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## Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography

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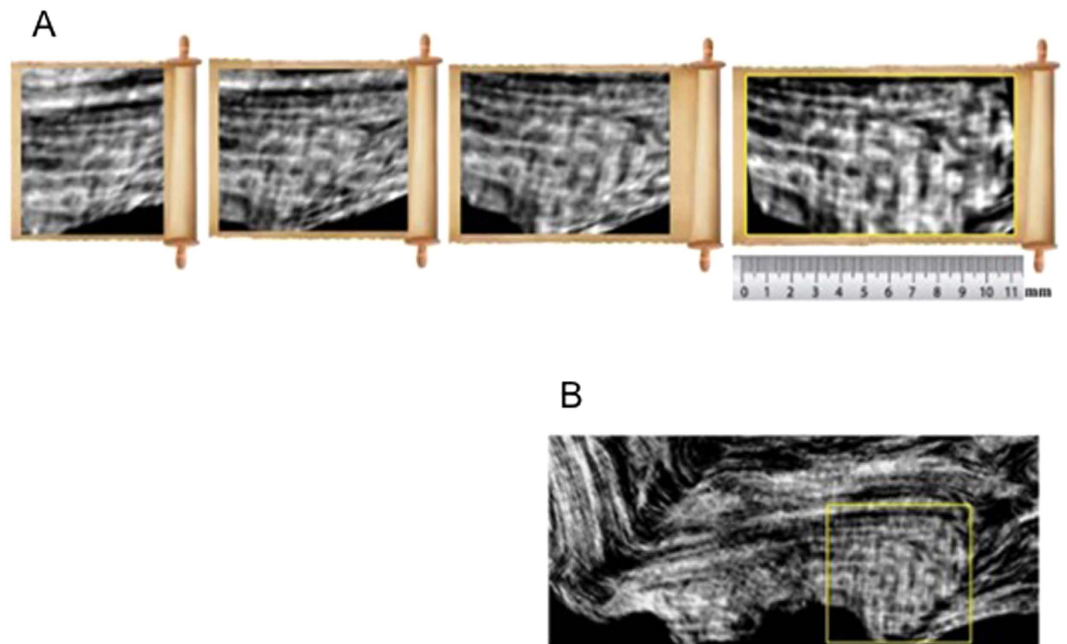
A collection of more than 1800 carbonized papyri, discovered in the Roman 'Villa dei Papiri' at Herculaneum is the unique classical library survived from antiquity. These papyri were charred during 79 A.D. Vesuvius eruption, a circumstance which providentially preserved them until now. This magnificent collection contains an impressive amount of treatises by Greek philosophers and, especially, Philodemus of Gadara, an Epicurean thinker of 1st century BC. We read many portions of text hidden inside carbonized Herculaneum papyri using enhanced X-ray phase-contrast tomography non-destructive technique and a new set of numerical algorithms for 'virtual-unrolling'. Our success lies in revealing the largest portion of Greek text ever detected so far inside unopened scrolls, with unprecedented spatial resolution and contrast, all without damaging these precious historical manuscripts. Parts of text have been decoded and the 'voice' of the Epicurean philosopher Philodemus is brought back again after 2000 years from Herculaneum papyri.

The Herculaneum papyri were discovered in the Roman 'Villa dei Papiri' during modern excavations of the Herculaneum site in Campania (Italy) in the middle of 18<sup>th</sup> century. This unique library survived from antiquity contains valuable works by Greek philosophers, such as Epicurus, Chrysippus and Philodemus, in particular an impressive amount of extensive treatises by Philodemus of Gadara, an Epicurean philosopher of 1<sup>st</sup> century BC<sup>1,2</sup>.

Since their discovery, numerous efforts have been made to open Herculaneum papyri and read the precious works hidden inside them and several destructive and non-destructive techniques were employed. Synchrotron X-ray phase-contrast tomography (XPCT) non-destructive technique<sup>3,4</sup>, originally introduced mainly in bio-medical imaging, in the present study has been optimised and combined with versatile algorithms developed to deal with extracting distorted and corrugated papyri. These are summarized in Supplementary Information (SI). Our findings provide new insights into the Herculaneum collection, going far significantly beyond a previous feasibility test experiment which showed the benefit of XPCT applied to rolled-up papyri in imaging letters<sup>5</sup>.

This paper shows our success in 'virtual-unrolling' two unopened papyrus rolls, i.e. *PHerc.* 375 and *PHerc.* 495, both stored in Naples' National Library. A phantom sample, composed of high quality sheets of bare papyrus paper, was constructed and carbonized in order to determine the capacity and reliability of XPCT technique and the viability of the numerical algorithms. The phantom sample was earlier examined as an archaeological object in both geometry and material using XPCT. Subsequently, both papyrus rolls, *PHerc.* 375 and *PHerc.* 495, were measured

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**Figure 1.** *PHerc. 375*. (A) virtual-unrolling; (B) textual portion.

through the same technique. In order to reveal the hidden text inside the original unopened papyri and the phantom sample, a new set of numerical algorithms for the ‘virtual-unrolling’ were developed ‘in house’ (see SI). These were tailored to adapt to the complex and diversified amorphous 3D deformed materials composing the rolls. The test performed on the phantom guided us, allowing to optimize and integrate the set of algorithms.

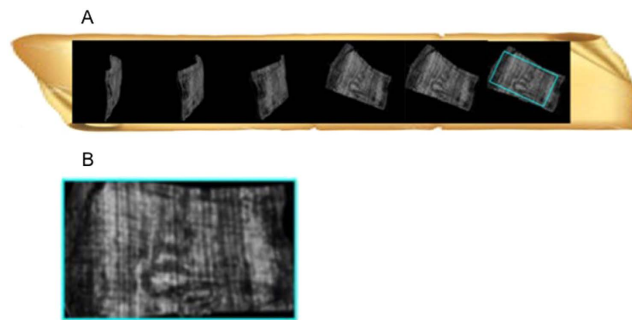
The result was a digital ‘virtual-unrolling’ of the unopened papyrus rolls with unprecedented resolution and contrast. Detailed tomographic images of the inner complex structure of the layers along the full longitudinal axis of the bookrolls were obtained (see SI). The optimized phase-contrast 3D tomography distinguished areas of different densities: those composed of amorphous carbon-based ink were differentiated from that of the papyrus substrate, made of ordered carbon fibres. The ‘virtual-unrolling’ procedure, despite the complex organization in the inner portions of the scrolls, allowed to reveal Greek sequences of letters and words and, for the first time, read and decipher expressions and textual portions as well as a *coronis*, a symbol used to mark the end of a textual section, a chapter or a book in classical papyri.

Different numerical procedures have recently been proposed to provide<sup>6,7</sup> a digital version of the text hidden inside rolled-up papyri starting from their non-invasive acquisition. Nevertheless the structure of carbonized Herculaneum papyri is quite different from that of a regular roll where a standard ‘virtual-unrolling’ algorithm is applicable. In recent years specific software has been developed<sup>8</sup> without achieving any reading of the text inside Herculaneum-papyri. Our success lies in combining XPCT with tailoring the basic principles of the ‘virtual-unrolling’ to the Herculaneum papyri and, consequently, virtually open, read and decode the largest portion of text, hidden inside unopened papyri, ever detected so far. This success is based on three main facts: i) the experience gained with the experiment on the phantom; ii) the optimal experimental conditions which provided, to the best of our knowledge, 3D images of the inner structure in carbonized Herculaneum papyri of the best quality ever obtained; iii) the very intricate internal arrangement of chaotic bundles of layers still presented sets of similarly bent, splayed and twisted layers. Once the XPCT provided the 3D volume of the bookrolls, ‘virtual-unrolling’ was performed. Upon partitioning the roll in subsets of similarly bent and twisted layers we were able to apply to each one ‘flattening’ procedures for each specific distortion of packed sheets (see SI).

Although the procedure is very elaborate and time-consuming, it is remarkable that the explorable partial area of the ‘virtually unrolled’ portion of the text was effectively unlimited. This adaptive procedure, allowing the complete unrolling of the rolls, is the propaedeutic tool for the future reading of entire columns of text, possibly paving the way for the first edition and interpretation of the works contained in unopened carbonized Herculaneum papyri.

Figure 1A shows the sequence of the images obtained during the ‘unrolling’ procedure of *PHerc. 375*. From left to right of Fig. 1A, an increasingly large portion of flat region appears, including an 11 mm large text of more than three lines. Its position inside the bookroll is shown in Fig. 1B. Figure 2A shows the sequence of the images obtained from the ‘unrolling’ procedure of *PHerc. 495*. Figure 2B discloses the *coronis* with an exceptional image quality.

