



Original article

Distinguishing between seemingly identical inks using scanning μ XRF and heat mapsGrzegorz Nehring^{a,*}, Nehemia Gordon^{a,b,c}, Ira Rabin^{a,d}^a Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany^b Bar-Ilan University, Ramat-Gan 5290002, Israel^c Institute for Hebrew Bible Manuscript Research, POB 919, Bedford TX 76095, USA^d Centre for the Study of Manuscript Cultures (CSMC), Warburgstraße 26, 20354 Hamburg, Germany

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ABSTRACT

This study will present a new approach to distinguishing writing inks that have the same elemental compositions and visual appearances. The approach is based on displaying the intensity of elemental distributions as heat maps that represent data recorded with a scanning μ X-ray fluorescence spectrometer. The heat maps present the data so as to facilitate digitally identifying and distinguishing between inks used to produce, correct, and reink two medieval Torah scrolls. As ritual objects, Torah scrolls had to be written in accordance with exacting standards that evolved over time. This requirement led to successive stages of modifications, sometimes over centuries. Both vitriolic and non-vitriolic inks used to modify Torah scrolls can be visually identical to each other. Furthermore, different non-vitriolic inks usually have an identical elemental composition. The solid material analysis evidence and its presentation as heat maps made it possible to discriminate between original and altered portions of text that in some cases would have been impossible. Our interdisciplinary work brought together conservation, material science, paleography, and philology to enable the identification of complex stratigraphy in multiple stages of production, correction, and reinking.

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1. Introduction

Writing has accompanied mankind for more than 4500 years, yet our scientific knowledge of writing materials, and in particular of inks, is still limited and primarily based on literary sources. Despite thousands of years of writing history, inks have only recently attracted scientific interest, and few scholars have given them special attention. To this day, Zerdoun's *Les Encre noires au Moyen Age* remains the only comprehensive monograph offering an insight into the material aspect of inks, based on the linguistic analysis of extant sources [1]. Chemically, we can distinguish among three main classes of black writing inks used in the period from antiquity to the Middle Ages [2]. To move in chronological order, the oldest preserved documents are penned in carbon-based inks. Such inks disperse carbon pigment in a water-soluble binder. Due to the size of the particles, carbon inks stay on the surface of the substrate. The second group is plant inks that have been in use since antiquity [1]; because they are composed of tannin extracts,

they penetrate the writing support. The third group on which we focus here is iron-gall inks. The oldest currently known examples of iron-gall inks come from late antiquity [3]. Such inks are produced by the chemical reaction between iron (II) and gallic or tannic acid in an aqueous solution of a binder of choice. Similar to plant inks, these inks penetrate the substrate. Iron-gall ink, initially brown, turns black upon oxidation when the writing is exposed to air [4]. At the Bundesanstalt für Materialforschung und -prüfung (BAM) and center for the Study of Manuscript Cultures (CSMC), our research concentrates on the transition from carbon ink to iron-gall ink [3,5].

Historical sources of hydrated iron (II) sulfate, known as *vitriol*, usually contain different quantities of additional sulphates of various metals such as copper, zinc, manganese, and others. One assumes that before the 16th century the elemental composition of iron-gall inks reflected that of the raw *vitriol*, which today is often used to compare the inks quantitatively or semi-quantitatively. In Europe, a new procedure to extract iron-vitriol in the 16th century resulted in a somewhat more homogeneous elemental composition of vitriolic inks and removed a simple correlation with the composition of the raw materials [6]. Since the 13th century, iron-vitriol has been the most popular reagent for iron-gall ink production—most European recipes mention it—but it was not the

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only possible source of iron. Iron shavings or nails soaked in acid also produce good-quality iron-gall ink [3]. In contrast to vitriolic inks, non-vitriolic inks do not contain the typical impurities of vitriol (although they may contain minor contaminants depending on the source) and therefore cannot be easily distinguished from each other [7].

In recent years, we have found numerous medieval manuscripts containing non-vitriolic inks whose differentiability and comparability have been questionable, since they lacked typical impurities and could not be subjected to the common analyses of iron-gall inks initially proposed by Malzer et al. [8] and later by de la Coudre [9]. The present study proposes a new approach by combining distributions and abundances of elements measured with an imaging μ XRF spectrometer into heat maps, where the warmer colors reflect higher signals, which in turn indicate higher concentrations of elements.

