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TECHNICAL ADVANTAGES BRIDGING THE PRESERVATION LIMITS OF PAINTED DECORATION OF NEOLITHIC CERAMIC FIGURINES

VENTAJAS TÉCNICAS QUE SUPERAN LOS LÍMITES DE PRESERVACIÓN DE LA DECORACIÓN PINTADA DE LAS FIGURILLAS CERÁMICAS DEL NEOLÍTICO

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Highlights:

- Painting on Neolithic figurines in Central Europe was more common than previously thought, revealing its significant participation in the communal narration of the figurine's social role.
- DStretch was proven as efficient tool of early detection of pigment residues, which prevents post-excavation damage, resulting from inadequate methods or intensity of surface cleaning.
- Improving the legibility of the motifs and the ability to reconstruct them opens up new possibilities to analyse even those artefacts whose surface suffered recent unintentional damage.

Abstract:

Painting on ceramic objects is one of the most outstanding features of visual narration of the Neolithic material culture in Southeastern and partly in Central Europe. Unfortunately, post-firing painting is usually poorly preserved due to deposition conditions. Moreover, it may have been damaged or contaminated during post-excavation and conservation processes in the past. New methods of visual detection of pigment traces bring about a higher success rate in the identification of pigment traces and the reconstruction of motifs, leading to both more targeted protection without contaminants and a broader understanding of the motifs preferred by Neolithic societies in their narrative expression. Decorrelation algorithms have been widely used to analyse rock art and wall paintings, but their application to fragile pigments on mobile artefacts remains limited. DStretch, a key tool in this process, enhances colour contrasts in digital images to detect faint pigment traces, which are often overlooked in standard macroscopic analysis. By applying DStretch to high-resolution photographs or 3D model textures, we can identify pigment residues without damaging the object. The algorithm's versatility extends to different colour channels, making it possible to detect subtle traces across different pigments, improving overall data preservation and analysis. 378 fragments of Neolithic ceramic figurines from the Lengyel culture site Těšetice-Kyjovice – Sutny, the largest known collection in central Europe, have been analysed. The DStretch results were verified using reflected-light microscopy, and samples of the most commonly used pigments were analysed by Raman spectroscopy. Previously, painting the figurines was considered a minor practice, amounting to 25 % of the collection at most. Using our methods, it is revealed that almost 60 % of figurines were painted, despite the intensive removal of pigments during post-excavation surface cleaning. New data on the structure and origin of pigments were collected as well as data concerning the nature of the motifs.

Keywords: DStretch image analysis; Neolithic figurines; paintings; pigments; central Europe

Resumen:

La pintura sobre objetos cerámicos es una de las características más destacadas de la narración visual de la cultura material neolítica en la Europa sureste y parcialmente en Europa central. Desafortunadamente, la conservación de la pintura aplicada después de la cocción suele ser baja debido a las condiciones de deposición. Además, esta puede haber sido dañada o contaminada durante los procesos posteriores a la excavación y la conservación en el pasado. Los nuevos métodos de detección visual de rastros de pigmento permiten un mayor éxito en la identificación de pigmentos y en la reconstrucción de motivos, lo que conduce tanto a una protección más centrada y libre de contaminantes, como a una comprensión más amplia de los motivos preferidos por las sociedades neolíticas en su expresión narrativa. Los algoritmos de decorrelación se han utilizado ampliamente para analizar el arte rupestre y las pinturas murales, pero su aplicación a pigmentos frágiles en artefactos móviles sigue siendo limitada. DStretch, una herramienta clave en este proceso, mejora

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los contrastes de color en imágenes digitales para detectar rastros de pigmentos débiles, que a menudo se pasan por alto en el análisis macroscópico estándar. Al aplicar DStretch a fotografías de alta resolución o texturas de modelos 3D, podemos identificar residuos de pigmento sin dañar el objeto. La versatilidad del algoritmo se extiende a diferentes canales de color, lo que permite detectar rastros sutiles en diferentes pigmentos, mejorando la conservación y el análisis general de los datos. 378 fragmentos de figurillas neolíticas de cerámica del yacimiento de la cultura Lengyel en Těšetice-Kyjovice – Sutny, la colección más grande conocida en Europa central, han sido analizados. Los resultados de DStretch se verificaron mediante microscopía de luz reflejada y se analizaron muestras de los pigmentos más utilizados mediante espectroscopia Raman. Anteriormente, pintar las figurillas se consideraba una práctica menor, estimándose que como máximo un 25 % de la colección estaba pitado. Con nuestros métodos, se revela que casi el 60 % de las figurillas estaban pintadas, a pesar de la eliminación intensiva de pigmentos durante la limpieza de la superficie posterior a la excavación. Se recopilaron nuevos datos sobre la estructura y el origen de los pigmentos, así como sobre la naturaleza de los motivos.

Palabras clave: análisis de imágenes con DStretch; figuras cerámicas neolíticas; pinturas; pigmentos; Europa central

1. Introduction

Visual image analysis determining the presence of pigment through decorrelation algorithms has been employed to study rock art and wall paintings (Kucukkaya, 2004; Kotoula, 2018; Hermon, 2018; González et al., 2019; Andrews & Brink, 2021; Monna et al., 2022; Skarbun et al. 2024). However, decorrelation techniques have not been fully established or tested within the field of archaeology, in particular while examining mobile artefacts. Tools, ornaments, and small household items often bear traces of pigments that are fragile and susceptible to damage or complete destruction during the post-excavation process. Despite being crucial to understanding the artefact's original appearance and use, these traces are often overlooked, especially when the assessment is based solely on naked-eye observation. The subtle variations in colour and contrast shifts that indicate the presence of pigments are particularly easy to miss when the surface of the artefact has undergone changes due to long-term depositional processes, i.e. the surface is archaeologised. Routine macroscopic analysis, whether conducted through photographs or direct visual inspection of the artefact, can fail to detect these nuances. Early and precise identification of pigment traces is crucial, allowing for the timely removal of these artefacts from standard mechanical cleaning procedures, which could further damage or erase these valuable traces. By setting these items aside for more detailed and complex analytical techniques, such as spectroscopic or microscopic methods, we ensure that these fragile, yet informative remnants of past material culture are preserved and examined appropriately, contributing to a deeper understanding of their historical context and significance.

Moreover, we can obtain additional information and augment our study of artefacts by adjusting the colour channels (RGB) of digital photography. In 2005, Jon Harman developed the software package DStretch (Harman, 2005), distributed as a commercial component of the analytical software ImageJ (see e.g., Schneider et al., 2012). Using decorrelation principles applied to the colour and contrast matrix of a digital image, Decorrelation Stretch (DStretch) soon became a groundbreaking tool, essential for studying rock art worldwide. Its foolproof design, moreover, allows for it to be broadly applied to virtually any digital content (e.g., Defrasne, 2014; Kotoula et al., 2018; or recently described comprehensively by Monna et al., 2022). The technical particularities of its functionality are described in detail by the algorithm's author (Harman, 2005); in this paper, we focus particularly on its results concerning graphical analysis. Beyond basic colour models such as RGB (red-green-blue colour ratio) and LAB (lightness 0-100, a as the green to red axis, b as the blue to yellow axis), other colour models can be emphasised from the RGB ratio through decorrelation, such as Harman's redefined YDS, YBR, YBK, LDS, and LRE. YDS and LDS generally enhance contrast and improve the visibility of yellow pigments, YBR and LRE accentuate red pigment, and YBK accentuates dark pigments, such as black, blue, and marginally yellow. Supplementary combinations of these chains, such as YRE or CRGB, may also be used. As pigment traces on fragments are often not detectable at all with the naked eye, it is advisable to apply a series of these decorrelations to cross-evaluate the result, and subsequently validate any findings by microscopy (illustratively Fig. 1).

The visualisation potential of the software interface is not limited to examining the basic form of raster graphic outputs. Visual analyses aiming to identify pigments were used even before the introduction of DStretch (e.g. Harry et al., 2001), especially in the field of rock art and rock paintings (Berrier et al., 2020; Wagner, 2021), where analyses that highlight traces difficult to see were crucially needed. At the same time, only a universal tool like DStretch (though utilising already known procedures and applications – e.g. Gillespie et al., 1986) brought about a truly mass use of visual decorrelation across archaeology, art history, and the study of past human activities in general (Göldner & Deter-Wolf, 2023). The ultimate advantage of Dstretch is its wide applicability, easy availability of software solution and basic ease of use (Quesada & Harman 2019). If a more complex analysis is needed, more advanced user experience is required, or the usage of other approaches, such as multispectral imaging.

Though originally designed for photographs, DStretch can also be applied to high-resolution 3D model surfaces. When working with 3D models, one of the methods of visualisation involves adjusting the colour information, represented as a 2D texture mapped onto the model's geometry. This texture can be enhanced using the DStretch algorithm, improving colour contrast. This method avoids issues such as shadows or reflections that affect standard photography, allowing for more accurate texture mapping. While virtual anomalies may occur, they can be filtered out through further examination. The process involves creating a detailed, colour-calibrated texture map of the artefact's surface.

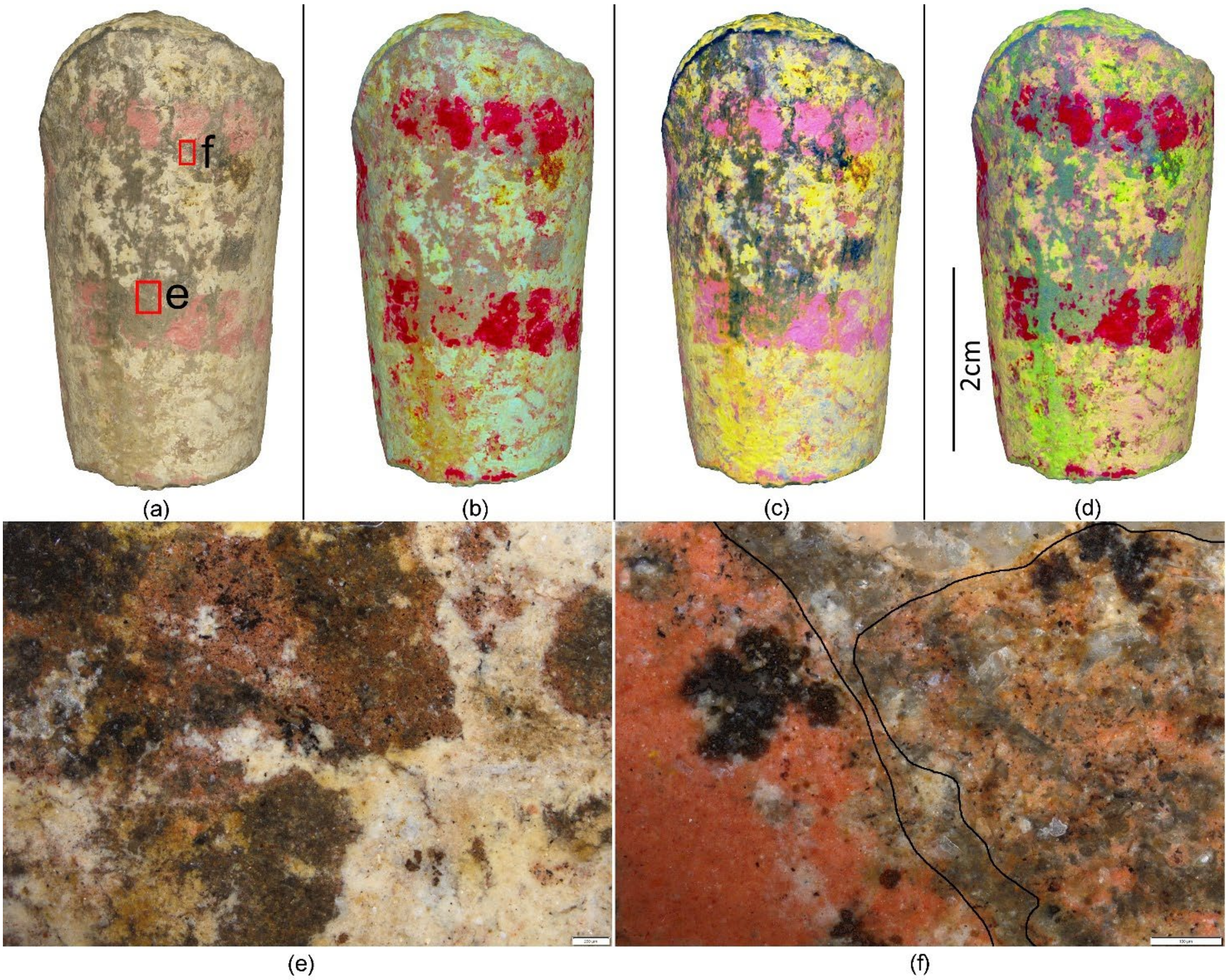


Figure 1: Stages of the process of locating pigment traces: a) Surface examination with the naked eye, b) 3D model surface and texture analysis using DStretch algorithms LRE enhances red pigment, c) YBK enhances yellow colours, unfortunately including calcareous crust, d) CRGB enhances all colour extremes, which helps to distinguish the calcareous crust (more greenish) from yellow pigment; another red pigment (enhanced as purple), e-f) Microscopic validation of two distinct red pigments. Visualised on sample TK043.

By applying the algorithm to the texture, the digitised surface can be studied more efficiently in real-time, which enables better tracking of colour patterns, even in hard-to-reach areas. Since the model is illuminated evenly, shadows and distortions are minimised, offering clearer results (Koklaj & Somrak 2019). The DStretch application, as seen in Fig. 2, reveals previously undetectable paint, enabling us to describe these new elements as an additional material layer.

The artefacts analysed in our case study are Neolithic ceramic figurines from the Lengyel culture, a period of advanced Neolithic in the eastern part of Central Europe. Neolithic ceramic figurines (Ilon, 2007, 34; Bánffy, 2017; Kokkinidou & Nikolaidou, 1997, 89) were commonly painted, yet this was generally neglected by analytical research. Although painted Neolithic pottery has been analysed commonly in terms of the pigment's chemical composition and provenance using X-ray fluorescence (XRF) (Constantinescu et al. 2007), Fourier transform infrared spectroscopy (FTIR) (Atanassova et al., 2024), X-ray diffraction (Bugoi et al., 2008) and Raman spectroscopy (Angeli et al., 2019), such research has never been carried out with figurines. The method of decorrelation has been used recently, but exceptionally and analysing only a few samples (Papadopoulos et al., 2019; Ramirez Valiente, 2023).