The revealed text was written on the papyrus side where the writing runs along the fibres (*recto*). Both rolls were ascribed on palaeographical grounds to Philodemus of Gadara, a remarkable philosopher and poet who studied in Athens before moving to Rome and Campania. In terms of textual extension, this assignment goes far significantly beyond that revealed in the previous XPCT study<sup>5</sup>. The handwriting was found to be a known typology in the Herculaneum library. As usual in classical antiquity, this was in capitals, with no word spacing,



**Figure 2.** *PHerc. 495.* (A) virtual-unrolling; (B) image of *coronis*.

breathings, accents or lectional signs. The ‘virtual-unrolling’ allowed i) to reconstruct a complete Greek alphabet for each bookroll (see Figure 5S in SI); ii) to detect several Greek sequences of letters and words, reported in Fig. 3A–B, D–E left) to read for the first time, expressions and portions of text in Fig. 3C, E right–G and Fig. 1; iv) to identify, also for the first time, a textual sign (*coronis*), reported in Fig. 3H left and 2. These all are clearly distinguishable from the papyrus substrate. Using the ‘virtual-unrolling’ it was possible to perform the reconstruction of the largest portions of text ever detected in unopened papyrus rolls. Three distinct sequences of letters, i.e. ]ΕΥ ΕΡ, ]ΨΙC [ and ]ΚΩC [ were detected in *PHerc. 375*. These are displayed from left to right in the top row of Fig. 3A; three words, i.e. τηρηι (*tērēi*), περιε (*perie*) and ]ειθεειν (*peistheien*), are shown in Fig. 3B. In the case of *PHerc. 495*, the sequences ]επ[ (*ep*), ]στ[ (*st*) and ]εχε[ (*eche*) are shown in Fig. 3D. Furthermore, it was possible to isolate the word ]τειπομ[εν (*teipomen*) (left of Fig. 3E) and the expressions ]εν γάρ (*en gar*) (right of Fig. 3E) and ]τελη βημ[α (*telē bēma*) (Fig. 3F). This last expression is formed by the second component stem of a compound adjective in –τελής, –έC or, less probably, the plural noun τέλη (from τέλος, ‘end’ or ‘purpose’) and the noun βήμα, ‘tribune’, in either the singular or the plural. The latter means the raised place from which orators spoke in a public assembly or in a lawcourt and is used twice in Philodemus’ *On Rhetoric* (col. 56, 8 Sudhaus II; col. 264, 21 Sudhaus I). The *coronis* is clearly shown in Fig. 3H left beside a known example from an unrolled portion of *PHerc. 1008* (Fig. 3H right). This latter is imaged by means of multispectral technique.

An example of textual portion is reported in Fig. 3C, for *PHerc. 375*, and Fig. 3G, for *PHerc. 495*, together with a proposed textual reconstruction. In the former case, the verb ἐδέδ]οκτο might refer to a resolution taken by, e.g., a political assembly. In the latter, the focus seems to be on either civil or political matters. It must be stressed that the different size and the deformation observed in some letters as well as some of the images is due to the distortion produced by the irregular surface of the papyrus substrate. Finally a *coronis*, namely a typical sign used by scribes in antiquity to signal specific articulations of the text, was revealed in *PHerc. 495* (Fig. 3H left). Full details of the textual reconstructions can be found in SI. In terms of spatial resolution and contrast, the present ‘virtual-unrolling’ permitted to fully exploit XPCT techniques.

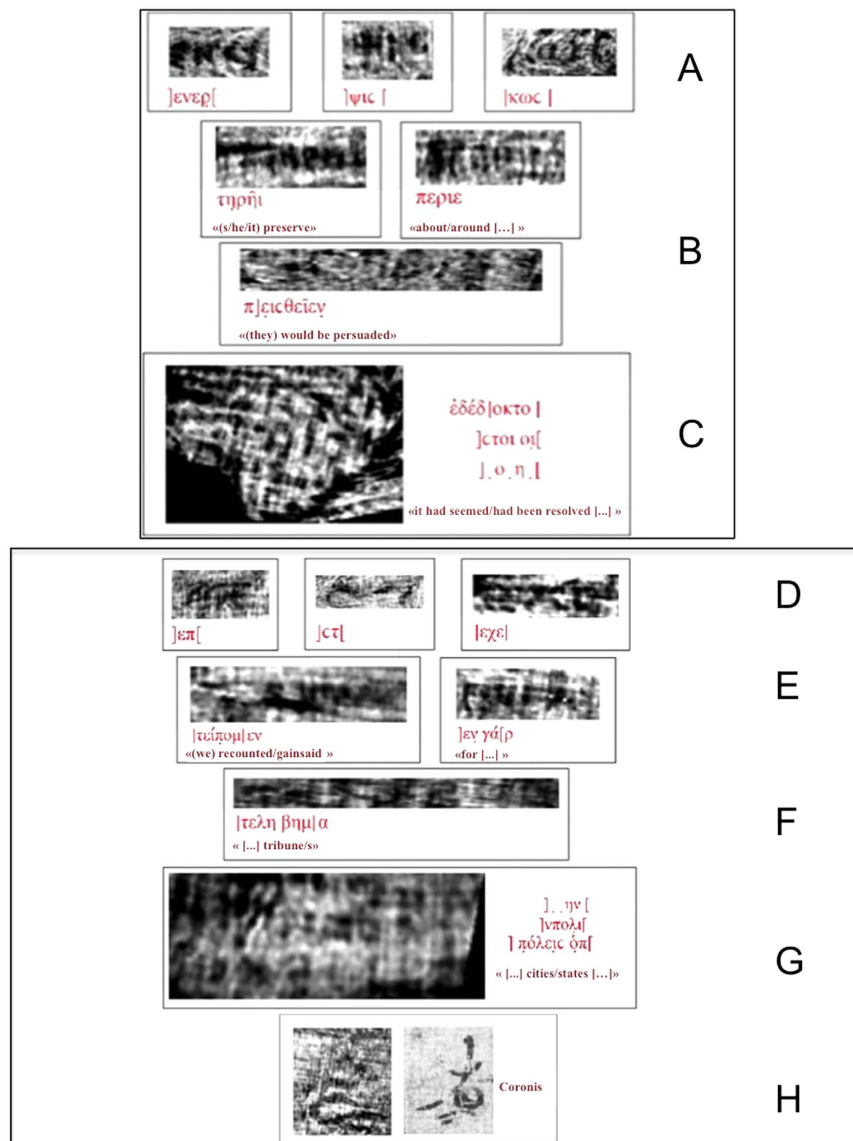
The large number of letters and texts revealed by the ‘virtual-unrolling’ made it possible to analyze the handwriting within each unopened roll. Despite the distortions of the letters caused by the irregular surface of the layers, detailed paleographical description was achieved. Full details of it can be found in SI. From a comparative analysis with different writing groups inside the Herculaneum collection, both unopened rolls could be attributed with a high degree of probability to the Epicurean philosopher Philodemus of Gadara. In particular, *PHerc. 495* might possibly represent a book of his twenty-books large treatise *On Rhetoric*<sup>9</sup>, either one partially known to us or a completely unknown one. In addition, our study revealed unexpected events historically experienced by the rolls, equally reported in SI.

These results demonstrate the potential of XPCT technique in reading inside rolled-up carbonized Herculaneum papyri. The investigation will enable our current knowledge of Hellenistic philosophy and classical literature to be expanded, with expected impact in fields such as papyrology, palaeography, classical philology and history of ancient philosophy.

## Methods.

**X-ray Phase Contrast Tomography imaging.** Standard X-ray tomography is based on absorption and it is a well known tool for imaging the internal structure of thick objects with hard X-rays. For low-absorption materials (like Carbon-based objects) small attenuation in the sample produces low contrast in the images. Thus standard absorption tomography is an unsuitable technique to discriminate details of similar densities in, for example, distinguishing carbon fibre-based papyrus foil from carbon-based ink used in writing on the papyrus. In the latter case, as shown in this study, a better contrast was achieved by imaging the phase modulation induced by the object in a coherent or partially coherent beam<sup>3,4</sup>. Several experimental approaches exist for detecting X-ray phase contrast. A simple yet effective phase-contrast method for hard X-rays is based on in-line imaging after free-space propagation.

