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VIRTUAL UNFOLDING OF FOLDED PAPYRI*

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One of the best sources of information about our cultural origin are written texts. Often, texts are hidden, sometimes erased, faded away, or written over, sometimes not easily accessible 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, most of them made out of parchment. However, revealing text on *folded* manuscripts is even more challenging. Due to the fragile condition of fragments, manual unfolding is often too risky, 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. Here, the progress in virtual unfolding is reviewed, focusing on papyri from Elephantine Island near Aswan. The project is a part of the European Research Council's starting grant ELEPHANTINE. Results on unfolding ancient papyrus packages from the papyrus collection of the Musée du Louvre and of the Ägyptisches Museum und Papyrussammlung, Berlin are discussed.

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1. Introduction

The best source of learning about ancient cultures is to read and understand their writings. Therefore, the decipherment of written languages was the great break-through not only for the Egyptian culture. However, texts are often not easily accessible, they may be hidden due to overwriting, due to erasure for reuse of the valuable substrate writing material, or on purpose by using "secret ink". In all these cases, where the text is facing us on inspection, revealing the text has experienced great progress in

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recent years. The most famous examples are the Archimedes palimpsest and the hand-written "Declaration of Independence" in the original writing by Thomas Jefferson (see an overview [1]), using hyperspectral imaging and synchrotron radiation.

In the case of books, in the modern form as bound pages since the middle ages or in the ancient form as scrolls, the access to hidden texts, deeply buried under several layers of writing material, needs penetrating radiation. Getting access to the text in books in the form we are still using (with large planar dimensions as compared to the thickness), may be easier by depth sensitive 2-dimensional scanning as compared to scrolls with only one extended dimension, the "axis of the scroll", where tomographic scans seem to be the method of choice. With the successful unravelling of text imprinted into metallic foils of lead [2] or silver [3] rolled to a scroll, the present resolving power of X-ray tomography for 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 [4–6]. Quite comparable to the text recovery on scrolls is the reconstruction of damaged motion pictures, the variable amount of silver on the tri-acetate film base giving a perfect contrast in X-ray absorption micro-tomography [7].

Even in the case of carbonized papyri, as shown on a Herculaneum papyrus, some Greek letters have successfully been identified [8]. These letters were assumed to be written with carbon ink and identified by phase-sensitive contrast tomography [9]. However, the fact that in other Herculaneum papyri admixtures of small amounts of lead have been found [10], opens up the possibility that the visibility of letters in tomograms of the carbonized base papyrus is due to such admixtures.

In the case of Egyptian writings on papyri, one finds papyri not only as scrolls, but also as folded packages. In addition to all sorts of fragments, even scrunched papyri, sometimes as disposed documents used as filling materials, are found in various collections around the world. The recovery of texts from scrolls of "normal", more or less preserved, ancient papyri which are also folded can be even more challenging. Various folding types and techniques are known for Egyptian papyri [11]. 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.

The examples presented in this review belong to an investigation which is part of a humanities oriented ERC-funded project called "Localizing 4000 Years of Cultural History in Egypt. Texts and Scripts from Elephantine Island", conducted by the Ägyptisches Museum und Papyrussammlung, Staatliche Museen zu Berlin and led by the principal investigator Verena Lepper. This project intends to reconstruct the hidden knowledge, written in various languages and scripts, distributed and spread out over papyri collections in 60 institutions in 24 different countries originating just from the Elephantine Island near Aswan. Most of them were obtained in excavation campaigns more than a century ago. As an example, the metal boxes shown in Fig. 1 house only a fraction of papyri from Elephantine at the museum in Berlin originating from excavations lead by Otto Rubensohn between 1906 and 1908. As one result of the international cooperation within this project, some folded papyri were discovered within the collection at the Musée du Louvre, also from the Elephantine Island, a few objects of this collection appeared to be appropriate candidates for applying our virtual unfolding approach as presented in this review.

