FROM ANALOG TO DIGITAL: PROTOCOLS AND PROGRAM FOR A SYSTEMATIC DIGITAL RADIOGRAPHY OF ARCHAEOLOGICAL POTTERY

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Abstract: *In this paper we present the results of three years of research and experimentation with the digital radiographic analysis of archaeological potsherd assemblages, with particular attention to discerning and distinguishing techniques of vessel formation. In contrast to previous digital radiographic efforts which have primarily been used to evaluate museum objects or archaeological finds of particular heritage import, the authors offer a digital radiographic application for the analysis of large archaeological potsherd datasets (n > 500), the basic fragmentary data of traditional archaeology. We describe the significant improvements over older analog techniques, the types of formation mechanics discernable through radiography, and demonstrate the way digital image manipulation can identify and discriminate between different formation strategies. The particular imaging protocols for producing image sets of maximum quality are delineated and the authors outline the post-processing tools that take advantage of the metric-matrix qualities of digital imagery.*
Keywords: *radiography of material culture, pottery, assemblage, digitization*

INTRODUCTION

The archaeometric understanding of pottery formation techniques has benefited greatly from instrumental (Courty and Roux 1995), ethnographic (Longacre 1991), and experimental (Wallaert-Pêtre 2001) examinations of archaeological pottery in recent decades. Formation practices interest scholars of pottery because they bridge important boundaries in the production process between the procurement of raw materials and the final achievement of a ceramic "product." Radiography provides a particularly powerful tool in the investigation of formation techniques due to its ability to reveal the traces of mechanical actions like coil-building, slab-building, and wheel-throwing, which determine a vessel's shape and texture, and are critical for understanding the organization of production practices in general (Carr 1990; Hamon, Querré, and Aubert 2005; Heinsch and Vandiver 2006; Lang and Middleton eds. 2005; Vandiver 1987, 1988). In this study, we focus on the relatively new field of *digital* radiography (DR) because it offers the additional benefits of: (1) incredibly rapid data acquisition speeds lasting less than 10 seconds and (2) immediate post-processing capacity in transforming radiographic images, obviating the need to scan film radiographs in order to make use of powerful digital tools (Lang & Middleton 2005; O'Connor and Maher 2001). These improvements over the previous analog technique now enable a truly systematic and assemblage-based radiography of formation techniques to take place.

Over the last half-century, ceramics have occupied an important position in archaeometric approaches using radiographic analysis (Braun 1982; Carmichael 1990; Digby 1948; Glanzman and Fleming 1986; Middleton 2005; Rye 1977). This work is contextualized within a host of other radiographic studies of archaeological fauna (Ambers 2005), human bone (Davis 2005), paper (Daniels and Lang 2005), metals (Lechtman et al. 1975), and textiles (Yoder 2008). Pottery, in particular pot*sherds*, however, have received comparatively less attention than have ceramic objects of art or particularly enigmatic museum pieces, certain notable exceptions notwithstanding (Braun 1982; Carr 1990; Heinsch and Vandiver 2006; Vandiver 1987). In the last quarter of the twentieth century, this limited work on potsherds showed much promise and innovative thinking, including intriguing indications that the radiographic examinations of pottery could distinguish (1) mechanical formation techniques of vessels (Vandiver 1987; 1988) and (2) potentially identify minerals over incredibly vast swaths of the container (Braun 1982; Carr 1990), permitting regional mineral sampling through an essentially nondestructive analytical program.

These early studies often utilized analog film techniques in hospitals or made use of instruments like the Xerox Corporation's "Xeroradiograph." By the 1990s, clear parameters for the production of high quality analog imagery were widely used and available (Lang and Middleton 1997). Since the debut of more robust digital equipment and techniques two decades ago, however, the obsolescence of xeroradiography (Lang and Middleton 2005) has not resulted in substantial advancements in radiographic imaging techniques for pottery and the general analysis and interpretation of their radiographic imagery. In fact, experimentation with digital radiography (DR) and X-ray computed tomography (XCT or CT) has tapered off considerably (Applbaum and Applbaum 2005; Lang and Middleton 2005; Vandiver et al. 1991).

Table 1 Optimal parameters for digital radiography determined from initial results.

kiloVolts (kV)	~ 275 kV
• Mid to high kV provides the power to send a strong signal to the detector.	
milliAmperes (mA)	~ 0.1 mA
• Low mA allows low-density inclusions to be picked up.	
Integration Time (IT)	8 seconds
• Longer IT increases contrast in image (adapted from xeroradiography).	
Source-to-Object Distance (SOD)	Close to source
• Magnification with a short SOD; applicable to both DR and CT.	