Anthropomorphic, usually feminine, ceramic figurines were common mostly during the 1st stage of the Lengyel culture (4770 - 4500 BCE; Trampota & Květina, 2020, 176-179; Chmielewski, 2020), and their occurrence coincided with the building of circular enclosures (Schier, 2023; Řídký et al., 2019). They are more frequent in the western part of the Lengyel culture territory (Barna, 2017) formed by Moravia, Lower Austria, south-western Slovakia and western Hungary (Fig. 3). Figurines were exceptionally numerous at several settlement sites in south Moravia, exceeding one hundred fragments (Koštuřík, 1979 - Jaroměřice nad Rokytnou; Vildomec, 1950 – Střelice; Podborský, 1985 – Těšetice–Kyjovice – Sutny). In total, more than 1600 such figurines were found in Moravia referred to in the last summarising publication (Kovárník, 2010, 91). Polychromy in ceramics and figurine decoration was soon identified (Skutil, 1940; Salm & Vildomec, 1936-1937), with a certain relation of the used colours to relative chronology. In Lengyel I, the combination of yellow and red was dominant, while the combination with black and white motives was rarer. White pigment or the combination of white and red was characteristic of Lengyel II, when speaking of Moravia. Podborský (1985, 92) stated a significantly lesser ratio of painting on figurines (10.1 %) in comparison with Lengyel culture ceramics. Painted figurines became less common in time; the greatest number of them comes from Lengyel I. Red pigment was most prevalent, followed by yellow pigment, whereas white and black were considered exceptional. The usage of pigment combination (usually two pigments were combined) was common.

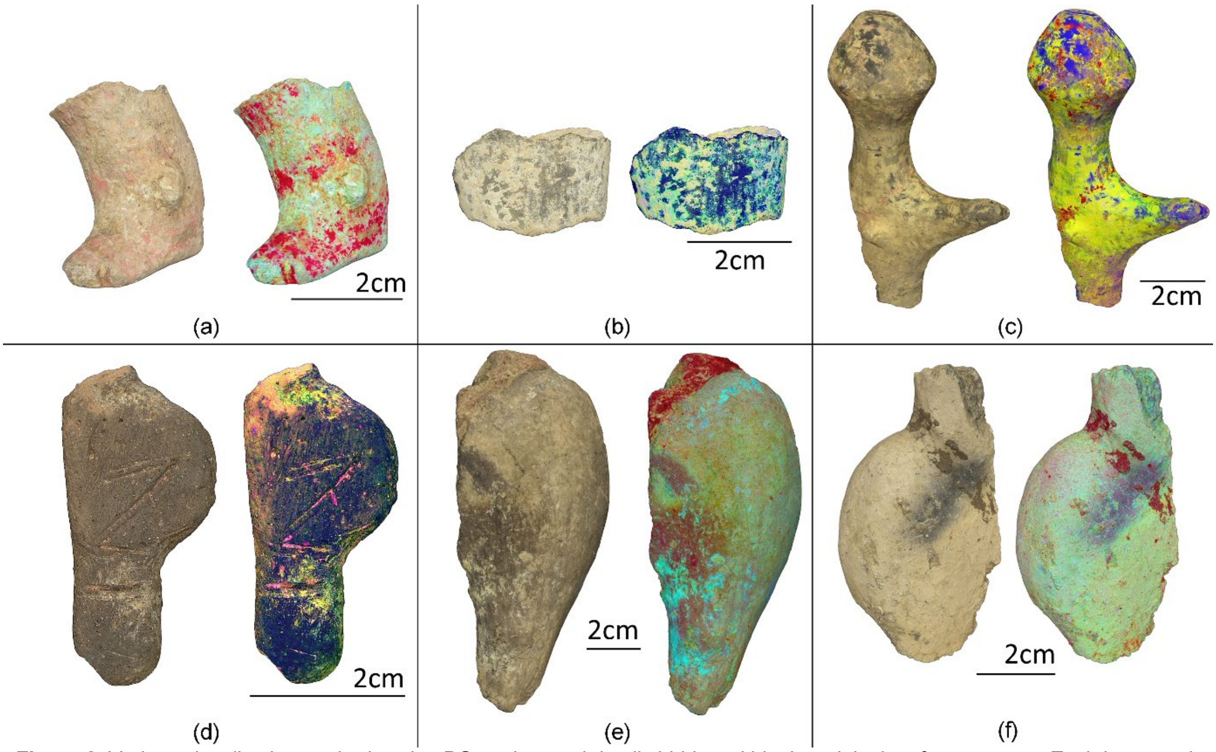


Figure 2: Various visualisation methods using DStretch reveal details hidden within the original surface textures. Each image pair includes a scan with the original texture on the left and the DStretch visualisation on the right, highlighting specific pigments or features of the surface: a) TK298 (YBK); b) TK088 (YBK); c) TK173 (CRGB); d) TK296 (YBK); e) TK278 (LRE); f) TK255 (LRE). All visualisations were created in Blender 4.1.

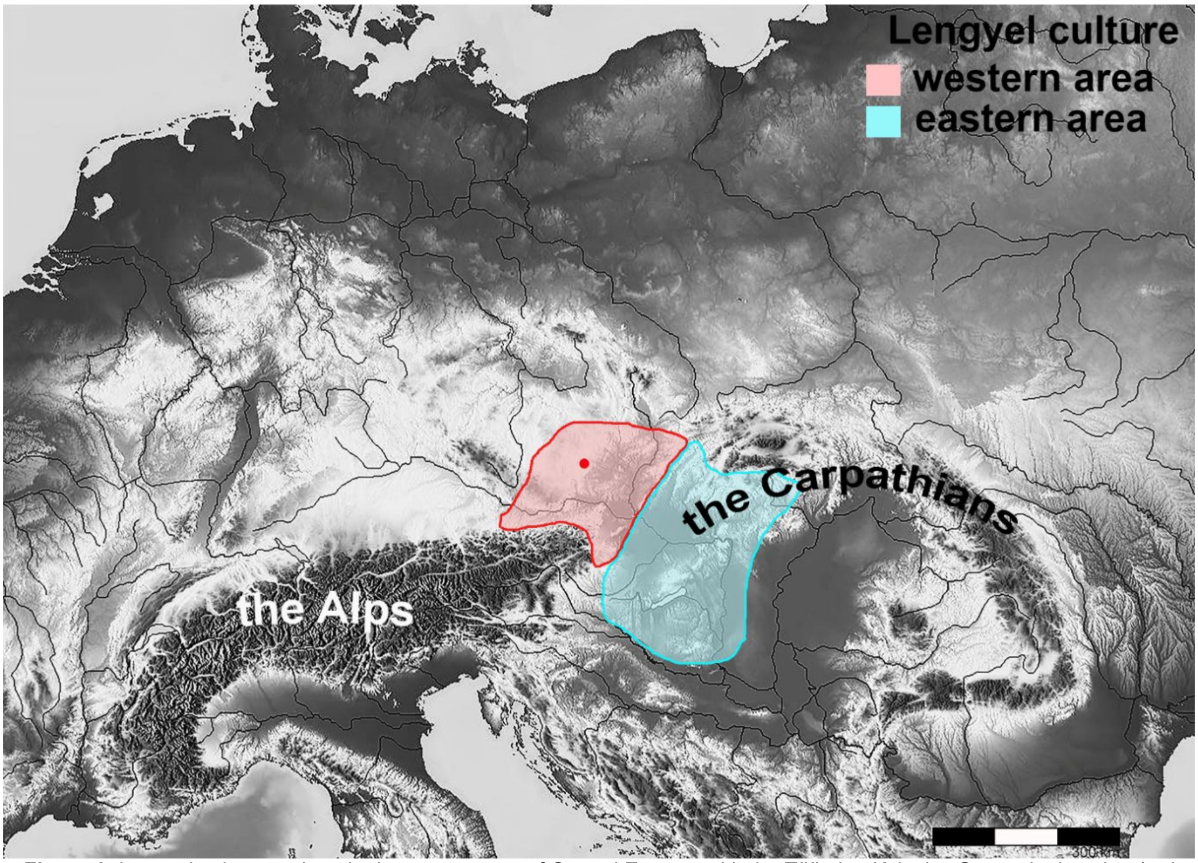


Figure 3: Lengyel culture territory in the eastern part of Central Europe, with the Těšetice-Kyjovice Sutny site location (red point). Western (pink) and eastern (blue) areas of the Lengyel culture.

Figure 4: Selection from the figurine collection from the Těšetice-Kyjovice – Sutny.

The preservation of the painting was usually described as poor (Podborský, 1985, 92; Pavúk, 2003, 302). Moreover, post-excavation processes (wet brushing, mechanic removal of the calcareous layer, a product of $CaCO_3$ precipitation from loess) partially damaged the surface of the figurines, which was then usually treated with a translucent conservatory coating. Due to the wide variability in colour of the fired surface, the contrast between the painted surface and the surroundings may have almost completely vanished, which makes it harder to identify the distribution, shape, and texture of painted motifs with the naked eye. Poor preservation also significantly limited the reconstruction, and thus the interpretation of the motifs. Despite these limitations in legibility and preservation, scholars attempted to interpret the motifs in the past. The relation of the painted motifs to real objects that were worn (skirts, loin cloths, necklaces, early copper jewellery – Podborský, 1985, 92; Neugebauer-Maresch, 1984, 193) was seen as more probable than a symbolic meaning of painted patterns (Červinka, 1908, 75; Neústupný, 1931, 33; Vildomec, 1965, 176). Podborský (1985, 93) pointed out that the pubic triangle was frequently highlighted with red lines. Neugebauer & Neugebauer (1982, 18) suggested a hypothesis, that yellow pigment applied as overall coating could have represented the colour of complexion, whereas red pigment may have been used to depict details of adornment and clothing, and black pigment could have represented hair. In some cases, tattoos were mentioned as another supposed pattern that could have been depicted (Kovárník, 2010, 106). Motifs painted on Lengyel culture ceramics were described in detail in the past (Podborský et al., 1977), defining a type list of motifs, but no correlation with figurine decoration was identified.

2. Materials and methods

The analysed collection of anthropomorphic figurines was excavated at the settlement site Těšetice-Kyjovice – Sutny, and dates to Lengyel I phase, at which time an outstanding circular enclosure (about 60 m in diameter) was built there. The collection comprises 378 figurine fragments (a sample is presented in Fig. 4), forming the largest known collection in European Neolithic. In the past, naked-eye observation identified traces of painting on 24.64 % of figurines in the past (Podborský, 1985, 92). Minerals that served as sources of pigment had been analysed in the past, but only pigment accumulations from settlement pits were sampled (Dražďák, 1973-1974, 69-93), not the figurines or the sherds themselves. With regards to the previously established presence of painting, photorealistic textures were applied when figurines were documented in 3D in our recent research. The resulting models can be used to predict or directly identify areas for extensive pigment analysis (such as microscopy, XRF measurement, and physical sampling for further analysis).

A comprehensive flow chart of the methodology developed by our group to assess decorative motifs is presented in Fig. 5.

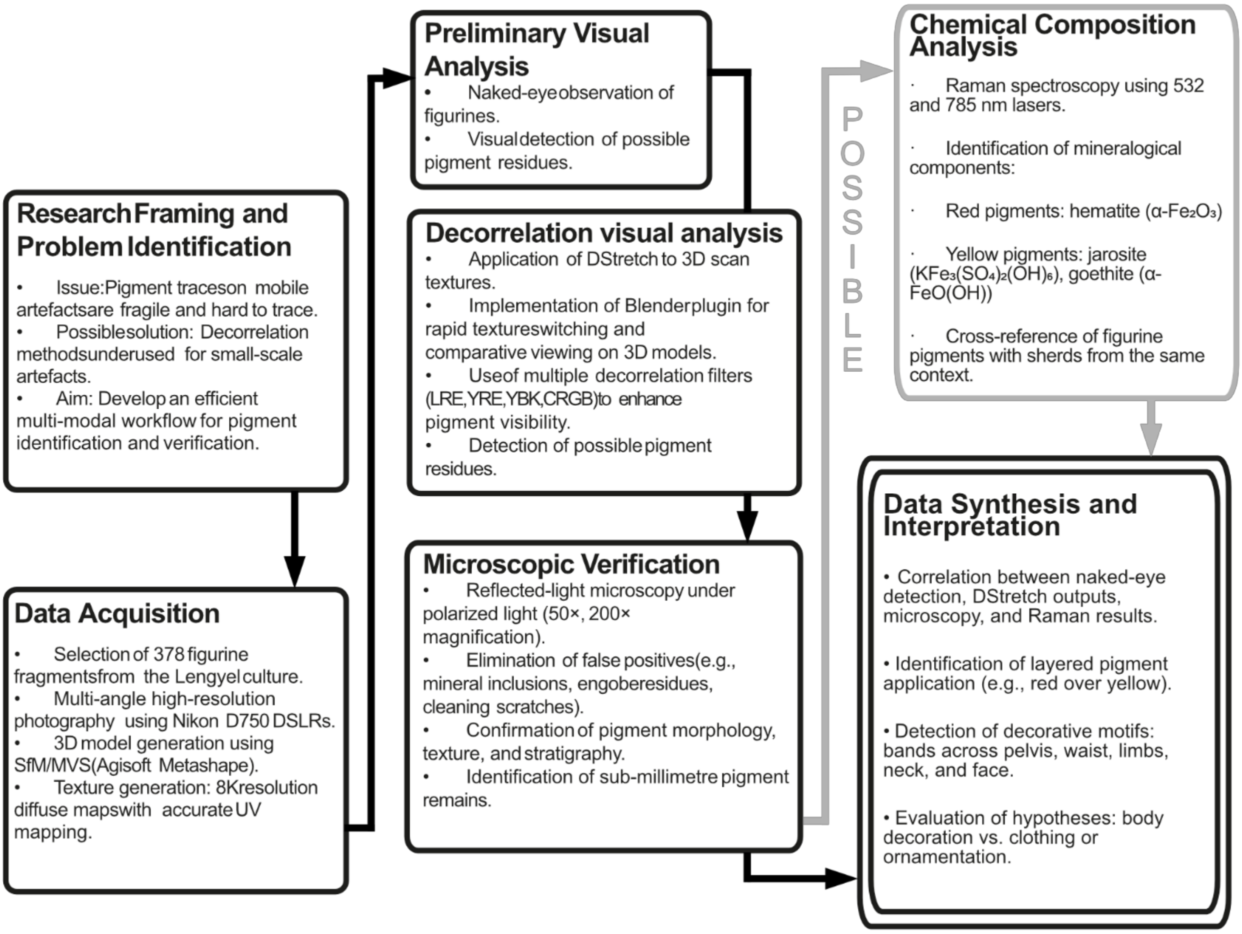


Figure 5: Flowchart.

