Jacek Kościuk*, Małgorzata Telesińska**, Maciej Nisztuk***, Marta Pakowska****

Documentation of the most important petroglyphs by structured light scanning and analysis of the most damaged petroglyphs by vPTM and vRTI methods

Dokumentacja najważniejszych petroglifów za pomocą skanowania światłem strukturalnym oraz analiza najbardziej zniszczonych petroglifów metodami vPTM i vRTI

Introduction

Digital image processing techniques have been developing since the beginning of this century, resulting in more and more uses for them. For documenting and analysing rock art heritage, two groups of techniques deserve special attention. Both of them help to identify items that are not visible to the naked eye.

The first group are applications based on the transformation of a single digital image. Among them, ImageJ [1] deserves special attention. This is an open-source Java application commonly used by many rock art researchers. It allows simple geometric transformations to be made (for example, cropping, scaling, resizing and rotating, flipping vertically or horizontally) as well as much more advanced image enhancement (for example, smoothing, sharpening, edge detection, median filtering, thresholding on grayscale and RGB images, and adjusting the brightness and contrast of 8, 16 and 32-bit images) and colour processing (for example, splitting 32-bit colour images into RGB or HSV components, merging 8-bit components into a colour image, converting RGB images to 8-bit indexed colour, and applying pseudo-colour palettes to grayscale images) [2].

From the more than 500 more advanced plugins available for ImageJ, DStretch [3] stands out. It is particularly useful for documenting and analysing rock art. To reinforce hue differences of neighbouring pixels, Dstretch algorithms use decorrelation stretch in the image colour space and manipulate the hue and saturation of the image [4]. ImageJ and the DStretch plugin are used extensively in the documentation and analysis of rock paintings (particularly pictographs) and shallow rock engravings.

The second group of applications process series of images of the same object taken in different lighting conditions. The first algorithm of this type dedicated to documenting and analysing cultural heritage was surface reflectance transformation, developed in 2000 at Hewlett-Packard Laboratories [5]. One year later, the same team from Hewlett-Packard Laboratories developed another method for picture enhancement – polynomial texture mapping (PTM) [6]. Since then, surface reflectance transformation was further developed by Cultural Heritage Imaging and today is commonly known as reflectance transformation imaging (RTI) [7]. In the traditional approach, as an input,

* ORCID: 0000-0003-0623-8071. Faculty of Architecture, Wrocław University of Science and Technology, e-mail: jacek.kosciuk@pwr.edu.pl

** ORCID: 0000-0002-1100-642X. Faculty of Architecture, Wrocław University of Science and Technology.

*** ORCID: 0000-0001-6520-5128. Faculty of Architecture, Wrocław University of Science and Technology.

**** ORCID: 0000-0003-0857-2700. Faculty of Architecture, Wrocław University of Science and Technology.
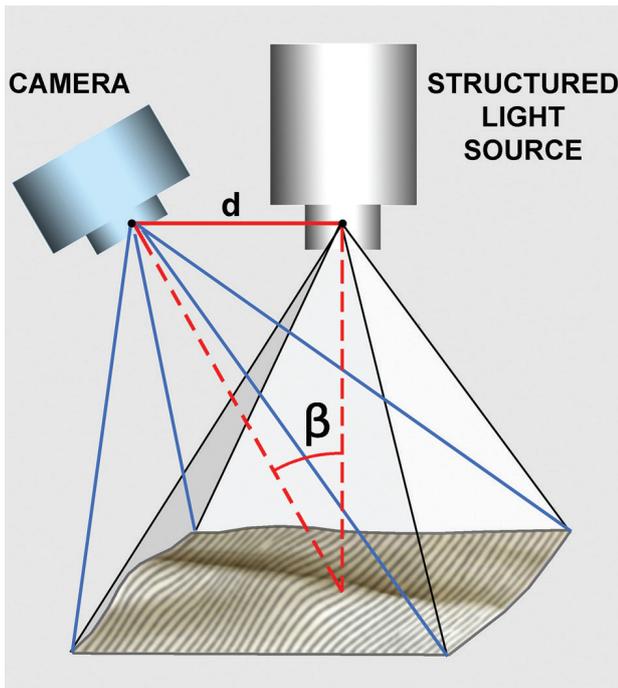
Fig. 1. Schematic idea of structured light scanning
(d – the distance between the camera and the structured light source;
β – the angle between the axis of the camera and the axis
of the structured light source) (elaborated by M. Pakowska)

Fig. 2. Screenshot from the Artec Studio user interface
(elaborated by M. Pakowska)

RTI needs photos taken on the field with the help of a tripod, strong portable light source, two black balls that later on help to calculate angles of illumination, measuring tape, and string. Usually, 40–90 images are collected, each with different vertical and horizontal angles of illumination. This method is mainly used when the distinguishing feature of an artefact is not the colour itself but rather its spatial shape, or both. In this last case, an interesting implementation of the method described here is the use of RTI on images enhanced with DStretch algorithms [8].

Purpose of research

The presented research is part of the larger project "Architectural examination and complex documentation of Samaipata (Fuerte de Samaipata/Bolivia) site from the World Heritage List". One of the main aims of this project was to document and analyse vanishing examples of pre-Inca and Inca petroglyphs[1].

Due to the rapid erosion of the rock at Samaipata, some petroglyphs, still well recognisable two hundred years ago [9], are now entirely unidentifiable, and in some cases, it is difficult to find any traces of them. Thus, documentation of the current condition of the rock itself and the most important petroglyphs was an urgent priority. The second goal of the research was to recognise and interpret what is depicted on each petroglyph (as far as their current
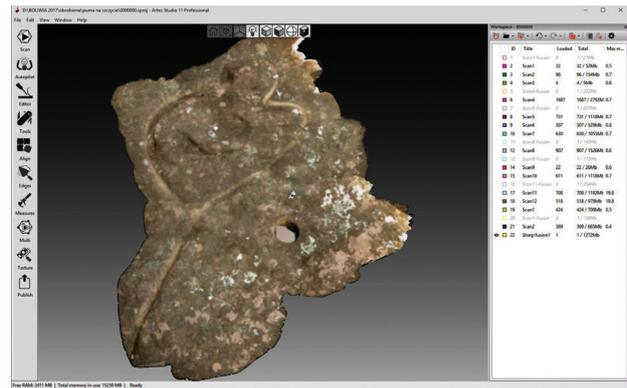
stage of preservation permitted). We were also aware that for some of the most damaged petroglyphs, this could be the last opportunity to document their quickly disappearing traces. Therefore, the proper selection of equipment, software, and analytical methods was fundamental to the success of the entire project.

Methods, equipment, software, and general workflow

Of the most advanced documentation methods available to us, structured light scanning and short-range digital photogrammetry were chosen as the most appropriate for detailed documentation of the petroglyphs.

Structured light scanning

One of the methods selected to collect data on the shape of the petroglyphs is structured light 3D scanning (Fig. 1).

Due to the portability of the equipment, as well as its technical parameters, an Artec Eva scanner was used for work. With an Artec Eva, the whole process of scanning is controlled by a computer, or more precisely, the Artec Studio software. It not only supports the scanner, but also aids the post-production of data. During the work, the Artec Eva scanner emits white strips of light that are deformed on the surface of the object according to its shape. The camera records them on the matrix. Knowing the mutual position of the light emitter and the camera and mapping the strips on the matrix makes it possible to calculate the distance of the examined point from the scanner. This results in getting the *x*, *y*, and *z* coordinates of each of the points. This is therefore a triangulation method using white light.

According to the manufacturer's technical specifications, the Artec Eva scanner offers 0.5 mm resolution of scanning with 0.1 mm accuracy [10]. The recommended optimal depth range for this scanner of between 40 and 100 cm was observed while registering to the common coordinate system. The registration algorithm based on comparing both, the geometry of the surface and the texture.

It must be noted that this scanner, like virtually all structured light scanners, is not particularly suitable for

---

[1] Cf. J. Kościuk, M. Ziółkowski, B. Ćmielewski, D. Ulloa Vidaurre, *Samaipata project – aim of the research, methodology, and methods of documentation*, in the same issue of "Architectus".

Fig. 3. Impact of multi-coloured texture on surface detail visibility: A – textured 3D model; B – same fragment after turning texture off (elaborated by J. Kościuk)
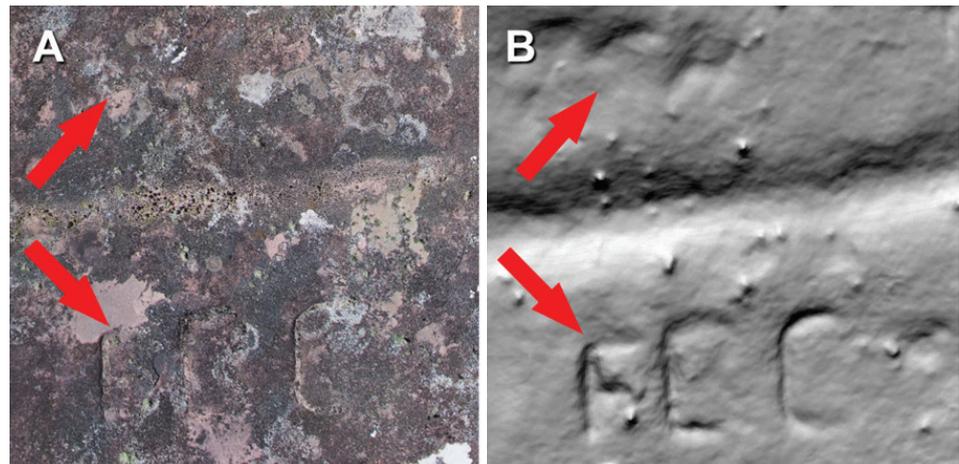
outdoor use. Direct sunlight falling on the scanned object competes too much with the light strips emitted by the scanner. Scanning in such conditions is practically impossible. This problem was overcome with the help of a big tarpaulin sheet that shaded each petroglyph from the sun. It also protected the scanner against gusts of wind particularly troublesome at noon. We noticed that gusts of wind in the afternoon significantly hindered scanning. Although this finding has been challenged by the manufacturer's representatives, it seems to us that differing density streams of hot and cold air disturb the strips of light projected by the scanner.

