Final report for the project „Identification of Classical Greek Sculptors – Master-hand Attributions by 3D-analysis” (no. 101755) 2014-2018

The project had two goals: the elaboration of a methodology or tool-kit for the identification of master-hands in sculpture and its application to a certain problem, i.e. the identification of the so-called Olympia-master.

All the relevant pieces of sculpture were digitized. Virtual 3D models were created from all the surviving fragments belonging to the sculptural decoration of the temple of Zeus at Olympia and also from many statues created in the same period (the „Severe Style” ca. 480-450 BC); in addition, all those ancient Greek sculptural assemblages were also digitized which were produced, according to written sources, by different sculptors or workshops simultaneously. Most models were created from the original marble and bronze pieces of sculpture, in some cases, however, we had to rely on plaster casts.

Digitization by 3D scanning was carried out in the following collections[1]

- Athens, National Archaeological Museum
- Berlin, Abguss-Sammlung Antiker Plastik der Freien Universität
  Abguss-Sammlung der Humboldt-Universität
- Bologna, Museo Civico
- Göttingen, Abguss-Sammlung der Universität
- London, British Museum
- Olympia, Archaeological Museum
- Paros, Archaeological Museum
- Rome, Musei Capitolini

The following pieces and assemblages of ancient Greek sculpture were digitized

- Friezes of the Siphnian treasury at Delphi
- Pediment and metopes of the temple of Zeus at Olympia
- Pediments and acroteria from the temple of Asclepius at Epidauros
- Friezes of the Maussoleion at Halicarnassus
- Pediments of the temple of Apollo Sosianus at Rome

- Selected pieces from the pediments of the temple of Aphaia at Aegina
- Selected late classical pieces from the sanctuary of Asclepius at Epidauros
- Selected pieces from the Athenian Acropolis (Kritios kouros, „Blonde boy”, Kore of Euthydikos, bronze head of a warrior)
- Selected late archaic and early classical pieces from Paros (Nike, Artemis, etc.)

[1] Access to the Acropolis Museum (Athens) and the Musée du Louvre (Paris) was denied, because the local authorities intended to carry out the digitization of their artefacts on their own. Important pieces in these collections were scanned from plaster casts.

- Theseus and Antiope from the pediment of the temple of Apollon Daphnehporos at Eretria
- Charioteer from Delphoi
- Zeus from Artemision
- Marble heads of the Severe style (from the Athenian Kerameikos, Selinunte, Sparta, Ludovisi acrolith, etc.)
- Head of the seated goddess from Tarentum
- Apollo Strangford (BM B475)
- Two statues from Xanthos (BM B317 and 318)

The work of scanning and processing the data and the creation of the virtual models was carried out by Péter Gyuris. The statues were scanned with the Artec eva scanner during the field surveys. The 3D data resulting have the accuracy between 0.1-0.3 mm (following fine registration, see below). The object data consist of individual frames captured with a rate of 15 frames per second. The models that were preprocessed with Artec Studio 9 subsequently. The workflow in Artec Studio was the following:

- after scanning fine serial registration automatically runs (texture and geometry algorithm for relative positioning of frames);
- global registration fits the individual frames into the same coordinate system (default settings);
- after alignment of the recordings(scans) of the whole statue, global registration run again to put the frames into the same coordinate system;
- run one of the fusion algorithms in order to get a single surface of the 3D model.

The uncertainty of the data based on the above accuracy information and the processing steps is around 0.5 mm. The theoretical resolution of the 3D models by Artec eva is 0.5 mm.

As an outcome, a collection of 3D models emerged, which is unique worldwide and enables a wide variety of measurements and analyses which would be in some cases possible by traditional methods, i.e. by using plaster casts as well, but would be cartainly more difficult to carry out and the results would be certainly less reliable, i.e. inaccurate. The virtual 3D models have the great advantage in comparison with plaster casts that they can be manipulated more easily and can be cut at any point in any direction and so often as it is needed, since every step is reversible. The measurements and profiles created in this way can be used to compare details on different statues and in this way stylistic similarities can objectively be quantified, i.e. it is possible to overcome the subjectivity inherent so far in connoiseurship.

Some basic measurements of point to point distances and section profiles were taken by Péter Gyuris using Artec Studio «Measures» toolbox on the 3D models and afterwards these measurements and curves were compared by Ágnes Bencze to each other in order to assess their similarities and differences. She reached the conclusion that „the diagnostic method based on the meticulous recognition of typical features on the basic level of material execution can provide a good amount of information about the individual who was responsible for the actual carving”. (Fig.1-3)

