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Short communication

Virtual unfolding of folded papyri

Heinz-Eberhard Mahnke[a,b,c,*], Tobias Arlt[d], Daniel Baum[e], Hans-Christian Hege[e], Felix Herter[e], Norbert Lindow[e], Ingo Manke[c], Tzulia Siopi[a], Eve Menei[g], Marc Etienne[h], Verena Lepper[a,f]

[a] *Ägyptisches Museum und Papyrussammlung, Berlin, Germany*
[b] *Freie Universität Berlin, Berlin, Germany*
[c] *Helmholtz-Zentrum Berlin, Berlin, Germany*
[d] *Technische Universität Berlin, Berlin, Germany*
[e] *Zuse-Institut Berlin, Berlin, Germany*
[f] *Humboldt-Universität zu Berlin, Berlin, Germany*
[g] *Visiting Conservator, 75016 Paris, France*
[h] *Musée du Louvre, 75058 Paris, France*

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ABSTRACT

The historical importance of ancient manuscripts is unique since they provide information about the heritage of ancient cultures. Often texts are hidden in rolled or folded documents. Due to recent improvements in sensitivity and resolution, spectacular disclosures of rolled hidden texts were possible by X-ray tomography. However, revealing text on folded manuscripts is even more challenging. Manual unfolding is often too risky in view of the fragile condition of fragments, as it can lead to the total loss of the document. X-ray tomography allows for virtual unfolding and enables non-destructive access to hidden texts. We have recently demonstrated the procedure and tested unfolding algorithms on a mockup sample. Here, we present results on unfolding ancient papyrus packages from the papyrus collection of the Musée du Louvre, among them objects folded along approximately orthogonal folding lines. In one of the packages, the first identification of a word was achieved, the Coptic word for "Lord".

1. Introduction

In various collections of Egyptian writings on papyri around the globe, one finds papyri as scrolls, as folded packages, as all sorts of fragments, as scrunched papyri, or even as disposed documents used as filling material. With the successful unravelling of text imprinted into metallic foils of lead [1] or silver [2] rolled to a scroll, the present resolving power of X-ray tomography virtual unrolling was convincingly demonstrated. When using inks that contain metal ions, such as iron gall ink, the increased absorption should produce a contrast sufficient to distinguish the writing from organic base material like parchment or papyrus. In the case of parchment, the recovery of text on a scroll, no matter how badly the scroll had been distorted or compressed, has by now successfully been achieved in various cases using X-ray tomography [3–5]. Even in the case of carbonized papyri, as shown on a Herculaneum papyrus, some Greek letters have successfully been identified [6]. These letters were assumed to be written with carbon ink and identified by phase contrast tomography [7]. The fact that in other Herculaneum papyri admixtures of small amounts of lead have been found [8], leaves open the possibility that the visibility of letters in tomograms of the carbonized base papyrus is due to such admixtures. The recovery of texts from scrolls of "normal" though ancient papyri which are also folded can be even more challenging.

Various folding types and techniques are known for Egyptian papyri [9]. While simple unfolding along one fold line is a process that is similar to unrolling flattened scrolls, unfolding along perpendicular fold lines is more complicated.

Our investigation is part of a liberal arts oriented ERC-funded project called "Localizing 4000 Years of Cultural History. Texts and Scripts from Elephantine Island", conducted by the Ägyptisches Museum und Papyrussammlung Berlin. This project intends to combine the hidden knowledge, written in various languages and scripts, including hieroglyphs, Hieratic, Demotic, Aramaic, Greek, Coptic and Arabic, distributed and spread out over papyri collections in 60 institutions in 24 different countries. As one result of this international cooperation, some folded papyri were

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[*] Corresponding author. Helmholtz-Zentrum Berlin GmbH, Hahn-Meitner-Platz 1, 14109 Berlin, Germany.
Adresse e-mail : hemahnke@zedat.fu-berlin.de (H.-E. Mahnke).

