Original article

A multidisciplinary approach for the study and the virtual reconstruction of the ancient polychromy of Roman sarcophagi

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A B S T R A C T

In this paper, we report a multidisciplinary approach for the analytic study and the reconstruction of the ancient colour used for Roman sarcophagi. For this purpose, we adopted the three-dimensional (3D) digital technology and found it to be a valuable tool for the identification, documentation and reconstruction of the ancient colour. This technology proved to be an excellent link between archaeological knowledge and scientific analyses. Therefore, 3D digital technologies would effectively facilitate the exchange of information and collaboration between experts in various disciplines. This is extremely important in order to obtain demonstrable results in a new area of study, such as polychrome Roman sarcophagi (and the ancient polychromy and gilding on the marble). In this study, the digital 3D model of Ulpia Domnina's sarcophagus (National Roman Museum in Rome, inv. no. 125891) has been used to identify both the pigments and the techniques of application used, and to explore the potential of emerging technologies in the reconstruction and visualization of the ancient colour.

1. Research aims

The aim of this work is to show the results of a practical application of 3D digital technology as a linking bridge between archaeological and scientific data, in order to provide a better knowledge of the original polychromy via the production of virtual reconstructions. This use of computer-based technologies with consolidated scientific analyses could succeed in obtaining a common work platform for a better knowledge of ancient colour (and gilding), and the dissemination of the results.

2. Introduction

Roman sarcophagi have been systematically studied from a typological, stylistic and iconographic point of view since the late nineteenth century. This has given rise to a great *Corpus* and an extensive scientific production [1]. Conversely, the papers related to the polychromy field are less than ten in a century. Therefore, nowadays there is only little knowledge about pigments, dyes, and binders used by Roman artists, and about the pictorial style and the techniques used to apply both colour and gilding [2]. For this reason, the considerations by Pietrogrande [3], Gütschow [4] and Reuterswärd [5] from the first half of the last century are of fundamental importance, although they are unsupported by scientific analysis. However, in the past few years, there has been a renewed interest in ancient polychromy that has generated several research projects and also two analytical publications on Roman sarcophagi [6,7].

This new interest involved the use of computer-based technologies in the study of the ancient polychromy and gilding. However, the polychrome reconstruction is not a consolidated subject of research, since a lot of work has to be done still to improve our

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Fig. 1. Sarcophagus of Ulpia Domnina and some polychrome details, National Roman Museum in Rome (inv. no. 125891).

knowledge of the methods and techniques of colour application on Greek and Roman artwork [2,8]. Some polychrome reconstructions are often based on the commonly known colours for the antiquity (i.e. red and yellow ochre, lead white, cinnabar, carbon black, Egyptian blue, etc.) with artistic interpretations.

The technical focus of this work is to show the potential of digital technologies coupled with high-quality 3D models in the experimentation of several painting techniques and reproduction of the alternative reconstruction hypotheses based on scientific analysis data. Our reconstruction uses all the information collected by visual observation of the sarcophagus and its virtual photorealistic 3D model, the historical and stylistic knowledge derived from these observation and the results of scientific analyses. It is thanks to multidisciplinary research that it was possible to propose an accurate virtual reconstruction from an analytical as well as a historical point of view.

A long testing campaign was also undertaken to define the more proper tools and pipeline for an effective selection and application of materials to the digital 3D model and the implementation of more realistic renderings [9].

As a case study, the sarcophagus dedicated to Ulpia Domnina (National Roman Museum in Rome, inv. no. 125891) was chosen here, mainly because of the fair state of preservation of its original polychromy (Fig. 1) that could have potentially shed light on the colouring techniques used. This sarcophagus is made of Proconnesian marble [10] and was found in 1953 during the construction of a building in Rome [11,12]. From a typological point of view, it is part of the serial production of sarcophagi with Victories holding a shield and funerary Cupids [12,13].

