APPLIED SCIENCES AND ENGINEERING

Ancient Greek text concealed on the back of unrolled papyrus revealed through shortwave-infrared hyperspectral imaging

A. Tournié[1], K. Fleischer[2], I. Bukreeva[3,4], F. Palermo[3], M. Perino[5], A. Cedola[3], C. Andraud[1], G. Ranocchia[6]*

Only a few Herculaneum rolls exhibit writing on their reverse side. Since unrolled papyri are permanently glued to paperboard, so far, this fact was known to us only from 18th-century drawings. The application of shortwave-infrared (SWIR; 1000-2500 nm) hyperspectral imaging (HSI) to one of them (*PHerc.* 1691/1021) has revealed portions of Greek text hidden on the back more than 220 years after their first discovery, making it possible to recover this primary source for the ongoing new edition of this precious book. SWIR HSI has produced better contrast and legibility even on the extensive text preserved on the front compared to former imaging of Herculaneum papyri at 950 nm (improperly called multispectral imaging), with a substantial impact on the text reconstruction. These promising results confirm the importance of advanced techniques applied to ancient carbonized papyri and open the way to a better investigation of hundreds of other such papyri.

INTRODUCTION

As is known, Greco-Egyptian papyrus rolls showing writing on the front (recto) were frequently reused through the addition of another text on the back (verso) (*1*–*2*). In contrast, among the 1840 Herculaneum papyri cataloged today, only eight (*PHerc.* 9, 227, 972, 1691/1021, 1670, 1506, Cass. XCIV s.n. IV, and possibly also Cass. I s.n. A) seem to also exhibit writing on the verso (*3*–*4*). Moreover, in further three papyri (*PHerc.* 339, 1491, and unidentified "scorza") and also *PHerc.* 1670, initial titles (or parts of them) written on the verso of the roll were detected in the recent past (*5*–*6*). The cases of *PHerc.* 1691/1021 and *PHerc.* 1670 are the most remarkable. Twelve and seven text columns, respectively, which belong to the same work as that written on the recto and which are, today, only legible from 18th-century drawings of Herculaneum papyri, were added on the verso of the roll by the scribe, either the same one who wrote the text on the recto or a different one. These were found during or after the mechanical unrolling of the two scrolls by means of Piaggio's machine in 1795 and 1798 and were manually transcribed by the draftsmen Gennaro Casanova and Giovan Battista Malesci (*7*–*10*, *3*). Afterward and as was usual for Herculaneum papyri (*11*), all fragments were bonded on the back to paperboard, and it has not been possible since then to read the text on the verso. The challenge today is to enable the reading of the text lying on the verso through noninvasive imaging techniques without removing the relative papyrus fragments from their support, which would both entail painstaking work and probably result in their irreparable disintegration. The use of advanced diagnostic techniques is not only a strong desideratum of papyrology but also, and above all, the only means at our disposition today for recovering the textual portions lying on the verso, an enterprise never before attempted. As is known, what has conventionally been dubbed multispectral imaging (MSI) in the visible and near-infrared (VNIR; 400 to 970 nm) (note that since only one single band was used in the specific case, the method should not properly be called multispectral), which was extensively applied to the Herculaneum collection between 1999 and 2002, has proven to be especially effective by using a filter at 950 nm (*12*–*13*). The differentiation in light reflectivity has increased the contrast between the writing and the papyrus substrate, enabling the reading of previously illegible texts and making it necessary to make new editions of previously edited ones, a sort of revolution in Herculaneum papyrology. However, this method was not able to penetrate far enough into the papyrus layers to allow the reading of text possibly written on the verso. In contrast, hyperspectral imaging (HSI), also known as reflectance imaging spectroscopy, in the shortwave-infrared (SWIR) range (970 to 2500 nm) has proven to be successful in this regard. In particular, SWIR HSI offered through the IPERION CH MOLAB program exploits wavelengths up to 2500 nm with an excellent spatial and spectral resolution, giving insights through most painted and written materials. So far, this technique had been tested, with best results, on medieval palimpsests and illuminated manuscripts (*14*–*16*). Infrared reflectography (also called infrared technical photography) was also used in transmission mode for investigation of artwork to penetrate and visualize underdrawings (*17*–*18*). We show here the successful application of SWIR HSI to ancient carbonized papyri and the successful use of spectral imaging for the reading of the reverse-side text of an unrolled papyrus (*PHerc.* 1691/1021). We succeeded both in revealing portions of the Greek text hidden on the verso, making it possible to recover this primary source for the ongoing new edition of Philodemus' *History of the Academy* by K. Fleischer, and in enhancing the legibility of the text lying on the recto, thereby producing a further substantial impact on the text reconstruction. These encouraging results make a future investigation of the whole Herculaneum collection and other ancient papyri through SWIR HSI both possible and desirable, with foreseeably important repercussions for our knowledge of ancient philosophy and literature, papyrology, paleography, and classical philology.

[1]Centre de Recherche sur la Conservation (CRC, USR 3224), Muséum National d'Histoire Naturelle, Ministère de la Culture, CNRS; CP21, 36 rue Geoffroy-Saint-Hilaire, F-75005 Paris, France. [2]Institut für Klassische Philologie, Julius-Maximilians-Universität Würzburg, Residenzplatz 2, D-97070 Würzburg, Germany. [3]Consiglio Nazionale delle Ricerche, Istituto di Nanotecnologia (NANOTEC), Rome Unit, Piazzale A. Moro, 5, I-00185 Rome, Italy. [4]P.N. Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr., 53, 119991 Moscow, Russia. [5]Dipartimento di Scienze di Base e Applicate per l'Ingegneria, Sapienza University of Rome, Via A. Scarpa 14/16, I-00161 Rome, Italy. [6]Consiglio Nazionale delle Ricerche, Istituto per il Lessico Intellettuale Europeo e Storia delle Idee (ILIESI), Via C. Fea, 2, I-00161 Rome, Italy.
*Corresponding author. Email: graziano.ranocchia@cnr.it

Papyrus roll *PHerc.* 1691/1021: Philodemus' *History of the Academy*

The so-called *History of the Academy* (*Index Academicorum* or similar) is commonly deemed to represent a book of Philodemus' large treatise *Systematic Arrangement of the Philosophers*, to which other sections devoted to the Stoics, the Epicureans, Socrates, and, possibly, the Pythagorean, the Eleatic, and Atomistic schools are also supposed to belong (*19*–*23*). This book is of extraordinary value for the history of philosophy and, in particular, for our knowledge of Plato's Academy. The main papyrus roll that transmits it (*PHerc.* 1691/1021) is a preliminary draft, and there is reason to believe that it probably represents Philodemus' actual working manuscript (*24*). This circumstance, together with the fact that it was also written on the verso, makes it unique among Herculaneum papyri in many respects. Apart from several marginal notes and additions written above and below the columns to be incorporated into the final version and authorial and transposition signs, the scroll contains extensive and literally quoted poetic excerpts and the corresponding prose paraphrases. The text columns written on the verso of the roll were partly added after the text on the recto was drafted and were intended to supplement or replace the latter in the final version, some portions of which survive in the poorly preserved *PHerc.* 164 (*7*–*10*). Today, these columns are no longer visible, since the papyrus fragments were glued to paperboard after their unrolling in 1795 (fig. S1). However, before this procedure was performed, concealing the text for the next 220 years, drawings of these verso passages were executed and are now kept in the Bodleian Library, Oxford. A total of 12 passages or columns was depicted, each one on a single paper sheet (fig. S2). Recently, K. Fleischer was able to localize these columns with respect to the visible text (recto) by exploiting the morphological features of the unrolled fragments (borders and gaps) and comparing them with those delineated, more or less faithfully, in the Oxonian drawings. By horizontally mirroring these drawings, borders and gaps match with those still visible on the papyrus recto (fig. S3) (*10*). Although this method may appear trivial, the disproportional and distorted reproduction of these features in the drawings and, especially, the progressive destruction (larger gaps and altered borders) of some papyrus portions, which occurred after the drawings were executed, make the exact localization of some columns from the verso challenging. Until recently (and, in part, still today), doubts remained concerning the exact position of these columns, and a conclusive proof still needs to be delivered.