The approach this study employs has the potential to reveal successive stages in the initial production of a manuscript as well as stages in its modification by later scribes. Naturally, later scribal interventions tend to involve the correction of errors that were made in the initial production of the text. However, in the case of Torah scrolls, “corrections” can result from changing ritual standards and the standardization of the biblical text. Normative practices at the time and place of writing a Torah scroll could be deemed errors in a different community or in a different century. Ashkenazi religious authorities came to consider their traditional texts of the Bible inferior to those transmitted by scribes in Tiberias, the best known of whom Aaron Ben Asher was, who pointed and proofread the Aleppo Codex circa 925 CE. They also gradually began to defer to the codification of Jewish law set down by Maimonides (1138–1204), who used the Aleppo Codex. This resulted in scribes updating what they believed to be errors in accordance with new standards [10–12]. Another type of scribal intervention involved reinking, that is, tracing over faded ink. In many instances, new ink was applied to change the shapes of letters in accordance with evolving standards [12]. Reinking was particularly necessary for Torah scrolls due to the abrasive action of rolling the scroll from one end to the other and back throughout the course of a ritual reading cycle.

This study will consider examples from two Ashkenazi Torah scrolls that reflect this process of modification and standardization. The first four examples (Figs. 2–5) deal with Rhineland 1217, which has been attributed to 13th-century Germany [12]. The scroll seems to have been used for multiple centuries, possibly even as late as the 19th century. Rhineland 1217 has been thoroughly revised by multiple hands especially in matters of orthography as well as in spacing between sections of text that had ritual significance. Reinking was also applied selectively throughout the scroll, although this is not always visually apparent.

The fifth example (Fig. 6) deals with the other Torah scroll, Erfurt 7 (Berlin, Staatsbibliothek, Or. fol. 1216), which is also believed to have been written in 13th-century Germany [11]. However, the example considered below in Fig. 6 comes from one of three sheets that were replaced in the 14th century. The originals of these three sheets were either damaged, worn out, or considered so full of errors that they needed to be replaced. The scroll as a whole had a ritual life of only about 150 years, and the replacement sheets of about fifty years, before the scroll went out of use.

2. Research aim and funding

Due to the uniform appearance of some of the textual features, paleographical observations were limited in identifying modifications to the text. The goal of our project was to establish a protocol allowing identification of all the layers of script and to assess how they were executed. Identifying successive layers of correc-

tions in these scrolls allows us a glimpse at the native Ashkenazi text type that existed before the completion of the lengthy process of standardization. Distinguishing among layers of scribal interventions further allows us to see some of the stages in the initial production of the text as well as stages in the subsequent homogenization in accordance with the Tiberian text.

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3. Material and methods

3.1. Object preparation

Due to the oversized nature of the manuscripts, we designed a mounting system to guarantee the safety of the scrolls during measurements. For this purpose, we prepared a custom-built aluminum and acrylic table-like “stage” with an iron magnetic frame. The stage was equipped with wheels allowing for its safe maneuvering with the scroll mounted on it. Fig. 1(b) shows the magnetic iron frame wrapped in acid-free paper to prevent the direct contact of the magnetic frame with the scroll. The acrylic glass plates composing the top part of the stage and supporting the object during measurements could be adjusted, leaving an open space over which the magnetic iron frame was placed. Since the X-rays penetrate the object, this setup permitted us to conduct measurements on an unrolled part of the scroll without the background interference that would otherwise be caused by anything below the object.

Mounting each object for the measurements was performed using neodymium magnets attached to a magnetic frame (Fig. 1[b] and 1[c]). At all times, acid-free paper separated the scroll from the metallic parts of the stage. To reduce the force with which the magnets held the parchment in place, the most powerful magnets were wrapped in Tyvek® [13] (due to limited availability, not all the magnets were identical). With this setup, a temporary nonin-



Fig. 1. Rhineland 1217 mounted on the stage, with (a) a weight used to flatten the unrolled part of the scroll; (b) the magnetic frame wrapped in acid-free paper; and (c) neodymium magnets, on acid-free paper washers, used for temporary noninvasive flattening of relevant portions of the scroll. The scroll is mounted upside down to give better access to the final columns.

vative flattening of relevant portions of the scroll was performed prior to scanning. The unusually large size of both scrolls required that two individuals, including a conservator, always handled the objects together.

3.2. Imaging micro-X-ray fluorescence spectroscopy

The X-ray analysis was performed with a Bruker M6 Jetstream high-speed scanning micro-X-ray fluorescence spectrometer featuring focusing polycapillary optics and a variable-sized X-ray spot. The instrument was equipped with a mobile XRF probe that moved over the manuscript at a distance of 5 to 10 mm. The areas of investigation and the scanning parameters (X-ray spot, xy resolution, and acquisition time) were determined before each scan. For the measurements presented here, the probe was operated under the following conditions: Rh X-ray tube at 50 kV, 600 μ A, and X-ray spot size of 100 μ m. We conducted 29 scans ranging in area from 3 to 1129 cm² for Rhineland 1217, and 8 scans ranging in area from 30.2 cm² to 298.4 cm² for Erfurt 7. The acquisition time for each scan ranged from 5 to 50 ms/pixel, with a pixel (step) size of 250 to 500 μ m.