3. Methodology

A laser triangulation scanner [14] was used to acquire geometric data and to create a 3D digital model of the artefact (see Subsection 3.1), whereas the colours of the remaining fragments of the original polychromies were measured by calculating the RGB (Red–Green–Blue) encoding of the selected painted traces (see Subsection 3.2 and Fig. 2). In addition to historical and iconographic researches, and a careful observation with binocular and portable stereoscopes, we also performed micro- and non-destructive investigations, namely Optical Petrographic Microscopy and Raman microscopy [15,16], in order to acquire information on the pigments and the techniques used to apply them on the marble surface (see Subsections 3.3 and 3.4). To this purpose, five small and representative samples, namely sample no. 5, 5A, 6, 6A and *interno* (Fig. 3), were chosen in collaboration with the Museum's restorers, respecting the criteria of minimum invasiveness.

3.1. Acquiring the 3D model

The digitization of the sarcophagus was performed first by producing a geometrical 3D model (acquired with a laser triangulation scanner) and then by acquiring the colour attribute [17] by means of high-resolution photographs (using a DSLR camera). The scanning system was chosen in laboratory considering the material and relief attributes; while the 3D scanning plan was decided on site, directly evaluating the spatial features of the sarcophagus [2]. Each scan provided data on a maximum area of nearly 50 × 30 cm; therefore, in order to obtain the complete relief of the sarcophagus, it was necessary to perform multiple scans from different angles. A total of 313 scans were acquired. The scanning resolution was kept at less than half a millimetre, thus allowing the generation of a highly-detailed digital model. A series of photographs was taken in order to enrich 3D models with high-resolution colour information, in parallel with 3D scanning [2]. All data were acquired in approximately eight hours by two expert operators.

The data collected were processed using MeshLab, an open source mesh processing system developed by Visual Computing Lab, ISTI-CNR [18,19]. The standard 3D scanning pipeline [14,17,20] was followed to produce a final 3D model of 19 million triangles; other lower-resolution meshes were created from this model, to support different phases of the virtual polychrome reconstruction process.

In addition to the characterization of the current colour traces [9,14], the 3D scanning can provide a very accurate digital model of the sarcophagus. The analysis of 3D geometry does not usually bring additional hints for the analysis of the ancient polychrome traces. Nevertheless, we shall see how the 3D model can be perfectly suited

