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Revisiting the Jerash Silver Scroll: A new visual data analysis approach

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ABSTRACT

This article revisits a complexly folded silver scroll excavated in Jerash, Jordan, in 2014 that was digitally examined in 2015. In this article we apply, examine and discuss a new virtual unfolding technique that results in a clearer image of the scroll's 17 lines of writing. We also compare it to the earlier unfolding and discuss progress in general analytical tools. We publish the original and the new images as well as the unfolded volume data open access in order to make these available to researchers interested in optimising unfolding processes of various complexly folded materials.

1. Introduction

1.1. Jerash, the silver scroll, and its cultural context

Since 2011, the Danish-German Jerash Northwest Quarter Project (DGJNWQP) has been working at the second-most visited archaeological site in Jordan, Jerash (Fig. 1), only surpassed by Petra in the south. Jerash, founded in the Hellenistic period, thrived throughout the Roman to the Early Islamic period until an earthquake hit the city in 749 CE, halting urban life for centuries (Kraeling, 1938; Lichtenberger and Raja, 2018a). The city, in antiquity named Gerasa, was one of the Decapolis cities, a group of more than ten cities, today located in modern Jordan, Israel, and Syria (Lichtenberger, 2003; Raja, 2012). According to legend, the city was founded by Alexander the Great or one of his generals, but it is more likely that the city was re-founded in connection with the resettlement of veterans who had served under the Seleucids in the era following Alexander's conquest of the East. Gerasa flourished from the Roman period well into the Early Islamic period, when in 749 CE it was hit by the earthquake (Tsafrir and Foerster, 1992). The earthquake left the city destroyed and only a small settlement continued to exist after this period (Lichtenberger and Raja, 2016). Only in the Middle Islamic period, from the 12th century, did Gerasa, then called Jerash, experience a moderate surge in inhabitants, although of a more decentralised nature than in the earlier periods (Lichtenberger and Raja, 2018b). From the Roman into the Early Islamic period, we can follow the development of the site and its cultural innovations through the archaeological and epigraphic evidence. We can observe the often slow advances and changes of the locally produced pottery as well as the constant but sparse number of imported ceramic vessels, which tell us about the strong tradition in Gerasa for being self-sufficient with everyday wares (Lichtenberger and Raja, 2019a, 2019b). Such observations were made possible through a full quantification approach applied in the excavations, including the ceramics excavated at the site by the Danish-German Jerash Northwest Quarter Project (Romanowska et al., 2018). Furthermore, we can trace the use and re-use of glass over centuries, which underlines the ways in which the society optimised its use of resources (Barfod et al., 2018). Studies of a coin hoard has shown how metal was kept, despite the fact that it may have been out of circulation and also underlines the take-over of Byzantine symbolic imagery in the Early Islamic period (Lichtenberger and Raja, 2015). Through studies of the urban soils and the hinterland developments we can also trace century-long slow process changes, which give insight into a gradual decline in the management of the hinterland as an effect of the climate changes in the late Roman and Byzantine periods (Lichtenberger et al., 2019). Such studies help us piece together the puzzle of a society which was multifaceted and complex and developed over centuries through shifting political and religious regimes and managed to flourish at least for more than eight centuries, until the earthquake put a hold to the city's development. The Jerash Silver Scroll represents one of the objects that give insight into continuing cultural traditions on the one hand and

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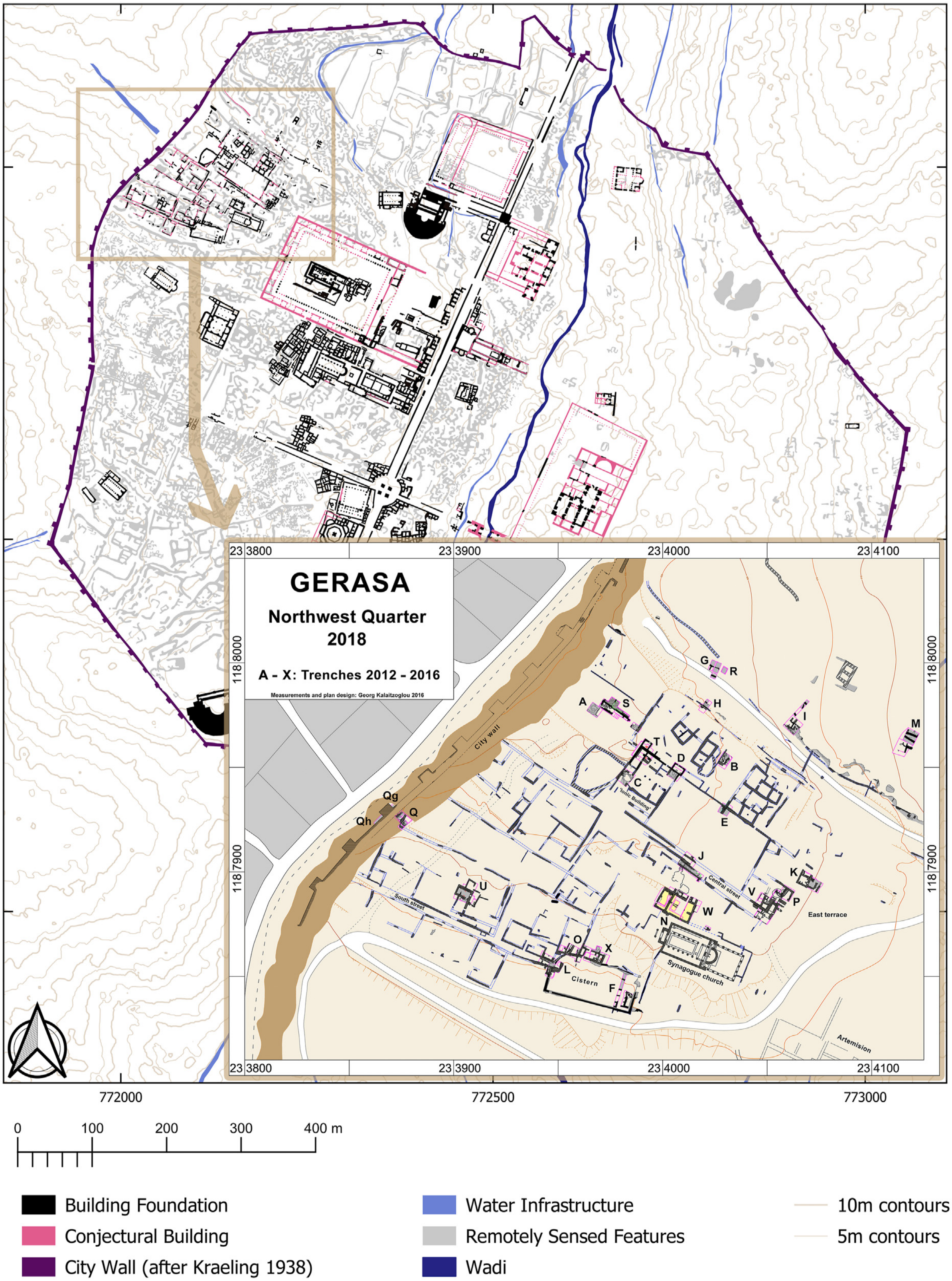