Mesh and texture were acquired using the pipeline of SfM (Structure from Motion) and MVS (Multi-View Stereo) approach. The high geometric resolution and photorealistic texture of SfM and MVS make an ideal interpretative medium, effectively capturing both morphology and surface details (Escarcena et al., 2011). The figurine fragments were photographed using several Nikon D750 DSLR cameras equipped with Nikkor 60 mm macro lenses. We followed a workflow similar to that described by Porter et al. (2016), with slight modifications tailored to specific characteristics of the artefacts. A minimum of 200 images were taken per photo-scanned artefact. Additional series of target-referenced images were taken for more topographically complex or less visible areas, such as the spaces between the limbs, perforations, and cavities. Images were taken concentrically to ensure homogeneous coverage of the surface for digital reconstruction via MVS, with a strong emphasis on the accuracy of the resulting model. The images were taken concentrically to ensure homogeneous coverage of the surface for digital reconstruction via MVS.

Digital 3D models were created using Agisoft Metashape software (versions 1.7 to 2.0). Maximum accuracy and resolution settings were applied wherever possible—high for the Align Photos step (photo resolution 6016*4016; photo align – high accuracy; key point limit 100000; tie point 2000; masks applied) and Ultra High for mesh reconstruction from depth maps (ultrahigh resolution of 3D surface, face count forced to 9,500000 polygons, then decimated to less, but focused to maintain surface detail). No surface approximation was used. For further details regarding data acquisition, 3D scan reconstruction, and workflow in general, see Kaňáková & Nosek (2025).

Since the primary focus and use of the 3D models is visual texture analysis, a highly detailed mesh beneath the texture is not necessary. Decimated mesh still allowed us to examine the surface in great detail.

The textures were created in 8K resolution in Metashape (as a diffuse map type; generic mapping mode; mosaic image blending; full resolution 8192x8192 and pixel size), exported with the decimated 3D scans, and their UV maps were subsequently modified using the DStretch plugin to produce several alternatives focused on pigment detection.

The decorrelation process works primarily with 2D data, adjusting images to better visualise subtle colour variations on the artefact's surface. While using DStretch, relying solely on 2D data decreases the effectiveness of surface examination, as 2D is inherently stationary. On the other hand, examining the 3D model in controlled motion allows for a deeper understanding of surface relations which is extremely helpful when dealing with fragmentary and sporadically distributed pigment or pigments in hard-to-see areas.

The inefficiency of examining pigment traces in 2D was shown in tests conducted on 20 fragments where pigment residues had been identified with the naked eye. However, digital identification on 2D images of these figurines revealed pigment traces successfully in only half of the cases. This prompted us to modify the 3D-model texture in DStretch when imported via UV coordinates instead of the original unaltered texture. The exported texture of the 3D model can be adjusted just like other image formats. Upon re-importing this modified texture back onto the 3D model mesh, the unclear nature of the surface's colour becomes much more discernible (Fig. 6).

The initial idea was to import the altered texture back into a software capable of examining a 3D mesh with texture (e.g., Metashape, CloudCompare, Meshlab, or Blender). This proved inefficient because the manual import of data and the mutual referencing to the original texture is time-consuming. Moreover, it does not enable switching between textures visualised through different filters. Therefore, visual identification verified through alternative colour model is essential. Since D-Stretch allows multiple outputs to be generated based on the particular selected colour anomalies, the speed and efficiency of switching between different 2D-texture variations on each 3D model is crucial. Therefore, the Python programming language (Van Rossum & Drake 2009) was used as the basis for an extension for the Blender software. Blender facilitates the automated attachment of textures to 3D models using the standard .OBJ format and accompanying material file (.MTL). By implementing relative paths for the newly generated 2D textures in the .MTL file, it becomes possible to automatically load the model with these textures. The method for switching between different textures in Blender is derived from its internal settings and the Workbench rendering engine (for further details, see *https://github.com/ArchaeoComp/D-stretchToBlender*).

The texture maps were edited using DStretch and prepared for import into Blender software for analysis. Editing involved applying pre-tested filters LRE, YRE, YBK, and CRGB (at scale intensity 20).

To maintain objectivity and comparability, flat lighting and visualisation via solid viewport shading was applied throughout the data corpus. This configuration results in an ideal depth and colour ratio of the surface that does not suppress the texture, but rather emphasises it and thus allows for detailed examination.

Due to the limited legibility of 3D traces in 2D media such as images, all 3D models of the analysed figurines are available in the open-access dataset NEOFIG (Kaňáková & Nosek, 2024). In this dataset, individual figurines were marked by an ID based on the code of the site (TK) and the order number (for example TK123).

Reflected-light microscopy was used for the further verification of the traces identified by DStretch. Polarised light had to be used, due to the conservatory coating on almost all the figurines, which reflected direct light and made any observations impossible. Standard magnification 50× was used, and 200× when it was necessary to observe pigment traces in more detail.

Small amounts of pigment were scraped from the ceramic sherds (seven samples) and the figurines (two samples), and placed on a glass slide. To analyse the chemical composition of the pigments, Raman spectroscopy was used. The analysis was carried out using a Renishaw inVia Qontor Raman microspectrometer. Diode-pumped solid-state lasers with excitation wavelengths of 532 (green) and 785 nm (near infrared) were used to illuminate the samples, displaying ~0.5-5 mW on the surface of the sample. A Leica 50× (N.A. = 0.50) and 100× (N.A. = 0.85) objectives were used to focus the laser on the surface of the sample. The instrument was used with both standard and high confocality and 1200 grooves/mm optical grating. The measurements were performed with varying exposure times to achieve the best possible noise-to-signal ratio. In order to identify the phases based on their Raman spectra, the RRUFF database was used (https://rruff.info/).

Seven pigment samples were taken from ceramic sherds found in the same archaeological context as the figurines, and two were sampled from smaller figurine fragments. We can assume that the pigments used for the painted ceramic vessels and figurines are of the same type, chemical composition and geological origin, since the ceramics were found in the same archaeological context as the figurines. Substituting the figurines by sherd samples was necessary for two reasons: the common contamination of figurine paintings by conservatory coating, which was previously used to fix and protect the paintings, and the high heritage protection of figurines, whose visual details should not be altered even by minor sampling. On the other hand, pigment sampling was permitted on painted sherds, which were coated only exceptionally. This enables us to increase the number of samples. Three samples were taken from two figurine fragments, which were not coated. Red and yellow pigments were sampled as they were the most frequent pigments identified on ceramic objects of the Lengyel culture. Black pigment was not sampled, because fragments with sufficient amounts of this pigment are scarce and all of them were coated in the past. The nature of black pigment was determined using microscopy due to different optical properties of both possible substances of black pigment origin – charcoal and manganese oxide.

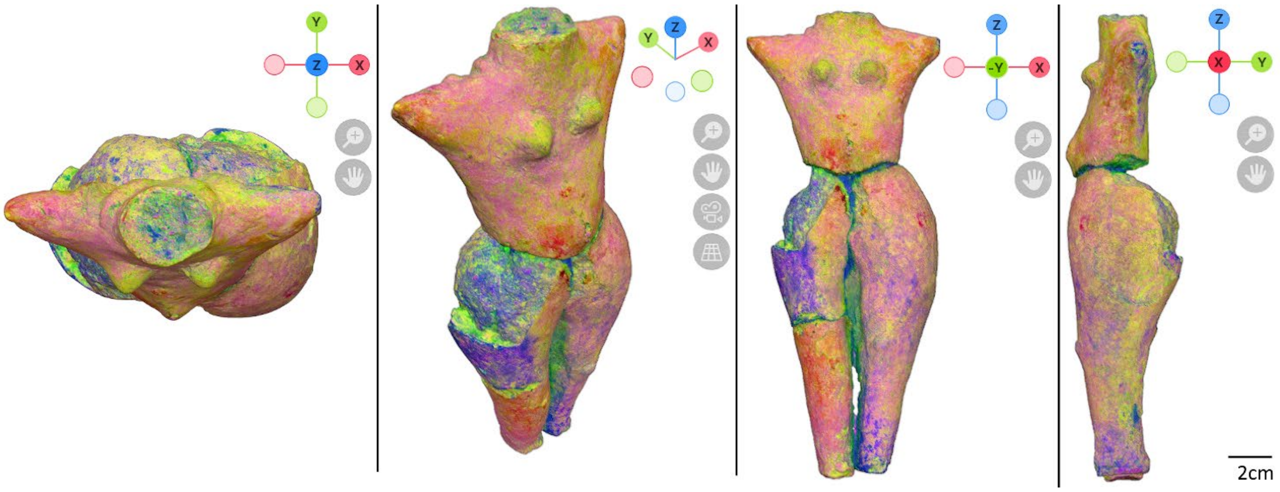


Figure 6: Texture modified by reapplying the DStretch onto the 3D model mesh – the previously concealed colour details of the surface become significantly more visible. Visualised on sample TK363 (CRGB).

3. Results

Careful naked eye observation reveals pigment residues on 123 figurine fragments, which amounts to 33 % of the collection, a substantial increase compared with the last results from the 1980s (24,64 %). This difference can be put down to a more focused observation directed at areas where the surface was irregular with crevices or grooves, which are more resistant to mechanical cleaning.

3.1. DStretch identification

Applying DStretch, a certain degree of false positives was expected due to the common presence of mineral inclusions of various colours in the surface layer of the fired clay. These inclusions were originally covered with fine engobe that was used to finalise the surface prior to firing and painting. The engobe was partly or entirely removed and the inclusions were revealed during extensive brushing (Fig. 7a). Another difficulty emerged when analysing the DStretch visualisation: in some cases, the mechanic cleaning was so rough that unidirectional band traces of the figurines' original surface were revealed in the calcareous layer, which resulted in false motifs of different colour (Fig. 7b). Therefore, it was always necessary to validate the nature of the detected structures through an alternative method of examining the surface, such as microscopy, which would either confirm or refute the previous visual identification. However, given the time-consuming nature of such microscopic analysis and the fact that some artefacts had an extensive surface to observe, it would be critically time-inefficient to examine the entire outer surface of each artefact in this manner. When combined with the preliminary identification through the analysis of decorrelated textures, this joint analysis becomes synergistic and significantly increases the efficiency of surface examination and the chance of identifying pigments and other anomalies on artefacts.

In a collection comprising 378 fragments, preliminary visual inspection with the naked eye identified 123 samples that showed pigment residues. Microscopy confirmed the presence of pigments in 29 instances where the detected traces were not captured by DStretch. DStretch analysis, on the other hand, revealed a total of 186 pigment traces, which is an increase of approximately one-third compared to those identified solely with the naked eye. Importantly, only one instance of a false positive was identified among the cases of colour traces identified through DStretch, which proves high reliability of this method.

This improvement in the detection of pigment traces is seen not only in the increase in the number of identified traces but also in the variety of detected pigments. In 29 cases, the macroscopically detected yellow pigment was complemented with newly detected red or several variations of red. In addition, black painting was secondarily identified in five other cases, and yellow painting was detected in two cases. These results highlight the effectiveness of DStretch in both expanding the range of detectable pigment traces and improving the accuracy of pigment identification on prehistoric ceramics.

Given that pigments often occur in multiple combinations within a single sample (typically red-yellow or yellow-black combinations), it is essential to analyse the surface of the artefacts using multiple visualisation filters. This approach facilitates the identification of painting residues that might have otherwise been missed (Fig. 7c,d). Using a single filter for the entire collection would result in the loss of valuable information from other spectra. The following filters were found particularly effective for identifying and visually locating pigments on the studied collection: LRE, YRE, and YBK. These filters do not suppress other colours but effectively highlight the target pigments – LRE and YRE enhance red in particular, while YBK is optimal for black and yellow.

In addition, YRE and YBK were also successful in detecting rare traces of white pigment, found in only 15 samples. Depending on the colour of the surrounding surface, these residues of white pigment typically appeared as shades of blue to green (Fig. 7e,f). Similarly, black pigments demonstrated colour shifts in the filters and sometimes appeared as purple (Fig. 7g) depending on their surrounding context. Understanding this shift, validated by further microscopic analysis, made it easier to empirically detect additional pigment traces.

The CRGB filter has proven to be most successful in revealing pigment residues across the database, effectively enhancing all target colours, including red, black, white, and yellow. However, its broad detection range also resulted in the highest number of false positives. CRGB is therefore most effective when used in conjunction with at least one other filter tailored to a specific colour, such as YBK, which is particularly successful in identifying yellow and black pigments. This combination of filters refines the localisation of pigments and reduces the risk of inaccuracy.

The CRGB filter is particularly effective at detecting red pigments, while yellow and black are most commonly identified through the YBK filter. However, the visual and morphological characteristics of the artefact's surface heavily influence the identification of pigments, which is yet another reason why areas initially identified by one filter had to be further examined using additional filters in real time.