The X-ray emission peaks were fitted based on Gaussian deconvolution using the Bruker M6 Jetstream software. The abundances of the elements in the resulting XRF maps are depicted as heat maps in Figs. 4, 5, and 6, where the warmer the color, the higher the signal for the element detected.

3. Results and discussion

Before we delve into the graphic representation of the XRF measurements as heat maps, let us look at the spectra of three kinds of inks we identified in Rhineland 1217. Fig. 2(a) shows accumulated XRF-spectra of selected inscribed and non-inscribed areas of column 210 that are marked in green in the elemental map presented in Fig. 2(b) whereby each area consists of 50 spectra. The spectra of non-inscribed areas show the elements present in the parchment. Comparing the top, middle, and bottom spectra of parchment, we find that the only the intensity of calcium varies considerably, as expected for parchment [14], with iron being only a minor contamination.

The spectrum of the primary original ink (henceforth, “main ink”) used throughout the scroll (the top spectrum in Fig. 2[a]) shows an unusually small amount of iron (Fe)—as compared to common iron-gall inks—expressed in Fe K α and K β lines at 6.39 and 7.05 keV, respectively. It is contrasted by a high amount of calcium (Ca) at 3.69 and 4.013 keV and some potassium (K) at 3.31 keV. Due to the lack of obvious vitriolic impurities such as copper and zinc, we identify this calcium-rich/iron-poor ink as a non-vitriolic type. The second example of a non-vitriolic ink, the middle spectrum of Fig. 2(a), has an elemental composition identical to that of the main ink, containing only the elements potassium (K), calcium (Ca), and iron (Fe). The only difference between the spectra of the main ink and the second ink is a considerable increase in the amount of iron in this second ink and the corresponding inversion of the signal intensities due to iron and calcium. We see this type of calcium-poor/iron-rich non-vitriolic ink used for reinking throughout Rhineland 1217. The third type of ink on column 210 of Rhineland 1217 is vitriolic and has a different elemental profile. It does not contain calcium (Ca) besides its main element iron (Fe). Moreover, this ink does contain copper (Cu, 8.03 and 8.9 keV) and zinc (Zn, 8.62 and 9.56 keV). This third ink was used for some reinking and corrections. All three inks contain potassium (K) that most probably can be attributed to gum arabic, commonly used as a binder.

Let us focus on the correction in column 210 of Rhineland 1217 that concerns the last three words (אלי קום ןך) on the third line from the bottom in Fig. 2(b). As mentioned above, the main ink contains a peculiarly high amount of calcium (Ca) and an abnormally low amount of iron (Fe). To illustrate the difference in the composition of the inks and to follow the scribal interventions in a single line, we conducted a virtual line scan using the M6 Jetstream software, as Fig. 3 shows. We drew a line through a portion of the text in the second row (Fig. 3[a], [b], [c]) to show the exact position of our virtual line scan, which is presented as signal intensities of calcium and iron along this line in Fig. 3 (the corresponding portion of the text can be also seen under the x-axis). The sampled area is shown in Fig. 3(a) (photograph), Fig. 3(b) (map of iron, Fe), and Fig. 3(c) (map of calcium, Ca). The results of the scan in the form of a chart showing intensities for the elements calcium (Ca, marked in black) and iron (Fe, marked in orange) across the scanned area are dis-