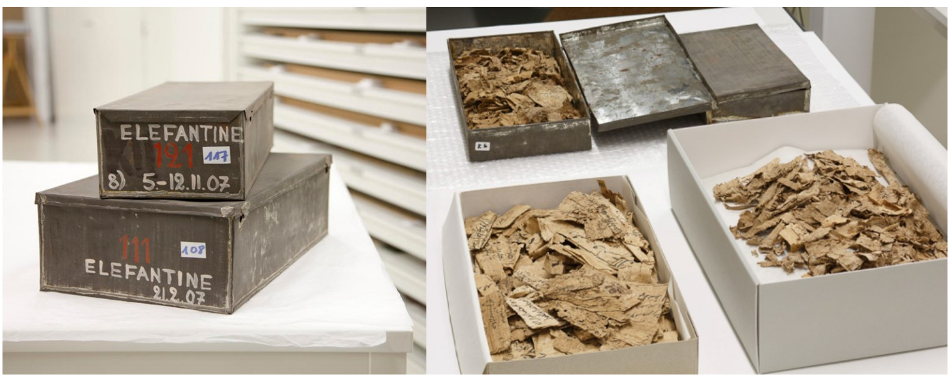

Fig. 1. Boxes originating from Elephantine 1907 at the Ägyptisches Museum und Papyrussammlung, Staatliche Museen zu Berlin. Photo: Sandra Steiß.

2. General concept

The general approach for unfolding (or unrolling) papyri follows three steps which fall into different fields and illustrate the need for a multidisciplinary cooperation of researchers from the humanities and restoration, natural science, and computer science:

(1) identify the object(s) of interest (archaeological arguments, cultural background), decide on how to handle and mount the object for the investigation with minimal additional material for mounting,
(2) try to find a signature for a distinction between possible text and substrate to decide on the most adequate tomographic method (absorption tomography, phase-sensitive tomography or other means for tomography) and take the tomographic data,

(3) volume rendering of the tomographic data yielding 3-dimensional imaging for preparing 2-dimensional projections using proper software procedures for unrolling and unfolding.

A simple Ansatz to determine which type of tomography might be successful is to identify chemical elements by X-ray fluorescence. When metal ions containing inks have been used, such elements would show up with varying intensities detected on different positions on the object. Typical elements occurring in inks are iron (Fe), sometimes accompanied with copper (Cu) and/or zinc (Zn). To emphasize certain parts of a text, symbols or letters have been written with precious inks produced from red pigments, such as cinnabar (mercury sulfide HgS) or minium (lead oxide Pb_3O_4), or with less precious iron oxide as red pigment (as ochre or generally labelled "rubrum"). With the strong Z-dependence of the X-ray absorption cross section due to the photoelectric effect, such inks should show a significantly strong contrast in absorption tomography. 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, even if found with position-dependent varying intensities [12]. In case the absorption tomography does not yield the identification of letters or writing, then, most likely, any possible text has been written with carbon ink, which was the standard ink from the Old Kingdom up to our era. If so, a possible distinction between ink and organic base material is still missing, but under intense investigation.

As compared to virtual unrolling, virtual unfolding is not yet established. Therefore, we have tested the unfolding successfully on a mockup prepared using modern papyrus written with high-Z-element containing ink like cinnabar (*i.e.* Hg) and minium (*i.e.* Pb) and folded according to the magic fold which contains perpendicular folding lines. The result is shown in Fig. 2. Details are given in Ref. [13].

For an application of the successfully tested procedure, objects from the collection at the Musée du Louvre, Département des Antiquités Égyptiennes, seemed to be promising candidates. They originate from the French excavations at Elephantine conducted by Ch. Clermont-Ganneau between 1906 and 1911. The packages of which virtual unfolding is reviewed in this article (and in Ref. [14]) belong to the box labelled El 227 b where El stands for Elephantine. They were selected by visual inspection to check if their sizes and conditions are suited for our tomography setup. 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, as discussed above, the detection of Fe is not necessarily proof of the presence of ink containing Fe (for details see Ref. [12]) and, therefore, yielding the

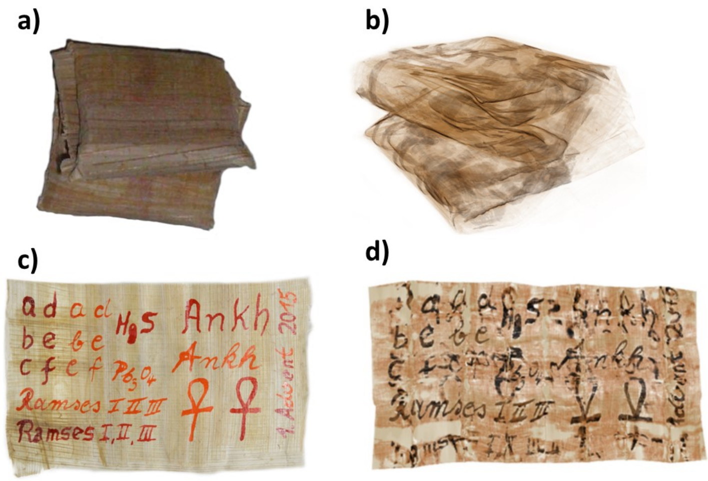

Fig. 2. Mockup papyrus folded according to the "magic fold" and written with cinnabar and minium: (a) photo, (b) volume rendered image, (c) photo of the text, (d) reconstructed planar image of the text (after some relaxation for reducing distortions, see for details Ref. [13]).