Fig. 1. Map of Gerasa/Jerash with insert of the Northwest Quarter and the excavated trenches (A–X). The scroll was found in trench K on the Eastern Terrace (DGJNWQP).

traditions that changed slowly as new cultures, and in this case languages, were introduced to the society (Larsen et al., 2016) on the other hand.

Gerasa flourished intensely in late antiquity and numerous churches were built in the city (Michel, 2011, 224-76). When the Levant was conquered by Muslims in 636 CE, including the city of Jerash, the Christian churches remained in use and Gerasa basically stayed a Christian city. Only one mosque was erected in the city center (Walmsley,

Fig. 2. Silver scroll (top) and lead case (bottom) after separation (DGJNWQP).

2018), and society remained mainly Christian until the earthquake. Therefore, it is highly interesting to shed more light on the city's cultural profile in the Early Islamic period. However, due to lack of inscriptions from this period, this proves difficult. The Jerash Silver Scroll employs two different scripts, but the one used for the main part of the 'text' could not immediately be identified. However, as a working hypothesis it is reasonable to assume that the scroll had been produced locally within a time frame of one hundred years, which would largely place it in the Umayyad period. Since the script is cursive and ligatured, the number of possible identifications is limited, and judging from the graphical repertoire, the best candidate is Arabic. However, since it has not been possible to establish a meaningful text, and since it contains some letters that cannot be interpreted as Arabic, the final evaluation is that the main script is pseudo-Arabic, serving magical purposes (Larsen et al., 2016). With this interpretation, the Jerash Silver Scroll, found in an Early Islamic destruction context, becomes an important contribution to our picture of the cultural profile of Jerash in this period. The scroll would have served as an apotropaic amulet or meant to cast a spell on someone other than its owner. The pseudo-Arabic script is complemented by letters that are interpreted as magical *charakteres* based on the writing on other amulets particularly from the Greek tradition (Larsen et al., 2016). The cultural historical importance of the scroll lies in the fact that at a time when Gerasa was a city under Islamic rule and had been so for more than a century, the Arabic language had not yet been fully adopted and the proficiency of writing and reading Arabic was not widespread. However, the fact that a look-alike Arabic script was applied shows that Arabic had begun to be an attractive cultural marker (Leitkultur) that was adopted by the Byzantine inhabitants of the city.

1.2. The Jerash Silver Scroll

In 2014, an earthquake-destroyed house was excavated in trench K in the Northwest Quarter (Fig. 1). The house gave a unique glimpse into the private sphere of the Umayyad period right before the earthquake struck (Lichtenberger and Raja, 2016). Among the finds was a 4 cm long lead

