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COMPUTERIZED PALEOGRAPHIC INVESTIGATION OF HEBREW IRON AGE OSTRACA

Shira Faigenbaum-Golovin[1,2] • Arie Shaus[1,2] • Barak Sober[1,2] • Israel Finkelstein[3] • David Levin[1] • Murray Moinester[4] • Eli Piasetzky[4] • Eli Turkel[1]

ABSTRACT. This article surveys ongoing research of the Legibility Enhancement of Ostraca (LEO) team of Tel Aviv University in the field of computerized paleography of Hebrew Iron Age ink-written ostraca. We perform paleographic tasks using tools from the fields of image processing and machine learning. Several new techniques serving this aim, as well as an adaptation of existing ones, are described herein. This includes testing a range of signal-acquisition methodologies, out of which multispectral imaging and Raman spectroscopy have matured into imaging systems. In addition, we deal with semi- or fully automated facsimile construction and refinement, facsimile, and character evaluation, as well as the reconstruction of broken character strokes. We conclude with future research directions, addressing some of the long-standing epigraphic questions, such as the number of scribes in specific corpora or detection of chronological concurrences and inconsistencies.

INTRODUCTION

The field of Hebrew Iron Age epigraphy (the study of inscriptions and writing) is important for the domains of biblical archaeology, the history of ancient Israel, and biblical studies. The most abundant texts that have come down to us from the First Temple period are on ostraca (clay potsherds inscribed in ink or incised), belonging primarily to the major corpora of Samaria (Reisner et al. 1924; first half of the 8th century BCE), Arad (Aharoni 1981), Lachish (Torczyner et al. 1938), Horvat Uza (Beit-Arieh 2007), and Tel Malhata (Beit-Arieh, in press), the latter four dating mainly to ~600 BCE. The ostraca are traditionally handled by experts who create manual facsimiles (binary depictions of the text), text transliterations, and translations. This analysis culminates with a construction of paleographic tables, comparing characters across different inscriptions, corpora, and periods, and thus helping to date inscriptions originating from contexts that are not well dated.

Naturally, such an effort is prone to subjective reasoning. This might explain the lack of experts' consensus on various epigraphic matters, for instance, the shape and characteristics of specific letters along the time axis, the interpretation of certain words in a text, and the degree of proximity or dissimilarity between characters. In particular, scholars dealing with Hebrew Iron Age epigraphy are divided over issues such as the relationship between Israelite and Judahite writing, the number of scribes in a given corpus, dating of certain inscriptions based on paleographic criteria, and the overall model of Iron Age writing development. As expected, the disparity of epigraphers' views regarding these issues leads to different archaeological and historical interpretation and understanding of the Iron Age in the Levant.

The present research of the Legibility Enhancement of Ostraca (LEO) team of Tel Aviv University deals with Iron Age ink-written ostraca. It addresses several important challenges in Iron Age epigraphy via adaptation and development of automatic image acquisition and analysis techniques, reducing human intervention. Among the issues at stake are obtaining the best imagery of the ostraca, improving the existing images and facsimiles of ostraca, automatically generating facsimiles, as well as analyzing and reconstructing individual handwritten characters.

The methods dealing with these problems can roughly be divided among the domains of image acquisition and automated facsimile evaluation and creation. Following this division, the next sections

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1. Department of Applied Mathematics, Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel.
2. Corresponding authors: shirafaigen@gmail.com; baraksov@post.tau.ac.il; ashaus@post.tau.ac.il.
3. Jacob M. Alkow Department of Archaeology and Ancient Near Eastern Civilizations, Tel Aviv University, Tel Aviv, Israel.
4. School of Physics and Astronomy, Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel.

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specify the techniques we developed, along with the main results. We conclude the paper with future research directions.

IMAGE ACQUISITION

Following millennia of being buried in the ground, ostraca display problematic features common to ancient texts, e.g. they are found broken, in many cases illegible, with stains and erased sections, or blurred ink. In addition, the ostraca were probably considered as an inexpensive, sometimes expendable medium. This is as opposed to papyri (which have mostly perished due to the local climate) or the rare monumental stone inscriptions, which had higher standards of writing (lapidary script). Furthermore, a potential hazard, specifically facing ostraca, is the fast ink fading after being unearthed. As a consequence, an adequate documentation of the ostraca immediately upon excavation is necessary. The negatives from the 20th century excavations are also gradually deteriorating, strengthening the need for digital documentation.