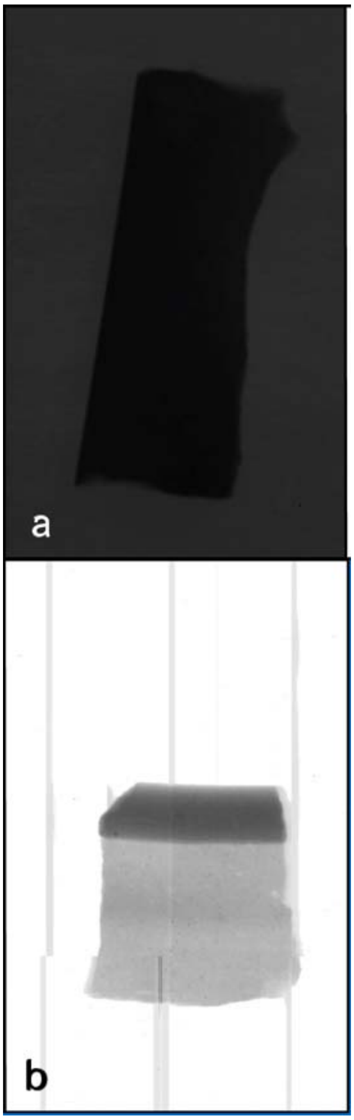

Fig. 1 Comparison of over-attenuated and over saturated radiograph images. **Figure 1a** displays the lack of detail exhibited by a potsherd that has not received enough kVp or integration time. **Figure 1b** displays the white background and "panelization" lines of a detector that has been oversaturated with too much energy.

This is most certainly due to the extreme difficulty and complexity of properly configuring such instruments (Casali 2006), but it is also in line with the traditional tendency of using radiographic analysis for the study of art objects, and not for the in-depth, assemblage-based analysis so essential to archaeological research. This study constitutes, to our knowledge, the first systematic application of digital radiographic techniques in potsherd assemblage analysis since the methods became available in the 1980s.

EXPERIMENTAL

The first phase of our technique development project involved the determination of settings for digital radiographic potsherd analysis that maximize the advantages of the technology. In order to gain the degree of accuracy required for consistent, sample-to-sample, assemblage-based analysis, image acquisition settings must reliably produce images of a high, measurable quality. Without the ability to produce comparable images with similar quality for each potsherd, a dataset with numerous cases would be largely useless.

Lang and Middleton (2005) published a recommended set of parameters for the analog radiography of material culture, but in the course of our research these parameters

Table 2 Comparison of X-ray Digital Radiography and Computed Tomography.

	Acquisition Time	Parallax Effect
Digital Radiography	~ 8 – 16 seconds	Significant: large spot size (1500 µm)
Computed Tomography	~ 4 – 6 hours	Insignificant: small spot size (20 – 200 µm)

quickly revealed themselves to be unsuitable for the newer digital device. Whereas analog film radiography and xeroradiography of pottery utilized long integration periods, requiring the artifact to sit in a relatively low kVp environment while the film soaked up radiation for minutes at a time, this kind of exposure would quickly saturate (and eventually damage) a digital X-ray detector. Concomitantly, the lower kVp necessary for long analog integration times results in too much attenuation of the source, resulting in overly dark imagery. In addition to these difficulties, the daily and weekly variability in the beam output of an X-ray tube introduces additional variation in potential attenuation, such that analysts working with a large dataset of potsherds acquiring data over a long period of time must have the ability to measure and calibrate the consistency of image quality as they work. So not only was it necessary to produce specific parameters of integration time, kV, and mA, we had to introduce a technique for measuring radiograph quality across a potential dataset, image-by-image.

Working in the X-ray Computed Tomography (XCT) Laboratory at Argonne National Laboratory (ANL) in the United States, our primary experimental setup in this endeavor consisted of a Phillips 420 kVp X-ray tube, which has small and large filaments generating a 1500µm spot-size and a 4500µm spot-size respectively. The tube is paired with a Perkin-Elmer 1640-A X-ray detector that has a 200µm resolution and measures 2048 pixels square. As a 16-bit digital detector it has the ability to discriminate 4096 shades of grey[1].