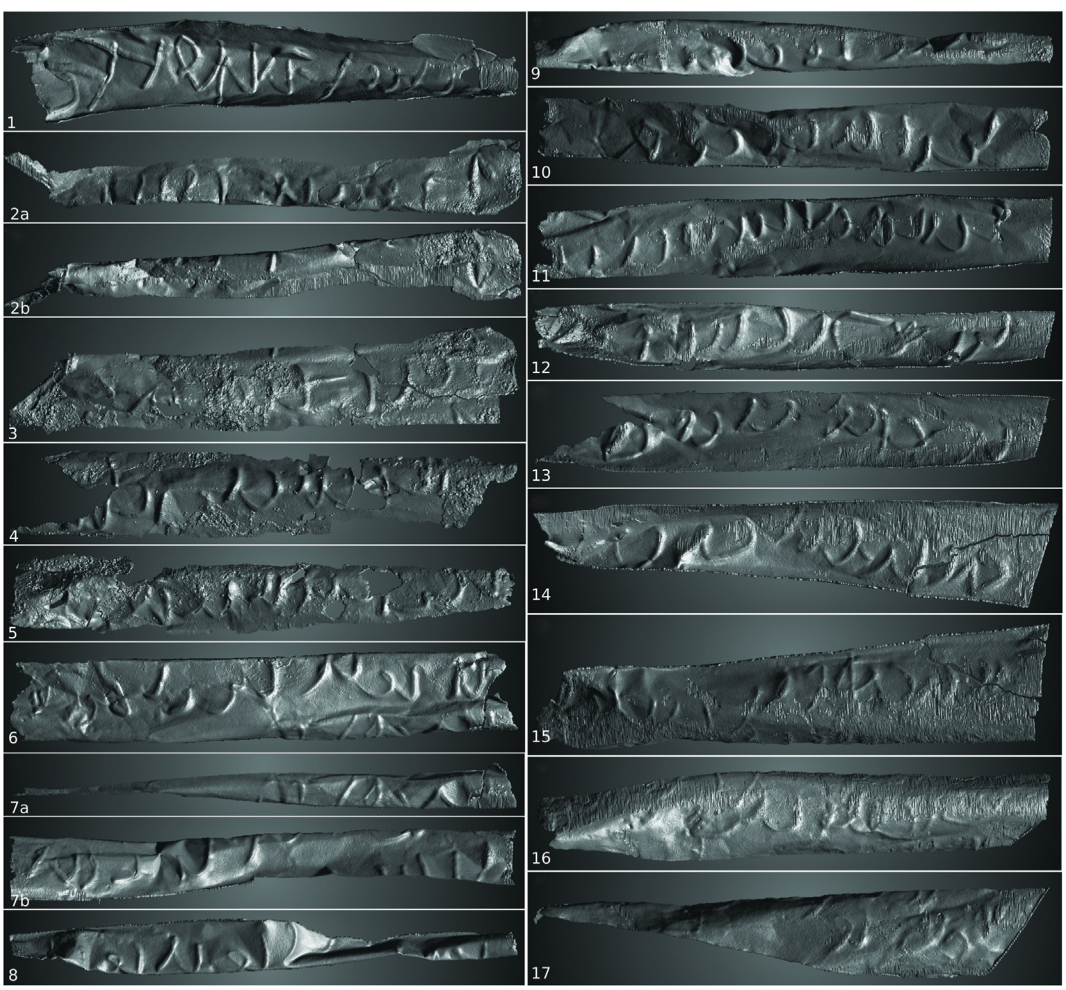

Fig. 3. Lines 1–17 from the silver scroll extracted with the previous approach (Barfod et al., 2015). The lines are all shown from the back sides, but are mirrored (DGJNWQP).

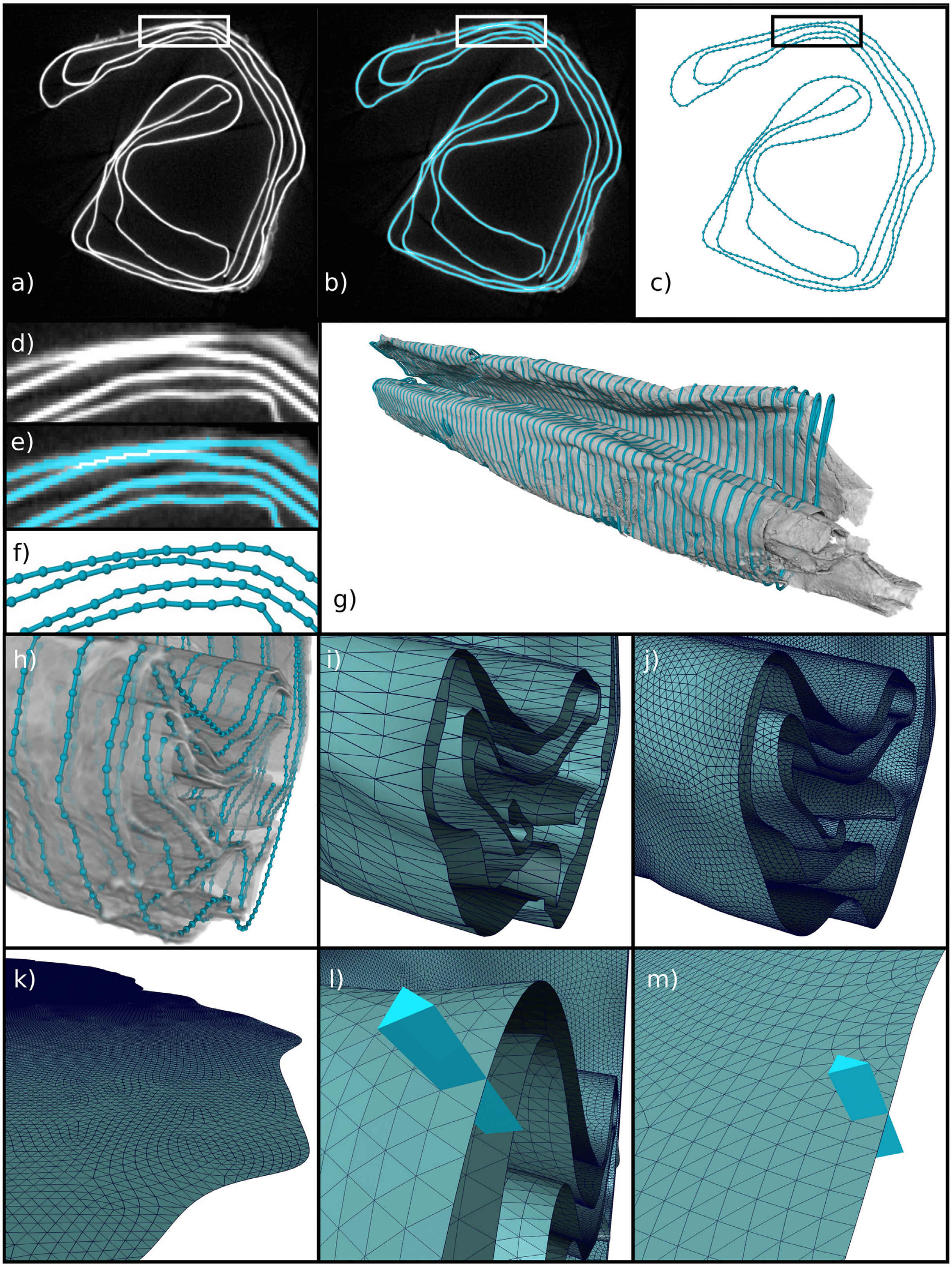

Fig. 4. Steps of new unfolding approach: (a–g) Creation of contours with details shown in (d–f) and all generated contours in (g). For the separation of the layers (d,e), manual correction was required. (h–j) Generation of medial surface approximation from contours: (i) Result after linking points on consecutive polylines; (j) Result after remeshing and smoothing. (k) Result of surface flattening. (l–m) Illustration of image transformation from 3D domain to flattened 2D domain using a prism for each triangle.