The scan data collected in the field were further processed with dedicated software – Artec Studio Professional (version 11, build 11.2.2.16) (Fig. 2). The final results were 3D mesh models with an average density of 7 triangles/cm^2. Documentation of four petroglyphs was created this way. The size of the models when stored as *.obj files ranged from 1500 to 3500 MB. The maximum resolution of the accompanying texture files was 16 384 × 16 384 pixels.

Close-range photogrammetry

Close-range digital photogrammetry was used for the largest petroglyphs. Digital photos were collected with a Sony Alpha STL-A65 camera with an APS-C sensor matrix of 24 megapixels. The Sony 18-55mm f/3.5-5.6 standard lens typically sold with a Sony Alpha camera was attached. The camera was set to 400 ASA in aperture priority mode, while the aperture itself was permanently fixed to $f = 11$. The focal length of the lens was set to 18 mm and locked. We determined that these settings were optimal when using this camera for digital photogrammetry. The problem of scaling individual photogrammetric projects was solved by placing a few measuring sticks (each 2 m long) around petroglyphs. Depending on the size of the petroglyph, 100 to 500 photos were taken, which were then processed by the AgiSoft PhotoScan Professional software (version 1.4.4, build 6848) [11]. As in the case of structured light scanning, the final results were 3D mesh models stored together with the corresponding texture as *.obj files.

Preliminary observations on 3D models

The red-brown colour of the Samaipata rock makes it difficult to observe the delicate shadows cast by shallow, strongly eroded petroglyphs. This applies to observations in the field as well as on textured virtual 3D models. The numerous lichens, mosses, and algae covering the rock cause additional difficulty. They create multi-coloured mosaics against which faint traces of petroglyphs and even inscriptions carved by modern tourists are practically invisible. Observation of virtual 3D models in grayscale with the texture preview turned off dramatically improved the readability of all these traces (Fig. 3).

It is worth noting that similar results were obtained from the observation of a much less detailed virtual 3D model of the whole rock delivered from 3D terrestrial scanning[2]. Additionally, in this case, turning off the texture preview showed many traces that were not visible either in the field or on the textured 3D model (Fig. 4).

The use of hill shading algorithms known from many practical applications in remote sensing [12]–[14] turned out to be particularly helpful in both cases. Further, previously invisible details were revealed when the lighting angle changed. This gave us the idea of using PTM and RTI techniques for detailed analysis of the most eroded petroglyphs. In our case, however, these techniques were used on virtual models and not on real objects. Therefore, unlike traditional applications, we will refer to them as virtual PTM (vPTM) and virtual RTI (vRTI).

Using vPTM and vRTI

While traditional PTM and RTI techniques are relatively easy to use in laboratory conditions where special rigging provides lighting at predefined angles, their use outdoors for large objects poses many problems (Fig. 5).

One of the basic issues is taking a sufficient number of photos with the camera in a fixed position and with

---

[2] Cf. J. Kościuk, B. Ćmielewski, M. Telesińska, A. Kubicka, *3D terrestrial laser scanning of El Fuerte de Samaipata*, in the same issue of "Architectus".
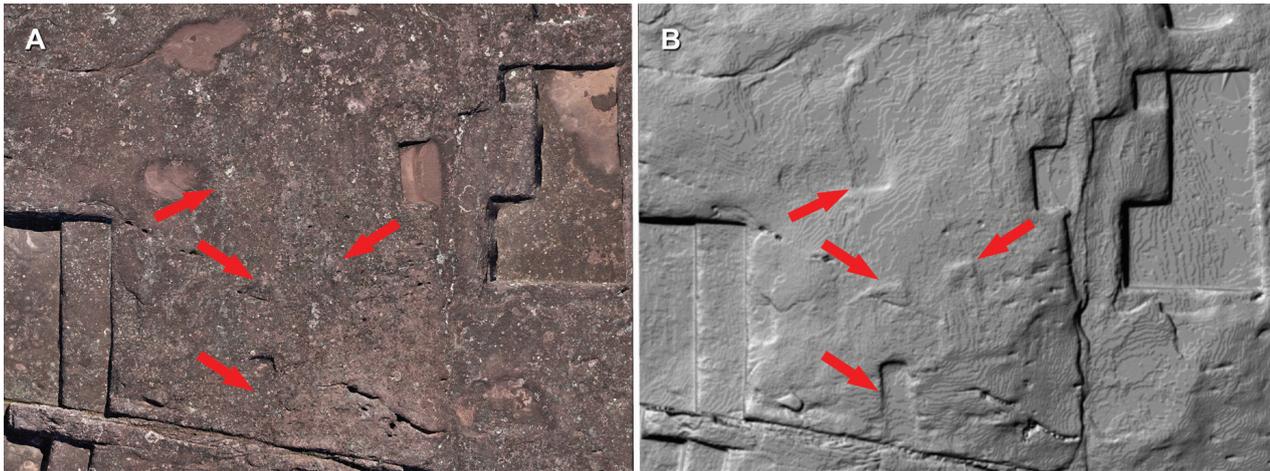
Fig. 4. Impact of multi-coloured texture on surface detail visibility: A – textured 3D model; B – same fragment after turning texture off
(elaborated by J. Kościuk)

different angles of lighting. The horizontal and vertical angles at which the object is photographed, as well as the angles of illuminating light, must be determined quite precisely. Hence, when using the traditional PTM or RTI method in the field, sophisticated procedures (Fig. 5) are used, with inclinometers, strings, and black, shiny spheres allowing the angle of incidence of light to be determined at the post-processing phase. In addition, canvas sheets are used to eliminate direct sunlight competing with artificial directional lighting. The work is tedious, time-consuming, and requires a lot of equipment to be brought to the site. However, since we have virtual 3D models, why not use them for this purpose instead of taking pictures in the field? Computer visualisations of virtual 3D models in pre-set lighting conditions and viewing angles evenly covering the entire hemisphere around the object may be equivalent to the lighting arrays used in laboratory conditions (Figs. 6, 7).

Virtual rig and computer visualisation of 3D models

The laboratory rules of creating photographs for PTM were applied to a computer program, and the photos were substituted with renderings prepared in Cinema 4D [15] software (version R15.008). The scanned and compiled model was moved to a virtual rig studio with 54 predefined positions of light equally spread over the virtual hemisphere at 15, 30, 45, 60, and 75 vertical degrees. On top of the dome, a virtual camera was placed (Fig. 7).

For particularly big and detailed 3D models, the mesh grid was decimated to 1 million triangles and 600 thousand points. The mesh file size was optimised for the rendering time of one frame as well as for sufficient resolution of the resulting file. The physical dimensions of the model had no relevance in the virtual environment.

The software provides the possibility to align the lights to the normal plane of the object. The selected
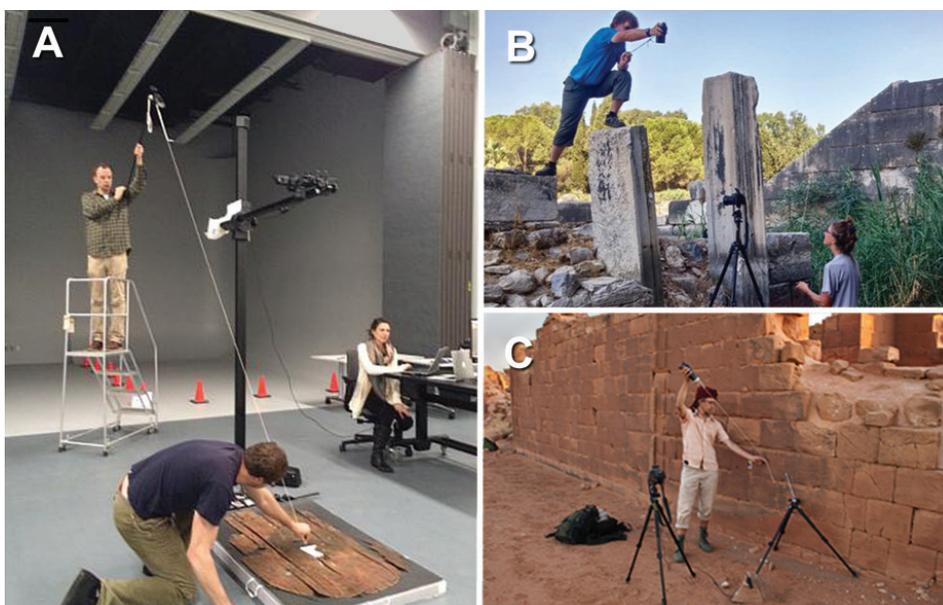

Fig. 5. Examples of using the RTI technique to document larger artefacts (sources: A – https://ipch.yale.edu/news/rti-training-ipch-digitization-lab; B, C – https://raan.hypotheses.org/1326) [accessed: 17.10.2018]
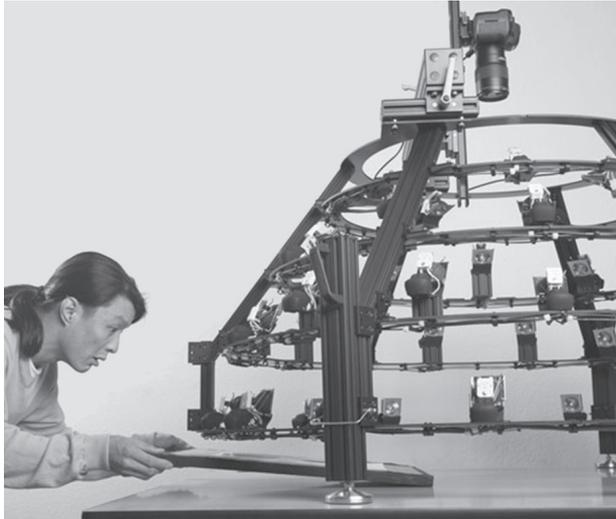
Fig. 6. RTI lighting array used in the laboratory
(source: http://culturalheritageimaging.org/
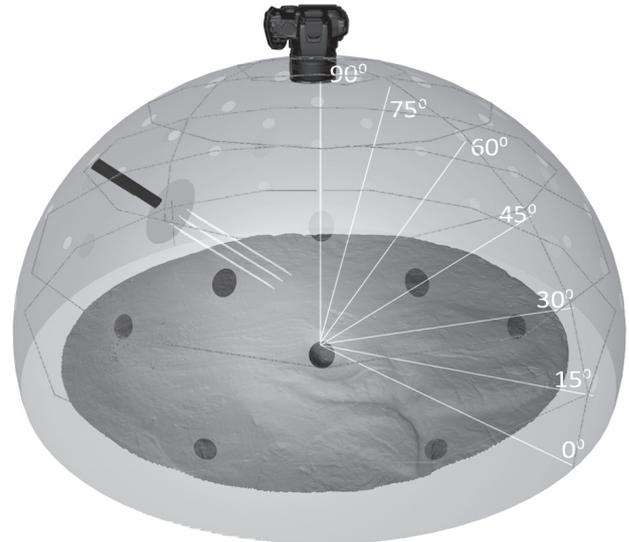What_We_Offer/Gear/Lighting_Array/) [accessed: 17.10.2018]

Fig. 7. Schematic idea of a "virtual rig"
(elaborated by M. Budlewska)

type of lighting was a surface emitting parallel rays of light. This eliminated the problem of a direct spotlight, which can disturb the shape of the shading. Additionally, a second diffuse light was also used to illuminate the scene evenly from all directions, assuring that details in the deepest shadows were lit up. This issue was also discussed and solved during consultations with Piotr Witkowski, who had previously used the traditional PTM and RTI methods [16].