This multi-filter approach allows for a comprehensive and nuanced examination of pigment traces, maximising the amount of information recovered from the surface of the artefacts. Even if the colour does not appear as clear with other filters, the way pigment residues are visualised through filter combinations—ideally CRGB paired with LRE or YRE, or YBK paired with CRGB—greatly assists in the accurate identification of actual pigments while minimising false positives. It should be emphasised, however, that this method is not automated; user control remains essential. The operator must interpret the findings, carefully evaluating the data.

Some false positives discovered during the analysis were caused by the combination of the original colours of the surface. For example, an orange surface, along with calcareous deposits and scratches from depositional and cleaning processes, appeared as a red trace under DStretch analysis, mimicking the colour of pigment residue (Fig. 7h).

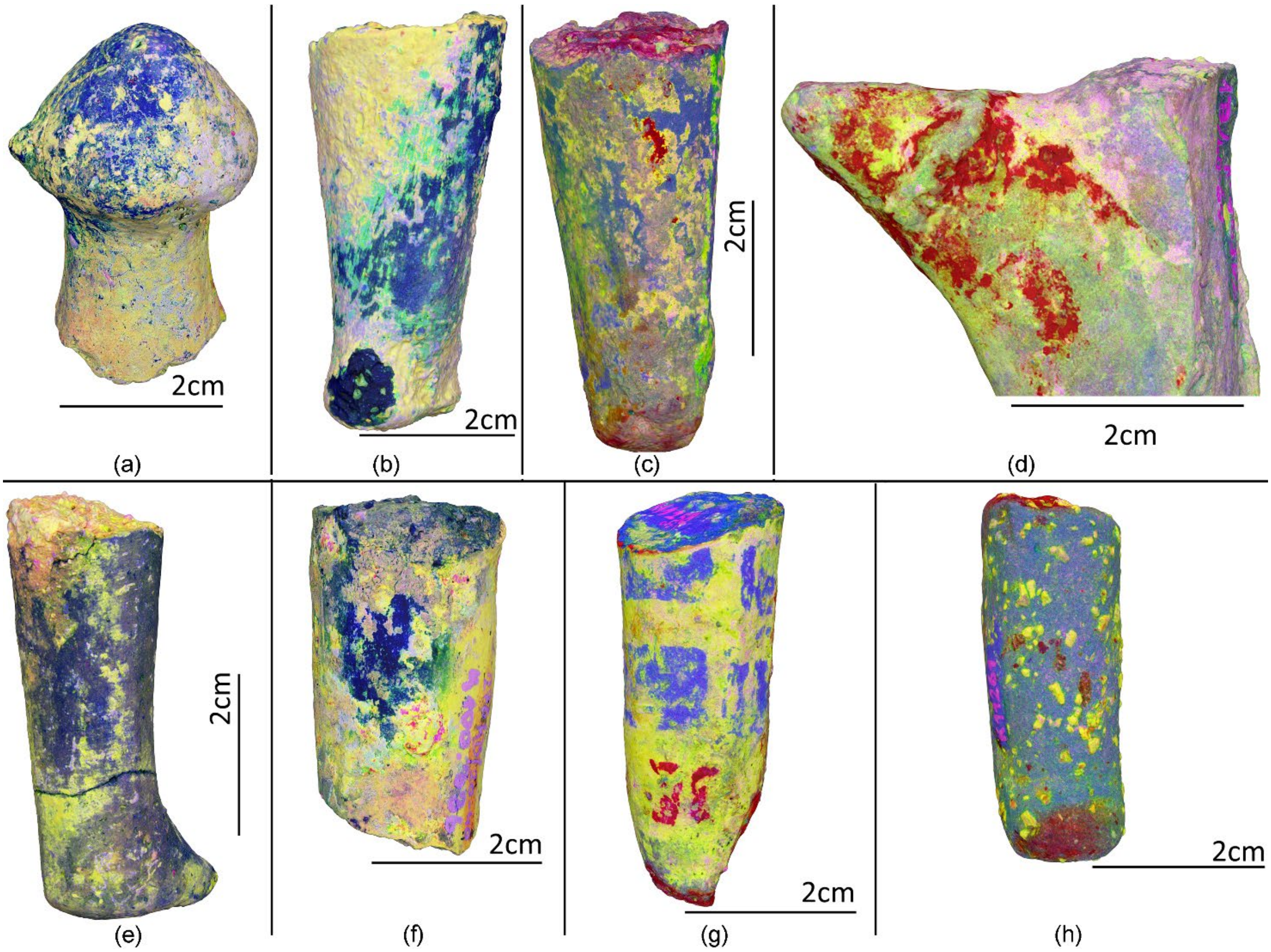


Figure 7: DStretch view of colour features on the figurine's surface: a) Revealed red inclusions – TK111 (YBK); b) linear traces of recent removal of engobe by brushing, which forms a false black colour trace – TK357 (YBK); c) differences in pigment trace visibility in the case of superposed pigments – TK044 (CRGB); d) differences in pigment trace visibility in the case of superposed pigments – TK145, (CRGB); e) visualisation of white pigment traces in blue shades of DStretch – TK124 (YBK); f) visualisation of white pigment traces in green shades of DStretch – TK181 (YBK); g) visualisation of a black pigment trace in a purple shade of DStretch – TK138 (YBK); h) a scratch revealing the orange core as a false positive red trace – TK141 (CRGB).

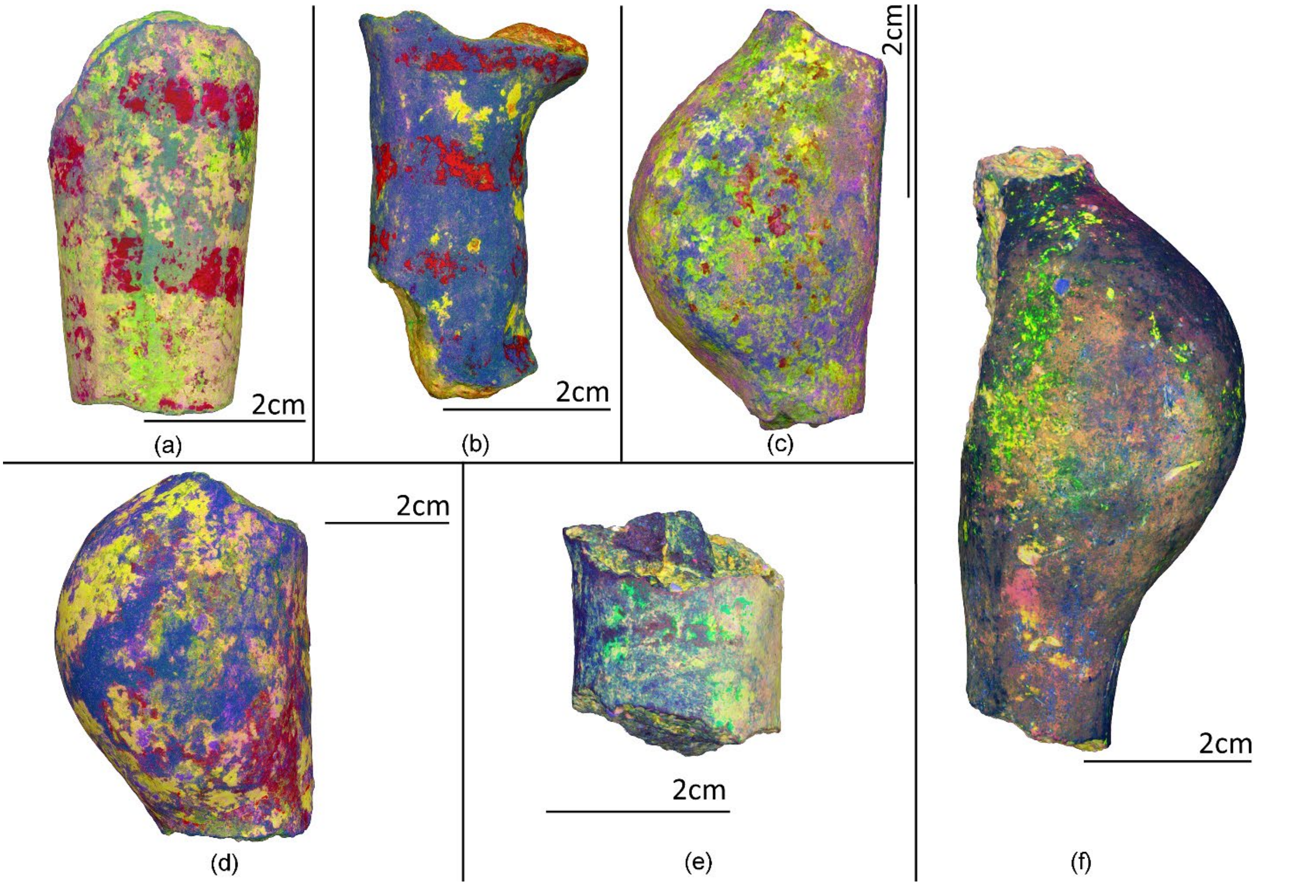


Figure 8: Band motifs in DStretch visualisation. Well preserved bands with legible trajectory and borders: a) TK043 (CRGB); b) TK052B (CRGB); fragmented band motifs whose trajectory can be reconstructed; c) TK222 (YBK); d) TK248 (YBK); examples of the presence of pigment traces in a location typical for band-motifs e) TK121 (YBK); f) TK227 (YBK).

Similarly, the calcareous crust was highlighted in yellow, resembling a base pigment. Without further validation, these areas could have been misclassified as pigment residues in an automated analysis.

However, human oversight and subsequent microscopic validation revealed the true nature of these colorations, allowing the sample to be correctly identified as a false positive. The surrounding surface plays a crucial role in pigment identification, as it can alter the perceived colour of the pigment in the DStretch filter. Successful identification, especially in the case of pigments preserved only fragmentarily, requires a combination of both visualisation techniques and a skilled operator, particularly when the surrounding surface morphology and texture are more complex.

The acquired data should be approached empirically, with constant revalidation of previous results. Ideally, a double cross-check should be performed to ensure the accuracy of pigment identification. This rigorous approach helps to reduce errors and ensures the reliability of the conclusions drawn from the analysis.

3.2. DStretch reconstruction of the motifs

Although painted motifs had been identified on well-preserved figurines in the past, DStretch significantly improved their legibility and thus their further evaluation. The motifs were preserved at a considerably different level of completeness: from a well–preserved band with clear borders and a legible trajectory (Fig. 8a,b) to fragmentarily preserved pigment traces outlined in an identifiable trajectory (Fig. 8c,d). In some cases, only small traces were identified in locations typical for motifs but not complete enough to prove any specific motif or unpreserved pigment coating (Fig. 8e,f).

Nearly all identified or successfully reconstructed motifs were formed by band lines, usually simply painted in a non-interrupted line. In two cases, band motifs composed of red fingerprints lined one after another were identified (Fig. 9a,b). The most frequent were red bands pronouncing the suprailium and the groin, running around the rear part of the waist and obliquely from the hips towards the lap in the front part of the pelvis (Fig. 9c,d,e,f). Such bands were proven in 35 cases. Another band motif was painted around the rear part of the neck, running obliquely from the shoulders towards the chest (21 cases identified - Fig. 10a,b,c,d). No case was identified, in which the potential meeting point of this motif was preserved, leading us to the conclusion that the lines did not meet, and their ends were free, running around the lower inner quarter of both breasts. Parallel band motifs were applied vertically on hips and buttocks (17 cases, Fig. 11a,b,c) or horizontally on limbs (32 cases, Fig. 11d,e,f). Pigment traces identified on the surface of the heads indicate that other motifs were applied both on the hair zone (20 cases, Fig. 12a,b,c) and even over the face (9 cases, Fig. 12d,e,f). Unfortunately, these were not sufficiently preserved and legible.

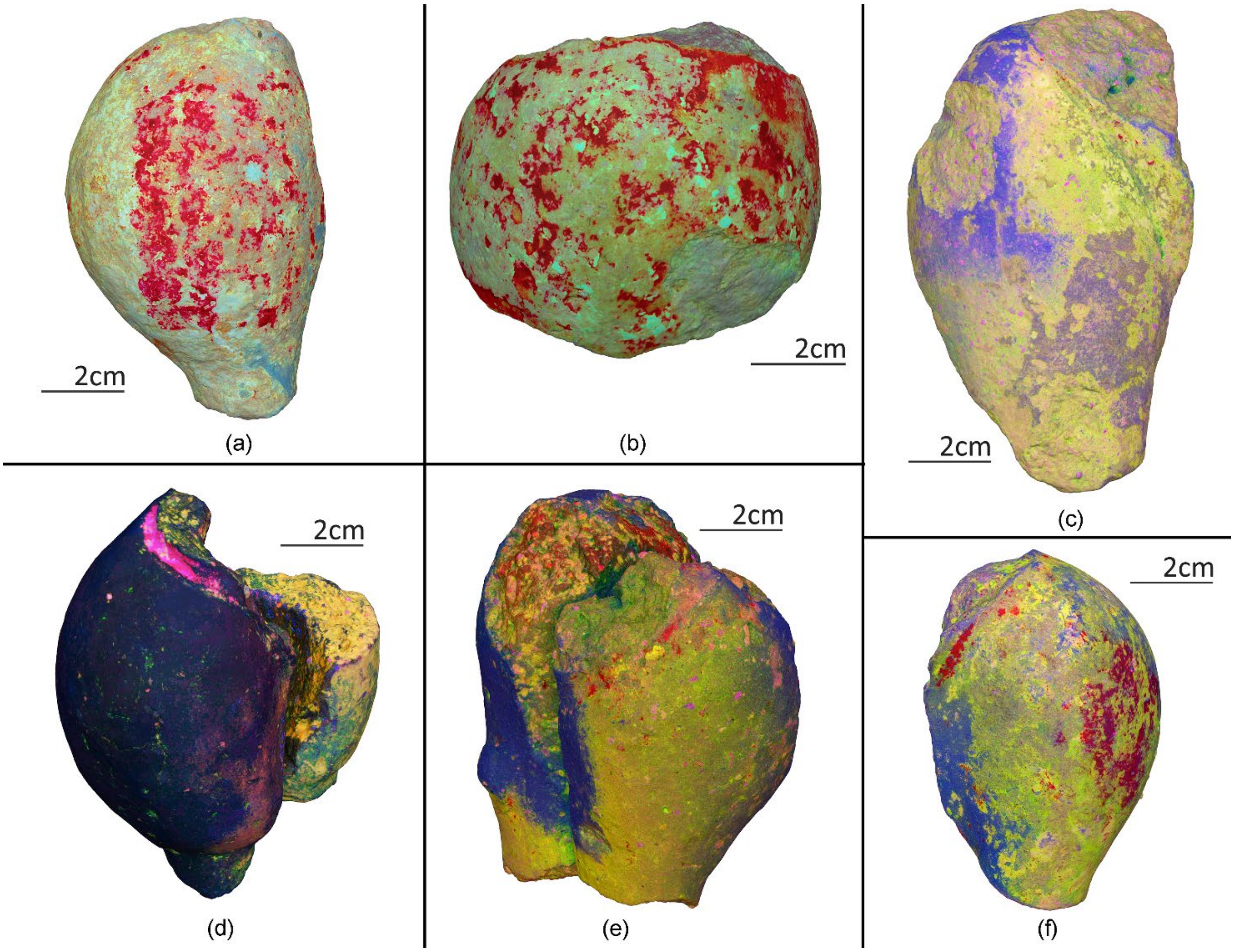


Figure 9: Painted motifs. Vertical lines over buttocks and hips formed by fingerprints lined one after another: a) TK079 (LRE); b) TK178 (LRE); band motifs over the suprailium and groins c) TK022 (CRGB); d) TK005 (YBK); e) TK234-235 (CRGB); f) TK075B (CRGB).