For documentation purposes, we attempted both an adaptation of already existing techniques, as well as development of new, potentially promising methods of image acquisition. The conventional imaging techniques include scanning of old negatives (depicting ostraca prior to their fading), standard digital imagery, and multispectral image acquisition. The pursuit for new imaging methods covered Raman spectroscopy, X-ray fluorescence, regular and IR point spectroscopy, and fluorescent imaging.

Scanning of Existing Negatives

The scanning of old negatives is an ongoing effort, aiming at assembling digital copies of all existing negatives of First Temple period ostraca. The task is performed utilizing a scanner (Microtek ArtixScan M2) capable of handling several types of negatives, including glass. So far, we have scanned hundreds of Hebrew Iron Age ostraca negatives depositories at the Israel Antiquities Authority, Tel Aviv University, and the Harvard Semitic Museum.

Multispectral Image Acquisition

The modern digital imagery provides us with detailed high-resolution data. However, the spectral information of the regular RGB (red, green, blue) imagery is usually insufficient, as only three color channels are recorded (see Figure 1). Therefore, our initial attempts at standard digital photography were soon substituted by multispectral (MS) techniques (Faigenbaum et al. 2012). Such methods were previously found to be beneficial in later historical documents written on parchment (e.g. Knox et al. 1997; Easton et al. 2003).

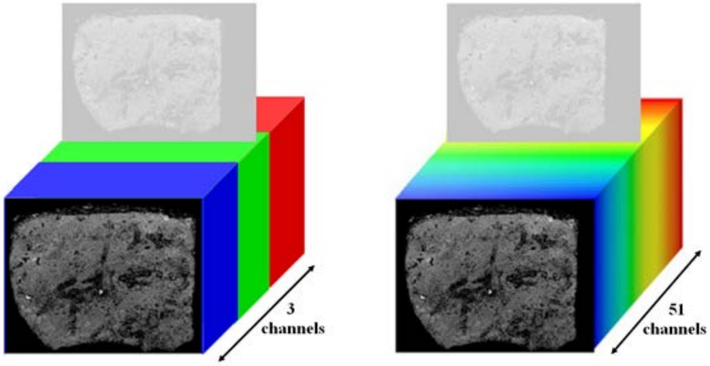

Figure 1 An illustration of RGB vs. multispectral data

We examined 33 Hebrew Iron Age ostraca from Horvat Uza, Horvat Radum, and Tel Malhata, sites located in the Beer Sheba Valley (Beit-Arieh 2007, in press), using a high-end commercial spectral imager, in order to establish an optimized imaging procedure. To assess the quality of the resulting images, we developed a new quality evaluation measure, which takes into account various contrast and brightness transformations. We showed that each ostracon possesses a unique wavelength range, where its readability is enhanced. Subsequently, we found that it is sufficient to use a small set of bandpass filters in order to acquire the most favorable images. This study paved the way towards constructing a low-cost multispectral device for the purpose of ostraca imaging.

Applying the MS imaging system was beneficial in several cases (Sober et al. 2014; Faigenbaum et al. 2015 and in press). For example, Figure 2 compares the standard and optimized MS images of Inscription No. 3 from Horvat Uza. In the enlarged parts of the images, one can see several characters that were absent or vague in the former, while present and legible in the latter.