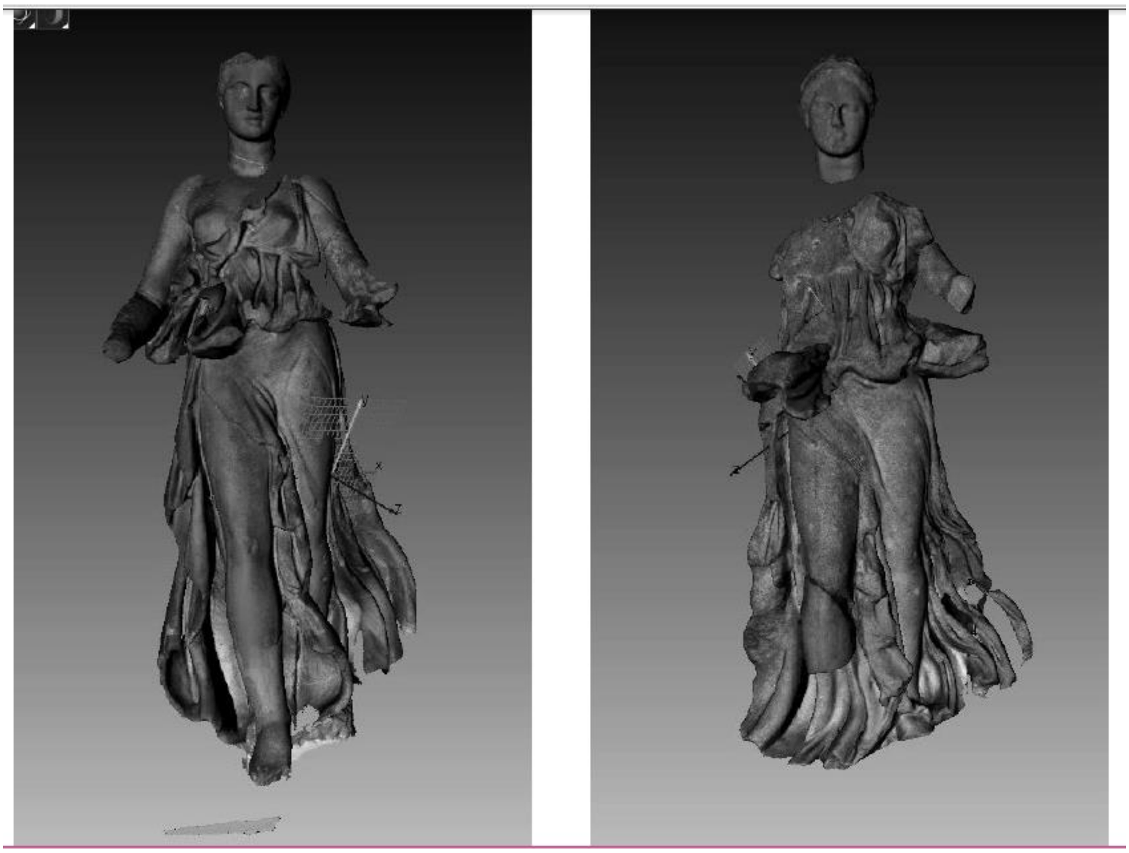

Fig. 1. Digital 3D models of two closely related statuettes from Epidauros (Athens, Nat. Mus. 159 and 161)

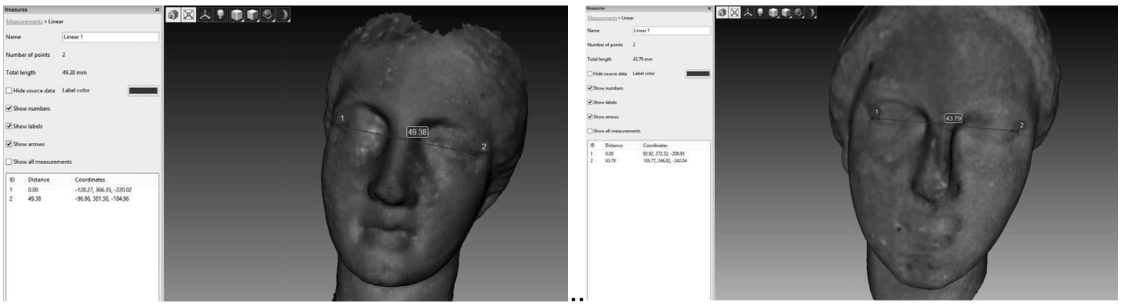

Fig. 2. Eye distances (4.37 and 4.93 cm) measured on the models in Fig. 1.