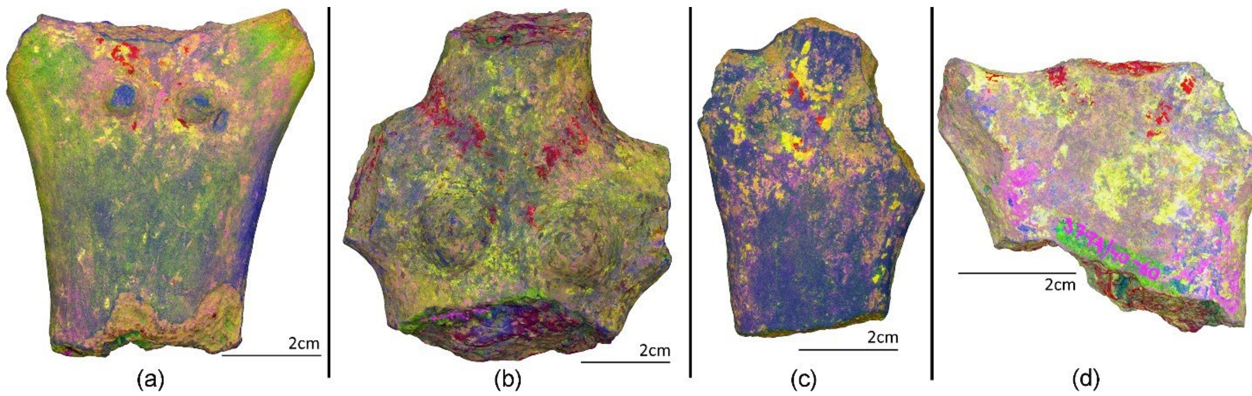
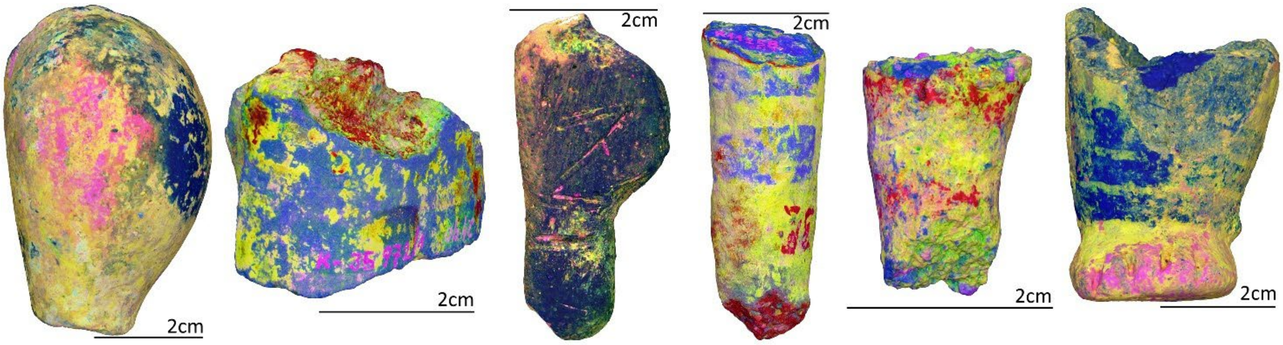
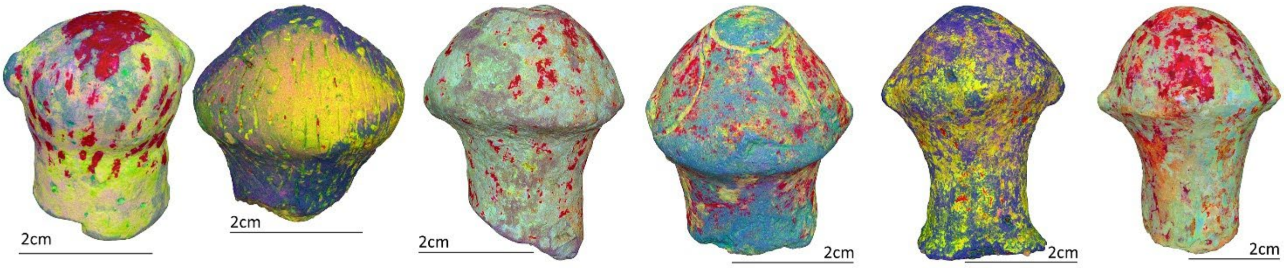


Figure 10: Painted motifs. Band motifs around the neck running towards the chest: a) TK182 (CRGB); b) TK193 (CRGB); c) TK228 (CRGB); d) TK310 (CRGB), with no proven frontal joint.



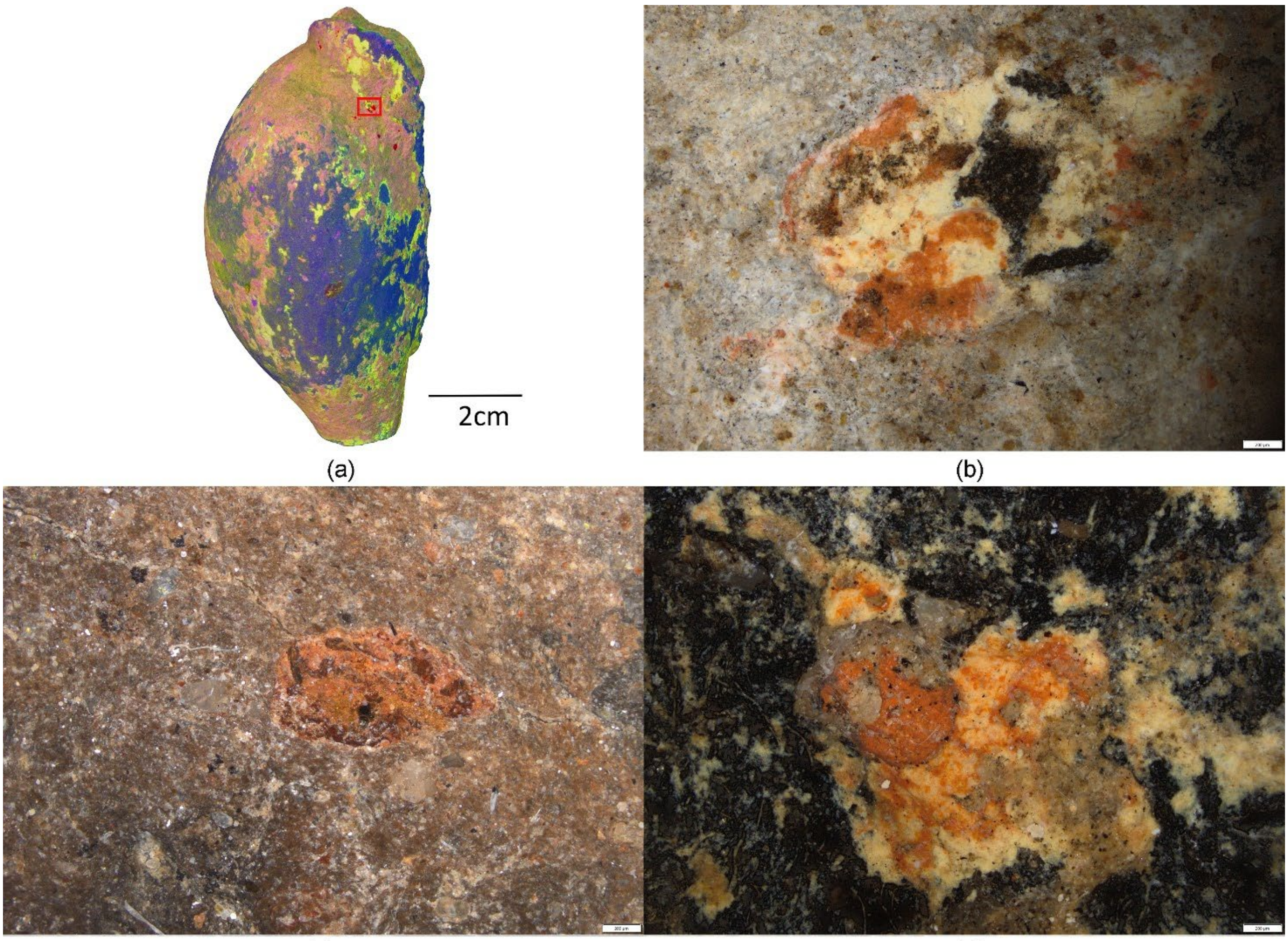
(a) (b) (c) (d) (e) (f)

Figure 11: Painted motifs. Parallel vertical bands on hips and buttocks: a) TK075B (CRGB); b) TK052A (CRGB); c) TK296 (CRGB); horizontal bands around the limbs d) TK138 (CRGB); e) TK197 (CRGB); f) TK203 (YBK).



(a) (b) (c) (d) (e) (f)

Figure 12: Painting applied over the hair zone: a) TK231 (CRGB); b) TK131 (CRGB); c) TK069 (LRE); and over the face: d) TK071 (CRGB); e) TK133 (CRGB); f) TK185 (LRE).



(a) (b)

(c) (d)

Figure 13: Pigment traces through microscopy, magnification 50× and 200×: a) Submillimetre red pigment trace (TK004) identified in DStretch and b) verified by microscopy; c) hematite inclusion emitting a false positive signal (TK114); d) red pigment trace next to a red inclusion (TK133).

3.3. Microscopy

The detailed examination of the surface using low power (50×) microscopy was not time-consuming (just a few minutes per sample) when verifying the DStretch results, in which the locations of pigment traces and their distribution patterns had been previously identified. Without such guidelines, it takes more than an hour per sample, depending not only on its size and area of the preserved original surface, but also on the time-consuming positioning and difficulties with regard to the shape irregularities and dimensions. The positively verified pigment traces identified by DStretch included many cases of even sub-millimetre pigment residue (Fig. 13a). It was easy to eliminate false identifications in the case of both inclusions and negative traces in the removed calcareous layer or engobe caused by improper surface cleaning. Inclusions could be mistaken for exclusively red traces. Inclusions emitted a false colour signal, mostly in the case of bright red or red-orange hematite grains (Fig. 13b), commonly present in the used clays. Their optical signal is the same as in the case of the used red pigment (Fig. 13c,d) due to their identical origin. Sometimes it was not easy to decide whether the colour trace was a hematite inclusion or a painting residue, because a certain part of these inclusions revealed on the surface had a flat and granular morphology, similar to that of the pigment trace, and they did not necessarily have sharp borders and a regular shape (Fig. 14a). In such cases, higher magnification was used to identify the typical fissure around the inclusions, which resulted from nearly indiscernible shrinking of the matrix during firing (Fig. 14b). Another mineral inclusion which emitted a false colour signal was feldspar; its dark brown-reddish variant was a common natural inclusion of the clay matrix (Kreiter et al., 2024). Eliminating feldspar inclusions under the microscope was much easier due to their optical properties and structure, because (unlike pigment traces) they are semitranslucent and their grains have a well readable surface relief, usually rounded (Fig. 14c). Nevertheless, not all inclusions highlighted by DStretch are false positive identifications. Occasionally, the pigment traces survived the brushing only on the surface of the inclusions (Fig. 14d), while the pigments were brushed-off from the surrounding ceramic surface. A false colour signal was also produced by traces of brushing when the distinct colour of engobe or core was revealed. Typically, this colour can be easily mistaken for black and yellow pigment traces due to the most common colour of the original fired surface of the figurines (Fig. 15a,b). If the engobe was also removed, false positive orange or reddish traces may have been produced (Fig. 15c). In both cases, the absence of pigment is evident even at low magnification, because the typical structure of the ceramic mass formed by the matrix and various types and fractions of mineral inclusions can be observed (Fig. 15d).

Undeniable pigment traces were identified on 215 figurine fragments, which amounts to 57 % of the collection.

