Journal of Archaeological Science 36 (2009) 867–872

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Point/counter point: the accuracy and feasibility of digital image techniques in the analysis of ceramic thin sections

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A R T I C L E I N F O

Article history:
Received 25 August 2008
Received in revised form
10 November 2008
Accepted 11 November 2008

Keywords:
Ceramics
Petrography
Digital image analysis
Ceramic temper

A B S T R A C T

Digital Imaging Analysis has been proposed as an efficient alternative to traditional petrography for some applications. This paper tests that proposition in the measurement of temper size and abundance in four pottery thin sections from the Pevey Site, Mississippi. The findings of both studies are presented here and the relative merits of the two techniques are evaluated in terms of accuracy, precision, cost, and time.

Digital Imaging Analysis (Gonzalez and Woods, 2007; Russ, 2006) has been proposed as an efficient alternative to traditional petrography for some applications (Hansen, 2000; Livingood, 2002, 2003, 2004, 2007;Velde and Druc, 1998; Whitbread, 1991; see Reedy, 2006 for review of applications). Advocates of each method decided to join forces to put this supposition to the test in the measurement of temper size and abundance in pottery thin sections. Both digital imaging analysis and traditional petrographic point counting were conducted on a small sample of grog- and shell-tempered Mississippi-Period pottery (Cordell and Livingood, 2004) from the Pevey site (22Lw510), Lawrence County, Mississippi (Livingood, 2006). The test sample consists of four thin sections that were selected from a larger sample of twenty-nine analyzed using digital image analysis (Livingood, 2007). The sample for this paper was randomly selected to cross-cut the common temper types in the larger study: two are grog- and shell-tempered, one is primarily grog-tempered, and one is primarily shell-tempered. The findings of both studies are presented here and the relative merits of the two techniques are evaluated in terms of accuracy, precision, cost, and time.

1. Digital imaging analysis

For this study the thin sections were scanned using an inexpensive consumer-quality Epson Perfection 1640 flatbed scanner with a transparency adapter. Scanning was set at the highest resolution offered, which was 3200 × 1600 dpi, extrapolated to 3200 × 3200 dpi. This resolution is such that silt-sized particles appear to be between .5 and 8 pixels wide, while sand-size particles are 8–126 pixels wide, using the Wentworth scale (Rice, 1987:38). Therefore this scanning resolution is appropriate for detecting and measuring temper inclusions such as grog and shell, but it is difficult to differentiate very fine and fine birefringent particles, and it is impossible to resolve silt. Each thin section was scanned three times. The first scan was a plane-polarized image, the second a cross-polarized image, and the third a cross-polarized image with the sample rotated 90°. The polarizing filters were low-cost plastic polarizing filters purchased from Edmund Optics.

A variety of software tools are available to conduct image analyses (for an evaluation of different software packages for petrographic application see Reedy and Kamboj, 2004a,b; Reedy and Vallamsetla, 2004a,b). For this project, Livingood used the Image Processing Toolkit (Russ, 2006) by Reindeer Graphics which are a set of Adobe Photoshop-compatible plugins. After the three scans were aligned by hand in Adobe Photoshop the Image Processing Toolkit functions were used to manipulate the image to improve the visibility of selected features and ultimately to isolate them. During this process, the thin section was mapped (Fig. 1) into the following categories: shell-temper, grog-temper, highly-birefringent particles, matrix, and voids. Leached shell voids were included with the shell counts following the standard for petrographic point-count analysis.

Macros were created that combined multiple image transformation to produce maps of the constituent categories. The macro-created maps were treated as rough drafts and were subsequently

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doi:10.1016/j.jas.2008.11.015