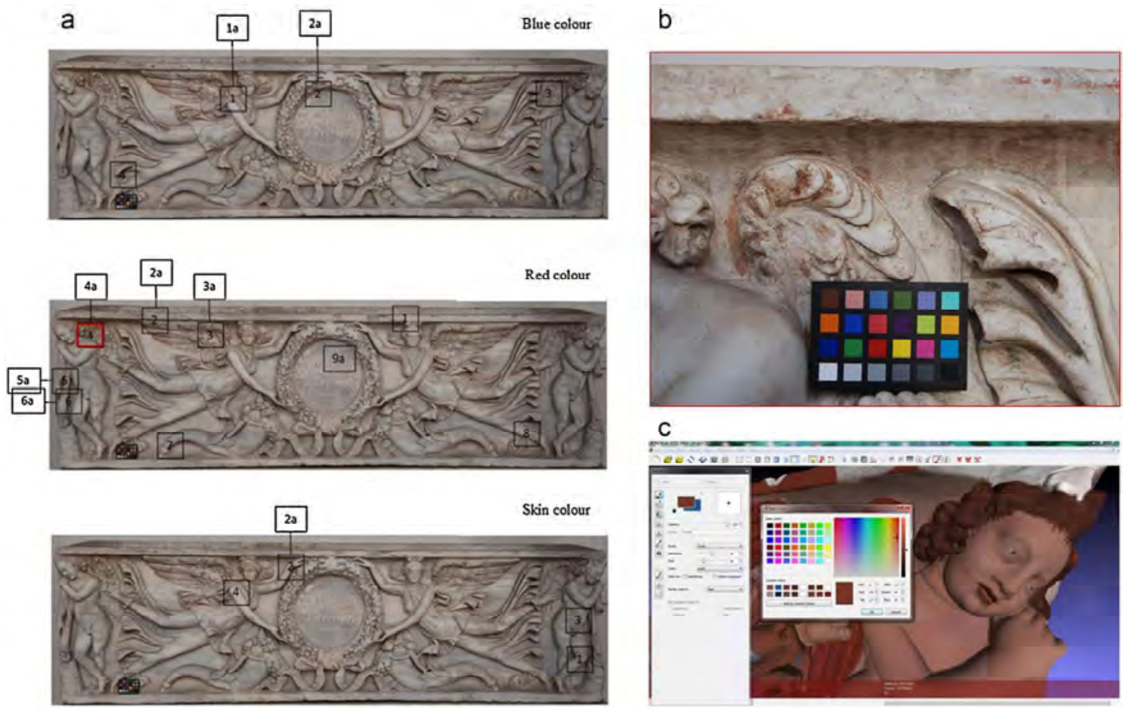

Fig. 2. Selected traces of colour have been converted in RGB coordinates (a) by using calibrated high-resolution images that are acquired by DSLR camera with a Mini Macbeth Colorchecker™ inserted in the images area, in the proximity of the sampled surface; b: the creation of a corresponding colour palette in MeshLab.

Fig. 3. Micro-sampling points of colours traces over Ulpia Domnina's sarcophagus (inv. no. 125891).

to support the colour investigation in all phases of the knowledge process (see Subsection 4.3).

3.2. Detecting RGB coordinates of colour traces

Aiming at creating digital reconstructions of the hypothetical polychrome decoration, we needed the reference values for the original colours corresponding to the polychrome traces that have been detected on the sarcophagus surface. Thus, high-resolution and calibrated images of the representative areas were acquired on Ulpia Domnina's sarcophagus by using a DSLR camera and a colour calibration table (a Mini Macbeth Colorchecker™). From the images, colour-corrected using the known colours on the chart, the RGB coordinates of the selected coloured traces were derived (Fig. 2) [21,22].

3.3. Optical petrographic microscopy

Optical microscopy allows a preliminary analysis of the samples, which were investigated with an Olympus SZ X10 stereomicroscope interfaced to a PC using digital camera Olympus Colour View I. The polished sections, prepared with epoxy resin, were then observed using an OLYMPUS BX51 microscope with visible and ultraviolet light and interfaced to a PC using an Olympus DP71 digital camera.

For all the five samples (Fig. 3), we wanted to investigate and verify the type of pigment and the application technique adopted. Therefore, we performed their petrographic analysis as thin sections with a polarizing microscope. In particular, the thin sections were observed using a Leitz Ortoplan-pol microscope equipped with a PloemOpak filter cubes (ACBP 340-380 nm).

3.4. Raman spectroscopy

Subsequently, all the samples 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× magnifying lens. The laser sources, a HeNe laser ($\lambda = 633$ nm) and an Nd:YAG laser ($\lambda = 532$ 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× and a 50× objective.