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Fig. 1. Box at the Louvre with various folded papyri packages awaiting unfolding and unrolling.

discovered within a collection at the Musée du Louvre that are related to the Elephantine Island near Aswan (see Fig. 1). They appeared to be appropriate candidates for applying our virtual unfolding approach.

2. Research aim

Virtual unfolding of packages folded along at least two approximately perpendicular folding lines is not straightforward. Before applying the developed technique to real, ancient objects, we have recently demonstrated virtual unfolding on a mockup sample [10] that was folded according to the so-called “magic fold” used for special purposes [9]. Since in our demonstration the emphasis was put on the algorithmic procedure, the mockup was prepared with the highest possible contrast between the papyrus and the writing ink by using the highly absorbing cinnabar and minium as (red) ink.

The objective in our present investigation was to apply the procedure to a real ancient object and get a successful virtual unfolding result. The final objective, of course, is to identify and recover not only some letters but full words after virtual unfolding, otherwise not accessible. Three objects, found within the collection of the Musée du Louvre, appeared to be appropriate candidates, at least one of them appearing to be folded along two orthogonal folding lines (Fig. 2).

3. Material and methods

3.1. Papyri objects

Following the successful demonstration of the algorithmic virtual unfolding procedure on a mockup papyrus, we searched for suitable objects in the papyrus collection of the Ägyptisches Museum und Papyrussammlung Berlin as well as in the Musée du Louvre, département des Antiquités égyptiennes. In the registry book of the Egyptian department, objects are recorded which entered the collection around 1925. They originate from the French excavations at Elephantine conducted by Ch. Clermont-Ganneau between 1906 and 1911. The objects are specified and labelled with L for Louvre and El for Elephantine preceding a number. As part of the collection consisting of “three tin boxes containing debris of papyrus” (El 227 a, b, c), another tin box is mentioned of the same kind but of smaller dimensions (El 228). Only two of these 4 boxes have been preserved in their original containers with their labels El 227 b and El 227 c, originally labelled with the numbers E 12917 and E 12918 when accessed. The packages studied in this article belong to the box labelled El 227 b or E 12917, resp. They were selected by visual inspection to check if their sizes and conditions are suited for our tomography setup.