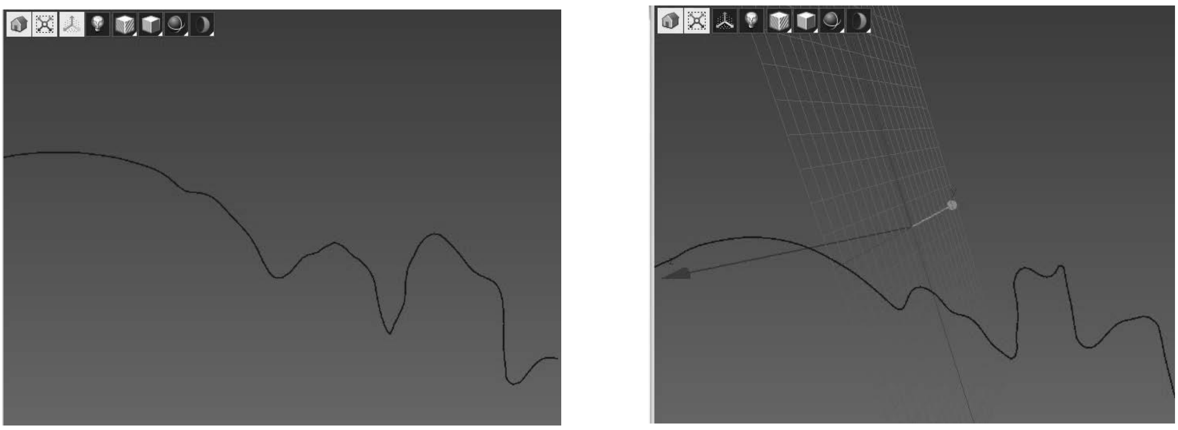

Fig. 3. Cross-sections of drapery folds on the models in Fig. 1.

This experiment concerned an exceptional case, because the analysed statuettes were based on a common prototype or scheme allowing some, but not fundamental freedom in execution for the individual masters and the analysis was also very restricted concerning just two isolated figures and involving just a limited set of measurements. Moreover the observation and comparison was carried out by the naked eye, thus implying still a high degree of subjectivity.

A larger set of comparanda (the acroteria and pediments of the temple of Asclepius at Epidauros) and another methodology (geometric morphometrics) was therefore chosen for another experiment, where inscriptional evidence provided a secure basis for the involvement of at least three different workshops executing different and clearly distinguishable parts of the decoration. In this case the heads were not preserved in a sufficiently large number and good condition, so it was only the drapery folds which could be analysed. In order to minimize the subjectivity involved in the selection of folds, it was our aim to extract as many of them as possible, but at the same time damaged sections had to be avoided.Thus the samples were different in length, but provided enough data for a statistically relevant analysis.

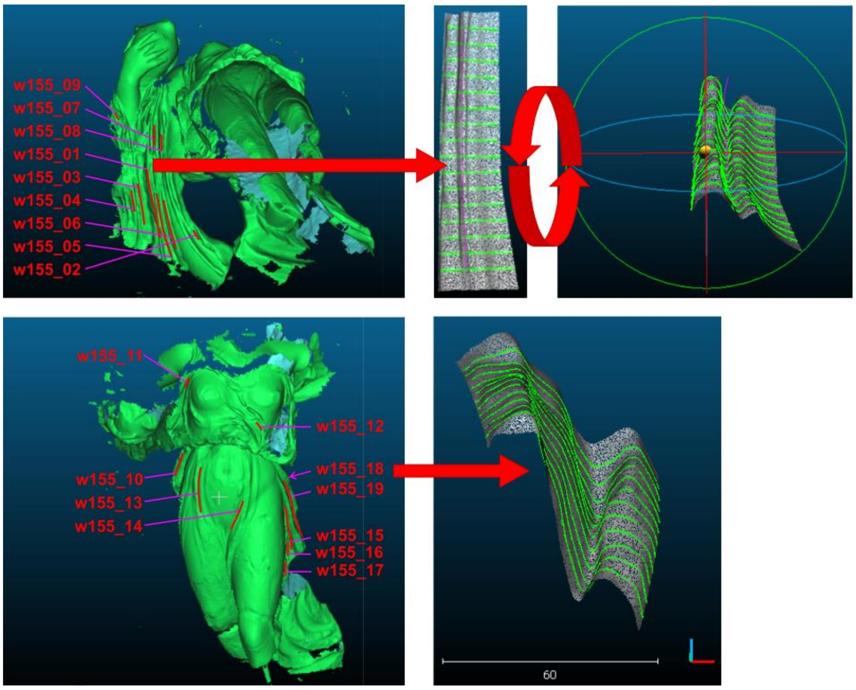

Fig. 4. Sections of folds selected for morphometrical analysis on an acroterion figure from Epidaurus

Sections perpendicular to the axis of the folds were made by Attila Virág and Bence Szabó with a spacing around 8-12 millimetres using the Cloud Compare software (available at: http://www.danielgm.net/cc/). The points (namely the local minima and maxima) that marked a change in the direction of the sections along the vertical axis from positive to negative or vice versa were identified using the diff() function of the R software (available at: https://www.r-project.org/). All sections were cut outside the lateral maxima of the folds, and those sections were excluded where the fold contained more than one inner minima. Thirty landmarks were placed equidistantly along each remaining curvature using the Morpho package of R.