**Experiment.** A series of experiments were carried out at ID17 of the European Synchrotron Radiation Facility (ESRF) in Grenoble (F), using a free-space propagation set-up. The imaging detector is a Fast Readout Low Noise (FReLoN) 2k charge-coupled device camera (CCD) connected with an X-ray optics determining an effective pixel size of  $47 \times 47 \mu\text{m}^2$ . The final spatial resolution in the images is about  $100 \times 100 \mu\text{m}^2$ . The field of



**Figure 3.** Sequences of letters, words, textual portions and *coronis*, revealed in papyrus rolls through the ‘virtual-unrolling’. (A–C) *PHerc.* 375 (top panel) and (D–H) *PHerc.* 495 (bottom panel). Row H shows the *coronis*: on the left, the image obtained by our ‘virtual-unrolling’ and, on the right, a known example from an unrolled fragment of *PHerc.* 1008. The latter is imaged by means of multispectral technique. By permission of Ministero per i Beni e le Attività Culturali e del Turismo (Steven W. Booras<sup>©</sup> Biblioteca Nazionale ‘Vittorio Emanuele III’, Napoli – Brigham Young University, Provo, USA). All rights reserved.

view (FOV) was limited to about 1 mm (vertical) × 75 mm (horizontal). A double-silicon (111) crystal system was used to monochromatize the incident X-ray beam. Samples were located at about 10 meters from the CCD camera and they were rotated around the vertical axis parallel to the longitudinal axis of the rolls.

a) multi-energy scans were performed on the phantom sample in order to distinguish between absorption and phase contributions: incident X-ray beam was monochromatized at three different energies: 80, 52 and 30 keV. For each energy, 1400 radiograms were recorded for each scan, covering a total angle range of 180°, with acquisition time of 0.05 seconds per point. Results of these experiments allow to read and decipher letters and numbers previously written inside papyrus roll and to optimize the experimental conditions. Because of the flow of CO<sub>2</sub> during the combustion severe and diversified deformations developed within the bulk of the phantom papyrus roll. This complex inner structure was ideal to develop and test the new numerical algorithms for the ‘virtual unrolling’ and to tailor and optimize them to reveal the hidden writing accordingly. From the multi-energy experiment on the phantom sample it was also possible to record and to test the capability of distinguishing between the high signal due to the Pb in the ink from the low signal due to the other elements composing the ink.

b) The XPCT experiments on the *PHerc.* 375 and *PHerc.* 495, were performed using a monochromatized incident X-ray beam with an energy of 73 keV. The choice of the energy is one of the essential conditions to achieve a suitable contrast in the final recorded images. The choice of the incident energy was selected following different

guidelines: a) the experience gained with the phantom, which indicated the range of energies where contrast would have been higher; b) the measurement of the sample thickness which determined the minimum energy to be used; c) finally the optimization was based on the maximization of the *contrast transfer function*<sup>3</sup> taking into account the fixed sample–detector distance and the pixel size of the CCD.

The two bookrolls, PHerc. 375 and PHerc. 495, were placed in cylindrical containers made of Plexiglas, specifically fabricated for the experiment, and safely mounted on a rotating plate at the sample position. About 2000 radiograms were recorded for each scan, covering a total angle range of 180°, with acquisition time of 0.05 seconds per point. Due to the limited FOV, in order to scan the whole scroll, several tomographic measurements were acquired at different vertical positions. The total data-acquisition time for each bookroll was about 5 hours.

**Data processing.** In the first step of data analysis, the phase retrieval algorithm proposed by Paganin *et al.*<sup>10</sup> was applied to all projections of the tomographic scans using a modified version of the ANKPhase code<sup>11</sup>. Using a PyHST2 code<sup>12</sup>, the recorded images were tomographically reconstructed. As a result a stack of 2D images representing the density distribution at different depths inside the sample was obtained. By means of a commercial 3D rendering software the 2D images of the stack were composed to build the whole 3D volume (see Figs 3S and 4S in SI). The inner structure of the whole reconstructed rolls shows the various papyrus layers to be diversely bent and twisted at the different depths inside the volume (see movie S1 in SI).

**Image treatment.** 3D rendering and segmentation of the impurities were carried out using the Visage Amira 6 software (interactive system from FEI) and VolView, an interactive system for volume visualization from Kitware Inc. (see SI). The 3D structure of the papyri was obtained through a sort of segmentation procedure. The images were generated by associating colors to the different gray-scale ranges in the 3D model.

**Virtual Unrolling.** In the last years virtual unrolling problem using volumetric scanning in virtual restoration and preservation of ancient artefacts like parchments or papyri has been an extremely active area of research. The use of X-ray Computed Tomography (CT) and X-ray Micro Computed Tomography for the data digitalization has encouraged the development of restoration algorithms. Different numerical procedures have been proposed to provide a digital version of the text hidden inside rolled-up scrolls by starting from non-invasive acquisition.

The procedure of virtual unrolling can be divided into three main steps: volumetric scanning, segmentation, layered texture generation and restoration.

*Volumetric scanning.* In this stage the experimental data are acquired and their digitalization is performed.

*Segmentation.* The process of segmentation is used in order to segment a voxel set into two categories: material voxels versus empty space.

*Layered texture generation.* This is the stage where the surface modelling is performed.

*Digital restoration.* The surface flattening and unrolling can be interpreted as an isometric mapping (i.e. it preserve distances, which minimises text distortion in the parchment) from 3D to 2D images.

To solve these problems different approaches were proposed. One of the most promising is described by Seales and colleagues<sup>6,8</sup>. The authors have developed software that integrates functions of flattening and unrolling based on mass-spring surface simulation. The algorithms proposed by O. Samko *et al.*<sup>7</sup> allows to solve the problem of touching points between adjacent sheet layers.

The internal structure of the Herculaneum papyrus is quite different from the regular roll where a simple ‘virtual unrolling’ was applicable. However the very intricate internal arrangement of chaotic bundles of layers still presented sets of similarly bent, splayed and twisted layers. The central part of the scroll is better preserved and the layers of papyrus are separated and loosely rolled up. The outer part of papyrus is tightly scrolled and stacked. It is evident that the virtual revealing of the text requires different approaches and has its own challenges. From the experiment performed on the prototype we learned that the letters can be deformed due to thermal and pressure impact and due to irregular surface of the fibres. *A priori* it is not possible to know the letters aspect and even whether the text is present in the analysed portion of rolls. In principle the text could be destroyed or could not appear due to the wrong position in the papyrus foil.

We performed semi-manually procedure to reveal the hidden text based on computed algorithms exploiting Matlab<sup>®</sup> codes ImageJ macros and different available commercial computer software. Once the phase contrast tomography provided the 3D volume of the bookrolls, to reveal the Greek text hidden inside, a multistep procedure has been settled:

1. Accurate optimization of the range of grey-levels has been done to individuate the inner structure of papyrus with preserving all information about text.
2. Selection of areas with packaging of sheets with similar orientation.
3. Flattening of packed sheets, using different strategies including transformation of coordinates.
4. Filtering and segmentation of individual sheets in 2D slices.
5. Surface modelling.
6. Segmentation based on threshold to reveal the text

## References

1. Zarmakoupi, M. *The Villa of the Papyri at Herculaneum: archaeology, reception, and digital reconstruction* Vol. 1 (Walter de Gruyter, Berlin, Germany, 2010).
2. Sider, D. *The library of the Villa dei Papiri at Herculaneum.* (Getty Publications, Los Angeles, USA, 2005).