RESULTS

Samples characteristics

PHerc. 1691/1021 was mechanically unrolled in June 1795 by means of the Piaggio machine and consists of nine dark gray and partially lacunose papyrus fragments with a minimum of 20.1 cm and a maximum of 21 cm in height and a minimum of 16.2 cm and a maximum of 36.9 cm in length, for a total extension of ca. 288.4 cm. The thickness of the papyrus sheet is about 0.15 mm. Each fragment is glued to a paperboard, which is slightly thicker than the papyrus sheet (ca. 0.30 mm), and is fastened to a cardboard (fig. S1). The fragments are distributed across nine frames ("cornici") kept in Cabinet 23 (*PHerc.* 1691) and Cabinet 14 (*PHerc.* 1021) in the Officina dei Papiri Ercolanesi of the National Library "Vittorio Emanuele III" of Naples. Over the course of three full days, we recorded data through SWIR HSI from all of the nine fragments (*PHerc.* 1691, cornice 1, pezzo 2 and *PHerc.* 1021, cornici 1-8).

Revealing of the verso

Our SWIR HSI experiment succeeded in revealing some textual portions lying on the verso of papyrus roll *PHerc.* 1691/1021. To this purpose, we applied principal components analysis (PCA), a well-known statistical approach based on an exploratory treatment (*14*, *16*, *25*–*27*). This process (full details of it in Materials and Methods) is commonly used to apprehend a huge quantity of data by reducing its dimensionality or variables (wavelength bands) and to make classifications. PCA builds up a new data space with new axes, which maximizes the variance in the original data. The first new axis, called principal component 1 (PC1), which is based on a linear combination of the variables (here to be understood as the wavelength), contains the largest variance of the whole data cube; the second axis (PC2), which is perpendicular to the first one, contains the largest remaining variance, and so forth. By looking at PC3, we could read without any doubt at various points on the papyrus verso groups of letters and words distributed across several lines. In our case, the PC3 contains only 0.4% of the total variance of the hyperspectral data cube. Within this very small quantity of data variance, we were able to visualize the ink from both the recto and the verso in various points. This means that the PC3 more clearly enhances spectral differences in the data cube. The spectra of the two inks located on each side of the papyrus are obviously the same, with only an offset of the global reflectance due to the papyrus thickness, as is "spectrally" shown in Fig. 1A. In particular, in the loading plot of the PC3, the wavelengths at higher weights are around 1000, 1300, and 1680 nm and between 2300 and 2500 nm (Fig. 1B). These combinations of bands in the SWIR range penetrate more deeply into the matter if no recto

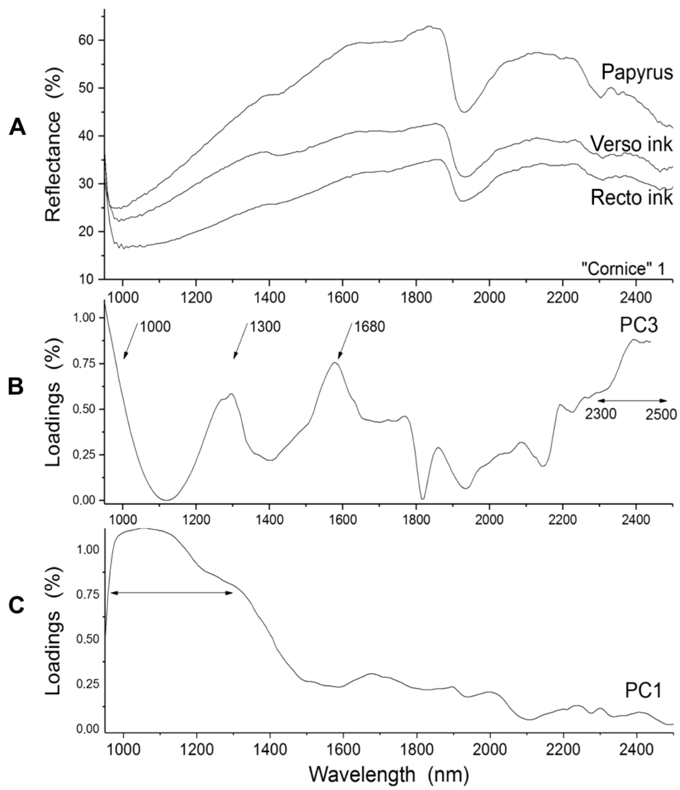


Fig. 1. HSI ink visualization data. Representative reflectance spectra (2 × 2 pixels) of the papyrus and the two inks (recto and verso) extracted from the SWIR HSI data cube (**A**) and the representative loading plots of PC3 (**B**) and PC1 (**C**) calculated from it.

ink stands in the way of the light. However, the spectra of the ink from the verso cannot be isolated because the level of reflectance is similar to that of the ink on the recto (Fig. 1A). We found the same reflectance spectra and loading plots represented in Fig. 1 in all the nine papyrus fragments analyzed in this study. The PC2 image enhances the papyrus fibers so that the writing emerges less clearly than through PC1 and PC3, which instead give a more uniform background. The results obtained through PC1 will be discussed in the following paragraph ("Enhancement of the recto" section).

The detection of several textual portions lying on the verso of *PHerc*. 1691/1021 was confirmed by comparison with the corresponding Oxonian drawings, where the same passages could easily be identified. These portions are localized in *PHerc.* 1021, cornici 1-2 and have turned out to belong to the first five verso columns witnessed by the Oxonian drawings (cols. Z, Y, X, V, and T). In Fig. 2, the text columns lying on the verso have been highlighted with red vertical lines. Specific areas where passages from the verso are comparatively clearly visible (typically in correspondence with intercolumnia on the recto or between lines of it) are marked with cyan ellipses. Sixteen passages have been marked altogether. However, many other faded letters, and sequences of letters, which cannot belong to the recto, emerge here and there between lines in the latter. Their identification and comparison with the Oxonian drawings will require more time and effort. The identification, in cornici 1-2, of textual portions belonging to the first five verso columns also allows for a precise relative placement of these latter and basically confirms their former localization on "morphological" grounds (*10*).