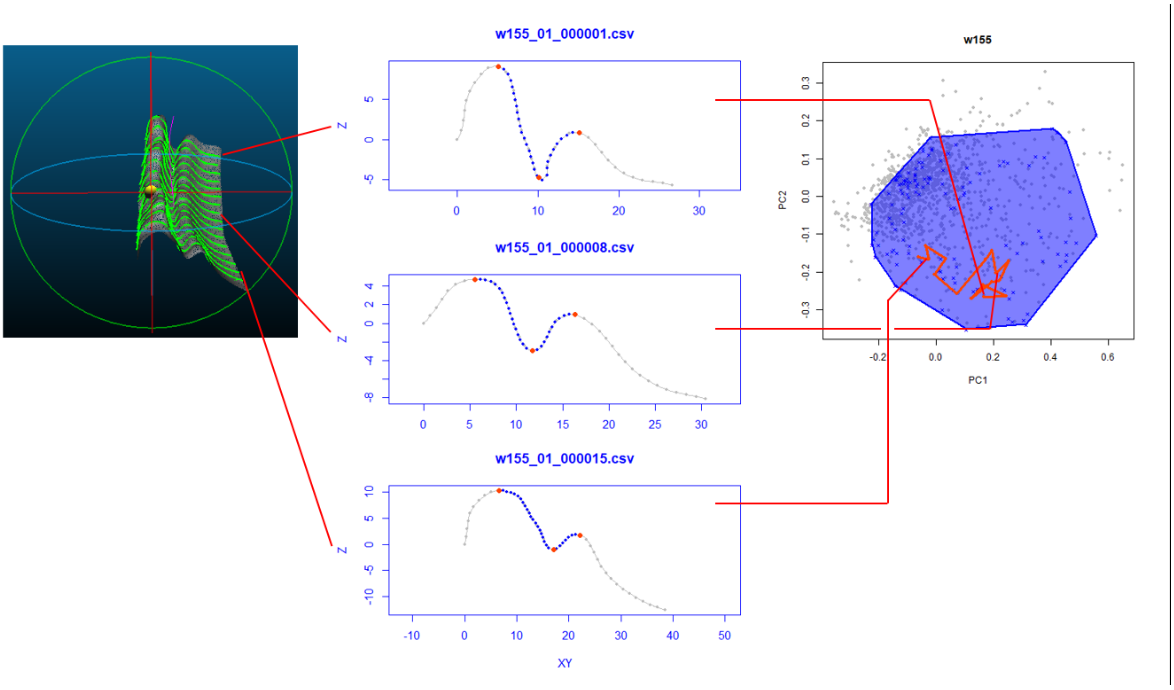

Fig. 5. Results of the morphometrical analysis carried out on a single drapery fold from the statue in Fig. 4.

Landmark analysis was carried out using the tpsRelw software (available at: http://life.bio.sunysb.edu/morph/). In order to eliminate variation in position, size, and orientation, the program executes the following subroutine: 1) the raw landmark configurations are superimposed on each other using the centroid (i.e. the arithmetic mean of all landmarks) as a fixed reference position; 2) the centred configurations are then rescaled to the same size based on the square root of the summed squared distances between all landmarks and their centroid; 3) the centred and scaled configurations are iteratively rotated until the minimum sum of squared distances between the landmarks and their corresponding sample average position is reached. After these steps, the program executes a relative warp analysis (RWA), which is basically a principal component analysis (PCA) on the covariance matrix of the resulting coordinates (namely the Procrustes shape coordinates). In the resulting coordinate system, the distance between two points correlates with the differences in the shapes of the original sections.

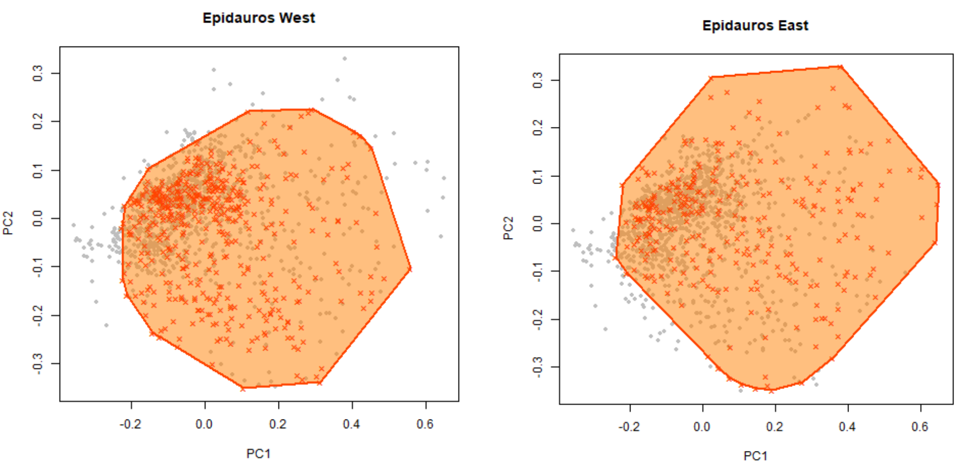

Fig. 6. PCA of the drapery folds in the pediments and acroteria of the temple of Asclepius at Epidaurus.

As shown in Fig. 6, the drapery analysis carried out on the sculptural decoration of the temple of Asclepius (5 figures from the east and 6 figures from the west pediment / acroteria) yielded the result that the different workshops cannot reliably be distinguished by this method. Since however, the workshops involved in this project were all originating from Athens, it might be assumed that their similarity in this respect is due to their common place of origin or simply reflects their chronological proximity.