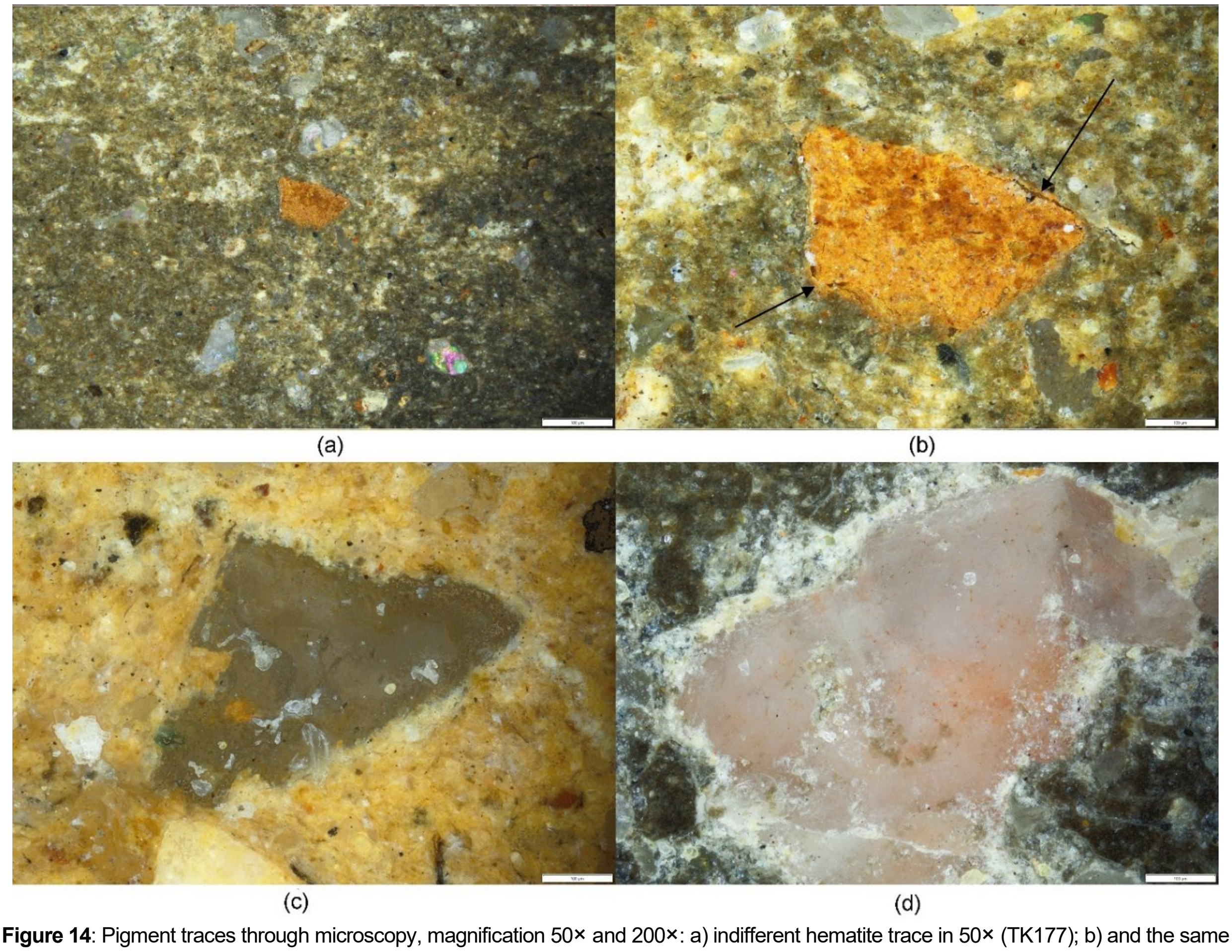


Figure 14: Pigment traces through microscopy, magnification 50× and 200×: a) indifferent hematite trace in 50× (TK177); b) and the same trace in 200× revealing the fissures caused by shrinking (TK177); c) feldspar inclusion emitting a false positive signal seen under the microscope (TK274); d) quartz inclusion coloured by pigment residues (TK172A).

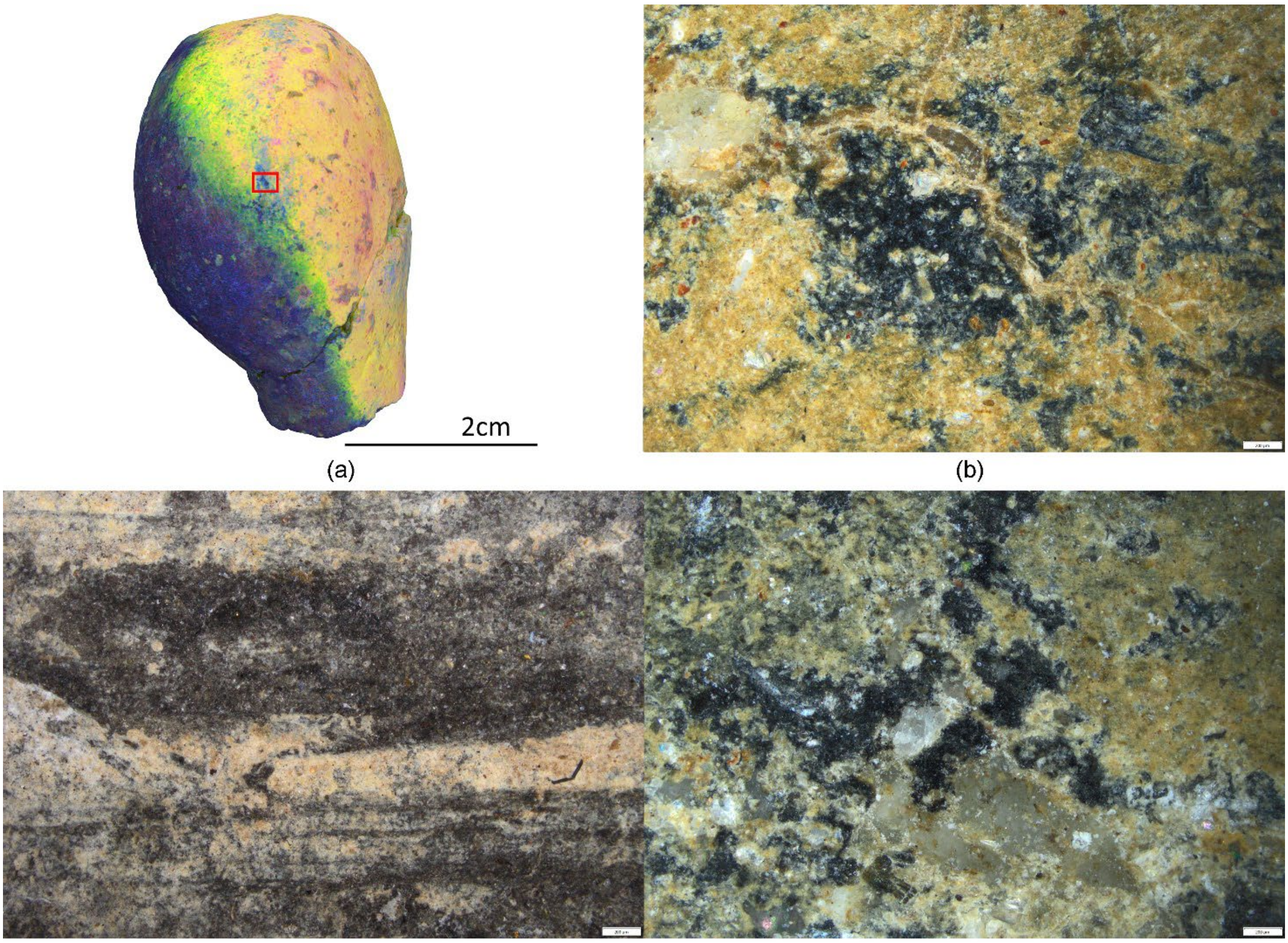


Figure 15: False positive identification of the colour of ceramic surface in DStretch: a) TK032 and through microscopy: b) TK049 magnification 50×; False positive identification of the colour of ceramic core through microscopy magnification 200×: c) TK029; d) TK032.

Compared to DStretch (186 identifications), the higher number of microscopic identifications falls to traces smaller than 0.1 millimetre.

In addition to the presence or absence of the pigments, we focused on pigment texture, homogeneity and stratigraphy. The most commonly used pigment was red, identified on 156 figurine fragments. Its typical appearance is bright and light red colour, granular and homogeneous, with sharp boundaries of the motifs (Fig. 16a,b). Surprisingly, another red pigment was identified; in 16 cases, both red pigments occurred on the same fragment. Its appearance differs in both colour and consistency, the colour tends to be more orange or dark, and the solution is heterogeneous, with more concentrated pigment corpuscles and spots, and a less coloured semitranslucent crust (Fig. 16c,d). Being aware of the previously common post-excavation practice of overall conservatory coating, the possible confusion with such contamination was carefully eliminated. Using excessive pressure, recent coating applied with brushes could hypothetically release pigment corpuscles from the original pigment traces and redeposit them over a wider area, colouring even the coating itself to a certain extent. However, the two red pigments never overlap, and their distribution is different (Fig. 17a,b). Red pigment was used only exceptionally for overall or partial coating (six times), and in one case only it was superposed by another pigment. Its dominant purpose was to paint band motifs, which were applied in a similar scale on the original fired surface of the figurine (Fig. 17c) or over previous yellow (exceptionally white) coating (Fig. 17d). Combinations with another pigment were frequent (96 pcs, 62 % of pigment occurrence); the most common is red superposing a yellow coating (49 times) or a yellow pigment trace (two times) that was not preserved sufficiently to prove overall coating. Only exceptionally does the red overlay a white coating (three times).

Yellow pigment was identified on 128 figurine fragments. Its typical appearance is homogeneous, well dissolved, and of bright light colour, well distinguishable from the ochre or orange colour of fired surfaces or from the grey-yellowish calcareous layer under the microscope (Fig. 18a,b). Yellow painting was predominantly used for the overall coating of the figurine (in 89 cases), while no proven isolated motifs were identified. In 39 cases, the pigment traces were not sufficiently preserved to prove there was an intention to coat the entire figurine. More than two thirds of the fragments, on whose surface the yellow pigment was identified, were painted with at least one other pigment. Thanks to microscopy, the direct superposition with another pigment was identified in 69 cases; in 68 cases, yellow was superposed by another pigment, whereas only in one case did the yellow pigment superpose another pigment. Red pigment dominated in both superposition and combination, whereas black and white pigments were rare (Table 1).

White pigment forms a homogeneous crust, identified in 15 cases, both as isolated traces (six cases), coating superposed by other pigments (three cases) or combined with them without superposition (six cases). Most likely, white pigment was randomly used to substitute yellow pigment. Black pigment was preserved in 18 cases. In almost all cases, the traces were formed by a manganese oxide solution, which left typical dark brown-red borders around the traces (Fig. 18c,d). Charcoal particles were identified on only one sample (Fig. 18e).

Black pigment was used only for band motifs, which were applied only on the lower half of the body. They never occurred on the thorax, neck or head, although this is known from other regions of the Lengyel culture (e.g. Falkenstein figurine displays black motifs on the head, sometimes interpreted as hair – Neugebauer & Neugebauer 1982, 18). The identified black pigment traces were isolated (five cases), combined with other pigments (two cases) or superposing another pigment (11 cases).

In one isolated case, it was proven that pigment residue on the surface of the figurine was not caused by intentional painting, but by depositional contact with pigment accumulation. It is the only case where pigment traces were distributed over a fracture surface (Fig. 18f). This figurine was found in settlement feature No. 379, where small accumulations of yellow pigment were found. Unfortunately, the excavation documentation is not detailed enough to prove the immediate finding location of the figurine near such accumulation.

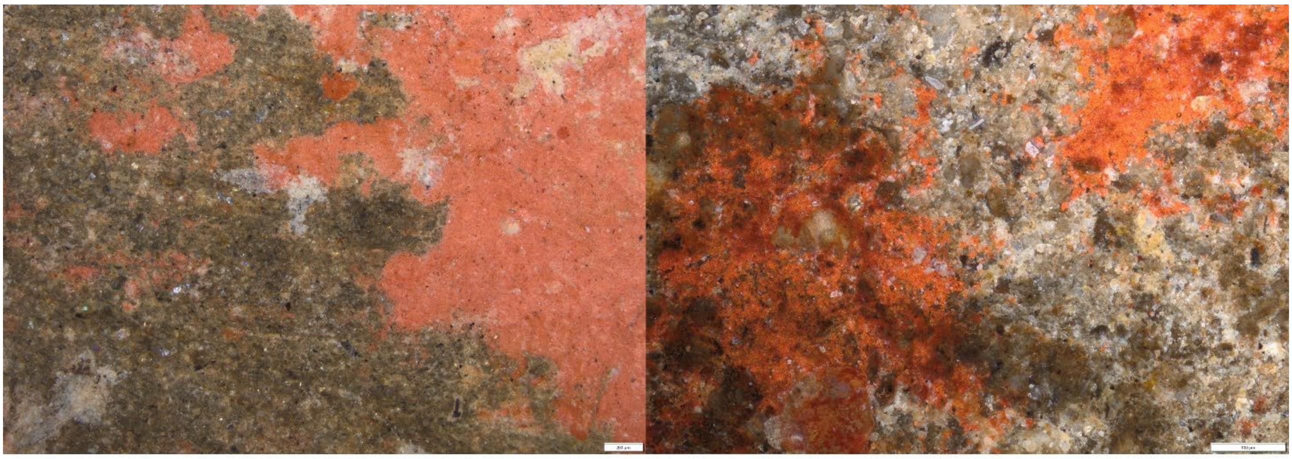
3.4. Raman microspectroscopy

The pigments could be identified with one exception (figurine No. TK010). On TK010, pigments were scarce in the white matrix and the few brownish-yellow grains could not be identified by Raman. All the other identified phases are summarised in Table 2.