One of the most notable examples of the textual portions that we detected on the verso is represented by verso col. V, which lies in *PHerc.* 1021, cornice 2 between recto cols. 5 and 6 (Fig. 3). On the image at 950 nm of this papyrus fragment formerly taken by a team from Brigham Young University (*12*–*13*), we cannot see any traces of writing in the intercolumnium between these two recto columns (Fig. 3A), whereas on the PC3 SWIR hyperspectral image, we read clearly distinguishable letters and words distributed across 15 lines in the same place (Fig. 3B). They appear mirrored here for the obvious reason that the text on the verso also regularly ran from left to right (Fig. 3C). By horizontally rotating it through any standard computer software, the text from the verso appears running in the right direction (Fig. 3D). This facilitates the comparison with the corresponding Oxonian drawing (Fig. 3F), where the passage in question appears immediately recognizable and with which it is perfectly congruent (Fig. 3E).

Sometimes, when overlapped with the corresponding verso passages obtained through SWIR HSI, the Oxonian drawings turn out to have mistakenly copied one or another letter. To take just a few examples: At col. V, 3, the drawing misreads an omicron (ο) as a sigma (c); in col. V, 6, the drawing has a theta (θ), but the SWIR hyperspectral image clearly indicates a sigma (c), as had already been assumed by editors for lexical/grammatical reasons. Other mistakes are more momentous. In line 4, the SWIR hyperspectral image strongly suggests the reading τιν, instead of υτο, which calls into question the reconstruction of the whole period. These examples unequivocally prove that the verso passages obtained through SWIR HSI help correctly restore the original text. Thus, despite the currently limited extension of the readable text from the verso, this remains the primary source for the textual reconstruction and, on occasions, proves to be crucial for it.

Apart from the detection of already known text from the verso, some new textual verso passages, which were previously unknown to us, were unexpectedly identified through SWIR HSI. This is the case of verso col. T. The Oxonian drawing suggests that this column did not reach below the first upper third of the papyrus and that it was, for whatever reason, quite short (figs. S2E and S4A). The PC3 SWIR hyperspectral image of the same column has clearly revealed unexpected text from the verso even in the lower portion of the papyrus (fig. S4B). The newly found text may either belong to the same column or alternatively represent a different and independent textual supplement. Its exact function will be clarified in the course of advanced editorial work on the papyrus text. In any case, this discovery is of great relevance for the textual constitution and will be

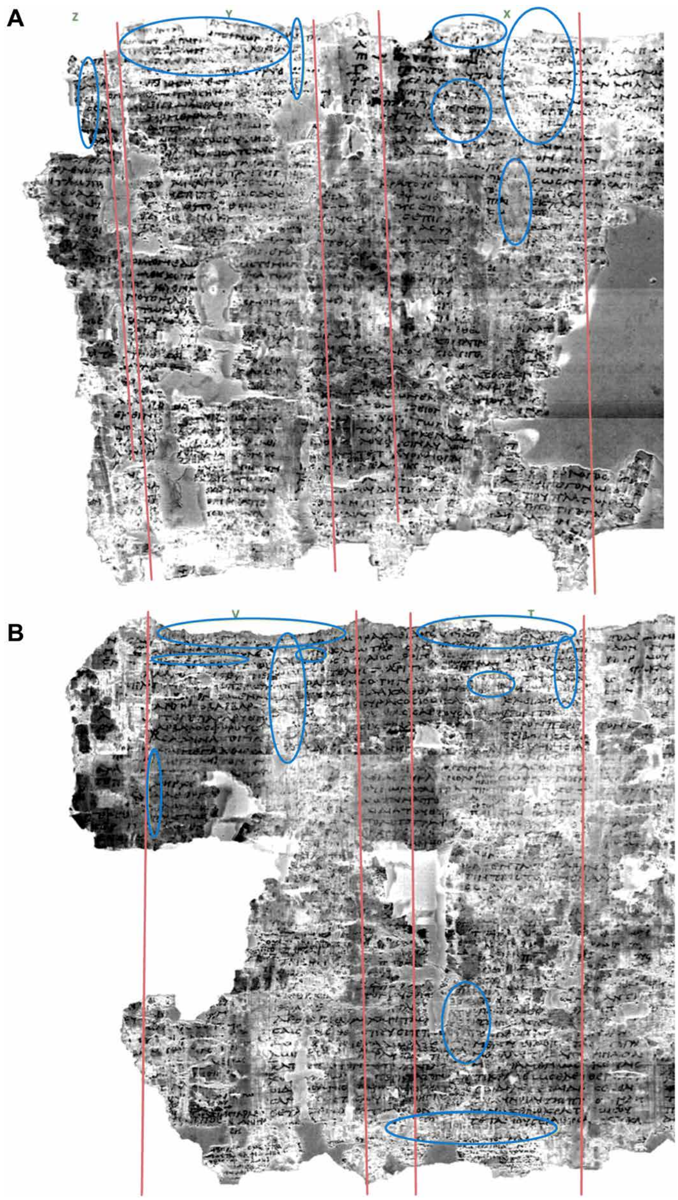
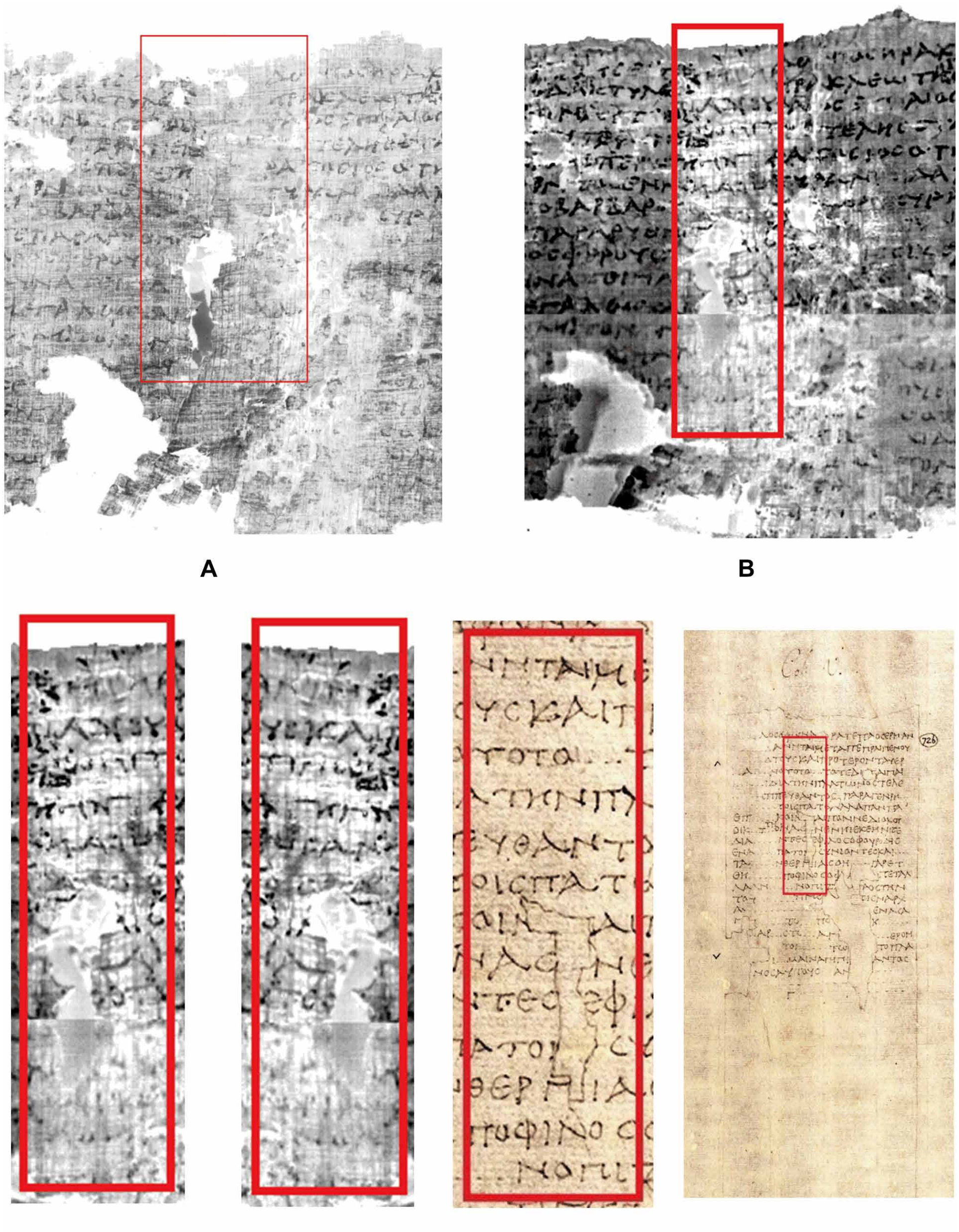