3. Bravin, A., Coan, P. & Suortti, P. X-ray phase-contrast imaging: from pre-clinical applications towards clinics. *Phys. Med. Biol.* **58**, R1 (2012).
4. Lagomarsino, S. *et al.* Phase contrast hard x-ray microscopy with submicron resolution. *APL* **71**, 2557–2559 (1997).
5. Mocella, V., Brun, E., Ferrero, C. & Delattre, D. Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging. *Nat. Commun.* **6**, 1–5, doi: 10.1038/ncomms6895 (2015).
6. Yun Lin and W. B. Seales, Opaque document imaging: building images of inaccessible texts. presented at *Tenth IEEE International Conference on Computer Vision*: Beijing, doi: 10.1109/ICCV.2005.182 (2005, October).
7. Samko, O., Lai, Y.-K., Marshall, D. & Rosin, P. L. Virtual unrolling and information recovery from scanned scrolled historical documents. *Pattern Recogn.* **47**, 248–259 (2014).
8. Seales, W. & Delattre, D. Virtual unrolling of carbonized Herculaneum scrolls: Research Status (2007–2012). *Cronache Ercolanesi* **43**, 191–208 (2013).
9. Ranocchia, G. Nuove acquisizioni sulla struttura del Περὶ ῥητορικῆς di Filodemo. Un trattato in almeno venti libri. *Zeitschrift für Papyrologie und Epigraphik*, accepted for publication (2014).
10. Paganin, D., Gureyev, T. E., Pavlov, K. M., Lewis, R. A. & Kitchen, M. Phase retrieval using coherent imaging systems with linear transfer functions. *Opt. Commun.* **234**, 87–105 (2004).
11. Weitkamp, T., Haas, D., Wegrzynek, D. & Rack, A. ANKAphase: software for single-distance phase retrieval from inline X-ray phase-contrast radiographs. *J. Synchrotron Radiation* **18**, 617–629 (2011).
12. Chilingaryan, S. *et al.* A GPU-based architecture for real-time data assessment at synchrotron experiments. *IEEE Trans. Nucl. Sci.* **58**, 1447–1455 (2011).

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## Author Contributions

A.C. proposed and coordinated the experiment, G.R. reconstructed the Greek texts and wrote the historical account, M.A. made the palaeographical analysis, R.B. coordinated the design and experimental measurements on the papyri puppet, R.G.A. and M.G. developed the concept of the papyri puppet and realized them. I.B. developed the algorithms for the ‘virtual-unrolling’ procedure and A.M. performed the tomographic reconstruction. A.B., P.C., F.C. and V.F. contributed to the experiments and the data collection at the ESRF beamline, G.F., M.F., L.M. designed the figures. C.A., R.B., A.L., G.G. contributed to the theoretical discussion and the writing of the manuscript. All authors discussed the results and contributed to the redaction of the manuscript.

## Additional Information

**Supplementary information** accompanies this paper at <http://www.nature.com/srep>

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# Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography

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## General Information

Since their discovery, numerous efforts have been made to unroll Herculaneum papyri and read the precious texts contained inside them. Initially, these attempts to unroll the scrolls failed, due to the extreme fragility of the manuscripts, and several of them were destroyed<sup>1</sup>. In the late 18th and 19th century the outer layers of bookrolls were usually cut off in order to expose the central windings, often less badly damaged than the exterior portions, and could be unrolled on Piaggio's machine using a sophisticated method proposed in 1756<sup>2</sup>. In the 1980s a chemical method based on a gelatine, acetic-acid and water solution, called the 'Oslo method', was used in further attempts to unroll the scrolls. However, this method caused most of the scrolls to break into hundreds of fragments<sup>3</sup>. Besides, some chemical analyses on ink were

performed<sup>4</sup>. Between 1999 and 2002 multispectral imaging (MSI) of all unrolled papyri was made with important results<sup>5</sup>. This approach showed that the writing could be clearly imaged and distinguished from the papyrus substrate with excellent spatial resolution, given the different characteristic absorption spectra of ink and papyrus and without damaging or destroying the manuscripts. This technique is now used extensively in papyrological and codicological research.

Shortly after MSI was introduced, other non-destructive techniques were applied to both papyrus scrolls and fragments, for use in reading both unrolled and rolled-up papyri. These additional techniques included, amongst other, Scanning Electron Microscopy (SEM)/EDX, Particle Induced X-ray Emission (PIXE), Computer Tomography (CT) and Nano-Computer Tomography (Nano CT), High Resolution Digital Radiography (HRDR), Thermographic Imaging (TI), X-ray Fluorescence (XRF) and Micro-CT analysis (MCT)<sup>6</sup>. Most recently, X-ray phase-contrast tomography (XPCT) was applied to a Herculaneum papyrus roll and a Herculaneum papyrus fragment owned by the Institute of France (Paris). This feasibility test-experiment showed the potential benefit of applying XPCT to papyri, but neither virtual unrolling nor extensive text reading was achieved<sup>7</sup>.

## **Materials**

The materials characterized in this study are: a) two lengthwise entire papyrus rolls (*PHerc. 375* and *PHerc. 495*), with dimensions 7,5 cm (diameter) x 16,5 cm (height) and 7,5 cm (diameter) x 17,5 cm (height), respectively; b) a phantom sample of papyrus roll was realized using sixteen high quality sheets of bare papyrus paper originated from Sicilian papyrus plants and manufactured to reproduce the above papyrus rolls in both geometry and material. 2 cm in diameter x 10 cm in length. Sequence of numbers and Greek letters were written on the paper sheets using home-made ink. The latter was manufactured following the elemental composition used for writing on Herculaneum papyri available in the literature<sup>4</sup>. Subsequently the paper sheets were first rolled up and then combusted - under vacuum chamber and CO<sub>2</sub> flow - at 350 C, a procedure which was designed to reproduce the physical condition of heat and no oxygen, the most similar to the volcanic flow of Vesuvius eruption in 79 AD.



The images of the phantom sample and of the distribution of complex components inside are shown in Figure 1S. The latter illustrates the capacity and reliability to image the contrast between the location of different fibres components and texts.

In Movie 1S one can appreciate the complex internal structure of papyrus roll *PHerc. 495*. Because of catastrophic events it is now composed of layers bent and twisted in random directions. The video shows a virtual slicing of the papyrus in the longitudinal direction, i.e. sections parallel to the long axis of the papyrus. Papyrus slices, followed during the video, represent the internal structure at different depths. Each slice has a thickness of about 50 microns and an area that covers almost all papyrus length times its diameter. Layers in the outer regions are well 'sealed', due to the thermal shock. This movie exploits the remarkable contrast and spatial resolution of XPCT experiment to its full potential.

Thanks to the XPCT technique, we discovered that *PHerc. 495* contained a large number of grains of sand. This result revealed the history this precious scroll underwent, after being written and stored in the Library of Herculaneum. Before the thermal shock caused by the eruption of Vesuvius, it is believed that a catastrophic phenomenon, such as an earthquake, occurred. During this event *PHerc. 495* might have been covered with sand, which penetrated inside. As the volcanic eruption took place, the thermal shock 'sealed' the roll in its outer surface for the subsequent centuries.

Movie 2S shows a virtual slicing of the papyrus into radial direction. The sequence of images in the movie represents the sections (each about 50 microns thickness) parallel to the transversal area of the papyrus at different height. The white grains are particles of high density, i.e. the sand grains. The video shows that sand comes from the outside and it is distributed in depth.

The history of the papyri revealed to us through the XPCT analysis, is fascinating. Most exciting is the possibility to read and decipher portions of text hidden for almost two thousand years inside the bookrolls. The 'virtual unrolling' has revealed valuable writings by, most likely, the Epicurean philosopher and poet Philodemus of Gadara, with remarkable contrast and legibility. Both the texts and the handwriting 'brought to light' in the bookrolls allowed us to guess the author of both rolls and the subject matter of one of them. Movie 3S shows the virtual opening of the most intact portion of such ancient text ever found.

## ***Supplementary Results***

### *History and characteristics of the bookrolls*

According to the *Catalogo dei papiri ercolanesi*<sup>6</sup>, *PHerc.* 375 was partially unrolled in 1848 by Carlo Malesci through the mechanical system developed by Antonio Piaggio. The bookroll, which appears severely squeezed in height, still exhibits small traces of the thin animal membrane ('pelle battiloro'), which was glued to the outer side of it during the unrolling. Five pieces of similar sizes for a total length of 1,725 m were obtained from this operation. These were glued upside down to paper sheets and fastened to wooden tablets. The charcoal-black color and the corrugation of the unrolled pieces seem *prima facie* compatible with those of the roll. However, the pieces' height (max. cm 22) is quite larger (max. 5,5 cm difference) than the roll's. This problem may be overcome only by postulating that, being the roll squeezed in height, the pieces could be stretched immediately after the unrolling. In fact, the height of the latter perfectly conforms to the standards known for unrolled Herculaneum papyri<sup>7</sup>. The unrolled pieces are severely layered and just a few letters are legible (Figure 2S a). Both the upper and the lower margin (blank space left by the scribe) are preserved. They contain a thoroughly unknown Greek text, which has never been transcribed nor edited.