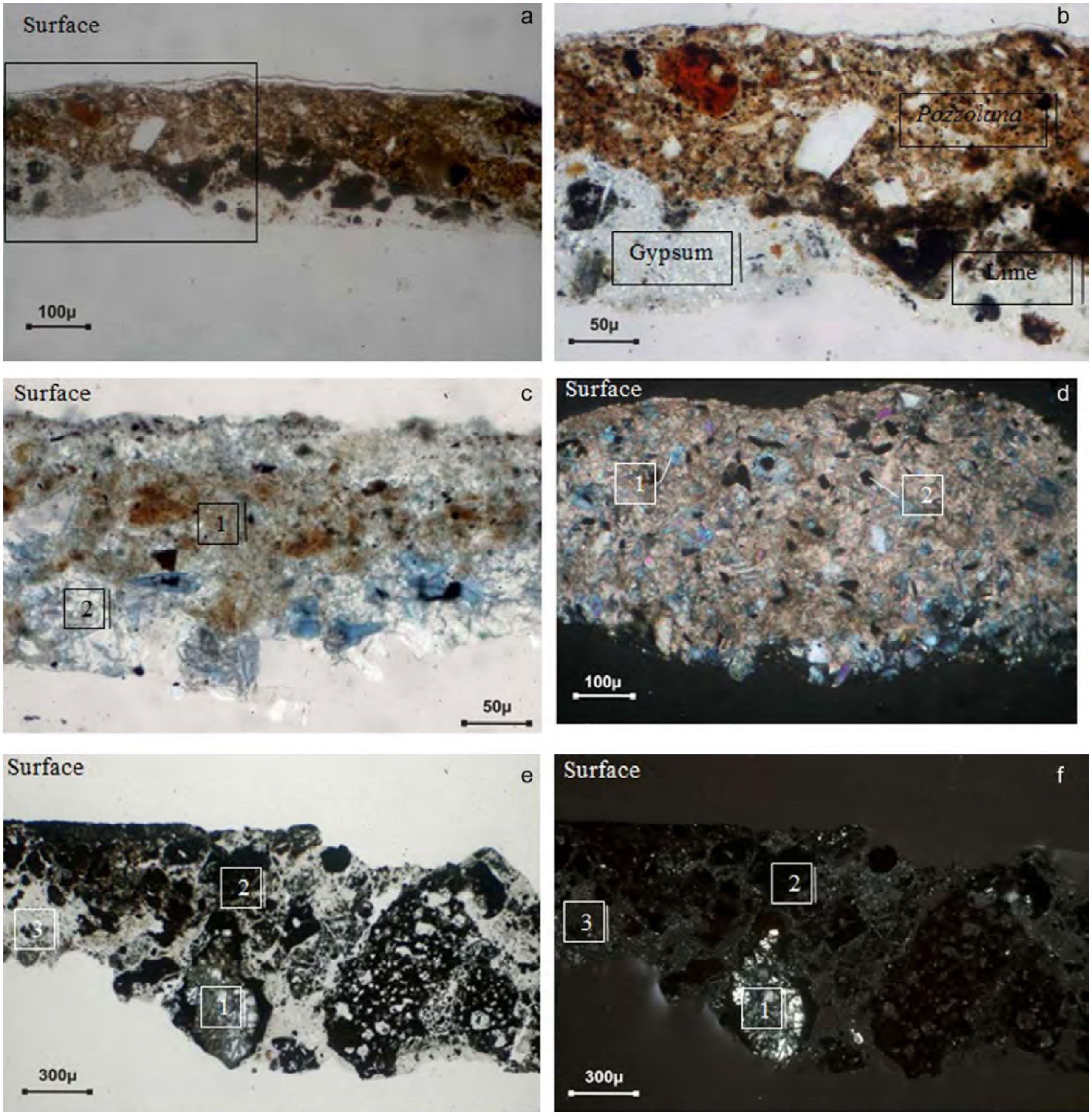

Fig. 4. Images (a and b) present thin sections of sample no. 5 parallel nicols at 100 μ and 50 μ length scale; the stratigraphy shows that the red ochre is applied over a ground layer of gypsum, red *pozzolana* and lime. Image (c) presents a thin section of sample no. 6 parallel nicols at 50 μ length scale; the stratigraphy shows that the red ochre (1) is applied over a layer of mixed Egyptian blue and bone black pigments (2). Image (d) shows that the Egyptian blue (1) and bone black (2) granules are visible better in the section of sample no. 6A crossed nicols at 50 μ length scale. Finally, the images (e and f) present thin sections of sample named *interno* (e) parallel and (f) crossed nicols at 300 μ length scale that show the presence of mortar composed of gypsum (1), red *pozzolana* (2) and lime (3).

3.5. Archaeological and historical researches

At the same time, we performed archival and literature searches to solve doubts about the authenticity of some pictorial elements by evaluating the description of the sarcophagus in the historical archive and in the catalogue of the National Roman Museum [12].

4. Results and discussion

The results of the scientific analyses have been indeed valuable in determining the pigments and stratification of some colours; however, they were not enough to understand that this sarcophagus is characterized by two different technical applications of colour without a visual observations and archaeological knowledge. All data (scientific analyses, archaeological information and visual observation supported by optical and computer graphic 3D tools) suggested that the sarcophagus was coloured in two different moments of its history. The first scheme was applied in the Late Antonine period (160–180 AD) when the sarcophagus was made. A closer look of some details of the cornucopias and wreath of oak revealed that the sarcophagus was painted when it was not completely finished (Fig. 1) [2,20]. The secondary scheme most likely came from a repainting in the middle 3rd century, when the original inscription was re-carved and dedicated to Ulpia Domnina, lowering the original level of the relief background [2,20].