Fig. 2. PC3 SWIR hyperspectral images of *PHerc.* 1021. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Consiglio Nazionale delle Ricerche). Cornice 1 (**A**) and cornice 2 (**B**). Red lines highlight text columns lying on the verso; cyan ellipses mark textual portions belonging to them.



A B C D E F

Fig. 3. *PHerc.* 1021, cornice 1, recto cols. 5-6, intercolumnium. Image at 950 nm (no text visible from the verso). By permission of Ministero per i Beni e le Attività Culturali (photo credit: Steven W. Booras, Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Brigham Young University, Provo) (**A**). PC3 SWIR hyperspectral image showing text from the verso (**B**) and detail of the same (**C**). The same text mirrored. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Consiglio Nazionale delle Ricerche) (**D**). The corresponding text in Oxonian drawing V (**E**). Full picture of Oxonian drawing V (photo credit: The Bodleian Library, University of Oxford, MS. Gr. Class. c. 4, 4, fol. 726) (**F**).

taken into due account in the new critical edition of *PHerc.* 1691/1021, which K. Fleischer is currently preparing.

A further discovery seems to confirm what, judging from what the drawings tell us, appeared only possible before. The first three columns from the verso (cols. Z, Y, and X) seem to belong to a hand different from that of the recto and the other nine verso columns. As is known, G. Cavallo has ascribed the latter to group F of his classification of the Herculaneum hands and has dated it to the second quarter of the first century BCE (*21*). This implies that the first three columns from the verso were added by a different scribe (or possibly even the author himself). A paleographical description of this new hand and the implications this circumstance has for issues related to the manuscript's production will be discussed on a later occasion.

Enhancement of the recto

Beside revealing the text from the verso, SWIR HSI substantially increased the legibility of the text lying on the recto by producing a much higher contrast between writing and papyrus substrate than was the case through previous imaging at 950 nm (improperly called MSI; see above). In Fig. 4, two images of the same papyrus fragment

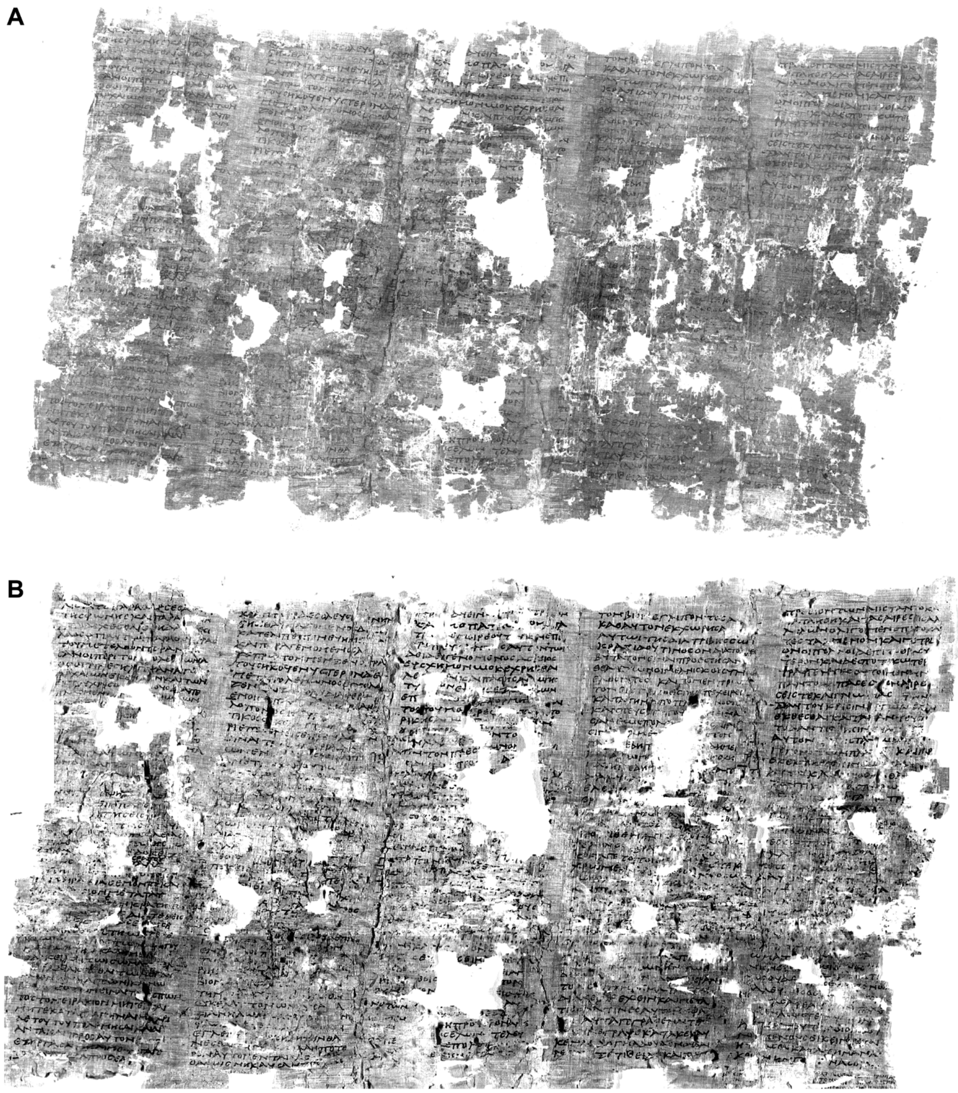


Fig. 4. *PHerc.* 1021, cornice 4, general view. Image at 950 nm. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Steven W. Booras, Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Brigham Young University, Provo) (**A**) and PC1 SWIR hyperspectral image. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Consiglio Nazionale delle Ricerche) (**B**).