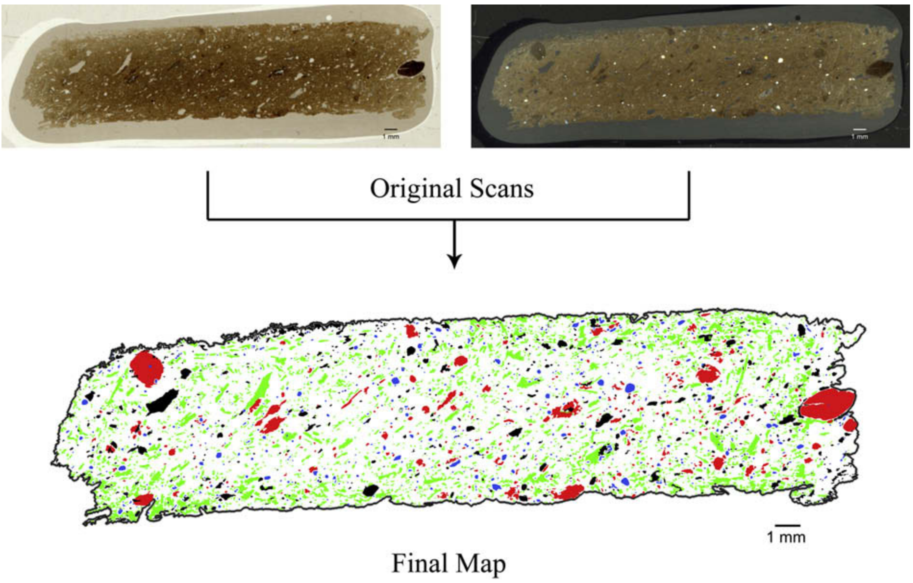

Fig. 1. Sample 19 original scans and final temper map.

edited by hand. Some constituent categories, because of their high visual contrast, were easy to identify using automated processes, while others required substantial hand editing. The sample boundary, voids, and birefringent particles were identified by the macros with nearly 100% success. In microscopic petrography an analyst makes a judgment call to determine which voids are from leached shell inclusions. With the digital approach, all voids with length to width ratios of three or more and a breadth not exceeding .5 mm were initially mapped as leached shell voids. The automated macros were approximately 75% successful in correctly mapping shell and shell voids. The most significant manual editing was required for samples with high enough densities of shell-temper that the shell or shell voids appeared to be nearly adjacent in the digital images. In those cases, the generated maps tended to lump together shell inclusions that were in reality separate pieces. Such problems could be overcome with higher image resolution. Finally grog, which can be challenging to identify even by a trained analyst using a standard microscopic approach (Di Caprio and Vaughn, 1993), was only mapped with about 25% accuracy by the macros and required extensive hand editing. The macros could have been refined to increase the success rate of all automated recognition but such refinements were not necessary with this small test sample. After the identifications were complete the software used the category maps as input to generate over fifty measurements on every identified feature, including color, location, nearest neighbor information, and geometric measurements such as length, breadth, area, perimeter, aspect ratio, symmetry, and convexity.

2. Petrographic point-count analysis

Petrographic techniques borrowed from the earth sciences have been applied to archaeological pottery since the 1930s. Petrographic point counts are made for quantifying relative abundance of inclusions. In this study, a petrographic microscope with a mechanical stage was used to conduct the Glagolev-Chayes point-counting procedure (Galehouse, 1971:389), following recommendations by Stoltman (1989, 1991, 2000). A counting interval of 1 mm by .5 mm with 10× magnification was used in which the mechanical stage advanced along the length of the thin sections at 1 mm intervals, but advanced across the width of the thin sections at .5 mm intervals. This counting interval was chosen as a compromise between the small particle sizes of matrix constituents and larger sizes of the grog- and/or shell-temper. Each point or stop of the stage was assigned to one of the following categories: clay matrix, non-temper voids, silt particles, grog-temper, shell-temper, including shell-temper voids, and very fine through medium aplastics of varying compositions, primarily quartz. Size of aplastics was estimated with reference to the Wentworth Scale (Rice, 1987:38). For one case in which fewer than 200 points were counted, the thin section was rotated 180° on the mechanical stage and counted a second time (after Stoltman, 2000:306).

The data generated by this method are actual counts of tempers and aplastics within specified size ranges (Table 1). Percentages can be calculated to estimate particle abundance and for comparison between samples. Temper and matrix compositions were also determined. In this study, two of the thin sections were found to represent micaceous clays. Given the minute particle size of the mica inclusions, the micaceous character of the pottery might not be obvious to the unaided eye. The petrographic analysis also permitted identification of accessory constituents and peculiarities of some tempers. For example, multigenerational grog-temper, i.e. recycled grog particles from pottery that was itself grog-tempered, was observed (Fig. 2). Some grog-temper contains shell, indicating that shell-tempered sherds were recycled as grog-temper. In another example, a micaceous grog-temper particle was present in a clearly non-micaceous matrix.

Table 1
Raw petrographic point counts.