As mentioned above, the parameters included in our protocol study were: (1) X-ray tube kilovolts and milliamperes, (2) the integration or "exposure" time on the detector, (3) the Source-to-Object Distance (SOD), and (4) the Source-to-Detector Distance (SDD). The possible settings used for each parameter are summarized in **Table 1**. Because the number of possible voltage/ampere combinations (producing the kVp of the tube) is essentially infinite, we selected settings at intervals of 100 kV (e.g.: 100, 200, 300, and 400 kV) paired with different sets of integration time, SOD, and SDD. In the course of our testing, we determined the mA settings that produced viable images when paired with these kV settings—in other words, some combinations of kV and mA setting produced either over-attenuation of the X-ray beam or over-saturation of the detector, rendering the images useless for analysis (**Fig. 1**). The possible integration times were determined by the hardware settings of the detector—for this experiment, we selected 5 different integration times of the 8 possible: 1, 2, 4, 8, and 16 seconds. Finally, the SODs and SDDs were organized into 9 different combinations of locations for the X-ray tube and sample stage because these also have essentially infinite combinations (**Table 2, Fig. 2**).

All possible permutations for kV/mA, integration time, SOD, and SDD, were then tabulated, resulting in 189 possible combinations. Of these, we selected a random sample of 50 combinations (or a 27% sample) in order to conduct our parameter testing[2]. To calculate image quality, the project utilized the metric of Modulation Transfer Function, or MTF value (cf. Casali 2006: Appendix B; Fujita et al. 1992; Pham 2006), essentially the number of line pairs per millimeter (lp/mm) resolvable at different experimental settings.

[1] While the average human eye can only discriminate approximately 20-30 shades of grey in an image (Russ 2007: 92), each digital-matrix image pixel posses a value between 0 and 4095 that can be (1) contrast-enhanced across the wide dynamic range of the instrument, allowing easier human viewing, and (2) statistically manipulated to show the greatest factors of variability, filtering and classifying the most relevant data sub-groups (Casali 2006; Lang and Middleton 2005; Lang et al. 2005).

[2] We also experimented with the use of metal screens over the detector and filters in front of the X-ray source. Different metals and densities affect the quality of the X-ray beam in different ways, but it was eventually determined that the best way to maximize image contrast was to operate without screen or filter (Lang and Middleton 2005).

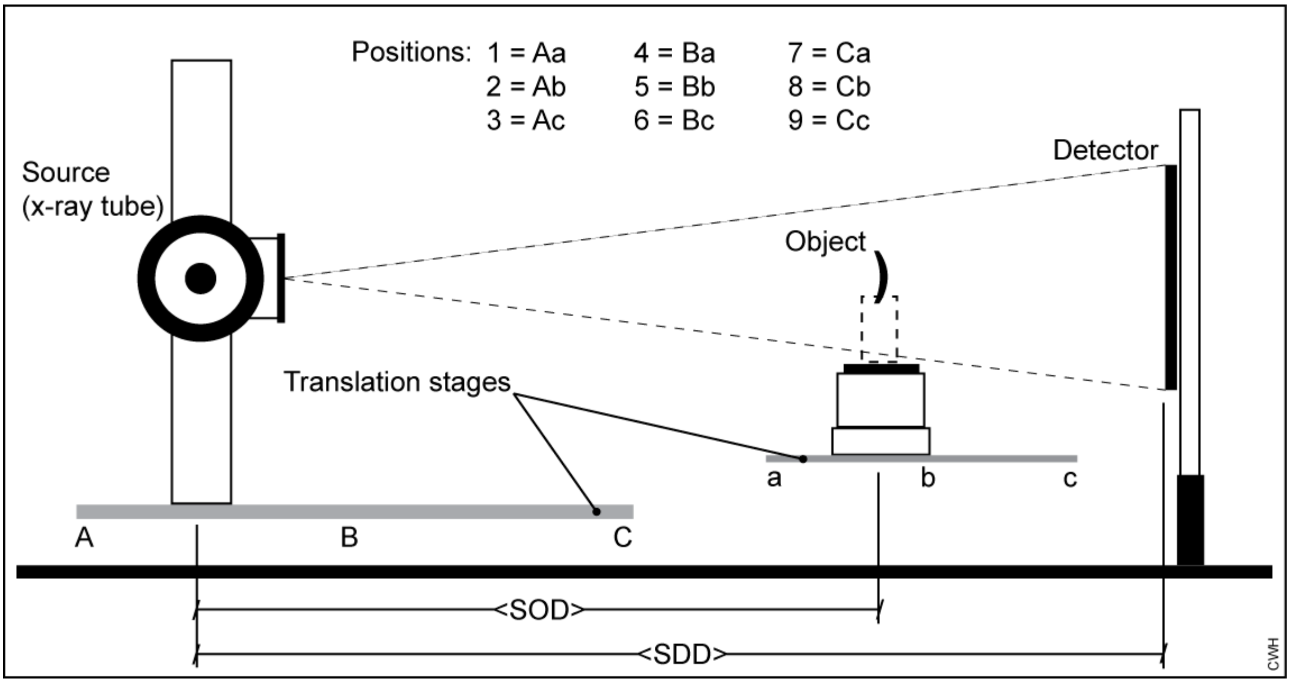

Fig. 2 The configuration of source, object, and detector stages at Argonne National Laboratory's X-ray Computed Tomography laboratory. Nine combinations of positions were used to develop the most appropriate instrumentation for the DR of ancient potsherds.