(*PHerc.* 1691/1021, cornice 4) are compared. These were respectively obtained through previous imaging at 950 nm by a team from Brigham Young University (Fig. 4A) and through SWIR HSI by ourselves after applying PCA (Fig. 4B). The best contrast between ink from the recto and papyrus substrate was obtained by visualizing the fragment through PC1, which gathers 93.8% of the total data cube variance. The loading plot of PC1 indicates significant weight between 1000 and 1300 nm, as is shown in Fig. 1C. This region represents the biggest spectral difference, which is a simple ramp for the reflectance spectra of the papyrus (Fig. 1A). In the SWIR range, the carbon-based ink absorbs the infrared light much better than the papyrus substrate does. By contrast, in previous imaging at 950 nm, both the spectral resolution (number of bands) and the number of wavelengths in the infrared range (only one band at 950 nm was selected) are possibly not enough and not sufficiently far in the infrared range to produce an acceptable contrast (*12*–*13*).

The higher contrast obtained through SWIR HSI by applying PC1 allowed us to read in each column several new letters and words, which were previously either illegible or indecipherable. Some passages, in which nothing could hitherto be read with certainty, now appear clearly legible. Some others, where readings were difficult to make and ink traces could not properly be distinguished from the dark gray background of the papyrus substrate, now show letters that are identifiable without a shadow of doubt. The application of SWIR HSI to *PHerc.* 1691/1021 enabled us to read an average of about five words more per column with respect to previous imaging at 950 nm, with an overall textual increment of more than 150 new words for the whole roll. This allowed complete new reconstructions of some passages and a substantial refinement of others. Moreover, many uncertain readings of passages, which, because of insufficient contrast, were, hitherto, to be regarded as highly conjectural, now are revealed to be certain or very likely. In other cases, the new images induced us to discard former readings and supplements by other scholars.

To show how fruitful SWIR HSI is for textual constitution, we have selected a passage from *PHerc.* 1021, col. 19, 38-39 Fleischer. So far, scholars read at this point the Greek word κη|λουμένους, "charmed" or "bewitched." Relying on the image at 950 nm formerly taken by a team from Brigham Young University (*12–13*), this reading seemed both defensible and compatible with the surviving traces, in as much as these were rather blurry and allowed for many different reconstructions (Fig. 5A). On that image, the low contrast between ink and papyrus background seemed to allow, among other possibilities, the sequence of letters κη-. Even the number of letters at the end of the line was uncertain. In contrast, the new SWIR hyperspectral image of this passage (Fig. 5B) clearly shows, at the end of line 38, the lower and the right part of a delta (δ), then omicron (ο), and, lastly, ypsilon (υ). The new word arising from it is, without any doubt, δου|λουμένους, "enslaved." This is not the place to discuss the philosophical implications of this new reading, but this example suffices to show how this technique can contribute to an improved Greek text of this precious book by revealing new valuable information about ancient Greek philosophers and their schools.

Marginal annotations

As mentioned above, *PHerc*. 1691/1021 shows several marginal annotations added in either the upper or the lower margin above or below some columns of text on the recto. These annotations were apparently added after the first draft of the papyrus was written (possibly or probably by a scribe different from the one who drafted the main text) and were probably intended to be incorporated into it. Since they exhibit much smaller letters than the main text and are placed in the most deteriorated portions of the papyrus, these annotations are hardly readable by the naked eye or even through previous imaging at 950 nm. In most cases, nothing meaningful can be drawn from them, and some annotations were even completely disregarded by former editors of the book. By applying SWIR HSI to them at a higher spatial resolution (30 μm) through a macro lens, the contrast between writing and papyrus substrate was considerably improved with respect to previous imaging at 950 nm. As a consequence, the marginal annotations are now much more readable than they were previously and can contribute to substantial textual discoveries and improvements. In many cases, they supply us with a text that was completely illegible before now. To illustrate this progress, we selected one such annotation in Fig. 6. Here, the image at 950 nm formerly taken by a team from Brigham Young University (*12–13*) (Fig. 6A) is contrasted with two different SWIR hyperspectral images obtained at PC1 and PC3 (Fig. 6B and Fig. 6C). In both cases, the contrast and the textual legibility appear much higher than in the image at 950 nm. In particular, the PC1 image (Fig. 6B) exhibits the best contrast between ink and papyrus substrate. However, at least in some places, holes are deceptively displayed as ink. In contrast, the PC3 image (Fig. 6C) does not have this inconvenience and sometimes displays letters more correctly.

DISCUSSION

Our work shows that SWIR HSI is capable of both disclosing the text hidden on the verso of ancient unrolled papyri and substantially enhancing the legibility of the text lying on the recto. As far as the verso is concerned, we revealed several textual portions, thereby confirming their existence and localization, as established in recent research (*10*). In addition, we found new textual portions previously unknown to us. As to the recto, we read passages in both the main text and marginal annotations that were previously either illegible or indecipherable through microscope reading and previous imaging

Fig. 5. *PHerc*. 1021, cornice 4, col. 19, 38 Fleischer (end of line). Image at 950 nm. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Steven W. Booras, Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Brigham Young University, Provo) (**A**) and PC1 SWIR hyperspectral image. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Consiglio Nazionale delle Ricerche) (**B**).

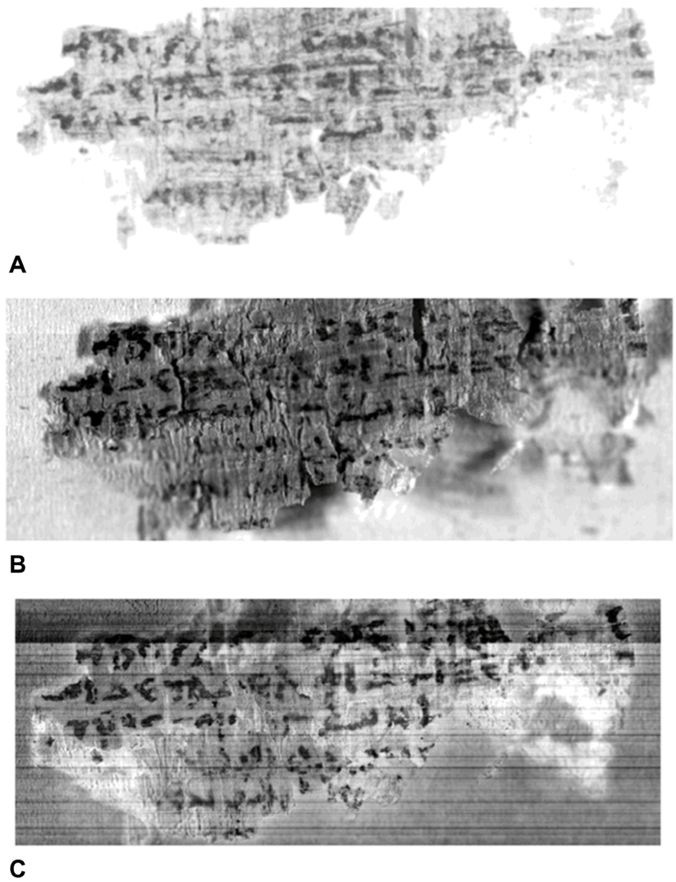


Fig. 6. *PHerc*. 1021, cornice 2, cols. 5-6, lower marginal annotation. Image at 950 nm. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Steven W. Booras, Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Brigham Young University, Provo) (**A**) and SWIR hyperspectral images obtained through PC1 (**B**) and PC3. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Biblioteca Nazionale "Vittorio Emanuele III," Napoli—Consiglio Nazionale delle Ricerche) (**C**).

at 950 nm, producing a substantial textual progress compared with former spectral techniques.