Sample number	Total count	Voids	Matrix	Total aplastics	Shell	Grog	Silt	Very fine quartz	Fine quartz	Medium quartz	Quartzite	Other
7	338	22	232	106	27	21	16	33	5	–	3	1
19	427	25	293	134	86	9	14	12	7	2	1	3
22	218	42	160	58	–	16	13	22	3	1	–	3
27	391	24	252	139	43	1	34	54	2	–	3	2

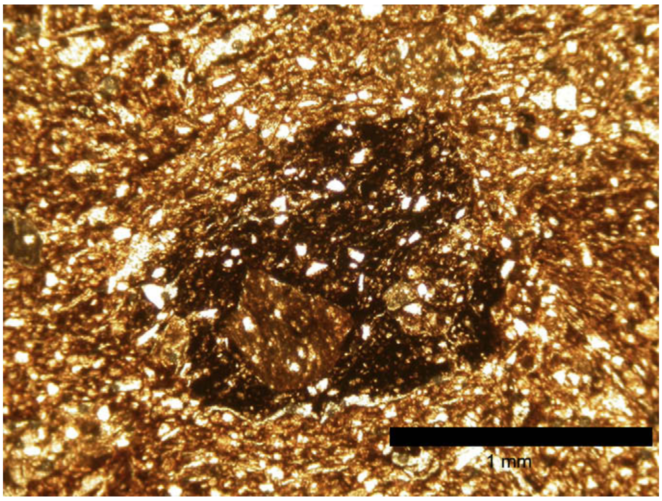

Fig. 2. Multigenerational grog-temper in sample 22.

3. Comparison of results

3.1. Summary of differences

To compare the results of the two methods, percents of birefringent particles, grog, shell, and voids were calculated from each data set for each sample, for a total of 16 measurements or observations (Table 2). Point counts of silt grains were excluded to equalize the basis for comparison. In the point-count literature, combined sampling and counting error of 3.5% is considered acceptable (Stoltman, 1989:150–153). Although the margin-of-error increases as relative particle abundance decreases, the 3.5% value was used here as the baseline for acceptable concurrence. The goal here is to discuss possible sources of methodological error involved with the digital image analysis technique.

This comparison shows that of the 16 measurements, 13 are within a 3.5% margin-of-error. Only three measurements exceed the margin-of-error and they will be discussed further (Table 3).

For birefringent particles, the two sets of measurements were close in most instances, but the digital technique consistently underestimates the number of birefringent particles (mostly quartz) pointing to a systematic difference. In addition, there is a severe undercount with regard to the birefringent particles of sample number 22. It is suspected that the digital technique was systematically under-identifying the smaller-grained quartz. We feel confident that all fine- and medium-sized quartz grains were identified correctly, but smaller particles were undercounted at the specified scanning resolution. Increasing the scanning resolution would move these counts into closer agreement. In the case of sample 22, the discrepancy is most likely due to higher relative abundance of very fine quartz, which was not measurable in the digital image at the given scanning resolution.

For grog-temper, the digital technique mostly matches the point-count technique for sample numbers 7 and 22, but was wildly divergent on samples 19 and 27. Livingood suspects this may be the result of interpretive differences on his part that exist apart from the method of analysis, a problem noted previously for grog (Di Caprio and Vaughn, 1993). With digital imaging analyses, grog particles are recognized by differing texture, space between the particle and matrix, color differences, and/or internal differences in clay constituents. Thus, ferric concretions, lumps or stains, and random clay lumps were most likely identified incorrectly as grog in the original analysis. After considering both the thin sections and digital images, we feel confident that this is the major source of the discrepancy. Fortunately, it would be relatively quick and easy to re-evaluate grains that had been designated as grog in the digital analysis, and make corrections if called for. This highlights some of the respective strengths of both techniques. With the digital approach the digital mappings could be easily reproduced and shared just like text in a word-processor, can be re-evaluated and edited, potentially by multiple researchers, and the measurements re-generated. In contrast the facility with which a microscope can switch between different magnifications and polarizing filters, including the Bertrand lens, provides the analyst with more tools with which to make fine distinctions.

For shell-temper, the digital technique and the point-count technique largely fall within the appropriate margin-of-error. The largest differences are for samples 7 and 27. In both these cases, the digital technique under-measured, compared to the point counts. This might be attributed to differences in interpreting some leached shell voids.

For other, non-temper voids, both techniques are roughly equivalent. The largest difference in measurement is on sample 7, but the observations are within the appropriate margin-of-error.