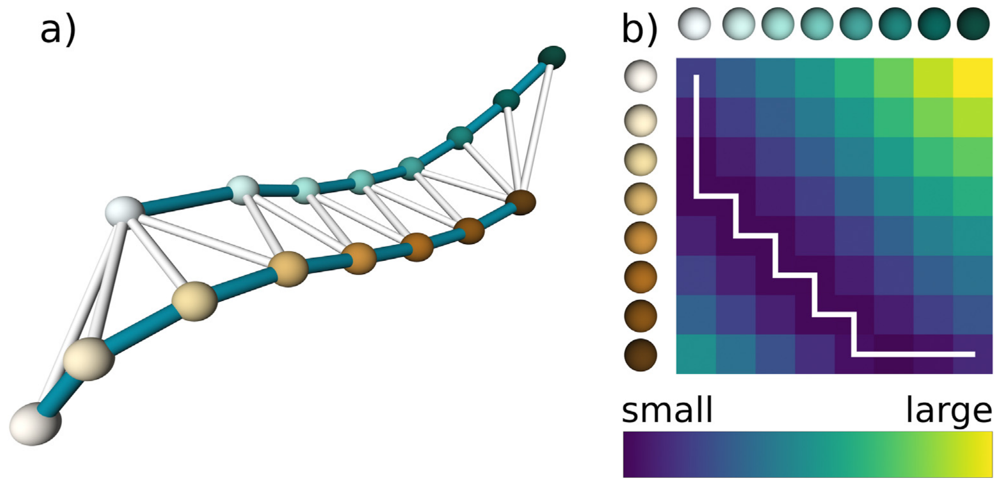

Fig. 5. Illustration of the point correspondence identification for neighboring polylines (contours). (a) Two sample polylines with the resulting point linkage. (b) Point-to-point distance matrix with shortest path drawn into it. This shortest path corresponds to the point linkage shown in (a).

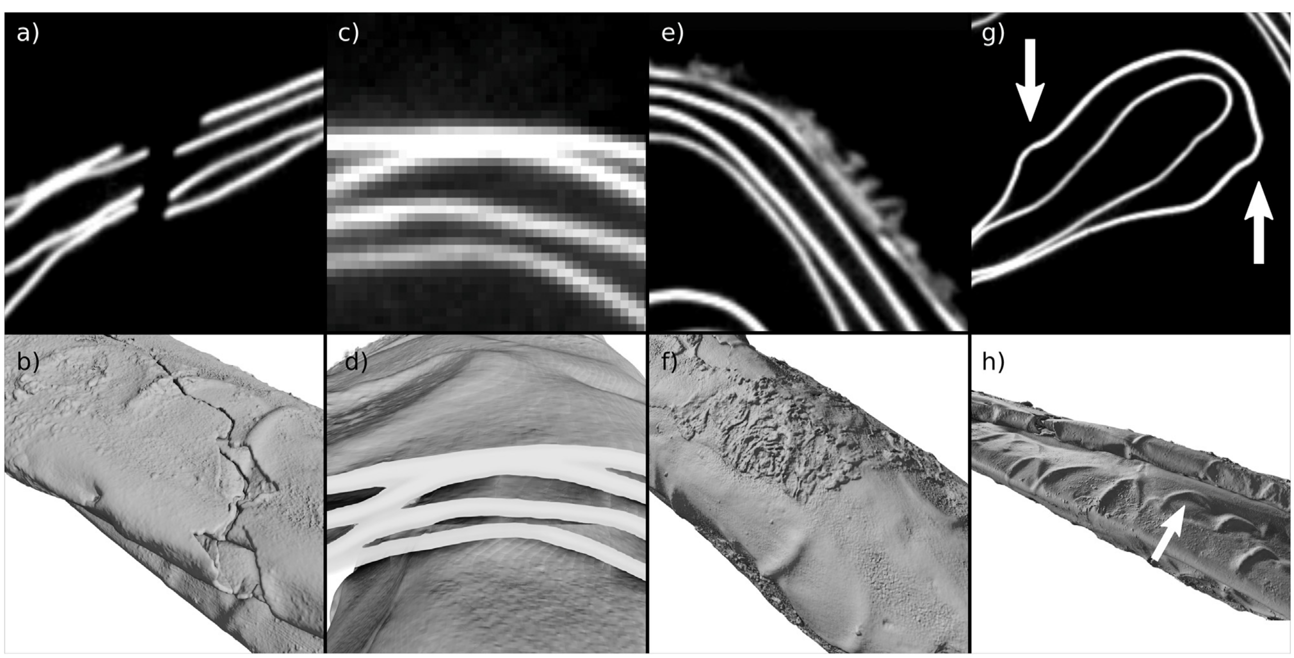

Fig. 6. Sample regions that illustrate the difficulty of using a fully automatic approach for contour determination: (a, b) broken layers; (c, d) fused layers; (e, f) corroded region; (g, h) contour bending resulting from imprinted script (indicated by arrows) that is hard to distinguish from bending due to folding.

tube containing a folded silver sheet (Fig. 2). The object was through its characteristics identified as a magical amulet, a token which was made and inscribed with a spell never to be read by any person after having been folded and put into a case, which either would have been carried by the owner or left in a secure place for protection (Barfod et al., 2015; Larsen et al., 2016). Since the thin metal sheet was too fragile to be unfolded manually, a non-invasive treatment was necessary and the entire scroll underwent a high-resolution micro-computed tomography (μCT) scan. The volumetric dataset was processed in VGStudio MAX developed by Volume Graphics in Heidelberg. Earlier, this software had been used to digitally unroll a Mandaean scroll (Neuber and Reinhart, 2012), but the complex folding of the Jerash Silver Scroll necessitated a different approach. The scroll was digitally dissected using a 3D drawing tool, revealing 17 lines of script (Fig. 3) (Barfod et al., 2015; Larsen et al., 2016). Most parts could easily be selected, but where folded parts touched others, processing was slow.

1.3. Contributions and data availability

Following the previous publication on the unfolding of the Jerash Silver Scroll, several attempts to reveal ancient texts on other sheet-like structures including metal sheets and papyri have been made with advanced image analysis methods (Seales et al., 2016; Baum et al., 2017; Liu et al., 2018; Rosin et al., 2018; Mahnke et al., 2020; Vavřík et al., 2020). These studies necessitated a reassessment of the scroll with a more advanced method. Hence, in this article we present an optimised, time-efficient unfolding of the Jerash Silver Scroll, which, despite not giving new results regarding the reading of the 17 lines of letters on the scroll, indeed gave a clearer and not least much faster result than the extremely time-consuming unfolding undertaken in 2015 (Barfod et al., 2015). With the new method we avoid the digital dissection of the scroll and obtain a reconstruction of the complete unfolded silver scroll in one piece. We thereby demonstrate that techniques are rapidly developing, that they can be applied much easier and more efficiently than just five

Fig. 7. Isosurface of unfolded scroll: front (left) and mirrored back side (right).

years ago, and that new unfoldings do not require revisiting the physical object but can be done on the basis of the earlier computed tomography data. Both the time-cost efficiency and the use of already obtained raw data bring with it new perspectives when it comes to optimised unfoldings of complexly folded ancient materials. In addition to these new results, we publish the three-dimensional (3D) μCT image data (Lichtenberger and Raja, 2020) and the digitally unfolded 3D image data (Baum et al., 2020) open access, allowing for a direct comparison with other approaches.