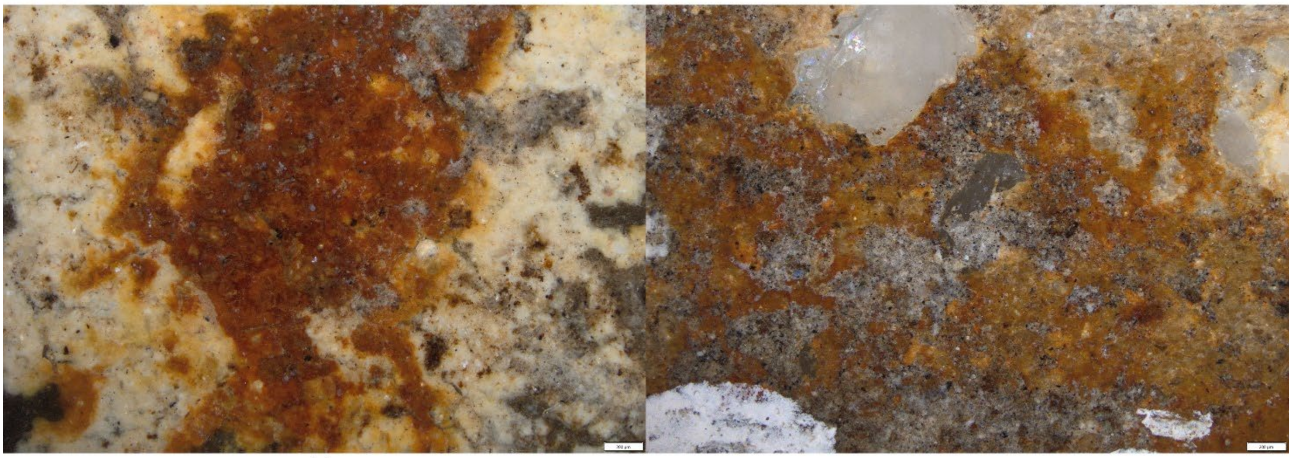
All the red pigments were identified as hematite (α-Fe_2O_3) on the basis of their main Raman bands near 225, 248, 293, 413 and 1320 cm^{-1} (Fig. 19a). In the case of yellow pigments, all samples from the ceramic sherds contain jarosite ($KFe_3(SO_4)_2(OH)_6$). Its characteristic Raman bands can be observed near 227, 436, 624, 1009 and 1105 cm^{-1} (Fig. 19b).

One of the figurine samples (TK314) also contains jarosite (Fig. 19c), however the other figurine sample (TK248) is different. Its scarce yellow pigments were identified as goethite (α-FeO(OH)). The main bands of goethite are ~ 302, 391, 480 and 548 cm^{-1}.

In summary, common earth pigments were identified in both pigment types (red and yellow). In the reds, the main pigment is hematite, which is the most common mineral in red ochre and red earth paints (Eastaugh, 2008). The yellows in all the samples are mainly composed of jarosite. Jarosite is usually a yellow or yellow-brown coloured mineral, which is a common weathering product

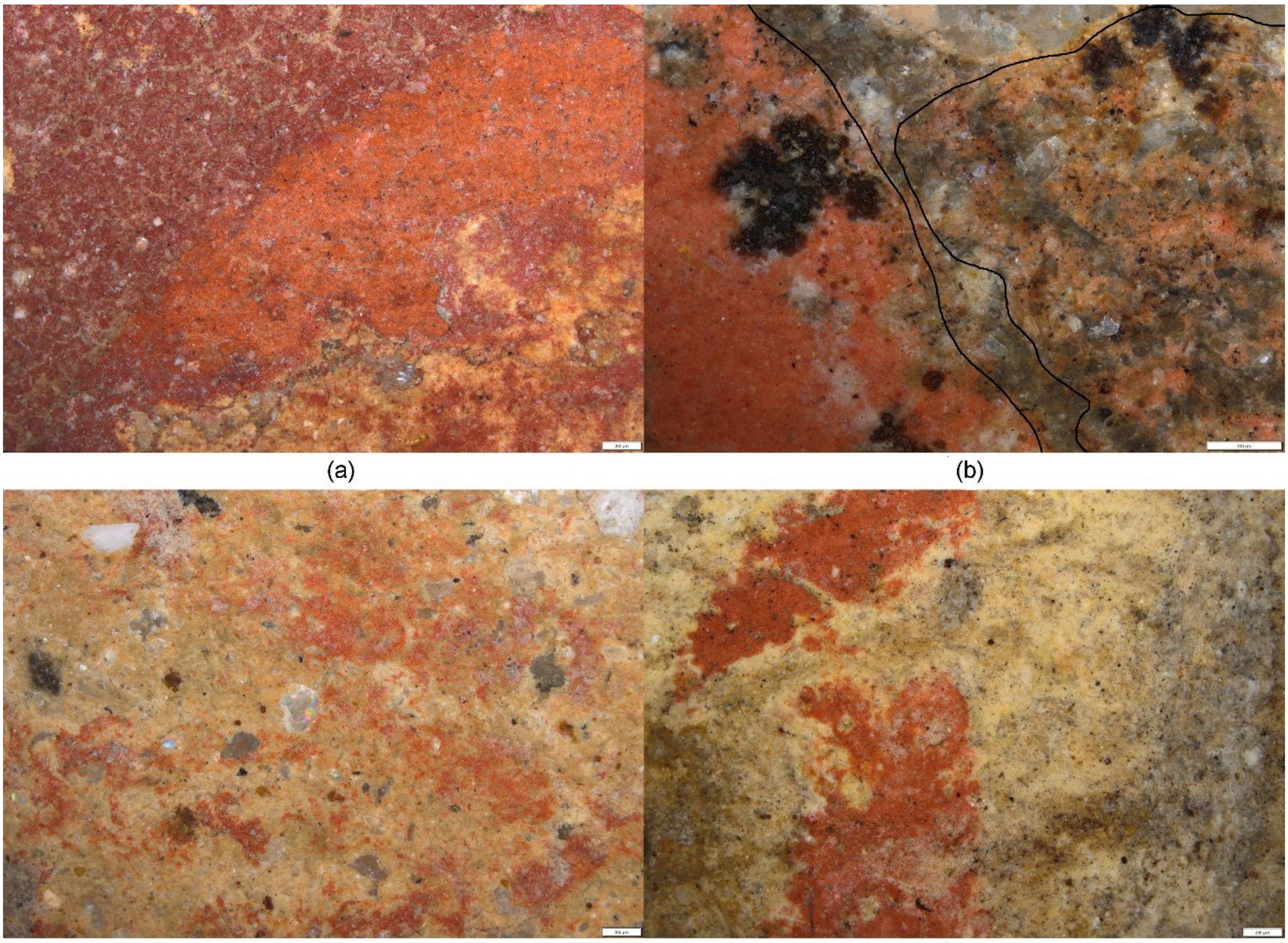


(a) (b)



(c) (d)

Figure 16: Pigments. Typical appearance of the red pigment: a) TK043; b) TK074; Heterogeneous red pigment: c) TK044; d) TK089.



(a) (b) (c) (d)

Figure 17: Pigments. Distribution of two distinct red pigments on the same figurine fragment: a) TK045; b) TK043; c) a red pigment motif applied over the original surface – TK078; and d) over previous yellow coating – TK138.

Table 1: Pigment occurrence in the collection of figurines from Těšetice–Kyjovice. Pigments are abbreviated by their initial (Y – yellow), combined with C for coating by that pigment (YC – yellow coating), RR means the presence of two distinct red pigments, * Combination with another red pigment.

	Single pigment		Combined with another pigment		Superposed by another pigment		Superposing another pigment
pigment	traces	coating	as traces	as coating	as traces	as coating	
Yellow	24	16	13 (10R, 1RB, 2W)	7 (6R,1RB)	2 (R)	66 (49R, 2B, 7RB, 8RR)	1 (1RC)
Red	56	5	29 (16Y, 2YB, 4W, 7R*)	n	N	1 (1YB)	68 (64YC, 2YT, 2WC)
Black	5	n	2 (2YR)	n	N	n	11 (9YC, 1RC, 1WC)
White	5	1	4 (2R, 2Y)	2 (2RR)	N	3 (2R, 1B)	n

of pyrite-bearing rocks (Eastaugh, 2008) and a common component of yellow ochres. The pigment on one of the figurines (TK314) has the same composition (hematite and jarosite) as that one on the sherds, but the pigment on figurine TK248 consists of goethite. Goethite is a common mineral of yellow ochres.

Most soils, formed by the weathering of the underlying rocks, contain various Fe-oxides and hydroxides. These minerals are common earth pigments, found in differently coloured ochres and have been used since prehistoric times, in the past 300000 years (e.g. Rosso et al., 2016; Zipkin et al., 2017). While red ochres are mainly dominated by the presence of hematite, yellow ochres are mainly composed of goethite (e.g. Sidall, 2018; Mastrotheodoros & Beltsios, 2022). Jarosite can also appear in yellow ochres (Sidall, 2018).

The difference of the main component of yellow pigment between TK248 and all the sherds suggests that the raw material of the earth pigments could have been sourced from a different locality. However, since red and yellow earth pigments are common, their provenance is impossible to assess. Concerning the provenance of the Jarosite, pyrite is the most common sulphide mineral and is widely distributed in igneous, metamorphic, and sedimentary rocks. It is a common accessory mineral in igneous rocks, such as granite (Brathwaite, 2014; Göd, 2017). The area surrounding the site primarily features various types of granite and gneiss and their metamorphosed variants (metagranitoids, schistose metagranitoids). Granite outcrops occur within a few hundred meters of the site (Valová, 2007, 9; Petřík et al., 2015, 41). Therefore, the yellow pigment could also have been sourced locally. It is clear, however, that figurine

TK248 was painted in a different yellow than the sherds and the other analysed figurine (TK314).

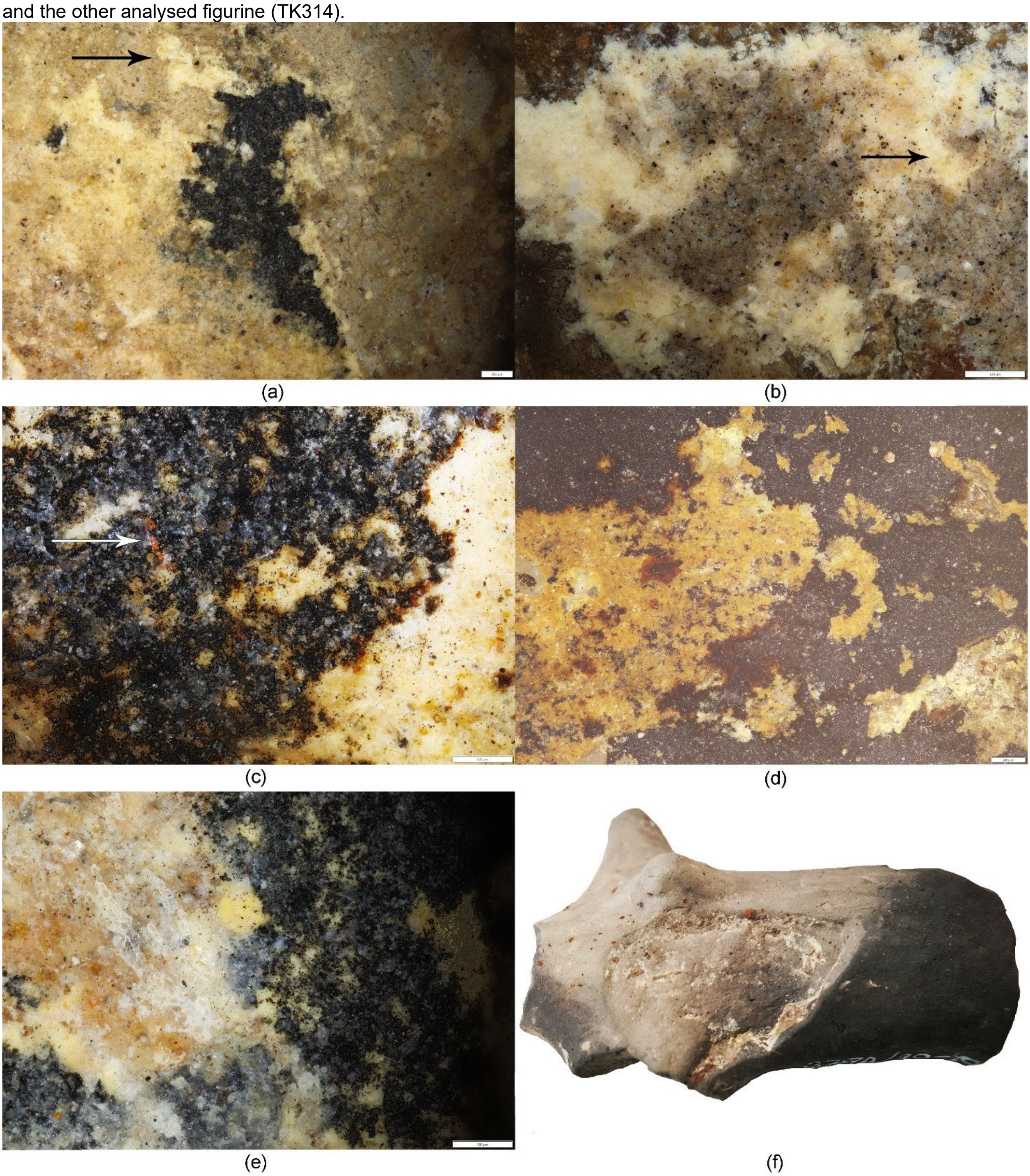


Figure 17: Pigments. Yellow pigment superposed by a calcareous crust: a) TK012; b) TK040; Black pigment trace with a dark brown reddish border: c) TK138; d) TK257; e) identified charcoal particles – TK007; f) exceptional distribution of the yellow pigment over the figurine's fracture caused by depositional coincidence with pigment accumulation – TK306).

Table 2: Summary of Raman analyses on the studied pigments. Phases in parentheses represent only rare grains. n.d. – not determined.