*PHerc.* 495 seems to be a similar case. According to our sources<sup>6</sup>, it would have partially been unrolled in 1820 by Humphrey Davy by applying sulfuric ether to the outermost side of the roll in order to soften it and in 1830 by Carlo Malesci through the Piaggio machine. Also in this case the roll, which appears fairly twisted and squeezed at 2/5 of its axis, still exhibits small traces of animal membrane. Ten pieces of different shapes and sizes for a total length of 1,657 m were overall unrolled and were glued to paper sheets and fastened to carton tablets. In 1987 a team led by Knut Kleve unrolled further thirteen small pieces through the chemical system known as 'Oslo method'. Due to the unsatisfactory results of this operation the team decided to stop the unrolling. The dark-anthracite color and the corrugation of the unrolled pieces do not seem, at first sight, incompatible with those of the roll. Nevertheless, the small size of most of them does not allow a morphological comparison between them and the roll. The pieces unrolled in the XIX century exhibit some layering and in most cases the lower margin is preserved in them. For this reason and due to their limited

height (max. 13,3 cm), they must represent the lower part of a bookroll. Only some textual portions are legible (Figure 2Sb). These have been transcribed in 1820 by W. Gell and P. Elmsey, in 1853 by Vincenzo Corazza and in 1915 by Mario Arman and have been edited in 2001, together with *PHerc. 558*, by Fabio Massimo Giuliano <sup>8</sup>. On the contrary, the pieces unrolled in 1987, which are hardly legible, have never been transcribed nor edited. On its turn, *PHerc. 558*, consisting in 27 fragments unrolled in 1888 by Luigi Corazza and formerly taken to be the upper part of the unrolled portions of *PHerc. 495* <sup>9</sup>, has been proved to belong to a different bookroll on physical, paleographical and textual grounds <sup>8</sup>. The unrolled portions of both *PHerc. 495* and *PHerc. 558* contain a Greek text, which has been recognized as a *History of Socrates and his school* by Philodemus, possibly belonging to his *Arrangement of the philosophers* <sup>8,9</sup>.

#### *Inner structure of the bookrolls*

In Figures 3Sa and 3Sc pictures of the two papyrus rolls are reported. To derive the 3D tomographic reconstruction of the internal areas inside these unopened scrolls, a software package for phase contrast tomography has been applied (see the Materials section). 3D tomographies of *PHerc. 375* and *PHerc. 495* are reported in Figures 3Sb and 3Sd, respectively. These show axial and longitudinal views in the 3D reconstruction, revealing the complex stress field and the layering of the material - twisted, bent and distorted - in the inner part of the scrolls. Zooms of specific areas highlight the fibre texture of the papyrus paper. The unprecedented contrast allows us to clearly distinguish and highlight portions of the bookrolls with different densities, i.e. between areas of package of sheets with different orientations and the complex individual layers. Full details of the measured distortions of the layers and changes as a function of depth inside the unopened scrolls can be seen in Movies S1. For example, one can appreciate how the outer layers in this region appear to be more closely stacked, while the interspace among carbon fibres of the papyri are drastically reduced. This was interpreted as a consequence of longer exposure of the outer portions of the rolls to thermic shock waves during the Vesuvius eruption. Indeed layers in the inner part of the rolls are better preserved, well separated and loosely rolled up. The result of 3D rendering of *PHerc. 375* and *PHerc. 495* are reported in Figure 4S. The full 3D tomographic images for *PHerc. 375* and *PHerc. 495* are plotted in Figures 4Sa-c, respectively. Images of Figures 4Sd and 4Se show very

clearly that *PHerc.* 495 exhibits a large number of impurities (yellow spots), identified as small particles of sand, embedded in its bulk (Figure 4Se). *PHerc.* 375 exhibits a small number of impurities, i.e. it looks like mostly uncontaminated. Distribution of sand particles in *PHerc.* 495 can be further seen in movie S2. Both images and movies reveal that the small particles of sand are visible in the outer layers of the scroll as well as in its bulk. This is a strong evidence that the small particles penetrated into the bookroll before these were actually exposed to thermic shock waves. These results allow the conclusion that *PHerc.* 375 was already better preserved than *PHerc.* 495 already before it was eventually exposed to the thermic shock waves of the volcanic eruption.

### *Textual reconstruction*

The virtual unrolling of the bookrolls revealed sequences of letters, words and, for the first time, expressions and textual portions as well as a textual sign (*coronis*). Just some instances of what was found are reported in Figure 3, together with a possible textual reconstruction. Please note that these reconstructions are partly conjectural and that alternative readings are also possible. Due to the large number of letters and texts detected inside the bookrolls we were also able to reconstruct a complete Greek alphabet for each roll. These are displayed in Figure 5Sa-b.

Sequences of letters. For *PHerc.* 375 the three sequences ]ενερ[, ]ψιϛ [ and ]κωϛ [ are displayed in Figure 3A. In the first case, we have three certain letters (*ene*) followed by a vertical stroke slightly reaching below the line, which is very likely to be a *rho*. Hence, either a single word like ἐνέργεια or ἐνεργέω or a phrase like ]εν ἐρ[ are equally possible. In the second case (*psis*), we have a substantive of the third declension in -ιϛ, -εωϛ like, e.g., ἀνάληψιϛ or πρόληψιϛ. In the third case, the sequence ]κωϛ [ (*kō s*) either coincides with the final portion of an adverb (-κῶϛ) or the termination of the first perfect active participle in the singular masculine nominative (-κῶϛ). As far as *PHerc.* 495 is concerned, the sequences ]επ[ (*ep*), ]στ[ (*st*) and ]εχε[ (*eche*) are clearly readable in Figure 3D. In the last case, we must either have a voice of a verb like, e.g., ἔχω or δέχομαι (or compounds) or the last component of a compound adjective of the third declension in -εχήϛ, -έϛ such as συνεχήϛ or προεχήϛ.

Words/expressions. For *PHerc.* 375 we have selected the words τηρήτι (*tē rē i*), περιε (*perie*) and π]εϛιϛθεῖεν (*peistheien*). These are displayed in Figure 3B. The first is the

active subjunctive present of the verb τηρέω, ‘watch over, preserve’, or a compound of it in the 3rd singular person. The second is the passive octative aorist of πείθω, ‘persuade’, in the 3rd plural person. The third word is either the preposition περί or the preverb περι-, ‘about’ or ‘around’, followed by a verb or any other word beginning in ε-. As to *PHerc.* 495, the word ]τείπομ[εν (*teipomen*), and the expressions ]εν γάρ (en gar) and ]τελη βημ[α (*telē bē ma*) have been selected in Figure 3E-F. The first one is the indicative aorist, 1st plural person, of a compound of λέγω like καταλέγω, ‘recount’, ‘enumerate’ (κατείπομεν) or ἀντιλέγω, ‘speak against or in reply to’ (ἀντείπομεν). It is probably a *pluralis auctoris* used by the author of the book for referring to a previous section of it in which he has either told at length some issues or has gainsaid to an opponent of his. This usage is well attested in Philodemus. The second expression may either be a combination of particles like μ]ὲν γάρ, ‘for, on the one side’, or an expression like ] ἐν γάρ or οὐδ]ὲν γάρ or even the 3rd singular or the 1st plural person of any active verb followed by γάρ. The third is formed by the second component of a compound adjective in -τελής, -ές such as πολυτελής or παντηλής or, less likely, the plural noun τέλη (from τέλος, ‘end’ or ‘purpose’) and the noun βῆμα, ‘tribune’, in either the singular or the plural. This term means the raised place from which orators spoke in a public assembly or in a lawcourt and, significantly, is used at least twice in Philodemus’ *On Rhetoric* (col. 56, 8 Sudhaus II; col. 264, 21 Sudhaus I).

