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DIGITAL IMAGE ANALYSIS IN MICROSCOPY FOR OBJECTS AND ARCHITECTURAL CONSERVATION

Elizabeth Goins and Chandra L. Reedy

Abstract

The advent of high-speed computers and comparatively large memories, coupled with digital microscope cameras, has brought about a revolution in computer-assisted image analysis. New software can ease the pain of previously laborious methods of thin-section and cross-section analysis. Image analysis not only speeds traditional microscopical methods, such as point counting, but also improves accuracy. By using image analysis software, a job that would have taken hours by traditional methods now takes only seconds. This increase in speed allows more time for additional investigations, such as examination of textural relationships between particles. The great accuracy enabled by area analysis of thin sections also allows more detailed comparison between samples in technological studies, and facilitates new tests of sampling issues and statistical accuracy.

Increased accuracy is now possible in examination of materials characteristics such as percentage of aggregates, pores, temper, or specific minerals; pore or grain size; grain shape; and other important features of petrographic thin sections. The increased accuracy and the ability to conduct more detailed and comprehensive studies can positively impact characterization, analysis, and interpretation of composition, technology, provenience, deterioration, and preservation. In this paper we explore new applications of image analysis technologies to the microscopical examination of a cross sections or by petrographic thin section analysis of low- and high-fired ceramics, unfired clay artifacts, stone objects, and historic mortars.

1. Image Analysis

Image analysis refers to the application of computer processing to aid in the measurement or quantification of features visible within an image. Typically the images are photomicrographs of sections either in transmitted or reflected light. Images from scanning electron microscope/ backscattered electron imaging are also analyzed by image analysis. In this paper all image analysis was conducted using the Image-Pro Plus package from Media Cybernetics..

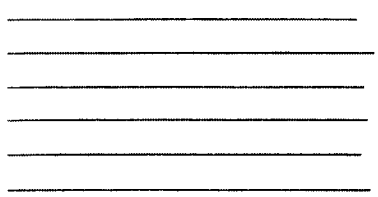
The major advantage that image analysis has over traditional visual estimations is that it facilitates efforts to characterize, classify and compare images by using numerical values. It then becomes possible to accurately measure features of an element or number of elements, such as length, width, distance between features, roundness, size distribution and clustering of features, among others.

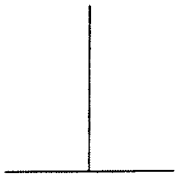
Image analysis was developed from the traditional methods of modal analysis, like point counting,

and therefore must hold to the same rules. Modal analysis, commonly used in geology for estimating the relative proportions of phases in a rock, is based on the De Lesse (1956) relation which states that the ratio of the area occupied by a mineral (A) to the area occupied by all minerals (the total measurement area) is a consistent estimate of the volume percentage of mineral A in the rock.

The problem with the traditional method of modal analysis is that the estimates can be biased by optical deception. The human eye is very effective in some areas of visual comparison but is somewhat poor in its ability to determine quantitative information like length and area (Jähne 1995). With the advent of inexpensive, powerful personal computers, the development of image analysis as an effective tool became feasible so that more accurate information could be pulled from the sample.

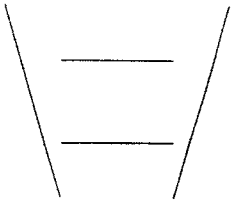
It is easy to trick the human eye in some cases. The following illustrations show some of these effects. In the figure to the right, a number of parallel lines are shown. The length of the lines varies by up to 5%, and, in this case, it is easy for our eye to determine that they are of different lengths.

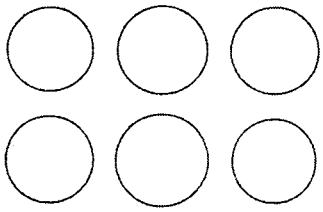




This illustration shows the influence of the direction of the lines. Both of these lines are the same length, yet to our eyes the vertical line appears longer than the horizontal.

Perspective: The two parallel lines in the center are of equal length, but our eyes interpret the upper line as being longer than the lower line.





The eye is a poor estimator of volume or area. The area of the circles to the left varies by up to 10%, yet it is difficult for us to determine much difference - let alone by what percentage they vary!

Traditional modal analysis attempted to compensate for the inability of the human eye to quantify features by a number of different methods. In the beginning DeLesse based his work on areal ratios. He would trace the minerals of a section onto wax paper then transfer the design to tin foil which was then cut out and each mineral component was weighed. The time it would have taken to accomplish the measurement for one section must have been enormous. And, the possibilities for error must have been extreme.

Eventually, it was found that by measuring the length of each mineral an estimate of relative ratios could be found. This is called the lineal traverse (Figure 1) where a mechanized stage moves the sample over evenly spaced traverses.

$$\text{Relative amount of mineral (mode)} = \frac{\text{Length of the mineral traversed}}{\text{Total length traversed}}$$