Type	**Sample**	**Raman bands (cm^{-1})**		**Identified phases**	
		Red	***Yellow***	***Red***	***Yellow***
Ceramics	TKs18	229, 295, 413, 616	224, 440, 624, 1012, 1101	hematite	jarosite
	TKs10	-	n.d.	-	n.d.
	TKs43	-	227, 436, 624, 1009, 1105	-	jarosite
	TKs38	224, 289, 409, 611, 1309	-	hematite	-
	TKs84	225, 294, 410, 1322	-	hematite	-
	TKs79	226, 296, 414, 600	-	hematite	-
	TKs143	223, 292, 408, 607, 1320	-	hematite	-
Figurine	TK314	226, 294, 412, 610, 1320	225, 435, 632,1107	hematite	jarosite (hematite)
	TK248	-	302, 391, 480, 548	-	goethite (hematite, carbon)

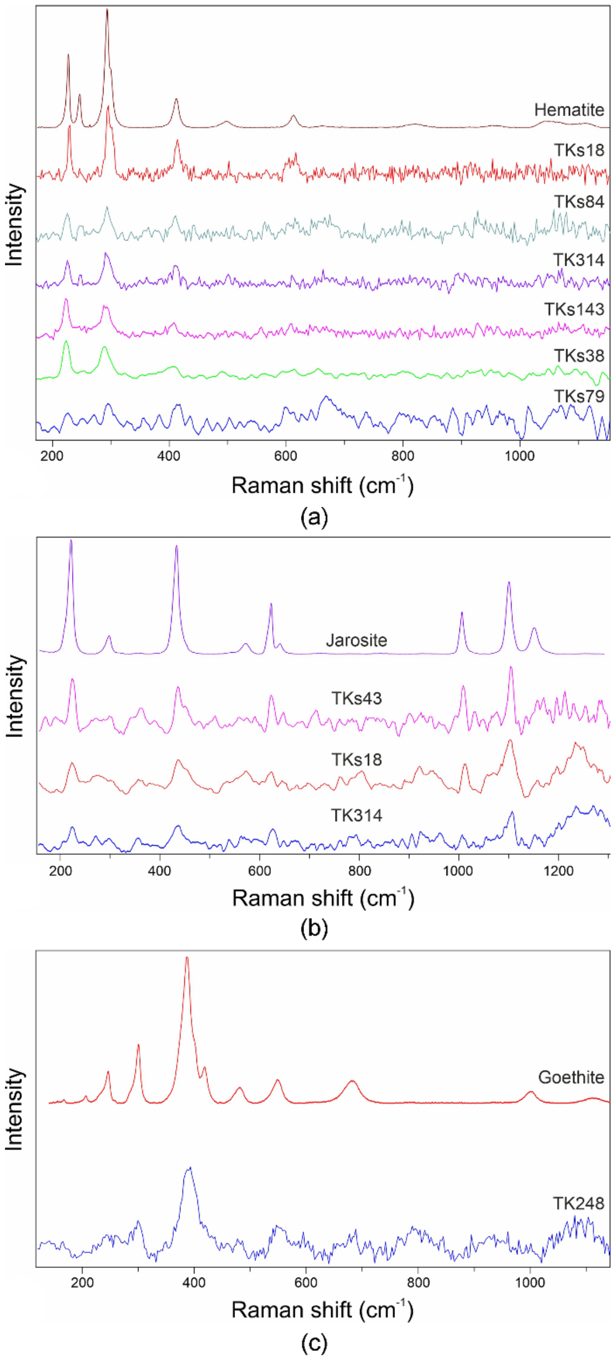


Figure 18: Results of Raman spectroscopy: a) spectra of hematite identified in red pigments; b) spectra of jarosite identified in yellow pigments; c) spectra of goethite identified in yellow pigment of sample TK248.

4. Discussion

While it would undoubtedly be ideal to produce 3D scans of artefacts immediately after excavation, we understand that this is not always feasible or a priority in the immediate post-excavation phase. However, even lightly cleaned artefact surfaces can still benefit from preliminary analysis, particularly using DStretch applied to photographs (which is rather quick). This relatively simple and accessible approach can provide valuable insights that might otherwise be overlooked, even before more advanced scanning or microscopy is possible.

Implementing DStretch analysis at this stage could play a crucial role in identifying areas with potential pigment traces, thus guiding the subsequent handling and cleaning processes. The early detection of pigment residues, however tentative, could lead to a more careful and targeted approach when cleaning, increasing the likelihood of preserving these fragile elements. Such an approach would encourage greater awareness and caution in areas where pigments are more likely to survive, thus reducing the risk of accidental damage.

Although less comprehensive than using 3D scans, DStretch applied to 2D photographs at this preliminary stage could still be instrumental to preserving valuable cultural data. By providing an initial understanding of pigment distribution, it would enable conservators and researchers to adjust their methods accordingly. Even a simple increase in attention and care in the exposed areas could significantly enhance the preservation of ancient pigments and improve the overall quality of the artefacts' restoration and study in the future.

The same visualisation of the surface via DStretch as was done for the figurines was also applied to the sherd samples intended for Raman microspectroscopy. Once identified as a particular mineral such as hematite or goethite through Raman, the same colour signal in DStretch could be determined as the same mineral with a high degree of reliability (Fig. 20). The visual distinction between yellow pigments of jarosite and goethite could only be identified using the CRGB visualisation (Fig. 19 – samples TK248 and TK314). The application of the same procedure guarantees the same identification and interpretation of the detected pigment traces regardless of their wearer.

The presented approach frequently led to the detection of layered pigment traces – typically yellow overlaid with red, which were further covered by a calcareous layer. This calk exhibits similar macro-optical properties to the yellow and white pigments, so distinguishing it from actual painting relies on microscopic analysis. Similarly, black paint is often faded and appears grey, resembling the pigment-negative surface altered by long-term deposition.

That being said, the use of the YBK visualisation makes it possible to distinguish black pigment from false positives. The YBK filter, specifically adapted to these pigments, helps distinguish these subtle traces from the background noise that might otherwise obscure their detection.

We can conclude that despite the previous assumption that painted decoration of anthropomorphic figurines was rare or exceptional (Podborský, 1985, 92), painting residues were positively identified on almost 60 % of the same collection. With regard to the widely proven systematic unintentional damage through the post-excavation cleaning of the figurines, we can assume that most likely all or almost all figurines were originally painted. Although the motifs are fragmentary and rarely preserved in large areas or clear context, we can attempt to group the surviving painted patterns into several distinct variants. These patterns appear to be contextually limited to specific areas of the artefacts. This restriction may have been driven by cultural factors (band motives in the suprailium, around the neck or limbs), but it is also possible that certain parts of the figurines just provided larger surfaces for painting more extensive designs or motifs (hips and buttocks). The distribution and consistency of pigment traces across the artefacts suggest that these areas were selected intentionally.

Considering the hypotheses about the meaning of the motifs that were formulated in the past, when only the naked eye or a small lens could be used, our results have supported some, but refuted others. As for the hypothesis that some motifs depicted clothing, we can conclude that no clothing, such as skirts and shirts was depicted. The apparent support for this hypothesis was the existence of two tiny figurines whose hollow lower parts were formed conically, like a skirt, without the legs (Těšetice, Pottenbrunn). Judging by their lower rim, however, they were most likely not autonomous figurines, but small figural pot-lids. Figural applications on pot-lids were quite common in the Lengyel culture (Doneus & Rammer, 2017, 337; Kalábková, 2010, 49-50). Therefore, there is no evidence supporting the idea that figurines had skirts – formed from clay or painted; all figurines were depicted naked. The rich vertically delineated patterns preserved on the figurines' hips and buttocks can thus be interpreted as yet another way of accentuating the pelvic area, in addition to its volume. We see it as potentially important that the patterns formed by fingerprints (requiring repeated direct touching) occur only in the pelvic area.

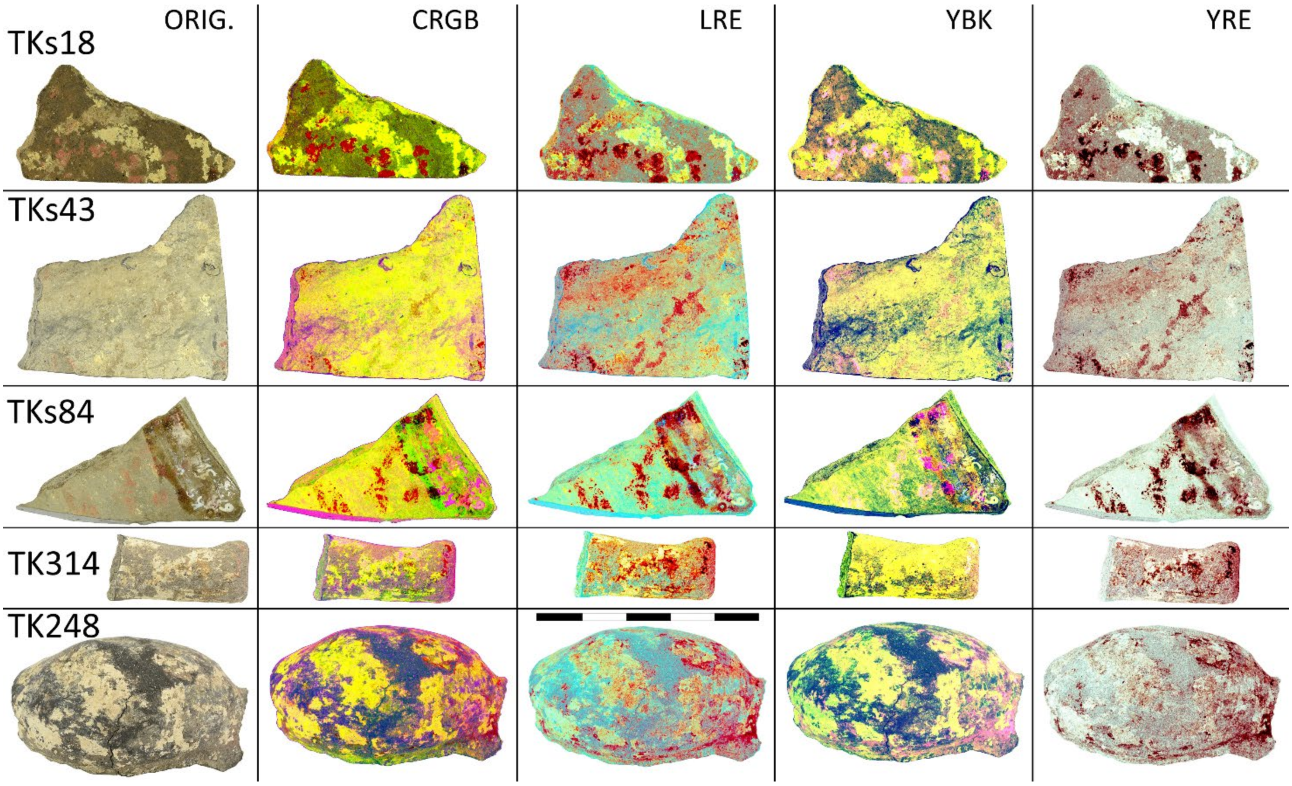


Figure 20: DStretch visualisation of painting sampled for Raman spectroscopy. Sample TK248 (yellow phased by goethite) and sample TK314 (yellow phased by jarosite).

The hypothesis presenting the red bands as early copper jewels also remained weak, because the trajectory of the motifs reconstructed via DStretch does not present any way how such jewels could have held on the body. We can leave out the argument that such jewels are unknown from archaeological evidence in central Europe in this period, because such a motif could spread in visual form only, but not necessarily as a tangible object. The supposed necklace contour is not reliably joined on the chest in any of the samples. Moreover it is not comparable with the few double-spiral pendants of the type Malé Leváre or Jordanów, the first copper jewels known from later periods (Dobeš et al., 2019, 42). In the case of the supposed waist belt, it also would have been impossible to be worn in the way it is depicted. The horizontal band motifs on the limbs might have depicted certain actual body decorations. Textile bands attached to limbs were depicted in Levantine art (Beltrán 1968, 44), even if in the opposite part of Europe. Of course, this cannot be used as an a priori analogy, but at least it shows us that such a kind of band motifs did exist in the live culture and the common human appearance or visage. In the case of the pigment applied to the area of the head, we agree with the previously stated opinions that the colour most likely represents hair in the majority of cases. Where the engraved hairline was accentuated, it may evoke the use of pigment surviving in certain cultures until recently, whereby a coloured parting served as a status indication. However, this motif is too scarce to be interpreted. Therefore, we lean towards the conclusion that band motives could have had their origin both in common profane body decoration and in certain accentuation of specific body parts. Their possible symbolic meaning on ceramic figurines is still unproven. If symbolic narration was somehow reflected in any of the painted motifs, it would have been most likely those applied to the pelvic area.

5. Conclusion

Pigment traces are at risk of degrading during standard post-excavation processes, and thus their early detection is essential for research as well as conservation. However, relying on a single method, whether it is based on naked-eye observation or advanced image processing, risks producing incomplete or inaccurate results. Therefore, we have developed a workflow that combines different detection methods and is suitable for analysing 3D objects such as figurines.

The combined use of naked eye observation, decorrelation algorithms, and microscopic analysis forms a comprehensive approach to identifying pigment traces. Having specified the areas of interest by preliminary naked eye observation, the decorrelation algorithm plays a crucial role in enhancing the visibility of faint pigments by increasing the contrast between colour channels. We have managed to adapt this image processing tool to 3D textured scans, which is more suitable for the complex morphology of the figurines than simple 2D. However, the algorithm can sometimes generate false positives by exaggerating the natural colour variations or surface features. Therefore, the results had to be validated through microscopic analysis, which is able to detect false positives thanks to the optical and structural properties of the surface and thus confirm whether the traces identified by the decorrelation algorithm are indeed pigments or simply natural discolouration. The last step in our workflow was Raman spectroscopy, which enabled us to identify the chemical composition of the pigments, possibly hinting at the provenance or local sourcing of the material. While microscopy is highly accurate, it can be time-consuming, so the preliminary analysis through DStretch is essential. The multi-faceted approach presented in Fig. 5 highlights the importance of continuous revalidation and cross-checking to ensure the highest possible standards of accuracy, but at the same time, aims to be efficient enough to process large collections of artefacts. These yield big data necessary to observe cultural patterns.

Thanks to the efficient workflow, we managed to analyse the largest figurine dataset of the Lengyel culture. The results suggest that figurine painting was more common than was previously thought. Much of the original pigment may have been lost during the post-excavation processes, which led to a more problematic reconstruction of the motifs. That being said, every pigment trace potentially holds information and could provide a clearer picture of ancient artistic expression.

Most importantly, this workflow could be adjusted to be useful even in field conditions, where the preliminary identification of pigment traces could reduce the risk of artefacts being damaged when cleaned or otherwise handled, ultimately preventing the loss of valuable cultural data.

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