Given this success, it appears unusual that we could not detect any textual portions behind *PHerc.* 1021, cornici 4-5, where the remaining seven verso columns (cols. S, R, Q, P, O, N, and M) are supposed to be written. In absolute terms, given that the papyrus thickness is regularly constant in every single roll (except in correspondence with a *kollesis*, i.e., a localized overlap between two sheets), a different penetration capacity of light through cornici 1-2 and cornici 4-5, depending on a hypothetical difference in the relative papyrus thickness, would not theoretically seem to be a reasonable explanation for this problem. However, since cornici 1-2 are in a worse state of conservation than the following papyrus fragments, including cornici 4-5 (the former appear worn and their fibers are less cohesive than in other fragments), this might justify a slight accidental difference in papyrus thickness with respect to the other papyrus fragments and, therefore, a different penetration capacity of light through them. In any case, this circumstance can hardly invalidate the factual existence of the remaining seven verso columns. It is simply unrealistic to believe that only a number of columns from the verso actually exist and that another coherent group of perfectly similar ones, which successfully integrate the text lying on the recto, is the product of an 18th-century draftsman's imagination.

It remains true that, after our experiment, there can no longer be any doubt about the existence of textual portions on the verso of *PHerc.* 1691/1021. Speaking more generally, while the contrast produced by SWIR HSI is much superior to that obtained through previous imaging at 950 nm, the spatial resolution that we have applied to the main text is lower than the latter's so that holes and thin fractures or wrinkles in the papyrus are sometimes mistakenly displayed as ink. At the moment, only a comparison with the original manuscript or the corresponding images at 950 nm makes these deceptions easily detectable. On the other hand, the high resolution that we have applied to marginal annotations, although producing excellent results in terms of contrast and legibility, caused some focusing difficulties and the extremely weak depth of field negatively affected the quality of the SWIR hyperspectral macro image. Both problems, which were due to the two different lenses available to us at the time of our experiment, can suitably be resolved in the future by using a lens leading to an intermediate spatial resolution of about 100 μm. As an ink stroke in *PHerc.* 1691/1021 is about 0.5 mm wide on average, a resolution similar to that would be sufficient (0.5 mm equals 5 pixels).

The several new textual discoveries and improvements made by applying SWIR HSI to *PHerc.* 1691/1021 are being taken into account within the new innovative critical edition of Philodemus' *History of the Academy* currently being prepared by K. Fleischer. A selection of SWIR hyperspectral images will be made available open access in an online digital repository run by the National Library "Vittorio Emanuele III" of Naples. The excellent results obtained through SWIR HSI open up new encouraging perspectives in the analysis of the unrolled papyri from Herculaneum and raise the question of whether and how to extend the investigation through this technique to other Herculaneum papyri or even the whole Herculaneum collection. Judging from the successful case of *PHerc.* 1691/1021, a large-scale investigation of the entire papyrus collection (1840 cataloged papyri) through SWIR HSI would greatly increase the overall quantity of legible text from Herculaneum papyri with a foreseeably great impact on the reconstruction and the interpretation of the precious works that they provide us.

To that effect, owing to the huge amount of papyrus fragments to be scanned (about 30,000 frames), the setup will need to be improved accordingly. In particular, a specific automatic sample tray for papyrus fragments should conveniently be designed/optimized, and new larger lenses should be produced to scan samples more quickly, namely just once, instead of four or five times per fragment. As far as the imaging strategy is concerned, the digitalization of the entire collection through imaging at 950 nm performed in Naples between 1999 and 2002 by a team from the Center for the Preservation of Ancient Religious Texts (now The Neal A. Maxwell Institute for Religious Studies) of Brigham Young University can be used as a useful term of comparison (*12*–*13*). The team entrusted with this task, led by S.W. Booras and D.R. Seely, took about 8 months to image the entire papyrus collection through a specifically adapted Kodak Mega Plus 6.3i, 2000 × 3000, 8-bit digital camera. The use of more suitable equipment such as that outlined above could considerably shorten that time. To this end, the launching of the new European Research Infrastructure for Heritage Science (E-RIHS), currently being prepared and entering into its operational phase in 2022, could be an excellent framework in which to place this initiative.

MATERIALS AND METHODS

Hyperspectral imaging

The SWIR HSI technique combines imagery and reflectance spectrometer systems. The image recording is called hyperspectral data cube. This is defined by two spatial dimensions (x, y) and one spectral dimension (z), meaning that each pixel of the image contains a reflectance spectrum. The images were acquired with a spectrograph coupled with a cooled-temperature stabilized mercury cadmium telluride (MCT) detector [9.6-mm detector having 320 (spatial) pixels × 256 (spectral) pixels] using a push-broom scanning method. This camera (IMSPECTOR N25E; Specim, Finland) covers the SWIR spectral range (970 to 2500 nm). Integration times and scanning speeds were set to 3.5 ms and 41.7 mm/s, respectively. Two lens were used: The former (OLES56; focal length, 56 mm) has a spatial sampling of 200 μm for a working distance of 380 mm and a field of view spanning 60 mm. The latter (macro lens; focal length, 73.3 mm) has a spatial sampling of 30 μm for a working distance of 100 mm and a field of view spanning 10 mm. Each papyrus fragment was scanned with the OLES56 lens. Four or five scans were needed to image every single fragment with an adequate spatial resolution. The images obtained in this way were manually combined together in one data cube. The macro lens was only used to image very tiny marginal annotations located in three different papyrus fragments (cornice 1, upper margin, col. 4; cornice 2, lower margin, col. 5, col. 7, col. 8 and upper margin, cols. 7-8; and cornice 4, lower margin, col. 19). Two ramps of three 35-W halogen lamps (one on each side of the detector) were used as illumination sources. They were fixed together with the camera and moved along a motorized bar. All these measurements represent a mild cumulated exposure of 14 lux hours for each papyrus fragment.

Experimental design

Before starting any data analysis, we normalized the hyperspectral data cube by using the white and black images. A diffuse white reference (99% reflectance; Spectralon) covering the entire field of view of the detector was scanned both in each image/scan and separately to convert the resulting image cubes to reflectance factor. A dark reference was also acquired at each acquisition through a built-in shutter so as to quantify the electronic noise of the detector. Last, we spectrally reshaped the data cube by subtracting the first wavelengths, which were too noisy. As a result, we worked on data from 1000 to 2500 nm.