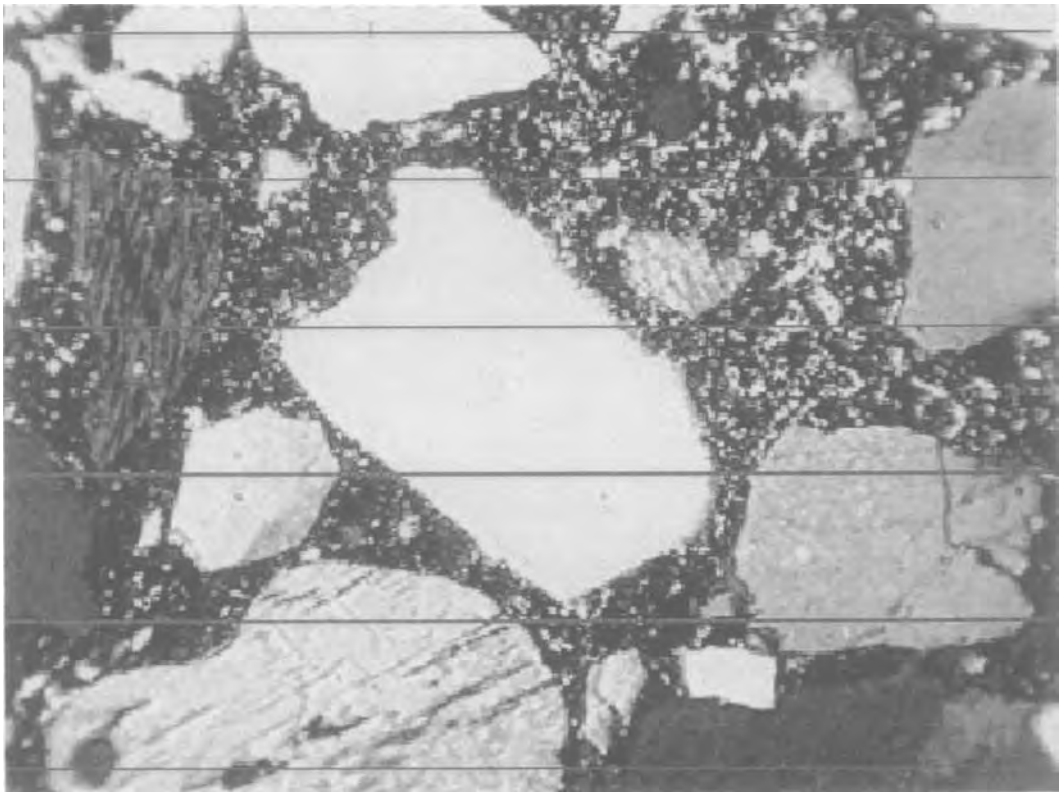


Figure 1: A polished cross section of a lime mortar and aggregate. The lines superimposed over the image would measure the relative areas in the lineal traverse method (distance separating the traverses has been compressed for illustrative purposes).

Finally, the point counting method developed that is most commonly used today. This technique estimates the relative proportions of phases by identifying and counting minerals located at grid intersections or points (see Figure 2).

$$\text{Relative amount of mineral (mode)} = \frac{\text{Number of times a mineral is found at grid intersections}}{\text{Total number of points counted}}$$

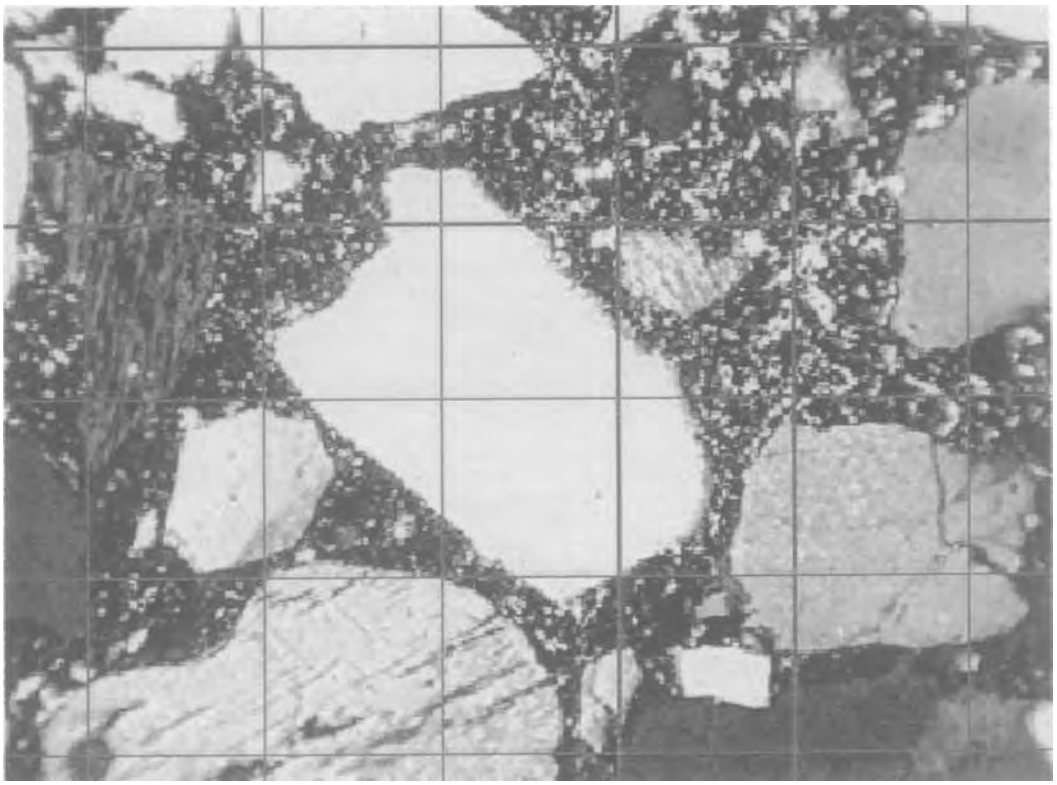


Figure 2: The same polished section as in Figure 1 with a grid superimposed over the image for the point counting technique. Again, distances between parallel lines have been compressed for illustrative purposes.