2. Material and methods

2.1. Image acquisition

After the folded silver sheet had been removed from the container, it was obvious that it could not be unfolded manually. It was too fragile and thin and an unfolding would have resulted in the destruction of the object and its text. Therefore, the sheet underwent a high-resolution μCT scan in a Phoenix GE v|tome|x M equipped with 300 kV microfocus X-ray tube and 2k imaging detector. The computed tomography was conducted by the company Vohtec in Garching at Munich in February 2015. The scan was done at an X-ray voltage of 270 kV and a current of 87 μA. The imaging setup produced a magnification of approximately 8.5x with a voxel size of approximately 23 μm. The 3D volume was then created on the basis of 1600 2D X-ray images recorded during the scan as the object was rotated 360° around its main axis.

2.2. Digital unfolding approach

To digitally unfold the Jerash Silver Scroll from the 3D μCT image data, we apply a general workflow that has been used in most previous work pertaining to digital unfoldings of sheet-like structures. The three steps of such a workflow are:

1. Specification of a two-dimensional (2D) surface approximating the sheet-like structure.
2. Flattening of the previously defined surface into the plane.
3. Visualization of the unfolded image in respect to the flattened surface.

The major differences in the methods that have been developed for unfolding sheet-like structures lie in the way these three major steps are implemented (see Section 2.2.1.). Accordingly, the approaches make different assumptions about the data. As a result, the approaches are applicable to different types of sheet-like structures.

In the following subsections, we first describe related work followed by the workflow that we implemented for unfolding the Jerash Silver Scroll. Note that the application of this workflow is not restricted to the Jerash Silver Scroll but can be used to unfold sheet-like structures of varying origins that were folded multiple times around axes which all point in the same direction, such as scrolls, fan-like zig-zag folds, and

Fig. 8. Volume rendering of unfolded scroll: front (left) and mirrored back side (right).

combinations thereof. Advantages and disadvantages of the described approach are discussed in Section 3.

2.2.1. Related work

A common approach for defining the surface approximating the sheet-like structure is to first define cross-sectional contours, which are then concatenated to form a surface. For the definition of contours, Neuber and Reinhard (2012), Baum et al. (2017) and Mahnke et al. (2020) use manual approaches to define contours in a few cross-sections for maximal flexibility. Mills et al. (2012) use a combination of manual and automatic methods without giving details. Samko et al. (2014) use shape priors with a graph cut approach to segment the sheets of parchment. They assume nearly uniform thickness to separate touching layers. Seales et al. (2016) start from a manually defined contour, which is then propagated through the volume. To guide the propagation, they compute structure tensors from the 3D image. Liu et al. (2018) and Rosin et al. (2018) developed fully automated approaches based on several sophisticated methods that take into account the special properties of the material to be unfolded. Thus, similar to Samko et al. (2014), they make the assumption of uniform thickness, which is valid for parchment but not for many other writing materials. The concatenation of the points of neighboring contours can be done, for example, using dynamic programming with an energy function (Liu et al., 2018).

For the flattening of the sheet-like structure, the surface is usually represented as a triangular or quadrangular mesh. For rolled or folded documents, it can usually be assumed that there exists a near-isometric mapping of the folded mesh to the plane, that is, a mapping that only introduces small changes between the distances between neighboring vertices of the mesh. Brown and Seales (2001) and Baum et al. (2017) use a mass-spring model to flatten the folded mesh, while Brown and Pisula (2005) utilize a flattening that is based on conformal mapping (Desbrun et al., 2002).

Once the surface (mesh) has been flattened to the (2D) plane, it needs to be visualized to reveal the writing. Most approaches only create a 2D image of the unfolded sheet by extracting the values from the 3D image or project values in the close vicinity to the surface. Baum et al. (2017) extract a thin volume around the surface from the original 3D image. The latter approach has the advantage that powerful visualization tools like volume rendering or isosurfaces can be directly used for the visualization.

2.2.2. Surface approximation of the folded sheet-like structure

Generation of cross-sectional contours. We generate cross-sectional contours (Fig. 4a–f) using a multi-step approach. Note that the cross-sections need to be oriented roughly perpendicularly to the major fold axis, showing the folding geometry as a single connected contour (Fig. 4a). A single contour is traced by separating the sheet from the background (Fig. 4b) and computing its centerline as one polyline. To do so, we first create a binary segmentation of the sheet using simple thresholding. A good threshold for this can be easily found by visual inspection or Otsu's method (Otsu, 1979). If the sheet touches itself in the current cross-section or contains missing parts, we need to correct the segmentation by separating touching layers or filling in missing pieces. For the Jerash Silver Scroll, we manually corrected the segmentations. Once the segmentation has been corrected, we apply distance-based skeletonization proposed by Fouard et al. (2006) on the binary segmentation to obtain a one-pixel-thick line. This line can then be turned into a dense polyline by connecting neighboring foreground pixels by edges. As a result, we obtain a very dense polyline that can then be coarsened to achieve a suitable density. We use equi-distance resampling, but a curvature-dependent resampling could also be used.

