the related hieroglyphic inscriptions; a second, denser survey phase (**Fig. 21**), with an acquisition sequence at intervals of 1-1.5 metres, allowed for the detailing of the postern blocks and their hieroglyphs in a single high-resolution

Fig. 19. Scanning activity of the western sector of Yerkapı.

Fig. 20. Textured point clouds of the Sphinx Gate.

Fig. 21. Postern scanning activity.

model with reduced shadow areas due to the strong irregularity of the boulders.

The large number of acquisitions required them to be performed automatically, by setting the parameters directly from the desktop integrated in the instrument. Alignment was then carried out in the laboratory by means of an initial automatic registration, a subsequent Multi Station Adjustment procedure and a verification using the Global Registration algorithm. Since the procedures were carried out in an enclosed location it was not possible to acquire GPS data, and since markers were not used to make the procedure as expeditious as possible, the alignment of these clouds to the previously produced external model was carried out by homologous points using specific processing software. The procedures involved the export of part of the clouds of the external survey, already referenced, the subsequent export of a reduced model of the internal points of the postern (to speed up the procedure) and finally the alignment of all the scans.

On the Yerkapı area itself, structural analysis of the faults and fractures of the exposed rocks was started, with a focus on the southern area. The in situ lithological analysis of the construction materials on the south and east slopes of the so-called pyramid was also initiated, also aimed at mapping the blocks found in situ during the excavation activities and the parts subject to restoration and integration.

IDENTIFICATION, MAPPING AND SURVEY OF THE HIEROGLYPHICS FOUND IN THE YERKAPI POSTERN

The exceptional discovery of ca. 250 painted hieroglyphs within the Yerkapı postern required the development of an articulated digitisation plan of the same aimed at documenting the geometries and colours of the signs, but also the shapes of the rocks on which they stand, the surface characteristics of the blocks in order to verify possible levels of preparation of the natural surfaces, as well

Fig. 22. Orthophoto by photogrammetry.

as the sequence of the hieroglyphs within the architectural space. 3D scans using Artec structured light scanners were made of the areas of the postern near the hieroglyphs. Prior to the surveys, each hieroglyph was numbered, according to the north-south direction, with the letter O preceding the number for the east side and the letter W for the west side. Along the east wall 18 areas covering 122 hieroglyphic inscriptions were surveyed, on the west wall 11 areas covering 127 inscriptions.

After the last acquisitions by means of Artec, the photogrammetric procedure using Canon EOS was started (**Fig. 22**). Progressive areas of the postern delimited by 50 cm aluminium scalebars were again marked out. The aim of this survey was to identify the progression of the inscriptions on orthophotos, the basic models of which were then transferred by means of alignment by homologous points onto the referenced general model.

In the course of the activities carried out in August 2023, structured light scan was used on specific types of signs in order to obtain models with higher resolution textures, modulating the ambient light by means of an LED lamp with different color tones and light intensity. Furthermore, the small size of the scanned surfaces made it possible to reduce the interpolation processes of the colored spot lights, automatically produced by the instrument, and thus to select textures with higher contrast.

Data processing at DiSTAR laboratories

The processing of the data acquired by UAV followed the standard procedures provided by the MetaShape software, obtaining a dense cloud of 39 million points, from which a polygonal model of 34 million triangles was generated following the vegetation elimination and noise filtering phases, from which zenith and frontal orthophotos were obtained, as well as perspective views. In order to move the model in local topographic coordinates, the ground control points, consisting of 50-centimetre scale bars and 5-10-centimetre cylindrical markers, were assigned the coordinates as

detected by the total station located on the topographic points No. 100 and 110 of the DAI mission reference system.

The post-processing phases of the data were carried out using two specific starting data sets obtained through the use of Riscan VZ400 Time-of-Flight (TOF) Laser Scanner instrumentation: a series of 89 scans through which textured point clouds of the Sphinx gate and the Yerkapı pyramid were obtained, and a series of 49 scans referring to the tunnel passing under the pyramid. The 49 point clouds related to the postern were merged into a single point cloud discretized with Octree 10mm in order to remove redundant reflections and subsequently exported in text file format. The scans relative to the postern file, once imported, were sectioned into two respective EAST and WEST portions, aligned with respect to two identical sections of the cloud belonging to Sphinxes, obtaining an alignment with an *average distance* of 2.5cm. Once the process of aligning the point clouds of the postern was completed, the meshes were created.

Orthophotogrammetric models were then aligned on the polygonal models for a better characterisation of the hieroglyphs inside the tunnel (**Fig.23**). On the three-dimensional models combined with the orthophotogrammetric models, very high-resolution Artec Eva 3D models were then aligned with an error margin of 0.2mm.