Areal measurements (Figure 3) could not be reliably, or easily, carried out until the advent of personal computers and image analysis software. The software analyzes the image and picks out areas of different intensity or color values. This makes contrast within the image to be analyzed an important issue. In this figure we were able to pick out grains within a particular size range and contrast. This image is the same as used for the point and lineal traverse illustrations. Notice that the software did not pick out the darker grains along the edges. Once the features or minerals of interest can be separated from the matrix then we can begin to try and characterize the material in more detail.

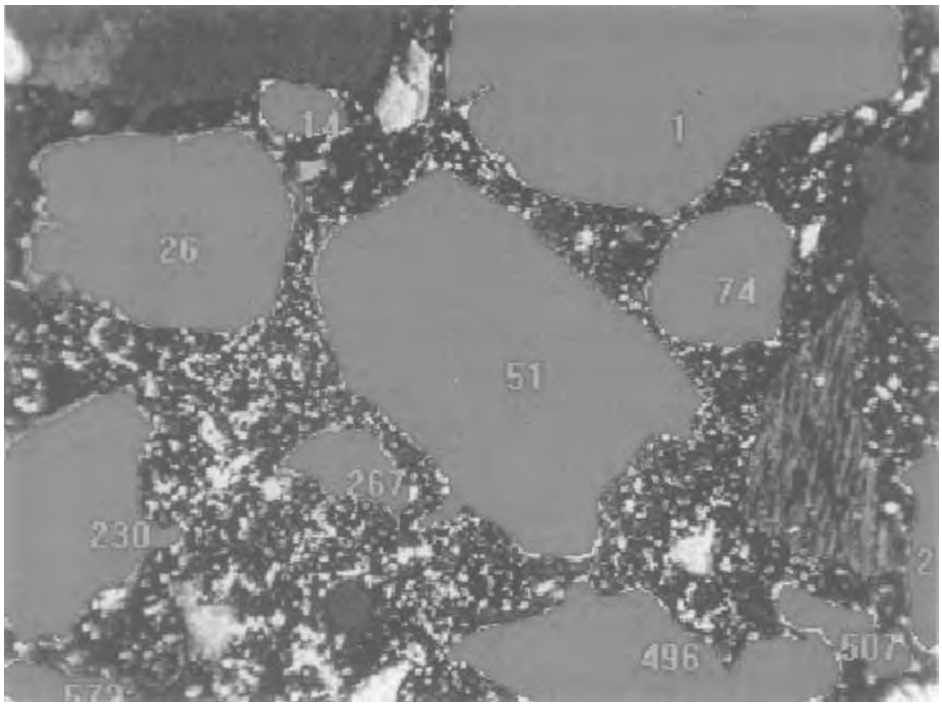


Figure 3: The polished section of Figures 1 and 2 again but the sand grains are highlighted for measurement within Image-Pro Plus.

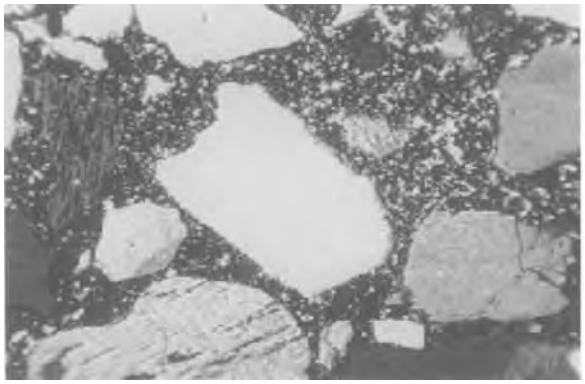
One major issue that is of concern for any method of modal analysis, be it point count, lineal traverse or the areal analysis by image analysis, is statistical validity. It is imperative that enough points or grains are examined to give the analysis statistical validity.

This begins with the design of the experiment; that is, the samples must initially be selected so that they are truly representative of the material being studied. The samples selected then must be large enough so that they can include any variations that may be present.

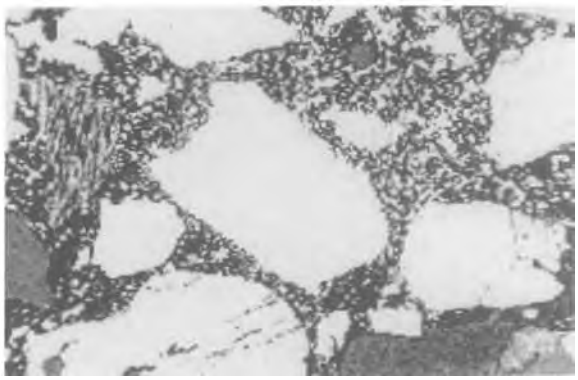
The sample size and number of grains studied will vary with the material. In particular the grain size will have a great impact. The bigger the particle sizes the larger the sample required. Also, the amount of that phase present within the material will influence number of grains counted. Obviously, if the phase of interest is a minor phase, present in low amounts, more grains will have to be counted overall to give a high enough confidence level.