Generation of folded surface mesh. To obtain the approximated medial surface of the silver scroll, consecutive polylines are connected to form a triangular mesh (Fig. 4h and i). Note that one does not need to generate polylines in all cross-sections. Details about the number of cross-sections in which polylines were created for the Jerash Silver Scroll are given in Section 3. To identify the corresponding points on two consecutive polylines (Fig. 5a), we first compute the pairwise Euclidean distances of all points of the two polylines. These pairwise distances are stored in a distance matrix (Fig. 5b), where the rows represent the points on one polyline and the columns the points of the other one. The rows and columns are sorted according to the order of the points on the polylines. In this distance matrix, we now compute the shortest path from the uppermost left entry to the bottommost right entry. We only allow edges of this path to connect either neighboring matrix entries that belong to the same row or the same column (Fig. 5b); no diagonal edges are allowed. Furthermore, the path must not move left or upwards but only right and downwards, that is, the path represents a monotonic, but not strictly monotonic, falling curve. As a result, the path forms a triangulation of the two contours for which it is guaranteed that no crossing edges appear. Furthermore, this path represents the triangulation with the smallest accumulated distance between corresponding points. The shortest path in the distance map can be efficiently computed using Dijkstra's shortest path algorithm (Dijkstra, 1959). The described method computes the desired correspondence if the polylines are ordered in the same direction. In case one of the polylines is reversed, we also need to compute the shortest path from the top right matrix entry to the bottom left one. In fact, we can always compute both shortest paths and select the one that is shorter. When repeating this procedure for all consecutive polylines, we obtain a triangular mesh which can then be refined and smoothed (Fig. 4j) to enhance the quality of the final result as desired.

2.2.3. Generation of flattened surface

In order to flatten the still folded surface mesh into the 2D plane, we use an approach based on the work by Ambellan et al. (2019). The approach assumes that the surface mesh to be unfolded is near-isometric to the plane, which is well-justified for the Jerash Silver Scroll.

2.2.4. Visualization of the unfolding image

In order to visualize the flattened silver scroll, we first transfer the image information around the folded surface mesh from the 3D input image to the volumetric domain around the flattened surface. Then, standard volumetric visualization techniques like volume rendering and isosurfaces can be used to depict the unfolded silver sheet.

We implemented an efficient and accurate image transformation. The approach first expands each mesh triangle to a triangular prism with the appropriate height, both in the original 3D image domain and the new 2D domain defined by the flattened mesh (Fig. 4l, m). Around the 2D domain of the flattened surface mesh, the cross-section of the prism along the height is constant. However, in the original 3D ‘folded’ domain, this will in general not be true. Not only might the shape of the triangle change along the height of the prism, but the prism might also be rotationally distorted. In our implementation, we therefore further subdivide each prism into tetrahedra for which corresponding coordinates can be efficiently computed using barycentric coordinates. The image information is then transferred between corresponding tetrahedra from the 3D domain to the ‘2D’ domain. Image information contained in overlapping prisms (in areas where the scroll gets close to itself or even touches) is only transferred for the prism for which its base triangle is closest to the considered location. An efficient triangle closeness test guarantees a fast image transformation.

2.3. Visualization data analysis software

We implemented the virtual unfolding approach presented in this paper in the visual data analysis software AmiraZIBEdition (version 2020.10; Stalling et al., 2005). Processing of the Jerash Silver Scroll was done using tools available in the commercial version of Amira and additional custom modules that were specifically developed for unfolding sheet-like structures. Details are given in Section 3.

3. Results and discussion

Using the tools described above, we unfolded the 3D image of the Jerash Silver Scroll in one piece, thus also reconstructing its original shape (**Video**). For defining the medial surface of the silver scroll, centerline contours were traced in 64 out of 1834 slices (Fig. 4g). We started with much fewer traced contours and iteratively added contours until we were satisfied with the unfolding results. Tracing a single contour took up to 20 min for very complex cross-sections but usually was much faster. Contours in cross-sections where the scroll touches other parts or appears broken were manually corrected using a standard Wacom tablet and Amira's *Segmentation Editor*. Polylines representing the contour centerlines were then automatically computed from the contours using Amira's *Auto Skeleton* module. The resulting polylines were resampled with equidistant spacing using the *Resample Spatial Graph* module. They were then linked to form a triangular mesh using a custom Amira module implementing the method described in Section 2.2.2. The initial triangle mesh was then remeshed with the *Remesh Surface* module (Zilske et al., 2008) and subsequently smoothed with the *Smooth Surface* module (Taubin, 1995). The refined and smoothed mesh was then flattened to the x-y plane using a custom Amira module as described in Section 2.2.3. Finally, another custom Amira module was used to transfer the image data from the μCT scan to the flattened domain (Section 2.2.4). Standard techniques like volume rendering and iso-surfaces then allowed its interactive rendering (Figs. 7 and 8).

The approach presented in this paper has several advantages. First, it supports both automatic and manual contour tracing for efficient processing of even damaged data in fused or broken regions (Fig. 6a–d) or where the silver scroll is corroded (Fig. 6e and f). If any of the previously proposed methods for automatic contour extraction, like the one proposed by Liu et al. (2018) and Rosin et al. (2018), should work sufficiently well on this dataset, our current approach for contour tracing, which is a combination of automatic and manual processing, could simply be replaced by the fully automatic one. Since we are able to handle automatically created contour polylines with an unequal number of points, the presented approach is much more flexible than the previous approach by Baum et al. (2017). In addition, it creates less distortions of the flattened scroll. Second, due to the coarsening of the contours when creating polylines and due to the remeshing and smoothing of the medial surface approximation, the impressed script (Fig. 6g and h) is preserved during the unfolding step. This would not be the case if the polylines and, hence, the medial surface would exactly follow the contours because the impressed script would then be flattened out, leaving no trace of the script. A third advantage comes from the fact that we can start with only a few contours and add more contours as and where needed, thus reducing the overall amount of time spent. Furthermore, our procedure to generate the medial surface mesh (including the contour tracing) as well as the flattening allow an extension to handle missing parts. For example, the point correspondence identification is able to deal with several polylines in a single cross-section as long as the points are ordered. The resulting mesh might then have holes, which can be handled by the subsequent processing steps. Finally, the volumetric image unfolding is a necessity for the successful visualization of the Jerash Silver Scroll because a mere intersection of the surface with the volume or even a projection of intensity values onto the surface will not yield the desired result due to the fact that the intensities do not vary in regions where the script is present. Without this volumetric unfolding, an isosurface rendering as shown in Fig. 7, which represents the clearest depiction of the inscription, would not be possible.

