Digital Study and Web-based Documentation of the Colour and Gilding on Ancient Marble Artworks

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***Abstract*—Greek and Roman marble artworks have been deeply studied from a typological and stylistic point of view, while there is still a limited knowledge on the pigments, dyes, binders and technical expedients used by Roman artists. In a renewed scientific interest towards the ancient polychromy (colour and gilding), a digital methodological and multidisciplinary approach can provide valuable information to better investigate and understand this fundamental aspect and to get a complete sense on Greek and Roman marble artworks. Following this research direction, the paper proposes a systematic methodological process defined to detect, document and visualize the preserved (and in some cases the digital reconstructed) original colour and gilding on Roman marble sarcophagi (II-IV century AD). The process defines a working pipeline that, starting from the selection of the artefact to study, proposes a set of investigation steps to improve our knowledge of its original painting. These steps include the direct virtual inspection, the archaeological and historical research, the on-site scientific investigation by multispectral imaging, spectroscopic and elemental analysis (eventually supported by micro-invasive techniques performed in laboratory), the accurate polychrome surface acquisition by colour calibrated 2D images. All the data produced are integrated with a high-resolution 3D model to support enhanced analysis and comparison and to create a digital 3D polychrome reconstruction by virtual painting. Finally, all those data are also made accessible on the web by using a cutting edge platform for visual media publication and interactive 3D visualization. This systematic and multidisciplinary process was tested on the so-called 'Annona sarcophagus' (Museo Nazionale Romano - Palazzo Massimo, inv. no. 40799).**

***Index Terms*—Polychrome and gilded marble artworks, Annona sarcophagus, Digital analytical process, Scientific analyses, Interactive 3D Web visualization**

I. Introduction

A renewed interest in the study of the ancient colour of Greek and Roman architectures and artworks has emerged in the last decade, originating multidisciplinary studies in the Digital Humanities field [1], [2], [3], [4]. Despite the important results achieved within a few years, the existing projects on the study of the ancient polychromy do not take into account the need to define a standard methodological approach focused on the use of new technologies as a mean to connect the different data gathered and to improve our knowledge on this subject. For this reason, we present a multidisciplinary approach to identify, document and visualize the ancient polychromy (colour and gilding) on marble artefacts, starting from the analytical study of a well-defined archaeological class of artefacts with known historical period and production place: the Roman marble sarcophagi made in Rome from the first half of the 2nd century to the end of the 4th century AD [5].

978-1-5090-0048-7/15/$31.00 ©2015 IEEE

The definition of the proposed protocol (Fig. 1) started from the archaeological and historical researches of eighty polychrome sarcophagi, some also in fragments, identified in the collections of the Musei Vaticani, the Museo Nazionale Romano and the Musei Capitolini by direct visual inspection. The research was integrated by the use of scientific examinations based on multispectral imaging (ultraviolet, infrared, visible-induced IR and ultraviolet-induced visible fluorescence imaging) and spectroscopic and elemental analysis (Fourier-transform infrared spectroscopy, X-ray fluorescence). Since in some cases several substances and overlapped layers are applied on the marble surface, micro-invasive analysis techniques (optical petrographic microscopy, scanning electron microscope and energy dispersive X-ray spectrometer, Raman spectroscopy) was necessary for a better scientific investigation of polychrome traces.

A fundamental aspect of the proposed method is the new and innovative role of 2D and 3D digitalization technologies: a link between the archaeological information and the scientific analyses results to provide a better-integrated documentation (and interpretation) of the acquired data and to improve the knowledge of the original polychromy via the production of virtual reconstructions. The main idea is to integrate the computer-based technologies with consolidated scientific analyses to define a common work platform to use both for a better insight of ancient colour and gilding and for the dissemination of the results.

Main contributions of this work are:

- a multidisciplinary method to study the marble polychrome artworks by integration of digital technologies, scientific analysis and archaeological data;
- the interactive 3D Web visualization and navigation of all acquired (and processed) data to improve their interpretation and to allow an easy and effective dissemination of the obtained results.

The goal is to use the gathered data ant their interpretation:

- to improve the knowledge on pigments and dyes used by Roman artists and the recognition of the pictorial styles and the techniques used to apply both colour and gilding;
- to create a digital 3D polychrome reconstructions by virtual painting.