Adequate material parameters were also selected to simulate light absorption and reflection properties of the sandstone rock. The chosen settings were neutral grey (RGB: 232, 232, 232, 232), 80% diffuse, and rough surface. The environment lighting was switched off, and the Phong rendering model was chosen. The aperture size was set to $f = 8$, and exposure time for the virtual camera was constant and equal to 1/30 sec. Thanks to these settings, the problem of overexposure was eliminated. For extremely eroded petroglyphs, to highlight small differences on almost flat surfaces, the 3D models were scaled twice according to the vertical axis.

Near each rendered petroglyph 3D model, at least one shiny black ball was placed. Its position did not change for each of 54 rendered images, and later, one black ball was used in the RTIBuilder software for computing the horizontal and vertical angles of the light source. The user marks the location of the shiny black balls, and the software calculates light angles for each respective image.

All the visualisation calculations were executed on a desktop computer equipped with an Intel® Core™ i7-4790 CPU and 16 GB RAM, running a 64-bit operating system. The graphics card was 2x NVIDIA GeForce GTX 970 4 GB. The time to calculate rendering for each scene depended on the lighting orientation and was variable. The maximum timing for one frame was 30 sec for an image 2000 × 2000 pixels at 200 dpi resolution. The total time to generate 54 renderings of one 3D model was approximately 20 min. The rendering process was automated by applying the Winparrot (version 2.1.3) macro script, which took care of automatically adjusting the light position for each of the 54 images, queuing all tasks, and saving final results.

Processing of images from the "virtual rig"

The series of renderings delivered from our "virtual rig" were processed with RTIBuilder [17] (version 2.0.2). Based on the input images from our virtual rig, the software calculated data for light angles and stored it internally.

All the renderings were processed and combined into a single file containing the mathematical model of the inspected surface. The RTIViewer (version 1.1) attached in the software bundle [18] allows the object to be interactively re-lit from any angle, permitting accurate examination of all its parts. In addition, it allows for various display enhancement (for PTM files: Diffuse Gain, Specular Enhancement, Normal Unsharp Masking, Image Unsharp Masking, Luminance Unsharp Masking, Coefficient Unsharp Masking, Static Multi Light, Dynamic Multi Light, Normals Visualisation; for RTI files: Specular Enhancement, Normals Visualisation) enabling details invisible in the standard viewing mode to be revealed (Fig. 8). Thanks to these various lighting and preview options, it was possible to examine the object in detail, especially with the PTM method.

In order to use all the possibilities offered by both visualisation techniques, an RTIBuilder-compatible PTM Fitter [19] plug-in from Hewlett-Packard was also used. The PTM Fitter extends the functionality of the RTI software and is operated via the host-software interface.

When the CGI input data are ready, they can be processed into RTI or PTM images via the fitting action. Fitting is the process of matching together the lighting data from input photos in order to produce a final RTI/PTM image. Each image type has a particular fitting method. Workflow with the RTIBuilder is straightforward.
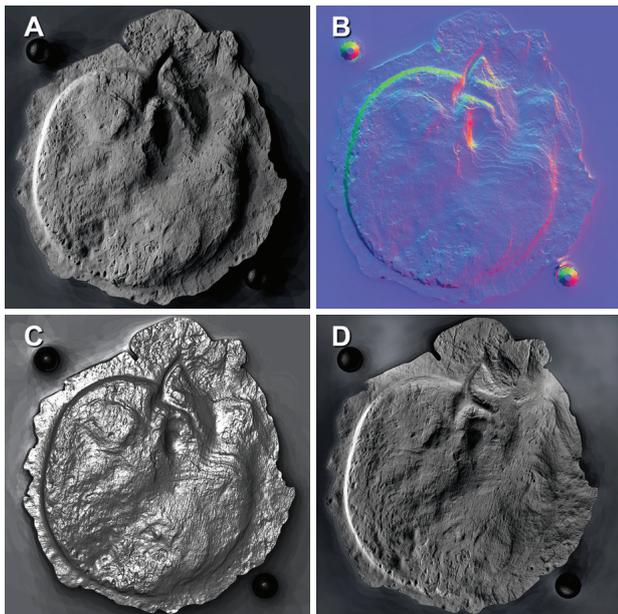
Fig. 8. Examples of RTIViewer display modes of PTM files:
A – default; B – normal visualisation; C – specular enhancement;
D – static multi-light (elaborated by J. Kościuk)

Using a wizard-like interface, the software guides the user through the following steps:

– Selecting input images from the folder data source. The files should be named sequentially using only alphanumeric text without spaces and should be organised according to the RTIBuilder software manual [20] suggestions;

– Choosing the RTI or PTM fitting method;

– Pre-processing the input data set. The user selects the black glossy ball model location on the images;

– When the computing of light source directions is completed, the software is ready to process the series of images and produce the final RTI or PTM file.

Although the workflow is relatively simple, it is necessary to observe some basic rules regarding the preparation of the files and the structure of the folders. The preparation process is explained in the software user manual [20].

The RTIBuilder provides two computational methods of images processing: RTI and PTM. In order to create PTM images, we used the PTM Fitter method from Hewlett-Packard. For RTI images, the Hemispheric Harmonics (HSH) Fitter method was chosen. Each method has several settings responsible for the accuracy of the computed mathematical model. For PTM, two options are available: LRGB (medium accuracy) and RGB (high accuracy). For the RTI method, lighting mapping accuracy should be set up – a higher numerical value of lighting mapping accuracy creates a more accurate model at the cost of bigger files.

Based on experience gathered during this project, the PTM method gives more options for displaying the final model file. According to RTIBuilder software developers [21], RTI produces a more accurate model of the examined object at the cost of fewer model display options. In the case of eroded bas-relief petroglyphs, we did not find any evidence that the quality of the produced RTI

images in corresponding display modes was higher than in PTM images. It is possible that better results from the RTI method could be revealed when using a higher quality input, for example, images with higher colour depth or with non-compressed file formats. As the input, we used renderings saved in JPEG format with 24-bit colour depth and compression level set to 95%.

During the project, we encountered some software limitations. Apparently, fitters are single-threaded and are limited to a 2 GB RAM usage limit. A software crash can occur when RAM usage exceeds 2 GB. This limits the processing of images with a resolution above 4k pixels. The RAM usage depends on the software settings and selected method, with the RTI fitter generally better handling higher resolution input data. For example, we processed RTI fitter images with resolutions of 4000×4000 pixels and with third-level accuracy in 385 sec with a file size of 411 MB. The PTM Fitter did not manage to finalise the process with the 4k resolution images when the RGB option was enabled.

Results and discussion

In total, using alternatively short-range digital photogrammetry and structured light scanning tools, 11 petroglyphs of varying sizes and different stages of preservation were documented in detail. For many of them, it was almost the last moment when their traces could still be captured. However, in a few cases, despite using the vPTM technique, it was already too late to unambiguously reconstruct their original shape.

However, it should be borne in mind that only a small group of petroglyphs was selected for this study – those for which there was a theoretical chance that the application of the methods proposed by us could give satisfactory results. On the Samaipata rock, more than 200 other places were identified where once there were undoubtedly other glyphs (zoomorphic or geometrical), today completely indistinguishable.

Petroglyph from sector W06 – "Jaguar?"

As it is one of the best-preserved petroglyphs, we used it to test various documentation methods. Structured light scanning, TLS scanning, and short-range digital photogrammetry were used.

The figural representation of a sniffing feline is easy to recognise, so there was no need to use PTM or RTI. Instead, the possibility of using alternative methods to visualise the results of 3D laser scanning and digital photogrammetry were tested. The documentation made with a structured light scanner (Fig. 9A), as theoretically the most accurate, served as comparative material.

The petroglyph and its immediate surroundings were scanned with a Leica P40 scanner from six positions with distances from the centre of the figural representation of 5 to 10 m. The scanning density was set to 6 mm @ 10 m. Overlapping 3D point clouds guaranteed coverage and points were measured every 3 mm in the worst case. The results were presented in the visualisation mode that

highlighted all slopes (Fig. 9B), referred to in Leica Cyclone as "Cloud Silhouette" (CS). The results, although not as detailed as in structured light scanning due to scanning resolution, proved to be satisfactory. This method of visualising the 3D point cloud was used to enhance the legibility of subsequent analyses. The combination of the CS with the standard visualisation mode of the 3D point cloud (greyscale reflection intensity) offered in Leica Cyclone turned out to be a better representation of all surface details than the "Cloud Shaded" option implemented by Leica (Fig. 9C). An analogous effect was obtained by combining the CS with an RGB-coloured 3D point cloud image (Fig. 9D).

Photogrammetric documentation consisting of 48 photos with resolutions of 24 million pixels each was compiled with the AgiSoft PhotoScan Professional software. By applying a CS layer, a flat orthoimage that was devoid of spatial depth (Fig. 9E) obtained the third dimension (Fig. 9F). This method proved to be particularly useful when the high accuracy and sampling density guaranteed by structured light scanners were not needed, and at the same time, texture details and the high resolution of an RGB image was important.

A detailed analysis of the obtained images indicated an alternation of the earlier original petroglyph. The channel surrounding the figure might have been a later addition or at least have been recut. More clear images (especially Figs. 9B, D), in which not only outlines but also details are visible much better than in nature, also allowed to propose the identification of the feline as possibly a jaguar.