Because we were interested in the ability to distinguish the sharpness of ancient potsherds, and not the typical line pair gauge used in radiographic calibration, each test image contained the same sherd, cut so that one edge was straight and the MTF could be reliably calculated using an edge-spread function (ESF) (Casali 2006; Pham 2006)[3].

To measure MTF, the fifty test images were run through a software module written by the project in Interactive Data Language (IDL), entitled the "Sherd Image Viewer and Analysis" Program 2 (ShIVA2). The program imports imagery into its display module (**Fig. 3a**), samples the pixel values across the sherd edge (**Fig. 3b**), calculates the MTF value for each successive image via fast Fourier Transforms (cf. Fujita et al 1992; Pham 2006), and outputs the MTF value and a graph of its distribution (**Fig. 3c**).

The second phase of the experiment involved the identification of productive image filters that would identify the most relevant features of discrimination in the ceramic images. Important diacritica in this endeavor include: the presence and organization of joins, coils, or rings, the orientation and disposition of voids and elongate particles of temper (to help identify the use of wheel throwing or forming), and the presence of mold traces, often shown by the cavities left by textiles and basketry during the molding process (Heinsch and Vandiver 2006; Rye 1977; Vandiver 1987, 1988). Using statistical and filtering modules present in Interactive Data Language (IDL), we composed several texture and gradient filters which identify and classify the factors of maximum density difference into distinct groups and then display them color-coded on a new image (cf. Deemer and Metzger 2006).

RESULTS

This study of radiographic pottery techniques produced two primary results: (1) a set of standardized parameters for the mass radiographic imaging of ancient potsherds and (2) new analytical methods for the bulk analysis of vessel formation techniques through digital manipulation and analysis routines of the resultant datasets.

[3] The ceramic materials used in the study were drawn from the Making of Ancient Eurasia (MAE) collection, an interdisciplinary collaboration between scholars at the University of Chicago and ANL that studies ceramic and metal objects from the Neolithic, Bronze, and Iron Ages of Central China, the Russian Steppe, and the South Caucasus (Koryakova and Epimakhov 2007; Liu et al. 2002; Smith et al. in press).

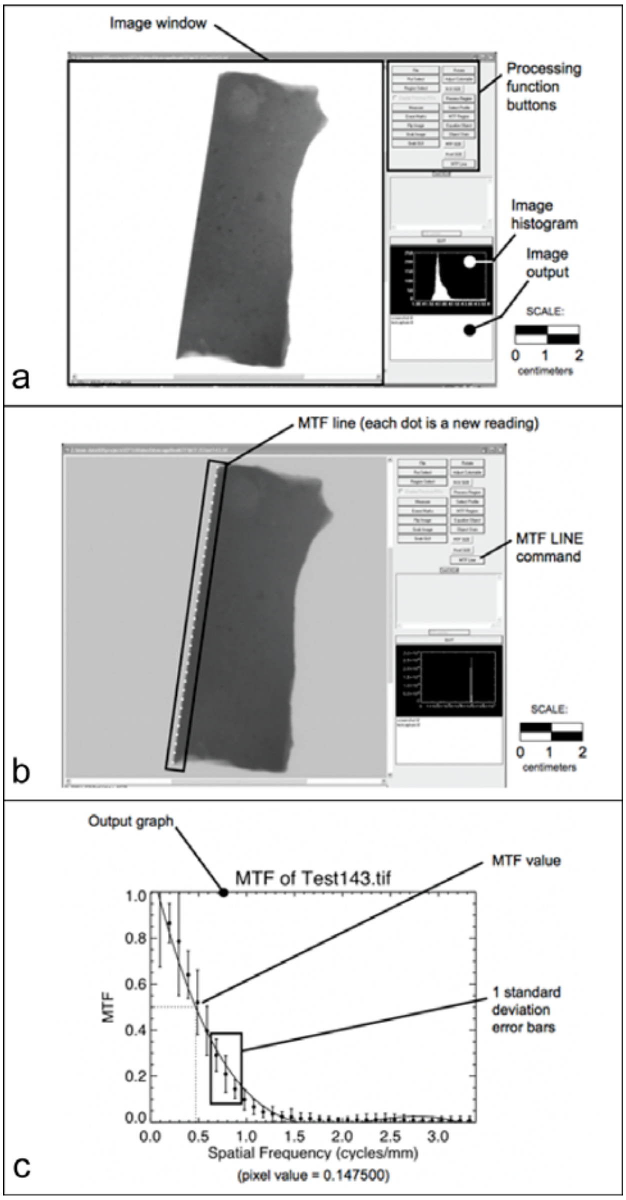

Fig. 3 Potsherd visualization (a), MTF calculation (b), and MTF output (c) from the ShIVA2 program.