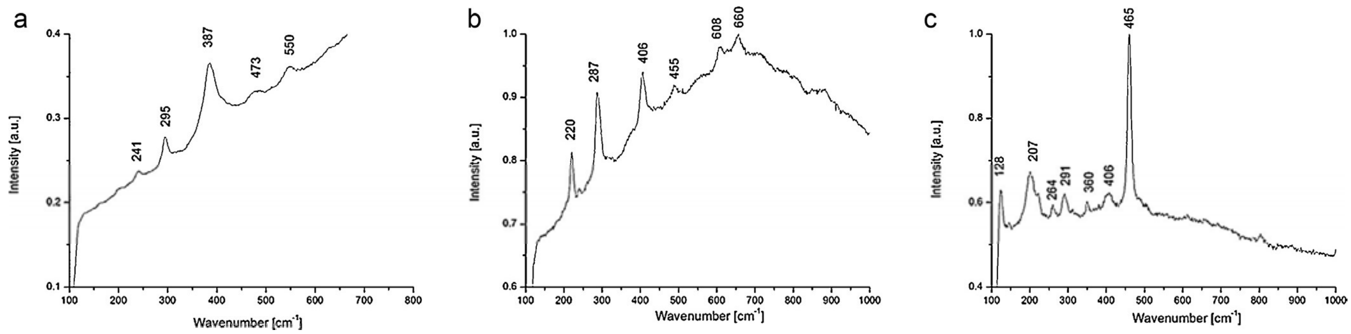

Fig. 5. Raman spectroscopy of sample 5: (a) Goethite, (b) Haematite and (c) Quartz.

This sarcophagus is therefore very important because it is a first analytically documented case study of reuse and repaint during the antiquity [2]. Until today, the studies of Roman sarcophagi never considered the possibility of the ancient re-colouring presence [3–5].

4.1. Scientific analyses and visual observation results

The visual observation of sample 5 shows a red colour applied over a layer of white colour with red and black inclusions; sample 5A shows a white layer with red and black inclusions. The petrographic analysis of the thin sections of samples no. 5 and 5A shows that red ochre was applied over a fine ground layer of gypsum, red *pozzolana* (a Roman porous variety of volcanic tuff) and lime (Fig. 4a and b). Samples no. 6 and 6A are blue in colour and the analysis of their thin section shows that the blue colour is Egyptian blue mixed with bone black, applied directly onto a smooth marble surface (Fig. 4c). Traces of iron oxides in the upper part of the thin section sample no. 6 suggest that red ochre was applied over Egyptian blue (Fig. 4d). The last sample (named *interno*) is a fragment removed from the internal surface of the sarcophagus. The thin section shows that the interior of the sarcophagus was covered with a coarse mortar of gypsum, red *pozzolana* and lime (Fig. 4e and f).

Subsequently, the five samples were investigated by Raman spectroscopy. The spectra were interpreted using reference spectra taken from the literature [23,24]. Generally, the spectra have confirmed the presence of some of the pigments already observed in the thin sections. Fig. 5 shows spectra of sample no. 5, in which the typical peaks of goethite, haematite and quartz are clearly identified; the Raman spectrum of the sample no. 6 shows the typical peaks of Egyptian blue, thus confirming the findings of the optical analysis (Fig. 6a). Concerning the *interno* sample, Raman spectroscopy has revealed the presence of gypsum and haematite (Fig. 6b). This may suggest the possibility that the interior of the sarcophagus could have been coloured using red ochre. Anyway, *pozzolana* does contain iron oxides, so this attribution could be questionable. Therefore, at the moment of research, we are not certain that the inside of the sarcophagus was painted red but it was certainly plastered with a coarse mortar of gypsum, red *pozzolana* and lime. However, this discovery is a very important achievement, since it represents a novelty in the studies of marble sarcophagi [2].