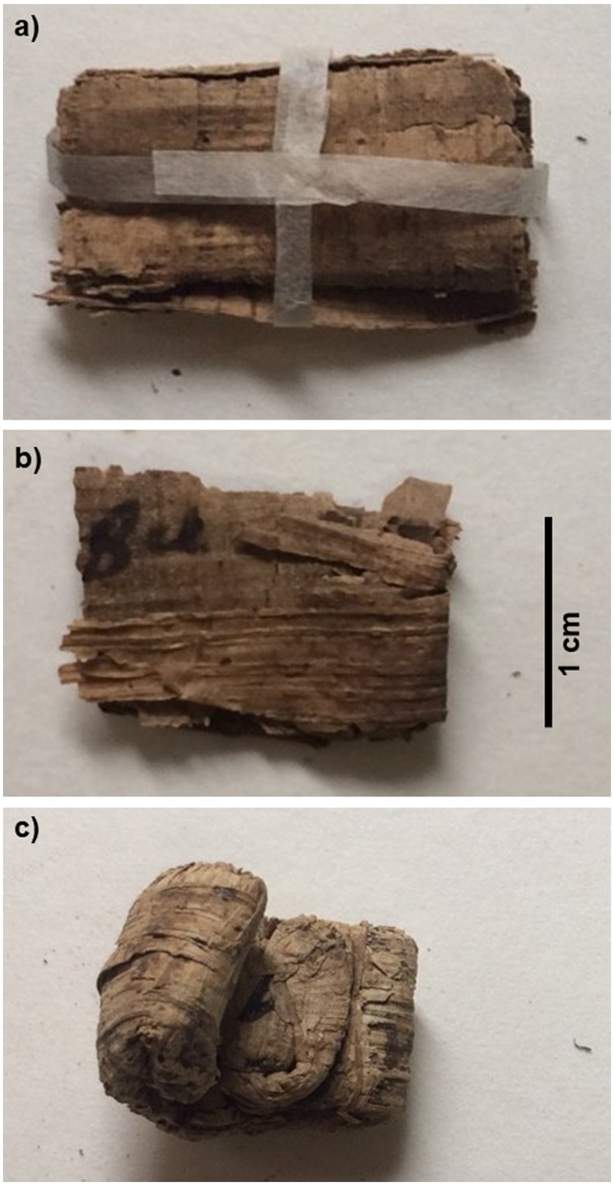

Fig. 2. Photographs of papyri packages: (a) L/El227b/1-pC, (b) L/El227b/4-pG, and (c) L/El227b/2-pU.

3.2. X-ray fluorescence and tomography

A decisive test to determine whether absorption X-ray tomography has a chance of distinguishing writing from the papyrus base material is the detection of high Z-material in the objects, as an indicator of metal-ion-containing ink. Therefore, in an experiment prior to tomography, the objects were tested for the presence of Fe, using a XGLab Elio portable X-ray fluorescence (pXRF) system with a 1-mm beam spot at the Centre de Recherche et de Restauration des Musées de France (C2RMF). However, since Fe is a frequent impurity (e.g. from sand or dust), often in the chemical form of ochre, the detection of Fe is not necessarily proof of the presence of ink containing Fe (for details see [11]). Three specimens showed some variations in the intensities of the Fe characteristic fluorescence line depending on the position. Because of that, these packages