When plotted together, the fifty test images suggested optimal settings of kVp and stage positions, which prompted further parameter experimentation with 25 additional setting cohorts in the 200-300 kV range in setup position 7. Those final experiments indicated that the following parameters would be ideal for the DR of ancient ceramic potsherds: an integration time of 8 seconds (**Fig. 4a**), a kV between 250 and 275 (**Fig. 4b**), a mA setting of approximately 0.1 to 0.15, and the positioning of the source and object as close together as possible (**Fig. 4c**). These results are further summarized in **Table 1**. At present, this is the best combination of parameters to acquire ancient potsherd imagery, yielding a maximal MTF value around 0.6. It is important to note that extensive variability existed across the range of setting permutations, so that the highest MTF value was not necessarily the best indicator of a reliable or preferred cohort of settings. For example, while the highest MTF values were achieved at setup positions 3 and 9 (**Fig. 4c**), the low level of magnification available in those positions made them less preferable for potsherd visualization overall.

In addition to standardizing the image acquisition process to produce images of a consistent quality and resolution, the project also developed post-processing tools in ShIVA2 for data normalization and analysis. Here we distinguish the normalization or pixel values from the acquisition of consistent quality images (MTF values). In a photographic analogy, MTF can be compared to image *focus* and pixel value normalization can be understood as *contrast* enhancement. If the images are not sufficiently focused, no amount of contrast enhancement will be able to improve their clarity and usefulness. Pixel normalization takes advantage of the full "dynamic range" of the X-ray detector, what Casali calls "…the ratio of maximum to minimum detectable signal (2006: 55-56)." During the normalization or "equalization" process, all of the pixel values within the sherd are stretched across a histogram based on the highest and lowest values.

Using ShIVA2, the analyst identifies the region of interest (ROI) on the "raw" image (the sherd and the background or scale), eliminates the background values around the sherd, and normalizes the histogram within the ROI. **Figure 5** shows the results of this process through the normalization of an Early Bronze Age (ca. 3500-2600 B.C.) sherd from Azerbaijan. A properly normalized image (**Fig. 5b**) provides an instant visual improvement over a "raw" digital radiograph (**Fig 5a**) and is a prerequisite for further filtering analyses of sherd sub-regions and structural features. Observe the difference between the lighter xeroradiograph image in **Figure 5d** and the normalized DR image in **Figure 5b** that utilizes the maximum dynamic range. Particular areas can be further contrast-enhanced by the use of a bounding box (**Fig. 5c**). Only after images are normalized can filtering tools provide analytical insight into the structural aspects of various vessel formation techniques.

The routines written into ShIVA2 filter each dataset based on texture and gradient aspects, identifying the primary cohorts of variability and classifying them by color. These filters are able to identify features such as joins, particle orientations, clay gradients, layer boundaries, and variation in inclusions frequencies over different regions of a particular sherd. In **Figure 6**, a progression from photograph, to "raw" radiograph, to normalized radiograph, concludes with a filter named "entropy" (**Figure 6d**) that has identified linear stacking in the wall of a first millennium B.C. bowl from Tsaghkahovit, Armenia.