Compared with the previous, time-consuming digital dissection (Barfod et al., 2015), the approach presented here is much faster and allows easier access to the writing. In the results from 2015, lines 2 and 7 each required the extraction of two different images, since these lines are situated at bends in the scroll (Fig. 3b–c, h-i). Line 8 was difficult to read due to deformation of the scroll. In the new rendering, these lines are all visible in one image. Also, the difficulty of dissecting lines on parts of the scroll touching a different part in some cases previously resulted in fine 'scratches' due to the digital draw tool. Yet, despite the higher quality of the new unfolding, the previous assessment of the text as pseudo-Arabic script did not change.

The reconstruction of the original shape and format of the sheet, which was not possible with the earlier unfolding, is another obvious advancement, because it allows to better understand the materiality of the object and adds a further dimension to the textual evidence. Although in the case of the Jerash Silver Scroll this has little impact on the overall interpretation, the method has the potential to contribute to a much better understanding, for example, of production processes of such objects.

4. Conclusion

The aim of this paper was to re-examine the Jerash Silver Scroll using an unfolding approach that allows one to fully unfold the scroll in one piece. In order to do so, we developed a new digital and non-invasive unfolding method that is suitable for complexly folded metal sheets with imprinted scripts based on 3D datasets. Note that our method might not be directly applicable to more complicated data like those presented by Rosin et al. (2018) and Mocella et al. (2015). To make the method applicable also for such type of data, more automated methods are needed to create the folded surface mesh and to finely adjust the prism heights.

We re-used the previous μCT image scan and showed that an unfolding with higher quality and less time requirement is possible without requiring a re-acquisition of the object. By making available the raw data as well as the unfolded volumetric data of the object in open access format, we support the FAIR principles of scientific data management and stewardship on such archaeological objects (Wilkinson et al., 2016). This eases further advances in digital unfolding and data visualization by providing an important object of cultural heritage on which new techniques can be tested.

Author contributions

Daniel Baum: conceptualisation, data curation, investigation, methodology, project administration, resources, writing - original draft, review, and editing.

Felix Herter: conceptualisation, data curation, investigation, methodology, writing - original draft, review, and editing.

John Møller Larsen: investigation (2015 visualization), methodology (2015 visualization), writing - original draft, review, and editing.

Achim Lichtenberger: conceptualisation, data curation, funding acquisition, investigation, methodology, project administration, resources, writing - original draft, review, and editing.

Rubina Raja: conceptualisation, data curation, funding acquisition, investigation, methodology, project administration, resources, writing - original draft, review, and editing.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2021.e00186.

References

Ambellan, F., Zachow, S., von Tycowicz, C., 2019. A surface-theoretic approach for statistical shape modeling. MICCAI 2019. Lect. Notes Comput. Sci. 11767 https://doi.org/10.1007/978-3-030-32251-9_3.

Barfod, G., Larsen, J.M., Lichtenberger, A., Raja, R., 2015. Revealing text in a complexly rolled silver scroll from Jerash with computed tomography and advanced imaging software. Nat. Sci. Rep. 5 https://doi.org/10.1038/srep17765.

Barfod, G., Freestone, I., Lichtenberger, A., Raja, R., Schwarzer, H., 2018. Geochemistry of byzantine and early islamic glass from Jerash, Jordan: typology, recycling, and provenance. Geoarchaeology 33, 623–640. https://doi.org/10.1002/gea.21684.

Baum, D., Lindow, N., Hege, H.-C., Lepper, V., Siopi, T., Kutz, F., Mahlow, K., Mahnke, H.-E., 2017. Revealing hidden text in rolled and folded papyri. Appl. Phys. A 123, 171. https://doi.org/10.1007/s00339-017-0808-6.

Baum, D., Herter, F., Lepper, V., 2020. Jerash Silver Scroll: Virtually Unfolded Volume. figshare. https://doi.org/10.6084/m9.figshare.12145236. Dataset.

Brown, M.S., Seales, W.B., 2001. Document restoration using 3D shape: a general deskewing algorithm for arbitrarily warped documents. Proc. Eighth IEEE Int. Conf. Comput. Vision (ICCV) 367–374.

Brown, M.S., Pisula, C.J., 2005. Conformal deskewing of non-planar documents. In: IEEE Computer Society Conference on Computer Vision and Pattern Recognition 2005 (CVPR'05), vol. 1. IEEE, San Diego, CA, USA, pp. 998–1004. https://doi.org/10.1109/CVPR.2005.110.

Desbrun, M., Meyer, M., Alliez, P., 2002. Intrinsic parameterizations of surface meshes. Comput. Graph. Forum 21 (3), 209–218. https://doi.org/10.1111/1467-8659.00580.

Dijkstra, E.W., 1959. A note on two problems in connexion with graphs. Numer. Math. 1 (1), 269–271.

Fouard, C., Malandain, G., Prohaska, S., Westerhoff, M., 2006. Blockwise processing applied to brain micro-vascular network study. IEEE Trans. Med. Imag. 25 (10), 1319.

Kraeling, C.H. (Ed.), 1938. Gerasa. City of the Decapolis. American Schools of Oriental Research, New Haven (CT).

Larsen, J.M., Lichtenberger, A., Raja, R., Gordon, R., 2016. An Umayyad period magical amulet from a domestic context in Jerash, Jordan. Syria. Archéol. Art et Histoire 93, 369–386.

Lichtenberger, A., 2003. Kulte und Kultur der Dekapolis: untersuchungen zu numismatischen, archäologischen und epigraphischen Zeugnissen. In: Abhandlungen des Deutschen Palästina-Vereins, vol. 29. Harrassowitz, Wiesbaden.

Lichtenberger, A., Raja, R., 2015. A hoard of byzantine and arab-byzantine coins from the excavations in Jerash. Numismatic Chronicle 175, 299–308.

Lichtenberger, A., Raja, R., 2016. A newly excavated private house in Jerash: reconsidering aspects of continuity and change in material culture from late antiquity to the early Islamic period. Antiq. Tardive 24, 317–359.