Petroglyph from sector W05 – "Puma(?)"

Only very weather-beaten traces of this figural petroglyph were extant. Earlier research described it as a representation of a puma or jaguar [22], but today it is difficult to determine the shape of the figure, not to mention the particular species.

To document the last traces that will soon be gone forever, the petroglyph and its closest vicinity were scanned with a structured light Artec Eva handheld scanner. Both the analysis of the 3D model in the textured version (Fig. 10A) and the one without colour information (Fig. 10B) did not reveal new details enabling the identification of the petroglyph shape.

In this situation, the vPTM and vRTI techniques proposed above were used. By putting together 54 renderings from our virtual rig, each with a different lighting direction (Fig. 10C), it was possible to recognise a shape which might suggest the representation of puma (Fig. 10D). However, this reconstruction (Fig. 10D) must be treated with great caution since the surface is highly eroded and additionally disturbed by mosses and lichens. Further doubts can be raised when comparing this reconstruction with the drawing by Alcide d'Orbigny and Ponce from 1832 [23]. There, the schematic representation of the feline is turned 180 degrees. Additionally, the map of the rock of Samaipata drawn by Leo Pucher in 1936 [22] shows this petroglyph in an inverted orientation. It is difficult to unequivocally determine the reliability of either drawing,
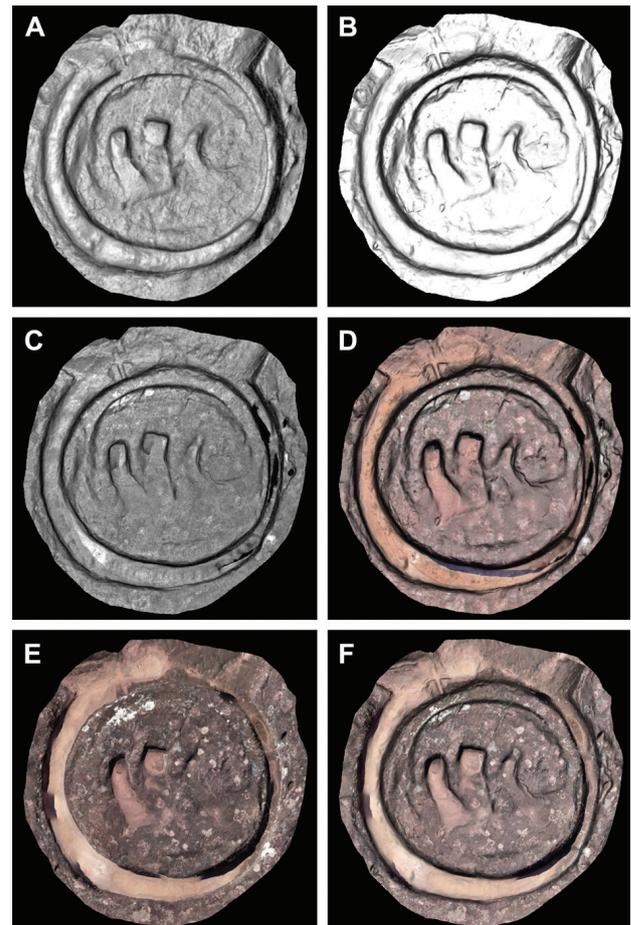

Fig. 9. Petroglyph from sector W06 – "Jaguar(?)".
Comparison of documentation and methods of visualising results:
A – structured light scanning (image without texture);
B – TLS (slope gradient); C – TLS (reflection intensity and slope gradient);
D – TLS (RGB image and slope gradient); E – digital photogrammetry
(RGB image); F – digital photogrammetry (RGB image)
and TLS (slope gradient) (elaborated by J. Kościuk)

especially since, for example, rhea representations are presented in a different orientation by both authors. The presented reconstruction (Fig. 10E) should therefore be treated only as one of the possible interpretations of the traces that have survived to this day.

Fragments of the rough rock surface, especially around the north-western edge of the oval, were detected on the images obtained with the vPTM technique. This suggests that the figure has been intentionally recut (and perhaps also erased) by the latest occupants of the site. This observation may point to the pre-Inca origin of this petroglyph.

Petroglyph from sector W06 – "Crawling Snake"

This petroglyph, or more precisely, the place where it once was, is one of the worst preserved among the examples analysed. It is even difficult to identify exactly where to look for traces of it. Analysis of the drawings by d'Orbigny and Pucher [22], [23] only indicates the area north of the petroglyph probably depicting the jaguar – more precisely, between it and the steep rock fault in the north-west (Fig. 11A).
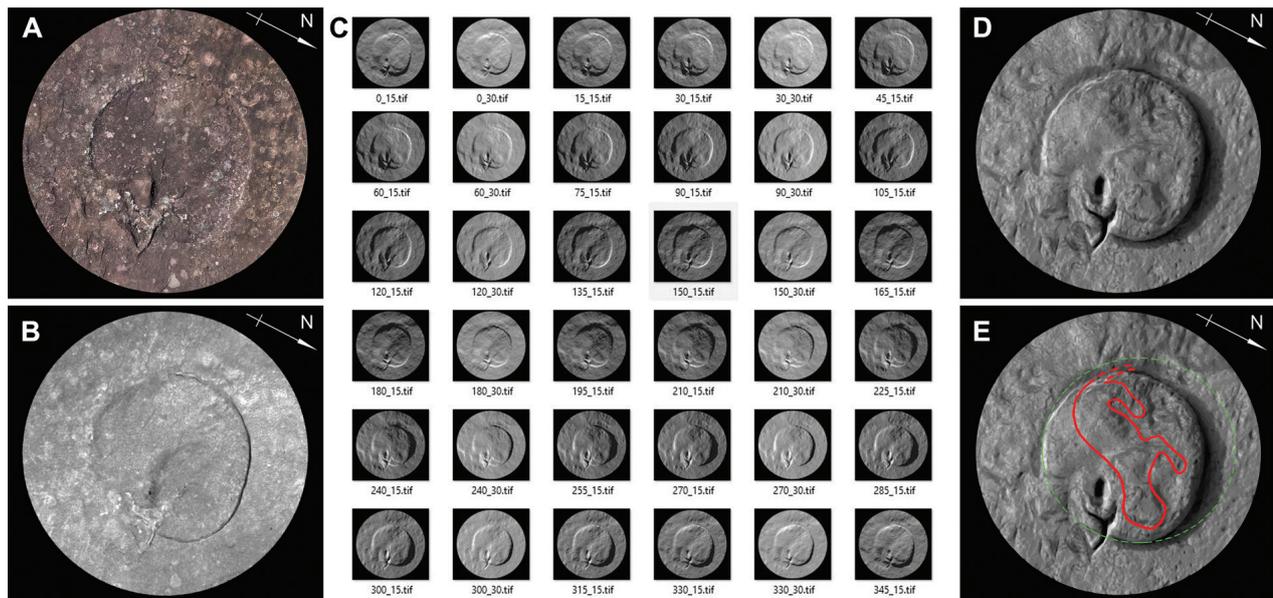
Fig. 10. The "Puma(?)" petroglyph from sector W05:
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)
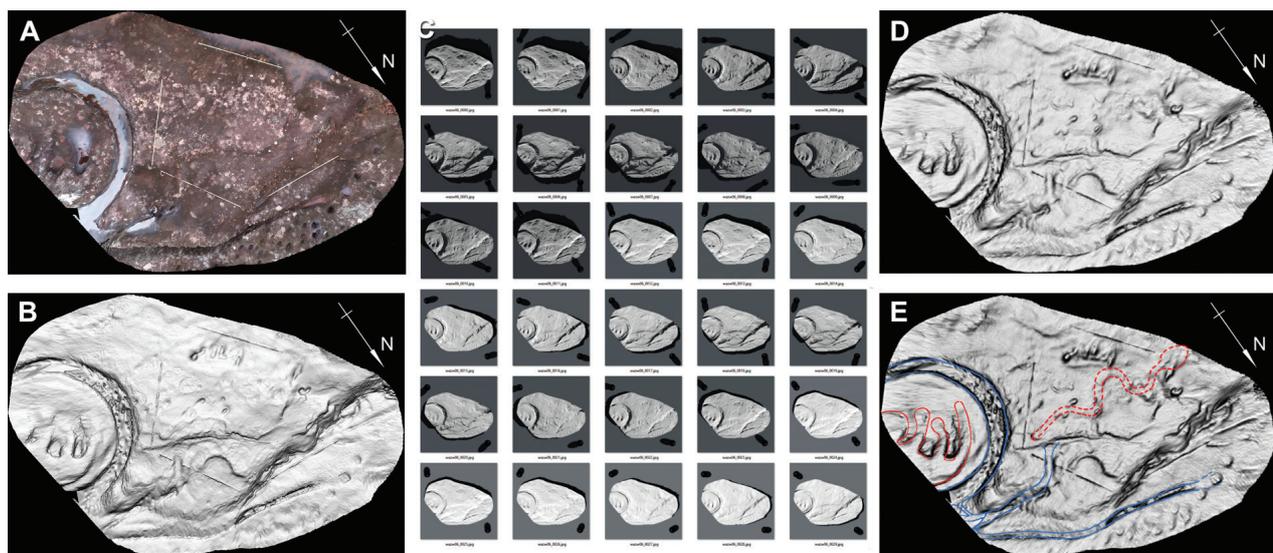

Fig. 11. Petroglyph from sector W06 interpreted as "Crawling Snake":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)

As the area where one should look for traces of the lost petroglyph was much larger (approx. 5 × 10 m), structured light laser scanning was replaced in this case by short-range digital photogrammetry. Based on 74 photos, each with a resolution of 24 million pixels, a 3D model was built consisting of over 15 million triangles (Fig. 11B). Using vPTM and vRTI techniques (Fig. 11D), we were able again to identify at most a vague outline of a snake crawling towards the north-west (Fig. 11D). However, according to some earlier investigators, this petroglyph was interpreted a coiled snake representation – at least, that is

how Leo Pucher depicts it on his map of Samaipata rock from 1936 [22]. We did not find any archival photographs that indisputably confirm that there was a representation of a coiled snake, rather the opposite – Alcide d'Orbigny on the drawing from 1834 [23] shows, although schematically, the snake crawling towards the north-west. This might be perhaps a random coincidence that does not prejudge the correctness of our reconstruction. The preserved traces are so indistinguishable that they also allow for several other interpretations, but in the light of collected data, this one seems to be the most reliable.