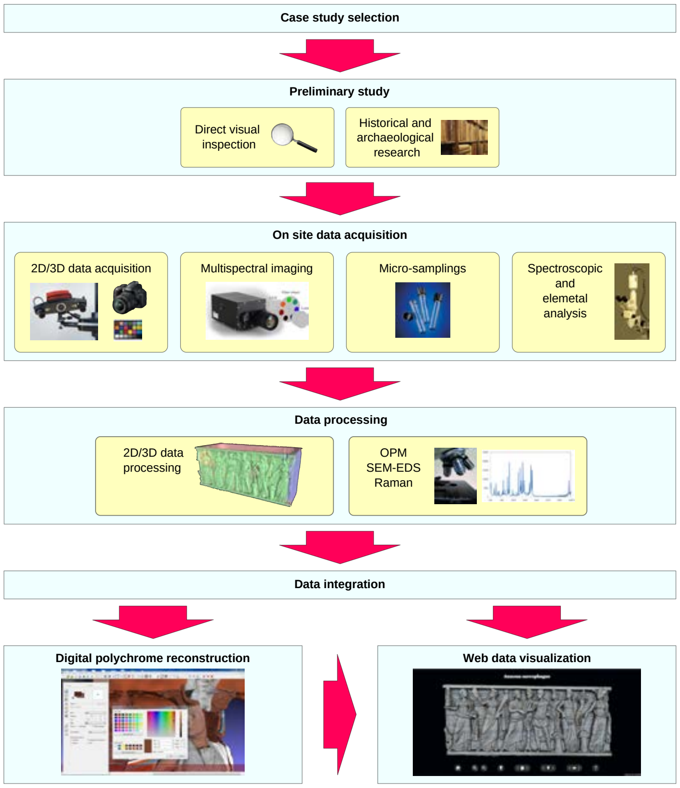

Fig. 1. Overview of the systematic methodological process adopted to detect and study the ancient polychromy on marble artefacts (e.g. Roman sarcophagi), and the subsequently dissemination of achieved and elaborated data.

II. Related Work

A new attention about the knowledge of the ancient polychromy has generated several research projects and important exhibitions using different investigation approaches [4]. In this context, experimental archaeology is working on the reconstructions of polychromy through digital 3D models and physical replicas. Following a more traditional approach, the first exhibition of "Bunte Götter. Die Farbigkeit antiker Skulptur" [1], [6] showed the used of physical copies obtained through digital 3D models to propose the original polychrome status of Greek sculptures. Another interesting case-study is the physical polychrome reconstruction of the Caligola Roman portrait [7]. A different approach to reconstruct the ancient colour directly on the digital 3D model of the artefact was proposed in [8] for the polychrome reconstruction of a young Roman portrait. This approach is designed for skilled users and it does not provide specific resources for dissemination to ordinary public or to the general community, since it does not supply any Web-based access to the gathered data.

This research context has recently encouraged the development of a first attempt to do systematic study, enriched by the proposal of some open source tools in order to help us to gain understanding of various polychrome and gilding issues on the Roman marble sarcophagi carved in Rome (II- IV century AD) [5], [9]. This class of artworks has been systematically studied from a typological, stylistic and iconographic point of view. This has given rise to a great *corpus* [10] and an extensive scientific production [11], [12]. Several studies concerned also the types of marble used, the production sites and the issues related to their use and re-use [13]. Conversely, the study of ancient polychromy (painting and gilding) has often received less attention, producing few knowledge on pigments, dyes, and binders used by Roman artists, and on the pictorial styles and the techniques used to apply both colour and gilding [5]. For this reason, the considerations by Pietrogrande [14], Gütschow [15] and Reuterswärd [16] from the first half of the last century have a fundamental importance, although they are based on direct visual inspection and not supported by scientific analysis. However, in the last years, a renewed interest in ancient polychromy has generated several research projects and some analytical publications relating to two Roman marble sarcophagi dated to the late 3rd or early 4th century AD [17], [18].

III. Overview

The proposed systematic method (Fig. 1) extends and improves the process already presented in [9] and tested on the *Ulpia Domnina*'s sarcophagus exposed in the Michelangelo's cloister of the Museo Nazionale Romano – Terme di Diocleziano in Rome (inv. no. 125891).

The method defines a working pipeline that starts from the selection of the artefact to study. To better present the method we show the results obtained on the so-called 'Annona sarcophagus' in Museo Nazionale Romano – Palazzo Massimo (inv. no. 40799). This rectangular sarcophagus without lid (Fig. 2) is decorated only in the frontal part with allegorical characters: *Portus*, *Annona*, *Concordia* (behind a married couple making a *dextrarum iunctio*), *Genius Senati*, *Abundantia*, and *Africa* (from the right to the left of the sarcophagus). It is dated at the last third of 3rd century (270-280 AD) [19]. The sarcophagus was selected because it presents several visible colour and gilding traces and it poses interesting open problems on their application techniques. The academic literature reports that the sarcophagus shows a great amount of red and gilding [20]. The main goals for this case study are:

- to verify the presence of other colours besides the red;
- to characterize the used pigments and dyes;
- to identify the application techniques of the colour and gilding;
- to provide documentary evidence to understand and virtually reconstruct the original polychromy;
- to produce an integration over the 3D model and the related interactive visualization of all (raw and processed) data.

The main steps of the process (Fig. 1) are:

- the preliminary study of the artefact (Section IV);
- the on-site data acquisition (images, spectra, micro-samples, 3D data) (Section V);
- the processing of the gathered data (Section VI);
- the integration of the acquired and computed data with the 3D model (Sections VII and VIII);
- the digital reconstruction of the original polychromy (Section VII);

- the Web visualization (Section VIII)

In the following sections, for each step, we describe only the main activities performed on the Annona sarcophagus.

Fig. 2. The so-called 'Annona sarcophagus', Museo Nazionale Romano – Palazzo Massimo (inv. no. 40799).