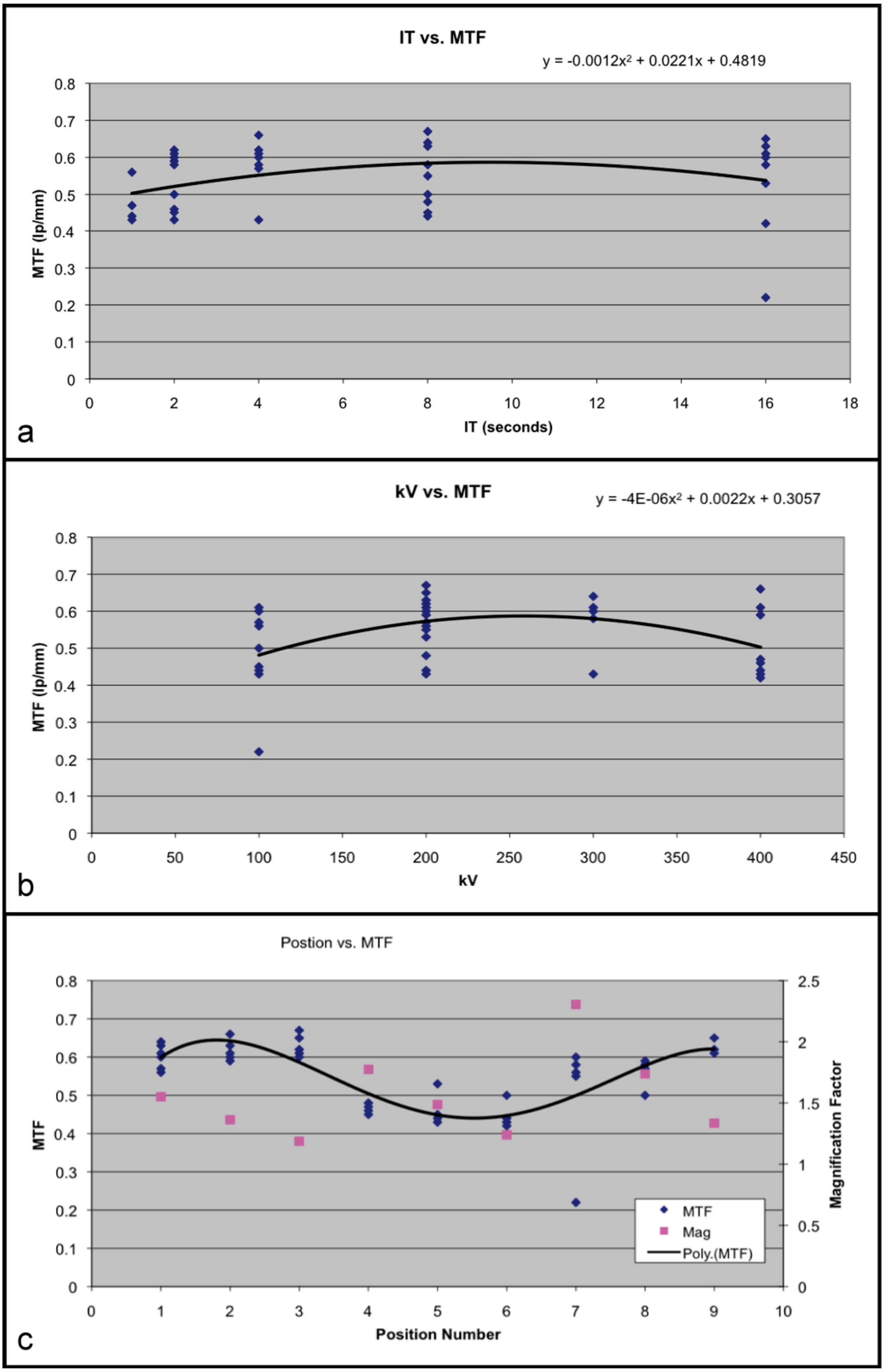

Fig. 4 Plots of the resultant MTF calculations from the test image dataset.