Assuming that the sample is statistically relevant, getting the image analysis software to work often requires enhancement of the image. This means that the initial analyses of the material can be time consuming until a reliable method of enhancements has been found. In the image below we would like to measure all the grains. However, they are different shades of gray and the

software would have difficulty "thinking" that they were all the same phase. There are a number of ways to compensate for this. One way would be to take a series of measurements within each gray or intensity scale and then add the results together. However, software like Image-Pro Plus allows one to manipulate the image. In this example we have simply upped the image contrast and brightness.



4a: Polished section.



4b: Polished section (a) with increased contrast and brightness.

There are a number of different filters and algorithms that may be applied to the images in order to enhance features of interest. The filter in the example below (Figure 5) emphasizes all the edges and ignores particle masses.

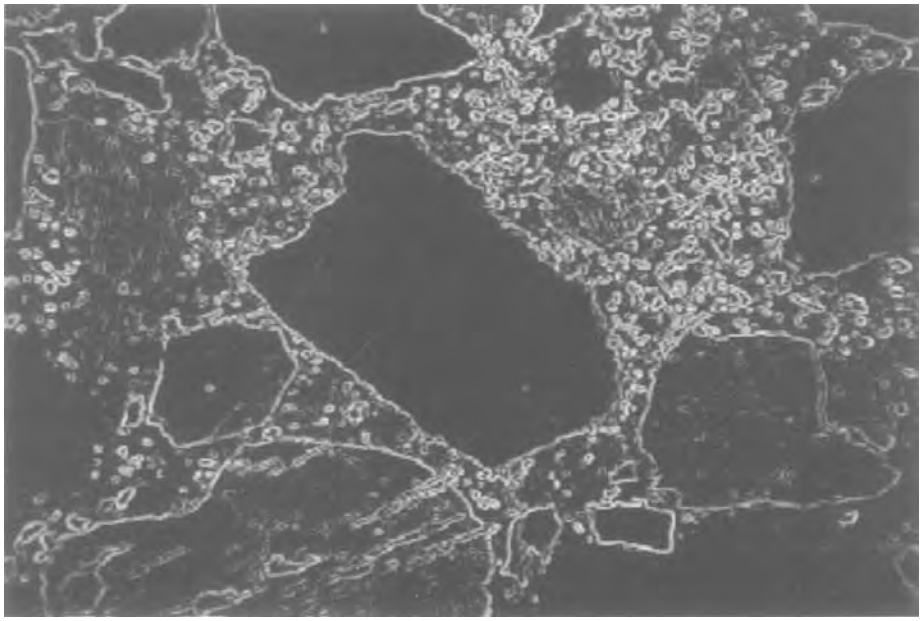


Figure 5: The polished section (as in previous figures) with an edge filter applied.

Once the features of interest can be separated reliably by the software, the analysis can begin. In the example below (Figure 6), the first step was to define an area of interest by simply drawing a rectangle around the grains we wanted to study. The grain boundaries were determined and then data was collected on the perimeter, roundness, length of axes, etc., of each grain.

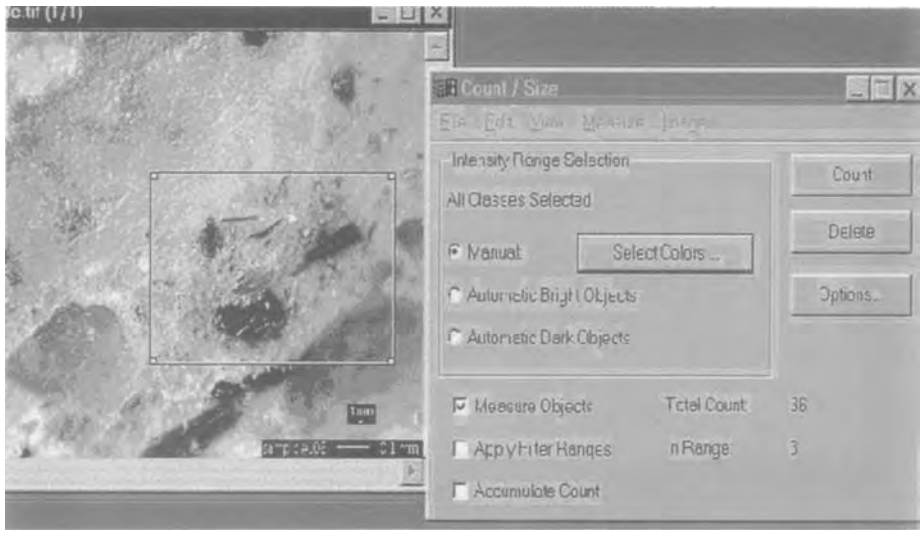


Figure 6: A polished section within the Image-Pro Plus environment. The grains to be studied are outlined and then selected for measurement.

The software nicely determines the area of the grains for the measurement of many of the features (Figure 7).