Textual portions. For *PHerc.* 375 we have chosen a clearly decipherable text with an unexpectedly high contrast and legibility (Figure 3C). At line 1, we read the sequence of letters οκτο (*okto*). In an author like Philodemus (by far the most represented in the Herculanean library) this textual sequence does not seem to exist. Conversely, the sequence οκτ does exist and gives place to the words ὀκτώ, ἀποκτείνω and δέδοκται, middle perfect from δοκέω, ‘think’, ‘seem’. All three possibilities must be excluded when adding an -ο (*omicron*) after οκτ-. However, the third one stands provided that we inflect it in the impersonal middle pluperfect ἐδέδοκτο, ‘it had seemed’, ‘it had been resolved’, a quite spread form in Greek (126 occurrences in the TLG). At line 2, the succession of letters στωιοι (*stioioi*) is not possible as such in Greek. Yet, by dividing στωι from οι, we can either have a syntagm like ἕκαστωι οἱ, ‘each of’, or, as alternatives, an adjective in the plural masculine nominative such as χρηστωί or also a superlative like πλείστωι followed by either a definite article (οἱ) or a relative pronoun (οἷ) agreed with the preceding adjective or also any word beginning with οι-. At line

3, parts of an *omicron* and a large *eta* are distinctly legible. As for *PHerc.* 495, among the various textual portions that we were able to identify, we have decided to present here one which may give us an idea of what is being discussed (Figure 3G). At the end of line 1, we read  $\pi\eta\nu$  ( $p\bar{e} n$ ) or  $\tau\eta\nu$  ( $t\bar{e} n$ ). At line 2, we find the succession  $\nu\text{πολι}$  ( $n\text{poli}$ ) that can either admit a single word like, e.g.,  $\text{c}\nu\text{νπολίτης}$ , ‘fellow-citizen’, or  $\text{c}\nu\text{νπολιτεύω}$ , ‘live as fellow-citizens’, or two different words whereof the latter must be something like  $\text{πόλις}$ , ‘city-state’,  $\text{πολιτικός}$ , ‘civil’ or ‘political’, etc. In effect, in the following line we clearly read  $\text{πόλεις}$  ( $po\text{leis}$ ), ‘city-states’, followed by  $\text{ὅπ[ι]}$  ( $hop$ ), which may either belong to a conjunction like  $\text{ὅπως}$ , ‘as’, ‘how’, ‘that’, or an adjective like  $\text{ὅποιος}$ , ‘of what sort’, or a pronoun like  $\text{ὅπερ}$ , ‘what’, or also an adverb like  $\text{ὅπου}$ , ‘(some)where’ or even be divided into  $\text{ὁ}$  or  $\text{ὄ}$  followed by any word beginning with  $\pi$ -. In any case, the discussion seems to focus on civil or political matters. Please note that the different size and the deformation of some letters in this as well as other images is due to the optical distorsion produced by the (even extremely) irregular surface of the papyrus substrate.

*Signs.* We also detected inside *PHerc.* 495 a typical sign used by scribes in antiquity for signalling specific articulations of the text (Figure 3H left). It is a *coronis*, viz. a special textual marker usually indicating the end of a chapter, a book section or even a whole book. Normally, it looks like a more or less stylized sketch of a bird. So as it appears here, it roughly consists of an ellipse from which an oblique straight stroke departs on its left-bottom hand. This ellipse is superimposed on a squeezed wider oval, which appears to be open to the right. At the bottommost we find a horizontal line. Traces of other decorative strokes (possibly an upright crossed by a horizontal or an arch) are still visible at the top of the figure.

#### *Palaeographical description*

Given the large number of texts identified, it was possible to analyse the handwriting exhibited by each roll. While being aware that the irregular surface of the layers on which the letters lie may well cause optical distortions, we could make a detailed paleographical description. In this respect, we have to do with two similar, though not identical, hands. Both represent very formal round bookhands with a geometrical shaping and no modular contrast. The letters, which are ca. 2-3 mm high in an average, are accurately written and are endowed with a few decorative elements. Bilinearity is strictly followed, with the exception of *phi* and *psi*. In neither case were

ligatures detected. In particular, in *PHerc. 375 alpha* has the middle stroke either horizontal or ascending, *epsilon* has the middle bar outreaching the arch and either detached from or attached to it, *eta* is either epigraphical or with an ascending middle stroke joining the right vertical at the top, *kappa* has a rounded vertical stroke and is made with either very long arms or in a narrower way with the lower arm fairly suspended above the line, *my* is made in four strokes and is very angular, *zeta* and *xi* are epigraphical, *pi* is very large and has slightly divergent verticals which appear rounded at the end, *tau* is made in two strokes and is also quite large, *ypsilon* and *omega* are made in two strokes, *chi* has the descending stroke with symmetrically hooked finials. In *PHerc. 495*, *alpha* is sometimes performed more cursively, *delta* and *lambda* have the right stroke projecting above, *epsilon* has the middle bar often outreaching the arch and always attached to it, *zeta* has slightly undulated horizontals, *theta* is ogival and sometimes shows the middle bar in a higher position, *kappa* has either the lower or both arms rounded at the end, *my* is in four strokes and is very angular as in *PHerc. 375*, *xi*, *pi* and *tau* have the horizontal stroke gently rounded on the left, *pi* shows the verticals blobbed at the end and the right one often concave and suspended above the line, *ypsilon* is made in three strokes with a wide chalice and a short vertical, *omega* is either as in *PHerc. 375* or shows slightly angular curves. On the basis of these features, it is possible to date tentatively these hands to the middle and the third quarter of I century BC, respectively. Useful parallels are, for *PHerc. 375*, those represented by *PHerc. 1021* (belonging to G. Cavallo's Group F) and *PHerc. 1005/862* (Group G) and, for *PHerc. 495*, that witnessed by *PHerc. 1050* (Group I)<sup>10</sup>. Among Greco-Egyptian papyri, the closest parallel to *PHerc. 375* is *POxy XXIV 2399* (I century BC) and, for *PHerc. 495*, *PLouvre inv. E 7733 verso* (end of I century BC)<sup>11</sup>. Since Cavallo's Groups F, G and I<sup>11</sup> mostly include texts by Philodemus (the others' authors being either unidentified or controversial), it is very likely that both bookrolls hand down writings by this philosopher. In particular, *PHerc. 495*, in which allusions are made to both orators and civil or political matters and is used a term (βήμα) which is found in his *On Rhetoric*, might possibly represent a book of this large Philodemean treatise, either one partially known to us or a completely unknown one.

By comparing these hands with those of the already unrolled portions of each roll we obtain both a confirmation and a surprise. Despite their worst state of preservation, the hand of the unrolled portions of *PHerc. 375*, which has never been investigated so

far, appears compatible with that of the corresponding roll. Here as well we have to do with a highly formal, strictly bilinear and geometrical round bookhand with no modular contrast and some blobs or serifs at the end of the straight strokes. Among the single letters, only *ypsilon*, made in three strokes with high branches and a low seriffed stem, and *pi* (epigraphical) seem at first sight to be different from those of the roll. Yet, there are instances of both letters that are made in the same way as in it (*ypsilon* in two strokes with a high stem, *pi* with divergent verticals). The case of *PHerc. 495* is more remarkable. The hand inferable from the unrolled portions bearing this number appears unquestionably different from, and hence incompatible with, that of the roll. In effect, the writing of the unrolled fragments of *PHerc. 495*, belonging to Cavallo's Group D<sup>10</sup>, is a formal upright bookhand with a marked modular contrast and no decorative elements. *Epsilon*, *theta*, *omicron* and *sigma* are fairly narrow and angular. Not only *phi* and *psi* but also *ypsilon* and *rho* and sometimes even *tau* and *kappa* are extrabilinear. *Delta* has a convex basis, *eta* shows often a high middle bar, *my* is in either three or four strokes with a rounded paunch, the oblique stroke of *ny* joins the right vertical before the bottom of it, the *pi* has parallel and reciprocally distant verticals, the vertical stroke of *tau* encounters the horizontal on the right portion of it, *ypsilon* is made in two strokes and has a wide chalice, the ellipse of *phi* is severely triangular. These characteristics distance indisputably the hand of the unrolled portions of *PHerc. 495* from that of the roll bearing the same number. One may wonder why this is possible. There may be two different answers to this question: either the book was written in two different hands (as is elsewhere attested in the Herculaneum library) or, more likely, was wrongly associated with these unrolled portions at some time after its partial unrolling. In the latter case, the roll would obviously contain a different text as that handed down by the unrolled portions in question.