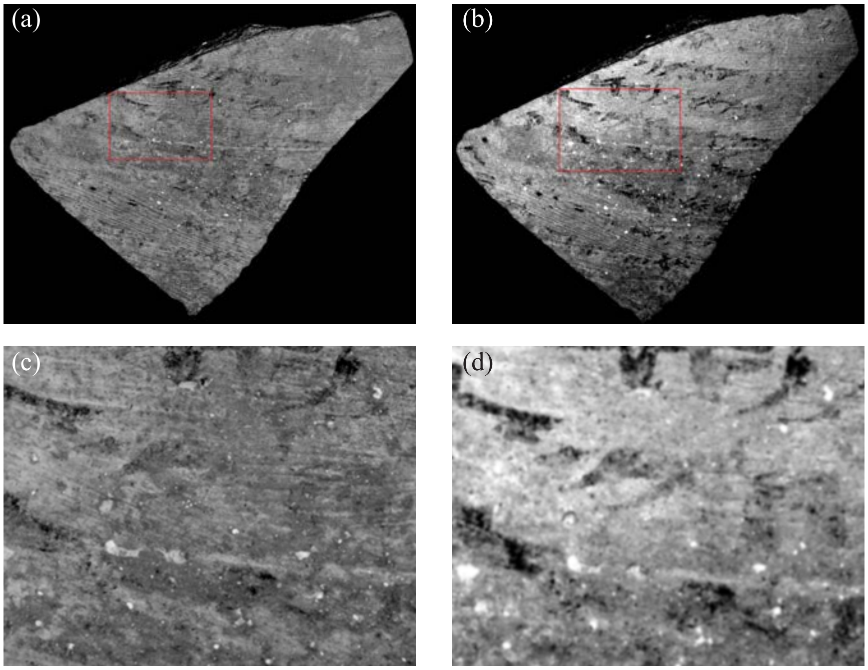

Figure 2 Ostracon No. 3 from Horvat Uza: (a) a full color image (~400–700 nm) converted to grayscale; (b) an image with enhanced readability (700–720 nm); (c, d) zoom-in on the area marked in red in images (a, b), respectively.

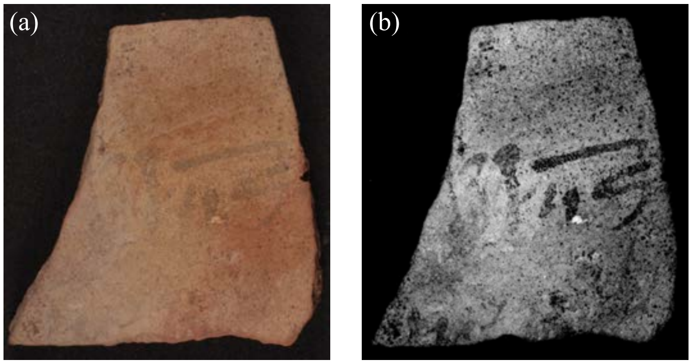

Figure 3 Two images of Inscription No. 13.056-01-S01 from Qubur el-Walaiydah, taken a year after excavation: (a) a color image; (b) image taken with the MS system at the wavelength range of 670–715 nm.

Another interesting example is a Hieratic 12th century BCE inscription from Qubur el-Walaiydah in the southern coastal plain of Israel, with an overall improvement by MS imaging, as displayed in Figure 3.

Raman, XRF, and Other Image Acquisition Methods

We tested several approaches to image acquisition. These were based on attempts to differentiate between "signals" of ink and clay on a microscale. Among the techniques considered were X-ray fluorescence (XRF), regular and IR point spectroscopy, fluorescent imaging, and Raman spectroscopy. With the exception of XRF and Raman spectroscopy, these methods did not yield significantly different signals.

Using the XRF (Nir-El et al., in press), we determined that the red ink in a rare red ink ostracon from the Tel Malhata corpus (Beit-Arieh, in press) contains iron as the principal component. We can therefore assume that the ink's pigment contained iron oxides, most probably hematite, Fe_2O_3. We also carried out an XRF analysis on the black ink of another Tel Malhata ostracon. We found that the net concentration of iron in the black ink of this ostracon is consistent with zero. Although the analysis could not explicitly identify carbon (since its characteristic X-ray energy is far below the detection threshold), we suspect that it is carbon-based (e.g. soot), mainly based on our Raman results (see below). Since we did not find a differentiating material in common black ink ostraca, XRF was not used as a basis for a new image acquisition mechanism.

On the other hand, our Raman spectroscopy experiments showed a clear distinction between clay and black ink spectra, which was utilized to construct a macroscale scanning device (Shaus et al. 2013a, unpublished data). This method exploits the observed difference to produce a new automated facsimile (black and white image) of the inscription. Our method circumvents the preparatory ink composition analysis (common in Raman spectroscopy), allowing for a straightforward detection of indicative Raman lines (wavelengths). Utilizing these lines, the most legible facsimiles are obtained.

The method was tested on an Edomite ostracon from Horvat Uza. The scans were performed on a character level. In Figure 4, a scan result of one character, as well as a facsimile created after simple postprocessing steps, can be seen. *A posteriori* analysis also revealed several indicative Raman lines, including ~1600 cm^{-1} (corresponding to aromatic rings, possibly humic acid or soot).