4.2. Archaeological, historical and iconographic results

The archival data found did not provide the amount of information we hoped for, but was still useful. The text of the catalogue gave a detailed iconographic description, the year and place of discovery and the indication to reference publications. Some information reported by Felletti Maj at the time of its discovery (1953) is very important to understand and solve some doubts raised during the current investigation. In particular, she wrote: "The sarcophagus was not found *in situ*, but within a section of a modern wall that was demolished in that context. It appeared as a rectangular block covered in lime that fortunately was soon recognized as a sarcophagus and transported to the National Roman Museum. Here it was cleaned and it appeared as a box without a lid, with marble reliefs and exceptionally well-preserved colour" [11]. This report informs us that the sarcophagus was subjected to one or more modern restorations. This strengthens the results of our visual observations and allows us to confirm the attribution of the black lines, identified on the relief and made of a substance seeping through the marble (Fig. 7), to modern restorations, a characteristic that was already identified by Reuterswärd in 1960 [5]. This also solves the problem of traces of mortar present above the layer of red colour, as seen in the letters of the inscription or in the feathers of wings (Fig. 7) [2].

The study of the polychromy was also based on the iconographic comparison with similar subjects, such as other Roman sarcophagi that still preserve good traces of colour, or paintings and mosaics (see Subsection 4.3). These associations have provided useful support for the detection of colours that are no longer visible to the

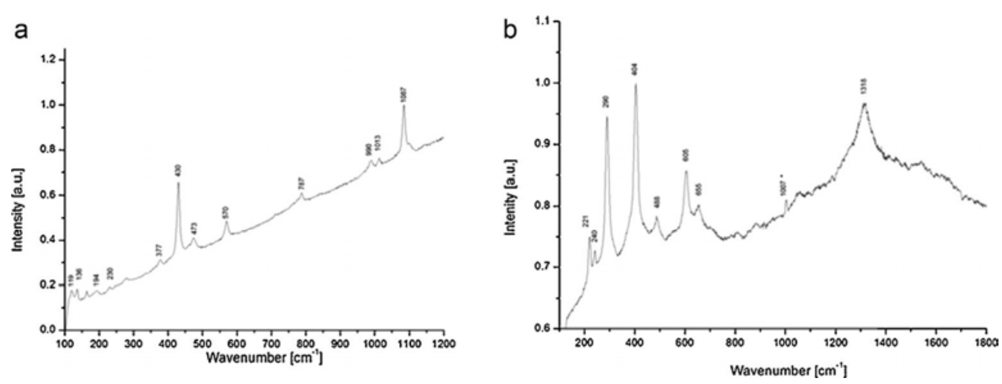

Fig. 6. (a) Raman spectrum of Egyptian blue in sample no. 6; and (b) spectrum of Haematite and Gypsum (peak 1007 cm^{-1}) in sample named *interno*.

Fig. 7. Detail of the black lines attributed to modern restoration and of a modern mortar visible over the colour.

naked eye (or unassisted by an instrument such as a portable microscope) and their subsequent study. These comparisons have also confirmed a tendency to naturalism of the Roman pictorial execution, which was followed especially in the virtual reconstruction of the hair and the wings of the Victoria and Cupid (Fig. 8). The virtual colour reconstruction that we have proposed reports only the preserved colours and it is based on the evidence of scientific analyses; thus we avoided to produce a more spectacular reconstruction that could be based on an artistic interpretation [2].

4.3. Reconstruction of hypothetical ancient colour

The determination of the original painting of Late Antonine period was complicated by the distribution of the secondary one of the mid-3rd century, which was applied in a rather crude manner over a ground layer with gypsum, red *pozzolana* and lime [2,20].

It is only thanks to the multidisciplinary approach that we were able to overcome these incongruences and the limitations of each individual investigation method, avoiding the pitfalls of reconstructions only driven by analyses or only by historical considerations. These two research direction were combined, using the 3D digital technology as a glue and as a support for direct experimentation and visual rehearsal.