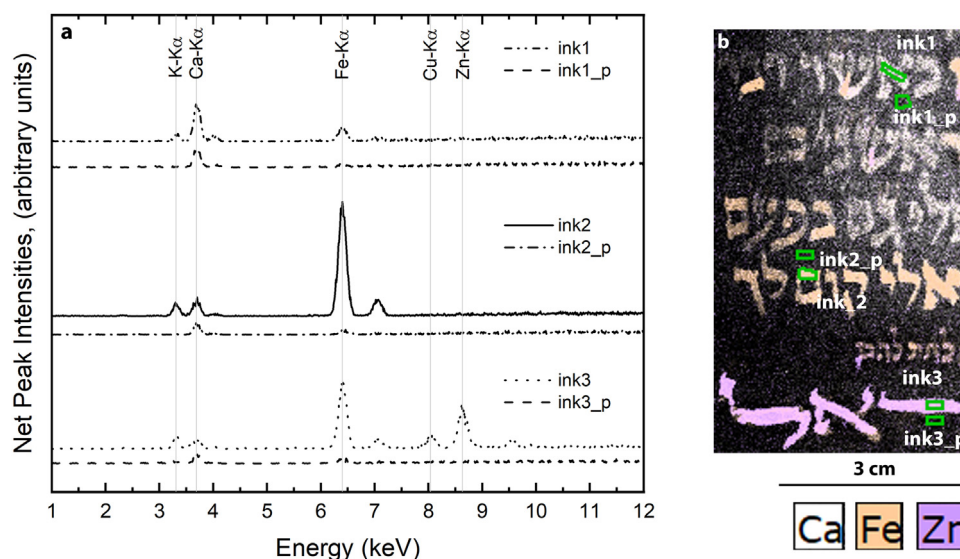


Fig. 2. Accumulated spectra of inks from column 210 of Rhineland 1217: (a) XRF spectra from the regions of interest (ROIs) shown in b and (b) ROIs are outlined in green in the XRF elements map (white = calcium, Ca; orange = iron, Fe; purple = zinc, Zn). Each ROI consists of 50 spectra. Scan parameters: acquisition time 20 ms/pixel, pixel size 250 μ m, 36,868 spectra, 15 min.

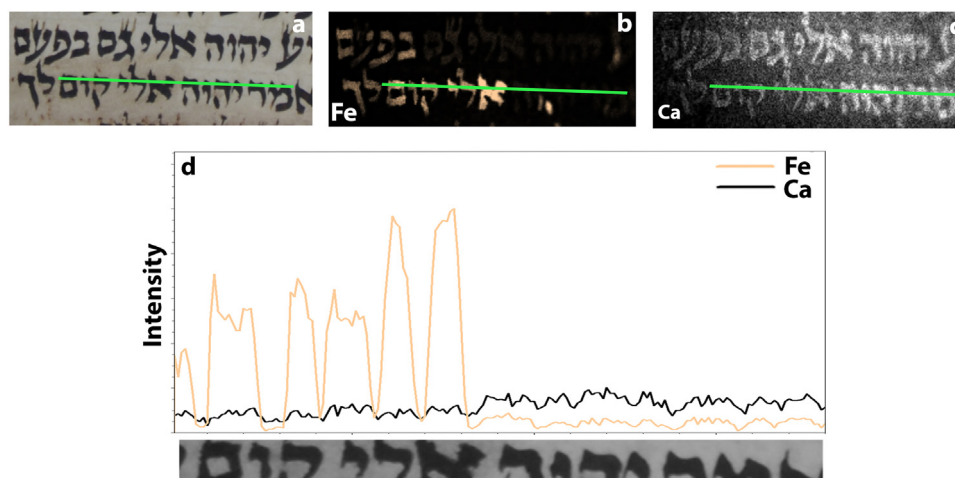


Fig. 3. Line and area XRF scan of a portion of column 210 from Rhineland 1217; (a) photograph corresponding to the area scanned; (b) map of iron, (c) map of calcium; (b-c) line scan marked in green; (d) elemental intensities along the line scan: Fe (orange curve), Ca (black curve). Area scan parameters: acquisition time 5 ms / pixel, pixel size 250 μm , 24,511 spectra, 5 min.

played in Fig. 3(d). Below the chart, there is a cropped image of the area analyzed.

There is no obvious difference (in visible light) between the appearance of the first two words (אמר יהוה) and the final three words (אלי קום לך) as far as the color of their inks or the morphology of the letters is concerned (Fig. 3[a]). Hence, from a paleographical perspective their inks would be expected to be identical. Indeed, this text is perfectly legible, with a rather homogeneous distribution of calcium (Ca, Fig. 3[c]). Nevertheless, the text is only partially legible in iron (Fe, Fig. 3[b]), which, based on the stronger iron signal, reveals that the last three words were reinked using an iron-rich ink. Note the dramatic variation of the ink composition in the graph depicting the results of this scan (Fig. 3[d]). A very low iron signal (Fe) characterizes the right-hand side of the text, as opposed to the left-hand side, which is characterized by its high signal. At the same time, the calcium signal (Ca) in the right-hand side of the text is approximately twice that of iron in this region. If we consider that the response of iron to X-rays is about 10 times stronger than that of calcium, the actual ratio of calcium content to that of iron is much higher than the one presented in the graph in Fig. 3(d). This result stresses again the difference between the original iron-poor/calcium-rich non-vitriolic ink (main ink) and the iron-rich/calcium-poor non-vitriolic ink used for reinking this section.

Let us analyze now the data displayed in the form of maps of elements presented as heat maps. Fig. 4 shows part of column 94 from Rhineland 1217 in visible light (Fig. 4[a]) and the corresponding XRF maps displayed in the form of heat maps of the elements calcium (Ca, Fig. 4[b]) and iron (Fe, Fig. 4[c]).