## References

1. Sider, D. *The library of the Villa dei Papiri at Herculaneum*. (Getty Publications, Los Angeles, USA, 2005).
2. Angeli, A. Lo svolgimento dei papiri carbonizzati. *Papyrologica Lupiensia* **3**, 43–84 (1994).
3. Fosse, B., Kleve, K. & Störmer, F. C. Unrolling the Herculaneum Papyri. *Cronache Ercolanesi* **14**, 9-15 (1984).
4. Störmer, F. C., Kleve, K. & Fosse, B. Ink at Herculaneum. *Cronache Ercolanesi*. **16**, 7-9 (1986)



5. Booras, S. W. & Seely, D.R. Multispectral Imaging of Herculaneum papyri. *Cronache Ercolanesi* **29**, 95-100 (1999).
6. Gigante M. *Catalogo dei papiri ercolanesi*. (Bibliopolis, Napoli, Italy, 1979).
7. Capasso M. *Manuale di Papirologia Ercolanese*. (Galatina, Congedo, Italy, 1991).
8. Giuliano F. M. *PHerc. 495-PHerc. 558* (Filodemo, *Storia di Socrate e della sua scuola?*). Edizione, commento, questioni compositive e attributive. *Cronache Ercolanesi* **31**, 37-79 (2001).
9. Crönert, W. Herkulanensische Bruchstücke einer Geschichte des Sokrates und seiner Schule. *Rhein. Mus. Phil.* **57**, 285-300 (1902).
10. Cavallo G., *Libri scritte scribi a Ercolano*. (Macchiaroli, Napoli, Italy, 1983).
11. Del Corso, L. Dalla Grecia arcaica all'età romana. In. *La scrittura greca dall'antichità all'epoca della stampa: Una introduzione*. (Eds Crisci, E. & Degni, P.) 35-75 (Carocci, Roma, Italy, 2011).

## FIGURE CAPTIONS

**Figure 1S: Modern papyrus roll.** **a**, before and **b**, after carbonization; **c**, axial and **d**, longitudinal view of the 3D tomographic reconstruction of the internal part of the carbonized papyrus roll; **e**, text of the papyrus written (before burning) using ink mixed with Pb; **f**, virtually unrolled text of the carbonized papyrus in absorption and **g**, phase contrast.

**Figure 2S: Multispectral images of unrolled pieces.** **a**, *PHerc. 375* ('cornice' 1) and **b**, *PHerc. 495* ('cornice' 2). By permission of Ministero per i Beni e le Attività Culturali e del Turismo (Steven W. Booras © Biblioteca Nazionale 'Vittorio Emenuelle III', Napoli – Brigham Young University, Provo, USA). All rights reserved.

**Figure 3S: Pictures and 3D tomography of the two carbonized Herculaneum papyrus rolls.** *Top panel:* **a**, picture of *PHerc. 375*; **b**, axial (left) and longitudinal views (central) 3D reconstruction revealing the complex stress field of the inner part of the scroll, a zoom of its specific area (top right); an enhanced zoom of top right figure (bottom right) highlighting the fibre texture. *Bottom panel:* **c**, Top panel: picture of the *PHerc. 495* scroll; **d**, axial (left) and longitudinal views (central) 3D reconstruction revealing the complex stress field of the inner part of the scroll; zoom of a specific area of previous picture, to highlight the fibre texture (right).

**Figure 4S: 3D rendering images of papyrus roll.** **a-b**, *PHerc. 375*, and **c**, papyrus roll *PHerc. 495*. **d-e**, Segmentation of *PHerc. 495*, which highlights the sand diffusion.

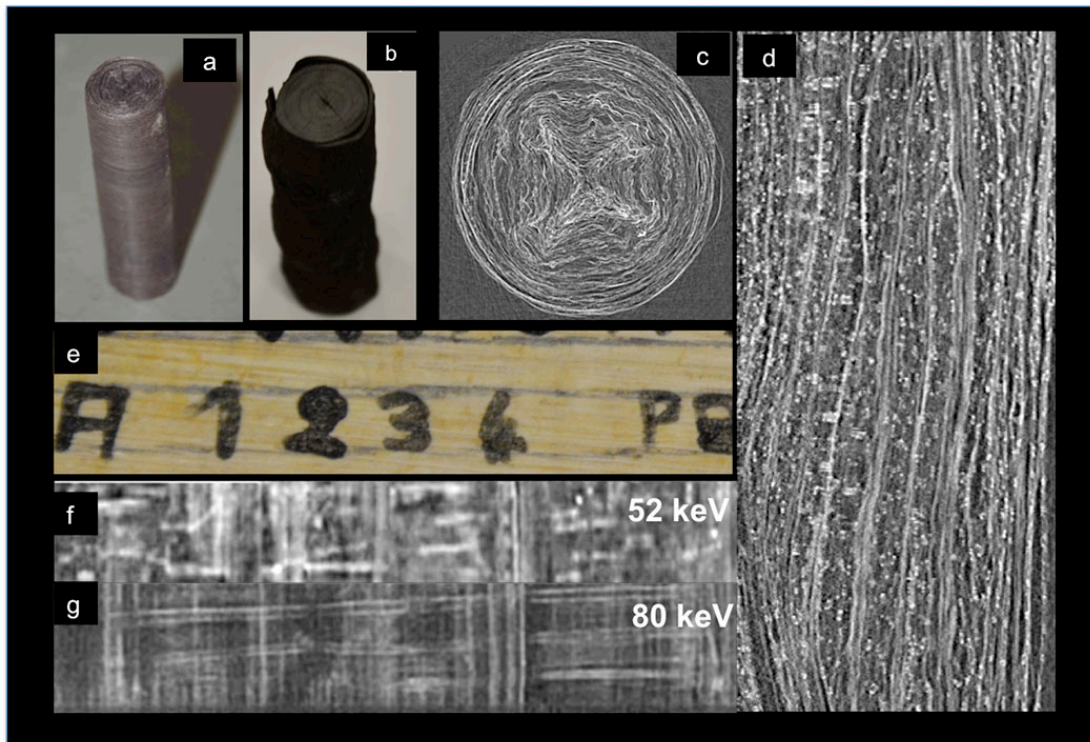
**Figure 5S. Greek alphabet inferable from papyrus rolls. a, *PHerc. 375* and b, *PHerc. 495***

### **MOVIE CAPTIONS**

**Movies S1:** Virtual re-slicing of the rolls: longitudinal slices follow one another during the movie. The distortions of the layers change as a function of depth inside the rolls.

**Movies S2:** Little sand particles coming from outside and penetrating up at some time into the roll. Axial slices follow one another during the movie.

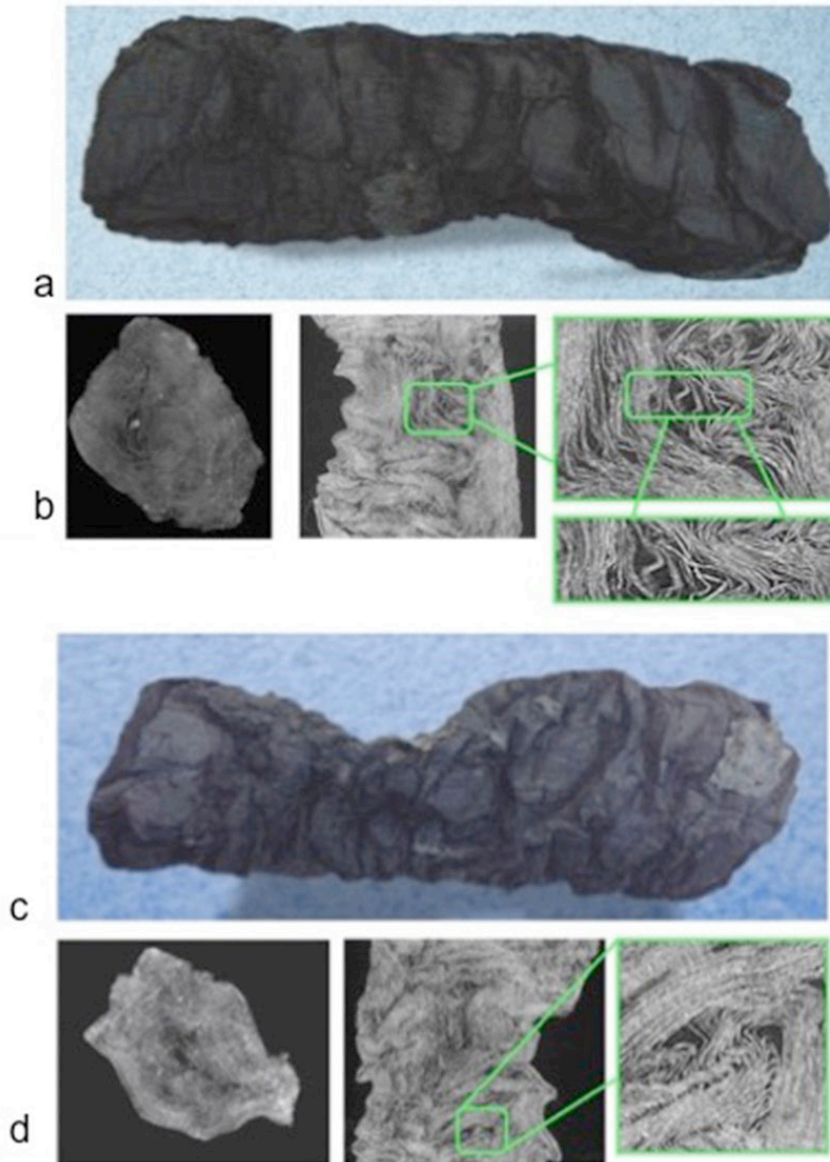
**Movies S3:** Movie of the virtual unrolling of one portion of text.