In order to test these assumptions, the same methodology was applied to the drapery folds of statues, which are more than a century earlier. These included some selected pieces of the Olympia sculptures, a seated Artemis from Paros, and a standing Athena from the west pediment of the temple of Aphaia at Aegina. All these statues were carved from Parian marble and the one from Paros can certainly be assumed to have been made by a Parian workshop. The most recent study argued that its folds are so similar to those from Olympia, that these latter ones have to originate from a Parian workshop as well. As shown in Fig. 7, the morphometrical analysis revealed indeed a strong similarity between these pieces and also a marked difference from the folds of the Epidauros groups, but it is still uncertain, how this similarity has to be interpreted, since if we assume that similar design of the folds is a decisive proof of the same workshop tradition, then the pediments of the temple of Aphaia should be attributed to a Parian workshop as well, because the Athena from Aegina is also quite similar to the Parian and Olympian pieces in this respect. Traditionally, the sculptures from Aegina and the Artemis from Paros are considered a generation earlier than the sculptures from Olympia, but on the basis of the present evidence it is also possible that they are all contemporary and/or were all produced by Parian sculptors. Further investigations and the analysis of other samples are clearly needed to arrive at a sound conclusion in this matter.

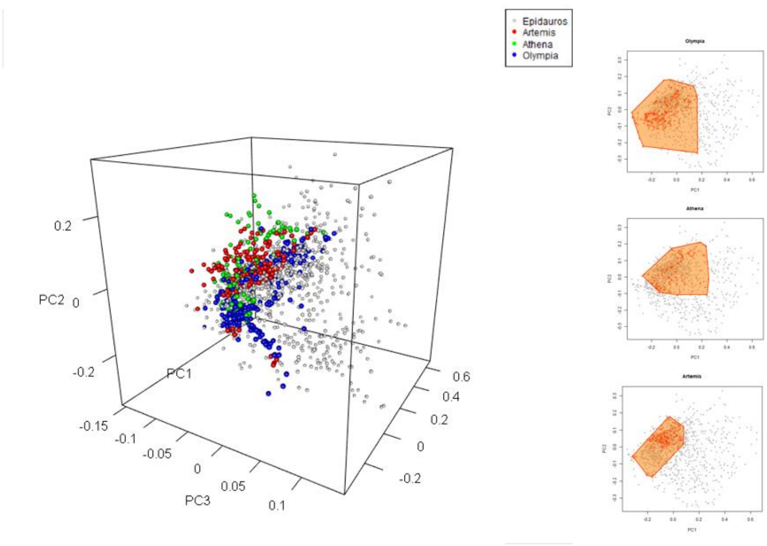

Fig. 7. PCA of the drapery folds in Epidauros (grey), Olympia (blue), Paros (red) and Aegina (green)

The morphomeric analysis of drapery folds cannot confirm nor prove beyond doubt that the sculptures of the temple of Zeus were produced by the same workshop or by different ones possibly coming from the same geographic area. Another way for approaching this problem was the analysis of the anatomical features, mainly the facial ones. Eyes, eyes with accompanying brows, mouths, and noses were extracted by Leif Christiansen from the models resulting in a data set of 44 total features. Examples of extracted facial features may be seen in Fig. 8.

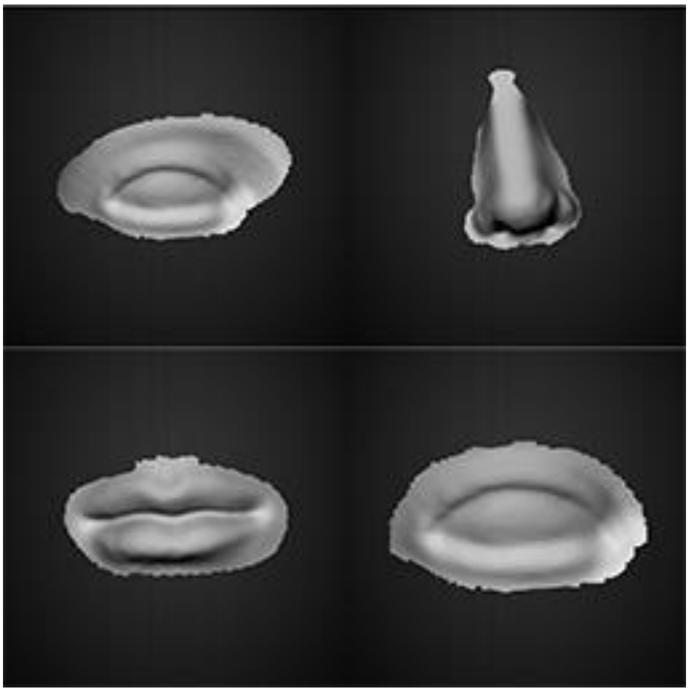

Fig. 8. Examples of facial features extracted from the models.