The polychrome reconstruction was carried out using the painting tool of MeshLab, exploiting the previously identified RGB colours (see Subsection 3.2 and Fig. 2) [2,9]. The capability of painting with MeshLab over the high-resolution 3D model provides an immediate feedback over the colour reconstruction on the 3D surface; this was really helpful to help us in better understanding the problem of ancient repaints [2,9], since it provided an intuitive and immediate visual feedback.

We decided to paint only the left half of the sarcophagus (where the colours are less preserved than the right part) to better compare the current visible colour and the hypothesis of virtual reconstructed colour (Fig. 8) [2,9].

The final result – a virtual hypothetical reconstruction of the secondary painting – comes from the integration of the results of scientific analyses and visual observations of the traces of polychromy on the sarcophagus (Fig. 8).

Another testing activity was also carried out by starting from the results of this virtual reconstruction. We have first to assign the correct material to each different layers of colour (i.e. ground layer, Egyptian blue mixed with bone black, red ochre, etc.) defined on the digital 3D model; then in order to produce realistic images we should implement sophisticated rendering that consider the light effect on apparent colour. In particular, starting from the accurate study of the polychrome sarcophagus shown above, we tested different open source tools to evaluate their capabilities and limits in the reconstruction and visualization of the ancient colour. Therefore, we cross-compared the features of MeshLab and Blender focusing on how to support the polychrome reconstruction stage and how to achieve a more sophisticated visual presentation of the current and reconstructed ancient colour. The result was a method based on a combined usage of MeshLab and Blender tools [9].

In Table 1, the evaluation of colour coordinates in RGB space (using calibrated high-resolution images that are acquired by DSLR camera and a Mini Macbeth Colorchecker^{TM}) shows that most colours (listed in the Object column) were characterized by two slightly different chromatic hues (RGB (1) and RGB (2) columns). Conversely, the layers of preparation, the contour line of the figures and the background of the sarcophagus had only a single chromatic value (RGB (1) column). The RGB coordinates, which characterize

Fig. 8. Virtual reconstruction of the secondary painting (mid-3rd century AD) and polychrome reconstruction details of Ulpia Domnina's sarcophagus.

Table 1
Results of RGB coordinates of the measured colours.

Object	Measurement points	RGB (1)	RGB (2)
Blue colour	6	30, 85, 149	5, 40, 72
Ground layer	14	160, 137, 131	
Red colour			
Ledges	3	94, 34, 23	122, 44, 32
Wings	4	*Ibidem*	*Ibidem*
Cornucopia	1	*Ibidem*	*Ibidem*
Inscription	1	*Ibidem*	*Ibidem*
Stone	1	*Ibidem*	*Ibidem*
Chiton	1	102, 58, 49	112, 54, 42
Skin colour	5	139, 87, 74	142, 102, 90
Hair	3	60, 29, 26	85, 53, 40
Lips	1	79, 34, 28	83, 38, 32
Stick of the torch	4	163, 76, 49	173, 76, 49
Flame	1	122, 74, 70	168, 99, 94
Outline of the figures	2	87, 36, 32	
Background	2	94, 46, 32	
Grey colour (eyes)	1	52, 53, 53	

a colour, are the same across multiple measurements of the same colour in different Measurement points.

In particular, the results of this investigation showed that the red hue used for the ledges had the same colour values of the one used for the wings, cornucopias, rocks and sculpted letters of the inscription. The blue colour values were the same in all sampled areas of the sarcophagus. The skin colour of Victories and Cupids was the same, although the one used in Cupids seemed slightly darker than Victories. They both had brown hair and red dark, almost brownish, lips. The eyes of the figures had dark grey pupils and irises (black-blue), and the inner contour was delineated with a red line over a black line (black-red). White substance traces were visible in the inner corner of the eyes. The only red hues, which were different from the others (black-orange instead of black-red) were present on the torch stick. This colour is visible where no remains of the secondary repainting was found. The observation is similar for the yellow traces visible in other areas of the sarcophagus, for example, the acorns and hidden areas of the ribbon of the wreath. These colours could be a remnant of the original painting of the second half of the 2nd century AD.