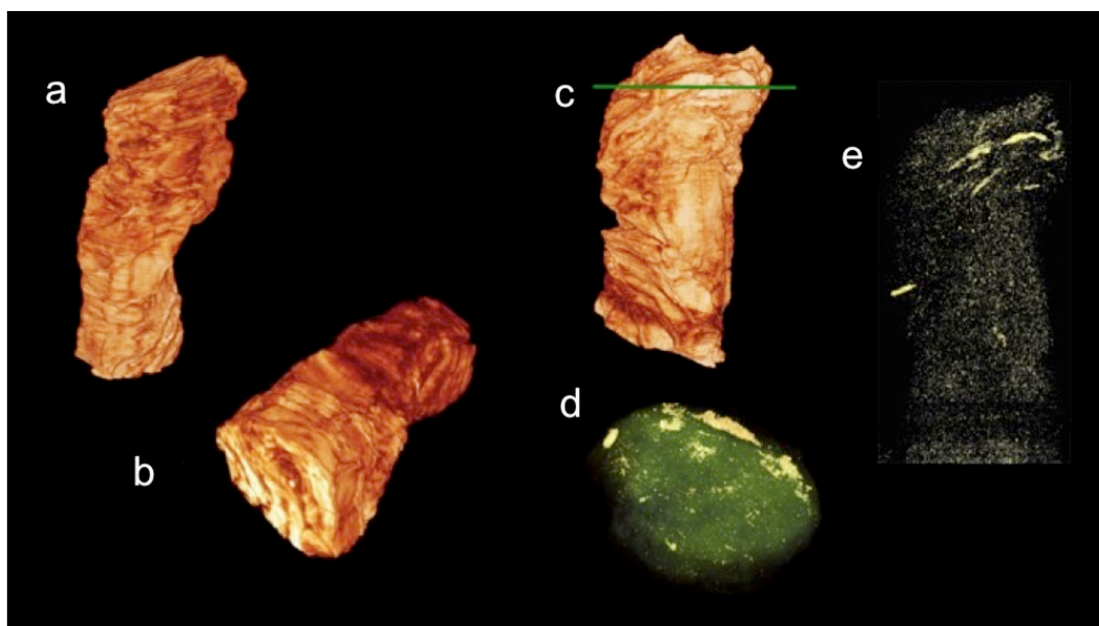
**Figure1S: Modern papyrus roll.** **a**, before and **b**, after carbonization; **c**, axial and **d**, longitudinal view of the 3D tomographic reconstruction of the internal part of the carbonized papyrus roll; **e**, text of the papyrus written using ink mixed with Pb; **f**, virtually unrolled text of the carbonized papyrus in absorption and **g**, phase contrast.



**Figure 2S: Multispectral images of unrolled pieces. a, *PHerc.* 375 ('cornice' 1) and b, *PHerc.* 495 ('cornice' 2).** By permission of Ministero per i Beni e le Attività Culturali e del Turismo (Steven W. Booras © Biblioteca Nazionale 'Vittorio Emenuelle III', Napoli – Brigham Young University, Provo, USA). All rights reserved.



**Figure 3S: Pictures and 3D tomography of the two carbonized Herculaneum papyrus rolls.** *Top panel:* **a**, picture of *PHerc.* 375; **b**, axial (left) and longitudinal views (central) 3D reconstruction revealing the complex stress field of the inner part of the scroll, a zoom of its specific area (top right); an enhanced zoom of top right figure (bottom right) highlighting the fibre texture. *Bottom panel:* **c**, Top panel: picture of the *PHerc.* 495 scroll; **d**, axial (left) and longitudinal views (central) 3D reconstruction revealing the complex stress field of the inner part of the scroll; zoom of a specific area of previous picture, to highlight the fibre texture (right).



**Figure 4S: 3D rendering images of papyrus roll. a-b**, papyrus roll *PHerc.* 375, and **c**, papyrus roll *PHerc.* 495. **d-e**, Segmentation of *PHerc.* 495, which highlights the sand diffusion.

a

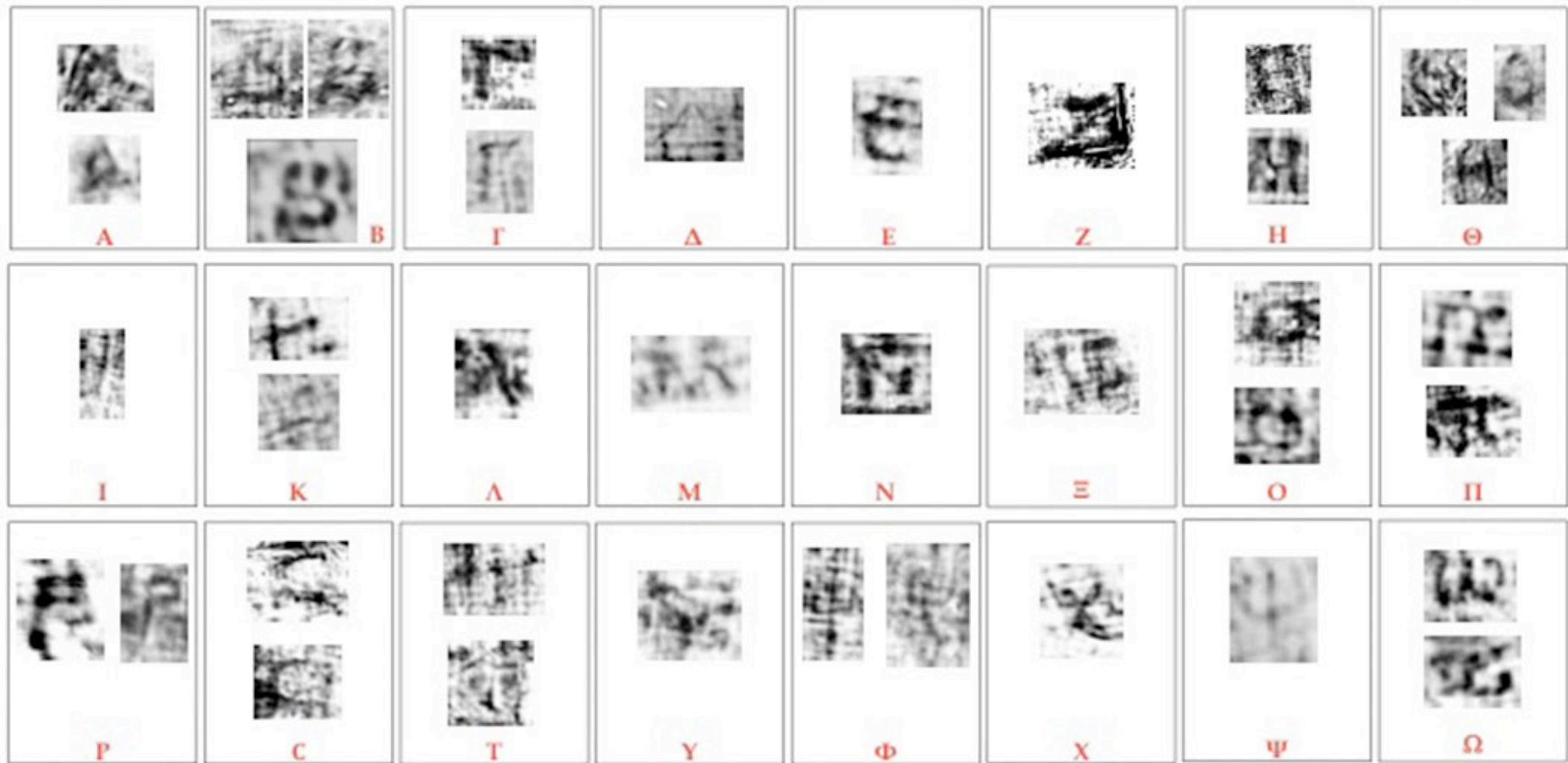




Figure 5S. Greek alphabet inferable from papyrus rolls. a, *PHerc. 375* and b, *PHerc. 495*