To facilitate the discussion, we numbered the lines of the script from top to bottom in increasing order, from 1 to 4. Based on paleographical observations, lines 1 and 4 were written by the main original scribe of the scroll.

Line 2 is written in a much smaller, finer, and denser script than that used in lines 1 and 4. In contrast, the letters in line 3 appear stretched and spaced more than the script in the other lines. We suggest that lines 2 and 3 are corrections, since they are executed in a different hand than lines 1 and 4. The hue of all the inks in the described portion of text is identical, despite the differences in handwriting. To prove that the original text was modified, and to uncover other features of the original text and corrections that might not be visible to the naked eye, let us look at the maps of elements displayed in the form of heat maps.

Both lines 2 and 3 are characterized by a much higher iron signal (Fe, Fig. 4[c]) and a lower calcium signal (Ca, Fig. 4[b]) than the main ink in lines 1 and 4, with a striking example of letters in line 3 displayed in the color red (the highest signal on the scale). In contrast, the main ink in lines 1 and 4 is shown in a dark blue color corresponding to the very low intensity of the iron signal. Noteworthy, the crowns (thin paratextual decorations) at the top of some letters in lines 1 and 4 are highlighted in light green/yellow in the iron heat map (Fe, Fig. 4[c]), indicating that they were added to the existing text at a different stage of writing and employed a different ink. The crowns show a much higher iron signal than the main ink used throughout the scroll. The main ink contains an abnormally high calcium signal (Ca, Fig. 4[b]) in contrast to an abnormally low iron signal (Fe). The last property of the main ink helps to identify that the crowns were added at a later stage in a different ink. Although the crowns are not visible in the calcium map (Ca), similar to lines 2 and 3, the letters (attached to these very same crowns) written in the main ink on lines 1 and 4 are visible. The main ink is calcium-rich/iron-poor, whereas the crowns in contrast are calcium-poor/iron-rich. In line 1, we also discovered some examples of reinking, with fragments of letters appearing highlighted in red and light green/yellow in the iron map (Fe, Fig. 4[b]). The iron heat map (Fe, Fig. 4[c]) also sheds light on the process of writing the corrections. The changes in the intensity of the iron signal in lines 2 and 3 (Fig. 4[c]) can possibly be correlated with dipping of the pen, as the intensity of iron (Fe) is sometimes higher at the beginnings of words. On the other hand, the heat map for calcium (Ca, Fig. 4[b]) indicates how the original text on lines 2 and 3 has been erased by being scraped off the surface of the parchment. In this process, the calcium (Ca) content in the substrate has been locally reduced and appears as a darker rectangle covering the space between lines 1 and 4. Interestingly, the upper border of the rectangle covers part of the bottom of line 1. The bottoms of some letters on line 1 within this region have been reinked, as seen in the iron map (Fe, Fig. 4[c]). It is possible that the bottoms of these letters on line 1 were inadvertently erased together with lines 2 and 3, and then reinked while the corrector was writing the new text on lines 2 and 3.

Paleographical and philological explanations of these results suggest that lines 2 and 3 were written by the same corrector. This correction brought the scroll in compliance with the rules established by Maimonides based on the Tiberian text. According to