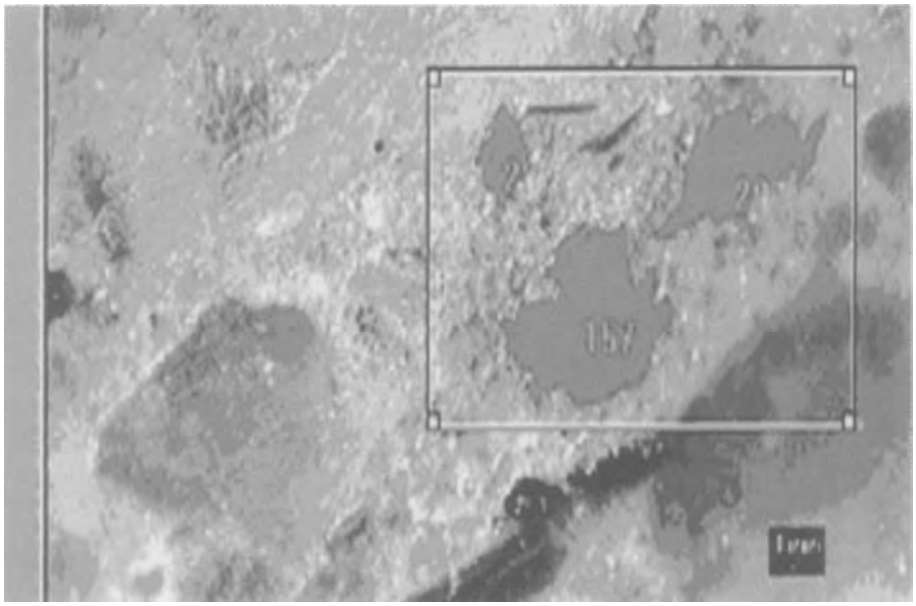


Figure 7: Image Pro-Plus has determined the area of the grains to be measured.

Once the data is collected, which takes only a few seconds, it is easily exported into a spreadsheet like Excel (Figure 8).

Obj.#	Axis (major)	Axis (minor)	Diameter (mea	Radius (max)
28	0.19905038	0.14419197	0.16504091	0.11242238
29	0.46274218	0.22671236	0.32958165	0.29607078
157	0.47132242	0.35698923	0.39760616	0.2755248

Obj.#	Size (length)	Size (width)	Perimeter	Radius Ratio
28	0.22164917	0.15682983	0.60503036	1.7304498
29	0.56881714	0.29718018	1.5529007	3.6174127
157	0.51876068	0.38704681	1.717976	2.467848

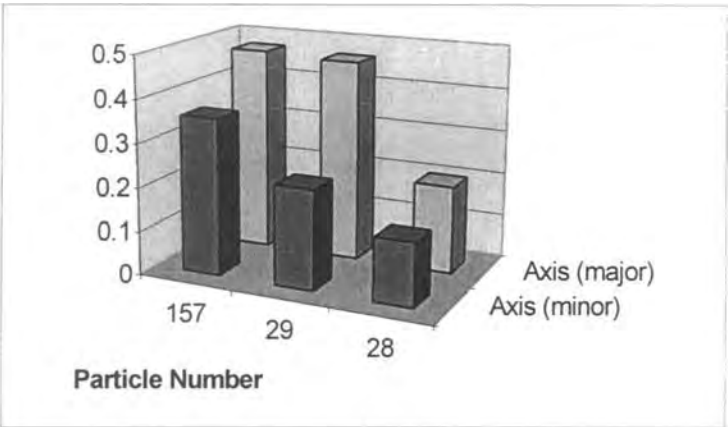


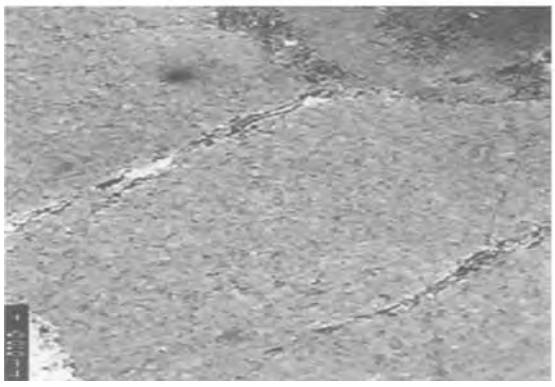
Figure 8: Results from Image-Pro Plus analyses output to Excel.

2. Conservation Research Applications

One of the most obvious uses for this procedure is to determine the thickness of layers with great accuracy. In this example we have defined a number of different layers. The example (Figure 9) shows a thin foil of copper over a mortar substrate. The surface layer runs along the very right edge. The foil is being pulled apart from weathering and the crack is outlined and measured in the center of the foil layer on the right. We are able to measure both the lengths of the traces and the distances between them. A number of points are measured along each line and the minimum; maximum and average distances are easily determined (these are given by the CT values in the chart).

Figure 9: Measuring thickness in Image-Pro Plus.

One example of the usefulness of image analysis in studies of objects or architectural materials is in studies of the deterioration of stone. In granite, for example, the presence of microcracks in quartz grains (Figure 10a, b) has been shown to be related to degree of weathering (Dearman and Irfan 1978; Ordaz et al 1978; Rainey and Whalley 1994; Hernandez 1996; Molina et al 1996). Typically, researchers want to count the number of microcracks found while moving along a linear transverse area in a thin section of standard size. The overall length and average fracture length is also computed. Multiple thin sections, usually at least 5, are analyzed to characterize a stone or to check for differences between external surfaces and interior samples. For relatively wide cracks, such as the ones in Figure 10a, the width of the crack may also be assessed.



10a. Two microcracks within a quartz grain in granite; both are relatively wide.

10b: This microcrack extends into multiple grains and is developing numerous offshoots.