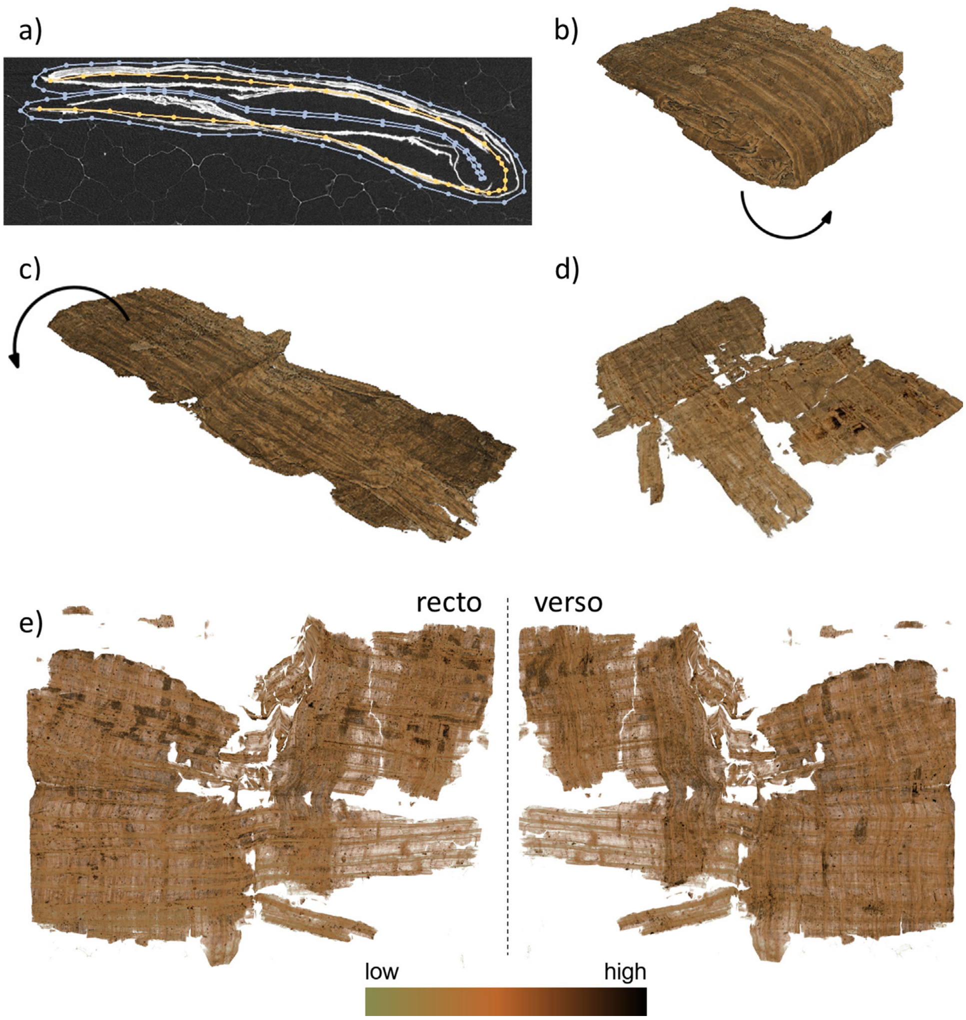

Fig. 3. Package L/El227b/4-pG Greek papyrus: (a) cross section, (b–d) successive unfolding, (e) magnified 2D-projection with some Greek letters.

were selected for absorption tomography at the micro-computed tomography (μCT) setup at the Helmholtz Zentrum Berlin.

The μCT system used consists of a Hamamatsu tube with W anode. The accelerating voltage applied can go up to 150 kV. For our packages, an accelerating voltage of 40 and 50 kV was used. The X-ray source spot size and distance between sample and detector plate allowed a resolution size down to approximately 10 μm. The specimens were positioned in plastic beakers, the papyri were secured against motions with air-cushioned plastic foils, and the beaker was then mounted onto the turning table of the CT setup. The 3D data were then processed for volume rendering using the Amira software [12].

3.3. *Virtual unfolding*

Here, we briefly summarize the method for virtual unfolding. Details can be found in our previous article [10]. Virtual unfolding is done in two major steps. In the first major step, the papyrus is unfolded until it is geometrically similar to a scroll. This process may require several unfolding steps. Then, in the second major step, the papyrus package is unrolled, which is substantially simpler than the first step and can normally be done directly. In case the folded package is only a rolled papyrus, the first step can be omitted and we can directly unfold the package with the second step. For the algorithm we describe here, we assume that the package has either been rolled or folded such that it can in principle get unfolded by applying a series of unfolding steps. Crumpled papyrus, for example, cannot be unfolded with our approach.

We start by describing a single unfolding step. This step is done in a slice-by-slice fashion. For all slices we choose an orientation orthogonal to the fold axis. In each slice, we then define two contours, an inner and an outer contour. While the inner contour mainly defines the unfolding, the outer contour helps to decide where certain parts of the image should be moved during the transformation of the image (Fig. 3). The inner contour should be positioned such that it presumably was a straight line before folding. Often, the medial axis of the folded papyrus in the respective slice is a good choice. Unfolding is done by flattening the inner contour to a straight line while maintaining the spacing of the points along the inner contour during the flattening process. For transforming the image with respect to the flattened inner contour, we use an algorithm that is based on the idea of moving least squares [13]. This algorithm takes as input a set of control points consisting of source points and an equal number of target points. In our application, source and target points are defined by the inner contour points of the curved and flattened inner contour, respectively. The image transformation is computed by transforming the source points to the target points. The transformation is done in such a way that locally the image is deformed as little as possible, resulting in an as-rigid-as-possible transformation [13]. The outer contour helps the algorithm decide where certain parts of the image should be moved to. This is particularly important for areas of the

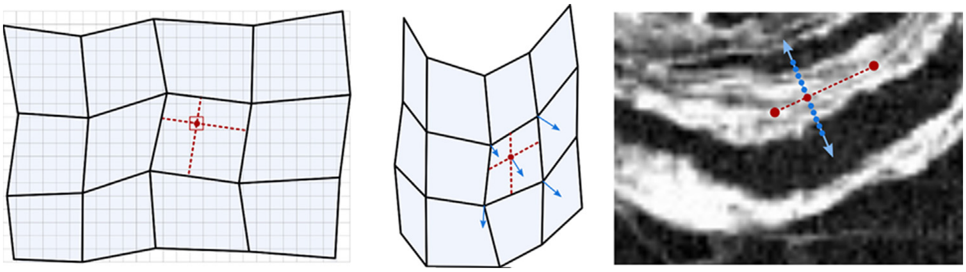

Fig. 4. Illustration of the flattening algorithm. For each voxel in the flattened mesh (left), the corresponding point in the unrolled mesh is computed (middle) and the thickness of the papyrus is sampled along the surface normal (right).

papyrus that during folding have come very close to other areas of the papyrus that would otherwise be far apart.