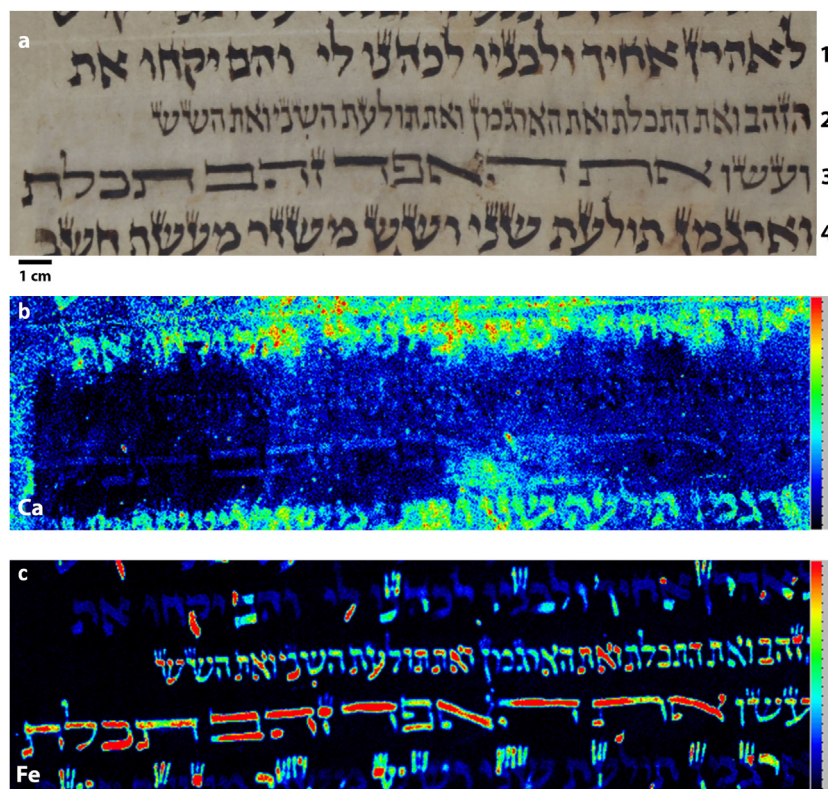


Fig. 4. Portion of column 94 from Rhineland 1217: (a) area scanned in visible light; (b) map of calcium displayed as a heat map; (c) map of iron displayed as a heat map. Scan parameters: acquisition time 40 ms/pixel, pixel size 250 μm , 106,731 spectra, 80 min. Note the color scale on the right side of each heat map: the higher the intensity of the element signal (amount), the warmer the color.

Maimonides, Exod. 28:26 begins an “open” section of text, which requires that it begin on a new line, with a blank space at the end of the *previous* line [15]. However, the native Ashkenazi text type deemed Exod. 28:26 to be a “closed” section, meaning that it had to begin on the *same* line (following a blank space) as the preceding section of text [16]. The original scribe apparently wrote Exod. 28:26 as a closed section in accordance with the native Ashkenazi tradition. To bring Rhineland 1217 into conformity with the Tiberian tradition, the corrector erased lines 2 and 3, which included the end of Exod. 28:25 and the beginning of Exod. 28:26. He then rewrote the end of Exod. 28:25 in small letters so that he could squeeze them into line 2 followed by a blank space at the end of the line. This newly added blank space at the end of line 2 was crucial for his purposes since it transformed the section beginning in Exod. 28:26 into an open section. On line 3, the corrector began by writing the first word of Exod. 28:26 in normalized script, but then stretched out the letters of the following four words so they would fill out the rest of the line without leaving any large blank spaces. The XRF analysis shows that when initially erasing lines 2 and 3, the corrector also inadvertently erased parts of the bottom of line 1. The erased portions of line 1 were reinked using iron-rich/calcium-poor non-vitriolic ink, presumably by the same corrector who wrote lines 2 and 3.

In Fig. 5, we show that a high-resolution XRF scan is not necessary for quick identification of scribal interventions when they were made with a different ink. Here, the area scan of approximately 1129 cm^2 covers a range exceeding the size of one column of the text. Fig. 5(a) presents a photograph of the scanned area that was registered in visible light while the corresponding map of iron (Fe) appears as a heat map in Fig. 5(b). As seen in the photograph in Fig. 5(a), all the writing appears relatively uniform. In some areas, the parchment appears smudged (e.g., column 159,

line 8; column 160, lines 8, 11, 14, 23, 31), which may correspond to corrections or possibly surface dirt. In this area, we have identified no metallic impurities in any of the inks, indicating that only non-vitriolic inks were present. The iron heat map (Fe) in Fig. 5(b) identifies alterations ranging from simple reinking to applying ink to reshape letters based on evolving standards, and all the way to such major modifications as rewriting erased text. Fig. 5(c) illustrates an example of such a major modification that is visible in the iron heat map. The first word (וייברך) on column 160, line 33 is erased (the resulting empty space is marked with a yellow box), and appears now at the end of line 32 (encircled with a yellow box) in a handwriting that differs from that of the main text; this modification transformed an open section into a closed section [17]. Such an overview scan, performed in the time needed to complete a high-resolution measurement of a small area as presented in the previous example, can be suitable for identifying scribal interventions quickly and precisely. However, in the example of the columns shown in Fig. 5, the uneven substrate (resulting from difficulty in making the parchment perfectly flat for scanning) in some areas did not allow for a reliable identification of lighter elements such as calcium.

Turning to the famous Erfurt 7 scroll, let us have a look at how the use of heat maps complements the results of the XRF study of vitriolic inks. As we suggested in a recent publication [18], the scribe writing column 1 from sheet 19 (a 14th-century replacement sheet) left some areas empty for God’s name. We suggested that the master scribe filled in these blank spaces with God’s name while also correcting some errors on the sheet. This was corroborated by the finding that the ink in both God’s name and the corrections had the same elemental composition, which differed from the primary ink used on the sheet. In Fig. 6(a), we show the area of the scan in visible light, while Fig. 6(b), (c), (d), and (e) present