The same procedure was performed on the point cloud referring to the Tunnel on which new point clouds were generated by aligning the 89 scans in a new data set in the order: GATE, EAST, WEST further subdivided into the main sub-layers GATE_Hill, GATE_Architecture, EAST_Hill, EAST_Architecture, WEST_Hill, WEST_Architecture. The vegetation layers referring to orography and architecture have also been processed separately.

All sub-layers were processed individually with the same workflow in mind. After meticulous manual operations to eliminate noise, the point clouds were discretized using an Octree 10mm filter and the files exported in txt format. In addition, in order to retain an important level of architectural detail useful for the production of high-resolution meshes, the EAST and WEST portions of the pyramid were further segmented into its main levels, i.e., LEVEL 0, LEVEL 1, LEVEL 2, EXTERNAL WALLS, WALLS, discretized with an Octree 1mm filter and finally exported in text file format. The processing of the respective point cloud first proceeded with its meticulous segmentation and manual removal of residual noise and then, based on the specific point density of the analysed portion of the layer, filters were used to reduce the degree of noise that could not be removed manually and reduce outliers. In some cases it was deemed necessary to further discretize the point clouds at 3mm and 8mm in order to obtain good resolution.

Fig. 23. Photogrammetric models of the hieroglyphics aligned on the west side of the postern.

Once the production phases of the meshes referring to the architecture of the Yerkapı Pyramid were completed, the levels were exported in .obj format to be rendered and subsequently used in a CAD environment through Rhinoceros software, for the production of the necessary drawings and analytical models for the detailed study of the monument (**Figs 24-25**).

Concerning the high-resolution Artec models, digitised during the 2023 campaign, once the clouds had been processed and the meshes generated, texture editing procedures were carried out, of which the brightness, saturation, hue, contrast and gamma correction parameters were varied in a combined manner in order to better characterize the geometries of the hieroglyphs in false colours (**Fig. 26**).

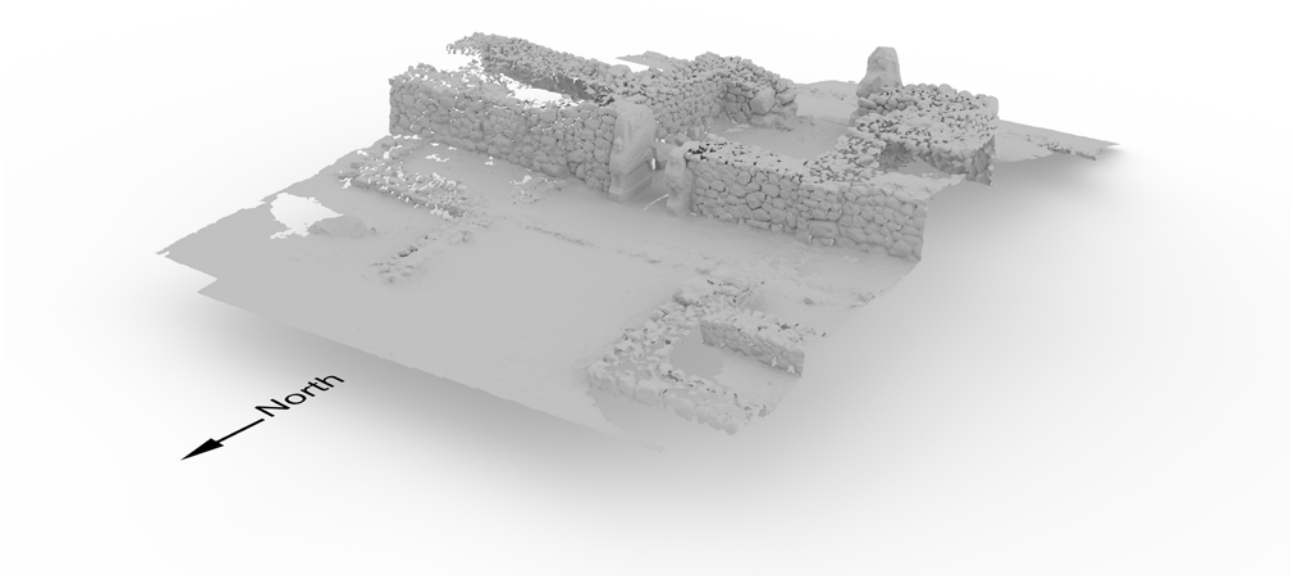

Fig. 24. Model of the Sphinx Gate on the north side.