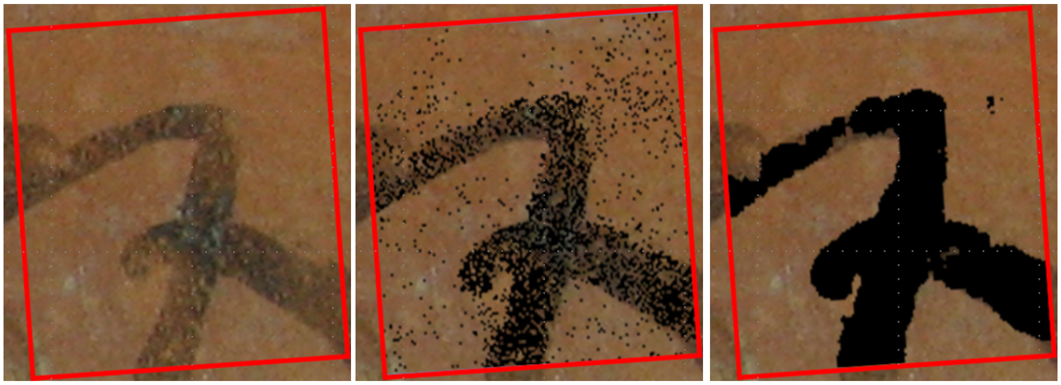
(a) (b) (c)

Figure 4 Raman scanning: (a) photograph of the scanned area; (b) scanning result overlaid; (c) scanning result after post-processing.

Currently, the scans and their processing take several days to accomplish, even for a single character. Scanning a whole inscription would likely take several weeks, and therefore was not pursued. Still, the process can be accelerated in the future using novel Raman technologies (Schlücker et al. 2003). This opens the possibility to produce facsimiles of entire ostraca in a completely automated and bias-free fashion.

FACSIMILE EVALUATION AND CREATION

Evaluation of Manual Facsimile

In accordance with the key role of facsimiles in epigraphic research, attention should be devoted to quality evaluation that is independent of the human eye. By *quality evaluation* we mean an assessment of how well a given facsimile represents the original writing on the ostracon.

We established a straightforward mathematical procedure (algorithm) that quantifies the quality of the fit between the facsimile and the image of a given ostracon (Shaus et al. 2010, 2012a). The quality of the fit is evaluated on a relative basis, ranking different facsimiles of the same ostracon. Figure 5 illustrates the correspondence between a facsimile and an ostracon image. Figure 6 shows three different depictions of the same character, overlaid on top of the ostracon image.

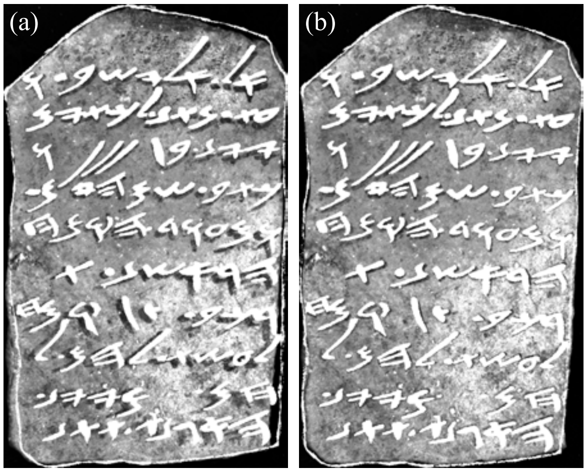

Figure 5 Arad ostracon No. 1 (Aharoni 1981): (a) facsimile overlaid over the ostracon's image; (b) aligned facsimile.