Other variables that are often recorded include whether the cracks are located within single grains, or if they are intergranular, extending into adjacent grains, as on Figure 10b. The fractal character of the crack is also considered an indication of severity of deterioration -- as the lower crack in figure 10b has begun developing many tiny crack offshoots from the original crack. This is often found where there are intergranular cracks and multiple cracks.

In contrast, grains with mostly single isolated microcracks (Figure 11) tend not to have yet developed many offshoots or feathering characteristics.

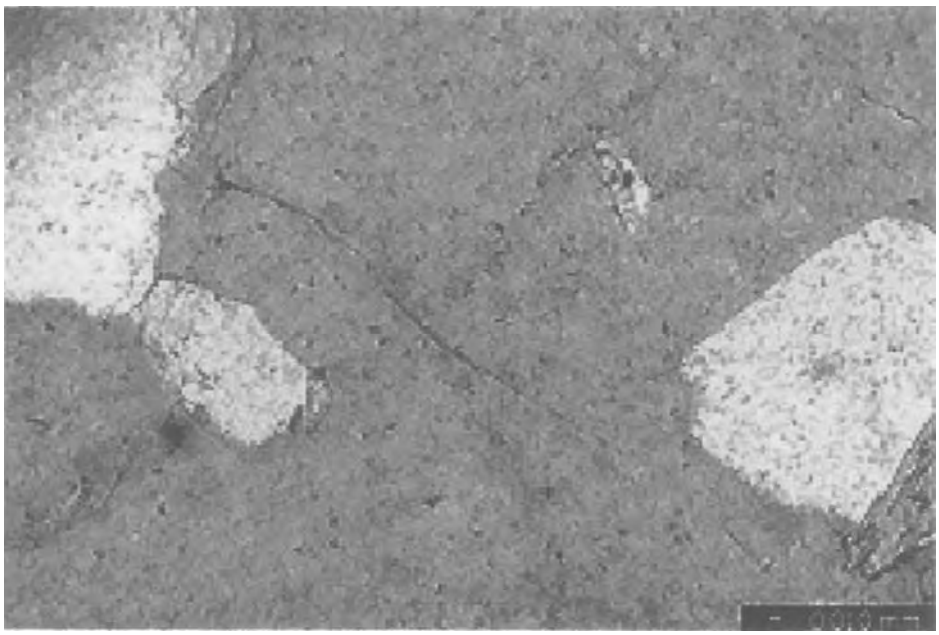


Figure 11: Quartz microcrack without offshoots or feathering.

The tedious task of trying to accurately measure the length of many curving microcracks is made much easier by digital image analysis. But first each image must be calibrated so a length in a specific unit, such as microns, can be calculated, rather than simply the number of pixels measured. This is done by including a scale bar for each magnification , then using that bar to save the spatial calibration for use in all calculations.

Using a tracing tool, we can trace along the crack we want to measure (Figure 12), here labeled T1. The length will be automatically calculated in whatever units we used for the calibration. The ease of this method is especially apparent for samples with more complex cracking patterns.

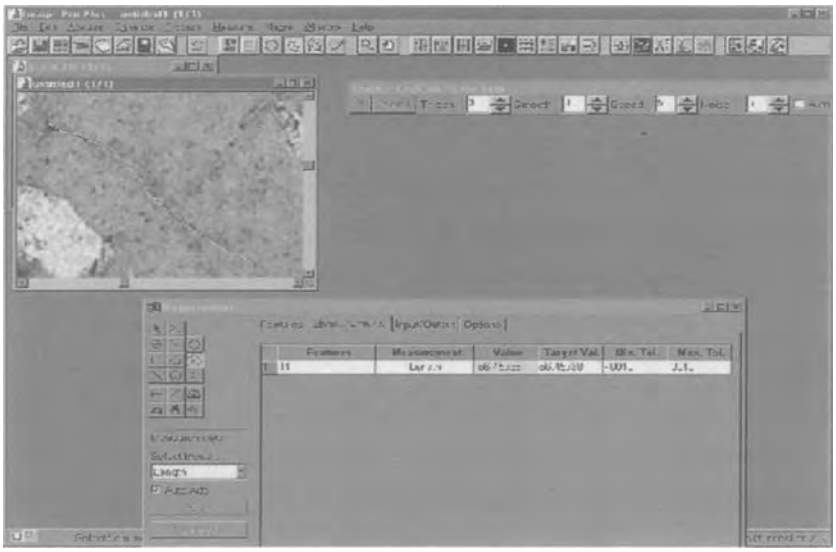


Figure 12: A tracing tool is used to measure the length of a curving microcrack in a quartz grain within granite.

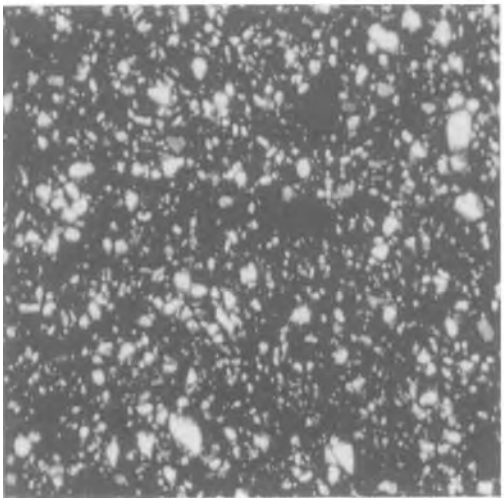
Another example with stone is in measuring deterioration layers, as an assessment of weathering. In Figure 13 we have volcanic tuff with an outer layer of severely altered material, very different in appearance from the layer below. The method of measuring thickness of the layer is the same as we saw for the corrosion layer above. Lines are traced along the two edges of the layer, T1 and T2, and the distance between them measured. We are generally interested in not only the average width, or distance between the two lines, but also in the minimum and maximum distance. This process allows us to examine variation in the outer weathering layer (CT) that would be very tedious to do by traditional methods using a micrometer to take each individual measurement by eye.