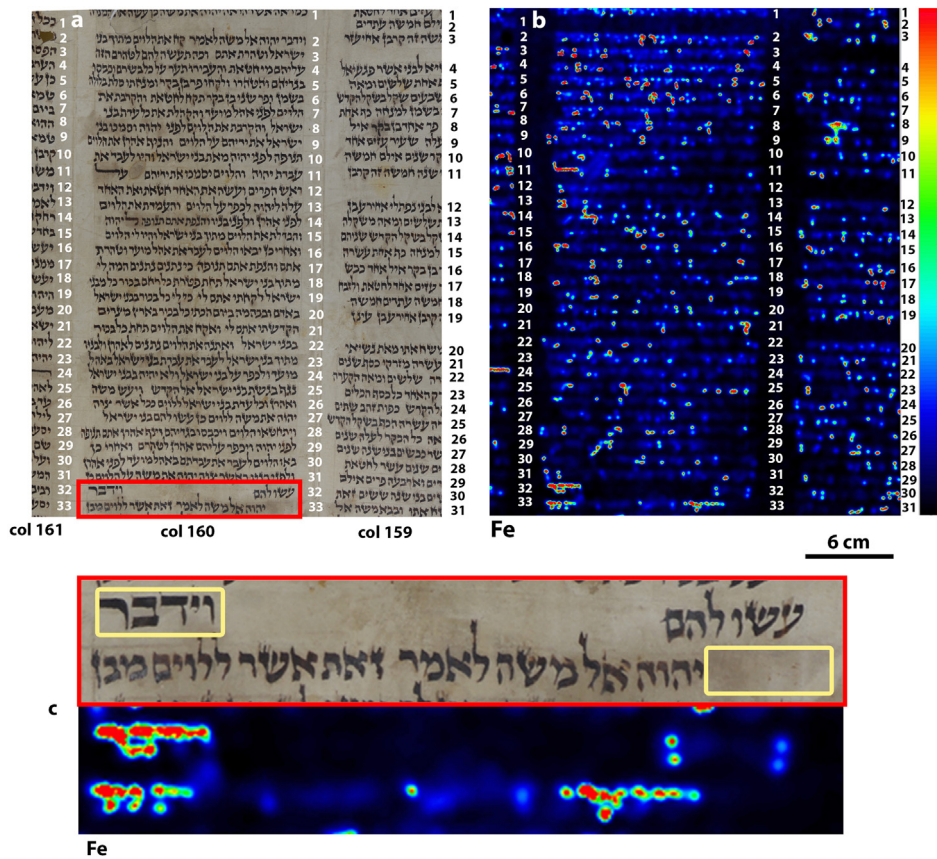


Fig. 5. Portion of columns 159, 160 and 161 from Rhineland 1217: (a) area scanned, (b) map of iron displayed as a heat map (the stronger signal, the warmer color), (c) lines 32 and 32 of col 160 with a major modification of the text. Scan parameters: acquisition time 5 ms / pixel, pixel size 500 μm , 452,160 spectra, 128 min.