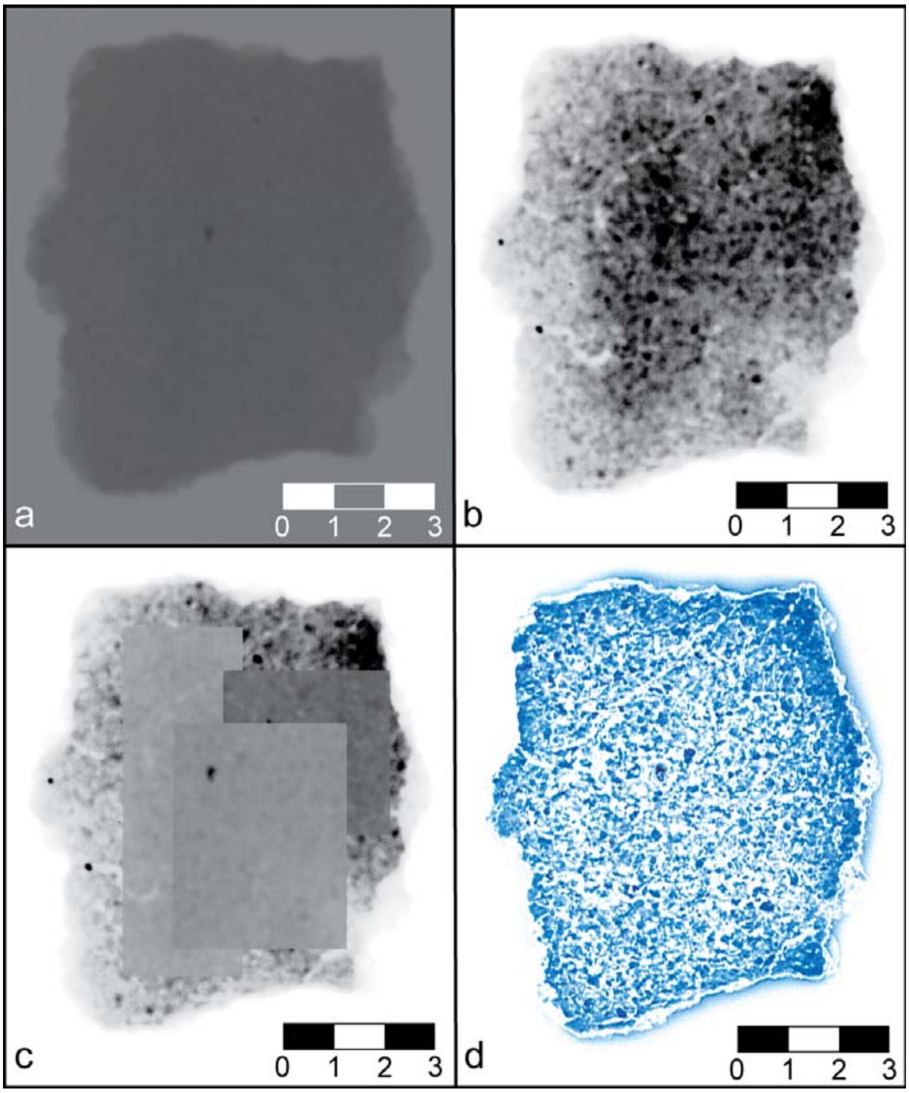

Fig. 5 Demonstration of the ShIVA2 normalization technique from "raw" radiograph (a), to contrast-enhanced radiograph (b). Figure 5c demonstrates the targeted contrast enhancement feature that applies a bounding box. Figure 5d shows the same potsherd imaged with an older analog xeroradiograph technique.

This patterning in the vessel wall is characteristic of a coil or ring-building technique (Gelbert 2005; Sall 2005), an important revelation as most tablewares from Achaemenid Armenia are assumed to be wheel-thrown (Khatchadourian 2008).

DISCUSSION

While these new parameters for the digital radiography of ancient potsherds enable significant data collection to now take place, the delineation of a systematic strategy of radiographic data acquisition is also essential. To ensure that an assemblage analysis project utilizing radiographic techniques remains connected to other aspects of traditional and archaeometric pottery analysis, it is important that DR analyses are directly informed by other research methods, particularly in the constitution of the original assemblage dataset. Pre-existing knowledge regarding the objects of study resulting from traditional ceramic analysis techniques (morphological, stylistic, and fabric analysis), compositional analysis, or SEM examination form an essential background from which to draw samples and organize a dataset that is as "representative" as possible. This will allow for a focused analytical program that will offer data on formation techniques that can immediately inform the ordering of production typologies and assemblage variability in general.

Once the dataset has been properly selected and stratified, we suggest a telescoping, multistage method for the implementation of DR techniques that exploits the powerful resolution of the method, while acknowledging the complex data management imperatives involved in assemblage-based analysis.