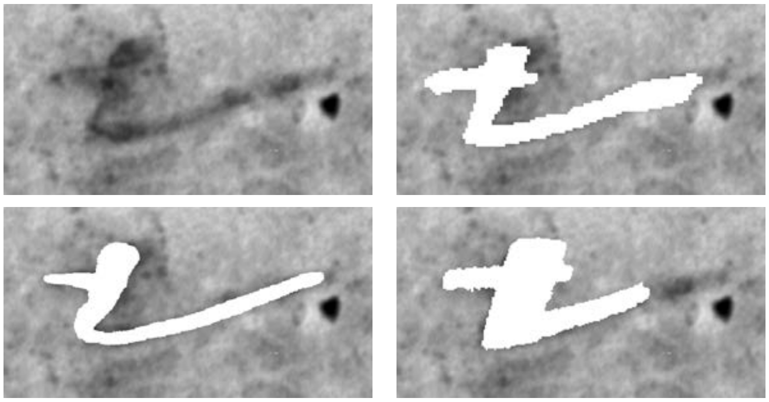

Figure 6 Arad ostracon No. 34: facsimiles of the same character created by three different individuals (details in Shaus et al. 2012a). The lower left facsimile was ranked first by the algorithm.

The proposed procedure was tested on a few cases in order to assess its reliability. A certain amount of variability was found between the facsimiles produced by different scholars, leading to different evaluation scores. It is interesting to note that the facsimiles with the best score were produced by a draftsperson rather than an epigrapher. This supports the assumption that the prior knowledge possessed by the epigraphers influences their documentation.

Creation of a New Facsimile

Our experience with facsimile evaluation convinced us that automated facsimile creation techniques ought to be pursued. As a first step, several existing binarization techniques were implemented, tested, and found to be inadequate for our purpose (Figures 7a–c). Therefore, a new method for automatically creating a facsimile was developed (Shaus et al. 2012b; see Figure 7d). This technique uses a digital image of an ostracon, as well as some information from an existing manual facsimile, in order to obtain an automatic and improved binarization (facsimile). A further noise reduction step, based upon automatically learned characteristics of the writing, has been developed and tested (Shaus et al. 2013b; see Figure 7e).

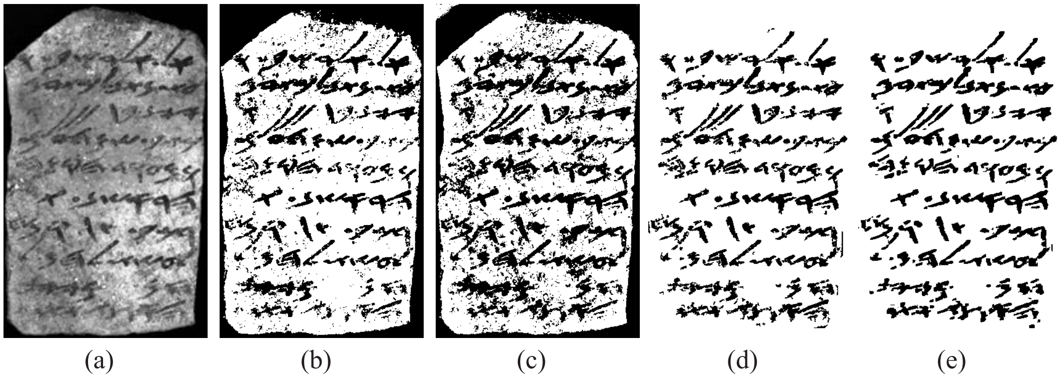

Figure 7 Arad ostracon No. 1 and its binarizations: (a) ostracon image; (b) Otsu (1979); (c) Niblack (1986); (d) Shaus et al. (2012b); (e) Shaus et al. (2013b).

Our experience with binarizations paved the way to a method that dealt with the evaluation of individual characters, as opposed to the binarization of entire ostraca (Faigenbaum et al. 2013). We chose to pick the most plausible characters on an individual basis, combining the best of all the binarization options. The characters were judged relying on their intrinsic properties (measuring the smoothness, completeness, and the amount of noise within the character). The algorithm managed to produce a credible ranking of characters' binarizations, comparable to human experts' opinions (Figure 8 illustrates the ranking results).

Even though the aforementioned algorithms produce results superior to a manual facsimile, they may still be insufficient for automated epigraphic analysis purposes. This is especially relevant in cases where parts of the character are missing. Therefore, a semiautomatic procedure for restoration of incomplete handwritten character strokes was developed (Sober 2013; Sober and Levin, unpublished data; see Figure 9). The method attempts at imitating the reed movement by using manually sampled key points of a character. The resulting character's reconstruction provided us with a smooth and complete facsimile, complemented by a full mathematical description of the constituent strokes. This opens the possibility of extracting sophisticated mathematical features, which may be used for letter analysis and comparison purposes in the future.