IV. Preliminary Study

This step involves the archaeological and historical research and the direct visual inspection. The first activity allows solving doubts about the authenticity of some pictorial elements evaluating the description of the sarcophagus in the historical archive library and in the catalogue of the Museo Nazionale Romano.

The direct visual inspection with naked eye or through a portable microscope allows a preliminary understanding of pigments and their application techniques on the marble surface. In our case, a fixed magnification 2× Olympus VMF stereo-microscope mounted on a tripod was used to better examine colours and gilding details of the marble surface.

V. On Site Data Acquisition

Starting from the data of the preliminary study, the following step is the identification of the areas where to perform non-invasive analyses based on multispectral imaging, spectroscopic and elemental techniques. In the cases where the surface presents overlapped layers with interesting features of difficult interpretation, some micro-samples can be taken to do more accurate laboratory analyses.

The step is completed by an accurate polychrome surface acquisition by colour-calibrated 2D images and a 3D digitalization of the artefact (using passive or active 3D scanning technologies).

A. Multispectral Imaging

The multispectral imaging techniques are useful to characterize the spatial distribution of the remaining traces of painting materials [6]. Such techniques generally include InfraRed (IR) and UltraViolet (UV) images and photo-induced fluorescence (VIL and UVL). Their selection depends on the physical and chemical properties of the compounds under investigation. The Visible-induced IR Luminescence (VIL) plays a key role in the characterization of the Egyptian blue pigment. It captures the fluorescence effects in the IR-spectrum when the Egyptian blue is illuminate by a light with only visible radiation. The UltraViolet-induced (visible) Luminescence imaging (UVL) allow us to identify a rose madder lake on surface [21]. In this case, the image captures the fluorescence effects in the visible spectrum when the madder lake is illuminated by an UV light.

The VIL and UVL images was acquired with a Canon 350EOS camera without IR-blocking filter. The camera operates in manual mode. For the VIL analysis we use a LED light (1100 lumen) without IR radiation and a longpass IR filter Schott RG830 in front the camera lens. For the UVL we use a UV LED light and a combination of a bandpass visible filter (Schneider – Kreuznach UV-IR-CUT) and a longpass filter Schott KV418 for the camera lens. The photos were acquired using a small portable dark room to remove all possible environment lighting.

Fig. 3. Polychrome detail of the *parapètasma* (left) and the same area in VIL imaging that shows the distribution of glowing white particles of Egyptian blue (right).

B. Micro-sampling

Among the examined sarcophagi, the Annona sarcophagus shows some peculiar properties about the technique used for colour and gilding application. For this reason four micro-samples (Fig. 4) have been taken respecting the minimal invasive standards.

Fig. 4. Micro-samplings position of colours and golden traces on the Annona sarcophagus (MNR-PM, inv. no. 40799).

C. 2D images acquisition and 3D digitalization

High-resolution and calibrated images of the sarcophagus were acquired using a Nikon DSLR camera and a colour calibration chart (a Macbeth X-Rite ColorChecker Passport), taking more attention in the captures of the representative polychrome and golden areas.

For the 3D digitalization, we decided to test and use the multiview-stereo 3D reconstruction approach. For this purpose, we captured another set of images that guarantee an optimal sampling of the surface from different point of views.

VI. DATA PROCESSING

This step involves the processing of the acquired data. On one side, there is the 2D/3D data processing to create a high-resolution 3D model; on the other side, the selected micro-samples examination by Optical Petrographic Microscopy (OPM) and Raman spectroscopy to extract further information. Where the situation is more complicate, they are examined by Scanning Electron Microscope and Energy Dispersive X-Ray Spectrometer (SEM-EDS). Naturally, some of the analytical investigation performed on site by means of portable spectroscopic and elemental techniques (e.g. Fourier-Transform InfraRed spectroscopy-FTIR, X-Ray Fluorescence-XRF) can be also performed in laboratory on the micro-sample with more precise instruments.

A. Optical petrographic microscopy

Optical microscopy allowed a preliminary analysis of the micro-samples (Fig. 4), which were investigated with a WILD Heerbrugg M10 stereomicroscope with variable magnification. The crushed-grains were then observed by means of Leitz Orthoplan-pol microscope in reflected and transmitted light (under crossed and uncrossed polars). The microscope was also provided with a PloemOpak fluorescence illuminator and a filter cube (excitation filter BP 340-380 nm) for examination under UV light; the UV light source was an HBO 200W high pressure mercury vapour lamp. Usual magnifications were from $4\times$ to $40\times$, and $63\times$ oil immersion.

B. Raman spectroscopy

Subsequently, all the micro-samples (Fig. 4) were also examined by Raman spectroscopy using a Renishaw Raman Invia instrument and an XploRA Horiba Jobin-Yvon microscope. The first device was equipped with an 1800 grooves/mm diffraction grating, a CCD detector and a $50\times$ magnifying lens. The laser sources, a HeNelaser (λ = 633 nm) and an Nd:YAG laser (λ = 532 nm), were selected according to the kind of sample analysed. The second instrument was equipped with two diode lasers (638 nm and 532 nm, respectively) and an Olympus microscope with a $10\times$ and a $50\times$ objective.