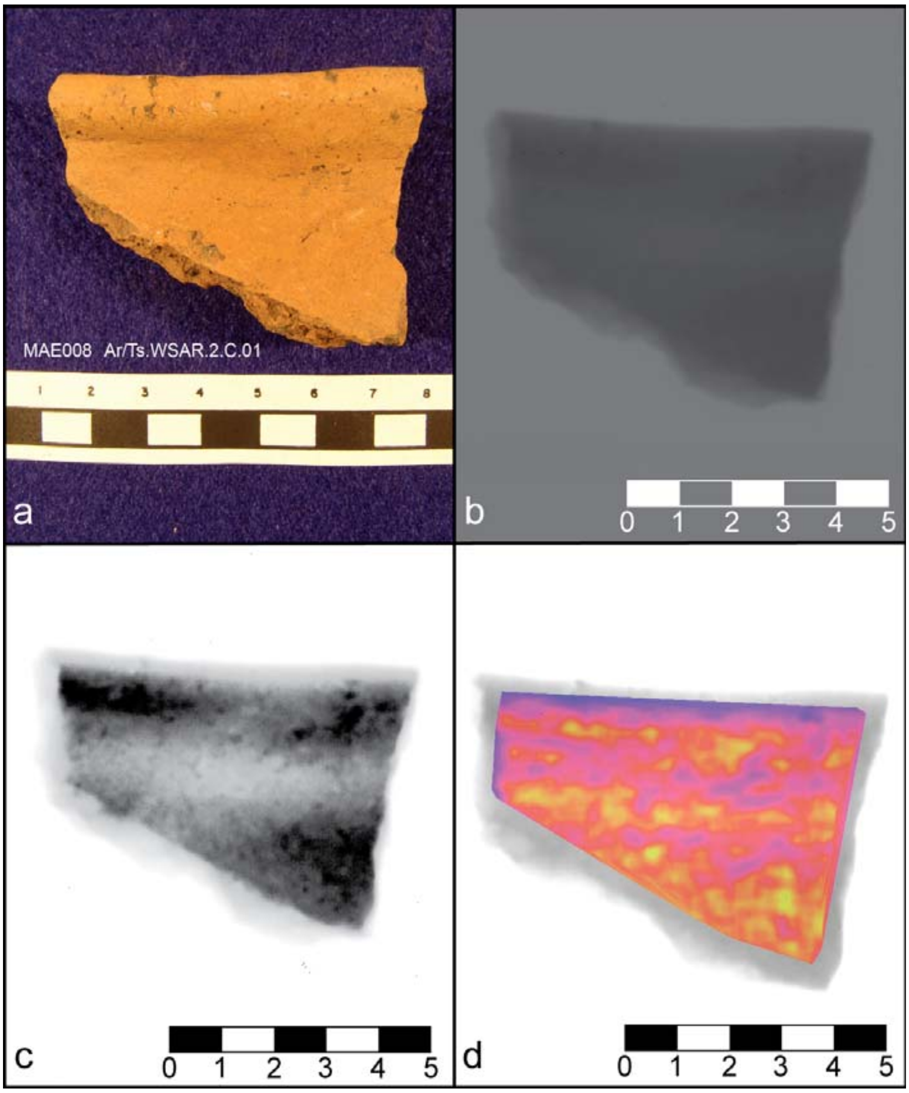

Fig. 6 Demonstration of the ShIVA2 "entropy" filter revealing stacked bands in a potsherd wall.

The figure shows the sample as it moves from photograph (a), to "raw" radiograph (b), to normalized radiograph (c), to filtered radiograph.

In the first stage, a large assemblage of pottery, or a sample of a larger assemblage, can be imaged using the standardized parameters for digital radiography outlined earlier. Easy manipulation of these images using Photoshop or IDL programming allows the investigator to quickly mine the data for multi-scalar evidence of production techniques, documenting patterning of voids and inclusions, gradient features in the clay matrix, and structural joins not visible externally. As a second stage of analysis, the investigator can then put together a shorter list of objects for further analysis using higher resolution techniques such as microfocus radiography or CT (Casali 2006; Lang and Middleton 2005; Lang et al. 2005).

CONCLUSION

While archaeologists and archaeometrists have been aware for several decades of the analytical potential of assemblage-based radiography, it is only now, with the full digitization of the data acquisition, normalization, analysis, and storage of these massive datasets, that the large-scale radiographic examination of potsherds is possible. Traditional ceramic analysis and radiography may well characterize the production techniques for one particular vessel, but the analytical value of those results can only be evaluated in light of that vessel's position within a broader ceramic assemblage. If there is any essential conclusion to be drawn from the past 30 years of ceramic ethnoarchaeology, it is that pottery is situated within enormously complex and highly variable production organizations; even on the simplest social level they are true "industries" (Balfet 1984; Leeuw 1993; Mahias 1993; Wallaert-Pêtre 2001).

From a statistical and anthropological viewpoint, the significance of results is inexorably linked to the construction of a representative dataset. An analytical perspective such as this demands closer working relationships with field archaeologists, as the composition of an assemblage-level dataset is mostly dependant on the expertise and research design of excavators.

This technique development project has laid the groundwork for assemblage-based digital radiographic analysis of potsherds by providing the foundational tools for data acquisition, normalization, and analysis—made available through a modular and adaptable set of software tools[4]. These tools will need to be augmented through high volume "batch-oriented" routines and high capacity storage systems, to effect the efficient analysis of pottery formation techniques. Future work is intended to perform the same protocol and application development for high-resolution microfocus and computed-tomographic techniques. This scale of analysis provides archaeologists with the ability to gain a systematic and detailed picture of the variability in formation techniques and shed new light on the organization of past pottery industries.

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[4] The binary version of the ShIVA2 program is available at http://mae.uchicago.edu

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