Figure 13. Measuring the weathering layer on a volcanic tuff specimen.

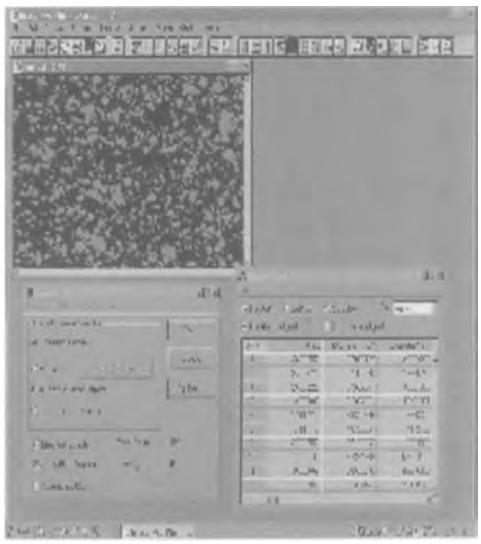
With thin sections of ceramic materials, there are many things we look for depending on the goals of the study. Thin sections may be used as part of an assessment of deterioration, or for investigation of the range of technological choices made by the producers, or for provenance studies (grouping objects by a region of production or a workshop, based either on geological characteristics of temper additives, such as shape of quartz grains, or by technological characteristics, such as the amount of temper added). In addition to extremely tedious point counting, determining the amount of temper additives has often been done by visual estimation, using diagrams to try to visually determine the percentage of components such as quartz sand, shell, organic tempers, or pores left from burnt-out organic temper. The British Museum published very detailed versions of the visual estimation diagrams (Matthew et al 1990), but still it is extremely difficult to be very accurate, thus making it difficult to use such criteria to distinguish between workshops.

In Figure 14a, a crossed-polarized image of a ceramic thin section (x20), we want to determine the percentage of quartz and feldspar grains of the sand temper (the white and gray spots) within the clay matrix (the dark background area). It is also useful to characterize the size and homogeneity of temper materials.

In this case the bright objects were selected for counting. If some seem to have been missed, the filter could be changed to include anything slightly gray; or certain mineral grains (such as small rectangular mica grains) could be eliminated from the count.



14a: A ceramic thin section (x20) in crossed polarized light, showing white sand grains (mainly quartz and feldspar) within a dark clay matrix.



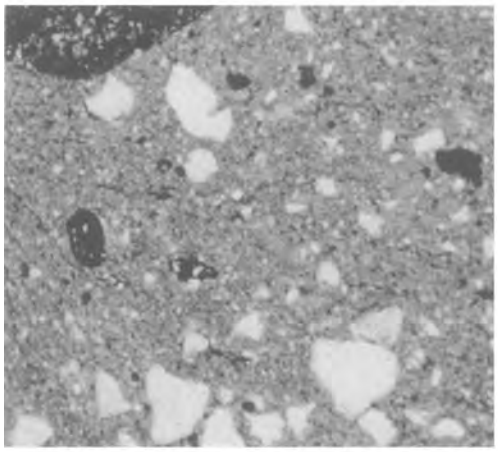
14b: Using Image-Pro Plus, the bright sand grains were highlighted for counting. The area of the sand temper is given as a percentage of the total area of the image.

A wide variety of measurements can be taken. In Figure 14b we are looking at area. The area of each of the 881 counted objects is given, along with their minimum and maximum diameter. Any particular grain can be examined more closely if needed. The total area of the counted sand grains is then given as a percentage of the total area of the image.

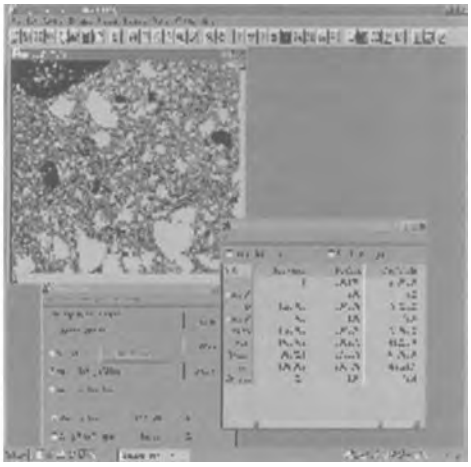
A variety of statistics can be calculated. One example would be to do a histogram of the distribution of grain lengths. Or, the data can be exported to a statistical package to compare the characteristics of two or more ceramic groups.

For comparison, Figure 15a shows another ceramic thin section, in plane polarized light. The hematite-rich clay has a sand temper that appears different from the previous one, more angular in shape and with more variation in size. These characteristics can be much more quickly and accurately measured with digital image analysis. Here again the counted sand grains are the bright objects within the darker clay matrix.

We can choose any number of measurements that might be significant in distinguishing between technological choices and/or between geological sources of the sand. In Figure 15b, for example, we are looking at the range and average degree of roundness, range and average lengths, and overall percent area covered by the sand grains. We might want to eliminate some grains from the measurements (the smaller ones, for example), or measure them separately if we think they may be characteristics of a coarse clay rather than being part of the temper additive.