C. 3D processing

For the 3D digitization of the sarcophagus we employed a multi-view stereo approach using a set of 165 photos. The images were processed using Agisoft PhotoScan [22] to compute the camera parameters and a dense point cloud. Since the processing of the whole set of images produced an incomplete point cloud, we split the images in several set corresponding to the main parts of the sarcophagus (the front, the interior and the sides). For each set we perform the processing with PhotoScan, producing different point clouds. Each clouds was triangulated using the Screened Poisson Surface Reconstruction algorithm [23] in order to make easier the alignment of the different parts inside MeshLab [24]. The aligned triangular meshes have been merged together with the standard volumetric algorithm based on the Marching Cube available in MeshLab, producing a final high-resolution model of 72M triangles. Finally, the colour images have been projected and integrated on the high-resolution model to document the current state of the colour and gilding using the algorithm in [25] and available in MeshLab. Even if the model presents some imperfections in the area where it was difficult to obtain an optimal multi-view acquisition (area hidden by high-relief part), the final model shows how the image-based 3D reconstruction can be a good and cost-effective alternative to active 3D scanning techniques.

VII. DIGITAL POLYCHROME RECONSTRUCTION

For the Annona sarcophagus we propose a preliminary virtual polychrome version of the *Africa* personification (Fig. 9) with the purpose to show the distribution and overlapping of the colours on the sarcophagus surface, without any simulation of the light interaction with the painting that requires more complex reflectance functions (BRDF, SVBRDF, BSSRDF) and rendering systems [26]. It is partially reliable due to the lack of clear clues on the original colour of some elements that need additional scientific and archaeological investigation. The polychrome reconstruction has been made using the painting tool of MeshLab, exploiting the RGB coordinates identified in the most representative colour traces in the set of calibrated images acquired in the previous step. In the identification process of the RGB coordinates of each color, we took multiple samples in different measurements points and we noted very similar RGB coordinates across the multiple samples of the same colour. A fundamental step for the polychrome reconstruction is the integration of the data acquired and computed in the previous step. In the specific, the VIL and UVL imaging are useful in the characterization of the spatial distribution of Egyptian blue pigment and organic dyes, such as the rose madder lake (see Section V-A). The OPM and Raman spectroscopy identify the inorganic pigments and the organic dyes. They are also useful to determine if a colour is made of a single pigment (with binder) or a mixture of more pigments and dyes. Therefore, the OPM can reveal a possible stratigraphic sequence and if the colour is applied directly on the marble surfaces or over a fine ground layer. Finally, the scientific results, connected with the direct visual inspection and archaeological data, are very useful to reproduce a proper shading of single or overlapping colours and to propose a painting style as similar as possible to the original.

VIII. DATA INTEGRATION AND VISUALIZATION

The integrated comparison of scientific and archaeological data is usually a complex process done by the researchers (or conservators) while studying the archaeological artefacts. Having the possibility to combine different diagnostics modalities with archaeological data is very interesting for the specialists of polychromy. In order to resolve this problem we have developed specific components for the 3D Heritage Online Presenter (3DHOP) platform [27], where the 3D models is used to manage and display all achieved information about the ancient polychromy and the history of the artefacts (Fig. 5). The advantages of the 3DHOP framework for our method are: an easy and interactive visualization of 3D models directly inside HTML pages, enhanced by all the types of data gathered; the streaming of multiresolution 3D meshes over HTTP, supporting the exploration of very large models on commodity computers and standard internet connections.

The main features of the documentation system, useful both for the analytical process and the dissemination, are:

- the interactive navigation of the 3D multi-resolution model with the possibility to freely examine any details of the artefact using the zoom and pan commands;
- the interactive navigation using a predefined set of views related to most interesting details (more preserved colour area, polychrome details useful for the virtual reconstruction, elements that attested particular events like an ancient or modern re-painting/restoration) (Fig. 6);
- the possibility to interact with a directional light that can help to highlight some details of the relief otherwise not discernible (for example small inscriptions);
- the management of the information in multiple levels with special attention to the scientific analyses data. They are visualized in a drop-down menu that allows the user to choose one item from a list (Fig. 7);
- the placing of a set of hotspots to link the different data to the 3D model. The hotspots are subdivided in different groups that can be visually identified by using different colours (Fig. 7). In our case each group correspond to a different acquired data (e.g. VIL and UVL imaging, OPM, Raman spectroscopy, etc.). For each hotspot there is the possibility to associate a movable window that allows the user to consult the hotspot data content (Fig. 8);
- the interactive visualization of the geometrical 3D model and the scientific polychrome reconstructions in multiple levels. Specifically the user can switch from the current colour to the original virtual colour proposal (or more presumed reconstructions) by clicking the palette colours icon (Fig. 9).

Fig. 5. 3DHOP interface with the rendering of the 3D multiresolution model of the Annona sarcophagus.