necessary contrast. Three specimens showed some variations in the intensities of the Fe characteristic fluorescence line depending on the position, and additionally some traces of copper, which is not known to be present in the substrate papyrus alone. Because of that, these packages were selected for absorption tomography at the micro-computed tomography (μCT) setup at the Helmholtz-Zentrum Berlin. Details of the tomographic data-taking are given in Ref. [14].

How to proceed for virtual unfolding is briefly summarized here, details can be found in Refs. [13, 14] with further references given therein. After identifying folding lines by inspecting the 3D-images, virtual unfolding is done in two major steps. In the first major step, the papyrus is unfolded until it is topologically 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 the 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 used here, it is assumed 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 this approach.

3. Results and discussion

The package, labelled L/El227b/4-pG, is highly fragile, but with only a few layers. Figure 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

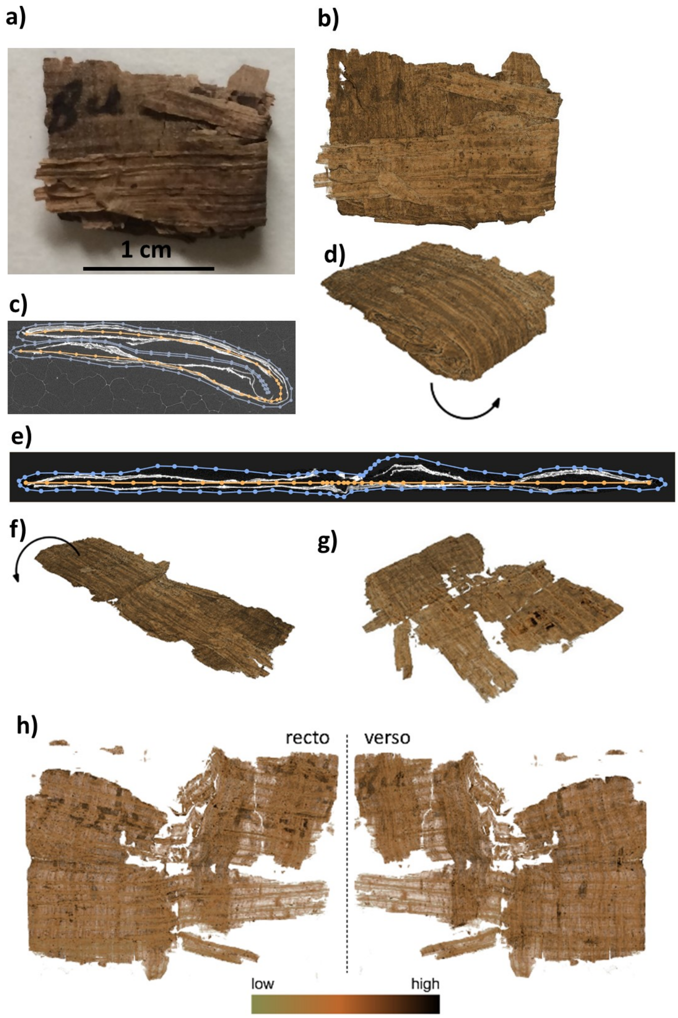

Fig. 3. Package L/El227b/4-pG Greek papyrus: (a) photo, (b) volume rendered image, (c) cross section with contour lines and central line for unfolding, (d) unfolding, (e) cross section after the first unfold, (f) and (g) unfolding/unrolling, (h) magnified 2D-projection with some Greek letters.

holes and missing fibers, a few Greek letters can be identified. Due to the difficult status of the object with large fractions destroyed and missing, it is not possible to identify a meaningful text out of the letters.