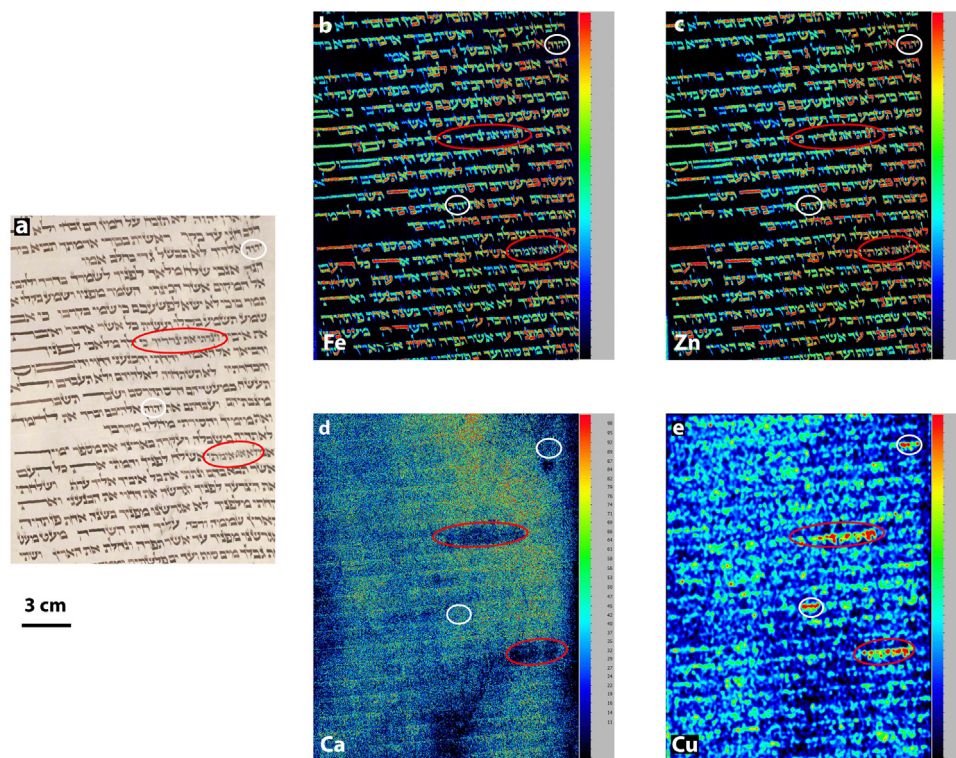


Fig. 6. Portion of sheet 19 (replaced in the 14th century), column 1 from Erfurt 7: (a) area scanned and (b–e) maps of calcium, iron, copper and zinc, respectively, displayed as heat maps (the stronger the signal, the warmer the color). White ellipses mark instances of God's name added in a second stage of writing in blank spaces left for this purpose. Red ellipses mark corrections that involved erasing and rewriting. Scan parameters: acquisition time 10 ms / pixel, pixel size 200 μm , 747,840 spectra, 157 min.

heat maps of calcium, iron, copper, and zinc, respectively, in that scan area.

The white ellipses in Fig. 6 mark instances of God's name that were filled in during a second stage of writing. The red ellipses mark corrected portions of text. Let us first compare the heat maps of iron and zinc, in Fig. 6(c) and 6(e). Both maps appear to display an identical pattern of intensities. These identical profiles reflect the heterogeneity of the ink application and, thus, suggest that both the iron and the zinc belong to the same ink. In the copper heat map, Fig. 6(d), the scanned portion of the column appears almost uniform, except for the areas marked with ellipses, where the intensity of copper is higher. Note that the copper signal in all the areas marked with ellipses has the same hue, suggesting that these scribal interventions were performed using the same ink. We have shown in our recent publication [18] that the signal for the copper in the ink used for the correction (marked with red ellipses) is very low, and copper is present only as an impurity. In this example, presenting the data in the form of heat maps draws attention to the difference between the compositions of the original ink and the ink of the added text with the copper impurities confirming that the added text was written in a different ink.

The calcium heat map in Fig. 6(b) reflects the distribution of calcium in the parchment because the inks of this scroll contain only a minute amount of this element. The calcium heat map reveals that the corrected text (marked with red ellipses) was written over portions of the parchment that were erased through abrasion. The abrasion removed not only the ink (containing the error or textual variant) but also some of the calcium, leaving a dark shadow on the calcium map. In contrast, the calcium underlying the two instances of God's name (marked with white ellipses) has the same concentration as the main text, indicating that there was no erasure. This corroborates the paleographical thesis that God's name was filled into blank spaces left for it during the first stage of writing [20].

5. Conclusions

The combination of elemental maps and abundance profiles (heat maps) helped distinguish between the original and altered portions of text in two medieval Ashkenazi Torah scrolls. In the case of the thirteenth century scroll Rhineland 1217, the original and altered portions of text were written in very similar non-vitriolic inks, whereas in a fourteenth century replacement sheet of Erfurt 7 they were written in two different vitriolic inks. The intensities of the elements visible on the heat maps allowed us to identify the stratigraphy of ink layers. Evaluating the area scans allowed us to locate the corrected portions of the text and expose how these alterations were made. We have also shown that it is possible to locate corrections within a large portion of text by conducting quick scans and presenting the resulting element distributions as heat maps. We never could have achieved these results by simply distinguishing between vitriolic and non-vitriolic inks. Nor could these results have been achieved without using an area-scanning μ XRF spectrometer and displaying the resulting data as heat maps.

In the case of Rhineland 1217, it would have been virtually impossible to identify all the scribal interventions based solely on visual observations. In the case of Erfurt 7, heat maps of calcium, iron, copper and zinc complemented our previously published XRF study of vitriolic inks [18]. The heat map for copper made it possible to distinguish between the original ink and a second ink used to modify the text. The heat map for calcium made it further possible to distinguish between two types of modifications carried out using the same ink. Erasing the original text left a dark shadow in the calcium map whereas the blank spaces left for God's name had no corresponding dark shadow, thus indicating no erasure.

The visualizations of XRF data employed in this study reveal otherwise inaccessible information about the ritual life of medieval Jewish objects and about medieval Jewish scribal culture. Without recourse to the specific approach involving heat maps in this study, our ultimate identification of the stages of writing and correction would have been based on paleographical intuition along with some scholarly speculation rather than on the solid evidence of material analysis. It is our hope that these methods will change the way inks and historical objects are studied in the future.

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