IX. Results

The archival and literature searches, performed in the historical library and in the Museo Nazionale Romano catalogue, revealed that the Annona sarcophagus was discovered in via Latina, Rome some years before 1877. It was found with its fragmented lid in a modest tomb [20] together with the sarcophagus with Cupids holding clypeus and garlands, dedicated to *Flavius Valerius Theoponpus Romanus* (Museo Nazionale Romano – Terme di Diocleziano, inv. no. 514). The sarcophagus was described with a lot of polychromy (red

Fig. 6. 3DHOP supports the definition and visualization of a predefined set of views, selected to show the most representative polychrome areas on the Annona sarcophagus.

Fig. 7. Visualization of the selected areas where the VIL analysis were performed.

Fig. 8. Visualization of data linked to the 3D model by directly clicking on the hotspots.

Fig. 9. Visualization of an hypothesis of 3D polychrome reconstruction by directly clicking on the palette colours icon.

colour) and gilding [20] traces, which were largely vanished in 1983 [19]. Direct inspection shows a great amount of dark red, red like cyclamen, and gilding. Specifically, red tending towards cyclamen (or bright pink) was applied to the *thymiaterion* flame (Fig. 10, at left) with wide background paintings or, more probably, with large brushstrokes. This red pigment was possibly superimposed to the thin white layer, or, even more plausibly, it was applied as a mixture with white, pink and blue to create a lighter shade or a nuance effect. Indeed, OPM and Raman spectroscopy results highlighted that the white substance, characterized by low refractive index and birefringence, is attributable to the gypsum, while the red tending towards cyclamen is made of haematite granules [5], [28]. VIL imaging reveals a few number of small Egyptian blue particles (Fig. 10, at right), while visual inspection through portable microscope allow us to also identify many traces of presumably rose madder lake vegetable dye (UVL analysis is planned on May 2015).

Fig. 10. *Thymiaterion* flame polychrome detail (left) and the same area in VIL imaging that shows the distribution of glowing white particles of Egyptian blue (right). On the flame the EB is located as scattered particles, while on the shaft shows a enough compact layer.

Dark and brown red – composed by iron oxides and hydroxides – is visible on the hair of the figures, on the beard of the *Genius Senati* and on the hidden areas of the *parapètasma*. It was always directly applied on the marble surface with wide background paintings or large brushstrokes.

Traces of dark red solid lines are preserved in the engraved areas of the personifications attributes and diadems (Fig. 11) and of the *thymiaterion*. Thin dark red lines outline also the eyes contour, the iris and pupil inner boundaries, along the incised lines. At present it is still not completely clear if this colour has been applied either on top of a white substance layer, or as a mixture of more pigments, such as haematite, vegetable dye and gypsum.

This new investigation has also identified some traces of blue and white colours that seem unpublished until now in the academic literature [20], [19]. The blue areas are visible with the naked eye in a hidden area of the *parapètasma* near *Africa* and under the node of the *parapètasma* near the *Annona*'s shoulder (Fig. 3). The blue pigment is applied directly on the marble surface probably with broad brushstrokes [5], [28]. In addition, the VIL imaging shows Egyptian blue (invisible to the naked eye) also on the *thymiaterion*, on the sea waves, on the horn of plenty and on the *Annona* and *Abundantia*'s interior tunic. A uniform distribution of small Egyptian blue granules are also revealed in the white ornamental edge of

Fig. 11. Polychrome detail of the *Concordia* personification.

the *Annona*'s palla as glowing white (Fig. 12). That is also confirmed by OPM (see below).

White colour is preserved along the inferior ornamental edges of the *palla* over the *stola* and interior tunic, on the decorative horizontal bands of the *parapètasma*, into the engraved lines of the face features and into the outlines of figures and objects. In particular, white solid line is visible along the inferior ornamental edge of the *Annona*'s *palla*. Specifically, we see a white band of approx. 2 cm wide, which was outlined by red lines of approx. 0.5 cm and enriched by dots of red colour of approx. 0.5 cm in diameter and drawn at a range of approx. 1 cm (Fig. 12) [5], [29].

The reading of the crushed-grains by polarizing microscope has not allowed us to see the stratigraphic sequence and then to define for certain if the white can be considered a real colour or rather a fine ground layer aimed at getting the proper intensity of overlapping colours. The absence of lead traces suggests us to rule out the possibility we are dealing with white lead pigment, or *cerussa* ($2PbCO_3Pb(OH)_2$) [30]. Otherwise, the observation of patches made of microcrystalline texture natural calcium carbonate ($CaCO_3$), which incorporates dark red to yellow-orange granules attributable to iron oxides and hydroxides, suggests the use of a white lime pigment. It is a calcium carbonate plus calcium hydroxide ($CaCO_3 + Ca(OH)_2$), which is less covering than white lead but more suitable to lighten the hue of some colours and get the proper intensity [30]. The presence of dark red and yellow-orange granules composed by iron oxides and hydroxides indicates that the red colour of ornamental band is made from haematite and red-based ochre pigments. Using Raman spectroscopy the presence of haematite (Fe_2O_2) was proved. Recently, traces of white calcium carbonate ground, topped with yellow and red ochre, was also identified on the garment's border of a colossal statue of naked hero, probably interpreted as Achilles (Aphrodisias Museum inv. no.67-28/29/30), dated to 2nd century AD [31].