Since the package L/El227b/1-pC is rather fragile, too, it was "bandaged" with Japanese tissue, as seen on the photograph in Fig. 4. Volume rendering the tomographic data then revealed that the object L/El227b/1-pC is a flattened scroll. A cross section through the volume and the 2D projection are also shown in Fig. 4. 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 [Jesus Christ]" or "oh Lord [Jesus Christ]" in vocative

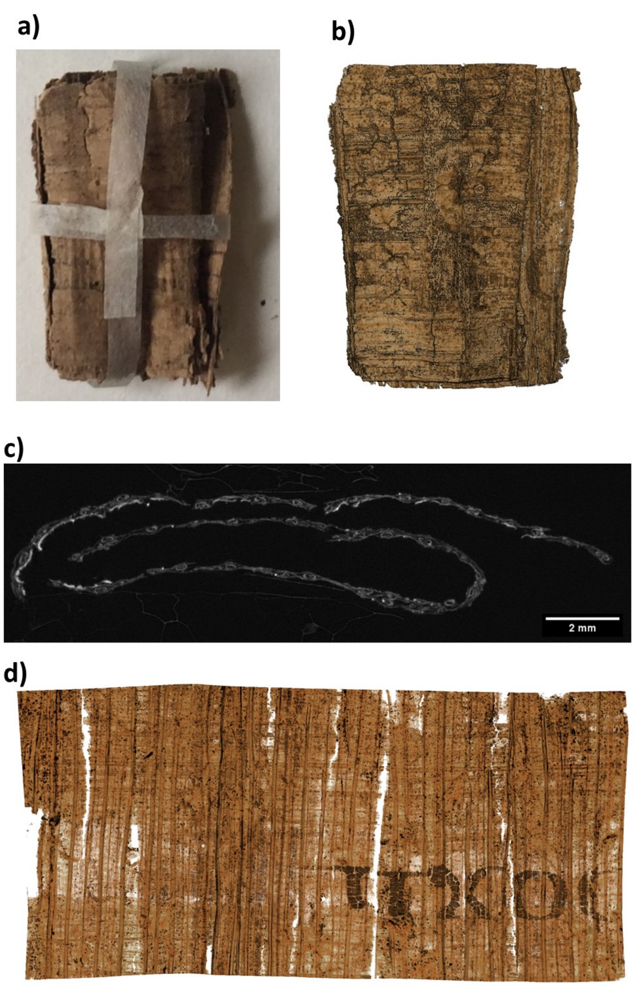

Fig. 4. Package L/El227b/1-pC Coptic papyrus: (a) photo, (b) volume rendered image, (c) cross section, and (d) 2D-projection showing a Coptic word for "Lord".

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 have been written in carbon ink and only the word for "Lord" was written in ferrous ink.

A third package from the Louvre collection, not shown here, appeared to be folded along two orthogonal lines quite similar to the mockup papyrus folded in the "magic" fold. Although small fractions of uncovered writing in black ink could be identified by simple inspection by eye, no indication of letters were found in the unfolding. This, most likely, means that in this case, we are dealing with carbon ink, which does not give sufficient contrast in absorption tomography.

4. Conclusions and outlook

In this short overview of the state of the art of getting access to text on rolled and folded papyri, we have focused on the recent success in virtual unfolding of Egyptian papyri originating from the island Elephantine. In one of the investigated objects, an ancient Egyptian papyrus package from the collection at the Louvre, a real Coptic word was identified. The examples shown clearly indicate the limit of the present imaging approach based on absorption tomography. Many papyri, however, especially papyri written before our era, are 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.

The work reported here has been done and is on-going in close cooperation with Tzulia Siopi from the Ägyptisches Museum und Papyrussammlung, with Tobias Arlt from the Technische Universität Berlin, with Ingo Manke from the Helmholtz-Zentrum Berlin, with Daniel Baum, Hans-Christian Hege, Felix Herter, and Norbert Lindow from the Zuse Institut Berlin, with Eve Menei, visiting papyrus conservator from Paris, and Marc Etienne from the Musée du Louvre. The authors are grateful to Tzulia Siopi for the photographs of the papyri objects, and to Felix Herter for the figures produced from the tomographic data. We additionally thank Kristin Mahlow and Johannes Müller (Museum für Naturkunde, Berlin) for acquiring the first tomography data on their "GE Phoenix Nanotom S" for the magic fold mockup and first attempts on packages from the Papyrussammlung. We are grateful to Leif Glaser (DESY, Hamburg) who wrote the cinnabar and minium ink letters on the mockup, to Frank Kutz and Philipp Hoelzmann

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