15a. A ceramic thin section (x20) in plane polarized light. The light areas are angular sand grains within the clay matrix.



15b: The sand grains are highlighted by Image-Pro Plus for counting and measurement for a variety of statistics.

Finally, one characteristic of sand tempers that often reflects a geological source is the degree of rounding of quartz grains, an indication of how much a sediment was transported and worn down before deposition. In the past, the most common method of assessing this was visual estimation against reference photographs to identify grains that are rounded, subrounded, subangular, or angular. It is often difficult to make decisions between these categories, and because there is usually some variation, many grains must be included in an assessment. In the previous examples, the roundness of all grains counted was measured. If we want to focus on individual grains, we can trace around the edges of a grain, and calculate its roundness; in Figure 16 it is 2.16.

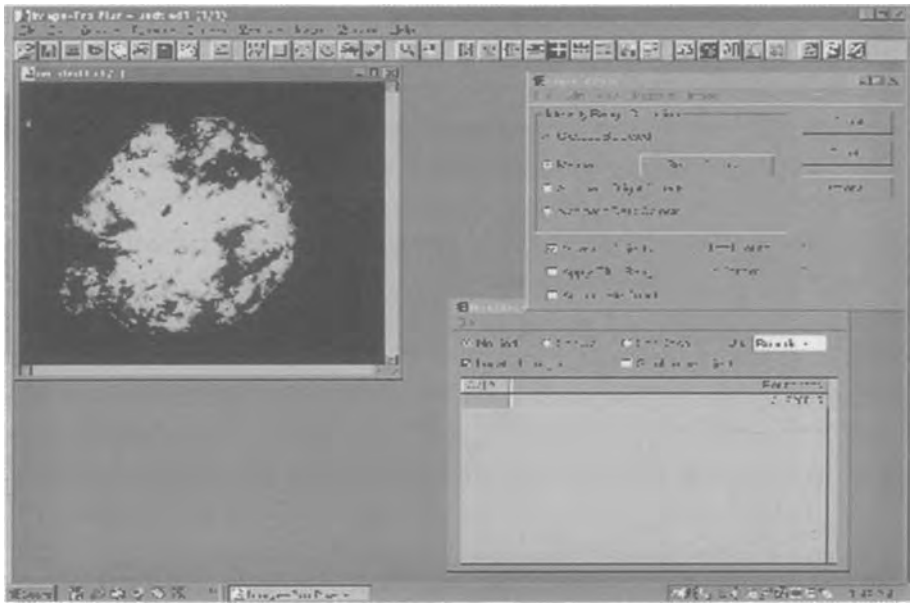


Figure 16. The roundness of an individual quartz grain within a ceramic sand component is calculated by tracing around the grain borders and selecting a roundness measure .

In Figure 17 we see a more angular grain, measured at 1.58. There are many, many more ways in which digital image analysis can aid in the characterization and study of objects and architectural materials. The existence of extensive materials analysis packages, eliminating the need for most in-house programming, makes this work practical and widely available. However, the analysis is by no means automatic, and still requires careful examination of each image and the selection of appropriate choices at each step of analysis.

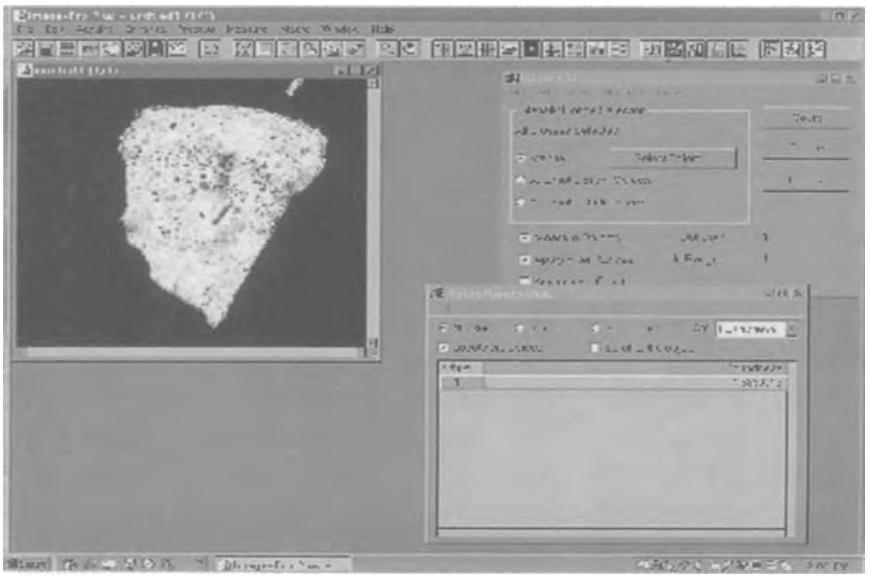


Figure 17. The roundness of this more angular grain (1.58) is found to vary greatly from that of the rounder grain (2.16) of Figure 16.

Note

Apologies for the low quality of many of the images used here. They were captured from screen shots and, unfortunately, the resolution is very low and could not be improved. Those interested in viewing the digital images should contact the author.

Acknowledgements

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Materials and Supplies

Image-Pro Plus, Media Cybernetics, www.mediacy.com