Statistical analysis

After trying basic image processing such as subtraction of wavelengths, spectrally cropping the data cube, continuum removal, band ratio, and spectral derivative, statistical analysis was applied. In particular, PCA was used in this study to handle the data cube acquired through HSI in the SWIR range (1000 to 2500 nm) (*25*). This process, applied to either MSI or HSI data, is a well-known statistical approach based on an exploratory treatment to investigate materials constituents of works of art (*16*, *26*) and enhance the readability of ancient manuscripts and papyri (*27*). PCA is commonly used to apprehend a huge quantity of data by reducing its dimensionality or variables (wavelength bands) and to make classifications. PCA builds up a new data space with new axes, which maximizes the variance in the original data. The first new axis, called PC1, which is based on a linear combination of the variables (here to be intended as the wavelength), contains the largest variance of the whole data cube; the second axis (PC2), which is perpendicular to the first one, contains the largest remaining variance, and so forth. After the PCA was performed on our normalized data cube, only PC1 to PC10, which gathered 99.99% of the total variance, were visualized and evaluated (typically, PC images get really noisy from PC6 or PC7). The weighting of each wavelength band for each PC is represented in a loading plot, which is potentially useful for understanding the influence or contribution of the different bands. Calibrations of the reflectance-spectral images and data analysis (including PCA) were performed using ENVI software (Harris Corporation, USA). After PCA calculation, all images were manually stretched through ENVI software and then sharpened through ImageJ (National Institutes of Health, USA).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/10/eaav8936/DC1

Fig. S1. Photographic reproduction of *PHerc.* 1021, cornice 4.

Fig. S2. Oxonian drawings of *PHerc.* 1021, verso cols. Z, Y, X, V, and T.

Fig. S3. Oxonian drawings of *PHerc.* 1021, verso cols. Z, Y, and X.

Fig. S4. *PHerc.* 1021, verso col. T: Oxonian drawing.

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Supplementary Materials for

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A. Tournié, K. Fleischer, I. Bukreeva, F. Palermo, M. Perino, A. Cedola, C. Andraud, G. Ranocchia*

*Corresponding author. Email: graziano.ranocchia@cnr.it

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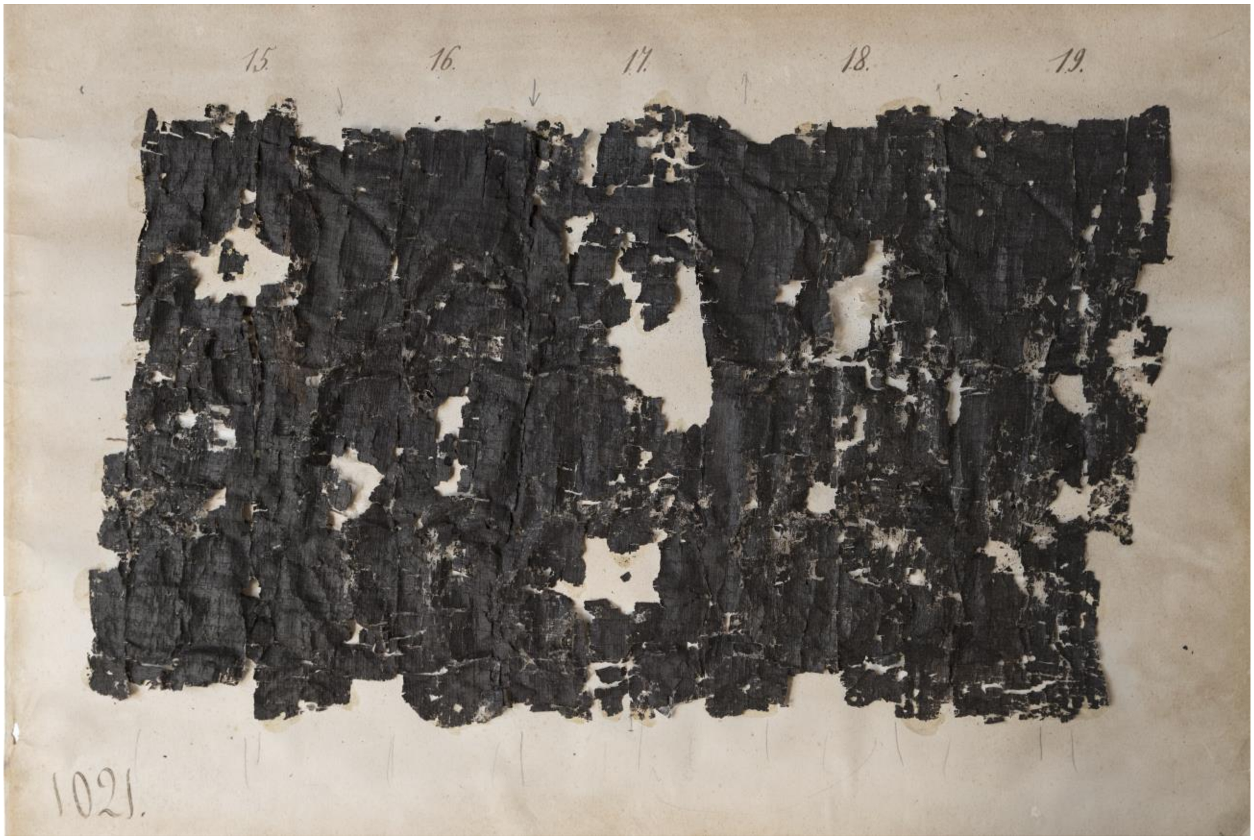

Fig. S1. Photographic reproduction of *PHerc.* 1021, cornice 4 (photo credit: Giorgio Di Dato, Biblioteca Nazionale "Vittorio Emanuele III," Napoli)**.**