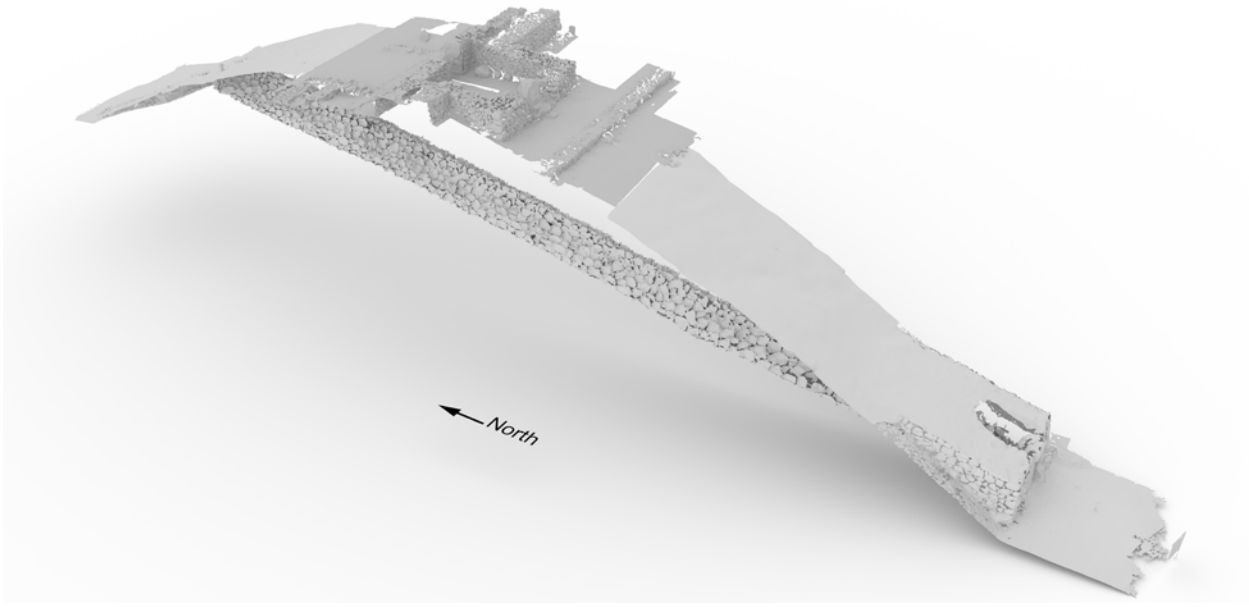

Fig. 25. Model of the Sphinx Gate and postern in relation to the surfaces of the pyramid architecture.

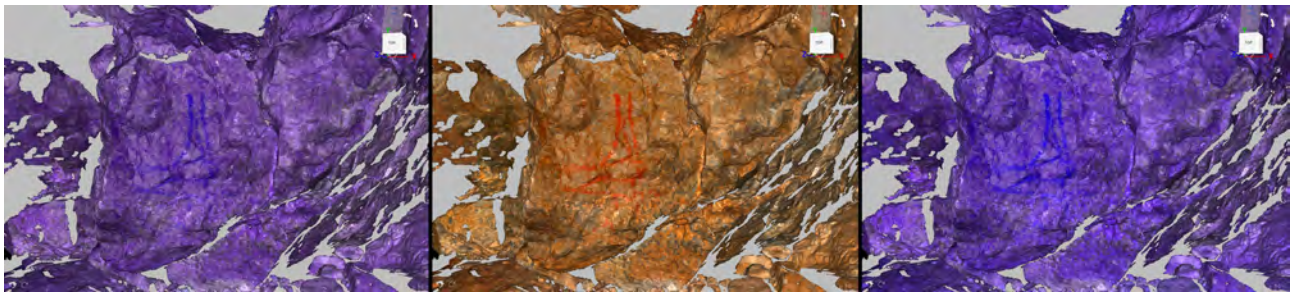

Fig. 26. False color models of hieroglyphics detected using Artec scanner.