These models were then compared using the open source software Cloud Compare. Cloud Compare was used to compute the mean and standard deviation of the distances between points in two facial feature models. Using Cloud Compare, facial features were aligned so as to maximize the overlap between the two models. Then, for each point in the reference model the closest point was found in the comparison model. Finally, the mean and standard deviation of the distances were calculated. These two values were combined into a single metric using the following equation:

$$d(x) = \max(\,|mean \ \pm standard\ deviation|\,)$$

Each feature was compared to every other, resulting in 43 values per feature. Then, a two-sample t-test was performed to test whether on average a feature from the West pediment was more similar to other features from the West pediment and whether features from the East pediment were more similar to other features from the East pediment. Only the eyes and eyes with accompanying brows had enough features to perform such a test. A p-value of less than 0.05 is considered significant. Only the right eyes from statues N and O on the east pediment were found to be statistically significant (Fig. 9). Assuming that $d(x)$ may reliably distinguish artists/workshops, we could then conclude that the eyes were all carved by the same artist/workshop. This result is currently checked by similar comparisons between other pieces of sculpture.

	files	perc_w	perc_e	f.p.value	t.p.value
1	E_N_eyeL.OBJ	0.6	0.4	0.0917	0.6102
2	E_N_eyeR.OBJ	0.2	0.8	0.9937	0.0196
3	E_O_eyeL.OBJ	0.6	0.4	0.5640	0.0728
4	E_O_eyeR.OBJ	0.4	0.6	0.3127	0.0302
5	E_P_eyeL.OBJ	0.6	0.4	0.3312	0.1168
6	E_P_eyeR.OBJ	0.4	0.6	0.4196	0.0385
7	W_A_eyeL.OBJ	0.8	0.2	0.2200	0.1016
8	W_A_eyeR.OBJ	0.8	0.2	0.3149	0.1634
9	W_B_eyeL.OBJ	0.8	0.2	0.1838	0.3205
10	W_B_eyeR.OBJ	0.8	0.2	0.0712	0.5014
11	W_D_eyeL.OBJ	0.8	0.2	0.0730	0.6274
12	W_D_eyeR.OBJ	0.6	0.4	0.0127	0.2382
13	W_E_eyeL.OBJ	0.4	0.6	0.0081	0.4567
14	W_E_eyeR.OBJ	0.6	0.4	0.6777	0.9316
15	W_I_eyeL.OBJ	0.6	0.4	0.0012	0.1373
16	W_I_eyeR.OBJ	0.8	0.2	0.0155	0.6554
17	W_U_eyeL.OBJ	0.8	0.2	0.0633	0.6175
18	W_U_eyeR.OBJ	0.6	0.4	0.0206	0.2428

Fig. 9. Results of statistical tests using values generated from comparing eyes.

In addition to the drapery folds and facial features, one could possibly rely on the rendering of hair locks. The sculptures from Olympia feature a wide variety of them and they are relatively well-preserved, but their analysis has still to be done. There were just some preliminary tests carried out on the friezes of the Siphnian treasury at Delphi by János Mészáros. This important monument was included in the project because there is a sculptor's signature preserved on it, stating that some parts or figures (or according to the current *communis opinio*, the entire north and east sides of the frieze, Fig. 10) were made by the same artist, while others were obviously carved by a different team.

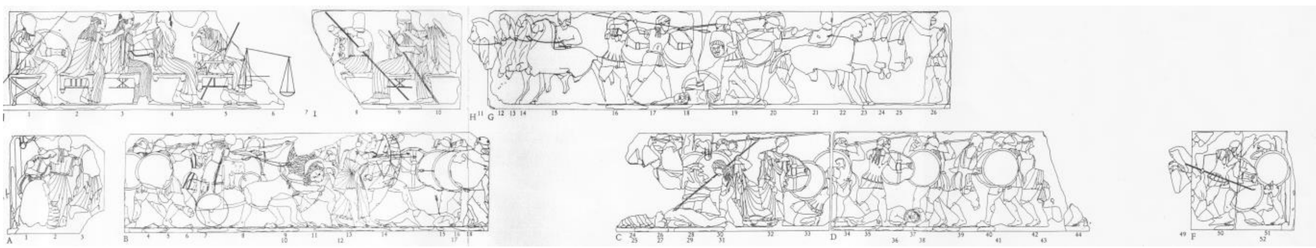

Fig. 10. Overview of the East (above) and North friezes (below) of the Siphnian treasury at Delphi

3D meshes were stored in raw Artec format, while sections in easily comparable areas of well-preserved figures were created using the open-source CloudCompare point cloud managing software (CloudCompare 2.7, 2016). The scanned meshes were migrated into PLY format, and they were transformed in CloudCompare from their arbitrary position into a proper position where the Z-axis of figures is parallel to Z-axis of CloudCompare coordinate system and horizontal parts are also parallel to X-Y plain. These rotated surfaces were subsampled back to 3D point clouds (stored in binary PLY files for later use) and using specific Extract cloud sections tool sections were generated through locks of hair, ankles, knees, clothes and cuirass on several figures (Fig. 11). Each generated 2D section was exported in DXF format and can thus be compared to each other.