Fig. 12. The "Puma(?)" petroglyph from sector W09.
Condition as in July 2016
(photo by J. Kościuk)

Fig. 13. The "Puma(?)" petroglyph from sector W09.
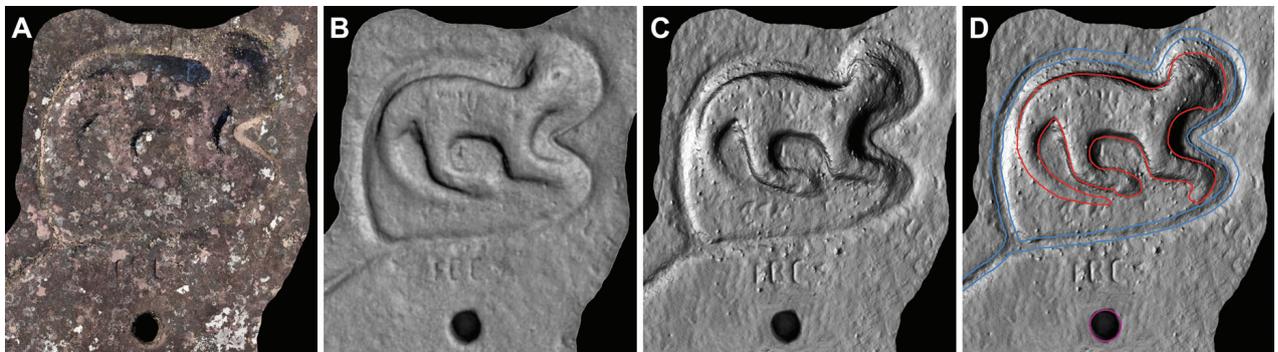Condition as in 1967
(source: [22])

Fig. 14. Petroglyph from sector W09 – "Puma(?)":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – vPTM image (multidirectional light) (elaborated by M. Nisztuk); D – tentative interpretation (elaborated by J. Kościuk)

Petroglyph from sector W09 – "Feline (Puma?)"

This petroglyph is the best preserved in the whole an-alysed group. However, comparing its current condition (Fig. 12) with photos published by Hermann Trimborn [22], it can be seen that the surface has eroded significantly in the last 50 years. Numerous inscriptions scratched by tour-ists on the surface of this petroglyph (Fig. 13), which were still clearly visible 50 years ago, are now barely noticeable.

Given the rapidly progressing erosion, it was decided, even though the puma drawing is still distinguishable, to scan the entire petroglyph using a structured light scanner in the highest resolution available to us (Figs. 14A, B). In the future, this may be the only source documenting this petroglyph.

In addition, vPTM analyses were compiled. The few inscriptions that are still legible (Fig. 14C) clearly show how far the surface of the petroglyph has eroded relative to the situation of the late 1960s.

The representation of the puma is carved in bas-relief, and a flat water channel surrounds it (Fig. 14D). A round-ed hole (ca. 25 cm in diameter) drilled into the rock in front of this petroglyph might have been used as an of-fering hole. It seems that the petroglyph was made at the same time as the platform arranged around it. Observation

of the sculpting sequence of the surrounding platforms leads to the conclusion that puma representation could be attributed to the period of Inca occupation of the site[3].

Petroglyph from sector W09 – "Rhea (Ñandú)"

This petroglyph, known nowadays only from historical sources, is an entirely different case. One can easily iden-tify the place where this petroglyph was once located, but the figure is completely indistinguishable.

The size of the area (ca. 6 × 7 m) excluded structured light scanning, so again digital close-range photogramme-try was used. More than 300 photos resulted in a dense cloud of ca. 21 million points, which was reduced to a 3D model of 4 million faces (triangles). It proved to be fully sufficient to reproduce all the details of the examined sur-face (Fig. 15A). An orthoimage of 0.5 mm/pixel resolution also met our requirements (Fig. 15B).

However, attempts to find any traces of the rhea (*ñandú*) ended only with a suggestion about the size and orienta-

---

[3] J. Kościuk, G. Orefici, M. Ziółkowski, A. Kubicka, R. Muñóz Risolazo, *Description and analysis of El Fuerte de Samaipata in the light of new research, and a proposal of the relative chronology of its main elements*, in the same issue of "Architectus".
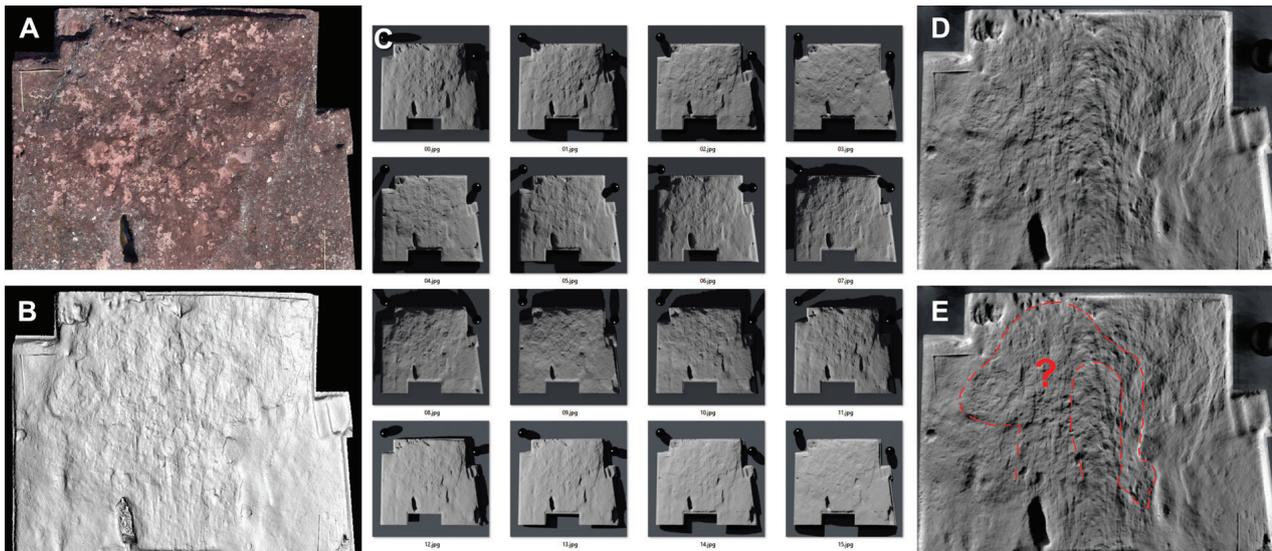
Fig. 15. Petroglyph from sector W09 interpreted as "Rhea (Ñandú)":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)

tion of the figure. Generally, it agrees with the schematic "icon" on d'Orbigny's drawing [23]. There, however, the figure is shown in an entirely different manner than all other petroglyphs, which, as we can see today, are of bas-relief type. Can this difference in the way of depicting the rhea (ñandú) on d'Orbigny's drawing mean that it was executed as a sunken relief? This difference might be one of the reasons that it has disappeared utterly[4], or it might have been intentionally hammered out.

Using vPTM and vRTI techniques, we ended up with a problematic reconstruction (Fig. 15E). Even attempts to scale the virtual 3D model twice alongside the z-axis did not bring clear results. One must admit at this point, that the reconstruction proposed there (with head down) has no analogies in pre-Columbian art in the whole region, so it can not be treated as a right interpretation. It should be also emphasized that this reconstruction is based solely on the technical analysis of preserved traces with no reference to possible analogies in Inca or pre-Inca iconography. Further iconographical studies may still indicate another direction of interpretation, but this interesting example of pre-Columbian rock art is anyhow lost forever[5].

*Petroglyph from sector W10
– "Snake-catching Animal"*

Small bulges on the surface of the rock in the central part of the W10 sector suggested that this could be another very blurred petroglyph (Fig. 16A). Structured light scan-

ning confirmed this assumption, but still, a clear interpretation was not possible (Fig. 16B).

It was only after scaling the virtual 3D model two times along the z-axis and using vPTM techniques that a more explicit identification was made – an animal catching a snake's head with its snout (Figs. 16D, E). The second snake is grabbing the tail of the first one, and the third snake catches the tail of the second snake. This complicated layout of four interacting animals covers approximately 1 m sq. It has no other parallels on the Samaipata rock. Additionally, the representation of the snake-catcher looks untypical. It does not resemble pumas or jaguars known from other petroglyphs in Samaipata. Attempts to identify the species lead towards the white-nosed coati (lat.: *Nasua narica*; local names: *pizote*, *antoon*, *tejón*), the only similar animal from this part of South America, which are known as snake catchers [24]. Consultations with specialists from the Wroclaw Zoological Garden have not ruled out such a possibility. Further studies on possible analogies in the Inca and pre-Inca rock art of Bolivia may confirm or exclude this preliminary interpretation.

Thanks to the exact virtual copy of this petroglyph, even if it erodes completely, additional research and identification attempts will be still possible.

*Petroglyph from sector W10
– "Meandering Snake"*

About 2 m northwest of the above-described petroglyph, an elongated twisting shape was observed at the bottom of the 25 cm wide channel draining rainwater down the slope (Fig. 17A). Due to the progressing erosion, additionally intensified by the rainwater flowing abundantly here, structured light scanning was used at the highest resolution available to us for this petroglyph (Fig. 17B).

---

[4] Marta Pakowska brought this possibility to our attention.