The presence of Egyptian blue crystals in the analysed white micro-sample [5], [28], combined with the VIL imaging results, lead us to assume that it was mixed with white lime to produce a glowing shades of white, as highlighted by analysis of some Roman wall paintings [32] and also observed in white lead preserved in some Roman sculptures [33]. It is less likely that white lime may constitute a substrate to Egyptian blue because the artificial pigment seems to be always applied directly on the marble surface, as the well preserved blue areas of this relief or those of other sarcophagi analysed [5], [28].

The inferior ornamental edge of the *Africa*'s *palla* preserves traces of a solid dark red line, approx. 0,5 cm wide. This colour corresponds to the presence of haematite pigment, which appears directly applied on the marble surfaces. A very small trace of this colour was also recently detected on the inferior ornamental of the bride's *palla* [5], [29].

Fig. 12. Polychrome detail of the ornamental edge of the *Annona*'s palla (left) and the same area in VIL imaging that shows the distribution of glowing white particles of Egyptian blue (right). On the white band the EB is located as scattered particles, while on the *stola* a compact layer is observed.

We observe traces of a whitish colour substance in the engraved lines of the face features and in the outlines of figures and objects. It appears as a fine grain plaster, often visible under the red colour but also individually, especially in depressed areas of hair, beard, face features, clothes of figures and their attributes. It is also present on the prominent areas of hands, arms, neck and face of the personifications. Finally, it is visible in those areas that presumably had to be polychrome. This suggests we are in presence of a thin ground layer rather than a real colour. However, the presence of materials used in the previous modern restorations on the sarcophagus relief should be taken into account [5], [28].

Traces of original gilding are visible on the upper surface of the *parapètasma*, on clothes, on hair, on the flame of the *thymiaterion* and in some attributes of the personifications. Gold is visible over the red and blue of the *parapètasma*; while on the beard and hair it is applied over a dark yellow to reddish ground coat [5]. A purple colour substance is also discernible in association with the gold on the hair of the *Annona* personification. Even in this case study we identified it as a deteriorated gold leaf and, therefore, transformed into colloidal gold [5], [34].

Regarding the identification of the technical used to apply the colour, the situation is very complicate because we have recognised the probably coexistence of two procedures. The dark red made of haematite visible along the inferior ornamental edge of the *Annona*, *Africa* and bride's *palla* (Fig. 12) is applied directly on the marble surface, while a few traces of colour preserved on the skin surface of the *Annona* and *Abundantia* hands is applied over a ground layer of whitish colour. As for the dark red tending towards cyclamen preserved in the engraved areas of the personification attributes (Fig. 13) and of the *thymiaterion* flame (Fig. 10), we have seen previously that it is still not completely clear if this colour has been applied either as a mixture of more pigments, such as haematite, vegetable dye and gypsum, or on top of a white ground layer. That can be attributed either an ancient repainting or restoration, or most likely at the simultaneous use of two different techniques in applying the colour. Moreover, the Annona sarcophagus is characterized by the rendering of the completely polychrome figurative elements, similarly to the investigated sarcophagus with Dionysus and Ariadne (MNR-TD, inv. no. 124682) [5], [28], and the so-called 'Casali sarcophagus' (Ny Carlsberg Glyptotek, inv. no. 843) [35].

Fig. 13. Polychrome traces in the lighthouse areas of the *Portus*' attribute.

X. Conclusion

We have presented a systematic and multidisciplinary approach to detect, study and visualize the polychromy (colour and gilding) on Greek and Roman marble artworks.

The integration (and visualization) of the archaeological data and the scientific analyses results over a high-resolution 3D model represents a novelty in the study of the ancient polychromy and allows significant improvement for the dissemination of the knowledge gathered. Indeed, new results and better understandings of Roman sarcophagi are (and can be) obtained by linking together and comparing digital datasets gathered with several techniques. In the presented case study, the Annona sarcophagus (MNR-PM, inv. no. 40799), we have detected new pigments (Egyptian blue and white lime) and probably a rose madder lake vegetable dye and, consequently, we have identified the techniques used to apply the colour and gilding on the marble surface. We have showed how the 3DHOP framework could be used to define new components supporting visualization and dissemination of all collected (raw and processed) datasets on the Web, once those data are mapped on a high-resolution 3D model (http://vcg.isti.cnr.it//roman-sarcophagi/annona-sarcophagus/index.html).

At the end of this analytical and multidisciplinary process, we have also obtained scientific information to understand the history of the polychromy (colour and gilding) of the Annona sarcophagus and to propose a preliminary version of a 3D scientific polychrome reconstruction that is partially reliable. This virtual reconstruction (Fig. 9) shows the distribution on the surface of the main identified colours, highlighting the potentiality of the proposed digital system and multidisciplinary approach. Our digital and systematic solution seems to be an efficiently solution both for specialists and for not-expert thanks to the virtual presentation of the results on any device equipped with a common Web browser, included museum kiosks.