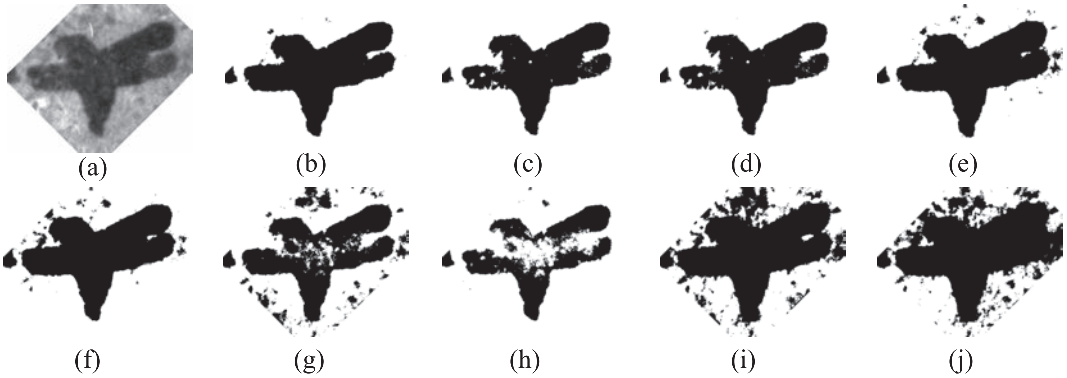

Figure 8 Expert's ranking of one character's facsimiles produced by several algorithms, in decreasing quality order; *w* is the window size, a parameter in the following algorithms (see details in Faigenbaum et al. 2013): (a) original image; (b) Sauvola and Pietikäinen (2000) [*w*=200]; (c) Shaus et al. (2012b), including unspeckle stage; (d) Shaus et al. (2012b); (e) Otsu (1979); (f) Niblack (1986) [*w*=200]; (g) Niblack (1986) [*w*=50]; (h) Sauvola (2000) [*w*=50]; (i) Bernsen (1986) [*w*=50]; (j) Bernsen (1986) [*w*=200].

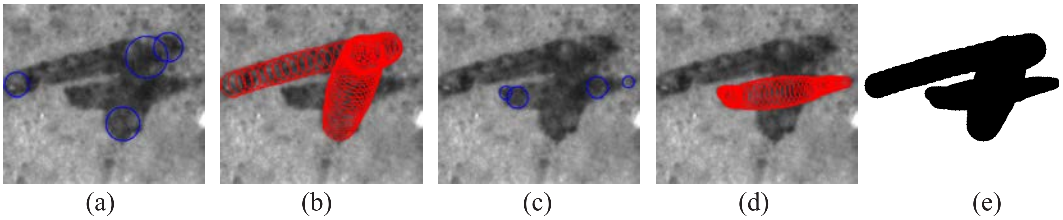

Figure 9 Reconstructing a *yod* from Arad ostracon No.1: (a, c) the initially sampled points; (b, d) the reconstructed strokes; (e) the resulting facsimile.

FUTURE RESEARCH DIRECTIONS

Our main objective is to perform paleographic tasks using tools from the fields of image processing and machine learning. This does not aim at replacing human experts, but rather supplying them with additional modern tools to perform their tasks. Our research paves the way to applying such techniques to the disciplines of Iron Age epigraphy and paleography.

The legible images obtained by the various methods, along with automated facsimiles, are already usable in their own right. Moreover, one of our main research goals is the establishment of a database containing the most legible images of Hebrew Iron Age ostraca.

Ostraca images can also be perceived as the foundation blocks in a large computerized epigraphy building currently under construction. Borrowing ideas from the field of optical character recognition, we are currently designing a metric that measures the similarity between two characters. The metric relies on extraction of features describing the shape of the characters. We use both well-established and new descriptors, and aim at combining them into a single efficient measure.

Based on this metric, paleographic comparison (cluster analysis) can be performed at the character, inscription, or the corpus level. Using this analysis, we are beginning to address some of the long-standing epigraphic questions, such as the number of scribes in a specific corpus or detection of chronological concurrences and inconsistencies.

Another research direction is an automated creation of paleographic tables. This may be achieved by means of detection (or calculation) of the most representative prototype for each of the characters present in the inscription. This may also be performed on a corpus basis. Initial experiments demonstrate the soundness of several of these research directions.

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