[5] For alternative reconstruction cf. J. Kościuk, G. Orefici, M. Ziółkowski, A. Kubicka, R. Muñóz Risolazo, *Description and analysis of El Fuerte de Samaipata in the light of new research, and a proposal of the relative chronology of its main elements*, in the same issue of "Architectus".
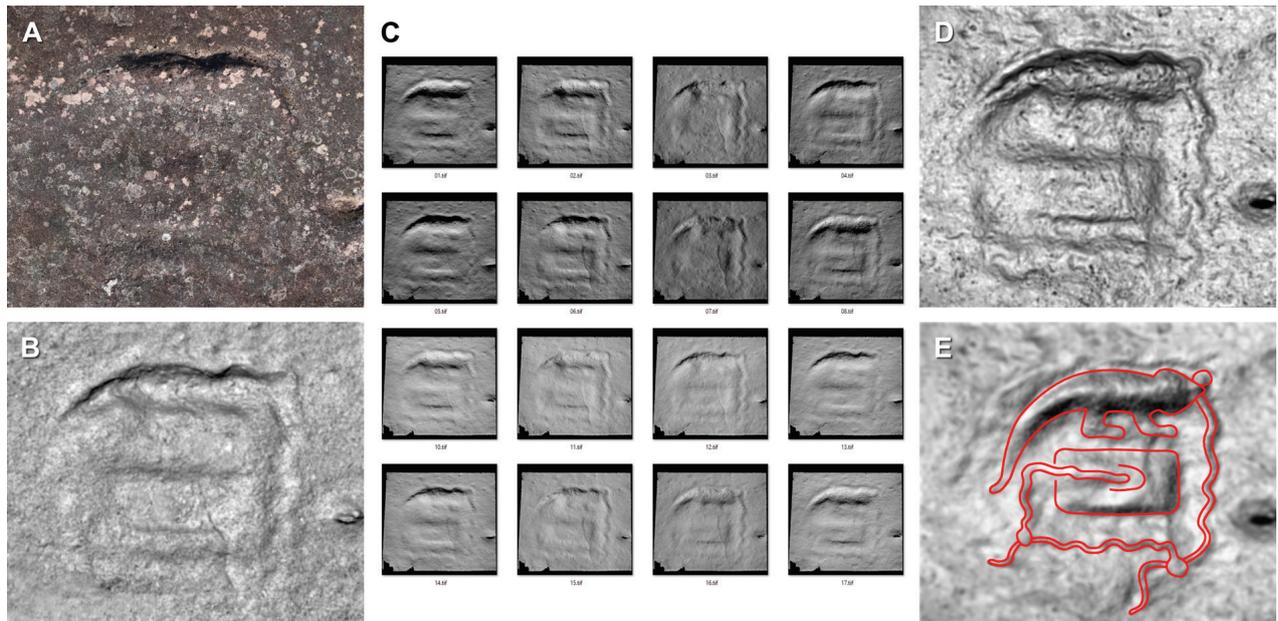
Fig. 16. Petroglyph from sector W10 – "Snake-catching Animal":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)

After computing the vPTM analysis (Fig. 17C), a clear image of a snake meandering up the slope in the middle of the channel was shown (Figs. 17D, E).

The degree of erosion, proximity to the petroglyph representing a snake-catching animal, and the similar way of carving suggest that both petroglyphs form one panel.

The iconography of the crawling snake is often found in both Inca and pre-Inca rock art. On the Samaipata rock, this type of glyph occurs in three other places: in sector W05, along a long ramp in sector S12 (this petroglyph is over 20 m long), and in the channel draining water from the pool in sector N10.

Petroglyph from sector C05 – "Choir of the Priests" or "Altar"

On the central part of sector C05, one of the most important sculpted parts of the Samaipata rock can be identified: it is what was called the "Choir of the Priests" or the "Altar".

Due to the large size of this sculpture (roughly 9 × 13 m when measured together with the leading north-east water channel), digital short-range photogrammetry was used as the documentation method. Based on 83 photos, each with a resolution of 24 million pixels, a 3D point cloud of
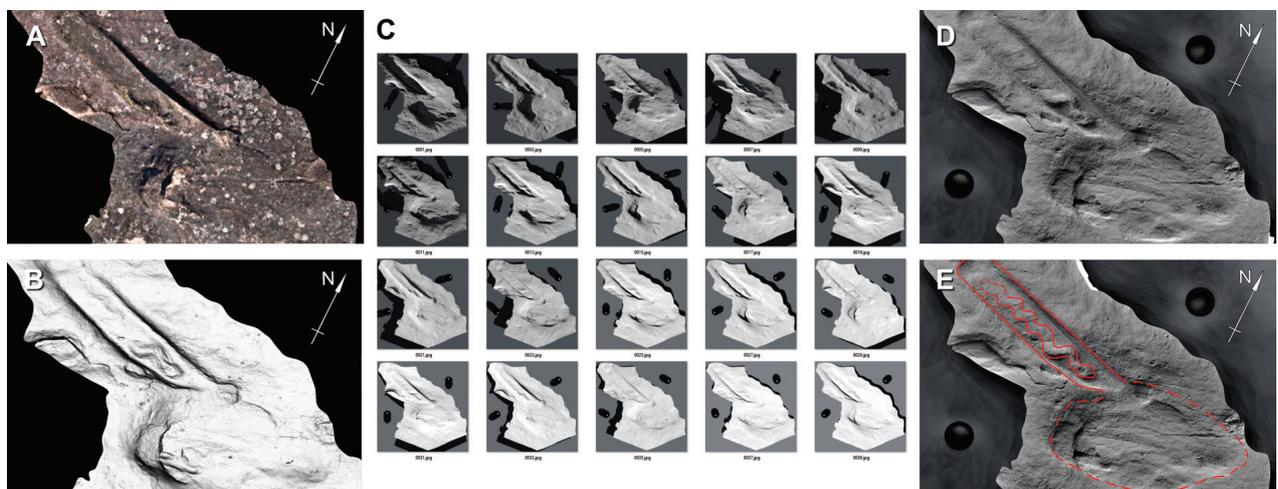

Fig. 17. Petroglyph from sector W10 – "Meandering Snake":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)
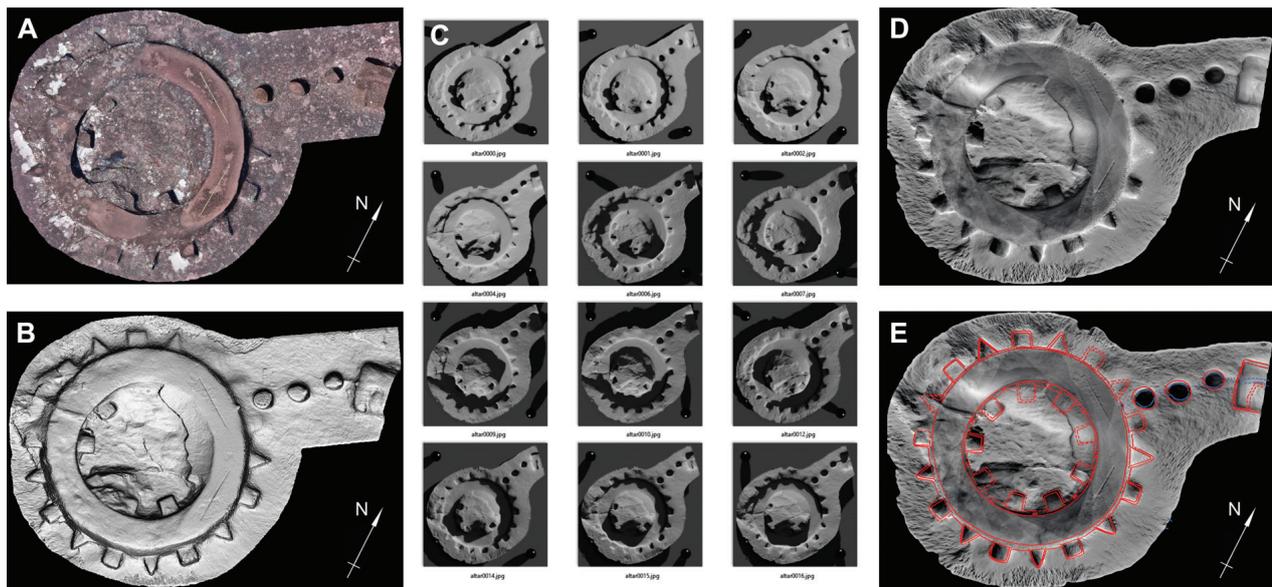
Fig. 18. The "Altar" petroglyph from sector C05:
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)

over 15 million instances was built. Due to the size of the file, when converting to the mesh model, it was decimated to 3.5 million triangles (Figs. 18A, B). This resolution proved to be sufficient for interpretation of its main parts.

Special attention was devoted to the central part surrounded by a nearly 1-meter wide water-channel. Beside nine rectangular "seats", most of them very eroded, traces of small (ca. 14×14 cm) double-recessed niches were found on the vertical surfaces between sitting places. Further studies included vPTM analysis (Fig. 18C) in the hope that the top of the central part would reveal traces of another petroglyph (Fig. 18D). Unfortunately, no such traces were observed. Even if such a petroglyph existed here once, it has been completely eroded or has been intentionally damaged. Additionally, no indication was found for Giuseppe Orefici's suggestion of a representation of a feline preceding a circular channel with radiating triangular and rectangular niches. This does not exclude the hypothesis made by Orefici based on his observations in the field. At most, it can be said that the use of vPTM did not confirm his direct observations. However, vPTM analyses yielded data that allow for a more detailed reconstruction of all rectangular and triangular niches.

Petroglyph from sector S14 – "Double Puma(?)"

On the southern slope of the Samaipata rock, in a very prominent position, two images of felines (possibly pumas?) attract the attention of many visitors. The animals are facing each other, and a narrow gap is left between their heads. Only the animal on the western side is preserved in full. Of the other one, only the general outline remains. The main part of its torso has vanished and traces of its head are no longer visible.

Since the continued existence of this petroglyph is endangered by both the expanding lithic surface and the strongly inclined slope, digital photogrammetry and structured light scanning were used to document its current state. Due to the very difficult access, only 34 photos were collected. They were, however, sufficient to produce ortho-images of 1 mm/pixel resolution (Fig. 19A) and a detailed 3D mesh model consisting of 8 million triangles. The last, when inspected with textural information switched off (Fig. 19B), revealed interesting details. A small rectangular depression (ca. 45×70 cm) above the heads of both animals might have been meant as a reservoir from which water flowed between the two pumas below.

More detailed structured light scanning shows two circular protrusions inside this depression (Fig. 19D). Small cavities in the centre of each protrusion were also detected. The whole, together with the water drain located below, looks a bit like a stylised mask of a mythical creature.

Since no traces have been preserved to undoubtedly reconstruct the head of the eastern animal, our interpretation reproduces the outline of the feline preserved next to it (Fig. 19E).

Petroglyph from sector N10 – "Triple Snake"

This petroglyph is a very elaborate, nearly 4 m-long channel through which water flows to the east from a set of three cascading reservoirs located up the hill on the western side[6].