This discussion shows that digital image analysis technique has the potential to match the results of the petrographic point-count technique for some pastes/constituents, once analyst error has been accounted for and assuming the scanning resolution is appropriate to resolve the smallest constituents of interest. However, a comparison of only percentages of constituents overlooks some important differences in the additional information each technique provides.

In this study, the Petrographic methods are able to observe a variety of optical properties to identify mineral composition by means of higher levels of magnification, plane-polarized and cross-polarized light, and even occasional use of a Bertrand lens. These standard petrographic techniques permit a skilled analyst to accurately identify most constituents and features and produce more specific identifications that can be used to address clay resource and compositional questions.

As mentioned previously, with digital image analysis the margin-of-error increases if the resolution is not adequate to detect the features of interest because they may not be detected and identified correctly. In addition, even when small features are correctly identified, measurements are less precise than for larger features because of quantization problems associated with the use of pixels. The scanning resolution used in this study was incapable of resolving the smaller features that can be seen easily with the petrographic microscope. It is also more limited in its ability to

Table 2
Comparison of digital image analysis and petrographic point-count data.

Sample #	Digital image analysis				Petrographic point counts			
	Birefringent pct (%)	Grog pct (%)	Shell pct (%)	Void pct (%)	Birefringent pct (%)	Grog pct (%)	Shell pct (%)	Void pct (%)
7	8.9	4.4	5.1	8.3	12.4	6.2	8.0	6.5
19	5.6	6.2	21.8	6.2	5.9	2.1	20.1	5.9
22	4.8	8.4	1.1	20.5	13.3	7.3	0.0	19.3
27	12.4	4.2	7.7	6.5	15.6	0.3	11.0	6.1

Table 3
Percent difference between digital image analysis and petrographic point-count data.

Sample #	Percent difference (digital minus point count)[a]			
	Birefringent pct (%)	Grog pct (%)	Shell pct (%)	Void pct (%)
7	−3.5	−1.8	−2.9	1.8
19	−0.3	4.1	1.7	0.3
22	−8.5	1.0	1.1	1.3
27	−3.2	4.0	−3.3	0.4

[a] Negative percent indicates digital result was less than the point-count result.

identify unusual particles. For example, the scanner cannot identify unknown aplastics that would require use of the Bertrand lens with petrography. However, the scanner is extremely adept at identifying visually distinct aspects of the sample, and can do so with a minimal investment of time. Furthermore, once the sample has been mapped the software provides numerous measurements describing the size and shape of each feature. These measurements essentially come as "freebies" of the software with no additional investment of analyst time.

In summary, the petrographic point-counting technique is ideally suited to provide a more in-depth description of sample composition, while the digital image analysis provides a more complete numerical description of the size, shape, color, and position of features.

3.2. *Accuracy and precision*

Accuracy of a measurement refers to how close it is to the true or accepted value. The point-count method in this study is a systematic sampling procedure in which grains at specific intervals within the entire thin section are counted. The percentages generated are estimates of true percentages. Point-count data following Stoltman's method are considered to have acceptable accuracy based on literature on the reliability of point-count analysis (Stoltman, 1989:151–152) and the point-count data in this study has been used as the standard for evaluating digital results. Digital analyses that consider the entire surface of a thin section certainly have the potential to generate more accurate estimates of true percentages than this point-counting method. However, while digitally-produced grain percentages have the potential for higher accuracy, it is apparent that the method, as implemented, had difficulty in discriminating certain particles and particle sizes below a certain size threshold.

Precision refers to the reproducibility of measurements or observations. Tests involving repeated counts of thin sections indicate counting errors of less than 5%, such that point-count estimations of paste composition are considered to have a high level of precision (Stoltman, 1989:152–153). Regarding units of measurement, digital image analysis offers the potential for more precise measurements of particle sizes. The dimensions of inclusions can be measured on a ratio scale. Petrographic point counts are generally less precise because inclusions are sized using an ordinal scale, within standardized particle size ranges. More precise measurements could certainly be made in traditional petrography, but the extra time involved to measure each counted grain would be prohibitive. And, given the replicability of test results, such precision is not deemed essential.

3.3. *Costs*

Both methods use thin sections, so there is a comparable base cost for both techniques (Table 4). Thin section preparation typically costs $20 per sample. Farming out this chore is generally more cost effective than purchasing the proper cutting and grinding

Table 4
Comparison of costs.