XI. Acknowledgement

We wish to thank the Soprintendenza Speciale per i Beni Archeologici di Roma and the director of the Museo Nazionale Romano in Palazzo Massimo Rita Paris who facilitated the research and allowed us the permits; Miriam Roghi for the kind cooperation and Debora Papetti for the sampling process. Special thanks are due to Corrado Gratziu and Alessandra Moscato (University of Pisa) for the optical petrographic analysis; Vincenzo Palleschi, Stefano Legnaioli, Giulia Lorenzetti (ICCOM-CNR in Pisa), and Lucia Burgio (V&A Museum of London) for the Raman spectroscopy. This work was partially funded by EU INFRA Project Ariadne (GA n. 313193).

References

[1] V. Brinkmann, U. Wünsche, and U. Wurnig, Eds., *Bunte Götter: die Farbigkeit antiker Skulptur; eine Ausstellung der Staatlichen Antikensammlungen und Glyptothek München. In Zusammenarbeit mit der Ny Carlsberg Glyptotek Kopenhagen und den Vatikanischen Museen, Rome*. Munich: Glyptothek Munchen, 2004.

[2] P. Liverani, Ed., *I colori del bianco. Policromia nella scultura antica*. Città del Vaticano - Roma: De Luca Editori d'Arte, 2004.

[3] J. S. Østergaard, "The Copenhagen Polychrome Network: a research project on ancient Greek and Roman sculptural polychromy in the Ny Carlsberg Glyptotek," in *Circumlitio. The polychromy of antique and medieval sculpture, Proceedings of the Johann David Passavant Colloquium*, V. Brinkmann, O. Primavesi, and M. Hollein, Eds. Munich: Hirmer, 2010, pp. 324–337.

[4] R. Panzanelli, E. D. Schmidt, and K. Lapatin, Eds., *The colour of Life. Polychromy in Sculpture from Antiquity to the Present*. Los Angeles: Exhibition Catalogue, J. Paul Getty Museum, 2008.

[5] E. Siotto, "Nuove tecnologie per lo studio della policromia sui sarcofagi romani: proposte per una standardizzazione metodologica," Ph.D. dissertation, University of Pisa, 2013. [Online]. Available: http://vcg.isti.cnr.it/~siotto/thesis/index.html

[6] V. Brinkmann, "Research in the polychromy of ancient sculpture," in *Gods in color: painted sculpture of classical antiquity*, V. Brinkmann and U. Wünsche, Eds. Munich: Glypt. Munchen, 2007, pp. 21 –28.

[7] J. S. Østergaard, "Der Caligula in der Ny Carlsberg Glyptotek, Kopenhagen. Ein Projekt zur Rekonstruktion der polychromen Fassung eines römischen Porträts," in *Bunte Götter: die Farbigkeit antiker Skulptur*, V. Brinkmann and A. Scholl, Eds. Munich: Glyptothek Munchen, 2010, pp. 218 –225.

[8] C. A. Graham, "Digitalization in an applied context: polychromy research," in *Tracking Colour: The polychromy of Greek and Roman sculpture in the Ny Carlsberg Glyptotek. Preliminary Report 4*, J. S. Østergaard, Ed., Copenhagen, 2012, pp. 64–88. [Online]. Available: http://www.glyptoteket.dk/sites/default/files/trackingcolour-4.pdf

[9] E. Siotto, M. Dellepiane, M. Callieri, R. Scopigno, C. Gratziu, A. Moscato, L. Burgio, S. Legnaioli, G. Lorenzetti, and V. Palleschi, "A multidisciplinary approach for the study and the virtual reconstruction of the ancient polychromy of Roman sarcophagi," *Journal of Cultural Heritage*, no. 16, pp. 307–314, 2015.

[10] C. Robert *et al.*, *Die antiken Sarkophag-Reliefs*. Berlin: Deutsches Archäologisches Institut, 1880-.

[11] G. Koch and H. Sichtermann, *Römische Sarkophage*. Munich: C.H. Beck, 1982.

[12] P. Zanker and B. Ewald, *Living with Myths. The Imagery of Roman Sarcophagi*. Oxford: Oxford University Press, 2012.

[13] B. Andreae and S. Settis, Eds., *Colloquio sul reimpiego dei sarcofagi romani nel Medioevo: Pisa, 5-12 September 1982*, ser. Marburger Winckelmann-Programm, Marburger, 1983.

[14] A. L. Pietrogrande, "Sarcofago policromo con raffigurazione bacchica," in *Bullettino della Commissione archeologica comunale di Roma*, 1932, vol. LX, pp. 177–215.

[15] M. Gütschow, "Das Museum der Prätextat-Katakombee," in *Rendiconti, Atti della Pontificia Accademia Romana di Archeologia*, ser. III, Memorie, 1938, vol. IV, pp. 26–267.

[16] P. Reuterswärd, *Studien zur Polychromie der Plastik. Griechenland und Rom*. Stockholm: Svenska Bokfôrtaget, 1960, pp. 227–250.

[17] P. Liverani, "New Evidence on the Polychromy of Roman Sculpture," in *Circumlitio. The polychromy of antique and medieval sculpture, Proceedings of the J.D. Passavant Colloquium*, V. Brinkmann, O. Primavesi, and M. Hollein, Eds. Munich: Hirmer, 2010, pp. 290–302.