Lichtenberger, A., Raja, R., 2018a. A view of gerasa/jerash from its urban periphery. The Northwest Quarter and its significance for the understanding of the urban development of Gerasa from the roman to the early Islamic period. In: Lichtenberger, A., Raja, R. (Eds.), The Archaeology and History of Jerash: 110 Years of Excavations in Jerash. Brepols, Turnhout, pp. 143–166.

Lichtenberger, A., Raja, R., 2018b. Middle islamic Jerash (9th – 15th century). Archaeology and history of an ayyubid-mamluk settlement. In: Jerash Papers, vol. 3. Brepols, Turnhout.

Lichtenberger, A., Raja, R., 2019a. Byzantine and Umayyad Jerash reconsidered. Transitions, transformations. In: Continuities. Jerash Papers, vol. 4. Brepols, Turnhout.

Lichtenberger, A., Raja, R., 2019b. Introduction: the conundrum of chronologies of the byzantine and Umayyad periods in Jerash. In: Lichtenberger, A., Raja, R. (Eds.), Byzantine and Umayyad Jerash Reconsidered. Transitions, Transformations, Continuities. Jerash Papers 4. Brepols, Turnhout, pp. 1–6.

Lichtenberger, A., Raja, R., 2020. Jerash silver scroll: computed tomography data. figshare. https://doi.org/10.6084/m9.figshare.12136380.v1. Dataset.

Lichtenberger, A., Raja, R., Seland, E., Kinnaird, T., Simpson, I., 2019. Urban-riverine hinterland synergies in semi-arid environments: millennial-scale change, adaptations and environmental responses at Gerasa/Jerash. J. Field Archaeol. https://doi.org/10.1080/00934690.2019.1625619.

Liu, C., Rosin, P.L., Lai, Y.K., Hu, W., 2018. Robust virtual unrolling of historical parchment XMT images. IEEE Trans. Image Process. 27 (4), 1914–1926.

Mahnke, H.E., Arlt, T., Baum, D., Hege, H.-C., Herter, F., Lindow, N., Manke, I., Siopi, T., Menei, E., Etienne, M., Lepper, V., 2020. Virtual unfolding of folded papyri. J. Cult. Herit. 41, 264–269. https://doi.org/10.1016/j.culher.2019.07.007.

Michel, A., 2011. Les églises d'époque et umayyade de la Jordanie (provinces d'Arabie et de Palestine), Ve–VIIIe siècle: typologie architecturale et aménagements liturgiques. Turnhout: Brepols.

Mills, D., Samko, O., Rosin, P., Thomas, K., Wess, T., Davis, G.R., 2012. Apocalypto: revealing the unreadable. In: Proc. SPIE 8506, Developments in X-Ray Tomography, vol. VIII, p. 85060A. https://doi.org/10.1117/12.928917, 17 October 2012.

Mocella, V., Brun, E., Ferrero, C., Delattre, D., 2015. Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging. Nat. Commun. 6 (5895) https://doi.org/10.1038/ncomms6895.

Neuber, D., Reinhart, C., 2012. Geheimnisvolle Bleischriftrolle der Mandäer: moderne Computertomographie erlaubt virtuelle Entschlüsselung eines antiken Rätsels. ZfP-Zeitung 132, 39–41.

Otsu, N., 1979. A threshold selection method from gray-level histograms. IEEE Trans. Systems, Man, Cybernetics 9 (1), 62–66.

Raja, R., 2012. Urban Development and Regional Identity in the Eastern Roman Provinces, 50 BC – AD 250: Aphrodisias, Ephesos, Athens, Gerasa. Museum Tusculanum Press, Copenhagen.

Romanowska, I., Brughmans, T., Lichtenberger, A., Raja, R., 2018. Urban networks seen through ceramics. Formal modelling approaches to pottery distribution in Jerash. In: Raja, R., Sindbæk, S.M. (Eds.), Urban Network Evolutions. Towards a High-Definition Archaeology. Aarhus University Press, Aarhus, pp. 131–138.

Rosin, P.L., Lai, Y., Liu, C., Davis, G.R., Mills, D., Tuson, G., Russell, Y., 2018. Virtual recovery of content from X-ray micro-tomography scans of damaged historic scrolls. Sci. Rep. 8, 11901. https://doi.org/10.1038/s41598-018-29037-x.

Samko, O., Marshall, D., Rosin, P., 2014. Virtual unrolling and information recovery from scanned scrolled historical documents. Pattern Recogn. 47 (1), 248–259. https://doi.org/10.1016/j.patcog.2013.06.015.

Seales, W.B., Parker, C.S., Segal, M., Tov, E., Shor, P., Porath, Y., 2016. From damage to discovery via virtual unwrapping: reading the scroll from En-Gedi. Sci. Asia 2. https://doi.org/10.1126/sciadv.1601247.

Stalling, D., Westerhof, M., Hege, H.-C., 2005. Amira: a highly interactive system for visual data analysis. In: Hansen, ChD., Johnson, C.R. (Eds.), The Visualization Handbook Elsevier, pp. 749–767. Amsterdam.

Taubin, G., 1995. Curve and surface smoothing without shrinkage. In: Proceedings of IEEE International Conference on Computer Vision, pp. 852–857.

Tsafrir, Y., Foerster, G., 1992. The dating of the 'earthquake of the sabbatical year' of 749 C.E. In Palestine. Bull. Sch. Orient Afr. Stud. 55 (2), 231–235.

Vavřík, D., Knauber, K., Urbanová, D., Kumpová, I., Blazková, K., Sámal, Z., 2020. Unveiling magic from the middle ages: tomographic reading of a folded lead amulet from Dřevíč fortress (Czech Republic). ArchaeolAnthropolSci 12. https://doi.org/10.1007/s12520-019-00976-4.

Walmsley, A., 2018. Urbanism at Islamic Jarash: new readings from archaeology and history. In: Lichtenberger, A., Raja, R. (Eds.), The Archaeology and History of Jerash: 110 Years of Excavations. Turnhout: Brepols, pp. 241–256.

Wilkinson, M.D., et al., 2016. Comment: the FAIR Guiding Principles for scientific data management and stewardship. Nat. Sci. Data 3.

Zilske, M., Lamecker, H., Zachow, S., 2008. Adaptive remeshing of non-manifold surfaces. Proc. EUROGRAPHICS 393–402.