Expense categories	Digital imaging analysis	Petrographic point counts
Thin section preparation	about $20 per sample	about $15 per sample
Analysis charges	NA	NA (but can range $75–$150 per sample)
Supplies	$20 for polarizing filters	NA
Equipment	$100–$200 for scanner; <$2000 for computer if required	a few hundred to several thousand dollars for purchase of microscope and mechanical stage, if not accessible
Software	$350–$850 for image analysis software and Photoshop (or Photoshop-like software)	NA

equipment to prepare thin sections, not to mention time required to achieve proficiency with the task. Several companies are in the business of preparing thin sections for the earth sciences (e.g. Spectrum Petrographics in Vancouver, Washington). The thin sections in this study were made at the geology lab at the University of Michigan for $15 per sample.

The cost of the digital image analysis can vary greatly depending on the available equipment. Assuming access to a computer, the other important piece of hardware is a scanner. It is possible to use an inexpensive consumer-grade scanner with a transparency adapter that can be purchased new for $100–200. Polarizing filters can be purchased from Edmunds Optics for as little as $20. The most expensive purchase for most researchers will likely be the software. This study used an analysis package sold by Reindeer Graphics called Image Analysis Toolkit that can be purchased for $250, although other software options exist including a few free programs (see Reedy and Kamboj, 2004a,b; Reedy and Vallamsetla, 2004a,b). Image Analysis Toolkit requires that you have a graphics program that can use Photoshop-compatible plugins. Adobe Photoshop can cost $650 to purchase new or $250 with an educational discount. But less expensive software can also support the plugins such as Photoshop Elements for $40–100 or Ulead Photoimpact for $50. Thus the total cost of the equipment necessary for this technique could vary from as little as $300 for the cost of the polarizing filters and Image Analysis software to as much as $2500 if one has to purchase the computer, scanner, and all of the software.

The cost of petrographic analyses will also vary mightily if one does not have convenient access to a polarizing microscope with a mechanical stage. Most academic geology departments will have polarizing microscopes, although mechanical stages may be less common. The purchase of a good polarizing microscope with a mechanical stage would involve a substantial one-time cash outlay ranging in the thousands of dollars for a new one and much less for a serviceable used instrument.

Petrographers who are also archaeologists, or vice-versa, are few and far between. Analysis charges might range from $75 to $150 per sample. Some companies that prepare thin sections also provide analytical petrographic services. Spectrum Petrographics, for example, will analyze thin sections for a base price of $75 per hour. Thus the total estimated minimum cost per sample is $90 preparation and analysis. The thin sections in this study were analyzed by Cordell at no cost.

3.4. *Time considerations*

The average time required to perform the digital image analysis procedure can vary tremendously based on the size and nature of the sample (Table 5). Much of the time is invested up-front in developing the techniques and macros needed for classifying the image. Approximately 8 h were invested in developing the macros

Table 5
Comparison of analyst time.

Digital imaging analysis	Petrographic point counts
15 min of analyst time per sample	60 min of analyst time per sample
20 min of computer processing per sample	
(+8 h to develop macros)	(depends on area of thin section, counting interval, minimum number of counted points required)

Table 6
Comparison of advantages and disadvantages.

Petrographic methods	
Advantages	• proven standard for accuracy in microscopic compositional analyses • only technique suitable and appropriate for analyzing smaller, highly heterogeneous samples, or samples about which there is no prior knowledge • best technique for discriminating compositions of birefringent grains and for resolving silt and very fine particle sizes • especially adept at correct identification of similar-looking constituents • would be recommended as a precursor to a proposed digital image analysis study
Disadvantages	• may be more time-consuming • may be more expensive
Digital Imaging Analysis	
Advantages	• can provide many more measurements on particle size, shape, and location • digital nature makes it much easier to share the steps and the results of the analysis with others • may be faster under some circumstances
Disadvantages	• it is necessary to match the resolution to the smallest and least visually distinct feature of interest. In this study the resolution selected was unable to resolve silt and very fine particle sizes of birefringent grains and compositions of certain tempers and other inclusions

used in Livingood's original analysis of 29 thin sections. This would have been a lousy investment if there were only four samples to analyze, but would have been very economical with 100 samples. It was necessary to develop different techniques for different sherds in the sample. For example, different batches of macros were required in the test sample for sherds with dark-brown and black versus light brown or reddish pastes.