Although unfolding is done slice by slice, we do not manually draw inner and outer contours in each slice. Instead, we take advantage of the fact that successive slices are very similar and, thus, the contours in successive slices should also be very similar. We therefore adjust the contours only in those slices for which the contours do not match the image structures of the first slice well. Between those slices for which we actually have defined the contours, the contours are linearly interpolated, thus defining new outer and inner contours in each slice.

As mentioned before, we usually need to do several unfolding steps. For each unfolding step, we choose the slice orientation that is orthogonal to the folding axis. Finally, after several unfolding steps, the papyrus shown in the transformed image looks similar to a roll, although this roll might be flattened or even highly distorted in some regions. If we have reached this stage, we turn to the second major step, the unrolling step.

In contrast to the unfolding step, which is done per slice, unrolling is really done in 3D. For this, we create a 2D surface mesh that should be positioned such that it passes through the center of the papyrus sheet and represents its medial surface. To create the medial surface mesh, we define contours only in a few slices. In fact, to minimize the manual labor, we aim at defining contours in as few slices as possible. As slice orientation we choose the plane that is orthogonal to the axis around which the papyrus sheet is rolled. Our tool automatically ensures that all contours have the same number of points. Thus, in all slices, the i-th contour points correspond to each other. It is therefore easy to create a 2D mesh by connecting corresponding points. As already mentioned, we want to minimize the number of slices in which we manually draw contours. We therefore take advantage of the fact that the papyrus sheet in successive slices looks very similar. Hence, we only draw (or modify) the contours in those slices where the contour no longer fits the papyrus sheet. Between those slices, the contours are linearly interpolated, thus yielding a contour in each slice. These interpolated contours, however, are only used to show how well the papyrus sheet is matched and whether additional contours need to be defined. They are not used to generate the mesh. The mesh is defined exclusively from the contours that have been manually drawn or corrected. However, at least two contours are needed, one in the first and one in the last slice.

Once we are satisfied with the coincidence of contours and the papyrus sheet, we can perform the actual unrolling. For this, we flatten the mesh into the 2D plane. During this flattening, we try to minimize the distortions. That is, we try to preserve the distances between the neighbored mesh vertices when mapping them into the 2D plane. We use an approach that resembles a mass-spring model [14,15], with the additional constraint that during the deformation process all cells in the mesh must remain convex.

The flattened mesh is then used to create the unrolled image of the papyrus, which is a thin 3D volume. The depth of this image represents the thickness of the papyrus sheet and will be specified by the user. In detail, the whole process works as follows (see Fig. 4): First, the 2D bounding box of the flattened mesh is computed. This box is then sampled by the same voxel size as the original tomogram. For each sampling point inside the mesh, the grid cell in which the point lies is determined and the parameters for the bilinear interpolation are computed. The cell and the parameters are used to compute the corresponding point in the 3D mesh. In addition, the surface normal at the 3D point is also computed based on the normal vectors at the vertices of the cell. Finally, the voxel size is used to determine the values of sample points in both directions of the normal, where the mesh is in the middle. The sampling is stopped if a sampling point is outside the tomogram or closer to another point in the mesh than to the original one. If this is the case, the value in the unwrapped thin volume is set to a user-defined padding value.