Not all of these profiles proved to be informative enough, but those generated from locks of hair seemed to be revealing for the present purpose, i.e. their differences and similarities point to the same direction. Locks of hair falling on the shoulders of male and female figures are rendered according to the same scheme both on seated and standing figures and irrespective of the subject of the scene and are thus easy to compare to each other. Several cross sections were made (both in the upper and lower part of the locks) and from these profiles (Fig. 12), one can easily recognize that some of them belong together because of their similar treatment (East nos. 1 through 5, North nos. 31, 35 and 50 all showing angular channels with a flat bottom between the locks), while others are clearly carved in a different manner (East nos. 16 and 17 with rounded channels). These observations clearly show, that even if the same master was responsible for the overall design of the east and north friezes, different sections were carved by different workmen who rendered the same features in quite different ways.

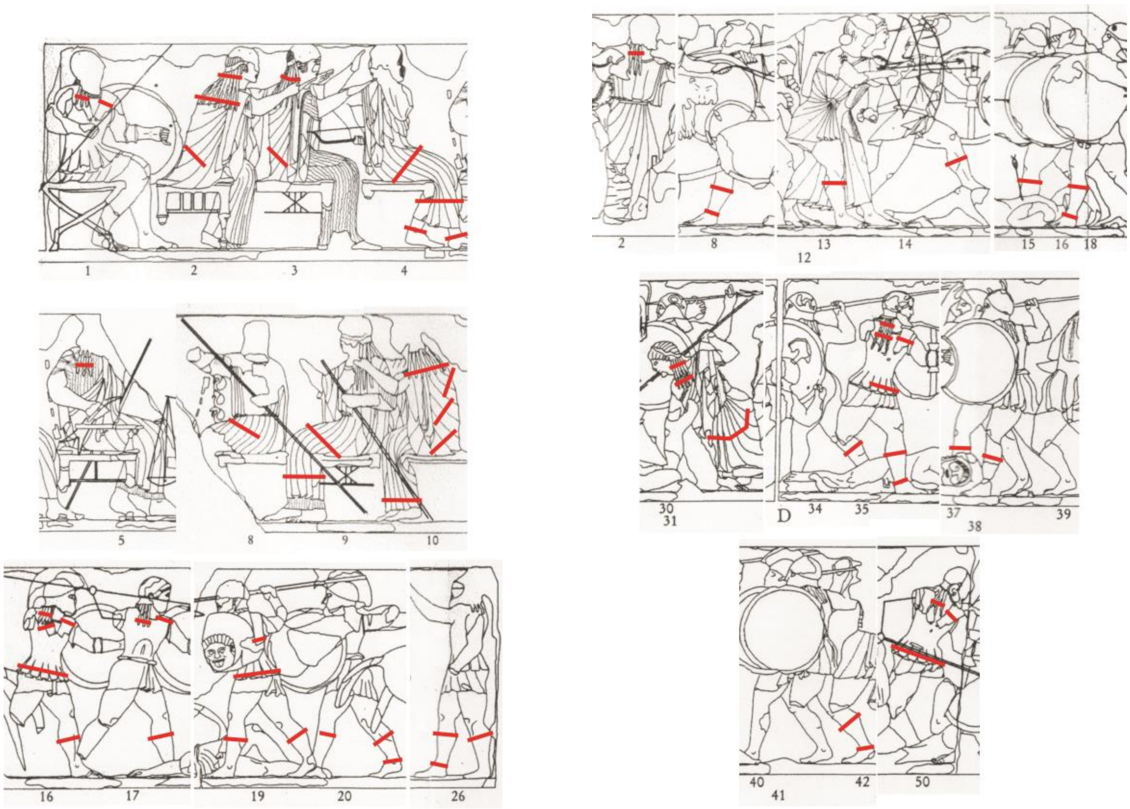

Fig. 11. Placement of the cross sections taken from the East (on the left) and North friezes (on the right) of the Siphnian treasury at Delphi