---

[6] Cf. J. Kościuk, G. Orefici, M. Ziółkowski, A. Kubicka, R. Muñóz Risolazo, *Description and analysis of El Fuerte de Samaipata in the light of new research, and a proposal of the relative chronology of its main elements*, in the same issue of "Architectus".
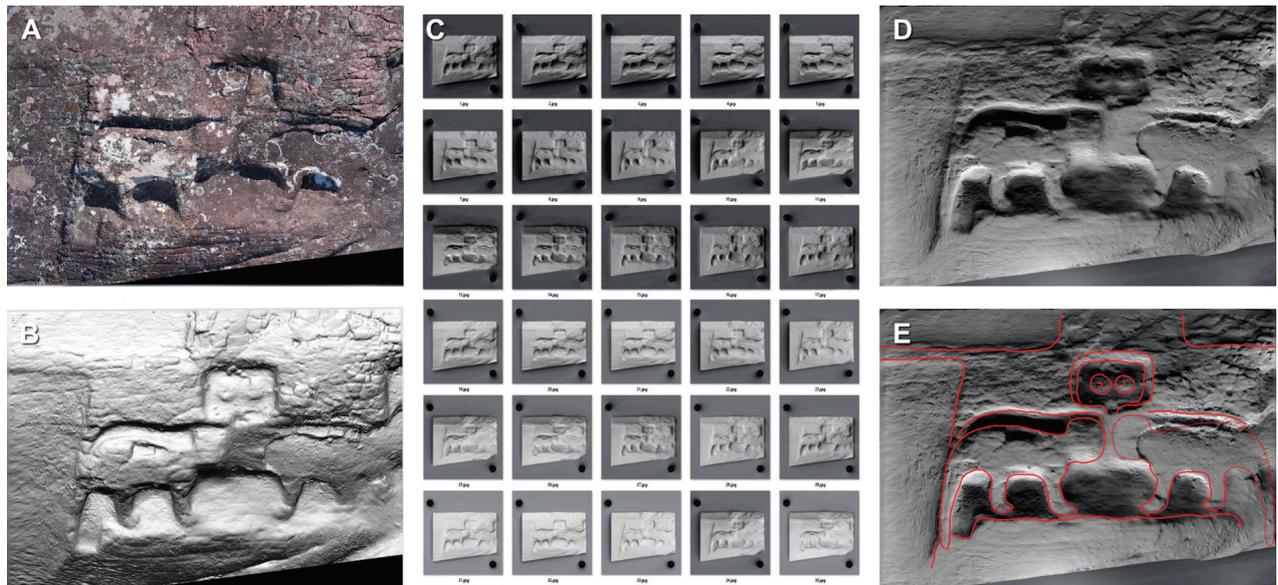
Fig. 19. The "Double Puma(?)" petroglyph from sector S14:
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)
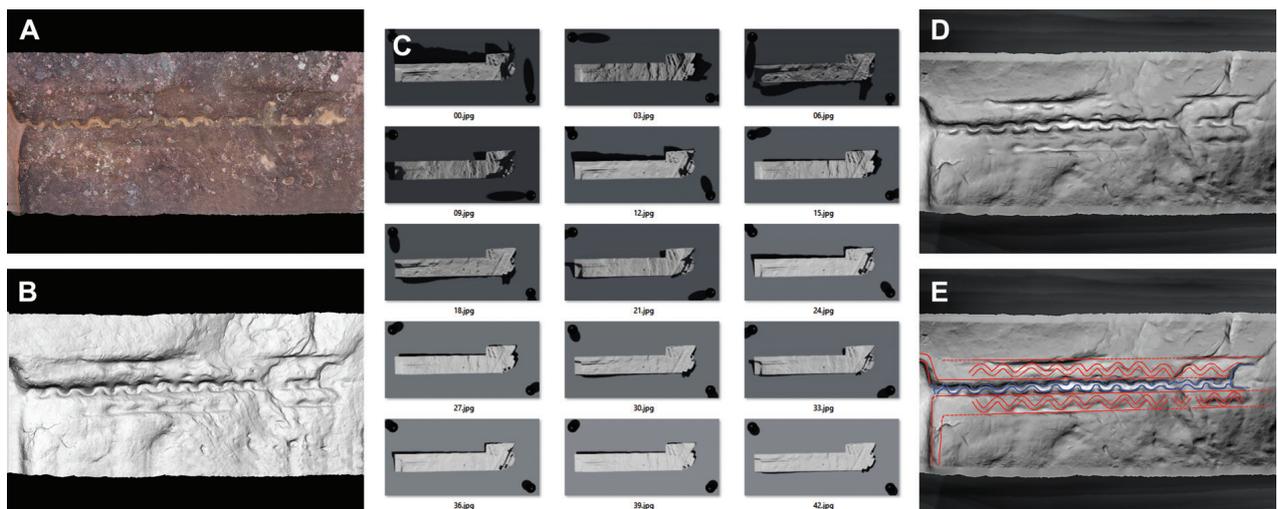

Fig. 20. Petroglyph from sector N10 – "Triple Snake":
A – RGB image (photo by J. Kościuk); B – greyscale image without texture information (elaborated by M. Pakowska);
C – samples of renderings with different lighting directions (elaborated by M. Budlewska);
D – multidirectional light vPTM image (elaborated by M. Nisztuk); E – tentative interpretation (elaborated by J. Kościuk)

The bottom of the channel has the form of a meandering snake, although some details of its easternmost part cannot be clearly seen. Two parallel shelves are also visible on both sides of this meandering channel, but their edges are not easily identifiable. The colourful mosaic of lichen and algae covering the rock surface makes it very difficult to observe this petroglyph directly in the field (Fig. 20A).

Since this site was lacking small details as well as highly eroded areas, only close-range digital photogrammetry was used as the documenting technique. More than 160 photos were shot to cover the area extending for a further 7 m to the east in the hope of finding traces of the contin-

uation of this canal. This resulted in a 3D cloud of 20 million points, which was converted to a 30 million-triangle mesh model (Fig. 20B).

The 3D model did not demonstrate the existence of a continuation of the meandering channel (Fig. 21D). Instead, it clearly defined the northern and southern edges of the shelves on both sides of the channel. Further details were observed on the vPTM image (Figs. 21C, D). On both 25 cm-wide shelves, a similar meandering pattern has been carved, but this time as a bas-relief (Fig. 21E).

This "Triple Snake" glyph with sunken relief and bas-reliefs used together has no parallel on the Samaipata rock.
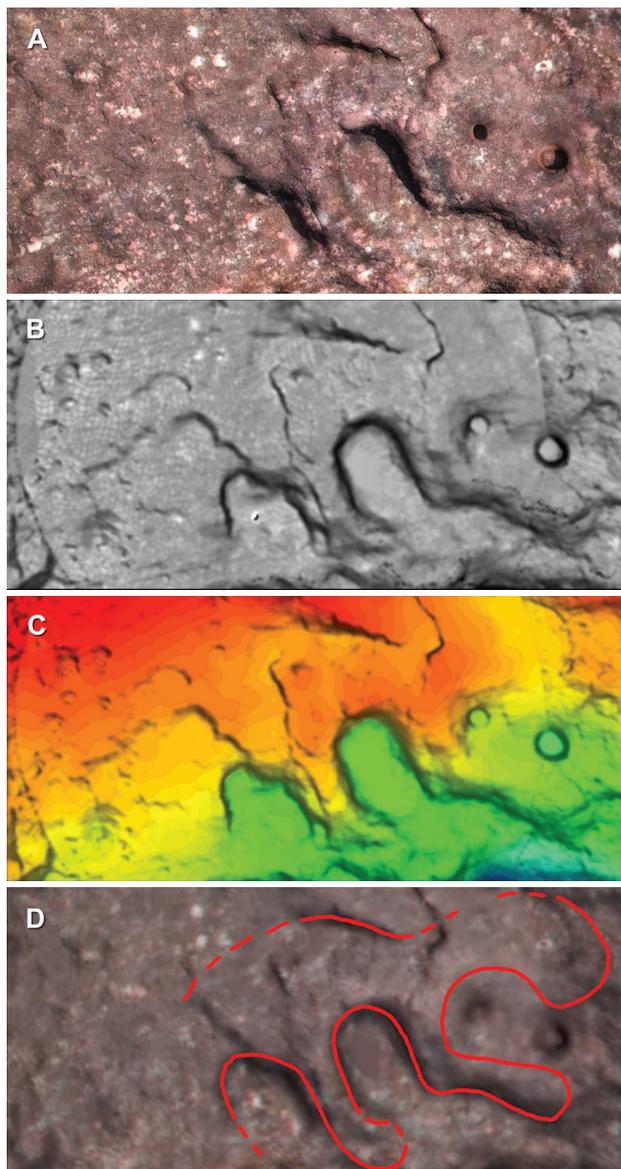
Fig. 21. Zoomorphic petroglyph from sector N10.
3D cloud from TLS representations:
A – RGB image; B – reflection intensity in greyscale;
C – elevation map with hill shading;
D – tentative interpretation (elaborated by J. Kościuk)

Zoomorphic petroglyph from sector N10

Traces of this petroglyph were identified by Rolando Marulanda [25]. Some irregularities of the surface of the central terrace of this sector may suggest another zoomorphic representation, unfortunately in an advanced state of erosion.

Unfortunately, this particular place was not recorded by us with either detailed photogrammetry or structured light scanning. The only data available for further interpretation were those from the general photogrammetry and TLS projects covering the entire site.

The last proved to be sufficient to render interpretation possible. Generally, TLS data are not particularly suitable as a source for detailed 3D models reproducing all the nuances of the surface. However, the mere observation of the

3D point cloud using different imaging methods proved sufficient for this task. Three different 3D point cloud visualisation modes were used in this case: RGB coloured, greyscale representation of reflection intensity, and an elevation map with hill shading (Figs. 21A–D). All of them are available in Leica Cyclone as basic colour schemes for point cloud representation.

Although our tentative interpretation (Fig. 21D) is slightly different from the one proposed by Rolando Marulanda [25], it has confirmed that a zoomorphic petroglyph could once have existed in this place. Its exact shape can no longer be reproduced. At most, one can venture to say that the petroglyph could represent an animal belonging to the felidae family. However, a shadow of doubt remains as to whether this is not the result of natural erosion of heterogeneously stratified sandstone.