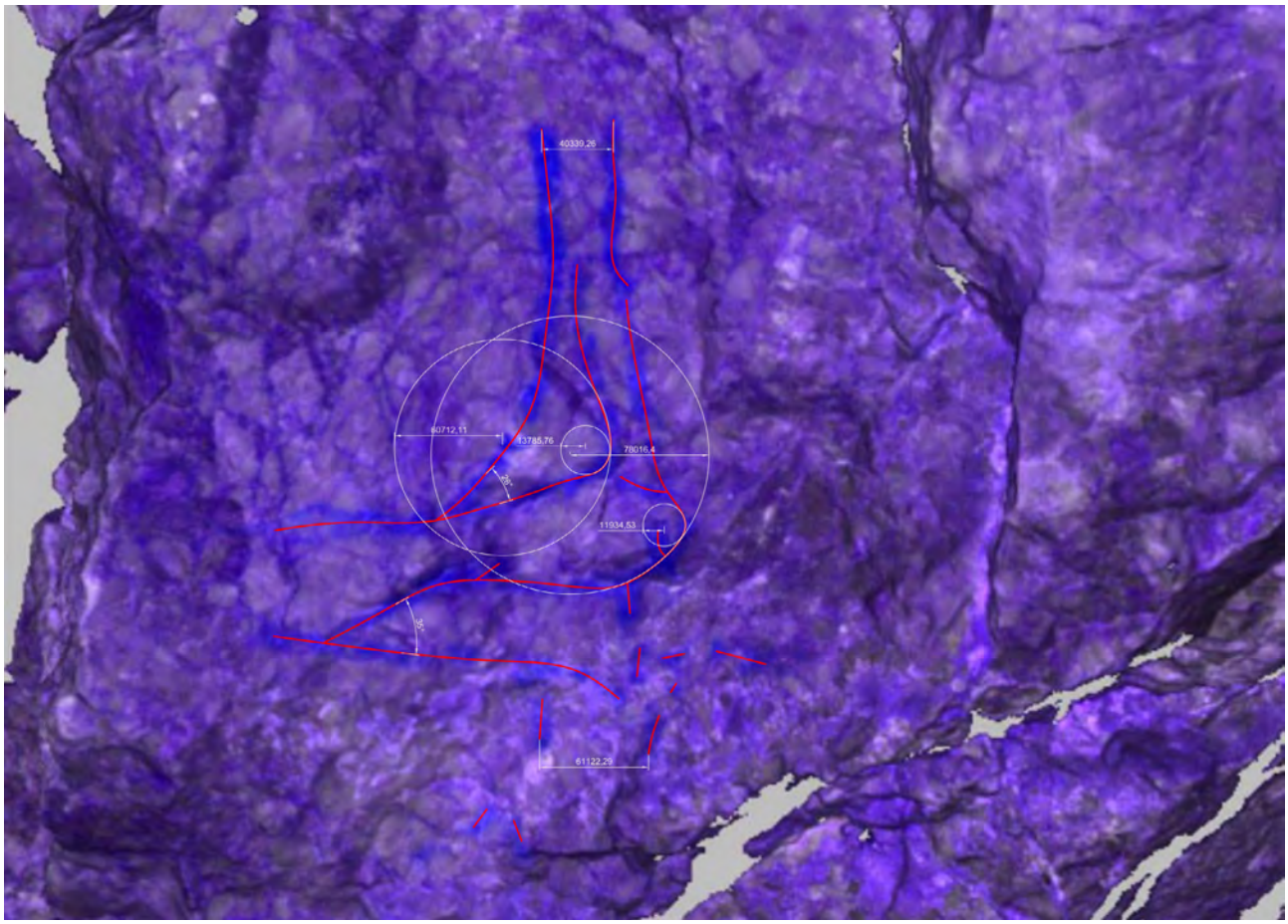

Fig. 27. Geometric analysis of the curvatures of hieroglyphic signs.

On the basis of these images, produced both in an orthophotogrammetric and perspective manner (to better follow the signs on the complex surfaces of the rocks), the painted figures were vectorially redrawn, thus enabling a comparative analysis of the curvatures on a mathematical basis (**Fig. 27**).

ABBREVIATIONS

DAAM 1
E. Rieken (ed), *Keilschrifttafeln aus Kayalıpınar l - Textfunde aus den Jahren 1999-2017*, (DAAM 1) Wiesbaden 2019

Güterbock *Zeichenliste*
H.G. Güterbock, *Siegel aus Boğazköy*, 2. Teil: *Die Königssiegel von 1939 und die übrigen Hieroglyphensiegel*, Berlin 1942, Zeichenliste: 84-104.

L. + Number
numbering of hieroglyphic signs on the basis of Laroche 1960, with additions and corrections in: Marazzi (ed) 1995, Lists, 23-124; Hawkins 2000, Introduction, D. Principles of transliteration, 23-34.

Meriggi *Zeichenliste*
P. Meriggi, *Hieroglyphisch-hethitisches Glossar*, 2. Aufl., Wiesbaden, Zeichenliste, 181-236.

SBo II
H.G. Güterbock, *Siegel aus Boğazköy*, 2. Teil: *Die Königssiegel von 1939 und die übrigen Hieroglyphensiegel*, Berlin 1942

SHS
Sammlung hieroglyphischer Siegel, Bd. I: *Vorarbeiten*, 2. rev. und erg. Aufl., M. Marazzi (ed), Wiesbaden 2009.

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