After generating the 3D thin volume of the unwrapped papyrus, one can visualize it using classical volume rendering [16]. Briefly, for each point on the screen, the corresponding 3D view ray is computed. This ray is sampled through the volume of the image. A user-defined color map, also called transfer function, assigns to each sampling point a color and a transparency value according to the value at this point. To create the final image, the colors and transparency values are accumulated in the order of their appearance along the ray until either the combined color is fully opaque or the end of the volume is reached. These accumulated colors are then used to generate the final image.

4. Results and discussion

Since the package L/El227b/1-pC is rather fragile, it was secured with Japanese tissue, as seen on the photograph in Fig. 2a. Volume rendering the tomographic data then revealed that the object L/El227b/1-pC is a flattened scroll. In Fig. 5, a cross section through the volume and the 2D projection are shown. One word in Coptic writing is clearly readable, as pjoe[is] or pjoe[is . . .], with the last letters in brackets missing. It can be translated as “the Lord” or “oh Lord” in vocative if it is perhaps used in a short prayer. Since the written word occupies only a small part of the area of the papyrus sheet, one is tempted to speculate that perhaps more text is written on the papyrus, which however is not detected by our absorption tomography. To be more specific in our speculation, such additional text, but invisible in our tomography, could be written in carbon ink and only the word for “Lord” could be written in ferrous ink.

The next package L/El227b/4-pG in Fig. 2b is even more fragile, apparently with less layers. Fig. 3 shows a cross section with contour lines (cf. the description above) along which the unfolding was done. As indicated by the arrows, two successive unfolds are needed along orthogonal folding lines to get a flattened layer. Although the papyrus sheet is highly damaged with holes and missing fibers, a few Greek letters can be identified.

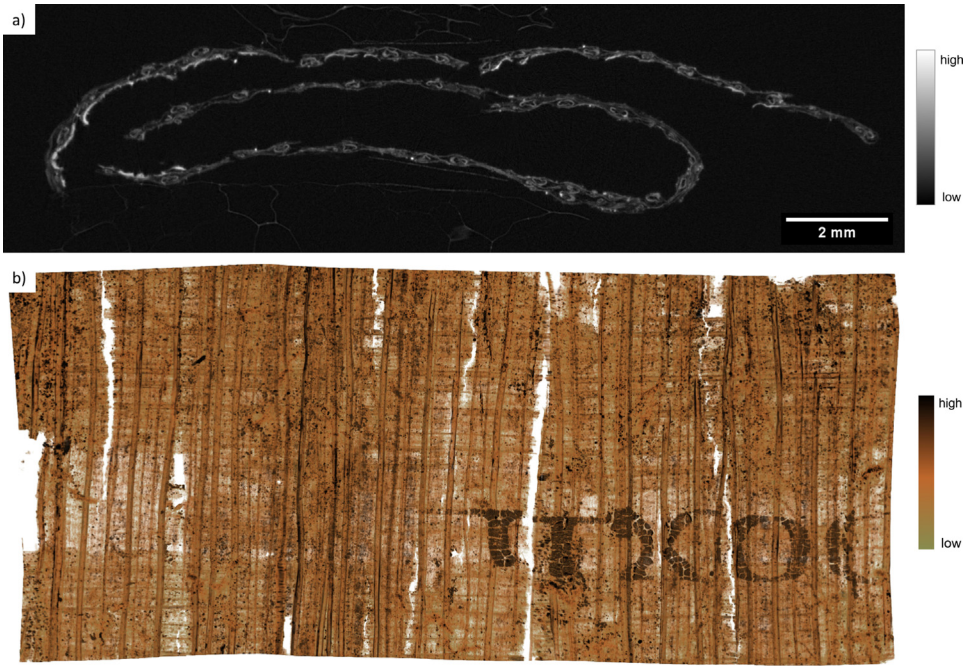

Fig. 5. Package L/El227b/1-pC Coptic papyrus: (a) cross section, and (b) 2D-projection showing a Coptic word for “Lord”.