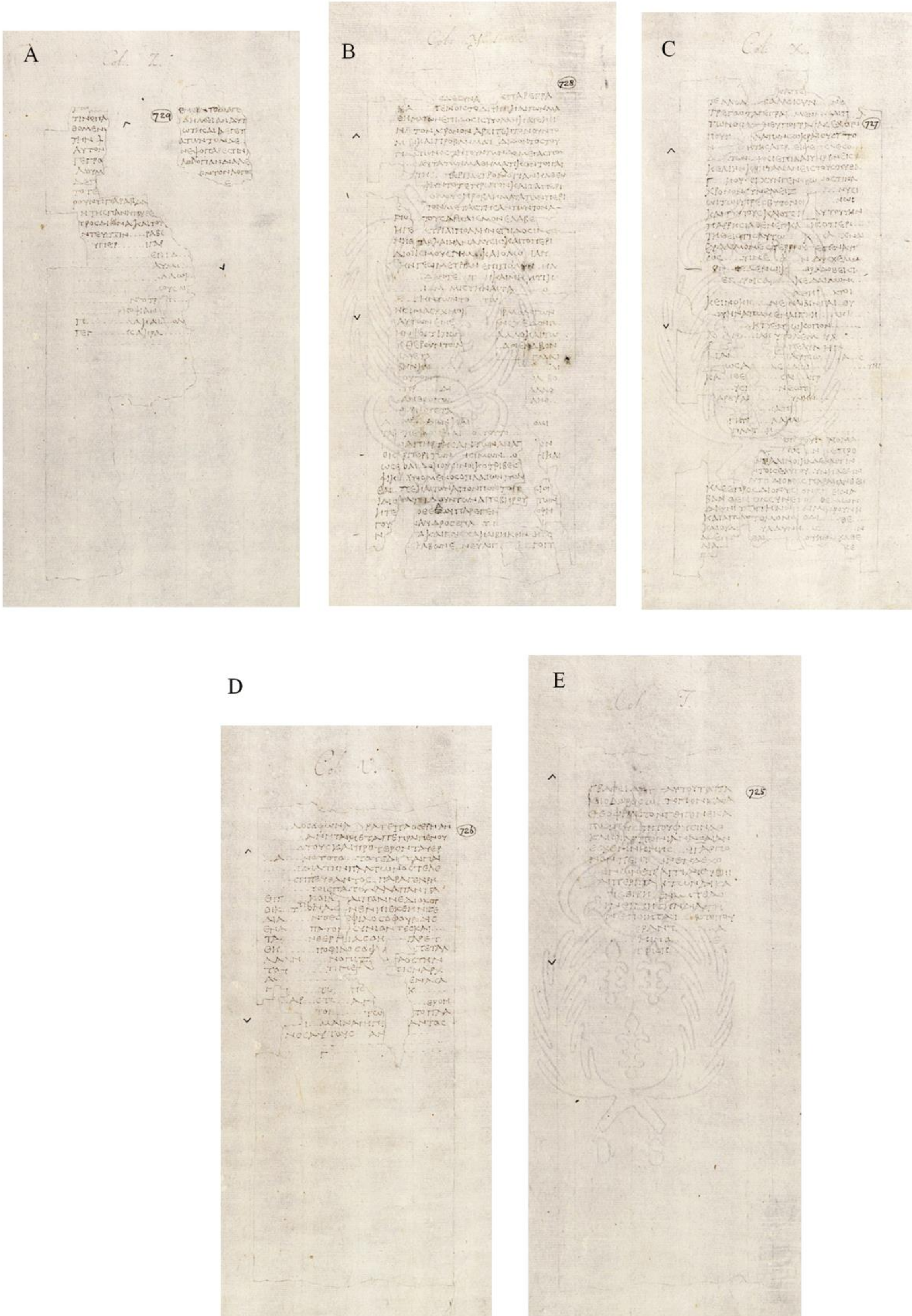

Fig. S2. Oxonian drawings of *PHerc.* 1021, verso cols. Z (A), Y (B), X (C), V (D), and T (E): columns are indicated with Latin capital letters in reverse order (photo credit: The Bodleian Library, University of Oxford, MS. Gr. Class. c. 4, 4, fols. 725-729).

Fig. S3. Oxonian drawings of *PHerc.* 1021, verso cols. Z, Y, and X. Schematic reproduction highlighting borders and gaps (not mirrored) (**A**); the same reproduction horizontally mirrored. Borders and gaps match with those displayed by the original papyrus (recto) (**B**); *PHerc*. 1021, cornice 1, image at 950 nm of the recto with localisation of the columns lying on the verso. Red lines mark the left and the right border of each column. By permission of Ministero per i Beni e le Attività Culturali (photo credit: Steven W. Booras, Biblioteca Nazionale "Vittorio Emanuele III," Napoli – Brigham Young University, Provo) (**C**).

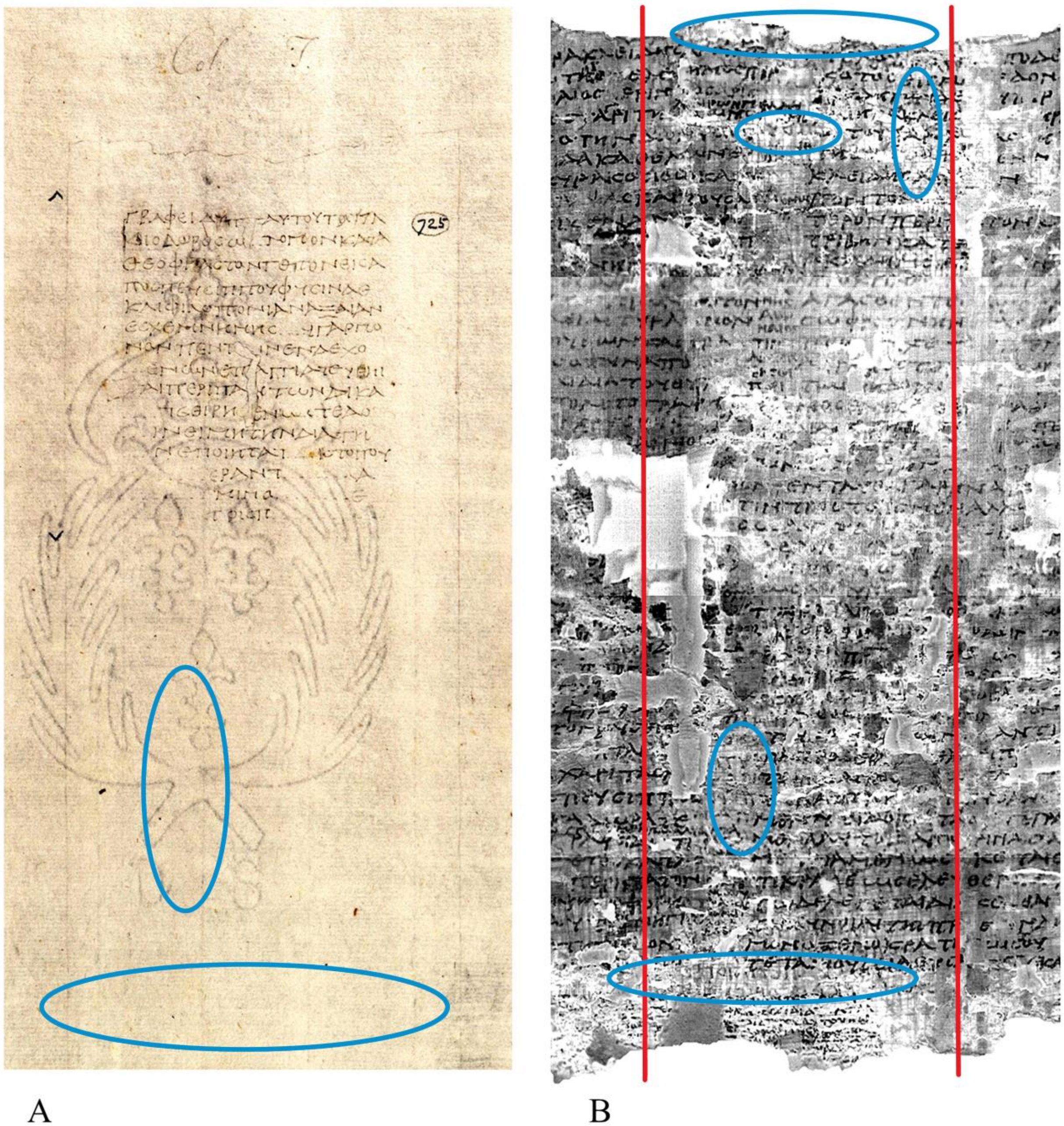

Fig. S4. ***PHerc.*** **1021, verso col. T:** Oxonian drawing. Cyan ellipses mark the position of the newly discovered textual portions from the verso (photo credit: The Bodleian Library, University of Oxford, MS. Gr. Class. c. 4, 4, fol. 725) (**A**) and PC3 SWIR hyperspectral image. The red lines mark the left and the right border of the column; cyan ellipses mark the newly discovered textual portions from the verso (**B**).