Conclusions and project limitations

The obtained results confirmed the correctness of the assumption that with an accurate 3D artefact model, the process of collecting photos at the different lighting angles necessary for PTM and RTI techniques can be successfully transferred from the physical environment to the virtual space. The project also resulted in many indications as to the correct and effective application of all the technologies used. The following discussion is divided into three areas: documentation techniques, rendering images in a virtual environment, and the use of existing PTM and RTI software.

In general, somewhat predictably, the outdoor use of structured light scanners presents many technical problems. The main one is poor visibility of structured light strips emitted by the scanner in daylight, and even more so in full sunlight. Scanning after sunset would be a natural solution, but for archaeological sites, this is usually not authorised or involves obtaining special permits and employing additional personnel (inspectors, guards, technical employees). Additional problems arise when the scanner and the associated laptop cannot be powered directly from the network. If powered by batteries, both work with much lower efficiency, which significantly hinders the correct completion of the scan of the entire object.

As the experience gained during this project shows, in most cases, structured light scanning can be replaced with short-range digital photogrammetry. The key to success is the use of a camera (full-frame cameras being highly recommended) with a resolution above 16 million pixels and a professional, fixed, focal length lens that complies with the basic principles of photography for digital photogrammetry purposes. The latter include the following in particular:

– The images should be as much as possible taken perpendicularly to the documented surface;

– The images must be sharp and devoid of reflections;

– The camera should work in aperture priority mode while the lens aperture should be permanently fixed at the value that will guarantee an optimal depth of field (usually $f = 8 \div 11$ – depending on lens model and dimensions of the object);

– The focus should be permanently fixed at a distance that will guarantee sharpness for all the images at the given aperture size;

– To avoid the effect of vibrations, the shutter speed should be high, so good lighting conditions are necessary since raising the ASA value to high will result in grainy images;

– There should be a minimum of 75% vertical and horizontal overlap between adjacent images;

– Too many photos may result in a blurry and noisy 3D model, so good planning of camera positions is advisable.

The additional benefit of using the photogrammetric method is flexibility during the acquisition phase, which enables data collection in places not directly accessible to hand-held scanners.

When the 3D model of the inspected artefact is ready (at this point the scanner or photogrammetry obtained do not matter), the phase of rendering images in a virtual lighting-array will start. The lesson we learned from our virtual rig prototype includes the following observations:

– In some cases, the 54 predefined lighting positions of our virtual rig were not sufficient, so an additional set of rigs should be defined;

– In order to assure good reproduction of all details, the script automating successive renderings should include adjusting the size of the frame according to the real size and proportions of the 3D model (the "Triple Snake" petroglyph is a good example where the rendered object occupied less than 50% of the image);

– More studies are necessary to establish light definitions and material properties optimal for the proposed vRTI and vPTM techniques.

Further studies will show if the proposed workflow is also adequate for documenting and analysing artefacts other than bas-relief petroglyphs.

References / Bibliografia

[1] http://rsb.info.nih.gov/ij/index.html [accessed: 15.07.2019].

[2] https://imagej.nih.gov/ij/features.html [accessed: 19.07.2019].

[3] www.dstretch.com [accessed: 11.07.2019].

[4] Harman J., *DStretch Algorithm Description*, http://www.dstretch.com/Algorithm Description.html [accessed: 3.07.2019].

[5] Malzbender T., Gelb D., Wolters H., Zuckerman B., *Enhancement of Shape Perception by Surface Reflectance Transformation*, "Hewlett-Packard Technical Report 2000-38R1", https://www.hpl.hp.com/techreports/2000/HPL-2000-38R1.pdf [accessed: 17.08.2019].

[6] Malzbender T., Gelb D., Wolters H., *Polynomial Texture Maps*, "Hewlett-Packard Technical Report 2001-33 (R.1)", 16.05.2001, http://www.hpl.hp.com/ptm [accessed: 17.08.2019].

[7] *Reflectance Transformation Imaging (RTI)*, http://culturalheritage-imaging.org/Technologies/RTI/index.html [accessed: 17.08.2019].

[8] Witkowski P., Chyla J.M., Ejsmond W., *Combination of RTI and decorrelation – an approach to the examination of badly preserved rock inscriptions and rock art at Gebelein (Egypt)*, [in:] S. Campana, R. Scopigno, G. Carpentiero, M. Cirillo (eds.), *CAA2015: Keep the revolution going. Proceedings of the 43rd annual Conference on Computer Applications and Quantitative Methods in Archaeology*, Archaeopress Archaeology, Oxford 2016, 939–944.

[9] D'Orbigny A., *Viaje a la América meridional (realizado de 1826 a 1833)*, Vol. 4, 1466, Buenos Aires 1945.

[10] *Technical specification, Eva*, https://www.artec3d.com/portable-3d-scanners/artec-eva-v2#specification [accessed: 19.08.2019].

[11] *Agisoft Photoscan professional edition*, https://www.agisoft.com/features/professional-edition/ [accessed: 31.02.2019].

[12] Horn B.K., *Hill shading and the reflectance map*, "Proceedings of the IEEE" 1981, Vol. 69, Iss. 1, 14–47, doi: 10.1109/PROC. 1981.11918.

[13] Kennelly P.J., *Hill-Shading Techniques to Enhance Terrain Maps*, 2009, https://pdfs.semanticscholar.org/26fc/7b5fbad0e3692d2040b59530add6d87215d3.pdf?_ga=2.140942640.329251785.1567283612-1142592307.1532500819 [accessed: 18.08.2019].

[14] Kennelly P.J., *Terrain maps displaying hill-shading with curvature*, "Geomorphology" 2008, Vol. 102, Iss. 3–4, 567–577, doi: 10.1016/j.geomorph.2008.05.046.

[15] https://www.maxon.net/en/products/cinema-4d/overview/ [accessed: 11.07.2019].

[16] Witkowski P., Polkowski P., *Reflectance transformation imaging about a photographic method for documentation and analysis of historical artefacts*, "Muzealnictwo" 2018, Vol. 59, 54–62.

[17] *Cultural Heritage Imaging, Reflectance Transformation Imaging. Guide to Highlight Image Processing, Version 1.4.*, 2013, http://CulturalHeritageImaging.org/downloads/ [accessed: 8.08.2019].

[18] *Cultural Heritage Imaging, Reflectance Transformation Imaging. Guide to RTIViewer, Version 1.1.*, 2013, http://CulturalHeritageImaging.org/downloads/ [accessed: 8.08.2019].

[19] HP Labs, PTM Fitter, 2001, https://www.dropbox.com/sh/jfsy0l-hxu6zv4i4/AADJpq6E_GJmNw_s5C8r94CVa?dl=0 [accessed: 8.08.2019].

[20] *Cultural Heritage Imaging, Reflectance Transformation Imaging. Guide to Highlight Image Processing, Version 1.4.*, 2013, http://CulturalHeritageImaging.org/downloads/ [accessed: 8.08.2019].

[21] Graichen T., *RTI – accuracy tests*, 2019, http://www.tgraichen.de/?page_id=542 [accessed: 16.08.2019].

[22] Trimborn H., *Der skulptierte Berg von Samaipata*, "Archäologische Studien in den Kordilleren Boliviens", Bd. 3, "Baessler Archiv, Beiträge zur Völkerkunde" 1967, NF 5.

[23] Ponce Sanginés C., *Alcides d'Orbigny y su viaje a Samaipata en 1832*, [in:] R.D. Arze Aguirre (dir.), *El naturalista francés, Alcide Dessaline d'Orbigny en la visión de los bolivianos*, Institut Français d'Études Andines, Plural editores, Lima–La Paz 2002 [1975], 307–315.

[24] https://en.m.wikipedia.org/wiki/White-nosed_coati [accessed: 15.03.2019].

[25] Marulanda R., *La roca esculpida del Fuerte de Samaipata: elementos de discusión para un enfoque interpretativo*, [in:] A. Meyers, I. Combès (comp.), *El Fuerte de Samaipata. Estudios arqueológicos*, Biblioteca del Museo de Historia, Universidad Autónoma Gabriel René Moreno, Santa Cruz de la Sierra 2015, 34–51.

Abstract

The case being studied is one of Bolivia's most important monuments – El Fuerte de Samaipata, a UNESCO World Heritage Site. This paper proposes a new workflow for the two most important aspects of studies on cultural heritage – detailed documentation and analysis. The former includes the well-known techniques of digital photogrammetry and structured light scanning. The latter comprises polynomial texture mapping (PTM) and reflectance transformation imaging (RTI), both of which have been used since the beginning of this century. The novelty proposed by the authors is the transfer of part of the data collection process from the physical environment to the virtual space.

Despite some technical problems, by eliminating the tedious and time-consuming process of shooting photos in the field using specific lighting angles, this new workflow proved to be very efficient, particularly in documenting and interpreting badly preserved examples of bas-relief rock art.

Key words: Samaipata, rock art, UNESCO World Heritage, PTM and RTI, 3D scanning

Streszczenie

El Fuerte de Samaipata to jeden z najważniejszych zabytków Boliwii wpisanych na Listę Światowego Dziedzictwa UNESCO. W artykule przedstawiono dwa sposoby dokumentacji, szczególnie istotne zarówno dla badań, jak i ochrony dziedzictwa kulturowego. Pierwszy obejmuje dobrze znane techniki cyfrowej fotogrametrii i skanowania światłem strukturalnym. Drugi dotyczy zastosowania technik polynomial texture mapping (PTM) oraz reflectance transformation imaging (RTI). Obie techniki są wprawdzie stosowane już od początku tego wieku, ale nowością zaproponowaną przez autorów jest przeniesienie części procesu zbierania danych ze środowiska fizycznego do przestrzeni wirtualnej.

Mimo pewnych problemów technicznych, dzięki wyeliminowaniu żmudnego i czasochłonnego etapu fotografowania w terenie przy użyciu dokładnie zdefiniowanych kątów oświetlenia, zaproponowana metoda okazała się bardzo wydajna, szczególnie w dokumentowaniu i interpretacji silnie zniszczonych przykładów rytów naskalnych.

Słowa kluczowe: Samaipata, sztuka naskalna, Lista Światowego Dziedzictwa UNESCO, PTM i RTI, skanowanie 3D