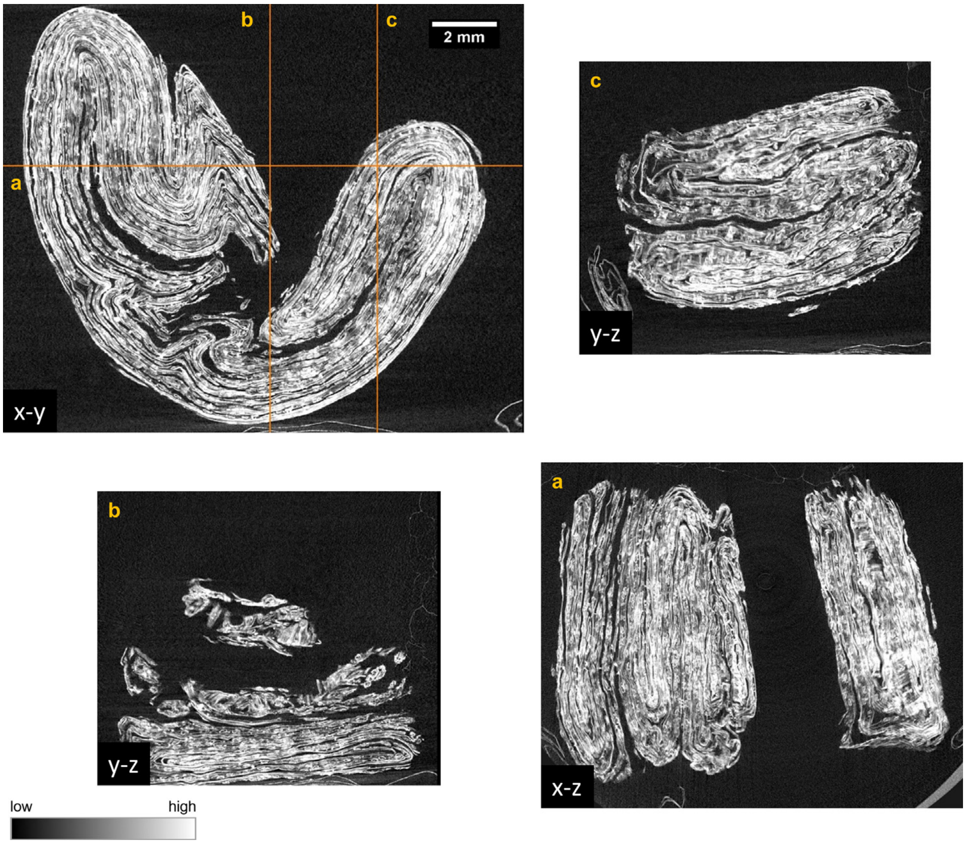

Fig. 6. Package L/El227b/2-pU “magic fold - like” packaged, with various cuts through the volume.

The third package L/El227b/2-pU is rather compact and appears to be folded along two orthogonal lines as well. Fig. 6 shows different virtual cuts through the volume. Due to distortions the unfolding is not as simple as in the case of our mockup in Ref. 7. A preliminary extraction of a 2D representation gives no indication of letters, although small fractions of uncovered writing in black ink can be identified on the photo (Fig. 2c). This probably means that in this case, we are dealing with carbon ink, which does not give sufficient contrast in absorption tomography.

5. Conclusions and outlook

We have successfully demonstrated that with the proposed algorithmic approaches we are able to virtually unroll a papyrus scroll. In addition, we succeeded in revealing some hidden text and identifying a real Coptic word in an ancient Egyptian papyrus package. We also demonstrated how to unfold packages that were folded along approximately orthogonal fold lines. To the best of our knowledge, this has not been achieved with papyrus, where the two-ply fiber structures make it difficult to identify individual papyrus layers. On the other hand, tracking fibers helps to define contour lines that are needed in the algorithmic procedure, which could be helpful in future unfolding. The examples shown clearly indicate the limit of the present imaging approach based on absorption tomography. The papyri seem to have been at least partially written with carbon ink, for which there is no sufficient contrast in the absorption-based tomography. For objects of this type, the development of suitable imaging techniques is imperative – a project we are currently working on.

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