[18] M. L. Sargent, "Metropolitan Roman Garland Sarcophagus," in *Tracking Colour: The polychromy of Greek and Roman sculpture in the Ny Carlsberg Glyptotek. Preliminary Report 3*, J. S. Østergaard, Ed., Copenhagen, 2011, pp. 14–34. [Online]. Available: http://www.glyptoteket.com/sites/default/files/trackingcolour-3.1.pdf

[19] L. Musso and R. Friggeri, "II,1. Sarcofago dell'Annona (inv. n. 40799)," ser. Museo Nazionale Romano. Le sculture esposte Aule delle Terme, A. Giuliano, Ed., Roma, 1985, vol. I.8, pp. 46–51.

[20] A. Aquari, "Di due sarcofagi scoperti recentemente nella vigna Aquari fuori la Porta Latina," in *Bullettino della Commissione archeologica comunale di Roma*, 1877, vol. V, pp. 146–159.

[21] G. Verri, "The spatially resolved characterisation of Egyptian blue, Han blue and Han purple by photo-induced luminescence digital imaging," *Analyt. and Bioanalyt. Chemistry*, vol. 394, no. 4, pp. 1011–1021, 2009.

[22] "Agisoft PhotoScan," http://www.agisoft.com/.

[23] M. Kazhdan and H. Hoppe, "Screened Poisson Surface Reconstruction," *ACM Trans. Graph.*, vol. 32, no. 3, pp. 29:1–29:13, Jul. 2013.

[24] P. Cignoni, M. Callieri, M. Corsini, M. Dellepiane, F. Ganovelli, and G. Ranzuglia, "MeshLab: an Open-Source Mesh Processing Tool," in *Eurographics Italian Chapter Conference*, V. Scarano, R. D. Chiara, and U. Erra, Eds. Eurographics, 2008, pp. 129–136.

[25] M. Callieri, P. Cignoni, M. Corsini, and R. Scopigno, "Masked Photo Blending: Mapping Dense Photographic Data Set on High-resolution Sampled 3D Models," *Comput. Graph.*, vol. 32, pp. 464–473, 2008.

[26] S. Dumazet and P. Callet, "Visual appearance of a middle age sculpture: Polychromy and lighting," in *14th International Conference on Virtual Systems and Multimedia*, Cyprus, 2008, pp. 215–219.

[27] M. Potenziani, M. Corsini, M. Callieri, M. Di Benedetto, F. Ponchio, M. Dellepiane, and R. Scopigno, "An Advanced Solution For Publishing 3D Content On The Web," in *Museums and the Web 2013*, N. Proctor and R. Cherry, Eds. Silver Spring, 2013. [Online]. Available: http://mwf2014.museumsandtheweb.com/paper/an-advanced-solution-for-publishing-3d-contents-on-the-web/

[28] E. Siotto, "Roman sarcophagi use and re-use: colour application techniques and ancient re-painting," in *5th International Round Table on Greek and Roman Sculptural and Architectural Polychromy*, H. Brecoulaki, Ed., Athens, in press.

[29] E. Siotto, "The use of colour on Roman marble sarcophagi," in *ASMOSIA XI – Association for the Study of Marble and Other Stones In Antiquity*, Split, in press.

[30] S. Augusti, *I colori pompeiani. Studi e documentazione*. Roma: De Luca, 1967.

[31] M. B. Abbe, "Recent research on the painting and gilding of Roman marble statuary at Aphrodisias," in *Circumlitio. The polychromy of antique and medieval sculpture, Proceedings of the Johann David Passavant Colloquium*, V. Brinkmann, O. Primavesi, and M. Hollein, Eds. Munich: Hirmer, 2010, pp. 227–289.

[32] P. Baraldi and C. Fagnano, "Regole di miscelazione e di pigmenti e coloranti in età Romana," in *Proceedings of the Prima Conferenza Nazionale del Gruppo del Colore: Contributi Multidisciplinari*, A. Raggi, Ed., Pescara, October 2005, pp. 162–167.

[33] J. S. Østergaard, "The Sciarra Amazon investigation: some archaeological comments," in *Tracking Colour: The polychromy of Greek and Roman sculpture in the Ny Carlsberg Glyptotek. Preliminary Report 2*, J. S. Østergaard, Ed., Copenhagen, 2010, pp. 50–60. [Online]. Available: http://www.glyptoteket.com/sites/default/files/trackingcolour-3.1.pdf

[34] H. Piening, "Gold to purple. Violet traces on Antique Marble," Bayerische Verwaltung der staatlichen Schlösser, Gärten und Seen, Tech. Rep., 2014. [Online]. Available: http://www.stiftung-archaeologie.de/Heinrich%20Piening%20Gold%20to%20purple%202014.pdf

[35] J. S. Østergaard, "Tracking Colour in 2011," in *Tracking Colour: The polychromy of Greek and Roman sculpture in the NCG. Prel. Report 3*, J. S. Østergaard, Ed., Copenhagen, 2011, pp. 8–10. [Online]. Available: http://www.glyptoteket.com/sites/default/files/trackingcolour-3.1.pdf