Besides the time it took to develop the procedures, about 5 min was required to scan each thin section and align the images, and 10 min of hand checking and editing the final results, for a total of 15 min of analyst time for each sample. In addition, it took the computer about 10 min of processing time to run the first batch of macros and about 10 min to measure the features, for an additional 20 min of computer processing per sample that can be done while the computer is unattended. These processing times are influenced by the processing power of the computer and the size and resolution of the scans.

Becoming a skilled petrographer is not an easy task. Cordell's efforts to learn petrography resulted in acquiring a supplementary BS in geology. Excluding extra semesters of schooling, the point-counting procedure required an average of just over 45 min of analysis time per sample. Analysis time is of course related to the size or area of the thin section, the counting interval, and minimum number of points or number of times the thin section must be counted. In this sample, the approximate areas ranged from 110 mm^2 for sample 27 to 217 mm^2 for sample 19. The analysis times ranged from a low of 30 min for sample 22 to a high of 60 min for sample 19. Although it has the lowest area, sample 27 required more analysis time because it had to be counted twice to obtain the requisite minimum number of counts. An additional 15 min per sample was expended to record other observations, such as matrix colors, presence/absence and/or relative frequencies of accessory constituents, and characteristics of the grog-temper. Thus the total average analysis time was just over 60 min per sample. Neither set of totals include time spent on data entry, tabulation nor write-up.

3.5. Advantages and disadvantages

From this discussion, there are several advantages to petrographic point counting and petrographic compositional analysis (Table 6). The established point-counting methods have acceptable accuracy and petrographic compositional analysis draws upon over a century of geologic literature on optical properties of minerals and decades of application to archaeological data. It is the preferred technique for analyzing smaller sample sizes, highly heterogeneous samples, or samples about which there is no prior knowledge. It is the best technique for discriminating compositions of birefringent grains and for resolving silt and very fine particle sizes. It is especially adept at making the close-calls with regard to identification of similar-looking constituents.

The principal advantage of digital image analysis of ceramic thin sections is that it can provide many more measurements on particle size, shape, and location (Table 6). Much of this information may not always be of interest, but the added information is "free" in that there is no extra time invested. Further, the digital nature of the project makes it much easier to share the steps and the results of the analysis with others. The work can be easily checked by others and the results can be quickly and easily edited to fit different classification schemes. Digital image analysis may be faster under some circumstances. It would be preferable for extremely large sample sizes or for certain very specific applications. The principal disadvantages of this test of digital analysis were the inability to resolve silt and very fine particles sizes of birefringent grains and compositions of certain tempers and other inclusions. One way to resolve both particle size and compositional inadequacies may be to scan at a higher resolution. This is a perfectly feasible proposition, as there are several <$200 scanners that can produce 4800 dpi scans, expensive publishing-grade scanners capable of scans >10,000 dpi, or there is the option to gather digital photomicrographs directly from a microscope. In this particular application Livingood proceeded with the analysis with the available hardware and resolution, opting to make no measurement on birefringent particles smaller than .2 mm^2 (Livingood, 2006, 2007). This would not have been adequate for some applications, but it was fine for Livingood's original purpose of recording the ratios of grog and shell across vessel types. These results also suggest that those planning to use a digital approach should start with the petrographic method to better anticipate the required scanning resolution and to determine whether there are visually indistinct particles of importance that might frustrate digital identification.

4. Conclusions and recommendations

In closing, it is agreed that both methods make valuable contributions to the understanding of pottery in archaeology. Petrographic methods have a much broader application, would be appropriate to use in most instances, would be recommended as a precursor to any proposed digital analysis, and have a much better capacity to permit fine distinctions. Digital image analysis remains a viable means of conducting temper analysis and might be preferable under certain circumstances. The advantage increases if the process can be more easily automated. Automation is facilitated when the samples are relatively homogenous and if the particles of interest have a high visual contrast or particular regularities in size, shape, color, or texture. If automation or partial-automation is feasible, then a digital approach would be preferable for the analysis of large sample sizes. It is also preferable when complex measurements of the features are necessary. The relative success of digital analyses with more pottery having a more complex paste matrix is unknown, but could be evaluated with a similar test case comparison of methods.

Acknowledgments

A version of this paper was presented in the symposium "Recent Contributions to the Application of Ceramic Method and Theory in the Archaeology of the Midwest and Southeastern US" at the 2004 joint meeting of the Southeastern Archaeological Conference and Midwestern Archaeological Conference in St. Louis, MO. We want to thank the three anonymous reviewers who provided thoughtful comments on the manuscript.

Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jas.2008.11.015.

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