The wings of Victories and Cupids still preserve a large presence of colour, applied in two different periods and using two different methods. In addition to data derived from observation and scientific analyses, it was helpful to make iconographic comparisons with other polychrome sarcophagi found during this research [2] or already known in the literature [4,25]. It was thus possible to understand that the use of red for the flight feathers, Egyptian blue for the short feathers and, in some cases, yellow, represent a recurrent colour scheme (see the reconstruction of wing in Fig. 8).

One of the most difficult decisions was to determine the colour of the background. Probably, at the beginning it was not painted and the outlines of the figures on the background were designed according to a linear pictorial style that we know from other examples [3,6,7]. On the other hand, in the second phase of the middle 3rd century, the finding of traces of fine ground layer of gypsum, red *pozzolana* and lime and the presumed red ochre suggested that also the background was painted. It is quite improbable that the background had been painted with Egyptian blue as Felletti Maj wrote in *Notizie degli Scavi di Antichità* in the first report of the discovery [11] and Silvia Allegra Dayan confirmed in the catalogue of the Museum [12]. In particular, Felletti Maj described traces of blue in the lower area near the Cupid to the right of the sarcophagus; here, the colour was actually grey-blue but due to the typical bands of Proconnesian marble. Hence, the Felletti Maj observation could be due to an erroneous interpretation or, alternatively, to the fact that the described traces of colour are no longer visible. Therefore, we decided to investigate this further by photo-induced luminescence digital imaging [26].

Traces of the ground layer of gypsum, red *pozzolana* and lime were more numerous on the sides of the sarcophagus [2]. These traces suggest that the ground layer was spread over the entire surface of the short sides with the griffins, during the repainting of the mid-3rd century. Red ochre was certainly used to paint the ledges as in front of the sarcophagus, while it is unclear if the griffins were painted entirely or only in the details and the outline, according to a scheme that we find in many sarcophagi of the third century [2]. We present the results of a reconstruction experiment in Fig. 9a, which follows a recurring decorative scheme of the sarcophagi of third century (such as the sarcophagus of *Flavius Valerius Theoponpus Romanus* (inv. no. 514) [27] at the National Roman Museum–Bath of Diocletian, Fig. 9b); but we cannot assume this result as a solid hypothesis because the simple visual analysis of red traces is not sufficient to understand if the griffin was entirely coloured or only decorated by marking its outline and details. Therefore, our reconstruction of the colour of the left side of Ulpia Dominina's sarcophagus is limited to the regions where

Fig. 9. (c) Polychrome reconstruction of the left short side of Ulpia Domnina's sarcophagus and (a) a test based on a recurring decorative scheme of the sarcophagi of third century, such as (b) the sarcophagus of *Flavius Valerius Theoponpus Romanus* (MNR, inv. no. 514).

we have solid and reliable data. Only the fine ground layer (of gypsum, red *pozzolana* and lime) and the red ochre on the ledges were reconstructed (Fig. 9c).

5. Conclusions

This study provided better knowledge of ancient colour and confirmed the complexity of this topic, which requires a combined approach, involving integration of data obtained by various analytical techniques.

The integration of archaeological and scientific data coupled with three-dimensional technology (used to provide a spatial experimentation environment) showed a new approach that allows a better understanding of which pigments were used and how they were applied.

Starting from the data analysis, we did several experiments for the reconstruction of the colour on the digital 3D model, trying to determine what colour traces belonged to the original first painting or to the secondary one. A feasible version of the secondary painting (middle 3rd century) carried out in this study and the polychrome reconstruction shows only the colours that were visible and documented objectively, without adding subjective art-historical interpretations to obtain an amazing reconstruction.

The results presented in this research paper are part of a larger project that aim to use digital technologies to study the ancient colour of Roman sarcophagi. The study of Ulpia Domnina's sarcophagus helped us to acquire more experience in this complex research field to detect some limitations of current digital 3D technologies and to assess and propose a common methodology of study that takes into account all the different information acquired.

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