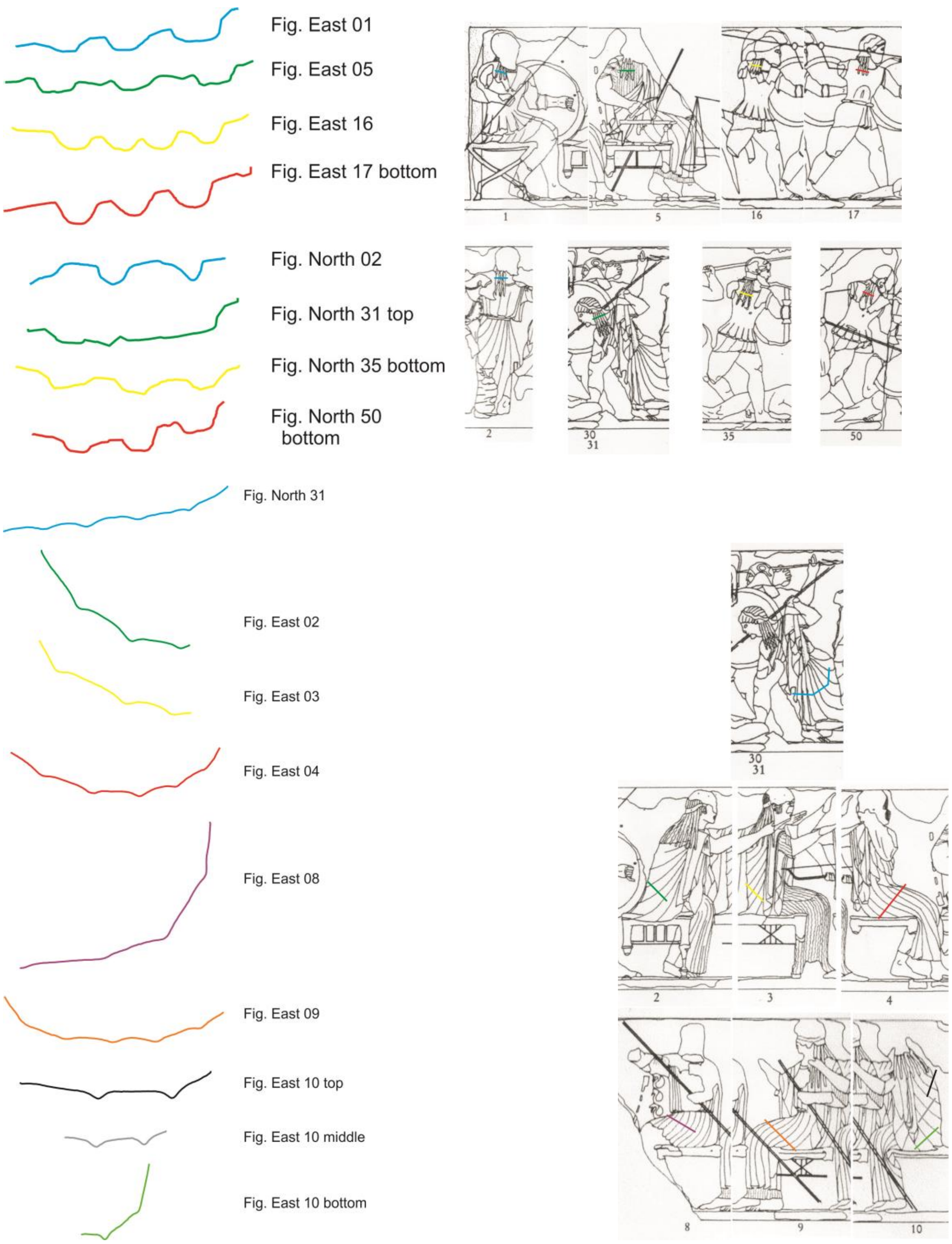

Fig. 12. Cross sections of locks and drapery folds taken from different figures on the the East and North friezes.

As shown by the above examples, several kinds of analysis were tested, but none of them has been completed. This was mainly due to the unpredictable working and long periods of non-working of the colleagues involved in the analitical parts of the project. First it was therefore necessary to remove Kristóf Kovács from the team and to search for someone else to replace him. It was possible to attract some PhD candidates (Leif Christiansen and Bence Szabó) and young scholars (János Mészáros and Attila Virág) for some specific tasks, but all of these employments led only to short-term collaborations, even if they were quite intense and fruitful for all those involved. Ágnes Bencze remained in the team for the entire duration of the project, but was working only intermittently and although she was allowed to pursue her own interests and received every kind of support for this, she did not even complete the tasks she selected for herself.

Under such circumstances, it was impossible to make full use of the inherent possibilities of the collected material and none of the two primary goals was reached. The results are preliminary, even though there are considerable steps forward. Concerning methodology, the Morellian masterhand attribution was applied in 3D by comparing the drapery folds and certain anatomical features of the statues and in the case of the Olympia-sculptures it could be clarified that on the basis of our present evidence, the hypothesis of two or more workshops creating the pediments and metopes parallel to each other can most probably be ruled out.

In addition to the publications already listed in the annual reports, the results summarized here were already published in two papers[2] and have also been presented at the CAA (Computer Applications and Quantitative Methods in Archaeology) 2018 conference. This conference offered the possibility to contact specialists who might be interested in pursuing this project and there is really hope for continuing the work with some new partners / collaborators.

[2] Bencze Ágnes - Gyuris Péter, Type, Scheme and Execution: Three basic concepts for the definition of a personal style. An experiment helped by virtual 3D model analysis, *Marmora. An International Journal for Archaeology, History and Archaeometry of Marbles and Stones*, vol. 12, 2016 [2017], 171-187; Patay-Horváth András - Leif Christiansen, From Reconstruction to Analysis. Re-use and re-purposing of 3D scan datasets obtained from ancient Greek marble sculpture, *Studies in Digital Heritage*, Vol. 1, No. 2, 491-500, 2017